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ASEAN grid flexibility: Preparedness for grid integration of renewable energy

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ABSTRACT

In 2015, ASEAN established a goal of increasing renewable energy share in its energy portfolio from approximately 13–23% by 2025. Renewable electricity, especially intermittent and variable sources, presents challenges for grid operators due to the uncertain timing and quantity of electricity supply. Grid flexibility, the electric grid's ability to respond to changing demands and supply, now stands a key resource in responding to these uncertainties while maximizing the cost-effective role of clean energy. We develop and apply a grid flexibility assessment tool to assess ASEAN's current grid flexibility using six quantitative indicators: grid reliability, electricity market access; load profile ramp capacity; quality of forecasting tools; proportion of electricity generation from natural gas; and renewable energy diversity. We find that ASEAN nations cluster into three groups: better; moderately; and the least prepared nations. We develop an analytical ramp rate calculator to quantify expected load ramps for ASEAN in an integrated ASEAN Power Grid scenario. The lack of forecasting systems and limited electricity market access represent key weaknesses and areas where dramatic improvements can become cost-effective means to increase regional grid flexibility. As ASEAN pursues renewable energy targets, regional cooperation remains essential to address identified challenges. Member nations need to increase grid flexibility capacity to adequately prepare for higher penetrations of renewable electricity and lower overall system costs.

1. Introduction

The International Energy Agency (IEA) forecasts a 30% increase in world energy demand by 2040; Southeast Asian nations are a major source of this increased demand and have stated goals to incorporate more variable renewable energy (IEA, 2016a). With IEA projecting 43% increase for global renewable energy capacity, grid flexibility is a key factor in integrating renewable energy into the electrical grid (Cochran, 2015; Hsieh and Anderson, 2017; IEA, 2017a; Martinot, 2016). Grid flexibility refers to the grid's ability to respond to changes in supply and demand from different sources. As more renewable energy is integrated to the electric grid, the uncertainty in electricity generation by variable renewable sources challenges the standard grid operation and affects grid stability (IEA, 2016b). In many regions, such as Denmark and Spain, electricity generation by renewable energy represents 30% or more within their grid system demonstrating technical and commercial viability (Cochran, 2015; Weiss and Tsuchida, 2015). Studies have also concluded grid integrated variable renewable energy at 30% is possible in United States' regional grids with minimal system changes (Bloom et al., 2016; California Public Utilities Commission, 2015; Lew et al., 2010). In China, wind alone could meet at least 15% of China's primary energy in 2030 with minimal expansion of new generation capacity and better restructuring of markets and institutions (Davidson et al., 2016). Although technological solutions have been developed to address the technical difficulties in integrating significantly more renewable energy, grid operational changes are needed for increasing grid flexibility (Cochran, 2015). A specific study on regional grid flexibility is needed to understand current progress and preparation for renewable energy grid integration.

In 2015, the ten member nations of the Association of Southeast Asian Nations (ASEAN) established a goal to increase the share of renewable energy in its energy mix from approximately 13–23% by 2025 (ACE, 2016). As a region with diverse renewable energy sources, the

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Table 1
The six indicators used to characterize grid flexibility.

Indicator	Grid Flexibility Characteristic
Grid Reliability	How reliable, in terms of disruptions, is the current grid?
Load Profile Ramp	How steep is the nation's worst-case scenario ramp in an average daily load profile?
Electricity Market Access	How much access to electricity trade does a nation have for balancing surplus and deficit electricity generation?
Forecasting Systems	Are forecasting systems used to predict the expected generation from solar and wind energy?
Proportion of Natural Gas in Electricity Generation	What is the proportion of electricity generation by natural gas?
Renewable Energy Diversity	How many different renewable energy sources are currently grid integrated?

Table 2
Questions presented in USAID and NREL workshop on grid flexibility (USAID, NREL, 2015).

Questions
What is the size of the balancing area?
How is wind and/or solar forecasting integrated into system operations?
How flexible is the system operator's scheduling and dispatch practice?
How flexible are the portfolio of generation and demand?
How geographically distributed are wind and solar resources?
Do system operators have access to additional balancing resources in neighboring interconnections?
How robust is the transmission system?

various levels of economic development and energy access of ASEAN member nation provide an opportunity for the region to benefit from adopting clean energy technologies. Nations with less investment into an electrical grid have the opportunity to leapfrog and adopt renewable energy, bypassing reliance on fossil fuels. Given ASEAN's renewable energy target is lower 30%, it is feasible for ASEAN to grid integrate more renewable energy with minimal system changes. Each ASEAN nation will need a flexible grid to support and prepare for more grid integrated renewable energy. Through a quantitative adaptation of United States Agency for International Development's (USAID) and National Renewable Energy Laboratory (NREL) grid flexibility analysis, this research identifies individual ASEAN nation's preparedness for its near future of more renewable energy grid integration.

In order to integrate more renewable energy, ASEAN member nations and the region need to shift their grid operational behavior. Here, we have identified representative characteristics of grid flexibility based on qualitative USAID and NREL framework tools in practice and analyzed them in a quantitative manner. By developing a grid flexibility analysis as a proxy for preparedness, we identify member nation's strengths and weaknesses in terms of current practices, grid system operation, and grid characteristics (USAID, NREL, 2015). For ASEAN Power Grid (APG) to successfully incorporate a high renewable energy penetration rate with its larger pool of resources, nations can address the specific weaknesses identified through the results of a preparedness analysis.

The results from this analysis will enable the region's transition to clean energy through lowered transaction costs of integrating renewable energy into the grid. Data collection for analyzing preparedness includes developing quantitative indicators for grid reliability, steepest ramp from electricity load profile, wind/solar forecasting practices, access to electricity trade, and diversity of renewable energy sources. We hypothesize that certain countries with greater income sources, such as gross domestic product per capita, and stronger renewable energy policies will be better prepared for a future with more grid integrated renewable energy.

Table 3
A list of indicators used in our grid flexibility analysis.

Indicator	Metric	Data Source
Grid Reliability	System average interruption duration index (SAIDI) System average interruption frequency index (SAIFI)	(Arlet, 2017)
Load Profile Ramp	Rate of worst-case scenario demand increase in megawatt per hour (MW/hour) normalized by flexible installed capacity available	(ACE, n.d.; Asian Development Bank, 2015; Department of Energy, Philippines, 2018; Electricité du Cambodge, 2015; Energy Market Authority of Singapore, 2018a, 2018b; ERIA, 2014; IEA, 2016c; IRENA, 2017; Japan International Cooperation Agency, 2014; KeTTHA, 2018; Ministry of Energy, Thailand, 2015; Surahanjaya Tenaga, 2018; Wholesale Electric Spot Market, 2017; World Resources Institute, n.d.)
Electricity Market Access	Capacity of interconnections currently operating and to be completed by end of 2018 in megawatts (MW) under the ASEAN Power Grid framework normalized by peak load	(Andrews-Speed, 2016; Electricité du Cambodge, 2015; Energy Market Authority of Singapore, 2018a; ERIA, 2014; IEA, 2016c; Japan International Cooperation Agency, 2014; Surahanjaya Tenaga, 2018; Wholesale Electric Spot Market, 2017)
Forecasting Systems	Yes or no	
Proportion of Natural Gas in Electricity Generation	Amount of electricity generated by natural gas as proportion of total electricity generated	(IEA, n.d.)
Renewable Energy Diversity	Number of renewable energy sources integrated into the grid	(ACE, n.d.; Asian Development Bank, 2015; Department of Energy, Philippines, 2018; Electricité du Cambodge, 2015; Energy Market Authority of Singapore, 2018b; IRENA, 2017; Japan International Cooperation Agency, 2014; KeTTHA, 2018; Ministry of Energy, Thailand, 2015; World Resources Institute, n.d.)

2. Background

2.1. ASEAN

ASEAN is an important region of study for renewable energy given its abundant renewable resources, and the future that ASEAN faces with energy security challenges and rising demand. The region consists of ten-member nations: Brunei Darussalam (Brunei), Cambodia, Indonesia, Lao People's Democratic Republic (Laos), Myanmar, Malaysia, Philippines, Singapore, Thailand, and Vietnam. Energy demand trends in the region are highly driven by economic and population growth. The IEA predicts an energy demand growth of 65% from 2017 to 2040, and 76% of generation in 2040 will be by fossil fuels (IEA, 2017b). Additionally, the region currently faces an energy insecure future due to decreasing availability of fossil fuel reserves in the region and increased reliance on imported energy resources (Tongsopit et al., 2016). Renewable energy has the potential to increase energy security of the region.

In 2015, ASEAN established a goal to achieve 23% of electricity generation from renewable energy sources by 2025. Each individual

Table 4
Description of the data formats and method used to generate average daily load profiles for calculating load profile ramp. Where data was unavailable for day 15 of each month, the closest date available was used.

Country	Source Format	Method Used to Calculate Average Hourly Demand
Brunei	Average daily load profile graph (ERIA, 2014)	WebPlotDigitizer used to extract hourly demand values
Cambodia	Average daily load profile graph (Electricité du Cambodge, 2015)	WebPlotDigitizer used to extract hourly demand values
Indonesia	Average daily load profile graph (ERIA, 2014)	WebPlotDigitizer used to extract hourly demand values
Laos	Average daily load profile graph (ERIA, 2014)	WebPlotDigitizer used to extract hourly demand values
Malaysia	Hourly demand values (Surahanjaya Tenaga, 2018)	First, we identified daily load profiles from day 15 of each month. Second, we calculated the average hourly demand from values provided by the source.
Myanmar	Average daily load profile graph (Japan International Cooperation Agency, 2014)	WebPlotDigitizer used to extract hourly demand values
Philippines	Average daily load profile graph (Wholesale Electric Spot Market, 2017)	First, we identified daily load profiles from day 15 of each month and used WebPlotDigitizer to extract hourly demand values. Second, average hourly demand was calculated with the 12 data points.
Singapore	Half-hourly demand values (Energy Market Authority of Singapore, 2018a)	First, we identified daily load profiles from day 15 of each month. Second, we calculated the average half-hourly demand from values provided by the source.
Thailand	Average daily load profile graph (IEA, 2016c)	WebPlotDigitizer used to extract hourly demand values
Vietnam	Average weekly load profile graphs (Electricity Regulatory Authority of Vietnam, 2018)	First, we identified weekly load profiles every 4 weeks starting from week 3 of the year and used WebPlotDigitizer to extract hourly demand values. Second, average hourly demand was calculated with the 13 data points.

Table 5
Grid reliability score by country using normalized SAIDI and SAIFI scores.

Country	Normalized SAIDI	Normalized SAIFI	Grid Reliability Score
Brunei	0.97	0.98	0.98
Cambodia	0.00	0.00	0.00
Indonesia	0.94	0.95	0.95
Laos	0.22	0.81	0.51
Malaysia	0.99	0.99	0.99
Myanmar[a]	–	–	0.00
Philippines	0.91	0.94	0.93
Singapore	1.00	1.00	1.00
Thailand	0.99	0.97	0.98
Vietnam	0.65	0.77	0.71
ASEAN	0.74	0.82	0.70

[a] Myanmar does not measure grid reliability, however reports indicated Myanmar suffers from an aging infrastructure and unstable grid (KWR International (Asia) Pte. Ltd., 2015; Macleod, 2017). Thus, we attributed a score of 0 for Myanmar.

Table 6
Load profile ramp score by country. We calculated worst-case scenario for each nation and the associated normalized value. See Appendix A for each country's average load profile.

Country	Load Profile Worst Case Ramp (MW/h)	Flexible Installed Capacity (GW)[a]	Load Profile Worst Case Ramp/ Flexible Capacity	Worst Case Load Profile Ramp Score
Brunei	11	0.586	0.019	0.90
Cambodia	130	0.936	0.139	0.00
Indonesia	970	19.0	0.051	0.66
Laos	17	3.15	0.005	1.00
Malaysia	970	21.7	0.045	0.70
Myanmar	210	3.78	0.056	0.62
Philippines	580	9.28	0.063	0.57
Singapore	300	10.9	0.027	0.84
Thailand	3200	28.8	0.111	0.21
Vietnam	1600	21.1	0.076	0.47
ASEAN Average	800	11.9	0.059	0.598

[a] See Appendix B for installed capacity by fuel type per country.

ASEAN nation has also established specific renewable energy targets (IRENA, 2018). As of 2014, 9% of ASEAN's electricity consumption is from renewable energy, which includes large hydropower (IRENA, ACE, 2016). Integrating more renewable energy on a grid poses certain challenges (as discussed in 2.2). Nations can benefit from the current initiative in creating a regional interconnected grid, ASEAN Power Grid. The project will link individual member nations' electric grid through constructing a series of transmission lines between nations and form a regional market for electricity trade (Hermawanto, 2016). Studies have shown the benefits of regional, interconnected grids to integrate renewable energy over a larger spatial area to cost-effectively transition toward a low carbon future (United Nations, 2006; Wu et al., 2017). Specifically, an interconnected grid provides a larger resource pool to balance surplus and deficit generation through the electricity trade market when compared to an individual nation's grid. The trade system reduces the need for every nation to construct new fossil fuel generation plants to meet its energy demands. As APG develops and the region continues to increase electricity generation by renewable energy, it will be beneficial for the region to be prepared on a long-term basis for the challenges that nations will face in integrating renewable energy. APG is not a solution for all challenges, and higher grid integration of renewable energy will require other changes beyond an electricity market.

ASEAN is a unique region of study. As a regional organization, agreements formed at regional level are non-binding and thus have no mechanism to enforce nations to their goal (Tripathi, 2015). In terms of electricity market, ASEAN has a mix of utility structures from state owned power utilities to privatized and independent utilities (IEA, 2015). It creates complexity for agreements and regional efforts in the electricity sector. This contrasts other international cases of regional cooperation such as European Union. However, characterizing each nations' grid flexibility and indicating practices to integrate more renewable energy can be applied to other nations with similar electricity market structures.

2.2. *Renewable energy*

Renewable energy is most commonly defined as energy produced from natural processes, which are inexhaustible. Common renewable energy sources include solar, wind, geothermal, hydropower, and biomass. Sources can be further classified by dispatchability, which refers to the source's ability to adjust power output in response to system requirements (IEA-ETSAP, IRENA, 2015). Non-dispatchable resources, also referred to as variable renewable energy, include intermittent

Table 7
Electricity market access score by country. We reviewed through the interconnection capacities according to projects completed by 2018 ASEAN Power Grid for each ASEAN country (Andrews-Speed, 2016).

Country	Interconnection Capacity (MW)				Peak Load (MW)	Interconnection Capacity/ Peak Load	Electricity Market Access Score
	Energy Exchange	Import	Export	Total			
Brunei	200	0	0	200	263	0.76	0.024
Cambodia	0	600	0	600	951	0.63	0.020
Indonesia	230	0	0	230	26827	0.01	0.000
Laos	0	0	5132	5132	160	32.08	1.000
Malaysia	1260	0	0	1260	15595	0.08	0.003
Myanmar	0	0	0	0	1542	0.00	0.000
Philippines	0	0	0	0	9929	0.00	0.000
Singapore	450	0	0	450	6475	0.07	0.002
Thailand	380	3584	100	4064	27340	0.15	0.005
Vietnam	0	1248	200	1448	27193	0.05	0.002

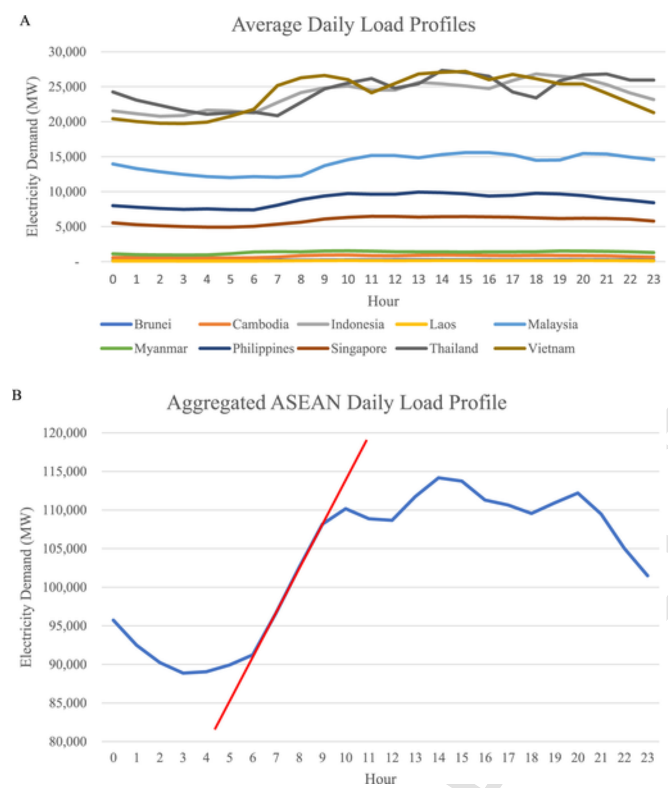

Fig. 1. Average and aggregated load profiles. A. Average daily load profile for each ASEAN nation. B. Aggregated ASEAN Daily Load Profile, which is the demand of each ASEAN nation summed. The red line indicates the steep ramp. See Fig. 2 for individual nation's load profile (Electricité du Cambodge, 2015; Energy Market Authority of Singapore, 2018a; ERIA, 2014; IEA, 2016c; Japan International Cooperation Agency, 2014; Surahanjaya Tenaga, 2018; Wholesale Electric Spot Market, 2017).

sources whereby output is affected by an external factor. For the purpose of this analysis:

- Dispatchable, renewable sources are geothermal, biogas, biomass, and waste-to-energy (WTE),
- Non-dispatchable, renewable sources are solar, wind and small hydropower (SHP). For the purposes of this analysis we define solar, wind, and small-hydropower as non-dispatchable. However, in the future storage may enable the dispatchability of these technologies (Kittner et al., 2017)
- Large hydropower will not be considered as a renewable energy source due to the extensive environmental impacts and associated emissions (Rosa et al., 2004),
- Ocean and tidal energy are not factored in due to the low technical potential in the region (ACE, 2016).

2.3. Challenges of integrating renewable energy

With a higher percentage of variable renewable energy sources, especially wind and solar, the uncertain timing of electricity generation remains an issue to maintain grid stability and frequency (IEA, 2016b; IEA-ETSAP, IRENA, 2015). Solutions to uncertainties require increasing the grid's flexibility, a key factor to addressing stability and reliability issues (IEA-ETSAP, IRENA, 2015; Martinot, 2016). Grid reliability refers to the ability to supply electricity and meet demands. To achieve reliability, a grid needs to remain stable by maintaining a balance of electricity demand and supply at every second. Flexibility describes the grid's ability to respond to the changes in supply and demand from different sources (Cochran et al., 2014). Various solutions exist through system operation, markets, load, flexible generation, networks and storage (Cochran et al., 2014).

Cochran et al. (2014) indicates that increasing grid flexibility through system operations and market changes cost the least for grid operators and nations in transition. Within system operations, technologies and solutions have been developed to address technical barriers of maintaining voltage quality, congestion management, power quality, and predicting electricity generation from renewable energy (Barth et al., 2013; Bullis, 2014; Georgilakis, 2008). These solutions include introducing distribution controls, advanced forecasting technology using artificial intelligence, and energy storage systems. However, other technical barriers require institutional and regulatory changes of grid operations (Cochran et al., 2014).

Institutional and regulatory changes of grid operations aim to address the way grids are operated. These include forming grid codes, using forecasting systems for renewable energy, higher frequency in resource allocation to meet demands, coordination with other grids and curtailments (Cochran et al., 2014). These solutions can be categorized into four main categories: forecasting practices, system flexibility, operational flexibility, and grid reliability. Implementation of these solutions often depends upon funding and large investments, along with policy changes. Understanding the grid flexibility through these measures will indicate the extent to which a nation's grid is adequately prepared to integrate more renewable energy into their power systems at low cost.

2.4. Current renewable energy research in ASEAN

2.4.1. ASEAN and ASEAN power grid

Many studies in the region have focused upon infrastructure issues related to APG. Li and Chang identify the institutional barriers related to financing APG (Li and Chang, 2015). They indicate the need for

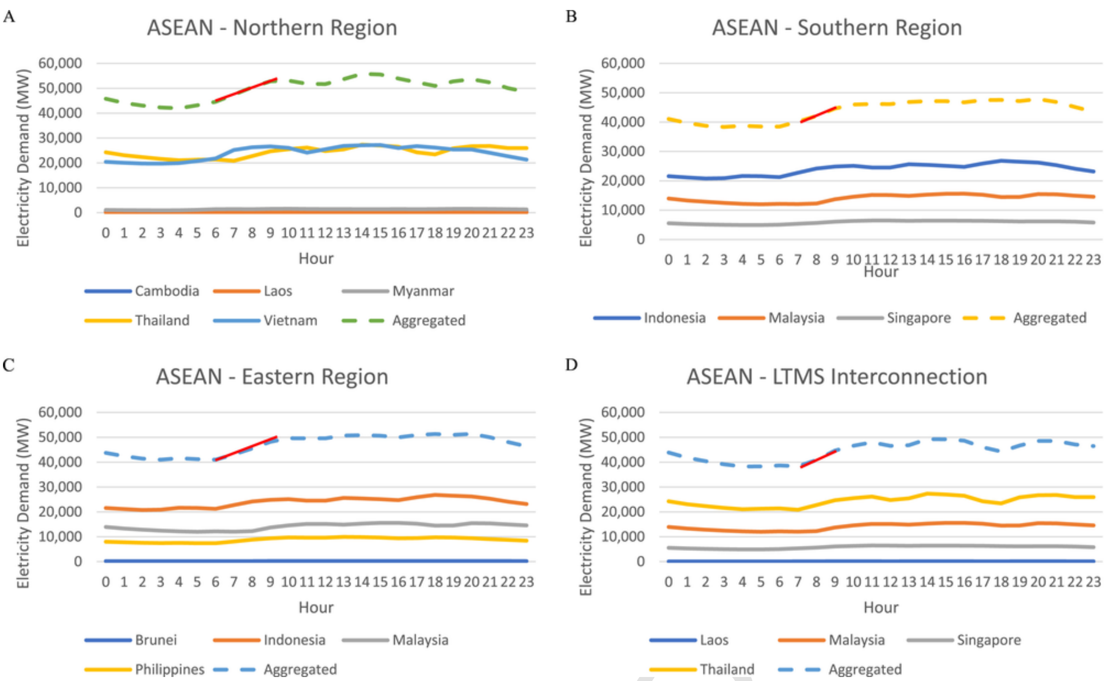

Fig. 2. A – C. Average daily load profile by ASEAN regions according to the APG plan, which identifies the sub-regional trade markets prior to a fully integrated ASEAN region system (Hermawanto, 2016). D. Average daily load profile for a recent agreement on multi-lateral electricity trade, LTMS Interconnection. The red lines in all figures indicate the steepest ramp.

Table 8
Proportion of electricity generation by natural gas for each ASEAN country (IEA, n.d.).

Country	Proportion of Electricity Generation by Natural Gas	Natural Gas Electricity Generation Score
Brunei	0.99	1.00
Cambodia	0	0.00
Indonesia	0.25	0.25
Laos	0	0.00
Malaysia	0.47	0.46
Myanmar	0.39	0.39
Philippines	0.23	0.23
Singapore	0.95	0.96
Thailand	0.71	0.72
Vietnam	0.33	0.34
ASEAN Average	0.99	0.44

Table 9
Renewable energy diversity score by country. We counted the different types of grid integrated renewable energy and conducted min-max normalization for the score (ACE, n.d.; Asian Development Bank, 2015; Department of Energy, Philippines, 2018; Electricité du Cambodge, 2015; Energy Market Authority of Singapore, 2018b; IRENA, 2017; Japan International Cooperation Agency, 2014, 2014; Ministry of Energy, Thailand, 2015).

Country	Renewable Energy Diversity	Renewable Energy Score
Brunei	1	0.14
Cambodia	1	0.14
Indonesia	5	0.71
Laos	3	0.43
Malaysia	4	0.57
Myanmar	0	0.00
Philippines	4	0.57
Singapore	2	0.29
Thailand	7	1.00
Vietnam	4	0.57
ASEAN Average	3.1	0.44

public-private partnerships as necessary steps beyond funding from intergovernmental organizations. The financial model produced uses a least cost approach and factors in transmission line costs, financing and power trade policies with various trade levels between nations (Chang and Li, 2013). The results indicate that Greater Mekong Subregion has financially viable interconnections at all percentages of optimal trade scenarios studied. Implying a focus upon these interconnections will benefit the region. Although the study is on APG, it is important to acknowledge that projects in the region require stable financial investments for project sustainability. This reflects possible financial struggles with changes needed to introduce greater flexibility to grid systems.

Focusing upon institutional and political barriers, Li and Chang (2015) identify issues with developing an integrated electricity market in ASEAN. Using the European Union's electricity market integration as a success model, identified barriers include: political will to develop integrated power grid and incentivizing the private market through public private partnership. Although brief, the chapter highlights an important aspect in the development of APG, which is political will. This can translate to the challenges of integrating renewable energy amongst the member nations. With uncertain electricity generation by variable renewable energy, electricity market access is a means to cope with surplus and deficit electricity generation, which increases grid flexibility. ASEAN will need to overcome political barriers for APG to facilitate a regional electricity trade. Even if a systematic approach is developed in the region for enhancing grid flexibility, the non-binding nature of ASEAN agreements will require great political will for the region to benefit from integrating more renewable energy.

2.4.2. *Renewable energy policies and effectiveness*

In terms of renewable energy policy studies, ASEAN Centre for Energy's renewable energy policy study indicates varying levels of initiatives to deploy more renewable energy and policies' effectiveness. It indicates Vietnam as the country with the largest increase in renewable energy installed between 2006 and 2014. Across the region, common financial support policies used to support renewable energy include tariffs, subsidies and grid codes for integration of renewable energy (ACE, 2016). The study concluded that feed-in tariffs is a key policy for increasing the amount of renewable energy electricity generation, regardless of the country's involvement/policies. It is important to ac-

Table 10
Results of grid flexibility analysis with a column indicating the GDP per capita by country (The World Bank, 2016).

Rank	Country	Grid Reliability	Load Profile Ramp	Electricity Market Access	Forecasting	Natural Gas Electricity Generation	Renewable Energy Diversity	Overall Grid Flexibility Score	GDP per capita (USD)
1	Philippines	0.93	0.57	0.000	1.00	0.23	0.57	0.55	2951.10
2/3	Brunei	0.98	0.90	0.024	0.00	1.00	0.14	0.51	26939.40
2/3	Singapore	1.00	0.84	0.002	0.00	0.96	0.29	0.51	52962.50
4/5	Laos	0.51	1.00	1.000	0.00	0.00	0.43	0.49	2338.70
5/5	Thailand	0.98	0.21	0.005	0.00	0.72	1.00	0.49	5910.60
6	Malaysia	0.99	0.70	0.003	0.00	0.47	0.57	0.46	9508.20
7	Indonesia	0.95	0.66	0.000	0.00	0.25	0.71	0.43	3570.30
8	Vietnam	0.71	0.47	0.002	0.00	0.34	0.57	0.35	2170.60
9	Myanmar	0.00	0.62	0.000	0.00	0.39	0.00	0.17	1195.50
10	Cambodia	0.00	0.00	0.020	0.00	0.00	0.14	0.03	1269.90

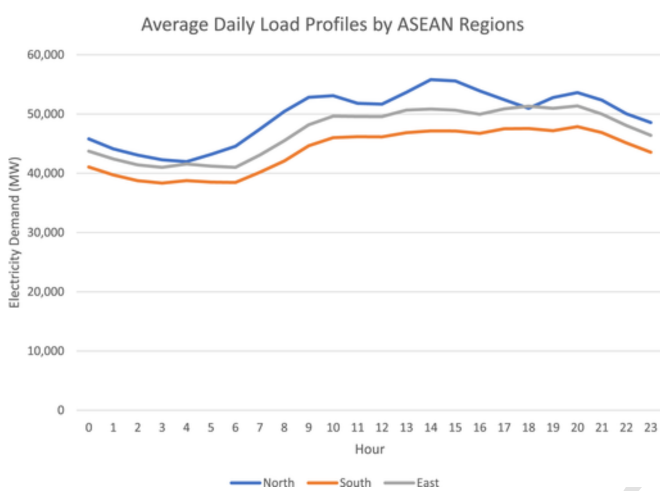

Fig. 3. Average daily load profiles by ASEAN regions.

knowledge that this study is conducted by ASEAN, and the feed-in tariffs effectiveness need to be further carefully studied. There are possibilities that indicated policies may not have been as successful in retrospect, and that now market-based mechanisms such as renewable energy auctions have garnered more support through USAID initiatives (Tongsopit et al., 2017).

Although ASEAN's evaluation of renewable energy policies suggests feed-in tariffs as the ideal policy, ASEAN's study does not explore renewable energy auctions. Auction is a mechanism governments use to procure specific renewable energy capacities through bids by project developers (IRENA, 2013). It is a newer policy trend seen in countries previously invested in feed-in tariffs, such as Germany, and also ASEAN countries, such as Indonesia, Singapore and Philippines (IRENA, 2013). Given the shift away from feed-in tariffs and other mixed experiences, such as Spain's experience that resulted in large financial burden upon the government, ASEAN needs to reconsider its future renewable energy policies (Institute for Energy Research, 2012). Additionally, each individual nation will need to consider designing renewable energy policies to enhance grid flexibility through targeting specific traits.

Important studies on APG and ASEAN region have primarily focused upon the financial aspects and electricity market creation. The renewable energy policy analysis indicates that the region continues to show commitment towards increasing renewable energy in its fuel mix. The gap in literature on integration of renewable energy in ASEAN suggests that ASEAN needs to focus upon the challenges with increasing renewable energy in each nation.

3. Methodology

To provide the basis for identifying institutional and regulatory barriers, the preparedness analysis is used to provide a quantitative approach in understanding the system operations for each nation's grid. It is a quantitative adaptation of a scorecard method presented in a workshop session co-hosted by GIZ at Asia Clean Energy Forum (USAID, NREL, 2015). The main purpose is to provide an understanding of an individual nation's grid flexibility. Many of the data sources developed by country governments and the ministries are inconsistent internally and sometimes lack data vetting. This analysis systematically aggregates government reports and academic studies to organize and validate the data including outage statistics, interchange capacity, and load shape. These are all useful for decision makers with system planning responsibilities. Using peer-reviewed literature on integrating renewable energy and the USAID-NREL analytical framework, six indicators are further developed here: grid reliability, load profile ramp, electricity market access, forecasting systems, proportion of natural gas in electricity generation, and renewable energy diversity. We recognize that USAID and NREL's framework is not a perfect representation of grid flexibility; however, the framework is comprehensive in scope and systematic to analyze groups of countries and diagnose areas for improvement. Each indicator identified aims to characterize grid flexibility (Table 1).

Our preparedness analysis uses a min-max normalization method, a linear transformation method used in data mining, to preserve the relationship between the data values. This is essential in understanding each nations' preparedness progress as most indicators do not have an ideal value for comparison. During the process of data collection, policies and practices documentation is essential in understanding potential explanation for the results shown in visualized data. It can indicate certain barriers and steps needed to achieve a more flexible grid in preparing for more renewable energy integration.

The radar chart is an effective visualization method given multiple objectives. This visual representation shows the tradeoffs between studied variables. Additionally, comparison across countries can be done to understand the weakness, the variable with a value closer to 0, in a system. There are limitations in using a radar chart to visualize information. For example, if the analysis of preparedness is developed with more indicators, the chart may not be as useful and instead another data visualization may need to be considered. It is important to note that various methods for analyzing grid flexibility as a means of preparedness continue to develop (Cochran et al., 2014). However, there is no standard in the analysis and our method takes an approach by utilizing standard metrics used by practitioners. This is one of the first studies to quantitatively compile and aggregate load ramps for each ASEAN nation in a flexibility framework. Furthermore, indicators considered here represent a comprehensive view of preparedness and grid

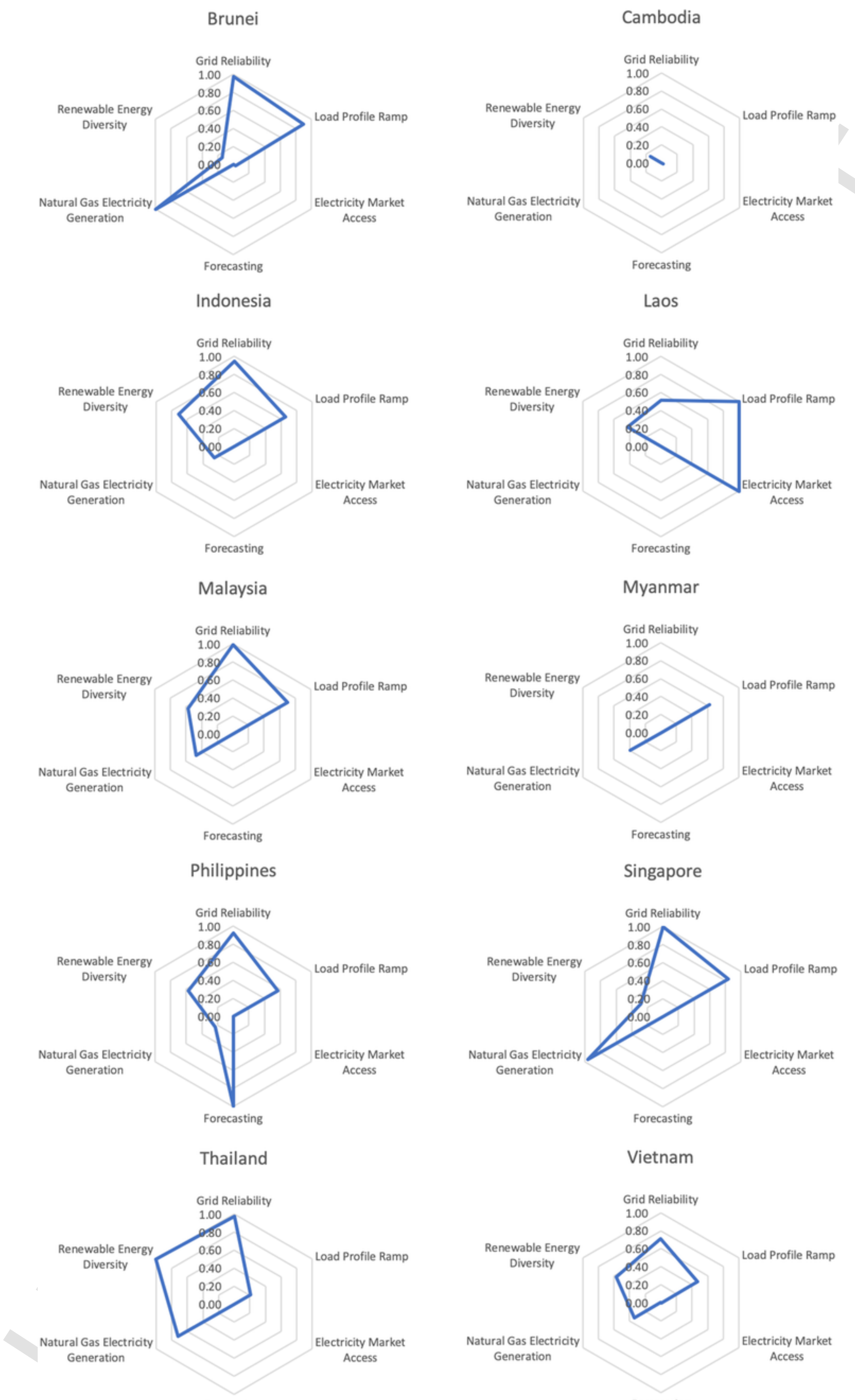

Fig. 4. Radar charts for each nation based on the results shown in Table 10.

APPENDIX A

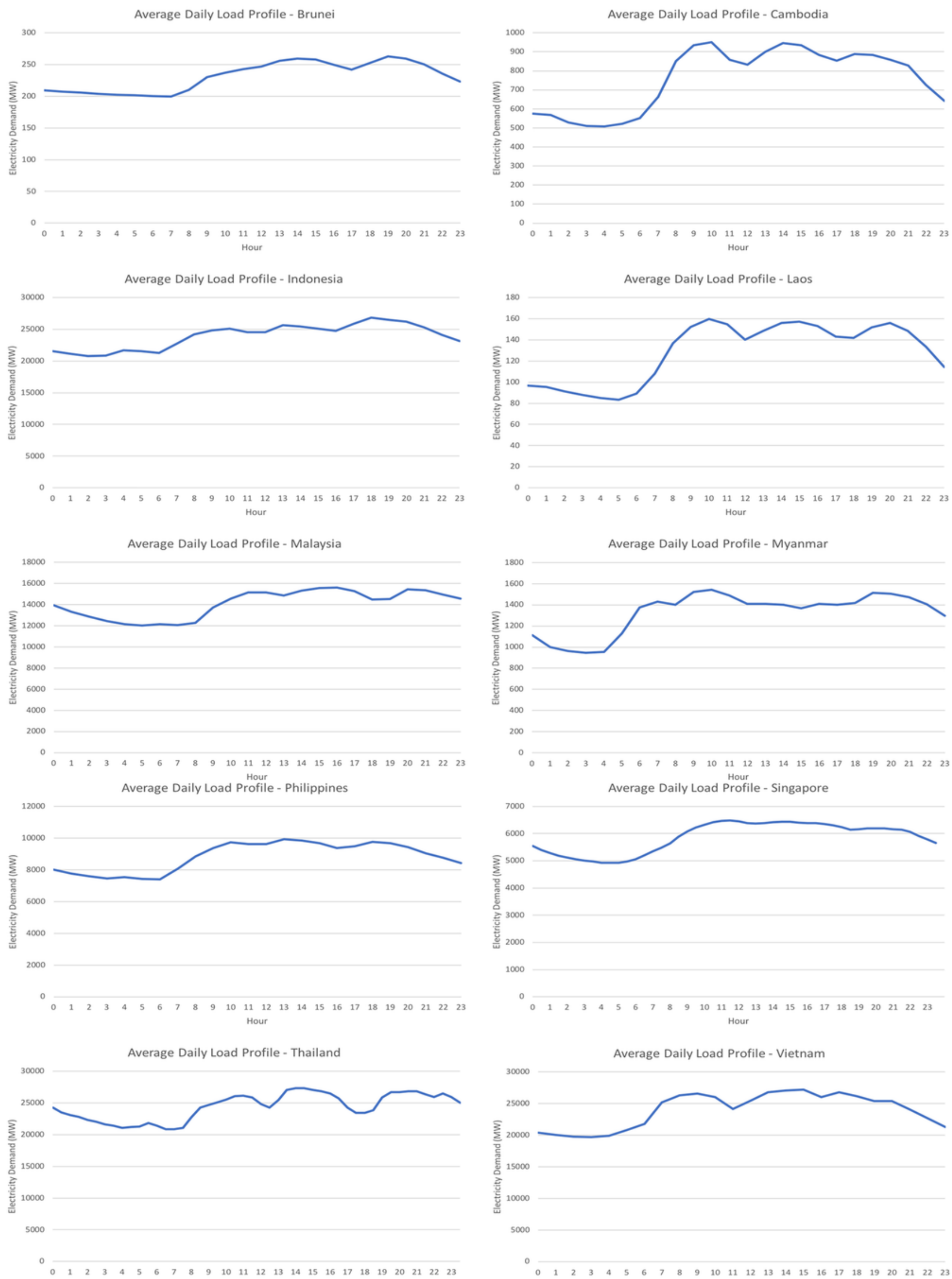

Fig. A.1. Average daily load profile by country (Electricité du Cambodge, 2015; Energy Market Authority of Singapore, 2018a; ERIA, 2014; IEA, 2016c; Japan International Cooperation Agency, 2014; Surahanjaya Tenaga, 2018; Wholesale Electric Spot Market, 2017).

flexibility, ranging from the current reliability to the expected load profile ramp, and existing forecasting systems that aid planners and utility operators in managing intermittent renewable energy sources.

Table B.1
Installed capacity in Megawatts (MW) by fuel type for each ASEAN country. Flexible sources are biogas, biomass, natural gas, geothermal, large hydro, and WTE. For Laos, values in italics are from ACE and all other values are from World Resources Institute. See Table B.2 for sources.

Country	Biogas	Biomass	Coal	Natural Gas	Geothermal	Large Hydro	Small Hydro	Oil	Solar	WTE	Wind	Diesel	Grand Total	Flexible Sources
Brunei				586.00				13.50	1.20				600.70	586.00
Cambodia		6.00	400.00			930.00		248.00					1584.00	936.00
Indonesia			26,700.00	12,200.00	1400.00	5130.00	170.00	10,300.00	10.00	92.00	9.40		55,910.00	18,822.00
Laos		*39.70*	1878.00			3108.86	*38.00*		*3.08*				5067.64	3148.56
Malaysia	63	783.00	10,489.00	14,735.00		6073.00	71.00		282.00			1268.00	33,764.00	21,654.00
Myanmar			120.00	996.50		2780.00							3896.50	3776.50
Philippines		258.00	8838.00	3453.00	1944.00	3620.00		3734.00	896.00		427.00		23,170.00	9275.00
Singapore				10,688.20				2554.60	114.80	256.80			13,614.40	10,945.00
Thailand	530.8	896.80	4564.60	23,926.20	0.30	3406.40	108.00	345.00	1149.60	56.72	193.69	26.40	35,204.51	28,817.22
Vietnam		48.00	9759.00	7354.00		13,719.00	1984.00	1155.00		2.40	52.00		34,073.40	21,123.40

Table B.2
Sources for Table B.1.

Country	Source
Brunei	(ACE, n.d.)
Cambodia	(Electricité du Cambodge, 2015)
Indonesia	(IRENA, 2017)
Laos	(ACE, 2016; World Resources Institute, n.d.)
Malaysia	(KeTTHA, 2018)
Myanmar	(Japan International Cooperation Agency, 2014)
Philippines	(Department of Energy, Philippines, 2018)
Singapore	(Energy Market Authority of Singapore, 2018b)
Thailand	(Ministry of Energy, Thailand, 2015)
Vietnam	(Asian Development Bank, 2015)

4. Methods

To analyze each nation's grid flexibility, we collected data for every indicator for the ten ASEAN member nations. The grid flexibility analysis is a quantitative adaptation of a workshop held by USAID and NREL at Asia Clean Energy Forum (USAID, NREL, 2015). The workshop presented 7 questions (Table 2).

The six indicators used are grid reliability, load profile ramp, electricity market access, forecasting systems, proportion of natural gas in electricity generation, and renewable energy diversity. In our analysis, we included specific indicators for each category (Table 3). Through data mining, we reviewed documents and databases published by ASEAN Centre for Energy, World Bank, National Renewable Energy Laboratory, World Resources Institute, and Asia Development Bank. Data used for the grid flexibility analysis are from 2012 to 2017; Brunei's load profile is the only exception with the latest quality-controlled data from 2006. During the data collection, notable policies or situations for specific indicators were documented. For example, any nations that do not use forecasting as a tool for predicting energy generation and any formal agreements for electricity trade were noted.

Some of the indicators required calculations for the data. First, load profile ramp refers to the rate of demand increase. The worst-case ramp rate of the average daily load profile was determined by using each nation's daily load profile. Due to the various forms of data provided by utilities, governing agencies and research institutes, an average daily load profile was calculated through using WebPlotDigitizer (Table 4) (Rohatgi, 2018). We identified the maximum demand and minimum demand associated with the steepest slope and calculated the worst case load profile ramp by

$$\mathrm{Worstcaseloadprofileramp} = \frac{\mathrm{Maximumdemandofsteepestslope\,(MW)} - \mathrm{Minimumdemandofsteepestslope}}{\mathrm{Timetaken\,(hours)}}$$

Graphically, it is represented as the slope's gradient and represents the largest demand increase in a small-time frame. To calculate flexible installed capacity as the normalizing factor for the metric, we identified flexible installed capacity sources as natural gas, large hydropower, and dispatchable renewable energy sources: geothermal, biogas, biomass, and WTE (Gonzalez-Salazar et al., 2018). Thus, the total flexible installed capacity is calculated by summing total installed capacity by the identified installed capacity sources. The final metric is calculated by

$$\mathrm{LoadProfileRamp} = \frac{\mathrm{Worstcaseloadprofileramp}}{\Sigma\mathrm{FlexibleInstalledCapacity}}$$

Second, we quantified electricity market access through summing interconnection capacities for imports and exports through power purchase (long term trade), and interconnection capacities for energy exchange (short term trade) under the ASEAN Power Grid. This quantification of interconnection capacities is between ASEAN member nations, and not within an individual nation or between islands at a subnational scale. It is represented by the formula:

$$\begin{aligned}&\sum \mathrm{Capacityofinterconnectionforimport\,(MW)}\\&+\mathrm{Capacityofinterconnectionforexport\,(MW)}\\&+\mathrm{Capacityforenergyexchange\,(MW)}\\&= \mathrm{ElectricityMarketAccess\,(MW)}\end{aligned}$$

We also identified the peak load for each country, which was determined by the maximum demand in the load profile data obtained. The final metric for electricity market achieved through
$\mathrm{ElectricityMarketAccess} = \frac{\mathrm{ElectricityMarketAccess(MW)}}{\mathrm{PeakLoad(MW)}}$

Thirdly, the proportion of natural gas used for electricity generation was calculated by

$$\mathrm{Proportionofnaturalgasforelectricitygeneration} = \frac{\mathrm{Electricitygeneratedbynaturalgas}}{\mathrm{Totalelectricitygenerated}}.$$

For data analysis, we used a min-max normalization to linearly transform the data to a new range between zero and one (Han et al., 2011). The equations are listed respectively for min-max normalization and reverse min-max normalization:

$$Y = \frac{X - X_{min}}{X_{max} - X_{min}}$$

$$Y = \frac{X - X_{max}}{X_{min} - X_{max}}$$

Where Y = normalized value in new range

$X = \mathrm{originalvalueofthedatapoint}$

$X_{max} = \mathrm{maximumvalueoforiginalrange}$

$X_{min} = \mathrm{minimumvalueoforiginalrange}$

The normalization method used depended upon the specific indicator, whether higher values are a positive or negative attribute. If a higher value is a positive attribute, min-max normalization was used and vice versa. For example, a higher number of interruptions in grid reliability is negative attribute and hence a reverse min-max normalization was used. To obtain a value for grid reliability, we calculated averages of both metrics' normalized values in the indicator. Radar charts were produced using the normalized data for each indicator and nation. The overall grid flexibility score is an average of all indicators' scores.

Using the radar charts created, we identified trends for ASEAN nations. This included noting any similarities in patterns between each nation's radar chart. For example, we identified poor performance in forecasting systems. With these trends, we researched into further policy or research initiatives for the indicator Additionally, to address our hypothesis, we collected data on GDP per capita from World Bank. This is used to further explain any trends found in the overall grid flexibility analysis.

5. Results

5.1. Grid reliability

Using SAIDI and SAIFI scores averaged from 2013 to 2015, we find an uneven distribution of grid reliability (Arlet, 2017). Six ASEAN nations have very reliable grids (grid reliability score ≥ 0.95), 2 nations have moderately reliable grids, and Cambodia has the least reliable grid in the region (Table 5).

5.2. Load profile ramp

Laos has the best load profile ramp for integrating higher penetrations of intermittent and variable renewable electricity, as indicated with its score of 1 (Table 6). The country is seen to have a gentle ramp slope with a large flexible installed capacity. This trend is also evident in Singapore's result. With score between 0.47 and 0.70, 50% of the ASEAN nations have ramps with moderate flexible installed capacity to meet the demands. Thailand and Cambodia both do not have a large flexible installed capacity compared to its worst-case load profile ramp needs (Table 7).

Additionally, we compared each nation's load profile and find that ASEAN nations have similarities in when the steepest ramps occur. Almost all nations' steepest ramp occurred between 8 a.m. and 10 a.m. We also notice that all nations sustained the high electricity demand from 10 a.m. to 8 p.m. (Fig. 1). When aggregated by the ASEAN groups for sub-regional electricity trade, established in the APG plan, each region's steepest ramps occur between 6 a.m. and 9 a.m., and more pronounced demand fluctuations are seen at the aggregated sub-regional level (Fig. 2).

5.3. Electricity market access

With peak load demands factored in total interconnection capacity available for electricity trade between member nations under the ASEAN Power Grid, Laos is ranked the top ASEAN nation for electricity market access. Overall, most ASEAN nations do not have large amounts of interconnections capacity for electricity trade when compared to the peak load demands. 70% of the countries have a score close to 0, whereas Cambodia and Brunei perform slightly better at around 0.020. Myanmar and Philippines are ASEAN's only two nations without access to electricity trade. Additionally, the countries have different forms of access to electricity trade market. Brunei, Indonesia, Malaysia, and Singapore only have access through energy exchange markets, which are spot markets for short term trades through bids. Cambodia, Laos, Thailand, and Vietnam have access to long term trade agreements through power purchase. Thailand is the only country that has access to all types of electricity trade.

5.4. Forecasting systems

We find that nine ASEAN nations do not have wind or solar forecasting systems in place. The Philippines is the only nation with a solar and wind forecasting system (Barrows et al., 2018). With the grid flexibility analysis, Philippines scored 1 and the rest of the nations in ASEAN scored 0 (Appendix B). This is an area where significant improvement and knowledge sharing across ASEAN nations could alleviate further costs.

5.5. Proportion of electricity generation by natural gas

Using data from IEA, most ASEAN nations do not have a higher proportion of electricity generation by natural gas. Only three countries have more than 70% of electricity generation by natural gas, and other nations all have less than 50% of electricity generation by natural gas (Table 8). Natural gas power plants are the most flexible fossil fuel source due to its ability to increase or decrease electricity generation over a short time frame (Gonzalez-Salazar et al., 2018). Countries with higher amounts of natural gas for electricity generation complement the variability from solar and wind sources. This resulted in a more flexible grid. For example, Brunei has 99% of its electricity generated by natural gas. This means that when Brunei integrates more renewable energy, the complementary source for variability will be natural gas. Countries lacking natural gas for electricity generation, such as Cambodia and Laos, have the lowest score.

Overreliance on natural gas in electricity generation poses system reliability concerns due to a lack of diverse generation options. We consider natural gas as a flexible generation option which is positive in the short term of this preparedness analysis, as natural gas peaking combustion turbines can ramp up and down within sub-hourly schedules. Natural gas may pose environmental risks and increase greenhouse gas emissions, however, in some cases could improve health impacts from air pollution of coal-fired power plants, while facilitating better integration of solar PV (Kittner et al., 2018). For instance, Thailand relies more heavily on natural gas for electricity generation, enabling higher flexibility scores and ability to integrate utility-scale solar onto the grid. Thailand has the highest share of utility-scale solar compared with other ASEAN members, providing fewer notable transaction costs for grid integration compared with less flexible grids, such as neighboring Cambodia (Tongsopit, 2015; Tongsopit et al., 2015). This remains the case for Brunei and Singapore, which with enhanced regional interconnections could become more flexible trading hubs for electricity and gas infrastructure (future offshore wind investments could also couple with power-to-gas facilities and pipeline infrastructure). In Myanmar, natural gas pipelines serve as a primary economic and energy integration linkage with China, which could facilitate cross-border trade and flexibility, but negatively affect energy security and increase China's influence in the region (Liu et al., 2017). IEA projects natural gas to decline in favour for coal growth in ASEAN's electricity generation (IEA, 2017b). It is possible natural gas would create system vulnerabilities as it has in higher gas dependent states (e.g. California and New England, but in the case of short-term renewable grid integration (five-ten year scales), ASEAN countries would likely benefit from having some flexible gas compared with inflexible coal, hydropower, or nuclear (California Public Utilities Commission, 2018; ISO New England, 2018).

5.6. Renewable energy diversity

We find that ASEAN nations do not have large diversity in renewable energy sources (Table 9). Only Indonesia and Thailand have more types of renewable energy source integrated in its grid. More renewable energy diversity reflects higher grid flexibility as it represents more sources available to meet electricity demands. The average for ASEAN nations is three types of renewable energy integrated to the grid. An issue that will impact all ASEAN nations, but highly differently based on their level of preparedness is the Chinese Belt and Road Initiative (BRI) with the potential for regional power trading, but also the risk of low-carbon resources being drawn off from member nations to China (He et al., 2016).

5.7. Overall grid flexibility score and radar charts

Using the normalized scores from each indicator, we find the average grid flexibility score for each nation. This resulted in a ranking order of the ten ASEAN nations (Table 10). The ASEAN nations are categorized by its performance. We find that Philippines has the most flexible grid. From the normalized score for each indicator, the radar charts for each nation show distinctive patterns across ASEAN (Fig. 3). It shows the clear tradeoffs in terms of indicators that countries have focused upon and indicators that countries need to address for a more flexible grid. These clustering patterns are discussed in the analysis section.

6. Analysis

As ASEAN pursues its goal of 23% of electricity generation by renewable energy, the grid flexibility analysis shows that Philippines, Brunei, Singapore, Laos, and Thailand are the most prepared for higher amounts of grid integrated renewable energy sources. Most nations have ambitious targets for integrating renewable energy and will need to be more prepared with a flexible grid to accommodate achieve these goals. ASEAN nations' grid flexibility can accommodate the current grid integrated renewable energy. However, most nations will need to address the absence of wind and solar forecasting practices and steep ramps in load profiles. Both issues result in a less flexible grid. The analysis summarizes the clustering trends found in terms of each country's relative preparedness by the factors studied, and not a justification if one country is truly prepared. Other trends from the data analysis are also described to provide supporting analysis of various ASEAN nations' strengths and challenges.

6.1. Performance by country

From the overall grid flexibility score, the ASEAN nations are not well prepared for an increase in renewable grid integration. Philippines has the highest score at 0.55, however it means that even the most prepared nation has room for improvement in the factors studied to achieve a higher score closer to 1. A score of 1 would indicate that the nation performs the best across all factors relative to the other ASEAN nations. The ASEAN nations' preparedness for higher renewable energy grid integration can be grouped into three distinctive groups: better prepared nations, moderately prepared nations, and least prepared nations. Using the average grid flexibility score of six indicators, this clustering trend is evident, which indicates the relative grid flexibility amongst the ten nations as a measure of preparedness (Table 10).

6.1.1. Better prepared nations cluster

The better prepared nations cluster group includes Philippines, Brunei, Singapore, Laos and Thailand. From the grid flexibility analysis, Philippines has the most flexible grid and is the most prepared ASEAN nation for more renewable energy grid integration. One strength of Philippines' grid operation is forecasting practices, which puts it at an advantage compared to other nations, due to the benefits from predicting electricity generation. Other studies have shown that Philippines has the potential to achieve 30–50% renewable energy within its power system (Barrows et al., 2018). The five nations all have a score of 0.9 and above for at least two of the indicators. Philippines and Thailand share similar characteristics to other regions with high amount of grid integrated renewable energy. For example, a modeling study on California indicates the diverse portfolio used in a flexible grid scenario to meet higher demand hours (Brinkman et al., 2016).

All the countries in this cluster have very different patterns in the radar chart, thus indicating separate foci needed to improve grid flexibility (Fig. 4). Brunei and Singapore are the only two countries with a similar radar chart shape; both score high for grid reliability, load profile ramp, and proportion of natural gas in electricity generation. Main challenges for this cluster include forecasting practices and accessing electricity market considering the countries' peak loads, with the exception of Philippines and Laos respectively. Due to its geographical location and archipelago, Philippines does not currently have access through interconnections and thus resulting in the lowest score for electricity market access variable (Andrews-Speed, 2016). Contrastingly, Singapore and Thailand struggle with enough interconnection capacity to meet peak demands when the system is stressed. These identified issues suggest challenges in meeting future demands. Philippines, Brunei, Singapore, Laos, and Thailand will need to address its respective grid flexibility weaknesses in anticipation for more renewable energy grid integration to achieve its country and ASEAN targets.

Interestingly, Laos has a very different radar chart compared to other nations in this group and yet scores well on average for grid flexibility. This is likely due to Laos' high amount of access to neighboring electricity markets through various interconnections and agreements (Andrews-Speed, 2016). It is important to note that Laos is an exporter whereas other nations in the same cluster have a variation of electricity trade available. This can be an issue for Laos as it means that Laos is unable to import electricity during higher demand periods in the future — given the assumption of integrating more variable renewable energy, which affects the predictability of electricity generation.

6.1.2. Moderately prepared nations cluster

Indonesia and Malaysia are categorized as moderately prepared nations. With grid flexibility scores ranging from 0.43 to 0.46, these two nations score very high for grid reliability and moderately well across load profile ramp, renewable energy diversity, and natural gas electricity generation. Both Indonesia and Malaysia have little access to neighboring electricity markets. With these characteristics, the moderately prepared nations need to increase grid flexibility by improving electricity market access and diversifying renewable energy sources.

6.1.3. Least prepared nations cluster

The least prepared nations in ASEAN are Cambodia, Myanmar, and Vietnam. When compared to other ASEAN nations, these three countries do not perform well in the indicators studied. Trends include low renewable energy diversity, low grid reliability, and little to no access of electricity markets. Although the radar chart shapes and overall flexibility scores for Cambodia, Myanmar, and Vietnam are very different, these countries are in the same cluster group due to significant difference compared to the other two cluster groups. Vietnam and Myanmar score moderately well in the load profile ramp indicator due to a moderate slope for its worst-case load profile demand compared to the large amount of flexible installed capacity available.

Although Cambodia, Myanmar and Vietnam are the least prepared, it is important to note that these countries are only the least prepared given the current infrastructure. The lack of prior investment in infrastructure may make it easier to accommodate distributed renewable energy or develop grid infrastructure with the intent to incorporate more renewable energy. These countries have the largest potential to incorporate renewable energy easily than other countries with extensive grid infrastructure embedded upon fossil fuels. Additionally, these countries could aid other ASEAN countries balance surplus and deficit generation through electricity trade.

6.1.4. GDP per capita and cluster groups

From the grid flexibility analysis and cluster group trends, it suggests that GDP per capita, a measurement of financial resource available, may not have an important role in determining which countries are the most prepared from a grid flexibility perspective. This does not support the initial hypothesis: certain countries with more financial resources and stronger renewable energy policies will be better prepared for a future with more grid integrated renewable energy. Within the better prepared nation cluster group, there is a wide range of GDP per capita (Table 10). However, the countries in the least prepared cluster group align with the lowest GDP per capita countries in ASEAN (The World Bank, 2016). This suggests that GDP per capita may have a greater influence on a country's grid flexibility for countries with less financial resources. Other factors could also affect a country's grid flexibility such as the country's rigor in pursuing a future with more renewable energy.

6.2. Trends in ASEAN: Implications for the future

6.2.1. Strengths of ASEAN nations and region

The grid flexibility analysis shows that most ASEAN nations can integrate at least 25% of the renewable energy target into the grid by 2025 with minimal system changes. There is still work to prepare for integration and here we demonstrate positive aspects from the analysis. ASEAN as a region has high grid reliability. This suggests that the countries value grid reliability and there is an intrinsic amount of flexibility within the nation's grid system. For example, Philippines has the highest amount of electricity generation by renewable energy at 15%, in 2015, and Thailand has the most diverse renewable energy source integrated to is grid while maintaining a high grid reliability score (IEA, n.d.). This means that the grid supports the current levels of integrated renewable energy. The increase in grid integrated renewable energy often affects the grid stability, thus the current grid reliability is a good indicator for how well a nation is integrating its current renewable energy sources (Cochran, 2015). The grid reliability results emphasize that ASEAN countries are currently able to integrate the 25% target of renewable energy into the grid by 2025.

Another strength is the initiative for establishing an electricity market through the ASEAN Power Grid. From the load profiles of ASEAN nations and the sub-regional groupings, complementary increases and decreases in electricity demand suggests the ability for the ASEAN nations to balance deficit and surplus generation (Fig. 2). This is evident within the Northern sub-regional group with Thailand and Vietnam's average daily load profile. Additionally, the Northern sub-region can briefly meet the Eastern and Southern sub-regions' demands from 4 p.m. to 8 p.m. (Fig. 3). Specifically, Thailand can maintain its generation and export electricity to Indonesia, which can be seen to increase its demand at around 4 p.m. This would prevent Northern sub-region ramping down to low levels and ramping up to meet its evening peak demand at 8 p.m. Also, the LTMS interconnection indicates the benefit and potential of exporting Laos' surplus generation to meet Thailand and Malaysia's variant and significantly higher electricity demands (Fig. 2).

Although only bilateral agreements currently exist for trade between two neighboring countries, access to regional electricity markets will be beneficial in improving grid flexibility (Matsuo et al., 2015; United Nations, 2006). Laos, Malaysia and Thailand recently signed ASEAN's first initiative for multilateral trade with possibilities for Singapore to sign on in the future (Bernama, 2017). This suggests a step forward in the direction of creating the regional electricity market beyond agreements for neighboring nations only. The regional electricity trade characteristic is similar to European's regional grid interconnection for electricity trade; notable countries in Europe, such as Denmark and Portugal, have more 30% of renewable energy integrated into their grid system (Cochran et al., 2012; Martinot, 2016). Europe benefits from the larger pool of resource access through a regionally interconnected grid smoothens the individual nation's deficit and surplus generation through electricity power exchanges across the region (Huber et al., 2014; Stappel et al., 2015). Further studies in Central America, East Africa, and South East Europe also highlight the value of regional integration to lower costs of future electricity systems (Carvallo et al., 2017; de Leon Barido et al., 2015; Kittner et al., 2016a). Although ASEAN is yet to complete an ASEAN Power Grid, the initiative and complementing average daily load profile suggest an optimistic future for individual nations to improve its grid flexibility through electricity market access indicator.

6.2.2. Challenges for ASEAN

With the current level of grid flexibility, there are various challenges that ASEAN will face in terms of preparedness for higher renewable energy grid integration. Some results from the grid flexibility analysis indicate potential issues with meeting future demands by renewable energy.

6.2.2.1. Challenge 1: Aggregated increase in electricity demand All ASEAN nations have maintained higher electricity demand between 10 a.m. and 8 p.m., and demand increase at 6–10 a.m., which is represented by the ramp slope (Fig. 1). These two trends suggest challenges with meeting demands by electricity trade. In an ideal balancing scheme, nations would complement each other in terms of periods of supply and demand. This means that a period of high demand by country X can be balanced out by the period of low demand by country Y through exporting the unused electricity generation to country X. For example, Thailand's high demand could be balanced by Laos' low demand. However, ASEAN's trend with all nations sustaining high demand creates difficulties for electricity trade to occur unless a country consistently has a surplus generation available for export. Aggregated increase in demands and sustained periods of high electricity demand across all countries means that ASEAN currently will not benefit from an overall smoothing effect seen in Europe through electricity trade (Stappel et al., 2015).

Another concern with the load profile of ASEAN nations is increase in renewable energy will intensify the ramp and increase variability during the day (Huber et al., 2014). An example of the renewable energy effect on the daily load profile is the "duck curve" in California's load profile, a state with 30% of electricity sale from renewable energy sources (California Energy Commission, 2018). It describes the intensified increase in electricity demand after sunset due to the sudden decrease in solar electricity generation (Denholm et al., 2015). Although none of the ASEAN nations experience such changes in the load profile, it is a concern for the future given ASEAN's pursuit and target for integrating more renewable energy sources. From the grid flexibility analysis, Thailand has the steepest worst case load profile ramp and second lowest score for load profile ramp metric amongst all ASEAN nations. The steeper ramp rate now suggests a stressed system and an inflexible grid because the system needs to meet increasing demands over a short period of time, which it may not have the right resources for. It can be even more challenging to meet demands in the future with the unexpected fluctuations of electricity generation by renewable energy. Despite its steep ramp and low electricity market access score, Thailand is in a better position that other nations due to the its renewable energy diversity and proportion of natural gas electricity generation. High renewable energy diversity paired with flexible capacity from natural gas provides more resilience to fluctuations from variable renewable energy sources. However, this will be an issue for Vietnam, which is seen to have a moderate ramp score but low renewable energy diversity and natural gas electricity generation score. These potential issues with ASEAN's aggregated load profiles and ramp must be considered in future planning and grid operations by ASEAN nations.

To address this challenge, ASEAN should consider the role of grid energy storage given the declining trend in battery cost (Eller and Gauntlett, 2017; Kittner et al., 2017). This technology can reduce the ramp steepness in load profiles through load shifting by either storing surplus electricity generated or supplying power when electricity demands increase (Dunn et al., 2011). Additionally, it complements the intermittency from solar and wind generation. ASEAN countries with a low score in proportion of electricity generation by natural gas can potentially adopt grid energy storage instead of expanding transmission systems. Furthermore, existing hybrid mini-grids in Thailand have improved sustainability and resilience and could offer further flexibility when combined with battery storage (Kittner et al., 2016b). In the long term, battery energy storage could improve grid flexibility.

6.2.2.2. Challenge 2: Forecasting practice All ASEAN nations, with Philippines as an exception, lack forecasting practices for both solar and wind power, which is a concern for meeting electricity demands.

Philippines has implemented a wind and solar forecasting system along with research into next day wind forecasting by Ateneo (Barrows et al., 2018; National Grid Corporation of the Philippines, 2016). Forecasting is an ideal practice for grid flexibility (Aggarwal and Orvis, 2016; Cochran et al., 2012; Martinot, 2016). Location specific wind or solar generation can be estimated in advance through using weather data and numerical weather prediction models (Zieher et al., 2015). Given the nature of procuring electricity generation, grid operators need to schedule the generation portfolio a day before the actual generation time. Various regions or countries with high levels of grid integrated renewable energy, such as Denmark, use forecasting system (Cochran et al., 2012). Additionally, modeling studies demonstrate forecasting systems benefits. Day ahead wind forecasting systems can result in cost reduction of 4 billion USD and day ahead solar forecasting can result in cost reduction by 13.2 million USD (Bird and Lew, 2012; Brancucci Martinez-Anido et al., 2016). In addition to the cost benefits, using advanced forecasting system reduces the system operator's reserve requirements, thus lowering the costs for renewable energy grid integration It accounts for the potential proportion of electricity generation by renewable energy. Thus, effectively reducing the risks for curtailment situations, a shutdown of certain generation plants due to over generation, and maintains grid reliability. Evidently, forecasting practices are extremely important for the ASEAN nations that have an intent in increasing the amount of wind power integrated to the grid. The absence of forecasting practices may be feasible now but given the renewable energy targets and the benefit in planning for the future, ASEAN nations will need to address their practices in preparation for more grid integrated renewable energy.

6.3. Limitations and future directions

Our analysis of grid flexibility for the ten nations in ASEAN summarizes the current performance in context of the renewable energy targets set by each nation and the region. The analysis remains limited to grid integrated renewable energy sources and does not account for the growing potential and development for micro and mini grids for sustainable development in regions without access to electricity. Therefore, it does not consider the possibility that Myanmar, Cambodia, and Vietnam may be more poised to integrate decentralized renewables at a more rapid pace in the future, if investment enables this type of deployment. Although the data found were from credible sources, such as statistic banks, government departments, international organizations, and research institutes, there are inherent issues with latest data availability and quality, and data formats used by individual nations. For example, Myanmar does not document grid reliability metrics used by most grid operators and energy suppliers (SAIDI and SAIFI). This makes it difficult to compare across different countries, even though reliability presents most critical challenges to stable power grid and operational efficiency. Additionally, this study is specific to ASEAN and the variables were chosen based upon the available data. Thus, the method can be adapted to other regions, but the results for this particular region are mostly useful when considering ASEAN affairs.

For future research, grid flexibility analysis can be done specifically for each country in cooperation with utility operators and governing ministries as a form of technical assistance. Direct communication with critical stakeholder to understand grid operations will be beneficial in future studies. The purpose is to highlight grid flexibility needs in the pursuit of more renewable energy to policymakers. Other future possibilities include specifically modeling systems under different renewable energy penetration scenarios.

7. Conclusion and policy implications

As ASEAN continues to pursue its renewable energy targets, all member nations will need to consider increasing its current grid flexibility to be adequately prepared for future scenarios with more renewable energy integrated to the electrical grid. The radar charts indicate the strengths and weaknesses of each country's grid operation; a comparison across all countries show that no countries perform extremely well across all indicators studied. Our method highlights specific priorities for each country, which are crucial in guiding governments to support renewable energy. For example, Thailand's Ministry of Energy recent change in its support for renewable energy does not reflect its potential and position as a better prepared nation for renewable energy (Tongsopit, 2018). Additionally, as discussed, nations in the least prepared cluster also have the potential to integrate renewable energy, given if governments address the weakness and investments are made. Each country is unique and different pathways could be pursued with renewable energy, such as decentralized renewable energy or continued focus on improving grid flexibility in the central system. Strategic investments remain important to overcome integration challenges in each member nations' existing grid system. Multilateral development banks are well suited to build flexible capacity for grid integration (Steffen and Schmidt, 2018).

Our study highlights the importance of regional cooperation in addressing ASEAN's grid flexibility and renewable energy challenges. The identified operational barriers, such as aggregated increase in electricity, will require regional cooperation to solve. As one of the first studies to quantify and detail a load profile and calculate worst-case ramp rate for each member nation, these results can be used for future studies on the interconnected regional grid. Addressing this main concern through regional cooperation and electricity trade market, ASEAN will need to focus on more detailed studies in grid operations and renewable energy grid integration economic impacts, whether by individual nations or as a region. ASEAN has the technical potential to improve grid flexibility in anticipation for more renewable energy integrated to the grid. Overcoming the barriers and addressing priorities will aid ASEAN in achieving its renewable energy targets and transition to a cleaner future.

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Appendix A

See Fig. A.1

Appendix B

See Table B.1

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