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Storage or Transmission? A Techno-Economic Analysis of ASEAN Grid Flexibility

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ABOUT THE SERIES

This policy brief is a series of research documents summarizing the knowledge of area contextualized to Southeast Asia and Malaysia, in particular from ongoing research work by the Center for Technology, Strategy & Sustainability (CTSS) at the Asia School of Business. The author of this issue is **Tiesa Willemen, ASB CTSS Visiting Research Associate** and **Dr Pieter E. Stek, ASB Senior Lecturer and Faculty Director of CTSS.**

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Executive Summary

The ASEAN region is undergoing rapid transformation in its energy sector, with electricity demand growing at over 7% annually, nearly double the global average. While fossil fuels still dominate the energy mix, renewable energy now accounts for 35% of installed capacity, primarily from hydropower and solar PV. The integration of large amounts of variable renewable energy (VRE) can introduce new challenges for grid stability, requiring flexible solutions to balance supply and demand. Two options stand out: expanding cross-border electricity interconnections through the ASEAN Power Grid (APG) and scaling up battery energy storage systems (BESS). This policy brief provides a high-level analysis of the most cost-effective pathways to enhance grid flexibility in ASEAN, based on the latest techno-economic analysis and regional context.

The ASEAN Power Grid (APG), first envisioned in 1997, aims to bolster energy security and support decarbonization by connecting regions with surplus power to those with deficits. Currently, 18 key interconnection projects are planned (both domestic and international), of which nine are operational, providing 7,700 MW of capacity. By 2040 the APG is expected to have 33,241 MW of grid interconnection capacity. Nevertheless, ASEAN's current cross-border transmission capacity remains modest at just 2% of total generation capacity, compared to 11% in the European Union. The development of the APG faces significant barriers, including the geographic challenges of archipelago Southeast Asia, divergent national energy strategies, a lack of harmonized regulatory standards, and in some member states, underdeveloped domestic grids.

The choice between investing in transmission or storage is not binary; both can act as substitutes or complements depending on system conditions. Battery energy storage systems can defer grid reinforcements, provide ancillary services, and improve system reliability, while transmission enables large-scale renewable energy integration and reduces curtailment. Techno-economic analysis reveals that the levelized cost of short-distance transmission and electricity storage with BESS are comparable at around $40/MWh, making them the most cost-effective options for ASEAN. In contrast, long-distance undersea high-voltage direct current (HVDC) transmission remains significantly more expensive, with costs ranging from $80 to $200/MWh, and is only viable for land-constrained systems like Singapore. Future cost reductions in solar PV and BESS are expected to further enhance the competitiveness of storage, reinforcing its role in grid flexibility.

From a policy perspective, grid flexibility concerns will come to the forefront between 2030 and 2040, allowing decision-makers time to plan. Currently, short-distance interconnectivity between neighboring countries and battery storage systems appear to be the most cost-effective technological solutions to enhance grid flexibility. The limited integration of ASEAN economies, especially in areas like energy markets or carbon trading, suggests that the future of the APG will be primarily shaped by short-distance bilateral interconnections, as well as limited long-distance undersea connectivity to Singapore aimed at meeting energy security goals.

Introduction

The Association of South East Asian Nations (ASEAN) is experiencing a significant increase in electricity demand, with one of the fastest growth rates globally. In 2024, demand growth exceeded 7%, which is nearly double the global average. This growth is driven by rapid urbanisation, population growth, industrialisation and rising living standards (International Energy Agency, 2025b). In 2024, 80% of primary energy sources in Southeast Asia came from fossil fuels. Furthermore, 35% of total installed electricity generation capacity in the ASEAN region was from renewable sources, primarily hydropower and solar photovoltaics (PVs) (ASEAN Centre for Energy, 2024a).

Within ASEAN, cross-border power grid interconnections were first developed in the early 1980s for the purposes of emergency grid stabilization, although the first cross-border electricity export arrangement stems from the 1970s, involving the sale of excess hydropower from Lao PDR to Thailand. Since the mid-2000s the number of grid interconnections have increased rapidly, driven primarily by a desire to export electricity from low-cost producers, such as Lao PDR, to neighboring countries (Nuchprayoon, 2004; International Energy Agency, 2026). High shares of variable renewable energy (VRE), such as PV and wind turbines, introduce supply uncertainties into electricity systems, increasing the need for system flexibility to balance supply and demand. Flexibility can be provided through multiple channels, including dispatchable generation, demand-side responses, energy storage, and transmission expansion.

In the ASEAN context, two options stand out as particularly relevant, due to their potential to increase grid flexibility at a relatively low cost: expanding cross-border electricity interconnections through the ASEAN Power Grid (APG), and deploying battery energy storage systems (BESS) at scale. Cross-border transmission can smooth variability across space by allowing surplus renewable electricity to be exported to neighboring systems, while battery storage can balance short-term mismatches between supply and demand within local or national power systems.

As energy demand rises and is increasingly met by deploying more VRE across ASEAN, there is greater urgency to build a more flexible grid. While previous studies have already highlighted the potential role of energy storage and cross-border interconnections as ways to increase flexibility (Chee et al. 2025), this study specifically addresses the economic trade-off between the two.

The study aims to provide high-level guidance about situations in which storage or expanded cross-border transmission are likely to lead to a more cost-effective increase in grid flexibility. This guidance considers ASEAN's physical and economic geography and is based on the latest techno-economic data available from projects implemented in the region.

The analysis is divided into three parts. First, a discussion of the APG, previous analysis of its development, and operational scenarios (section 2). Second, a discussion of how BESS interacts with other aspects of grid flexibility (section 3). Third, a simple techno-economic analysis identifying when transmission or storage is likely to be most cost-effective within ASEAN (section 4). This brief concludes with a number of policy recommendations (section 5).

The ASEAN Power Grid

The APG was first envisioned in 1997 as a regional infrastructure initiative to enhance energy security by connecting countries with surplus power generation capacity to those facing supply deficits. At the time, the primary objective of the APG was to support rapidly rising energy demand across the ASEAN region through cross-border power exchanges (International Energy Agency, 2016). In recent years, the growing emphasis on decarbonization and renewable energy (RE) has added a new strategic dimension to the APG. Beyond energy security, cross-border power interconnections can enable the large-scale integration of renewable resources, transporting surplus RE to regions with a deficit. This way, the APG could be an important tool for reducing greenhouse gas emissions and supporting ASEAN's Net-Zero targets (International Renewable Energy Agency & ASEAN Centre for Energy, 2022). As such, the APG is increasingly viewed as a key enabler of the regional energy transition.

The APG is proposed to have 18 key interconnection projects across the region with a total capacity of 17,550 MW. Currently, nine of these key interconnections are already completed, totaling 7,700 MW in capacity including 4,700 MW of dedicated Independent Power Producers (IPP) generation exports (ASEAN Centre for Energy, 2024a) and 3,000 MW of grid-to-grid interconnections (International Energy Agency 2026). Figure 1 shows a map of these 18 key interconnections, where the blue and red lines represent existing and planned transmission lines, respectively (ASEAN Centre for Energy, 2024a). Furthermore, Table A.1 shows the grid-to-grid interconnection projects as of 16 September 2024. The last column shows the transmission capacities of the ASEAN RE Target Scenario projections of the third ASEAN Interconnection Masterplan Study (AIMS-III) Phase 1 and 2 (2020) (ASEAN Centre for Energy, 2024c).

The remainder of this section provides an international perspective of the APG (section 2.1), a survey of earlier academic research (section 2.2), and discusses a number of operational scenarios of the APG (section 2.3).

INTERNATIONAL PERSPECTIVE

To gain a sense of the significance of the APG, we provide a comparison between the APG and the European Union (EU) cross-border power grid. While the physical and economic geography of both regions are very different, the comparison nevertheless provides a gauge againstwhich the scale of the APG can be evaluated.

In ASEAN, AIMS-III explores the viability of multilateral electricity trading in the ASEAN region to enhance grid resilience and modernization. The study evaluates three scenarios: a base case, an optimum case and an ASEAN RE Target case. The base case largely reflects the currently planned APG configurations shown in Figure 1. In contrast, the optimum and ASEAN RE Target cases envision a substantial expansion of the APG infrastructure, reaching total interconnection capacities of 33,241 MW and 33,487 MW, respectively, by 2040 (ASEAN Centre for Energy, 2024b). Besides these key projects, several studies analyze additional regional interconnectors to further strengthen system integration. Examples include potential links between Singapore and Vietnam, as well as Singapore and Sarawak (Malaysia), which could play a strategic role in enabling large-scale RE imports (TransitionZero, 2024; Winofa et al., 2025).

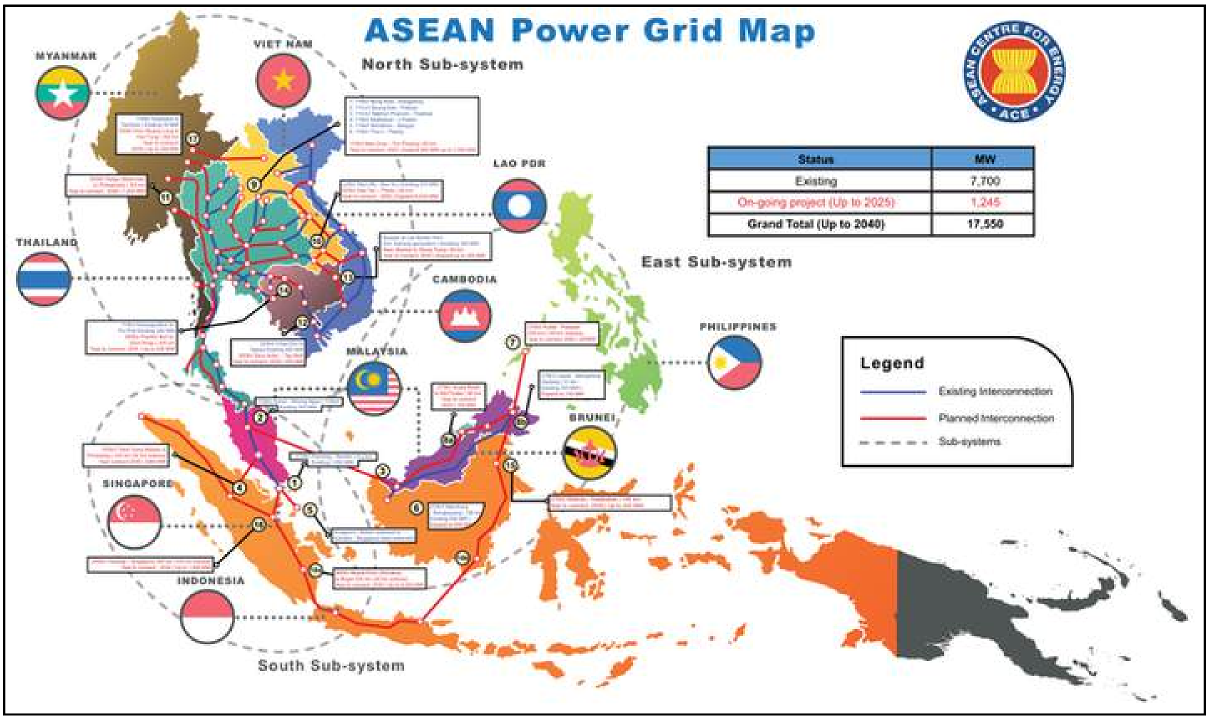
The European Union can be used as a benchmark for assessing ASEAN’s level of electricity market integration, as Europe hosts the world’s largest cross-border integrated electricity market (European Commission, 2025). As of 2025, available cross-border electricity transmission capacity in Europe is approximately 126 GW, - -as well as 77.3 GW of grid-level electricity storage capacity (Eurelectric, 2025; Solar Power Europe, 2026).The cross-border connections are expected to increase to 161 GW in 2030, which includes all projects currently under construction or in advanced stages and that are expected to be commissioned until 2030. Furthermore, European Network of Transmission System Operators for Electricity (2025) estimated that an additional 108 GW and 224 GW of capacity would minimize total system costs in 2040 and 2050, respectively. The cumulative installed electricity generation capacity in the European Union in 2024 was 1,131,215 MW (Eurelectric, 2025).

By comparison, in 2022, total installed power generation capacity across ASEAN reached approximately 315 GW. Under the Baseline Scenario, this capacity is estimated to grow to 434 GW by 2030 and 818 GW by 2050 (ASEAN Centre for Energy, 2024a). Installed capacity varies significantly across member states, ranging from 12 GW in Laos and 13 GW in Singapore to 39 GW in Malaysia, 61 GW in Thailand, and 85 GW in Vietnam (International Renewable Energy Agency, 2025b).In light of this, the current and planned APG transmission capacities remain relatively modest compared to total regional generation capacity, highlighting the limited degree of integration today. The ratio of cross-border transmission capacity / electricity generation capacity in ASEAN is approximately 0.02, while the EU has a ratio of 0.11, five times higher. Even with the capacity of all the 18 key interconnector projects, the ratio is around half of the EU ratio.

Given the longer history and much deeper energy market integration in the EU, as well as ASEAN's maritime geography, a lower ratio is to be expected. At the same time, these figures show the ambitions of the APG as a whole.

By employing regional interconnections in ASEAN, the energy system may behave more optimally and the need for storage and excess capacity could be reduced. Specifically, some research suggests that the APG is expected to reduce the need for 1.2 TWh of electrical storage, 16 TWh of hydrogen storage and 600 GW of solar generation capacity by 2050 (ASEAN Centre for Energy, 2024a). However, such reductions represent theoretical system optima rather than guaranteed outcomes. In practice, cross-border electricity trade in ASEAN remains constrained by political, regulatory and institutional considerations (International Energy Agency, 2025a), which may necessitate higher levels of domestic generation and storage capacity than projected under idealized modeling scenarios.

Figure 1: ASEAN Power Grid Map
(Source: ASEAN Centre for Energy, Jakarta: 8th ASEAN Energy Outlook



PAST ACADEMIC RESEARCH: FINDINGS AND LIMITATIONS

A number of studies have examined the APG from different disciplinary and methodological perspectives, reflecting both its potential role in supporting the regional energy transition and the complexity of its practical implementation. Existing academic literature broadly addresses two dimensions: first, the system-wide techno-economic impacts of regional interconnections on cost-optimal decarbonization pathways; and second, the institutional, regulatory, and market conditions that shape the feasibility and pace of APG development.

System-Wide Analysis

Chee et al.(2025) developed a mixed-integer non-linear programming model to identify the least-cost pathway for the ASEAN countries to achieve Net-Zero Emissions (NZE) by 2050 while satisfying growing energy demand. This paper highlights the storage vs. transmission trade-off, while assuming that BESS is needed in case of high use of VRE, limiting the use of VRE without BESS to 50% of the total generated energy to prevent grid instability. Furthermore, only short distance energy trading was allowed, thus only allowing for trade between neighboring countries. Their model found that all countries, except Singapore, could theoretically achieve NZE without cross-border transmissions, but the total costs would be higher compared to the energy-trade scenario. However, as the capital costs of building these cross-border transmission lines were not considered, the total costs of this 'optimal' energy grid are incomplete.

Ahmed et al.(2017) conducted a feasibility study of high voltage AC (HVAC) and high voltage DC (HVDC) transmission options in the APG, analyzing overhead as well as underground transmission options. The study considers capital costs, including transmission lines and substation costs, as well as operation and maintenance costs, including energy losses. It concludes that the cross-over distance at which HVDC connections become less expensive than HVAC depends upon the amount of power transmission through the interconnections, roughly occurring between 185 to 200 km. Furthermore, the results include an optimal cross-border transmission network, showing energy flows from regions with low generation costs and a high capacity to regions with high demand and generation costs. This includes long-distance flows, for example between Peninsular Malaysia and Sarawak, for which HVDC is the cheaper option. However, this study does not consider energy storage options in their analysis, which might be cheaper than both HVAC and HVDC.

Barriers

The development of a fully integrated APG faces several challenges, limiting the pace and scale of regional power system integration. These challenges can be divided into four categories: political and institutional, technical and regulatory, financial and commercial, and market and legal challenges.

First, ASEAN member states have different national energy strategies as well as different levels of commitment to cross-border links. This results in slow consensus-building and long-term planning (Weno et al., 2025). Sustained political commitment, supported by strong coordination mechanisms, is required for the APG to realize its full potential, and remains limited at present (International Energy Agency, 2025a).

Second, regulatory challenges arise from differences in national rules and market arrangements (International Energy Agency,2023). Regulatory rules (permitting, tariffs, market rules and PPA's)

-and technical standards (voltage, frequency, control systems) are not harmonized across the region, complicating cross-border electricity trade. Several member states have underdeveloped domestic transmission networks that constrain their ability to absorb imported RE (International Energy Agency,2025a). Financial and commercial constraints come from a lack of robust investment frameworks for large cross- border projects, making it difficult to attract low-cost financing.

Third, due to a lack of deployment scale and underdevelopment of supply chains, solar and wind project costs remain elevated in much of ASEAN (International Energy Agency, 2023). Fourth, market and legal constraints refer to the absence of regional legal frameworks and market mechanisms, which are needed for effective cross-border power trade (Weno et al., 2025). The absence of regional power markets, such as anti-competition acts or market structures, restricts efficient dispatch and limits incentives for interconnection investment (Supendi et al., 2017).

OPERATIONAL SCENARIOS

This section presents three operational scenarios for the APG, reflecting its potential role across multiple time scales and evaluates these using relatively simple, first-order estimations and assumptions. This includes intra-day balancing, seasonal balancing and continuous baseload substitution.

Intra Day

First, intra-day balancing refers to satisfying the energy demand peak in one country with the (renewable) energy from another country. Generally, there is a mismatch between VRE generation and energy consumption, peaking at different times of the day (Oduro & Taylor, 2023). During these periods of peak RE generation, the energy could be exported to areas with high demand, thus satisfying demand with energy that would otherwise have been curtailed (International Energy Agency, 2016). Srinivasan & Asundi (2024) found that transfer of energy surpluses across time zones, in combination with the optimal location of energy generators, aids in cost-efficient, time-efficient and climate-efficient energy transition in Central Asia. Grossmann et al. (2013) studied large-scale solar energy networks across the globe, combining various regions with different solar patterns to overcome the intermittency related to solar PV energy. By combining different time zones and transferring solar PV energy, demand can be met with substantially less storage and generation capacity.

The ASEAN region is characterized by four time zones: UTC+06:30 in Myanmar; UTC+07:00 in Thailand, Lao PDR, Vietnam, Cambodia and parts of Indonesia; UTC+08:00 in Malaysia, Singapore, Brunei, the Philippines and parts of Indonesia; and UTC+09:00 in Timor-Leste and parts of Indonesia.

This is likely to be too few time zones to enable significant reductions in intermittency, as the daily electricity demand and solar PV generation profiles remain relatively synchronized across the region. This results in a limited scope for exploiting east-west time-shifting of RE across ASEAN. Nevertheless, the APG could play a role in smaller-scale intra-day balancing in the region if there is sufficient spatial diversification of renewable resources and differences in demand patterns, thus enabling flexibility and reducing curtailment, although at a limited scale.

The International Energy Agency (2025b) showed that there are only a limited number of days in which Malaysia’s peak demand hour coincides with that of Thailand and Singapore in 2024, indicating the usefulness of interconnection between these countries. This same relationship might be found between other ASEAN countries.

Seasonal

The ASEAN region can be roughly divided into two main monsoon seasons: the Northeast Monsoon (December to March) and the Southwest Monsoon (June to September). These two monsoon seasons have opposite rainy and dry seasons in northern and southern ASEAN. The northern ASEAN region consists of Cambodia, Lao PDR, Myanmar, northern Philippines, northern Thailand and Vietnam. The southern ASEAN region consists of Brunei Darussalam, Indonesia, Malaysia, southern Philippines, Singapore and southern Thailand.

During the Northeast Monsoon, the northern ASEAN countries experience a dry season while the southern ASEAN region endure a rainy season. The opposite applies for the Southwest Monsoon. Furthermore, these two seasons are separated by two relatively shorter Inter-Monsoon periods characterized by afternoon and evening showers with light and highly variable winds along the tropical belt (ASEAN Specialised Meteorological Centre, n.d.).

These distinct monsoon seasons could allow for seasonal balancing of renewable energy generation across the ASEAN power system, particularly through the complementary availability of hydropower, solar PV, and wind resources between northern and southern subregions. During the dry season, there is plenty of sunshine for solar PV across ASEAN with a relatively consistent quality of solar. However, the quality of wind resources is unevenly distributed across ASEAN, with lower average wind energy potentials compared to Europe, North America and China. However, offshore wind potential is present in Vietnam and the Philippines, and onshore wind resources could be placed close to urban centers in Thailand, Cambodia, Vietnam and Myanmar. Both solar PV and wind generation experience seasonal fluctuations in output linked to variations in average cloud cover (International Energy Agency, 2024).

Furthermore, seasonal fluctuations are also present in energy demand. Countries that experience higher annual variations in temperatures,-

-such as Vietnam, Lao PDR or northern Thailand, experience higher fluctuations in electricity demand (e.g. for space cooling), and thus higher seasonal variability of the net load than in countries closer to the equator (International Energy Agency, 2024).

Continuous Baseload Substitution

Besides the daily and seasonal fluctuating energy demand and supply, the APG could also be used to transmit a continuous energy flow to specific regions. This baseload substitution is preferably RE, flowing from regions with an abundance in RE to regions unable to generate sufficient (renewable) energy. This operational scenario is particularly relevant for Singapore, as it lacks sufficient space for large-scale RE generation and remains dependent on imported energy (Energy Market Authority, 2023).

On the supply side, Lao PDR is often identified as a key exporter in a continuous baseload substitution scenario due to its substantial hydropower resources and existing ambition to function as the “battery of Southeast Asia” (Shang, 2025). Hydropower offers relatively dispatchable and predictable generation compared to VRE sources, making it particularly suitable for providing firm cross-border electricity flows. This relationship can already be seen in the Lao PDR- Thailand–Malaysia–Singapore Power Integration Project (LTMS-PIP), which is the first multilateral electricity trading project linking four countries in ASEAN. This project allows for renewable hydropower from Lao PDR being sold to Singapore via transmission through Thailand and Malaysia (Weno et al., 2025). The project started with a maximum trade of 100 MW, which will increase to a maximum of 200 MW in Phase 2 of LTMS-PIP (Energy Market Authority, 2024).

Finally, smaller “local” cross-border electricity export opportunities may exist. For instance, the Malaysian state of Sarawak, which has well-developed hydropower resources, has started exporting its lower cost electricity to neighboring West Kalimantan province in Indonesia in January 2026 (Sarawak Energy, 2026; Kamarani et al. 2023).

Grid Development and Storage: Trade-Off or Complement?

A discussion that is gaining popularity is the trade-off between cross-border transmission and other alternatives, particularly energy storage. In a situation of comparable electricity prices between countries, both transmission and storage investments can enhance system flexibility, improve reliability, and enable higher shares of VRE. Cross-border transmission lines are a key instrument for improving energy security and system stability, while improving decarbonization efforts by enabling the export of surplus RE and thus reducing curtailment and the associated economic losses. At the same time, many of these system-level benefits can, at least partially, be achieved through non-wire alternatives. In particular, BESS can address short-term mismatches between supply and demand, reduce rare network congestion events, and defer grid reinforcement investments (Biancardi et al.,2024).

Several studies highlight that transmission and storage can act as substitutes or complements, depending on system conditions. De Vries(2013) finds that, in most European power systems, cross-border transmission and pumped hydro storage substitute for one another, while under specific circumstances they become complementary technologies. Kumaraswamy et al. (2020) andBiancardi et al. (2024) further suggest that battery storage can act as a virtual transmission line or “grid booster”, increasing transmission capacity and offering network flexibility. From this perspective, storage is a substitute for a new or upgraded transmission line. This dual relationship suggests that investment decisions in storage or transmission should be evaluated jointly rather than in isolation.

The decarbonization of energy systems introduces two additional problems regarding the transmission infrastructure. First, the early phasing-out of already existing fossil fuel power plants leaves the connected transmission lines underused. This underutilization has financial consequences for the network owner, as the cost recovery time is between 25 and 30 years. Furthermore, new VRE plants are often built in resource-rich regions, which are often located in areas where the transmission infrastructure lacks sufficient capacity for large power flows, resulting in network congestion or renewable curtailment (Kumaraswamy et al.,2020). Although there are only limited plans for an early phase-out of fossil fuel power plants in the ASEAN region, battery storage could reduce congestion and enhance grid utilization for certain VRE projects.

Beyond transmission congestion relief, BESS provides multiple system services that influence its economic attractiveness. Battery storage can supply energy during peak demand periods, contribute capacity adequacy and deliver fast-acting ancillary services such as frequency response and frequency regulation. Importantly, BESS is not restricted to a single function and is able to generate income from various market opportunities, which can improve project economics relative to single-purpose transmission investments (Marnell et al., 2019). Nevertheless, these revenue streams are highly sensitive to market design and regulatory frameworks.

From an investment perspective, transmission and storage differ fundamentally in their cost profiles. Transmission expansion is characterized by high upfront capital expenditures, long permitting and construction timelines, and long asset lifetimes. A general rule for comparing HVAC and HVDC is that HVDC becomes the more economical option as the power requirements and the distance increase. This is because HVDC systems have high upfront costs associated with the converter stations, usually rendering them uneconomic for short distances or low transfers. Institution of Engineering and Technology & Mott MacDonald (2025) found that the break-even distance for 2,000 MW, 1,000 MW and 500 MW to be approximately 100 km, 140 km and 240 km, respectively. While the costs of transmission expansion have remained relatively stable over time, the costs of BESS have declined rapidly and are expected to continue falling (Ritchie, 2021; BloombergNEF, 2026). However, BESS assets typically have shorter lifetimes than transmission lines, and may require multiple replacements over the lifetime of a transmission asset. As a result, when evaluated over a comparable time horizon, the cumulative costs of storage-based solutions may exceed those of transmission expansion, depending on the assumptions used (Ghosh et al., 2024).

Studies also indicate that relying on storage alone to accommodate rising VRE shares may lead to higher total system costs. Yamujala et al. (2025) shows that including transmission expansion alongside storage is generally more cost-effective for large-scale VRE integration in the United States and Europe. Moreover, higher storage capital costs tend to shift optimal system configurations toward greater reliance on transmission, resulting in higher overall system costs. Similarly, Golombek et al. (2022) emphasize that the cost-optimal deployment of stationary battery storage depends strongly on parallel developments in solar PV costs and the extent of cross-border transmission expansion. This highlights that at an individual project level, storage economics cannot be assessed independently from transmission availability.

Simplified Techno-Economic Analysis for ASEAN

Although the cost of storage and transmission at the project level depends on grid geography, regulation and current technological and financial factors, it is useful to gain a high-level overview of the current costs of different technological options to enhance grid flexibility that are currently available. The analysis helps discern technologies that are likely to be economically competitive within an ASEAN context.

The simplified techno-economic model used in this study is based on a small set of key variables that influence the cost-effective integration of renewable energy in the APG. The model assumes that ASEAN countries can manage the intermittency of renewable energy generation through two principal mechanisms: (1) expanding cross-border grid interconnections, thereby expanding the possibility to import or export electrons, or (2) increasing domestic electricity storage capacity.

Currently, renewable energy generation remains relatively low in most ASEAN member states, implying that costly measures, such as large-scale storage deployment or cross-border transmission expansion, are not yet necessary to maintain system stability. Instead, the variability of renewable energy generation can, in the short term, largely be balanced using existing fossil fuel and hydropower plants.

According to the International Energy Agency (IEA), energy storage and enhanced regional grid integration will only become systematically relevant between 2030 and 2040 as solar and wind shares begin to rise substantially in the ASEAN region (International Energy Agency, 2025b). However, due to the long lead-time of cross-border transmission projects, which typically take 7-10 years from conception to realization, a long-term planning horizon is required.

The data used in this model is based on recent renewable energy and transmission projects in Southeast Asia, to ensure the most accurate inputs for the analysis being undertaken. Sources include Bloomberg New Energy Finance (BloombergNEF, 2025), Rystad Energy (2025) and the International Renewable Energy Agency (IRENA, 2025a). When the data is inconsistent across datasets, median values are used as a conservative approximation. All costs are expressed as levelised cost of energy (LCOE) to allow for direct comparison across generation, storage, and transmission technologies. The future dominant technologies of RE generation in ASEAN are expected to be solar PV and offshore wind turbines. Although the region also possesses hydropower potential, the scale at which new large hydro facilities can be developed is limited, partly due to environmental concerns.

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Consequently, solar and wind are expected to constitute the majority of future renewable capacity additions, and thus the primary sources of cross-border renewable electricity traded within the ASEAN Power Grid (International Energy Agency, 2025b).

An overview of the costs associated with solar PV and offshore wind energy generation are provided in Table 1, expressed as LCOE $/MWh. These values are based on large-scale energy projects, allowing for an accurate benchmark. Note that the costs of large-scale onshore wind projects may be competitive to solar PV globally, but the ASEAN region contains limited areas with viable wind resources, mostly in Laos, the Philippines and Vietnam. Furthermore, Rystad Energy reports that onshore wind LCOE in Vietnam remains above the global average values reported by IRENA, thereby reducing its competitiveness as a region-wide supply option.

Table 1: RE generation LCOE

Generation technology	LCOE $/MWh	Comments
Solar photovoltaics	46	Range 43-50
Offshore wind turbines	80	Range 78-124

VRE. However, gas turbines are also frequently mentioned as an important transition technology for increasing grid flexibility, as energy from combined-cycle gas turbines (CCGT) can be rapidly dispatched.

Although the cost of different grid flexibility solutions depends on their utilization rates, as well as technological factors (such as battery degradation rates) and financial considerations (such as cost of capital), a generalized comparison based on published LCOE values is provided in Table 2.

Storage costs reflect the LCOE of a 50% capacity factor battery energy storage system (BESS) for four hours, which is typically co-located with solar PV or wind farms. Table 2 presents this as an independent cost component.

For cross-border transmission, our analysis distinguished between short-distance overland interconnections (e.g. Malaysia and Singapore) and long-distance undersea connections (e.g. Singapore and Cambodia or Vietnam). The short-distance connections typically use high voltage alternating current (HVAC) transmission lines, while high voltage direct current (HVDC) is more cost-effective across longer distances. The exact break-even distance is highly dependent on project details. Furthermore, the effective LCOE of HVDC technology can be reduced by increasing the load factor of the line through storage, thus increasing the utilization rate of the transmission line.

Natural gas CCGTs are seen as a grid flexibility solution, and assume a 50% utilization rate. However a direct comparison is complicated, because unlike storage or transmission, the CCGT LCOE does include the cost of electricity generation. If one compares the cost of CCGT to the cost of solar with storage, they are within the same range: 78-89 $/MWh for CCGT, and 65-123 $/MWh for solar with storage. Hence, the ‘storage’ function provided by CCGT could be similar to that of a BESS system, at approximately 40 $/MWh.

However, it should be noted that if CCGT utilization falls, or the price of natural gas rapidly increases, these costs could be much higher. CCGT is also not a renewable energy source, and produces significant greenhouse gas emissions. Table 2 summarizes representative LCOE values for these storage, transmission and flexible generation options.

Table 2: Flexibility generation LCOE

Flexibility solutions	**LCOE $/MWh**	**Comments**
Storage (50% cap. BESS, 4 hour battery)	40	Range 37–40
Short-distance transmission (overland)	40	Range 40–45
Long-distance transmission (undersea)	80	Range 80–200 (200 assumes no storage)
Natural gas CCGT (50% capacity factor)	83*	Range 78-89*

Based on the above estimates, the costs for BESS and short-distance transmission are similar, while long-distance transmission (undersea) and CCGT is significantly more expensive. Forecasts from Bloomberg NEF suggest continued cost reductions in both PV generation and storage, approximately 27% by 2030 and up to 48% by 2050, would further improve the cost competitiveness of storage relative to long-distance transmission and CCGT.

Drawing conclusions from these cost relationships, short-distance cross-border transmission for load balancing, as well as domestic storage deployment, represents the most economically viable pathway for ASEAN countries to integrate higher shares of VRE. In contrast, long-distance undersea HVDC connections appear only economically justified in the case of land-constrained locations such as Singapore, which cannot generate sufficient domestic RE and which may wish to diversify their RE supply.

While natural gas could be seen as a grid flexibility solution, its emissions profile makes it a less attractive choice than BESS coupled with VRE. Furthermore, on a risk-adjusted basis, when natural gas and carbon pricing uncertainty are taken into account, the cost of providing grid flexibility through natural gas may be significantly higher than storage and transmission alternatives.

With regards to the intra-day, seasonal and baseload scenarios outlined earlier, the generalized cost analysis suggests that short-distance connections could be economically viable for both intra-day grid stabilization and continuous baseload substitution. Using transmission to meet seasonal demand changes is unlikely to be economically viable, as it would likely require transmission over larger distances, raising cost. Furthermore, energy demand for space cooling is typically high during the hot or dry season, which is also the period when solar panels can achieve peak energy production due to high solar irradiance.

Conclusion and Policy Recommendations

The simplified techno-economic model presented here demonstrates that short-distance cross-border transmission and domestic BESS are currently the most cost-effective options for integrating VRE, especially when used together. Their typical LCOE values are largely comparable, and both provide valuable operational flexibility. Long-distance undersea high-voltage direct current (HVDC) transmission remains significantly more expensive and is unlikely to represent a cost-optimal option except for highly land-constrained systems such as Singapore.

Across the region, ongoing cost reductions in solar PV and battery storage further strengthen the economic case for local VRE deployment, supported by short-distance grid interconnections across land borders. A high-capacity long-distance undersea HVDC transmission network seems unlikely to be the most cost-effective option in the foreseeable future. As a result, undersea inter-connectivity, for example between Sabah (Malaysia) and Palawan (Philippines) or between Java and Kalimantan (Indonesia) may not materialize by 2040.

Based on this analysis, policy makers should consider the following:

1. **Grid flexibility will become increasingly important between 2030-2040 as VRE penetration increases**. Most ASEAN countries have VRE generation capacities which can be supported by existing grids. Estimates by Chee et al. (2025) and the IEA suggest that VRE capacity approaching 50% will start posing technical challenges that could require investments in grid-interconnection or additional storage. Most ASEAN countries will only reach such a threshold during the 2030s. While BESS can be deployed relatively quickly (~3 years), cross-border grid interconnections may require a longer planning horizon, as they often take 2-3 times longer to materialize.

2. **Short-distance grid interconnections and battery storage are the most economically competitive technologies to enhance grid flexibility.** There does not seem to be a strong economic case for long-distance undersea transmission due to high construction costs and energy losses. The only country for which such projects may be economically viable is Singapore. Although Malaysian PV projects have the lowest LCOE for Singapore importers (Rystad Energy, 2025), Singapore may be willing to pay higher prices to diversify its foreign RE supply for the purpose of maintaining energy security. Using natural gas to increase grid flexibility could be relatively costly, especially when including fuel and carbon price risks.

3. **Bilateral or Minilateral Arrangements will shape APG development.** While there are a number of cross-border RE trade arrangements in ASEAN, whereby Lao PDR is often the seller, and Singapore the buyer, these are essentially bilateral arrangements (or minilateral, in the case of the LTMS-PIP, allowing hydropower exports from Lao PDR to Singapore via Thailand and Malaysia). There is no movement towards an ASEAN-wide electricity market, as only Singapore and The Philippines have market-based electricity systems. There is also no movement yet towards integrating two or more national markets. As a result, APG development will primarily be shaped by bilateral needs. Long-distance undersea transmission projects proposed under the APG that do not involve Singapore are unlikely to materialize in the foreseeable future due to a lack of economic drivers.

While the growth of electricity interconnections between ASEAN countries is encouraging, an integrated APG and ASEAN energy market is unlikely to emerge during the coming decades. However, due to the falling cost of BESS and growing experience with bilateral interconnections, ASEAN countries may still be able to achieve sufficient grid flexibility to successfully and cost-effectively absorb rising VRE generation capacity.

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