The ASEAN Power Grid Supporting Energy and Economic Security: Japan's Potential Contributions

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Executive Summary

Amid rising global uncertainty marked by a retreat from globalization and increasing geopolitical risks, the ASEAN Power Grid (APG) is being focused on not only as a foundation for decarbonization but also as a core infrastructure capable of simultaneously achieving ASEAN's "energy security" and "economic security."

For ASEAN to sustain its growth, it is essential to reduce excessive dependence on fossil fuels and enhance energy self-sufficiency by maximizing the use of renewable energy resources within the region. This constitutes the foundation of "energy security." At the same time, there is a strong need for "economic security," which entails avoiding the risks of dependency (lock-in) on any single country for infrastructure technologies and supply chains, thereby maintaining regional and national autonomy.

ASEAN is endowed with abundant renewable resources—including hydropower, solar, wind, and geothermal energy. From the perspective of building an efficient energy system that effectively utilizes these geographically uneven resources across the region, the APG represents a rational solution. Furthermore, as the share of variable renewable energy increases in individual countries, the APG's wide-area interconnection can significantly enhance grid flexibility.

Although nearly 30 years have passed since its conception in 1997[1], only about half of the officially planned interconnection lines have been completed, and full market integration has not yet been achieved. This is due to a complex interplay of "technical, financial, and institutional challenges," including shortages of advanced technologies for interconnection and system operation, a substantial investment gap, and inconsistent regulatory frameworks across countries.

To overcome technical challenges, "flexibility enhancing measures" such as high-voltage direct current (HVDC) transmission, submarine cables, large-scale battery storage, and energy management systems (xEMS) are indispensable. Given ASEAN's unique conditions—such as inter-island connectivity and harsh weather environments, such as typhoons—the technological capabilities of Japanese companies, which have accumulated experience under similar conditions, can provide highly effective solutions.

However, technological excellence alone is not sufficient to drive social implementation of infrastructure. The Japanese government is expected to play a key role in lowering financial barriers by providing risk capital through institutions such as JICA and JBIC. At the same time, through the AZEC framework, it is necessary to strongly promote public-private collaboration in areas such as harmonizing technical standards, establishing multilateral rules, and sharing expertise in wide-area grid operation (including human resource development).

The initial investment required for constructing APG cross-border interconnections is estimated at approximately USD 11.9–49.8 billion (equivalent to 1.5–6.4% of ASEAN's total fiscal expenditure in 2024). However, when comparing the investment cost of individual routes against national fiscal expenditures, the perceived burden does not necessarily correspond to the absolute magnitude of the investment.

Currently, in addition to the official APG framework, international interconnection projects involving external partners such as Australia, as well as independent long-distance interconnection initiatives within the region, are underway. From the perspective of viewing ASEAN as a unified bloc, these developments contribute to "outward grid resilience" by diversifying supply sources and procurement routes geographically, and, together with "inward grid resilience" through maximizing the use of regional resources, they strengthen ASEAN's energy security in a multilayered manner.

At the same time, while ASEAN seeks to build a diversified technology portfolio as a "hedging strategy" for economic security, Japan can be "one of the most important partners" to ASEAN for higher resilience. By providing advanced grid flexibility technologies together with financial and institutional public support as a comprehensive package—and by positioning itself as a central partner within a diverse set of partnerships—Japan can play a significant role supporting ASEAN's autonomous and sustainable development.

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[1] ASEAN Heads of State/Government at the 2nd Informal Summit (1997), "1997 ASEAN VISION 2020," https://www.icnl.org/wp-content/uploads/Transnational_vision.pdf (Accessed on May 11, 2026)

Contents

1. Introduction

ASEAN has achieved remarkable economic growth over many years. As an energy foundation supporting this growth, the ASEAN Power Grid (APG) initiative was launched in 1997 to establish cross-border electricity interconnections among ASEAN member states.

In recent years, amid growing uncertainty in global values—stemming from cascading geopolitical crises such as Ukraine and Iran, and, in some regions, a retreat from climate change countermeasures—the significance of the APG has expanded beyond being merely a measure for decarbonization. It is now being focused on as a cornerstone of energy security, enabling the large-scale utilization of renewable energy across the ASEAN region and enhancing energy self-sufficiency. Furthermore, from the perspective of economic security, there is an urgent need to strategically develop the APG in order to diversify the technology source and to mitigate the risk of disruptions in power infrastructure supply chains.

However, nearly 30 years after its inception, progress has not been entirely satisfactory, with approximately half of the officially proposed routes still uncompleted. This is due to a range of complex challenges, including economic disparities among member states, geographical constraints such as those faced by archipelagic countries, and diverse political systems and domestic instabilities. The fact that the APG initiative has continued to advance owes at least in part to cooperation from technologically advanced countries, including Japan. Multifaceted support from Japan will ensure further progress.

This paper first provides an overview of the APG, which contributes to energy and economic security in ASEAN while enabling the large-scale integration of renewable energy into the energy system. It then examines the technical challenges involved, along with potential solutions and mitigation measures through key technologies, including initiatives undertaken by Japanese companies.

Finally, the paper analyzes financial and institutional challenges and their mitigation measures, focusing on Japan's cooperation, and reviews current and future policy and institutional frameworks. It also quantitatively assesses the scale of investment required for the APG and the relative financial burden borne by each country.

2. Significance of the ASEAN Power Grid (APG)

(1) The Importance of Energy Security in the ASEAN Context

Since the 1990s, against the backdrop of globalization, ASEAN has achieved remarkable economic development as one of the world's growth centers. This growth, accompanied by rapid urbanization and industrialization, has led to a sharp increase in energy demand. Historically, this demand has been met primarily by conventional fossil fuels such as coal, oil, and natural gas. While some countries—such as Indonesia and Malaysia—were once net exporters of oil, most ASEAN member states have now become net importers of fossil fuels[2].

This vulnerable energy supply structure, heavily dependent on fossil fuel imports, has been exposed to severe risks due to geopolitical shocks, including the war in Ukraine and conflicts involving Iran. The global surge in fossil fuel prices has not only triggered rapid inflation across ASEAN countries and worsened their trade balances but has also placed considerable strain on national finances through the expansion of massive energy subsidies aimed at protecting citizens' livelihoods.

These experiences have deeply ingrained in ASEAN countries the lesson that ensuring energy security is not merely a policy objective, but a critical national issue directly tied to macroeconomic stability and fiscal soundness.

(2) Externally Driven "Decarbonization" to Internally Driven "Energy Security"

Amid exposure to geopolitical shocks and the volatility of fossil fuel prices, the role of renewable energy within ASEAN is being reassessed.

Until now, the deployment of renewable energy in ASEAN has largely been driven by the need to respond to climate change initiatives led by the international community, particularly Western countries. In other words, it has been promoted based on external drivers, such as attracting foreign direct investment (FDI) that emphasizes ESG considerations, and meeting environmental standards within the global supply chains of multinational corporations.

However, the fundamental nature of this transition is now undergoing a significant shift. It is evolving toward an internal driver based on energy security—namely, reducing dependence on imported fossil fuels and maximizing the use of energy that is effectively fuel-free and can be sourced within the region. By doing so, ASEAN countries aim to enhance energy self-sufficiency and safeguard economic independence.

Therefore, even if the global momentum toward decarbonization were to temporarily stall, ASEAN countries would not lose their incentive to promote the large-scale deployment of renewable energy, as it is essential for their national survival.

(3) The Emerging Significance of "Economic Security"

While ASEAN is accelerating the maximum utilization of renewable energy from the perspective of energy security, it is also confronting new risks related to economic security in the process. In seeking to reduce dependence on fossil fuels from regions such as the Middle East and Russia, there is a concern that ASEAN may instead fall into excessive dependence on specific countries (primarily China) for renewable energy supply chains and power infrastructure technologies.

The first risk lies in oligopolistic dependence on specific countries in the hardware supply chains for renewable energy equipment and critical minerals. Currently, certain countries hold overwhelming market shares in the manufacturing of solar panels, batteries, and wind turbines, as well as in the mining and refining of essential rare earth elements. If supply were to be disrupted due to trade frictions or geopolitical conflicts, the entire energy transition could be derailed. Nevertheless, for such relatively standardized hardware, there remains some room to mitigate risks through alternative sourcing and gradual replacement.

The second, more severe risk is the potential "lock-in" of core systems in transmission infrastructure—including the APG—into the technological standards and systems of a specific country. Power grids are the "arteries" of a nation and, when integrated with information networks, function as

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[2] International Energy Agency (2025), *World Energy Statistics and Balances 2025*

its "nervous system." Dependence on a single country may not only force reliance on that country for recovery from system failures in peacetime, but also create critical vulnerabilities in times of crisis. These include the suspension of maintenance parts supply and the triggering of large-scale blackouts through remote cyberattacks exploiting black-boxed systems, thereby fundamentally threatening national autonomy.

To mitigate these economic security risks, ASEAN is required to extend its traditional diplomatic and security principle of a "hedging strategy (equidistant diplomacy)"[3] to the field of energy infrastructure. It is essential to avoid technological lock-in to any single country in core infrastructure and instead diversify the portfolio of infrastructure technologies by sourcing advanced grid technologies and capital from multiple technologically advanced countries, including Japan. This diversification is urgently needed to ensure ASEAN's overall strategic autonomy and resilience.

(4) Significance as an "Energy System"

In recent years, ASEAN countries have experienced rapid growth in the deployment of variable renewable energy (VRE), particularly solar power, supported by policy and regulatory measures. As of 2024, VRE accounted for approximately 11% of total installed generation capacity in the region[4]. However, in countries such as Vietnam, generation facilities have been concentrated in areas with favorable solar resources without sufficient coordination with demand centers and transmission infrastructure, resulting in transmission constraints, network congestion, and curtailment of renewable generation[5].

VRE sources such as solar and wind power are inherently dependent on natural conditions, including solar irradiation and wind availability. As a result, their development potential is geographically uneven, while their output fluctuates according to weather conditions and time of day. Consequently, power systems must address two major challenges: the geographical mismatch between resource availability and electricity demand, and the temporal variability of supply-demand balance.

Cross-border interconnections can effectively address the geographical mismatch between renewable energy resources and electricity demand by enabling the wider regional utilization of renewable energy resources despite their geographically uneven distribution. Because VRE deployment is constrained by resource conditions, balancing supply and demand solely within national borders may limit the region's ability to fully utilize its overall renewable energy potential. Regional power exchange enabled by interconnections allows electricity generated in resource-rich areas to be utilized effectively across the region, thereby expanding the usable potential of renewable energy resources. This can also alleviate oversupply in specific regions or countries and help avoid renewable energy curtailment.

As VRE penetration increases, interconnections enable the wider regional sharing and more efficient utilization of flexibility resources needed to manage temporal fluctuations in supply and demand. In power systems, where maintaining a continuous balance between supply and demand is a fundamental principle, securing flexibility resources capable of responding to VRE output fluctuations is essential. Such flexibility can be provided by thermal power plants, hydropower, battery storage systems, and demand response (DR), among others. These flexibility resources differ in their locational characteristics and availability depending on their technical nature. In particular, resources such as hydropower, whose availability depends on natural conditions and is geographically unevenly distributed, and demand response, whose potential depends on demand scale and industrial structure, can benefit significantly from regional complementarities. Even for resources such as battery storage, which are relatively flexible in terms of siting, operation based on broader regional supply-demand conditions can maximize the utilization of individual storage assets and improve overall system efficiency.

Furthermore, wide-area interconnections can smooth the temporal and geographical variability of VRE output. Weather conditions do not change simultaneously or to the same extent

[3] K. Cheng-Chwee (2025), "Hedging as a Policy Without Pronouncement: A Tale of Three Defense White Papers," NIDS ASEAN Workshop 2025 New Strategies in Southeast Asia?. NIDS JOINT RESEARCH SERIES No.22, CHAPTER 1

[4] IEA (2025), "Integrating Solar and Wind in Southeast Asia", https://iea.blob.core.windows.net/assets/b0b39b60-8686-4043-b060-1f7655e7536c/IntegratingsolarandwindinSoutheastAsia.pdf (Accessed on June 3, 2026)

[5] International Energy Agency (2024), "Achieving a Net Zero Electricity Sector in Viet Nam", https://www.iea.org/reports/achieving-a-net-zero-electricity-sector-in-viet-nam (Accessed on June 3, 2026)

across different regions; therefore, upward or downward deviations in one area can be partially offset by conditions in another. As a result, fluctuations in aggregate generation across a wider interconnected region tend to be relatively smaller and smoother than those observed within individual areas. In addition, when multiple regions are integrated, individual fluctuations and forecasting errors are statistically averaged out, reducing the relative magnitude of aggregate variability. In other words, as the number of geographically distributed generation sources increases, the overall output profile tends to become smoother. This also effectively reduces forecasting errors for VRE output, making it easier to anticipate the magnitude of supply-demand imbalances in advance. Consequently, system operators can secure the necessary balancing capacity and reserves more efficiently, contributing to more efficient system operation.

These effects are also significant from an economic perspective, as regional interconnections can enable more cost-effective deployment and utilization of generation and flexibility resources and reduce overall system costs. VRE generation facilities and certain flexibility resources with geographically uneven availability can be deployed and utilized in optimal locations according to resource conditions, thereby reducing overall generation costs. In addition, reducing VRE curtailment through regional interconnections and optimizing the operation of flexibility resources based on broader regional supply-demand conditions can further lower overall system costs. Sharing reserve capacity across countries can also reduce the total reserve requirements compared with each country securing reserves independently, thereby contributing to cost reductions.

In this way, for ASEAN, where VRE deployment is expected to continue expanding, the APG can be regarded as an effective and rational means of optimizing the overall energy system through the effective utilization of renewable energy resources, the efficient provision of flexibility, and the stabilization of power system operation.

3. Overview of the ASEAN Power Grid (APG)

(1) Current Status of the APG

① Official APG Interconnection Projects and Subregional Systems

Nearly 30 years have passed since the APG was first proposed in 1997. During this period, some of the interconnection projects[6] have made progress and been realized. Of the 18 officially proposed interconnection projects, nine routes have already been confirmed to exist (Table 3-1, Figure 3-1)[7].

Table 3-1 Proposed APG interconnection routes and existing capacity

No.	Proposed interconnection routes	Subsystem	Existing Capacity (MW)
1	Peninsula Malaysia (Malaysia)－Singapore	South	525
2	Thailand－Peninsular Malaysia	North－South	380
3	Sarawak (Malaysia)－Peninsular Malaysia	East－South	-
4	Peninsular Malaysia－Sumatera (Indonesia)	South	-
5	Batam (Indonesia)－Singapore	South	-
6	Sarawak－West Kalimantan (Indonesia)	East	230
7	Philippines－Sabah (Malaysia)	East	-
8	Sarawak－Brunei－Sabah		
	a. Sarawak－Brunei	East	-
	b. Sarawak－Sabah	East	30-50
9	Thailand－Lao PDR	North	955
10	Lao PDR－Vietnam	North	-
11	Thailand－Myanmar	North	-
12	Vietnam－Cambodia	North	200
13	Lao PDR－Cambodia	North	300
14	Thailand－Cambodia	North	250
15	East Sabah (Malaysia)－North Kalimantan (Indonesia)	East	-
16	Singapore－Sumatera	South	-
17	Lao PDR－Myanmar	North	30
18	Internal Indonesia		
	a. Kalimantan－Java	East－South	-
	b. Sumatera－Java	South	-

[6] In the appendix of ASEAN Centre for Energy (2026), ASEAN Interconnection Masterplan Study (AIMS) III Phase 3: Minimum Requirements for Multilateral Trade in ASEAN, published in May 2026, more than 18 cross-border interconnection lines between grids are listed. However, as of May 2026, information on both new and existing routes remains insufficient. For example, in some cases it is unclear which cities are connected, or the distances of terrestrial and subsea segments are not specified. Therefore, this paper adopts the 18 routes identified in ASEAN Centre for Energy (2024), ASEAN Power Grid Interconnections Project Profiles as the official candidate routes of the APG.

[7] According to the ASEAN Interconnection Masterplan Study (AIMS) III Phase 3 report published by the ASEAN Centre for Energy (ACE) in May 2026, a larger number of candidate interconnection routes are identified. However, due to insufficient information for subsequent analyses, such as investment scale estimations, this paper— as noted in Chapter 3 (1)—adopts the 18 routes presented in ASEAN Centre for Energy (2024), ASEAN Power Grid Interconnections Project Profiles as the official APG candidate routes.

Total	2,900-2,920

Note: The source states that the Batam–Singapore route (No. 5) has been merged into the Singapore–Sumatera route (No. 16). However, since the map in ASEAN Centre for Energy (2025), "ASEAN Power Grid Updates" retains the Batam–Singapore route as No. 5 without merging it, this table also retains it as is.
Source: Compiled by The Institute of Energy Economics, Japan (IEEJ), based on ASEAN Centre for Energy (2024) *ASEAN Power Grid Interconnections Project Profiles*, p.2, and Borneo Post (December 13, 2025) "Sabah energy transition enters new phase."

In addition, the APG can be divided into three subregional systems: the Northern, Southern, and Eastern subregions (Table 3-1).

The Northern subregional system covers Cambodia, Lao PDR, Thailand, Vietnam, and Myanmar, where hydropower exports from Laos to Thailand and Cambodia have already been realized. The Southern subregional system includes Peninsular Malaysia, Singapore, Sumatra (Indonesia), and Java (Indonesia), where interconnection between Malaysia and Singapore has begun. The Eastern subregional system consists of Sarawak and Sabah (Malaysia), Kalimantan (Indonesia), Brunei, and the Philippines, with interconnection between Malaysia and Indonesia already underway[8].

As can be visually observed from Figure 3-1, the development of interconnection lines in the Northern subregional system is currently more advanced compared to those in the Southern and Eastern subregional systems.

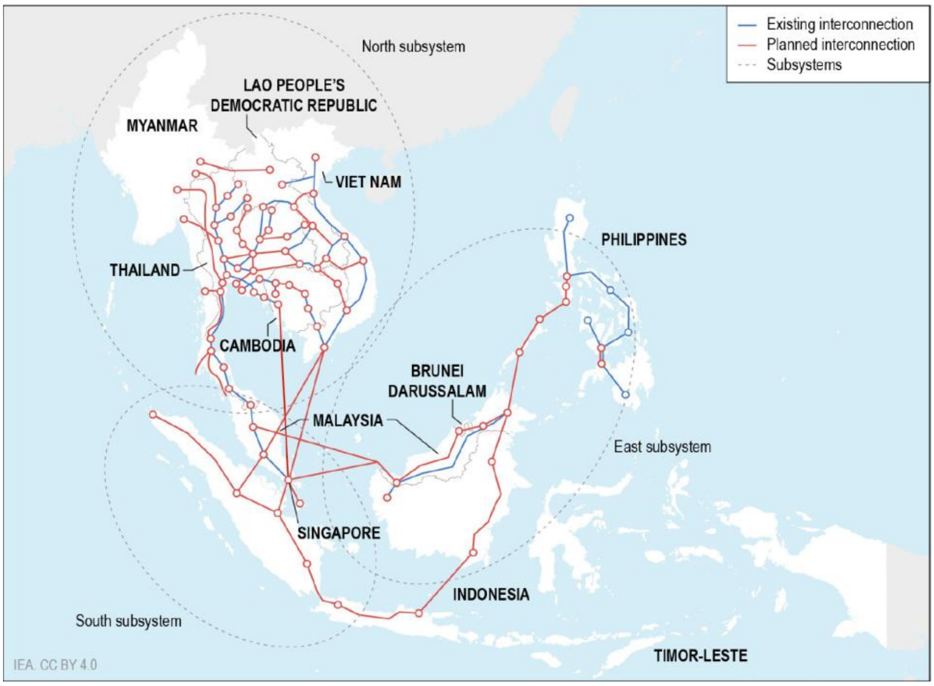


Figure 3-1 APG subregional system
Source: Adapted from International Energy Agency (2026), *Financing the ASEAN Power Grid*, p.26.

However, the current APG remains largely limited to bilateral interconnections centered on countries such as Thailand and Malaysia (with some multilateral initiatives, such as the Laos–Thailand–Malaysia–Singapore Power Integration Project (LTMS-PIP)), and the path toward full regional integration is still only halfway complete.

② The Role of the APG in Light of ASEAN Member State Conditions

The significance of the ASEAN Power Grid (APG) can be better understood by considering the uneven distribution of renewable energy resources, electricity demand, and flexibility resources

[8] ASEAN Centre for Energy (2022), *ASEAN Power Grid Planning and Implementation Stage*, https://www.unescap.org/sites/default/d8files/event-documents/Enabling%20MPT_ASEAN%20Power%20Grid%20Planning%20and%20Implementation%20Stage-%20by%20ACE_0.pdf (Accessed on December 24, 2025)

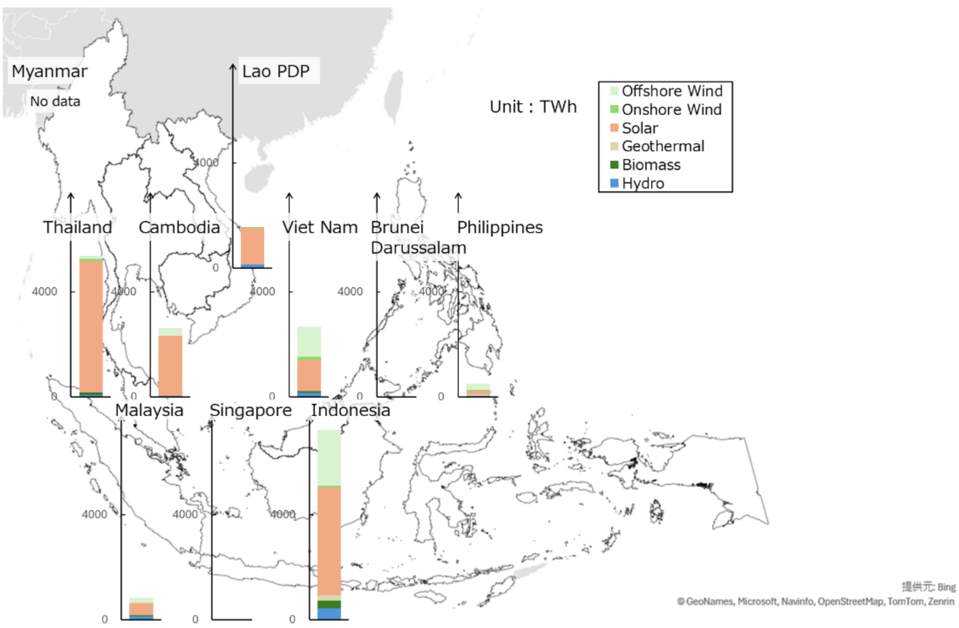
across ASEAN member states. This section examines these regional characteristics based on data on renewable energy potential and power generation mix, and discusses how cross-border interconnections could facilitate more efficient utilization of renewable energy and balancing resources within the region.

a. Mismatch Between Renewable Energy Potential and Demand Distribution

A key characteristic of the ASEAN region is that the geographical distribution of renewable energy resources does not necessarily coincide with the distribution of electricity demand. As a result, it may be difficult for individual countries to fully utilize the region's overall renewable energy potential if supply and demand are balanced solely within national borders.

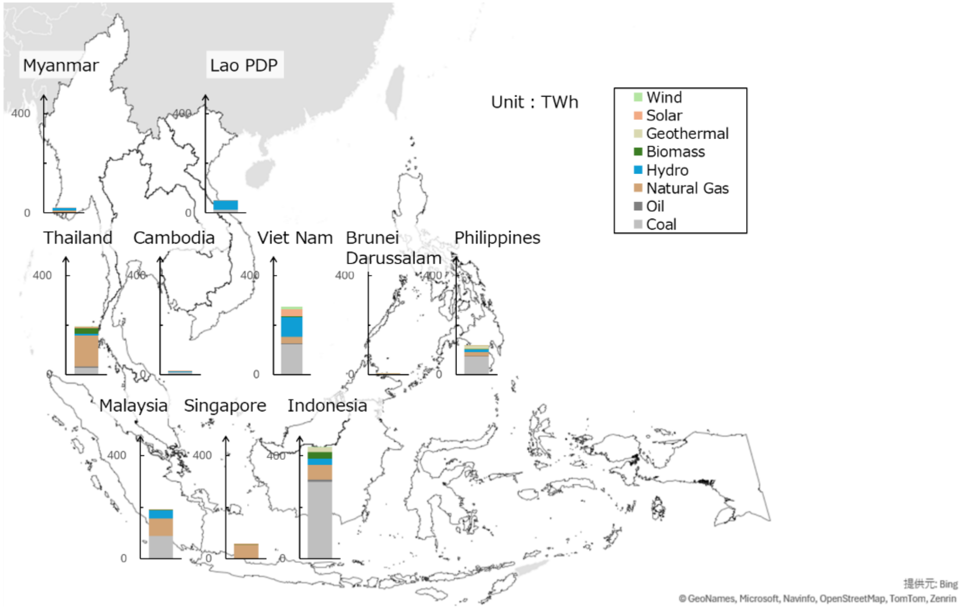
As shown in Figure 3-2(i), renewable energy potential varies significantly across ASEAN countries. Indonesia possesses the largest renewable energy potential in the region, particularly in solar and offshore wind resources, while Thailand also has substantial deployment potential centered on solar power. Vietnam has multiple renewable energy resources, including hydropower and offshore wind. Cambodia has relatively large solar potential, whereas Malaysia and the Philippines have comparatively smaller renewable energy potential. Singapore, due to geographical constraints, has extremely limited renewable energy potential. This analysis includes offshore wind potential; however, it should be noted that there remain uncertainties regarding its practical feasibility due to constraints related to costs, institutional frameworks, and infrastructure.

In contrast, Figure 3-2(ii), which shows electricity generation, used here as a proxy for electricity demand, indicates that demand is particularly great in Indonesia, Thailand, Vietnam, and Malaysia, while the scale and composition of renewable energy potential do not necessarily align with demand distribution. Singapore, in particular, has a certain level of electricity demand despite having almost no domestic renewable energy potential, making reliance on imported renewable electricity effectively unavoidable.



(i): Renewable Energy Potential by ASEAN Country[9]

[9] Recompiled based on data from the following sources. Installed capacity data were obtained from Japan International Cooperation Agency (JICA) & The Institute of Energy Economics, Japan (IEEJ) (2025), Study on ASEAN Power Grid, https://libopac.jica.go.jp/images/report/1000055597.pdf (Accessed on February 20, 2026). Capacity factor data were obtained from International Renewable Energy Agency (IRENA) (2024), Renewable Power Generation Costs in 2023, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf (Accessed on June 3, 2026)



(ii): Electricity Generation by ASEAN Countries (2023)[10]

Figure 3-2 Renewable Energy Potential and Electricity Generation Mix Across ASEAN Countries

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

Under such conditions, cross-border interconnections and electricity trading could enable broader utilization of electricity generated in resource-rich areas across the region. This may contribute to greater renewable energy deployment and mitigation of renewable energy curtailment.

b. Uneven Distribution and Sharing of Flexibility Resources

Another important characteristic of the ASEAN power system is the uneven distribution of flexibility resources for integrating variable renewable energy (VRE) across countries. ASEAN countries exhibit different patterns of power generation and balancing capability, creating opportunities for cross-border complementarities.

Regarding hydropower, Vietnam and Laos possess relatively large capacities. In Vietnam, hydropower utilization has already progressed significantly, and therefore additional flexibility potential may be limited. Laos, on the other hand, has abundant hydropower resources despite relatively small domestic demand and could potentially serve as a supplier of flexibility resources within the region.

For gas-fired power generation, Thailand, Malaysia, Singapore, and Indonesia have large generation volumes, and gas-fired plants are expected to remain key resources for balancing supply and demand in the short to medium term. In the longer term, as decarbonization progresses, the transition toward thermal power generation utilizing hydrogen or ammonia could become one of the promising options. If such a transition materializes, these power sources may continue to provide flexible output adjustment capabilities similar to those currently provided by gas-fired generation.

In addition, countries with large electricity demand, such as Indonesia and Thailand, are also expected to have relatively greater potential for securing demand-side flexibility, including demand response.

Thus, flexibility resources—including hydropower, thermal power, and demand-side measures—are geographically concentrated in different countries and exhibit complementary relationships at the regional level. Sharing these resources through interconnections could enable more efficient regional supply-demand balancing compared with a situation in which each country independently secures its own flexibility resources.

[10] IEA (2025), *World Energy Statistics and Balances 2025*

c. Country Typologies and the Role of the APG

Based on the distribution of renewable energy potential and flexibility resources described above, ASEAN countries can be broadly categorized into several types with differing characteristics and roles in the regional power system. These categories help illustrate how regional interconnections could support more efficient utilization of renewable energy and balancing resources across ASEAN.

First, countries such as Vietnam and Cambodia possess significant renewable energy potential but face constraints related to flexible resources and grid infrastructure. Although these countries have substantial room for further renewable energy deployment, continued expansion is likely to require supplementary balancing capability from neighboring countries within the region.

Second, countries such as Indonesia and Thailand—and, to a lesser extent, Malaysia—possess both renewable energy potential and flexibility resources to some degree. In addition to stabilizing domestic supply and demand, these countries could potentially play intermediary roles in regional electricity exchange and system balancing.

Meanwhile, Singapore represents a country with limited renewable energy potential but meaningful electricity demand and balancing capability. In such a case, reliance on imported renewable electricity is likely to increase, while domestic power resources may continue to contribute to regional supply-demand balancing.

Furthermore, some countries, such as Laos, may play more specialized roles as suppliers of flexibility resources based on abundant hydropower resources.

Taken together, renewable energy potential and flexibility resources are distributed unevenly across ASEAN countries, but in ways that create regional complementarities. The APG is therefore expected to play an important role as the regional infrastructure enabling the wide-area exchange of both electricity and flexibility resources across ASEAN.

(2) Future Plans for the APG

① Future Scenarios for the APG by the ASEAN Centre for Energy (ACE) [11]

According to ACE's analysis, there are three major future scenarios for the APG: the Updated PDP scenario, the ASEAN RE Target scenario, and the High RE Target scenario.

The updated PDP scenario reflects the latest Power Development Plans (PDPs) of each country and reuses the optimization model from AIMS Phases I and II, premised on coal reduction and the expansion of renewable energy. Under this scenario, the share of renewable energy in installed capacity is projected to increase to 52% by 2040, and in response to changes in the supply-demand structure, the APG interconnection capacity would need to be significantly expanded to 18 GW by 2040.

The ASEAN RE Target scenario adopts a model structure in which the level of variable renewable energy (VRE) deployment is given exogenously, while the expansion of thermal power and cross-border interconnections is optimized. It also incorporates the 2025 renewable energy targets (23% of total primary energy supply and approximately 31% of total installed generation capacity) into the outlook to 2040. According to this scenario, the share of renewable energy in installed capacity reaches 31% in 2040, while the APG interconnection capacity amounts to 25 GW.

The High RE Target scenario assumes a significant increase in VRE deployment in the future power mix and models very high levels of VRE penetration in both national grids and international interconnections. Under this scenario, renewable energy accounts for 59% of total installed generation capacity in 2040, and interconnection capacity reaches 105 GW.

The following section presents the projected APG interconnection capacity by route for 2040 under each of the above scenarios (Table 3-2).

[11] The ASEAN Centre for Energy (ACE) is an intergovernmental organization established in 1999 to accelerate energy cooperation and integration within the ASEAN region. It plays a role in providing information and expertise to member states, helping align energy policies with regional economic growth and environmental sustainability.

Table 3-2 ACE's 2040 scenarios for APG interconnection capacity by route
(Updated PDP・ASEAN RE Target・High RE Target)

No.	Proposed interconnection routes	Updated PDP Scenario (2040, MW)	ASEAN RE Target Scenario (2040, MW)	High RE Target Scenario (2040, MW)
1	Peninsula Malaysia－Singapore	1,050	1,050	3,154
2	Thailand－Peninsular Malaysia	380	1,043	10,300
3	Sarawak－Peninsular Malaysia	-	695	3,152
4	Peninsular Malaysia－Sumatera	2,000	2,130	10,000
5	Batam－Singapore	-	-	-
6	Sarawak－West Kalimantan	830	777	769
7	Philippines－Sabah	200	196	6,086
8	Sarawak－Brunei－Sabah			
	a. Sarawak－Brunei	100	100	643
	b. Sarawak－Sabah	150	177	2,819
9	Thailand－Lao PDR	1,300	700	5,630
10	Lao PDR－Vietnam	620	625	10,200
11	Thailand－Myanmar	1,250	1,262	1,310
12	Vietnam－Cambodia	250	1,353	10,200
13	Lao PDR－Cambodia	500	625	820
14	Thailand－Cambodia	1,000	1,315	10,120
15	East Sabah－North Kalimantan	200	174	4,319
16	Singapore－Sumatera	1,200	1,133	10,000
17	Lao PDR－Myanmar	350	624	4,606
18	Internal Indonesia			
	a. Kalimantan－Java	-	435	477
	b. Sumatera－Java	6,200	10,000	10,000
Total		17,580	24,414	104,605

Note: The source indicates that the Batam–Singapore route (No. 5) has been merged into No. 16. However, the map in ASEAN Centre for Energy (2025), "ASEAN Power Grid Updates" retains the Batam–Singapore route as No. 5 without merging it; therefore, it is also retained as is in this table.
Source: Compiled by The Institute of Energy Economics, Japan, based on Table 3-1, and ASEAN Centre for Energy (2023), *Findings of ASEAN Interconnection Masterplan Study (AIMS) III Phase 1 & 2 Update*.

The total transmission capacity of the APG is projected to increase sixfold from current levels by 2040 under the most conservative Updated PDP scenario (Figure 3-3).

While the total transmission capacities under the Updated PDP scenario and the ASEAN RE Target scenario in 2040 are relatively close, the High RE Target scenario is far more ambitious, aiming to achieve a total transmission capacity that is approximately four to six times larger than those of the other scenarios[12].

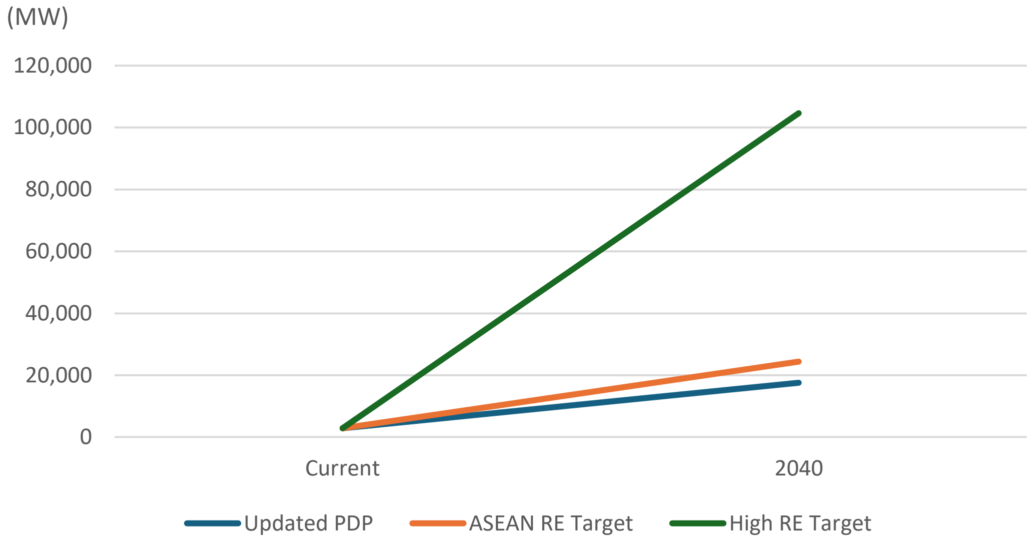


Figure 3-3 Illustration of transmission capacity expansion toward 2040 by scenario
Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

② Prioritization of Candidate Interconnection Routes by JICA and IEEJ

While the ASEAN Centre for Energy (ACE) does not assign priorities to the candidate routes, a study by JICA&IEEJ(2025)[13] has undertaken such prioritization.

In this study, the routes are evaluated based on three steps:

・Step 1: existence of existing interconnections and the presence of Development Partners (DPs);
・Step 2: economic feasibility of power trade, potential for renewable electricity imports and exports, and the novelty of international interconnection lines;
・Step 3: environmental impact, social impact, and construction difficulty of each route.

Based on this evaluation, the study concludes that the highest priority for development is the Sarawak–Brunei route (No. 8-a), followed by the Singapore–Sumatera route (No. 16, including the Batam–Singapore route, No. 5), and the Philippines–Sabah route (No. 7) as the third priority.

(3) Challenges of the APG

As described above, although the APG is expected to bring significant positive impacts to ASEAN countries in terms of the environment, stable energy supply, and economic development, many challenges remain for its realization. These challenges can be broadly categorized into three types: technical, financial, and institutional.

The technical challenges are wide-ranging. For example, there is a need to harmonize voltage and frequency across national transmission systems, to develop long-distance subsea transmission that spans island regions and straits, and to introduce advanced control technologies for wide-area interconnections. Some of the key technologies required to address these issues—such as HVDC and

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[12] The ASEAN Interconnection Masterplan Study (AIMS III) Phase 3: ASEAN-wide Integrated Resource and Resilience Planning (IRRP), published by the ASEAN Centre for Energy in May 2026, outlines plans for the next master plan, "AIMS IV." This plan proposes to consider five scenarios: (1) Scenario 0 – Power Development Plans (PDPs) without interconnections; (2) Scenario 1 – Business-as-Usual (BAU); (3) Scenario 2 – BAU with uncapped interconnection capacity; (4) Scenario 3 – High renewable energy (RE); and (5) Scenario 4 – High renewable energy including storage and demand flexibility.

[13] Japan International Cooperation Agency (JICA) & The Institute of Energy Economics, Japan (IEEJ) (2025), *Study on ASEAN Power Grid*, https://libopac.jica.go.jp/images/report/1000055597.pdf (Accessed on February 20, 2026)

subsea cables, which enhance grid flexibility—have already been commercialized globally. However, at present, ASEAN has little choice but to proceed with APG development in stages, relying on technology transfer and international cooperation from technologically advanced countries outside the region.

In addition, even where advanced technologies are available, the realization of the APG requires enormous financial resources, making financial barriers substantial. These include the bankability of cross-border interconnections, the mismatch between long asset lifetimes and short- to medium-term financing, high risk premiums, and uncertainty in long-term demand.

Furthermore, the construction of the APG faces significant institutional barriers in addition to technical and financial challenges. These include regulatory inconsistencies across countries, the absence of a unified certification body for Renewable Energy Certificates (RECs), and the lack of a regional coordinating or integration authority.

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Furthermore, the construction of the APG faces significant institutional barriers in addition to technical and financial challenges. These include regulatory inconsistencies across countries, the absence of a unified certification body for Renewable Energy Certificates (RECs), and the lack of a regional coordinating or integration authority. The following sections address these issues in greater detail: Chapter 4 focuses on technical challenges, while Chapter 5 examines financial and institutional challenges, including possible approaches to addressing them.

4. Flexibility Enhancing Measures Contributing to the Strengthening of the APG and the Involvement of Japanese Companies

(1) Flexibility enhancing measures

The APG has the potential to maximize the utilization of renewable energy resources within the region and contribute to the cross-border sharing of balancing capacity. At the same time, its realization presupposes the development and efficient operation of cross-border interconnections, a process that entails numerous technical challenges related to grid flexibility.

Given the inherently gradual and decentralized nature of APG development, each national power system will need to ensure both the enhancement of transmission and distribution network capacity and the maintenance of stable system operations throughout the transitional period[14].

Furthermore, even after the establishment of a future wide-area interconnected grid, achieving efficient supply-demand matching and stable system operation will require not only cross-border interconnection technologies but also the deployment of grid stabilization technologies and demand-side flexibility technologies.

In light of these considerations, this chapter examines and analyzes a range of technologies for maintaining and optimizing power supply-demand balance and power quality, in addition to core transmission infrastructure technologies underpinning the APG, such as HVDC systems and submarine cables[15]. The chapter also highlights Japanese companies involved in the development, demonstration, and commercialization of products associated with these technologies.

This chapter classifies the areas affected by the individual measures discussed into four categories: transmission, distribution, generation, and demand (Figure 4-1).

"Transmission" refers to the power grid domain responsible for the long-distance transport of high-voltage, high-capacity electricity, primarily between the grid connection points of generation facilities and substations, as well as between substations.

"Distribution" refers to the stage of the power system that receives electricity from the transmission network and delivers it to end-users at relatively lower voltage levels.

"Generation" includes power generation facilities such as hydropower plants, thermal power plants, and solar farms, as well as the connection points between such facilities and the grid. This domain also includes distributed generation resources owned by small-scale consumers for self-consumption purposes, such as residential rooftop solar PV systems.

"Demand" refers to the domain encompassing not only large-scale consumers such as corporations, factories, and commercial facilities, but also small-scale consumers such as households.

Figure 4-1 also illustrates the areas of impact for each individual grid flexibility enhancement technology. It demonstrates that a wide range of technologies — including battery energy storage

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[14] APG is a concept formed through the accumulation of individual cross-border interconnection projects rather than through a unified and centralized transmission planning framework such as that seen in Europe.
In addition, several ASEAN member states are archipelagic countries, and the distances between domestic and cross-border power systems are relatively large. As a result, integrating electricity markets in the same manner as regions with continuous geographic conditions, such as Europe, is more difficult, and the barriers to developing interconnection infrastructure are comparatively high. Therefore, alongside regional interconnection efforts, each power system must also independently ensure stable electricity supply, including maintaining power quality and responding to growing electricity demand.
< ASEAN Center for Energy (2026), *ASEAN Interconnection Masterplan Study (AIMS) III Phase 3 (Part 1 of 4)*, https://storage.googleapis.com/aceweb-bucket-261225/pdf/publication/AIMS%20III%20Phase%203_Part%201_L86xr8E8qx6t6S5bJDBBAjNZrJ7AX2o3GZvdxQzA.pdf (Accessed on July 12, 2026)>

[15] One well-known concept is Grid-Enhancing Technologies (GETs). Based on the definitions used by the International Energy Agency (IEA) and the U.S. Department of Energy (DOE), GETs generally refer to sensing, monitoring, and control technologies that can be deployed on transmission networks within a relatively short timeframe and at comparatively low cost. They function as interim measures to bridge short-term demand growth and long-term grid planning while maximizing the utilization of existing transmission capacity, and discussions of GETs are therefore primarily confined to the transmission sector.
In contrast, the scope of technologies examined in this study is broader. It extends beyond transmission-focused measures to include technologies such as generation control systems, the utilization of energy storage systems, flexible supply–demand adjustment, and the physical expansion of transmission capacity itself, including HVDC systems and submarine cables.
< International Energy Agency (2026), *Electricity 2026*, https://iea.blob.core.windows.net/assets/b73798cb-e452-42b9-9d8a-07542de7a041/Electricity_2026.pdf (Accessed on July 29, 2026)>
<Sandra Jenkins (2023), "Grid-Enhancing Technologies: From Research and Development to Reality", https://www.energy.gov/oe/articles/grid-enhancing-technologies-research-and-development-reality-0 (Accessed on April 27, 2026)>

systems and Flexible Alternating Current Transmission Systems (FACTS) — contribute to enhancing flexibility across different domains, while many technologies also operate across multiple domains simultaneously.

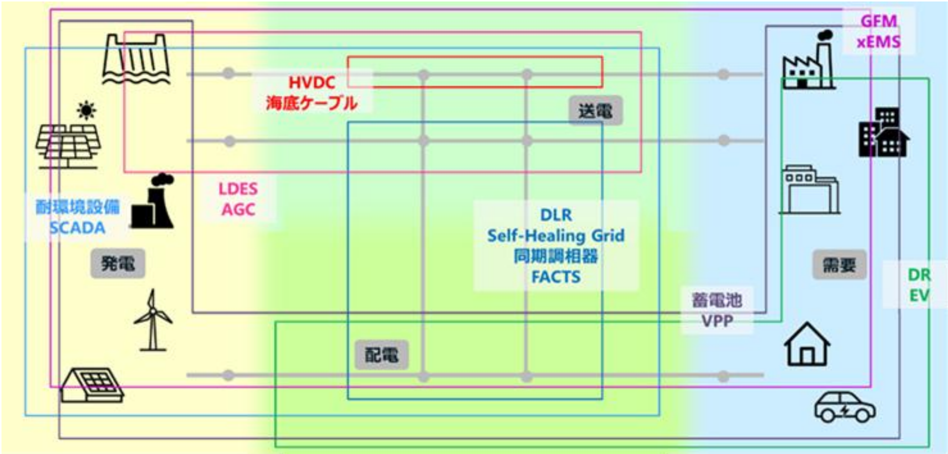

Figure 4-1 Implementation and Functional Concepts of Flexibility Enhancing Measures

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ), based on International Energy Agency (2023), *Electricity Grids and Secure Energy Transitions*.

Among these grid flexibility enhancement technologies, this study further focuses on technologies that are developed and utilized primarily for the purpose of enhancing grid flexibility (Table 4-1). For example, electric vehicles (EVs) are excluded from the scope of analysis, as their primary purpose is mobility rather than the provision of grid flexibility.

The check marks in the table indicate the domains in which each technology performs its functions and illustrate the correspondence between technologies and implementation domains. The table demonstrates that no single technology alone can secure flexibility across all four domains. Although GFM (Grid-forming inverters) and xEMS (Energy Management System) cover all domains, it is a control technology without physical energy resources and therefore cannot by itself ensure sufficient grid flexibility.

This suggests that it is important to introduce combinations of technologies tailored to the characteristics and requirements of each domain.

Table 4-1 List of Flexibility Enhancing Measures

	Transmission	Distribution	Generation	Demand
< Technologies for enhancing transmission infrastructure >				
High-voltage direct current (HVDC)	✓			
Subsea power cable	✓			
< Technologies for the efficient maintenance and management of power supply-demand balance and power quality >				
Dynamic line rating (DLR)	✓	✓		
Synchronous condensers	✓	✓		
Flexible alternating current transmission systems (FACTS)	✓	✓		
Self-healing grid	✓	✓		
Long duration energy storage (LDES)	✓		✓	
Automatic generation control (AGC)	✓		✓	

Battery Energy Storage System (BESS)		✓	✓	✓
Virtual power plant (VPP)		✓	✓	✓
Demand response (DR)		✓		✓
Grid-forming inverters (GFM)	✓	✓	✓	✓
Energy management system (xEMS)	✓	✓	✓	✓

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

In addition, Table 4-2 provides an overview of the characteristics of Flexibility enhancing measures and summarizes examples of Japanese companies that are engaged in related product and service businesses or are conducting development and demonstration projects associated with each technology.

Table 4-2 Overview of Flexibility Enhancing Measures and Related Japanese Companies

	Technology overview	Japanese companies
HVDC	- DC converters and transmission lines that enable the stable, low-loss transmission of large volumes of electricity over long distances	- Hitachi Energy - Mitsubishi Electric - Toshiba
Subsea power cable	- Transmission cables installed on the seabed and equipped with protective outer structures and insulation layers	- Sumitomo Electric - Furukawa Electric
DLR	- Systems that acquire weather data and transmission line temperature data in real time to dynamically calculate and forecast the allowable current capacity of transmission lines.	- Sumitomo Electric - Toshiba
Synchronous condensers	- Equipment that does not generate electricity itself, but regulates voltage through the supply and absorption of reactive power and suppresses frequency fluctuations through rotational inertia	- Hitachi Energy - Mitsubishi Electric
FACTS	- A group of power electronics-based devices that enable fast and flexible control of voltage and power flows in AC transmission and distribution networks	- Hitachi Energy - Mitsubishi Electric - Fuji Electric
Self-healing grid	- A self-healing power system that continuously monitors grid conditions through sensing and communication networks, automatically detects abnormalities using analytical algorithms, and isolates faulted sections and reconfigures transmission routes	- Hitachi Energy - Toshiba
LDES	- Energy storage systems capable of storing electricity and supplying it over long durations, primarily ranging from eight hours to seasonal timescales	- Sumitomo Heavy Industry - TEPCO Energy Partner - JGC Holdings
AGC	- Control technologies that monitor grid frequency and intertie power flows and automatically adjust generator output on timescales ranging from seconds to minutes	- Mitsubishi Heavy Industry - Mitsubishi Electric - Hitachi Energy
Battery storage	- Equipment that stores electricity and releases it when needed to help balance electricity supply	- Sumitomo Electric - Nipron

	and demand	- PowerX
VPP	- Systems that integrate and centrally control distributed energy resources such as solar power generation, battery storage, and EVs	- Kansai Electric Power - Osaka Gas - Toyota Tsusho
DR	- Control schemes that balance electricity supply and demand by adjusting electricity consumption in households and commercial facilities	- TEPCO Energy Partner - ENERES
GFM	- Inverters capable of autonomously establishing and maintaining grid voltage and frequency	- Hitachi Industrial Equipment Systems - Fuji Electric - Toshiba
xEMS	- Systems that integrally manage distributed energy resources and demand-side resources in households, buildings, and factories to enable more efficient electricity consumption and equipment operation through monitoring, measurement, control, and optimization	- Panasonic - Azbil - Marubeni Network Solutions

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

(2) Flexibility Enhancing Measures and Japanese Companies Responding to Technical Challenges under the APG

This section outlines the technical challenges that may emerge in realizing the APG, particularly in the context of ASEAN's geographical and power system conditions. It also discusses which of the solutions identified in Table 4-2 could contribute to mitigating or resolving these challenges, along with relevant developments among Japanese companies.

① Transmission

a. Efficient long-distance transmission of large volumes of electricity

The APG concept is primarily aimed at enabling long-distance power transmission from regions with abundant renewable energy resources to major demand centers. From a technical perspective, this requires reducing transmission losses and efficiently transmitting large volumes of electricity, particularly during peak demand periods.

HVDC systems and subsea power cables are core solutions to this challenge, enabling bulk power transmission from generation sites to distant consumption centers with higher efficiency than AC transmission.

Regarding HVDC technology, Hitachi Energy is characterized by its strong market presence built through a wide voltage range of installations and extensive deployment experience across multiple regions, dating back to its predecessor ABB. The company also offers comprehensive support services, including training and digital solutions that facilitate on-site operation and autonomous system management after commissioning [16,17,18,19].

Toshiba has secured multiple domestic projects, including an order for a voltage-source converter (VSC) system for the reinforcement of the new Kita-Honshu interconnection between Hokkaido and Honshu in 2025[20].

Mitsubishi Electric specializes in the development of advanced core technologies and component supply and is one of the few manufacturers with vertically integrated capabilities encompassing peripheral equipment and testing facilities, as well as in-house development and production of next-generation power devices[21,22,23].

In the submarine cable segment, global supply constraints continue, while Japanese companies are expanding production capacity, potentially offering relatively stable procurement channels compared to other regions.

Sumitomo Electric has recently expanded its production capacity and strengthened its market presence, with confirmed delivery records in Europe. Furukawa Electric is also reported to be planning the construction of a 500 kV-class HVDC cable production line in Japan in 2025[24], which is expected to support expansion into Asian and Middle Eastern markets[25].

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[16] In general, for interconnection lines with transmission voltages exceeding 600 kV, line-commutated converter (LCC) systems are typically preferred due to their ability to accommodate large current capacities.
In this case, however, approximately half of the transmitted electricity is derived from renewable energy sources. The project is therefore notable for adopting the world’s first voltage-source converter (VSC)-based ultra-high-voltage direct current (UHVDC) system in order to satisfy requirements for grid control through reactive power support and for improving renewable energy utilization rates.
< Hitachi Energy (Formerly Hitachi ABB Power Grids) (2025) , “Hitachi Energy to deliver pioneering HVDC solutions for China’s cross-regional clean power highway”, https://www.hitachienergy.com/jp/ja/news-and-events/features/2025/06/hitachi-energy-to-deliver-pioneering-hvdc-solutions-for-chinas-cross-regional-clean-power-highway (Accessed on April 27, 2026)>

[17] Hitachi Energy (n.d.) , Hallsjon: The first HVDC Light® transmission, https://www.hitachienergy.com/news-and-events/customer-stories/hallsjon-the-first-hvdc-light-transmission (Accessed on April 28, 2026)

[18] Hitachi Energy (n.d.), “Life-cycle services for HVDC ”, https://www.hitachienergy.com/products-and-solutions/hvdc/hvdc-services (Accessed on April 27, 2026)

[19] Hitachi Energy (n.d.), “IdentiQ™ for HVDC”, https://www.hitachienergy.com/products-and-solutions/hvdc/hvdc-identiq (Accessed on April 27, 2026)

[20] T. Ishiguro (2025), voltage-secured converter for high-voltage DC power transmission system facilitating further introduction of renewable energy, https://www.global.toshiba/content/dam/toshiba/jp/technology/corporate/review/2025/03/a06.pdf (Accessed on June 12, 2026)

[21] The product developed by Mitsubishi Electric is the MMC (Modular Multilevel Converter)-based technology known as “HVDC-Diamond®,” which employs self-commutated converters. Compared with line-commutated converter (LCC) systems, it does not require harmonic filters or reactive power compensation equipment, enabling more flexible grid interconnection. It is therefore regarded as particularly suitable for the integration of renewable energy and offshore wind power.
In addition, in June 2025, Mitsubishi Electric signed a memorandum of understanding with GE Vernova to establish a framework for supplying IGBT power semiconductors compatible with VSC-based HVDC systems.
<Mitsubishi Electric (n.d.), “ HVDC-Diamond®”, https://www.mitsubishielectric.co.jp/eig/energysystems/business_field/hvdc-diamond/pdf/hdvc_diamond.pdf (Accessed on April 27, 2026)>
<Mitsubishi Electric (2025), Mitsubishi Electric and GE Bernova to Strengthen Cooperation on Power Semiconductors for HVDC Transmission System, https://www.mitsubishielectric.com/en/pr/2025/pdf/0610-b.pdf (Accessed on June 12, 2026)>

[22] SiC power devices are expected to contribute to enhancing the competitiveness of next-generation HVDC systems by enabling higher-frequency operation and improved efficiency.
<Mitsubishi Electric (2018), 世界で初めて SiC を適用した MMC 型 HVDC 変換器セルの技術検証を実施[Conducted technical validation of the world's first MMC-based HVDC converter cell incorporating SiC technology], https://www.mitsubishielectric.co.jp/ja/pr/pdf/2018/0214-d.pdf (Accessed on June 12, 2026)>
< Mitsubishi Electric (2025) , Semiconductor & Device Business 2025, https://www.mitsubishielectric.com/en/pr/2025/pdf/0528-5.pdf (Accessed on April 27, 2026)>

[23] The company possesses a full-scale verification facility in Japan with a capacity of ±21 kV and 50 MW, where thermal testing and protection function verification are conducted. Such testing capability is considered rare even on a global scale and is expected to contribute to the reliability of its products.
<H. Sadakuni (2022), Verification of VSC Based HVDC System, https://www.giho.mitsubishielectric.co.jp/giho/pdf/2022/2206107.pdf (Accessed on June 12, 2026)>

[24] Furukawa Electric (2025), HVDC ケーブルの生産に係る設備投資について[Investment in production facilities for HVDC cables], https://www.furukawaelectric.com/ir/library/briefing/pdf/2025/202510_data.pdf (Accessed on June 12, 2026)

[25] In the field of HVAC (high-voltage alternating current transmission), the company has secured submarine cable projects on multiple routes within the ASEAN region, including the Cebu–Mactan and Sumatra–Bangka interconnections, demonstrating its ongoing regional business expansion.
< Furukawa Electric (2022) , Furukawa Electric secures submarine transmission project in the Philippines, https://www.furukawaelectric.com/en/release/2022/ene_20220316.html (Accessed on May 29, 2026)>
< Furukawa Electric (2020) , Contract Awarded for a Submarine Power Cable Project in the Republic of Indonesia, https://www.furukawaelectric.com/en/release/2020/ene_20200131.html (Accessed on May 29,2026)>

b. Interconnection between asynchronous power systems or weak grids

In the construction of cross-border interconnections, transmission routes may traverse regions operating at different frequencies. For example, the Philippines operates at 60 Hz[26], while neighboring countries operate at 50 Hz, making direct AC interconnection difficult. In such cases, asynchronous interconnection enables power exchange without synchronizing system frequencies[27].

Weak grids—characterized by low inertia and/or limited short-circuit capacity[28]—may experience system-wide vulnerability if directly integrated with stronger grids via conventional AC transmission[29]. Asynchronous interconnection technologies can help mitigate such risks and contribute to enhanced grid flexibility.

Back-to-back (BTB) HVDC systems, which connect two AC systems at the same location through a DC link without an intervening transmission line, enable fast and independent active power control decoupled from system frequency[30,31,32]. As such, they can facilitate interconnection not only between asynchronous systems but also serve as a stabilizing solution for low-inertia grids with high renewable penetration, where they can complement frequency stability. Several Japanese companies possess established technological capabilities and project execution expertise in this field. For example, Toshiba has secured domestic orders for BTB projects[33], while Hitachi Energy has delivered cross-border BTB installations overseas[34].

c. Maintaining the stability of individual power systems during the development of wide-area interconnections

During the transitional phase of transmission line development, the APG exhibits a "radial

[26] JICA・IEEJ (2025) , *Study on ASEAN Power Grid Final Report*, https://openjicareport.jica.go.jp/640/640/640_100_1000055597.html (Accessed on April 27, 2026)

[27] ASEAN Center for Energy (2026), *ASEAN Interconnection Masterplan Study (AIMS) III Phase 3 (Part 1 of 4)*, https://storage.googleapis.com/aceweb-bucket-261225/pdf/publication/AIMS%20III%20Phase%203_Part%201_L86xr8E8qx6t6S5bJDBBAjNZrJ7AX2o3GZvdxQzA.pdf (Accessed on May 12, 2026)

[28] Inertia refers to the capability of a power system to maintain frequency stability against instantaneous fluctuations in electricity supply and demand.
Short-circuit capacity refers to the magnitude of current that can locally flow during a fault condition, and it is also used as an indicator of a power system's robustness against external disturbances.
<TEPCO (n.d.), 再生可能エネルギー大量導入に向けた系統慣性低下対策の研究[Research on Mitigating the Decline in System Inertia Associated with Large-Scale Renewable Energy Integration], https://www.tepco.co.jp/technology/research/gridinnovation/re-sys-counter.html (Accessed on June 12, 2026)>
< The Institute of Electrical Engineers of Japan (2025), 用語解説　第 174 回テーマ：短絡容量[Technical Term Explanation No. 174: Short-Circuit Capacity], https://www.iee.jp/pes/termb_174/ (Accessed on June 12, 2026)>

[29] For example, in Laos, multiple unplanned outages have occurred due to external factors and system stability issues, while in Thailand, the growth in electricity demand has led to concerns over stability issues such as the unexpected disconnection of large-scale power generation facilities.
< Asean center for energy (2025) , *Future of the Grid: Strengthening ASEAN's Grid Power Quality by Harnessing Stability with DERs and Synchrophasor*, https://storage.googleapis.com/aceweb-bucket-261225/files/publication/1766846386_Future-of-the-Grid_-Strengthening-ASEANs-Grid-Power-Quality-by-Harnessing-Stability-with-DERs-and-Synchrophasors.pdf (Accessed on April 27, 2026)>

[30] James McCalley, Iowa State University (2025) , 7a Point to point HVDC systems, https://home.engineering.iastate.edu/~jdm/hvdclearn/AllYear1Modules/Module7a_Final.pdf (Accessed on April 27, 2026)

[31] Kaiqi Sun, et al. (2020) , Machine learning-based fast frequency response control for a VSC-HVDC system, https://ieeexplore.ieee.org/document/9215149 (Accessed on April 28, 2026)

[32] Jingya Huang et al. (2017), HVDC-based Fast Frequency Support for Low Inertia Power Systems, https://pure.manchester.ac.uk/ws/portalfiles/portal/48297721/ACDC2017_0024_final.pdf (Accessed on April 28, 2026)

[33] Toshiba (n.d.), HVDC enables long distance transmission and interconnection of asyncrous grids, https://www.global.toshiba/ww/products-solutions/transmission/products-technical-services/power-conversion.html (Accessed on June 12, 2026)

[34] For example, they have delivered BTB systems for interconnections between Argentina and Brazil, as well as between Canada and the United States.
< Hitachi Energy (n.d.) , Brazil-Argentina HVDC Interconnection, https://www.hitachienergy.com/news-and-events/customer-stories/brazil-argentina-hvdc-interconnection (Accessed on April 27, 2026)>
< Hitachi Energy (2022) , Hitachi Energy selected as technology partner to support the transmission of renewable power between Canada and the United States, https://www.hitachienergy.com/news-and-events/press-releases/2022/12/hitachi-energy-selected-as-technology-partner-to-support-the-transmission-of-renewable-power-between-canada-and-the-united-states (Accessed on April 27, 2026)>

(tree-like)" configuration[35]. Segmented regional management facilitates the control of power flows and has the advantage of limiting the impact on other regions even in the event of a blackout in a specific area. On the other hand, it also has the drawback that large-scale power exchange between distant regions becomes difficult[36].

This means that, although the APG is ultimately intended to enable seamless wide-area power exchange, measures to maintain power quality within each system will still be needed during the development phase, along with corresponding grid reinforcement investments[37]. In addition, the growing share of inverter-based renewable energy sources reduces system inertia and short-circuit capacity compared with conventional synchronous generators, creating another major constraint[38].

To address the challenges anticipated during this transitional phase, the introduction of grid-supporting assets that reinforce system stability is indispensable. FACTS devices enhance voltage stability in the short-time domain by mitigating voltage fluctuations through rapid reactive power control. Meanwhile, synchronous condensers improve system strength by supplying short-circuit capacity and inertia, leveraging the inherent characteristics of rotating machines.

Rather than serving as alternative solutions, these technologies are complementary, providing distinct functions over different timescales. Particularly in weak grids and systems with high renewable energy penetration, an appropriate combination of these technologies within each area is expected to play an important role in addressing deficiencies in short-circuit capacity and inertia.

Japanese companies offer products and solutions for both technologies. Hitachi Energy has installed more than 120 Static Synchronous Compensators (STATCOMs[39]), a type of FACTS device, as of 2024, covering both domestic and international markets[40]. These are often deployed in combination with the company's flagship HVDC systems, and the resulting synergies in grid reinforcement act as an incentive for transmission and distribution operators to prefer their adoption. Mitsubishi Electric's STATCOMs have strengths in large-capacity bulk power systems[41].

In the field of synchronous condensers, Mitsubishi Generator Co. provides large-capacity systems based on conventional generator technology and offers one-stop services from design through maintenance[42]. Hitachi Energy also offers related products[43].

d. Grid capacity constraints under high renewable energy penetration

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[35] At present, 9 of the 18 planned interconnection routes have been completed; however, the network can still hardly be regarded as a fully interconnected mesh configuration.
< Kanchana Wanichkorn (2025), ASEAN Power Grid: Driving Growth & Securing Energy, https://asiacleanenergyforum.adb.org/wp-content/uploads/2025/06/APG_ASEC_ACEF2025DeepDive_KW.pdf (Accessed on April 27, 2026)>

[36] Agency for Natural Resources and Energy (2017), 再エネの大量導入に向けて ～「系統制約」問題と対策[Toward Large-Scale Integration of Renewable Energy: Grid Constraints and Solutions], https://www.enecho.meti.go.jp/about/special/tokushu/saiene/keitouseiyaku.html (Accessed on June 12, 2026)

[37] The ASEAN Secretariat (2025), ADB and World Bank Group Launch the ASEAN Power Grid Financing Initiative with the ASEAN Secretariat and the ASEAN Centre for Energy (ACE), https://asean.org/adb-and-world-bank-group-launch-the-asean-power-grid-financing-initiative-with-the-asean-secretariat-and-the-asean-centre-for-energy-ace/ (Accessed on April 28, 2026)

[38] Energy Studies Institute (2025), Renewable, Regional and Resilient: The Role of GridForming Technology in ASEAN's Energy Sector, https://esi.nus.edu.sg/docs/default-source/esi-policy-briefs/esi-pb-81_renewable-regional-and-resilient.pdf?sfvrsn=aac061f8_1 (Accessed on April 28, 2026)

[39] STATCOM are devices that regulates the voltage at the grid connection point by supplying or absorbing reactive current.
<The Institute of Electrical Engineering of Japan (2020), 用語解説　第 32 回テーマ：　無効電力補償装置 (STATCOM)[Technical Term Explanation No. 32: STATCOM], https://www.iee.jp/pes/termb_032/ (Accessed on June 12, 2026)>
< ENTSO-E (2025), Static Synchronous Compensator (STATCOM), https://www.entsoe.eu/technopedia/techsheets/static-synchronous-compensator-statcom/ (Accessed on April 27, 2026)>

[40] Denki Shimbun (2024), GRIDTECH･STATCOM ブーム再燃[Resurgence of GRIDTECH and STATCOM], https://www.denkishimbun.com/sp/369847 (Accessed on June 12, 2026)

[41] In 2023, the company received an order from Tohoku Electric Power for a STATCOM system with a rated capacity of ±700 MVA, one of the largest in the world.
<Mitsubishi Electric (2023), Mitsubishi Electric Receives Order for ±700MVA STATCOM Aimed at Stabilizing Power Grid in Northeast Japan, https://it.mitsubishielectric.com/global/common/pdf/global-news/pr/2023/230328-a_3584_en_g.pdf　(Accessed on June 12, 2026)>

[42] Mitsubishi Electric (n.d.), 同期調相機, https://www.mitsubishielectric.co.jp/eig/energysystems/feature/onestop/synchronous-condenser/pdf/synchronous_condenser.pdf (Accessed on April 27, 2026)

[43] Hitachi Energy (n.d.) , Synchronous Condenser System, https://www.hitachienergy.com/jp/ja/products-and-solutions/facts/synchronous-condenser-system (Accessed on April 27, 2026)

As the share of variable renewable energy sources such as solar and wind power increases, short-term output fluctuations become more frequent, thereby increasing the difficulty of wide-area supply-demand balancing. However, because existing transmission lines are operated based on static thermal capacity assumptions[44], available transmission capacity is physically constrained, limiting power interchange and making wide-area balancing more difficult in practice.

One potential solution to this challenge is DLR. Commercialization efforts are also emerging among Japanese companies. Sumitomo Electric is developing a method that directly attaches sensors to transmission lines to measure temperature and current values in real time[45], while Toshiba ESS is developing a sensorless approach based on wind condition analysis, combining weather forecast data and topographical information[46].

The application of this technology may contribute to improving the utilization efficiency of existing assets and avoiding the construction of new transmission lines in regions where grid reinforcement is delayed, thereby also contributing to the optimization of investment allocation. Furthermore, by combining DLR with existing power flow control technologies and other transmission capacity enhancement technologies as a technological package, it is expected that the effective capacity of transmission networks can be expanded while maintaining power quality.

e. Increased complexity of stability assessment and protection coordination in hybrid AC/DC power systems

The introduction of HVDC enhances the flexibility of system operation; however, it also increases the complexity of system protection. In particular, the coexistence of HVDC and AC systems gives rise to increased complexity in system stability assessment, as well as in protection and interruption coordination during fault conditions, representing a critical challenge.

In conventional AC power systems, protection relays and circuit breaker logic are designed on the premise of a synchronous grid in which frequency and phase are commonly shared. However, with the expansion of HVDC interconnections, the number of asynchronous interconnection points increases. While this enables more controllable power flows, the fault current paths and system response characteristics are expected to differ significantly from those of conventional systems[47,48].

It is considered that, by integrating HVDC and FACTS in an integrated manner, it is possible to absorb the increased complexity of protection coordination in hybrid AC/DC systems while ensuring flexibility to accommodate the variability of renewable energy sources.

f. The growing importance of physical security in line with the expansion of cross-border

[44] For example, in Japan, operational capacity is determined by the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) and general transmission and distribution operators based on the most restrictive values among constraints related to thermal capacity, synchronous stability, voltage stability, and frequency maintenance. These limits are established to minimize supply disruptions, generation constraints, and impacts on equipment lifetime in the event of system contingencies or equipment failures.
< OCCTO (2024), 運用容量等に関する基本的事項について[Basic Matters Concerning Operational Capacity and Related Issues], https://www.occto.or.jp/assets/iinkai/chouseiryoku/jukyuchousei/2024/files/unyouyouryousagyoukai_1_06.pdf (Accessed on June 12, 2026)>

[45] The monitoring devices developed by the company are self-powered using the current flowing through transmission lines, eliminating the need for external power supplies or battery replacement. In addition, the company employs proprietary wireless routing technology designed for long-distance transmission lines, enabling stable communication even in physically remote areas such as mountainous regions.
<Denki Shimbun (2023), 住友電工、DLR 技術を本格展開[Sumitomo Electric Pursues Full-Scale Commercialization of DLR Technology], https://www.denkishimbun.com/sp/310992 (Accessed on June 12, 2026)>
<Sumitomo Electric (2018), Overhead Powerline Monitoring System for Dynamic Rating, https://sei.co.jp/technology/tr/bn193/pdf/193-13.pdf (Accessed on June 12, 2026)>

[46] Under the company's approach, wind speed and direction along transmission lines are estimated at high resolution, and transmission capacity limits are calculated by taking cooling effects into account. The system combines temporal forecasting (day-ahead and intra-day planning) with spatial forecasting (wind condition assessments for each transmission tower span), enabling updates at 30-minute intervals.
<Toshiba (2025), Dynamic Line Rating Technology without Use of Sensors for Effective Utilization of Existing Transmission Lines, https://www.global.toshiba/content/dam/toshiba/jp/technology/corporate/review/2025/03/a08.pdf (Accessed on June 12, 2026)>

[47] A. Pragati et al. (2023), A Comprehensive Survey of HVDC Protection System: Fault Analysis, Methodology, Issues, Challenges, and Future Perspective, https://www.mdpi.com/1996-1073/16/11/4413 (Accessed on May 29, 2026)

[48] Hui Cai et al. (2025), Coupling Characteristic Analysis and Coordinated Planning Strategies for AC/DC Hybrid Transmission Systems with Multi-Infeed HVDC, https://www.mdpi.com/2079-9292/14/11/2294 (Accessed on April 27, 2026)

transmission infrastructure

Ensuring the physical security of increasingly expanded and long-distance transmission infrastructure is a critical challenge. Cross-border transmission lines may be constructed in regions prone to natural disasters or in socially and politically unstable areas and are therefore exposed not only to risks of damage from typhoons, earthquakes, and floods, but also to the risk of deliberate shutdowns of facilities[49,50].

In addition, the likelihood increases that a single contingency could propagate across the entire system, and conventional localized protection and restoration designs face limitations in ensuring system resilience. Accordingly, minimizing the impact of disturbances requires autonomous control that can dynamically reconfigure power flows across the system.

As a potential solution to these requirements, the concept of a self-healing grid can be highlighted[51]. Related technologies have reached a relatively high level of maturity. Hitachi Energy has been recognized for its strong track record in grid control and operational management software[52]. In addition, Toshiba provides demand-supply control systems for regions, islands, and industrial complexes that enable islanded operation, allowing systems to continue autonomous operation even when disconnected from the main grid during disasters[53].

g. Increasing difficulty in restoring wide-area power outages due to differences in protection schemes and black-start procedures

As countries have historically operated their transmission and distribution systems under independent operational rules, in the event of a large-scale blackout following the realization of the APG through expanded interconnection, differences in restoration procedures and synchronization-in (i.e., conditions for connecting generators and other equipment to the power system) are expected to become barriers. These differences may complicate coordinated black-start operations and staged system restoration across interconnection lines.

To address these challenges, grid-forming (GFM) inverter functions that provide virtual inertia, as well as self-healing grid capabilities that autonomously isolate faulted sections and reconfigure the system during disturbances, are considered to contribute to mitigation.

In ASEAN, in addition to the development of transmission infrastructure, there is growing recognition of the importance of addressing operational challenges such as incompatibilities in system

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49 Rongquan Fan et al. (2023), Risk Reliability Assessment of Transmission Lines under Multiple Natural Disasters in Modern Power Systems, https://www.mdpi.com/1996-1073/16/18/6548 (Accessed on April 27, 2026)

50 For example, in November 2016, the Electric Reliability Organization (ERO) published priority reliability issues for the power system based on recommendations made to the North American Electric Reliability Corporation (NERC) Board of Trustees by the Reliability Issues Steering Committee (RISC). Among these, one of the key risks identified was the potential for disruptions to the transmission grid caused by intentional damage, destruction, or acts of interference targeting critical facilities.
< NERC (2019), Physical Security Guideline for the Electricity Sector, https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/swg/physical_security_guideline_-assessments_and_resiliency_measures_for_extreme_events_june_2019.pdf (Accessed on April 27, 2026)>

51 In Japan, products and services explicitly labeled as "self-healing grid" are rarely observed. One possible reason is that the Japanese power system has historically been designed on the premise of high reliability and redundancy, which may have resulted in relatively limited demand for technologies specifically positioned for emergency response functions.

52 Their remote monitoring and control device, the "RTU500" series, has core functions that acquire data such as voltage and current and support fault detection, isolation, and system restoration, and is considered to be contributing to the strengthening of its market presence.
<Hitachi Energy (2020), Hitachi ABB Power Grids launches all-new remote terminal unit to support grid modernization and renewables integration , https://www.hitachi.com/content/dam/hitachi/global/en/press/articles/2020/12/1217a/201217a.pdf (Accessed on June 12, 2026)>
<The Voice of Renewables (2025), ARC Advisory Group names Hitachi Energy world's leading supplier of grid automation products and services, https://voiceofrenewables.com/arc-advisory-group-names-hitachi-energy-worlds-leading-supplier-of-grid-automation-products-and-services/ (Accessed on June 12, 2026)>

53 "μEMS". The product is designed to enhance the resilience of distribution networks and is consistent with functionalities that form part of a self-healing grid.
< NEDO (n.d.), Case study: Japan－U.S. Collaborative Smart Grid Demonstration Project in New Mexico Part 1 Efforts in Los Alamos, https://www.nedo.go.jp/content/100763123.pdf (Accessed on April 27, 2026)>

protection schemes and restoration operations[54,55]. In this context, as practical solutions, products and technologies developed by Japanese companies are expected to demonstrate their effectiveness and value.

② Distribution

a. The necessity of microgrid development strategies for islands and remote areas

In islands and remote areas, electricity demand is generally small in scale and system inertia is limited, resulting in structural vulnerabilities whereby maintaining frequency and voltage stability becomes increasingly difficult as the share of renewable energy rises. Furthermore, considering the risk of natural disasters such as typhoons and earthquakes, the development of microgrids capable of independent operation disconnected from the main grid may also become necessary in certain regions.

GFM technologies, battery energy storage systems, and self-healing grids are grid flexibility enhancement technologies that can contribute to the development of microgrids.

Japanese companies have already accumulated demonstration experience regarding the operation of GFM technologies under microgrid conditions, and such knowledge may potentially be utilized in ASEAN as well.

Regarding battery storage systems, companies such as Sumitomo Electric, Nipron, and PowerX are expanding business operations in the fields of regionally independent power systems and microgrids[56]. In regions where grid systems are small in scale and dependence on diesel power generation remains high, the introduction of microgrids combining renewable energy and battery storage systems may reduce fuel transportation costs and blackout risks.

Japanese companies also provide well-established self-healing grid technologies and are well positioned to support automated system reconfiguration and restoration during local grid emergencies.

b. Maintaining voltage and frequency stability under increasing penetration of inverter-based resources

Inverter-based resources (IBR[57]), such as solar photovoltaic and wind power generation systems, inherently lack the inertia and short-circuit capacity traditionally provided by synchronous generators[58,59]. As a result, their ability to actively support voltage and frequency is limited, and their increasing penetration has been identified as a factor that may reduce distribution system stability.

To address this challenge, GFM are regarded as a core solution. GFM are capable of autonomously establishing and maintaining voltage and frequency, providing functions analogous to

54 Marcel Nicky Arianto et al. (2026), Learning from the Iberian Peninsula Blackout: Importance of Emergency Information Exchange and Restoration Procedures for the ASEAN Power Grid (APG), https://storage.googleapis.com/aceweb-bucket-261225/pdf/publication/Learning%20from%20the%20Iberian%20Peninsula%20Blackout_77BDCrpqPULCXsnj6Tht0foCU0RVbQPTm86eLcJg.pdf (Accessed on April 27, 2026)

55 Maximilian Heil (2025), The ASEAN Power Grid Advancement programme (APG-P)", https://caseforsea.org/wp-content/uploads/2025/07/01_03_CASE-APG-AP-Presentation-Final-MH.pdf (Accessed on April 27,2026)

56 Sumitomo Electric, in collaboration with NEDO, constructed a 2 MW-scale commercial distribution grid microgrid using a redox flow battery in California in 2022. This demonstration has been evaluated as a model that enables both electricity market participation under normal operating conditions and independent power supply capability during outages. It is considered to contribute not only to the adjustment of renewable energy output but also to improving regional resilience as a backup power source during disasters. Similar functionalities are also expected in emergency power supply and standalone power system deployment projects undertaken by Nipron and PowerX.

< NEDO (2022), First time in the U.S. and Japan to Successfully Build and Operate Microgrid with Battery Storage on Actual Power Distribution Network, https://www.nedo.go.jp/english/news/AA5en_100449.html (Accessed on June 12, 2026)>

< Nipron (2025), 蓄電システム納入事例[Battery Energy Storage System Case Studies], https://www.nipron.co.jp/extra/product_catalog_data/power_storage_system_delivery_example.pdf (Accessed on June 12, 2026)>

< PowerX (2025), Toyota Motor East Japan Selects PowerX's Battery Energy Storage Systems to Enhance Resilience in Kanegasaki Microgrid Project, https://power-x.jp/en/newsroom/2025-02-14 (Accessed on June 12, 2026)>

57 The Digital Grid Consortium (n.d.), Inverter-based Power System, https://www.digitalgrid.org/digital-grid-concept/inverter-based-power-system.html (Accessed on June 12, 2026)

58 NERC (2017), Integrating Inverter Based Resources into Low Short Circuit Strength Systems, https://www.nerc.com/globalassets/who-we-are/standing-committees/rstc/irpwg/item_4a._integrating-_inverter-based_resources_into_low_short_circuit_strength_systems_-_2017-11-08-final.pdf (Accessed on May 31, 2026)

59 Central Research Institute of Electric Power Industry (2023), インバータ電源による電力系統の安定化にはどのような課題があるか？[What are the stability challenges of inverter-based power systems?], https://criepi.denken.or.jp/press/journal/denkizemi/2023/230329.html (Accessed on June 12, 2026)

those of synchronous generators, including inertial response and voltage support[60]. Consequently, they can directly contribute to enhancing system stability, particularly in weak-grid environments.

In addition, FACTS devices can reinforce voltage stability through fast reactive power control[61], while BESS contribute to frequency regulation and supply–demand balancing through power injection and absorption. When deployed in combination with GFM, these technologies can help maintain both voltage and frequency stability even in power systems with high shares of renewable energy.

Commercialization efforts related to GFM are also emerging in Japan. Hitachi Industrial Equipment Systems has commenced operational use of GFM at one of its facilities in Chiba Prefecture[62]. Fuji Electric is currently developing GFM for integration into its BESS[63], while Toshiba demonstrated the effectiveness of combining GFM with photovoltaic generation in a microgrid application in 2022[64].

FACTS, while already well established in transmission networks, are also being adapted for distribution network applications. Companies such as Fuji Electric and Hitachi Energy are expanding their product portfolios with distribution-level STATCOMs and related solutions designed for deployment in distribution grids[65,66]. Similarly, several Japanese companies offer battery storage products, suggesting that a combination of GFM, FACTS devices, and battery storage systems could provide a comprehensive approach to maintaining power quality, including voltage and frequency stability.

c. Power system congestion caused by increasing reverse power flows

The increasing deployment of renewable energy resources, particularly distributed energy resources (DER[67]) such as rooftop solar photovoltaic systems, is transforming power flows in distribution networks from the traditional unidirectional pattern to bidirectional operation, resulting in the occurrence of reverse power flows[68,69].

Reverse power flows can lead to voltage rise and voltage unbalance within distribution

[60] Y. F. Sau et al. (2025), Renewable, Regional and Resilient: The Role of Grid Forming Technology in ASEAN's Energy Sector, https://esi.nus.edu.sg/docs/default-source/esi-policy-briefs/esi-pb-81_renewable-regional-and-resilient.pdf?sfvrsn=aac061f8_1 (Accessed on May 31, 2026)

[61] Hitachi Energy(n.d.), Static compensator (STATCOM), https://www.hitachienergy.com/products-and-solutions/facts/statcom (Accessed on June 12, 2026)

[62] Hitachi Industrial Equipment Systems (2025), Hitachi Industrial Equipment Systems Launches Next-Generation Inverter System to Support Stable, Resilient Power Grids, https://www.hitachi.com/en/press/articles/2025/04/0417/ (Accessed on June 12, 2026)

[63] Fuji Electric (n.d.), 再エネ活用促進に向けた新技術 「GFM インバータ」開発最前線[Grid-Forming Inverters: Latest Developments for Renewable Energy Integration], https://www.fujielectric.co.jp/about/stories/detail/PJ_story_grid-forming-inverter.html (Accessed on June 12, 2026)

[64] Their demonstration project was conducted in an environment closely resembling actual operating conditions, including parallel operation with a diesel synchronous generator, and has provided technical validation for the feasibility of deploying GFM in microgrid applications.
<Toshiba (2022), Toshiba Demonstrates the Effectiveness of Grid-forming Inverters in Preventing Power Outages due to Fluctuations in Renewable Energy Output and Sudden Changes in Demand to Ensure Stable Microgrid Operation, https://www.global.toshiba/ww/technology/corporate/rdc/rd/topics/22/2208-02.html (Accessed on June 12, 2026)>

[65] Fuji Electric (2024), AMSC® D-VAR VVO® Case Study: Accelerating Renewables by Integrating Solar Plants into Existing Distribution Circuits, https://smbe.fujielectric.com/wp-content/uploads/2024/11/Accelerating-Renewables-by-Integrating-Solar-Plants-into-Existing-Distribution-Circuits.pdf (Accessed on May 31, 2026)

[66] Hitachi Energy (n.d.), https://www.hitachienergy.com/products-and-solutions/facts/statcom/statcom-for-distributed-power, https://www.hitachienergy.com/products-and-solutions/facts/statcom/statcom-for-distributed-power (Accessed on June 12, 2026)

[67] DER are generally classified as small-scale energy resources deployed near electricity demand centers and capable of providing functions such as electricity generation, energy storage, and demand response.
<International Energy Agency (2022), *Unlocking the Potential of Distributed Energy Resources*, https://iea.blob.core.windows.net/assets/3520710c-c828-4001-911c-ae78b645ce67/UnlockingthePotentialofDERs_Powersystemopportunitiesandbestpractices.pdf (Accessed on May 31, 2026)>

[68] ASEAN Center for Energy (2025), *Future of the Grid: Strengthening ASEAN's Grid Power Quality by Harnessing Stability with DERs and Synchrophasors*, https://aseanenergy.org/publications/future-of-the-grid-strengthening-aseans-grid-power-quality-by-harnessing-stability-with-ders-and-synchrophasors (Accessed on May 31, 2026)

[69] International Energy Agency (2025), Integrating Distributed Energy Resources in China, https://iea.blob.core.windows.net/assets/62f63aba-ff58-4af3-b0bd-5cb852257f14/IntegratingDistributedEnergyResourcesinChina.pdf (Accessed on May 31, 2026)

systems, while also increasing the risk of overloading transformers and other network assets[70].. In addition, power systems with a high share of IBR tend to exhibit reduced short-circuit capacity, resulting in lower fault current levels and making conventional protection coordination schemes based on current magnitude more difficult to maintain[71].

These challenges related to voltage regulation and protection systems can ultimately manifest as operational constraints on distribution networks and limitations on renewable energy hosting capacity. Even if the construction of cross-border interconnections enables power exchange between systems and helps mitigate some of these risks, maintaining local power quality will still require dedicated measures.

BESS and VPP are considered effective solutions to address these issues. By aggregating and coordinating distributed energy resources, VPP can optimize the operation of distributed generation and battery storage systems, enabling the absorption of surplus generation and the implementation of output control where necessary. This helps regulate local supply–demand balance, suppress reverse power flows, and mitigate power flow fluctuations, thereby contributing to the prevention of voltage rise.

Furthermore, the parallel deployment of FACTS devices, particularly distribution-level STATCOM, can strengthen power quality management through their ability to rapidly inject and absorb reactive power. Such systems are expected to enhance voltage regulation performance and mitigate power quality issues, including voltage fluctuations and voltage unbalance.

d. Insufficient Visibility in Power Systems

The large-scale deployment of DER has led to a rapid increase in the number of grid-connected assets that are not directly controlled by system operators, making it increasingly difficult to accurately identify their location, capacity, and operational behavior[72].

In parts of the ASEAN region, this challenge may be further compounded by the fact that distribution infrastructure development and modernization have not always kept pace with growing electricity demand[73]. As a result, uncertainties may arise regarding actual network conditions, including voltage profiles, power flows, and equipment loading levels. Such a lack of visibility may become a factor that complicates voltage regulation, congestion management, and protection coordination within distribution networks.

These issues may also constrain the development of wide-area power integration initiatives such as APG. Effective coordination and planning across interconnected power systems require a clear understanding of system-wide supply–demand conditions and network constraints within each participating grid. Therefore, enhancing monitoring technologies capable of capturing the status of the entire power system, including distributed energy resources, as well as establishing data-sharing platforms among interconnected systems, will be essential foundations for regional power integration.

To address this challenge, the monitoring and control capabilities provided by VPP and xEMS are expected to play an important role. These technologies incorporate real-time monitoring functions that collect information on DER connections, output levels, and operating conditions. They also provide platform capabilities that integrate data across different devices and market participants, together with forecasting functions and optimization algorithms for demand and generation management[74].

Through these capabilities, system operators can gain visibility into the status and behavior of distributed energy resources that were previously difficult to observe and can coordinate the operation of multiple DER as an integrated portfolio. This enables more comprehensive system

[70] International Energy Agency (2025), Integrating Distributed Energy Resources in China, https://iea.blob.core.windows.net/assets/62f63aba-ff58-4af3-b0bd-5cb852257f14/IntegratingDistributedEnergyResourcesinChina.pdf (Accessed on May 31, 2026)
[71] J. Slane et al. (2026), Impact of Inverter-Based Resources on the Protection of the Electrical Grid, https://arxiv.org/pdf/2603.27816 (Accessed on May 31, 2026)
[72] International Energy Agency (2022), *Unlocking the Potential of Distributed Energy Resources*, https://iea.blob.core.windows.net/assets/3520710c-c828-4001-911c-ae78b645ce67/UnlockingthePotentialofDERs_Powersystemopportunitiesandbestpractices.pdf (Accessed on May 31, 2026)
[73] Asian Development Bank (2025), *ENERGY TRANSITION READINESS ASSESSMENT FOR DEVELOPING ASIA AND THE PACIFIC*, https://www.adb.org/publications/energy-transition-readiness-developing-asia-pacific (Accessed on May 31, 2026)
[74] J. Huang (2025), Review of Virtual Power Plant Response Capability Assessment and Optimization Dispatch, https://doi.org/10.3390/technologies13060216 (Accessed on May 31, 2026)

management by combining measures such as DER output control, demand response, and load shifting.

Enhanced visibility and controllability are also expected to improve the efficiency of power exchanges between interconnected systems and increase the accuracy of supply–demand forecasting across wider geographic areas. Consequently, these capabilities are likely to serve as a critical foundation for the efficient operation of APG.

③ Generation

a. Wide-area simultaneous output fluctuations during large-scale weather events under high renewable energy penetration

As the deployment of weather-dependent renewable energy sources such as solar PV and wind power expands, variability in power generation output is expected to increase inevitably, further intensifying the pressure arising from mismatches between electricity supply and demand. In particular, the ASEAN region is located within a monsoon climate zone and is characterized by the periodic occurrence of typhoons, squalls, and other severe weather events. In fact, several cases of power outages and transmission disruptions caused by typhoons have been reported in recent years in countries such as the Philippines and Vietnam, indicating that these risks constitute a tangible challenge[75,76].

When large-scale renewable energy deployment and natural disasters occur simultaneously, wide-area output reductions and transmission infrastructure failures may emerge, potentially affecting the stability of the overall power system. In particular, in the context of wide-area power interchange utilizing cross-border interconnections, it should be noted that increased weather correlation and infrastructure disruption risks may constrain the expected balancing functions and economic efficiency of such interconnections.

LDES can store surplus electricity generated from renewable energy sources and contribute to stabilizing the power supply by complementing existing balancing resources during periods of generation shortfalls and supply-demand tightness lasting from several days to several weeks, such as during the rainy season or after typhoon events.

In Japan as well, initiatives toward the demonstration and commercialization of various LDES technologies are progressing, and the deployment of these technologies is expected to expand further[77].

However, some parts of the ASEAN region have relatively weak grids, making it difficult to maintain voltage and frequency stability. Under such conditions, the performance of LDES may not be fully utilized or, conversely, the systems themselves may become overengineered relative to local

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[75] International Energy Agency (2024) , *Climate Resilience for Energy Security in Southeast Asi*a, https://iea.blob.core.windows.net/assets/4c5449ca-edde-4c54-8b86-61616c7c8c64/ClimateResilienceforEnergySecurityinSoutheastAsia.pdf (Accessed on April 27, 2026)

[76] In the spring to summer of 2025, intense widespread heavy rainfall in regions including Sumatra Island, Indonesia, is reported to have caused disruptions to transmission networks and damage to infrastructure.
< Fuad Nizam (2025), Rare tropical storm Senyar forms in Straits of Malacca for the 1st time ever, https://www.nst.com.my/news/nation/2025/11/1323598/rare-tropical-storm-senyar-forms-straits-malacca-1st-time-ever (Accessed on April 27, 2026)>
< BBC News Japan (2025), インドネシア、大洪水の死者 500 人超す　行方不明も 500 人以上[Indonesia Flood Death Toll Surpasses 500, with More Than 500 Still Missing], https://www.bbc.com/japanese/articles/c79x8g2rj5yo (Accessed on June 12, 2026)>

[77] Sumitomo Heavy Industries has constructed a commercial demonstration plant for liquid air energy storage (LAES) at an LNG facility in Hatsukaichi City, Hiroshima Prefecture, with operations commencing in December 2025. In addition, TEPCO Energy Partner entered the demand-response market in August of the same year by producing hydrogen from surplus electricity using electrolysis equipment. Furthermore, JGC Holdings has signed a memorandum of understanding with Italy-based Energy Dome to explore collaboration on the introduction of CO_2 battery technology in Japan. Energy Dome is already operating a commercial plant in Sardinia with a capacity of 20 MW and an energy storage capacity of 200 MWh, and synergies are expected through integration with JGC's EPC capabilities.
<Sumitomo Heavy Industries (2025), Commencement of Commercial Operations at LAES Commercial Demonstration Plant , https://www.shi.co.jp/english/info/2025/6kgpsq0000003x40.html (Accessed on June 12, 2026)>
<TEPCO Energy Partner et al. (2025), 電力需要家の DR リソースを活用し需給調整市場に参入　～水電解装置による一次調整力としての実運用開始～[Entering the balancing market through DR resources － Launch of commercial operation of electrolyzers providing primary frequency control –], https://www.tepco.co.jp/ep/notice/pressrelease/2025/pdf/250828j0101.pdf (Accessed on June 12, 2026)>
<JGC Holdings (2025), Signing of Memorandum of Understanding with Energy Dome S.p.A. to Explore Collaboration in the Japanese Market for CO2 Battery Technology , https://www.jgc.com/en/news/2025/20251023_11.html (Accessed on June 12, 2026)>

grid requirements. These factors should therefore be carefully considered in deployment planning.

b. Insufficient system inertia and short-circuit capacity resulting from higher penetration of inverter-based resources

Conventional power systems have traditionally been structured around synchronous generators such as thermal and hydropower plants, through which physical inertia has contributed to maintaining voltage stability and ensuring the reliable operation of protection relays. However, as the share of inverter-connected energy sources such as renewable energy increases, these characteristics are gradually lost from the system, giving rise to challenges such as rapid frequency fluctuations, voltage instability, and difficulties in protection coordination during faults[78,79,80].

Some parts of the ASEAN region already operate relatively small-scale power systems with insufficient short-circuit capacity and weak grid strength. Under such conditions, the rapid deployment of IBR could further destabilize the system and potentially undermine the reliability of power interchange through interconnections.

To address this challenge, the voltage- and frequency-forming capabilities of GFM are expected to be particularly effective. Furthermore, the APG development plan envisages a significant number of HVDC interconnections. However, where the receiving AC system is weak, the stability of power flow control across these interconnections may be compromised. GFM is regarded as a promising technology for strengthening the grid and improving control stability at HVDC receiving ends[81].

c. Coordinated operation with flexible power sources such as hydropower and gas-fired thermal generation

The expansion of renewable energy penetration and the cross-border interconnection of power systems make it essential not merely to address issues within individual grids, but to secure balancing capacity and establish operational frameworks from the perspective of the entire system.

In the ASEAN region, hydropower resources are unevenly distributed, particularly concentrated in countries such as Laos within the Mekong basin, and electricity is already traded with neighboring countries. However, hydropower generation is closely tied to industrial and agricultural water management, which imposes seasonal and institutional constraints on the flexibility of output adjustment[82,83,84]. In addition, for gas-fired thermal power generation, factors such as fuel procurement conditions and pricing structures are likely to create country-by-country differences in the amount of balancing capacity that can be provided[85].

Furthermore, the maturity of data integration infrastructures—including operational rules, frequency control capability, measurement and communication systems, and dispatch control systems—varies significantly across ASEAN member states. As a result, many elements necessary for the immediate implementation of wide-area real-time coordinated control remain underdeveloped. This further increases the operational complexity of internationally interconnected power systems.

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[78] ENTSO-E (2021), *FREQUENCY STABILITY IN LONG-TERM SCENARIOS AND RELEVANT REQUIREMENTS*, https://eepublicdownloads.azureedge.net/clean-documents/Publications/ENTSO-E%20general%20publications/211203_Long_term_frequency_stability_scenarios_for_publication.pdf (Accessed on May 29, 2026)

[79] ENTSO-E (2019), *SHORT CIRCUIT CONTRIBUTION OF NEW GENERATING UNITS CONNECTED WITH POWER ELECTRONICS AND PROTECTION BEHAVIOUR*, https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/190304_SOC_TOP_7.4_Short%20Circuit%20Contribution%20of%20Power%20Electronics%20Connecting%20Generators%20and%20Protection%20report.pdf (Accessed on May 29, 2026)

[80] NERC (2023), *Inverter-Based Resource Performance Issues Report*, https://www.nerc.com/globalassets/our-work/white-papers/nerc_inverter-based_resource_performance_issues_public_report_2023.pdf (Accessed on May 29, 2026)

[81] D. B. Rathnayake et al. (2021), Grid Forming Inverter Modeling, Control, and Applications, https://doi.org/10.1109/ACCESS.2021.3104617 (Accessed on June 2, 2026)

[82] International Energy Agency (2021) , *Climate Impacts on South and Southeast Asian Hydropower*, https://iea.blob.core.windows.net/assets/8827598a-486a-4ee3-bc0d-2a534b3dfd14/ClimateImpactsonSouthandSoutheastAsianHydropower.pdf (Accessed on April 28, 2026)

[83] ASIAN Development Bank (2023), *Asian Development Bank's Approach for Large Hydropower Plants*, https://www.adb.org/sites/default/files/institutional-document/902496/energy-guidance-note-large-hydropower-plants.pdf (Accessed on April 28, 2026)

[84] Mekong River Commission (2025) , *Annual Report 2024*, https://www.mrcmekong.org/publications/annual-report-2024/ (Accessed on April 28, 2026)

[85] International Energy Agency (2024), *Southeast Asia Energy Outlook 2024*, https://iea.blob.core.windows.net/assets/ac357b64-0020-421c-98d7-f5c468dadb0f/SoutheastAsiaEnergyOutlook2024.pdf (Accessed on April 28, 2026)

Although eliminating these constraints themselves is not easy, their impacts can be mitigated on the premise that such constraints exist through the wide-area integrated operation of AGC. Specifically, this would involve establishing a mechanism that comprehensively monitors system frequency and power flows across the entire interconnected international grid and automatically allocates output control signals, on a timescale of seconds to minutes, to flexible power sources in each country, such as hydropower and gas-fired thermal plants.

Conventional AGC has primarily been used for frequency regulation within individual national grids. Under a wide-area interconnected system, however, the adoption of a multi-area framework could prove effective, whereby Area Control Error (ACE[86]) across multiple areas is evaluated and utilized in an integrated and coordinated manner, and control commands optimized for wide-area system stabilization are distributed to each control area.

Trends by Japanese companies can also be observed in relation to these technologies. With respect to improving the response performance of generating facilities, Mitsubishi Heavy Industries and Mitsubishi Electric are jointly advancing the sophistication of gas turbine control systems, which could contribute to improved responsiveness to AGC commands[87]. Meanwhile, regarding grid-side control platforms, software developed by Hitachi Energy has already been implemented in regions and island systems with high levels of renewable energy integration[88,89,90]. This suggests that operational know-how applicable to ASEAN's geographical conditions is being accumulated.

④ Demand

a. Mobilization and utilization of demand-side flexibility

Electricity demand in ASEAN is expected to continue increasing as a result of economic development, urbanization, and expanding industrial activity[91]. At the same time, the growing deployment of renewable energy sources is increasing the importance of managing output variability and maintaining the balance between electricity supply and demand.

Under these circumstances, securing demand-side flexibility will become increasingly important[92]. However, the potential for providing such flexibility varies according to regional characteristics. In regions with a high share of manufacturing industries, the flexibility and response speed of load adjustment are often constrained by production processes and therefore depend on the composition of end-use applications. In contrast, urban areas, where electricity demand is great and

[86] ACE is an indicator that represents how far a power system deviates from its specified frequency and power flow conditions. It is used by system operators to keep the grid operating within prescribed frequency and voltage ranges, thereby helping to prevent blackouts and equipment damage.
< NAESB (2005) , Area Control Error (ACE) Equation Special Cases, https://ns.naesb.org/pdf2/weq_bklet_011505_ace_numbering.pdf (Accessed on April 28, 2026)>

[87] Mitsubishi Heavy Industries' DIASYS series is a control system for power generation plants, with deployment records in over 60 countries and more than 3,000 installations. In addition, Mitsubishi Electric has delivered over 1,000 units of its MELSEP instrumentation and control system series for thermal and hydroelectric power plants in Japan.
<Mitsubishi Heavy Industries (2025), Next-Generation Gas Turbine Control System for Thermal Power Plants Completes Functional Testing -- Jointly Developed by Mitsubishi Power and Mitsubishi Electric, Market Launch Targeted for Fiscal Year 2026 --, https://www.mitsubishielectric.com/en/pr/2025/pdf/1224.pdf (Accessed on June 12, 2026)>

[88] The company's software, "Network Manager Generation Management System (GMS)," is an integrated management system equipped with multi-area AGC capabilities for conventional thermal power plants, renewable energy sources, and widely distributed generation assets across multiple locations.
< Hitachi Energy (n.d.) , Network Manager Generation Management System (GMS), https://www.hitachienergy.com/products-and-solutions/grid-and-generation-management-network-manager/network-manager-generation-management-system-gms (Accessed on April 28, 2026)>

[89] Hitachi Energy (n.d.) , How Conduit Power manages costs by operating renewable power plants remotely, https://www.hitachienergy.com/us/en/news-and-events/customer-stories/how-conduit-power-manages-costs-by-operating-renewable-power-plants-remotely (Accessed on April 28, 2026)

[90] Hitachi Energy (n.d.) , Empresa de Electricidade da Madeira (EEM), https://www.hitachienergy.com/jp/ja/news-and-events/customer-stories/eem (Accessed on April 28, 2026)

[91] International Energy Agency (2026), *Electricity 2026*, https://iea.blob.core.windows.net/assets/b73798cb-e452-42b9-9d8a-07542de7a041/Electricity_2026.pdf (Accessed on May 12, 2026)

[92] It has been pointed out that a grid enhancement approach that depends on supply-side resources for the provision of balancing and flexibility services could result in substantial additional investments and operational costs, such as the deployment of peaking generation capacity. Leveraging demand-side flexibility can help reduce or defer the need for such investments.
< International Energy Agency (2025), *The Value of Demand Flexibility*, https://www.iea.org/reports/the-value-of-demand-flexibility (Accessed on May 28, 2026)>
< NREL (2021), *US building energy efficiency and flexibility as an electric grid resource*, https://docs.nrel.gov/docs/fy21osti/78196.pdf (Accessed on May 28, 2026)>

continues to grow, typically contain a vast number of small-scale demand-side resources distributed across the network. Aggregating these resources can create significant opportunities to provide flexible services at the system level[93].

If demand-side flexibility is not effectively utilized, system balancing may become increasingly reliant on supply-side resources, potentially limiting the effective utilization of interconnection capacity. Under such circumstances, variability management is primarily achieved through the output control of generation resources. In power systems with high shares of renewable energy, however, limited balancing capability may result in surplus electricity being managed through renewable energy curtailment.

Such an outcome would be inconsistent with the fundamental objective of APG[94], which is to smooth renewable energy variability by leveraging regional differences in supply and demand and to facilitate the transfer of surplus electricity across a wider geographic area. Consequently, the value of interconnections may not be fully realized.

Avoiding such a situation requires the systematic development of demand-side flexibility resources[95]. In addition to direct load control through DR, flexibility can be enhanced through the integrated management of demand-side and distributed energy resources using VPP and xEMS platforms. These approaches can unlock and mobilize demand-side flexibility tailored to local conditions and resource characteristics.

In Japan, a wide range of market participants, including electricity retailers and aggregators, have implemented DR programs supported by relevant regulations, subsidy schemes, and electricity market mechanisms[96].

Participation in VPP has also diversified across industries. For example, electric and gas utilities such as Kansai Electric Power and Osaka Gas have developed VPP-related services[97]. Outside the utility sector, Toyota Tsusho has implemented initiatives that aggregate electric vehicles and utilize

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[93] International Energy Agency (2025), *The Value of Demand Flexibility*, https://iea.blob.core.windows.net/assets/4f11d63f-ebb0-44a4-9a53-ed98f264dc38/TheValueofDemandFlexibility.pdf (Accessed on May 28, 2026)

[94] International Energy Agency (2026), *Financing the ASEAN Power Grid*, https://www.iea.org/reports/financing-the-asean-power-grid (Accessed on May 28, 2026)

[95] EU-ASEAN Business Council (2025), Accelerating The Energy Transition Through The ASEAN Power Grid, https://eu-asean.eu/wp-content/uploads/2025/10/Energy-Paper_FINAL.pdf (Accessed on April 27, 2026)

[96] ENERES aggregates electricity demand from customer-owned equipment such as refrigeration systems, pumps, and air-conditioning units, and provides DR services as an aggregator participating in the capacity market and balancing market. Meanwhile, Kansai Electric Power offers an incentive-based DR program that provides financial rewards and electricity bill discounts based on the amount of demand reduction achieved by participating customers. The program supports both upward and downward DR and participates in economic DR schemes—as an alternative to increasing generation output or procuring electricity from the market during periods of high wholesale electricity prices—as well as in the capacity market and balancing market. Specific examples of DR implementation can also be observed in Japan. During the electricity supply-demand tightness experienced in 2022, TEPCO Energy Partner requested demand reductions from approximately 300 customers and achieved a maximum load reduction of around 330 MW. Similarly, ENNET implemented an incentive-based DR program covering approximately 6,000 facilities, successfully reducing electricity consumption by around 230,000 kWh.

< ENERES (n.d.), デマンドレスポンスサービス[DR], https://www.eneres.jp/service/demandresponse/ (Accessed on June 12, 2026)>

<Kansai Electric Power (n.d.), デマンドレスポンスサービス[DR], https://sol.kepco.jp/dr/ (Accessed on June 12, 2026)>

<Agency of Natural Resources and Energy (2022), ディマンド・リスポンスの活用で広がる、電力需給調整の新ビジネス [New business opportunities in power balancing through demand response], https://www.enecho.meti.go.jp/about/special/johoteikyo/dr_business.html (Accessed on June 12, 2026)>

[97] Kansai Electric Power has established a subsidiary engaged in aggregation services that integrate BESS and EVs within its service area. In addition, Osaka Gas participates in the VPP market as an aggregator through a business model that remotely controls residential fuel cell systems.

<Kansai Electric Power (2023), 分散型リソースを束ね、安定供給へ貢献する VPP 事業——E-Flow[E-Flow: A virtual power plant business aggregating distributed energy resources to support reliable power supply], https://www.kepco.co.jp/corporate/report/yous/7/kanden-update/article3.html (Accessed on June 12, 2026)>

<Osaka gas (2021), 「エネファーム type S」3,600 台を活用した VPP 実証事業への取り組み～「蓄電池等の分散型エネルギーリソースを活用した次世代技術構築実証事業」の開始～[Initiatives for a VPP demonstration project utilizing 3,600 ENE-FARM Type S units − Commencement of a Demonstration Program to Develop Next-Generation Technologies Using Distributed Energy Resources, Including Battery Storage Systems], https://www.osakagas.co.jp/company/press/pr2021/1296779_46443.html (Accessed on June 12, 2026)>

them as distributed battery resources capable of providing flexibility services to the power system[98]. In addition, in 2023, a joint venture established by NGK Insulators and Ricoh launched a demonstration project to evaluate a new VPP model that aims to reduce costs and optimize system operation through AI-based coordination of distributed energy resources[99].

Japanese companies have also accumulated practical experience in the deployment of xEMS solutions, including applications involving multi-stakeholder coordination and performance-based business models such as Energy Service Company (ESCO) schemes[100]. These experiences suggest considerable potential for applying Japanese expertise to the development of demand-side flexibility frameworks tailored to the diverse regional characteristics of ASEAN countries.

This section summarizes the identified sets of challenges and the corresponding technologies for enhancing grid flexibility, along with the application domains in which these technologies are considered suitable for implementation and related case studies (Table 4-3).

Table 4-3 ASEAN-Specific APG Challenges and Applications of Flexibility Enhancing Measures

<table>
<tr><th>Technical Challenges</th><th>Measures</th></tr>
<tr><td>Efficient long-distance transmission of large volumes of electricity</td><td>- HVDC
- Subsea power cable</td></tr>
<tr><td colspan="2">【Potential use cases】
Among the 18 APG interconnection routes, an HVDC submarine cable project is planned to connect Singapore, a major load center, with [101]Sumatra Island in Indonesia, which is endowed with renewable energy resources such as solar power[102].</td></tr>
<tr><td>Interconnection between asynchronous power systems or weak grids</td><td>- HVDC</td></tr>
<tr><td colspan="2">【Potential use cases】
The Philippines is an archipelagic country, where the system frequency differs from that of neighboring countries and interconnection between domestic power systems remains limited. In</td></tr>
</table>

[98] Toyota Tsusho(2019), Toyota Tsusho and Chubu Electric Power Continue Virtual Power Plant (VPP) V2G Aggregator Demonstration Project Utilizing Batteries of PHV's/EV's for Storage
- Next step in V2G demonstration project to supply power from storage batteries of PHV's/EV's -, https://www.toyota-tsusho.com/english/press/detail/190605_004393.html (Accessed on June 12, 2026)

[99] Ricoh (2023), NR-Power Lab Collaborates with CollaboGate Japan and Sassor to Start Building the World's First VPP System Using Decentralized Identifiers , https://www.ricoh.com/release/2023/0912_1 (Accessed on June 12, 2026)

[100] Panasonic launched the international deployment of its commercial and multi-family residential heat pump system, Aquarea, in November 2024, integrating it with a Home Energy Management System (HEMS). Meanwhile, Azbil Corporation maintains local subsidiaries across Asia and provides end-to-end Building Energy Management System (BEMS) services, ranging from system design to maintenance. Several implementation cases have also been identified in ASEAN countries.
In addition, Marubeni Network Solutions has dev
loped an energy management solution based on its proprietary cloud IoT platform, MAIDOA plus. The system collects sensor data at one-minute intervals and controls air-conditioning equipment to optimize energy consumption. According to the company, the solution can reduce contracted power demand by 20–30% and lower electricity costs by 5–15% annually.
< Emiliano Bellini (2024), Panasonic testing smart thermostats in residential heat pumps, https://www.pv-magazine.com/2024/09/26/panasonic-testing-smart-thermostats-energy-management-system-in-residential-heat-pumps/ (Accessed on April 28, 2026)>
< Azbil (n.d.), Gaysorn Tower, https://www.azbil.com/case/bsc/app_033/index.html (Accessed on June 12, 2026)>
< Azbil (n.d.), The Okura Prestige Bangkok, https://www.azbil.com/case/bsc/app_060/index.html (Accessed on June 12, 2026)>
<Marubeni Network Solutions (n.d.), 建物 DX ソリューション「BEMS サービス」[BEMS Service for building digital transformation], https://www.marubeni-idigio.com/product/solution/ai_iot/bems.html (Accessed on June 12, 2026)>

[101] TotalEnergies (2025), Indonesia-Singapore: TotalEnergies and RGE Reach New Milestone in Large-Scale Solar and Battery Storage Project, https://totalenergies.com/news/press-releases/indonesia-singapore-totalenergies-and-rge-reach-new-milestone-large-scale-solar (Accessed on May 28, 2026)

[102] ASEAN Centre for Energy (2024) ASEAN Power Grid Interconnections Project Profiles, https://storage.googleapis.com/aceweb-bucket-261225/files/publication/1766846405_ASEAN-Power-Grid-Interconnections-Project-Profiles.pdf (Accessed on May 29, 2026)

addition, some regions are reported to lack well-developed transmission infrastructure[103,104].	
Maintaining the stability of individual power systems during the development of wide-area interconnections	- FACTS - Synchronous condensers
【Potential use cases】 In the Philippines, transmission capacity expansion and grid development plans have not kept pace with the rapid deployment of renewable energy, and weakening system inertia has been identified as a concern[105].	
Grid capacity constraints under high renewable energy penetration	- DLR
【Potential use cases】 Indonesia has significant renewable energy potential; however, its power system is characterized by high reserve margins and low flexibility. DLR has been identified as a technology that could alleviate grid congestion while deferring large-scale grid reinforcement investment plans[106].	
Increased complexity of stability assessment and protection coordination in hybrid AC/DC power systems	- HVDC - FACTS
【Potential use cases】 Power systems near interconnection lines	
The growing importance of physical security in line with the expansion of cross-border transmission infrastructure	- Self-healing grid
【Potential use cases】 Power systems near interconnection lines	
Increasing difficulty in restoring wide-area power outages due to differences in protection schemes and black-start procedures	- Self-healing grid - GFM
【Potential use cases】 Power systems near interconnection lines	
The necessity of microgrid development strategies for islands and remote areas	- GFM - BESS - Self-healing grid
【Potential use cases】 In the Philippines, electrification varies significantly across islands, and in certain areas, grid extension is not economically efficient. This has led to suggestions that decentralized renewable energy-based grids should be appropriately integrated as a complementary solution[107,108].	
Maintaining voltage and frequency stability under increasing penetration of inverter-based resources	- GFM - FACTS

103 JETRO (2023), フィリピンにおける再生可能エネルギー分野の市場調査(フィリピン・マニラ発)[Market Survey of the Renewable Energy Sector in the Philippines (Manila, Philippines)], https://www.jetro.go.jp/biz/trendreports/2023/b8534b6c1a74715e.html (Accessed on June 12, 2026)

104 Manila Bulletin (2026), Widening energy security gap flagged as power grid lags behind demand, https://mb.com.ph/2026/05/08/high-risk-business-environment (Accessed on May 28, 2026)

105 POWER Philippines (2026) , 1-year builds vs 10-year grids: transmission lag threatens PH renewable rollout, https://powerphilippines.com/1-year-builds-vs-10-year-grids-transmission-lag-threatens-ph-renewable-rollout/ (Accessed on April 28, 2026)

106 International Energy Agency (2022), Enhancing Indonesia's Power System, https://iea.blob.core.windows.net/assets/247b5328-2cd7-4fbb-a800-dd1c71f6e562/EnhancingIndonesiasPowerSystem.pdf (Accessed on April 28, 2026)

107 Grendell Vie Magoncia et al. (2026), Renewable Energy Transition in the Philippines: Trends, Opportunities, Challenges, https://www.imf.org/-/media/files/publications/selected-issues-papers/2026/english/sipea2026005.pdf (Accessed on May 28, 2026)

108 International Renewable Energy Agency (2017), *ACCELERATING RENEWABLE MINI-GRID DEPLOYMENT: A STUDY ON THE PHILIPPINES*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Philippines_Renewable_Mini-Grids_2017.pdf (Accessed on June 1, 2026)

【Potential use cases】 Power systems with increasing demand-side renewable energy deployment	
Power system congestion caused by increasing reverse power flows	- FACTS - BESS - VPP
【Potential use cases】 Power systems with increasing demand-side renewable energy deployment	
Insufficient Visibility in the Power System	- VPP - xEMS
【Potential use cases】 ASEAN countries	
Wide-area simultaneous output fluctuations during large-scale weather events under high renewable energy penetration	- LDES
【Potential use cases】 In Cambodia, Vietnam, and the Philippines, typhoons are projected to become more severe in intensity throughout the 21st century[109].	
Insufficient system inertia and short-circuit capacity resulting from the higher penetration of inverter-based resources	- GFM
【Potential use cases】 In Vietnam, the feed-in tariff (FIT) scheme has led to a rapid increase in the capacity of inverter-based resources such as wind and solar power. At the same time, it has been pointed out that short-circuit capacity within the power system is declining[110,111].	
Coordinated operation with flexible power sources such as hydropower and gas-fired thermal generation	- AGC
【Potential use cases】 ASEAN countries	
Mobilization and utilization of demand-side flexibility	- DR - VPP - xEMS
【Potential use cases】 Vietnam is experiencing significant growth in electricity demand, and DR pilot projects have been implemented, particularly in Ho Chi Minh City, a major hub of industrial and commercial activity[112,113].	

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

This chapter has organized not only technologies directly related to the construction of interconnection lines but also technologies that contribute to maintaining the supply-demand balance and quality of electricity. When specifying individual routes of the APG, the required approaches will vary depending on the progress of interconnection plans and the status of renewable energy deployment in each country. Specifically, it will be necessary to determine whether to prioritize the

[109] International Energy Agency (2024) , *Climate Resilience for Energy Security in Southeast Asia*, https://iea.blob.core.windows.net/assets/4c5449ca-edde-4c54-8b86-61616c7c8c64/ClimateResilienceforEnergySecurityinSoutheastAsia.pdf (Accessed on May 28, 2026)

[110] ASEAN Center for Energy (2021), Vietnam's solar and wind power success: Policy implications for other ASEAN countries, https://aseanenergy.org/publications/vietnams-solar-and-wind-power-success-policy-implications-for-other-asean-countries/ (Accessed on May 28, 2026)

[111] U.S. Department of State (2023), Regulatory Protection and Control Standards Applicable to the Vietnam Grid with High InverterBased Resource (IBR) Penetration, https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-34345.pdf (2Accessed on May 28, 2026)

[112] U.S. Department of Commerce (2024), Vietnam Country Commercial Guide, https://www.trade.gov/country-commercial-guides/vietnam-power-generation-transmission-and-distribution (Accessed on May 28, 2026)

[113] Viet Nam MW (n.d.), Demand Response, https://en.vmw.com.vn/product/demand-response.html (Accessed on May 28, 2026)

development of interconnection lines or to implement measures such as frequency control and voltage stabilization in parallel, as well as how to combine and apply these technologies. Therefore, these approaches need to be further examined in the future, considering the circumstances of each country.

(3) Implications for Japanese Companies Intending to Enter Emerging Grid Flexibility Enhancing Measures Markets

The challenges discussed in the previous section, along with trends in grid flexibility enhancing measures aimed at addressing them, suggest three key implications for Japanese companies considering entry into APG-related markets.

① Transition toward value creation through lifecycle support

First, Japanese companies should shift from a product-oriented business model (mono-uri) to a service-oriented business model (koto-uri) by providing agile support throughout the entire lifecycle of grid-related systems, thereby emphasizing reductions in total cost.

From the perspective of ASEAN as the customer, reliance solely on equipment provision may lead to a lack of transparency in system architecture, raising concerns over increased long-term operational expenditures (OPEX). In addition, such dependence may make restoration efforts more difficult when grid failures or system disruptions occur.

To address these concerns, Japanese companies should engage in continuous operational support. From the standpoint of avoiding substantial economic losses caused by system downtime, enhancing the reliability necessary for stable grid operation is essential. Moreover, from the perspective of the long-term benefits enjoyed by ASEAN countries over the entire lifecycle, not only reductions in total cost but also improvements in autonomy through the transfer of technical and operational capabilities can be expected.

Specifically, Japanese firms should go beyond merely supplying equipment and instead develop service models that include human resource development, technical training, and know-how sharing aimed at enabling local companies — such as construction contractors, procurement firms, and transmission and distribution operators — to conduct maintenance and operations autonomously at a certain standard.

Such technology transfer and the participation of local industries in supply chains not only facilitate the smooth implementation of projects but also directly contribute to the creation of new green jobs and the strengthening of industrial bases in ASEAN. Moreover, Japanese firms' proactive contribution to building ecosystems of human resources and technologies involved in infrastructure operation will serve as a powerful driver toward achieving a "Just Energy Transition," in which the benefits of renewable energy development are widely shared with local communities.

Furthermore, by maintaining continuous involvement in areas beyond routine maintenance, including periodic inspections, advanced maintenance services, software updates, and remote monitoring, Japanese companies may establish sustainable long-term revenue models.

Knowledge accumulated through such involvement regarding grid operations and equipment conditions may also contribute to securing advantages in responding to future additional demand, such as facility expansion or functional upgrades.

In this way, by positioning service deployment and operational support as the core of their business models, Japanese companies may pursue sustainable revenue generation and the establishment of competitive advantages while simultaneously supporting the autonomous development of grid operations within ASEAN countries.

In addition, when providing wide-area grid operation software, xEMS, and data systems, Japanese firms should avoid black-box approaches and instead pursue designs that allow ASEAN to retain sovereignty and governance over the systems—such as adopting open architectures and offering interfaces compliant with international standards. This functions as a "safeguard" to prevent ASEAN from becoming locked into any single partner (including Japan).

Furthermore, in cybersecurity design, Japanese firms should adopt zero-trust architectures and establish mechanisms to ensure that data does not inappropriately flow outside the region (thereby securing data sovereignty), while also taking a phased approach to transferring and sharing access rights and administrative authority with ASEAN counterparts. Such an approach will be critical for Japanese firms to gain strong trust.

② Deployment of region-specific technology packages

Second, adopting technology packages tailored to the existing infrastructure and institutional conditions of each region, rather than proposing uniform or one-sided standards, may provide Japanese companies with strategic advantages in APG-related markets. "Technology packages" refer to multilayered proposals that combine core technologies such as HVDC systems and submarine cables with supporting technologies for transmission and distribution networks, including FACTS and DLR, as well as demand-side technologies such as DR, VPP, and xEMS. Through such combinations, these packages can enable gradual and modular grid modernization.

This proposal-based approach may allow Japanese companies to leverage their experience in Japan, where grid sophistication has been advanced while responding to highly constrained system conditions and disaster risks as both a disaster-prone and island nation. As such, Japan's experience may be positioned as a realistic model for grid modernization applicable to ASEAN countries.

From this perspective, it will also be important for Japanese companies to engage proactively with grid modernization roadmaps formulated by each region, while coordinating with Japanese governmental agencies, financial institutions, and multilateral development banks.

③ Reduction of business entry barriers through local partnerships and service-based business schemes

Even if the above two strategies are adopted, Japanese products and services may still be perceived as requiring lengthy implementation and decision-making processes, as well as involving relatively high initial costs.

In response, a third potentially effective approach would be the establishment of strategic alliances with local companies and the introduction of flexible financing methods, including schemes that convert initial costs into OPEX.

Rather than relying on conventional package-based business development led primarily by Japanese companies, Japanese firms may benefit from shifting toward business models premised on international division of labor and collaboration, actively incorporating local companies into supply chains covering construction, maintenance, procurement, and operation. Such an approach may contribute not only to cost reductions and local job creation but also to improving Japanese companies' adaptability to local institutions and business practices. As a result, by reducing uncertainty and facilitating investment decisions, these arrangements may simplify decision-making processes regarding technology adoption and accelerate project implementation.

In addition, rather than limiting business models to one-time equipment sales, Japanese companies may consider introducing technology package-based leasing models that integrate equipment provision, operational support, and maintenance services. Such models could reduce upfront investment burdens and lower barriers to adoption.

Furthermore, Energy-as-a-Service (EaaS) represents a business model in which the functional value generated through energy infrastructure and operational management is provided to customers as a service in exchange for recurring payments. This model enables the conversion of large-scale capital expenditures (CAPEX) associated with infrastructure installation into periodic OPEX, thereby allowing customers to avoid substantial upfront investment burdens.

In this way, the combination of collaboration with local partners and the servitization of business models is expected to contribute to more sustainable and competitive business development.

As a final point in this chapter, it goes without saying that expanding the deployment of "flexibility enhancing measures," in which Japanese companies can be involved as discussed above, will not only create entry opportunities for Japanese firms in ASEAN markets, but also contribute to capacity building on the ASEAN side, operational self-reliance, the establishment of open standards, and the development of technology portfolios with multiple partners.

5. Financial and Institutional Challenges of the APG and Policy Approaches

(1) Financial and Institutional Challenges of the APG

The transfer and deployment of technology for a massive cross-border infrastructure such as APG cannot be achieved solely through the self-help efforts of private firms, regardless of the quality of Japanese or other technologies. In addition to technical challenges, there are financial and institutional barriers that hinder technology transfer and social implementation of the APG. These factors interact with each other and constitute structural bottlenecks that impede the flow of both public and private capital.

① Financial Challenges

a. Reduced Bankability due to State-Owned Monopoly Structures and the "Split Model"[114]

The first financial challenge lies in the structure of ASEAN electricity markets and the complexity of financing cross-border projects. In many ASEAN countries, electricity transmission is a regulated sector monopolized by state-owned utilities, and new market entry is generally not permitted. Because private developers and foreign firms face restrictions on direct participation and revenue generation, infrastructure financing depends heavily on government financial capacity. As a result, sovereign debt limits and financial constraints directly constrain APG progress.

In addition, the structure of revenue generation and allocation in cross-border APG projects further increases investment risk. These projects often adopt a "split model," under which multiple countries and entities share responsibility for different segments of the infrastructure. Rather than a single Special Purpose Vehicle (SPV) constructing and owning the entire cross-border transmission line, each country finances and builds its own domestic transmission lines, substations, and interconnection facilities at the border.

While this model is politically acceptable from the standpoint of national sovereignty, it presents challenges for financial institutions and investors. Costs and future revenues must be evaluated separately for each country rather than as a unified project. If construction in one country is delayed, investments in neighboring countries risk becoming stranded assets. This significantly reduces overall project bankability.

b. Structural Mismatch between Asset Lifespan and Loan Tenor

The second challenge is the "maturity mismatch" between the nature of infrastructure assets and financial market practices. HVDC systems and submarine cables require massive upfront investment, yet available domestic capital is insufficient across ASEAN[115]. A key reason for this investment gap is the mismatch between equipment lifespan and loan tenor.

For example, major HVDC components, such as converter transformers, typically have a lifespan of 35–40 years[116], implying very long-term revenue recovery. However, private financial institutions operate under regulatory constraints such as Basel capital requirements. These regulations oblige banks to secure stable long-term funding for long-term lending, effectively locking in capital over extended periods. As loan tenors increase, the associated capital costs rise significantly[117,118,119].

Consequently, even for long-lived infrastructure assets, private financiers tend to prefer short-to medium-term lending, leading to a structural shortage of long-term capital in the market.

c. High Risk Premiums and Country Risk

114 Japan International Cooperation Agency (JICA) & The Institute of Energy Economics, Japan (IEEJ) (2025), *Study on ASEAN Power Grid*, https://libopac.jica.go.jp/images/report/1000055597.pdf (Accessed on April 21, 2026)

115 International Energy Agency (2026), *Financing the ASEAN Power Grid*, https://iea.blob.core.windows.net/assets/ae91a87e-275b-48b8-81b9-2eacadc8d28b/FinancingtheASEANPowerGrid.pdf (Accessed on April 21, 2026)

116 L. Recksiedler et al. (2023), *Life Extension and Upgrading of HVDC Systems*, CIGRE Green Books, Springer.

117 Bank for International Settlements (2014), *Basel Committee on Banking Supervision, Basel III: the net stable funding ratio*, https://www.bis.org/bcbs/publ/d295.pdf (Accessed on April 21, 2026)

118 PwC (2014), "Basel III bearkfast briefing series, Stretched to the limit: Dealing with the implications of the NSFR," https://www.pwc.com/im/en/publications/assets/basel-iii-and-beyond-stretched-to-the-limit.pdf (Accessed on April 21, 2026)

119 Bank for International Settlements (2017), *Basel Committee on Banking Supervision, Basel III: Finalising post-crisis reforms*, https://www.bis.org/bcbs/publ/d424.pdf (Accessed on April 21, 2026)

Third, the high level of country risk inherent in ASEAN markets raises capital costs and discourages private investment. According to IEA (2024)[120], higher costs of capital in emerging markets, including ASEAN, significantly increase the levelized cost of electricity (LCOE) even for identical clean energy technologies.

The weighted average cost of capital (WACC), a key determinant of investment decisions, varies considerably across countries. For instance, in 2024, WACC for 50–100 MW solar projects is approximately 6.0–7.0% in Malaysia, compared to 8.5–10.0% in Vietnam[121].

One major driver of elevated WACC is inflation risk, reflecting macroeconomic instability. Inflation rates directly affect construction materials and labor costs; for example, projections for 2025 indicate inflation rates of approximately 5.0% in Laos and as high as 30.0% in Myanmar[122].

More critically, high inflation increases the risk of local currency depreciation. For foreign investors, currency depreciation reduces returns when converted into foreign currencies, undermining project profitability. Although currency hedging can mitigate such risks, it is not widely available in ASEAN due to managed floating exchange rate regimes in countries such as Cambodia[123], Laos[124], Myanmar[125], and Vietnam[126]. In practice, hedging instruments are available only for a limited number of currencies, such as the Singapore dollar, Thai baht, and Indonesian rupiah[127]. As a result, foreign exchange risk cannot be effectively eliminated in most ASEAN markets.

d. Long-Term Demand Uncertainty and Limitations of Existing ODA Frameworks

Fourth, uncertainty in long-term demand and the limitations of existing public support frameworks present additional challenges. Cross-border projects require large upfront investments that must be recovered over 20–30 years, necessitating reliable off-takers and long-term Power Purchase Agreements (PPAs) at fixed prices. However, policy uncertainties, differing national tariff structures, and regulatory inconsistencies create significant unpredictability, making projects difficult for investors to assess.

To address such market failures, there are high expectations for Official Development Assistance (ODA) from countries like Japan. However, existing ODA frameworks face structural limitations in supporting cross-border infrastructure. APG projects span multiple countries, often involving both high-income countries (which are typically ineligible for ODA) and low- to middle-income countries (which are eligible). This makes it difficult to support projects as a single integrated initiative under bilateral ODA schemes.

Moreover, Japan's ODA system is fundamentally based on bilateral agreements. Supporting multi-country projects like the APG requires complex coordination of funding shares and conditions across multiple partner countries, which reduces flexibility and makes rapid and efficient financing difficult.

② Institutional Challenges

Even if sufficient funding is secured to develop the physical transmission infrastructure (hardware), wide-area power exchange cannot function effectively without the institutional

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[120] International Energy Agency (2024), *Reducing the Cost of Capital, Strategies to unlock clean energy investment in emerging and developing economies*, https://iea.blob.core.windows.net/assets/227da10f-c527-406d-b94f-dbaa38ae9abb/ReducingtheCostofCapital.pdf (Accessed on April 21, 2026)

[121] International Energy Agency (2025), "Cost of Capital Observatory, Dashboard," https://www.iea.org/reports/cost-of-capital-observatory/dashboard (Accessed on April 21, 2026)

[122] WorldData.info (2026), "Inflation rates in a global comparison," https://www.worlddata.info/inflation.php (Accessed on April 21, 2026)

[123] International Monetary Fund (2025), "Cambodia: Staff Report for the 2024 Article IV Consultation—Informational Annex," https://www.elibrary.imf.org/view/journals/002/2025/022/article-A002-en.xml (Accessed on April 21, 2026)

[124] International Monetary Fund (2024), "Lao People's Democratic Republic: Staff Report for the 2024 Article IV Consultation—Informational Annex," https://www.elibrary.imf.org/view/journals/002/2024/319/article-A002-en.xml (Accessed on Aprial 21, 2026)

[125] International Monetary Fund (2023), "Annual Report on Exchange Arrangements and Exchange Restrictions," https://www.elibrary.imf.org/display/book/9798400260391/9798400260391.xml?cid=lk-com-dsp-imf.org (Accessed on April 21, 2026)

[126] International Monetary Fund (2024), "Vietnam: Staff Report for the 2024 Article IV Consultation—Informational Annex," https://www.elibrary.imf.org/view/journals/002/2024/306/article-A002-en.xml (Accessed on April 21, 2026)

[127] Bank for International Settlements (2022), "Foreign exchange markets in Asia-Pacific," https://www.bis.org/publ/othp60.pdf (Accessed on Aprila 21, 2026)

frameworks and operational rules (software) needed to manage it.

a. Differences in Electricity Market Structures and Lack of Regulatory Harmonization

The first institutional challenge lies in the lack of harmonization in regulations and operational rules across countries. There are significant disparities in electricity market structures among ASEAN member states.

For example, in liberalized electricity markets such as those in the Philippines and Singapore, retail tariffs are generally cost-reflective, and transmission tariffs are set to recover the costs of asset construction and maintenance, along with a regulated rate of return[128]. In contrast, in vertically integrated markets such as Indonesia and Cambodia, independent transmission tariffs typically do not exist; instead, investments in transmission are recovered as part of retail tariffs charged to end-users[129].

Under such fundamentally different market structures, designing cross-border electricity transactions becomes highly complex, particularly in allocating generation costs and transmission charges among participating countries.

In addition, technical standards such as grid codes differ across countries. Even if physical interconnection is possible, operational frictions may arise, potentially threatening system stability. Differences in frequency tolerance ranges, frequency recovery times, and voltage settings can complicate coordination during system disturbances and increase the risk of instability in interconnected grids[130].

b. Lack of Harmonized Certification Systems and Environmental Attributes

The second challenge is the lack of harmonized systems for certifying the environmental attributes of renewable energy. To create incentives for cross-border trade in green electricity, mechanisms such as RECs are essential.

Currently, REC systems are established in Singapore and Malaysia, and are being developed in countries such as Vietnam, Indonesia, and the Philippines[131]. However, such systems remain underdeveloped in countries like Laos[132].

Moreover, there is no unified ASEAN-wide certification body, and REC systems vary significantly by country. This makes it difficult to verify the origin of renewable electricity traded across borders[133].

As a result, global corporations with strong financial capacity—such as members of RE100—face reduced incentives to procure renewable electricity via the APG to meet their decarbonization targets. This lack of standardization thus hinders the development of a multilateral electricity market.

c. Absence of a Regional Integrated organization Responsible for Cross-Border Optimization

The third and most critical institutional challenge is the absence of a neutral and independent regional entity with the authority to plan and operate interconnected systems from a system-wide optimization perspective.

In the European Union (EU), the European Network of Transmission System Operators for Electricity (ENTSO-E) brings together national transmission system operators and plays a central role in developing cross-border transmission master plans and promoting market integration[134].

[128] International Energy Agency (2026), *Financing the ASEAN Power Grid*, https://iea.blob.core.windows.net/assets/ae91a87e-275b-48b8-81b9-2eacadc8d28b/FinancingtheASEANPowerGrid.pdf (Accessed on May 8, 2026)

[129] International Energy Agency (2026), *Financing the ASEAN Power Grid*, https://iea.blob.core.windows.net/assets/ae91a87e-275b-48b8-81b9-2eacadc8d28b/FinancingtheASEANPowerGrid.pdf (Accessed on May 8, 2026)

[130] International Energy Agency (2026), *Financing the ASEAN Power Grid*, https://iea.blob.core.windows.net/assets/ae91a87e-275b-48b8-81b9-2eacadc8d28b/FinancingtheASEANPowerGrid.pdf (Accessed on May 8, 2026)

[131] Kawamura (2025), “ASEAN パワー・グリッドにおける再エネ輸出入の課題—ガス需要との補完関係を踏まえて—,” https://www.mitsui.com/mgssi/ja/report/detail/__icsFiles/afieldfile/2025/10/21/2510_kawamura.pdf (Accessed on May 8, 2026)

[132] JETRO (2023), “再エネや排出権取引で企業参入、社会課題にも注目(ラオス),” https://www.jetro.go.jp/biz/areareports/special/2023/1002/91959983353ab7f6.html (Accessed on May 8, 2026)

[133] Kawamura (2025), “ASEAN パワー・グリッドにおける再エネ輸出入の課題—ガス需要との補完関係を踏まえて—,” https://www.mitsui.com/mgssi/ja/report/detail/__icsFiles/afieldfile/2025/10/21/2510_kawamura.pdf (Accessed on May 8, 2026)

[134] ENTSO-E (2025), “New Ten-Year Network Development Plan highlights power transmission and storage needs to meet the Energy Transition targets,” https://www.entsoe.eu/news/2025/01/31/new-ten-year-network-development-plan-highlights-power-transmission-and-storage-needs-to-meet-the-energy-transition-targets/ (Accessed on Aprial 10, 2026)

By contrast, ASEAN has the Heads of ASEAN Power Utilities/Authorities (HAPUA), established in 1981. HAPUA is a specialized organization that promotes cooperation among national power utilities with the objective of enhancing regional energy security and is responsible for supporting the implementation of the APG[135]. Specifically, it facilitates cooperation among member utilities, promotes private sector participation, encourages standardization of equipment, advances joint project development, fosters collaboration in human resource development and R&D, and aims to improve the quality and reliability of power supply systems[136].

However, HAPUA functions primarily as a technical coordination and cooperation body within ASEAN energy cooperation, while policy decision-making authority resides with the ASEAN Ministers on Energy Meeting (AMEM) [137].

Thus, while ENTSO-E serves as an operational entity for an integrated electricity market under EU law, HAPUA functions as a coordination network based on intergovernmental agreements (MOUs) for implementing the APG vision. Despite some superficial similarities, the two institutions differ fundamentally in their roles and authority.

(2) Policy Approaches to Overcome the Challenges

To overcome the complex financial and institutional challenges outlined above and to build a resilient core infrastructure such as APG, both ASEAN's own efforts and innovative, comprehensive support schemes provided by development partners (DPs), including Japan, are indispensable.

① Existing ASEAN Initiatives and Strategic Direction

As noted earlier, the absence of decision-making authority within HAPUA—the regional coordination body—is an inevitable consequence of ASEAN's unique political culture, the so-called "ASEAN Way," [138] which emphasizes non-interference in domestic affairs and consensus-based decision-making. Accordingly, it would not be realistic to attempt to establish a strong, top-down institution like Europe's ENTSO-E in the ASEAN context.

Recognizing this, ASEAN member states are not passively accepting these constraints but are instead pursuing a bottom-up approach that gradually harmonizes rules through pilot and demonstration projects. A representative example is the "Lao PDR–Thailand–Malaysia–Singapore Power Integration Project (LTMS-PIP)." Through this multilateral initiative, ASEAN has already begun testing contractual arrangements and operational rules for cross-border power transmission while identifying practical challenges[139].

Furthermore, building on the insights gained from such demonstration projects, steady progress is also being made at the policy level. At the 43rd AMEM held in October 2025, member states strongly acknowledged that differences in technical standards across national power systems hinder the realization of multilateral power trade (MPT) and broader renewable energy integration[140]. Although ASEAN lacks top-down enforcement mechanisms, the meeting resulted in a shared commitment to harmonizing technical standards and tariff systems, strengthening the reliability of cross-border PPAs, improving electricity traceability, and standardizing REC systems. A new memorandum of understanding (MOU) aimed at strengthening the APG was also concluded[141].

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[135] HAPUA (n.d.), "About HAPUA," https://hapua.org/main/hapua/about/ (Accessed on April 10, 2026)

[136] HAPUA (n.d.), "About HAPUA," https://hapua.org/main/hapua/about/ (Accessed on April 10, 2026)

[137] ASEAN (n.d.), "MEMORANDUM OF UNDERSTANDING ON THE ASEAN POWER GRID," https://asean.org/wp-content/uploads/2024/11/MoU-on-the-ASEAN-Power-Grid-1.pdf (Accessed on April 10, 2026)

[138] ASEAN (2015), *The ASEAN Charter*, https://www.asean.org/wp-content/uploads/2021/09/2.-February-2015-The-ASEAN-Charter-18th-Reprint.pdf (Accessed on May 8, 2026)

[139] ASEAN Ministers on Energy (2024), "FIFTH JOINT STATEMENT OF LAO PDR-THAILAND-MALAYSIA-SINGAPORE POWER INTEGRATION PROJECT," https://isomer-user-content.by.gov.sg/166/8e19d802-34ad-4ff5-afed-89da6cdfb2a4/5th-LTMS-Joint-Statement-Adopted.pdf (Accessed on April 10, 2026)

[140] AMEM (2025), "Joint Media Statement of the Forty-third ASEAN Ministers on Energy Meeting (43rd AMEM)," https://asean.org/wp-content/uploads/2025/10/Joint-Media-Statement-JMS-of-the-43rd-AMEM_Final.pdf (Accessed on April 10, 2026)

[141] The ASEAN Secretariat (2025),"The 43rd ASEAN Ministers on Energy Meeting (43rd AMEM) and Its Associated Meetings and Events," https://asean.org/the-43rd-asean-ministers-on-energy-meeting-43rd-amem-and-its-associated-meetings-and-events/ (Accessed on April 10, 2026)

In particular, the "AIMS III Phase 3" report[142] published by ACE in May 2026 proposes the future establishment of an "ASEAN Power Pool (APP)," which would optimize short-term electricity trading within the region, as well as an "ASEAN Member States Regulatory Board (AMSRB)" to help coordinate differing national regulatory frameworks. The report also outlines plans for the gradual development of regional grid codes[143].

Thus, even in the absence of a powerful centralized authority, ASEAN's approach—combining bottom-up identification of issues through multilateral pilot projects with gradual policy harmonization through ministerial consensus—represents a pragmatic and effective strategy consistent with the ASEAN Way.

② Japan's Contribution 1: New Financial Support Measures to Address Financial Challenges (Mobilizing Risk Capital)

To strongly support ASEAN's ongoing efforts and facilitate technology transfer from Japan, the first key contribution is the deployment of flexible financial support through public finance mechanisms.

a. Blended Finance and New Financing Models

Financial approaches such as blended finance and innovative funding models directly address the challenges outlined in (1)-①-c. High risk premiums and country risk and (1)-①-d. Long-term demand uncertainty and limitations of existing ODA frameworks.

First, with regard to country risk, in ASEAN markets where high risk premiums prevail, the use of blended finance is effective. Under this approach, public funds absorb long-term risks, while private capital supports portions of the project with relatively shorter asset durations. Japan has a proven track record in reducing risk premiums through instruments such as JICA's overseas investment and lending, transition finance provided by the Japan Bank for International Cooperation (JBIC), and trade and investment insurance offered by Nippon Export and Investment Insurance (NEXI).

Furthermore, to overcome the limitations of existing ODA frameworks, new support models should be developed in addition to conventional schemes. These include:

"Two-step loans"[144], in which Japanese public institutions provide lump-sum funding to recipient governments or central banks, which then allocate funds to individual projects; and

"Technology package-type leasing"[145], where leasing companies provide multiple technologies, equipment, and assets as a bundled solution.

In addition, Japan should strengthen collaboration with emerging multilateral frameworks such as the ASEAN Power Grid Financing (APGF) initiative[146] and Partners for ASEAN Connectivity on Energy (PACE)[147], launched by institutions including the World Bank, the Asian Development Bank (ADB), and ASEAN. This would facilitate a shift from traditional bilateral assistance toward multilateral, coordinated project support.

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142 ASEAN Centre for Energy (2026), *ASEAN Interconnection Masterplan Study (AIMS) III Phase 3: Minimum Requirements for Multilateral Power Trade in ASEAN*, https://aseanenergy.org/publications/asean-interconnection-masterplan-study-aims-iii-phase-3-minimum-requirements-for-multilateral-power-trade-in-asean (Accessed on May 13, 2026)

143 ASEAN Centre for Energy (2026), *ASEAN Interconnection Masterplan Study (AIMS) III Phase 3: Minimum Technical Standards for Interconnections*, https://storage.googleapis.com/aceweb-bucket-261225/pdf/publication/[DESIGNED]%20AIMS%20III%20Phase%203%20-%20Part%203%20-%20Minimum%20Technical%20Standards%20Harmonisation_Jy5XYyNZ5x12EfCuIS4GMYzgli1Y4C9TX94NnwF7.pdf (Accessed on May 13, 2026)

144 JICA (n.d), "円借款の種類," https://www.jica.go.jp/activities/schemes/finance_co/about/kind.html (Accessed on April 10, 2026)

145 International Finance Corporation (2009), *Leasing in Development, Guidelines for Emerging Economies*, https://documents1.worldbank.org/curated/en/998901468326962267/pdf/516730WP0Box341inDevelopment1Manual.pdf (Accessed on May 8, 2026)

146 The ASEAN Secretariat (2025), "ADB and World Bank Group Launch the ASEAN Power Grid Financing Initiative with the ASEAN Secretariat and the ASEAN Centre for Energy (ACE)," https://asean.org/adb-and-world-bank-group-launch-the-asean-power-grid-financing-initiative-with-the-asean-secretariat-and-the-asean-centre-for-energy-ace/ (Accessed on May 8, 2026)

147 ASEAN Centre for Energy (n.d.), "ASEAN Power Grid Financing Facility (APGF) Secretariat," https://aseanenergy.org/secretariat/asean-power-grid-financing-facility-apgf-secretariat (Accessed on May 8, 2026)

b. Application of JOGMEC-style Exploration Financing and Ensuring Liquidity through Equity Participation

As a further approach to addressing (1)-①-a. Reduced bankability due to state-owned monopolies and the "split model", it is important to expand equity-based financing schemes for high-risk projects.

One potential model is to adapt the mechanism of the exploration financing and equity participation system used by the Japan Organization for Metals and Energy Security (JOGMEC) in the resource development sector, applying it to APG projects through a different institutional framework. This approach would function as a supply of risk capital for early-stage project development—such as feasibility studies (FS) and licensing—where uncertainty is highest.

This mechanism is particularly suitable because the early stages of transmission infrastructure projects (e.g., feasibility assessments and intergovernmental MOUs) carry a significant risk of project suspension. In such phases, flexible risk capital—similar to exploration financing—is more appropriate than conventional infrastructure loans.

Specifically, this approach involves Japanese support institutions jointly investing—on an equal footing—with local state-owned power utilities to establish a Special Purpose Company (SPC) for cross-border transmission projects[148] (see Figure 5-1).

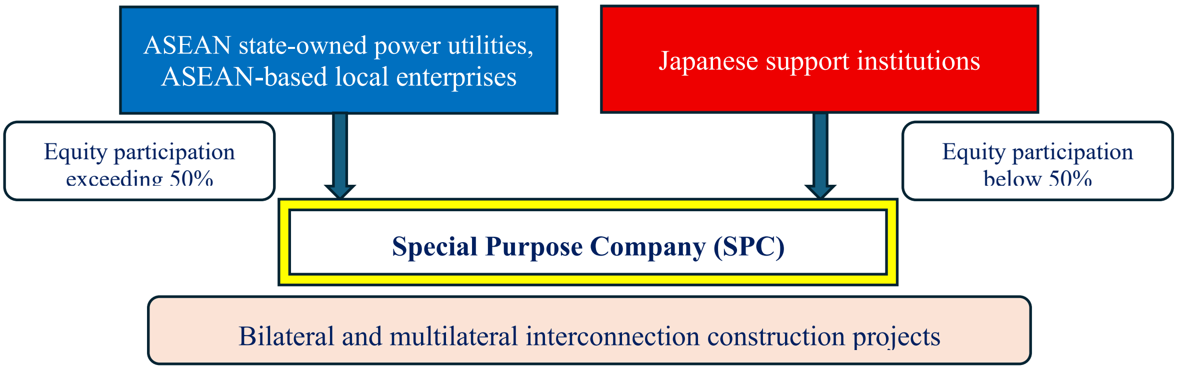

Figure 5-1 Application of the equity-based exploration financing mechanism to interconnection projects
Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

The key advantage of this scheme lies in its flexibility and liquidity. For example, if construction costs rise due to inflation or other factors, additional funding can be provided promptly in the form of equity contributions. As long as the eventual equity sale value matches the book value of the investment, no losses need to be recorded by the support institution, while significantly reducing the upfront financial burden on local state-owned enterprises.

Moreover, this equity-based framework directly addresses (1)-①-b. Structural mismatch between asset lifespan and loan tenor. Once the transmission project becomes operational and stable, equity stakes can be divested in consultation with local partners, thereby avoiding the long-term immobilization of capital in a single project. If the Japanese entity retains its shareholding, returns can be transparently captured through dividend income.

For the SPC itself, a stronger equity base enhances financial robustness, enabling more diversified fundraising options such as corporate bond issuance or syndicated loans from commercial banks, thereby improving overall financial sustainability and scalability of the project.

148 JOGMEC (n.d.), "出資制度の概要," https://www.jogmec.go.jp/activities/oilgas/investment-guarantee/investment-system.html (Accessed on May 8, 2026)

③ Japan's Contribution 2: Support for Rule-Making and Capacity Building to Address Institutional Challenges

The second area of contribution is institutional support (rule-making and human resource development) aimed at overcoming the previously identified institutional challenges—namely differences in market structures and regulations across countries, the lack of harmonized environmental value systems, and the absence of a regional integrated body—and ensuring that the developed physical infrastructure can be operated in a stable and effective manner.

a. Leveraging the Asia Zero Emissions Community (AZEC) Framework and Linking with the Joint Crediting Mechanism (JCM)

As an approach to addressing (1)-②-b. Lack of harmonization in certification systems and environmental attributes, Japan should fully utilize the framework of the Asia Zero Emissions Community (AZEC), which it has proposed and leads. Japan has already announced, through the Japan Bank for International Cooperation (JBIC), financing support for transmission and distribution network development in participating countries under the AZEC framework, as well as support for public–private dialogue[149].

Similarly, policy support through the Asia Zero Emission Center, established within the Economic Research Institute for ASEAN and East Asia (ERIA), is also important. At ERIA, the design of carbon market mechanisms has been identified as a key research area[150]. Moreover, it is noteworthy that coordination with Japan's Joint Crediting Mechanism (JCM) has been discussed at AZEC ministerial meetings[151].

By applying the rigorous Measurement, Reporting, and Verification (MRV) methodologies for greenhouse gas reductions developed under the JCM to ASEAN REC systems and cross-border PPAs, Japan can take the lead in establishing common standards for a clean electricity market aligned with international norms.

Promoting such rule harmonization will help create a market environment in which global corporations pursuing decarbonization—such as RE100 members—as well as Japanese companies operating in ASEAN can confidently procure renewable electricity through corporate PPAs. This, in turn, directly contributes to maintaining the competitiveness of supply chains, thereby benefiting Japanese industry.

b. Sharing Expertise in Wide-Area System Operation and Regulatory Harmonization Based on OCCTO and Transmission Operators

An effective approach to addressing (1)-②-a. Differences in electricity market structures and regulatory inconsistency and (1)-②-c. Absence of a regional integrated institution for cross-border optimization is the provision of Japan's expertise in wide-area system operation and advanced technical capabilities through capacity building.

From an institutional design perspective, the experience of Japan's Organization for Cross-regional Coordination of Transmission Operators (OCCTO) provides a valuable reference model. OCCTO's practices—such as the operation of supply–demand balancing markets, formulation of wide-area transmission development plans, congestion management, and nationwide cost-sharing schemes based on beneficiary-pays principles—offer important guidance for ASEAN as it incrementally designs future market integration and cost allocation mechanisms, even in the absence of a strong centralized authority.

From the perspective of physical system operation, it is equally critical to share the practical expertise accumulated by Japan's general transmission and distribution operators (electric power

[149] JBIC (2025), "Decarbonization Waves from Asia to the World," https://www.jbic.go.jp/en/information/today/today_202505/jtd_202505_sp2.html (Accessed on May 11, 2026)
[150] METI (2025) , "Report on the Outcome of the AZEC International Conference to Develop Carbon Market Published," https://www.meti.go.jp/english/press/2025/1023_002.html (Accessed on May 11, 2026)
[151] Ministry of Foreign Affairs of Japan (2024), "アジア・ゼロエミッション共同体(AZEC)首脳共同声明: 今後 10 年のためのアクションプラン," https://www.mofa.go.jp/mofaj/files/100737978.pdf (Accessed on April 13, 2026)

companies). To overcome frictions arising from differences in grid codes—such as variations in frequency and voltage settings—and to enable effective cross-border coordination during system disturbances, technical guidance based on Japan's advanced frequency control technologies and fault-response expertise would be highly effective.

On the ASEAN side as well, the "ASEAN Interconnection Masterplan Study (AIMS) III Phase 3: Implementation Strategy for Multilateral Power Trade in ASEAN," published by ACE in May 2026, highlights the extremely high demand for capacity building in harmonizing grid operation procedures.

In addition, the integration of information and communication networks accompanying wide-area interconnection entails the risk of increasing cybersecurity vulnerabilities. Here as well, Japan should not impose its own systems unilaterally; rather, it should support the establishment of governance frameworks that enable ASEAN to defend and monitor its grid networks with full sovereignty. Specifically, this could include assistance in formulating ASEAN-specific cybersecurity standards, establishing joint Security Operations Centers (SOCs), and providing institutional support for harmonizing data governance rules. Through these efforts, ASEAN can develop the capacity to autonomously prevent and eliminate cyber interference from external actors without becoming dependent on any single country.

In this way, sharing in a multifaceted manner not only the institutional expertise of OCCTO and the practical operational know-how of transmission and distribution operators, but also support for the development of cybersecurity governance, with ASEAN policymakers and utilities, will serve as a powerful form of soft support. Such efforts are essential for ensuring that technology transfer from Japan is effectively embedded and realized as practical implementation within ASEAN's evolving power systems.

④ Japan's Potential Contribution to ASEAN's Economic Security

As discussed above, providing a "three-in-one package"—combining advanced grid flexibility technologies, flexible financial support through equity and debt instruments, and institutional harmonization and knowledge sharing through frameworks such as AZEC and OCCTO—carries profound strategic significance. This integrated approach directly addresses the economic security imperatives of ASEAN, emphasized throughout this paper.

Electric power infrastructure constitutes the "arterial system" of a nation and, when integrated with information and communication networks, also forms its "nervous system." If ASEAN were to become excessively dependent on massive capital from a specific external power or on opaque, closed technological standards, it would face serious risks. These include disruptions in supply chains during emergencies and the potential for large-scale blackouts induced through external control, thereby undermining national autonomy.

Accordingly, Japan's role should be to support the development of transparent, internationally aligned rules and to provide alternative sources of risk capital through public–private collaboration. By doing so, Japan can help ASEAN maintain and strengthen a "hedging strategy (equidistant diplomacy)" in infrastructure procurement—one that incorporates multiple technologically advanced partners in a balanced manner.

Diversifying dependence on any single country and ensuring a diverse technological portfolio is essential to safeguarding ASEAN's sustainable and autonomous development. At the same time, the establishment of an open and transparent regional electricity market aligns with Japan's own national interests, particularly in maintaining the competitiveness of supply chains for Japanese companies operating in ASEAN, as discussed in the previous section.

If Japan, as one of the most important partners, provides this comprehensive support and ASEAN successfully implements its hedging strategy to avoid overdependence on any single country, the APG will not only contribute to decarbonization but will also emerge as a robust foundation that simultaneously strengthens energy security and economic security across the region, bringing its realization significantly closer.

6. Estimated Investment Estimation for the APG

Chapters 4 and 5 identified the technical, financial, and institutional challenges facing the APG and discussed possible solutions and mitigation measures. This chapter shifts the focus to a quantitative assessment of investment requirements for individual APG interconnection projects. It also assesses the relative fiscal burden of these investments by comparing them with the scale of government expenditure in each participating country.

The estimation covers, in principle, those transmission projects categorized as "Planned" among the 18 official APG interconnection routes identified in ACE(2024)[152, 153]. Based on the transmission capacities (line capacities) assumed under the three scenarios presented earlier in Table 3-2, the analysis estimates the initial investment costs associated with substations and transmission cable installation.

(1) Assumptions for the Cost Estimation

The initial investment cost for each transmission route was calculated as the sum of substation costs and cable installation costs. The estimation was conducted using the unit cost assumptions summarized in Table6-1Table6-1, based on each route's technical specifications, including voltage level, transmission capacity, and route distance.

The specifications of each route were determined according to the following principles.

① Cable Type, Voltage Level, Transmission Capacity, and Circuit Configuration

- The transmission capacity of each route was primarily determined based on the three scenarios shown in Table 3-2 derived from ACE(2023)[154].
- The technical specifications of each route—including cable type, voltage level, transmission capacity, and number of circuits—were principally based on the planned values reported in ACE(2024)[155]. Missing information was supplemented through additional estimation.
- For routes where the transmission technology (HVDC or HVAC) had not yet been specified, assumptions were made based on the characteristics of related interconnection projects and the presence or absence of submarine sections.
- - In this study, the unit of analysis for transmission lines is the "circuit." For HVDC systems, one circuit consists of a pair of positive and negative poles, while for HVAC systems, one three-phase transmission line set is treated as one circuit. In principle, the estimation assumes the construction of a single circuit. However, routes identified as "double circuit" in ACE documents were treated as two circuits. In addition, as discussed later, HVAC routes requiring capacities exceeding 5,300 MW were assumed to require two circuits.
- When the transmission capacity assumed under the scenarios differed from the planned capacity stated in ACE documents, the larger value was generally adopted. However, when the scenario explicitly assumed no additional capacity expansion, that assumption was prioritized.
- When the scenario-based transmission capacity exceeded the planned capacity indicated in ACE documents, the voltage specifications were revised as necessary. The voltage selection methodology is described below.

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[152] ASEAN Centre for Energy (2024), *ASEAN Power Grid Interconnections Project Profiles*, https://storage.googleapis.com/aceweb-bucket-261225/files/publication/1766846405_ASEAN-Power-Grid-Interconnections-Project-Profiles.pdf (Accessed on May 20, 2026)

[153] The AIMS III Phase 3 report published by ACE in May 2026 identifies additional APG project candidates. However, as the available information is insufficient for investment cost estimation, this study, consistent with the approach described in Section 3(1), uses the 18 interconnection projects listed in ASEAN Power Grid Interconnections Project Profiles (ASEAN Centre for Energy, 2024) as the basis for the analysis.

[154] ASEAN Centre for Energy (2023), *Findings of ASEAN Interconnection Masterplan Study (AIMS) III Phase 1 & 2 Update*, https://storage.googleapis.com/aceweb-bucket-261225/uploads/2024/06/02_AIMS-III-Phase-1-and-2_Updates-_Endorsed-AMEM41.pdf (Accessed on May 20, 2026)

[155] ASEAN Centre for Energy (2024) *ASEAN Power Grid Interconnections Project Profiles*, https://storage.googleapis.com/aceweb-bucket-261225/files/publication/1766846405_ASEAN-Power-Grid-Interconnections-Project-Profiles.pdf (Accessed on May 20, 2026)

a. HVDC Systems

- The maximum current was assumed to be 2.8 kA[156]. When the required transmission capacity exceeded the capability associated with this current limit, a higher voltage class was selected based on the examples provided in the _Transmission Cost Estimation Guide for MTEP25_ published by the Midcontinent Independent System Operator (MISO)[157], a regional transmission organization (RTO) in the United States.
  - For example, the maximum transmission capacity for a 250 kV HVDC line was assumed to be approximately 700 MW. If this capacity was insufficient, the next voltage class, 400 kV, was adopted. In the case of two circuits, the 250 kV class was assumed to accommodate up to approximately 1,400 MW.
- HVDC routes requiring transmission capacities exceeding 6,000 MW were assumed to utilize large-capacity overhead transmission lines on land.

b. HVAC Systems

- The maximum transmission capacity for each voltage class was determined based on the capacity assumptions presented in MISO (2025). When the required transmission capacity exceeded the capacity for a given voltage class, a higher voltage class was applied.
- If the required capacity still exceeded 5,300 MW even at the 765 kV class, the route was assumed to require two circuits.

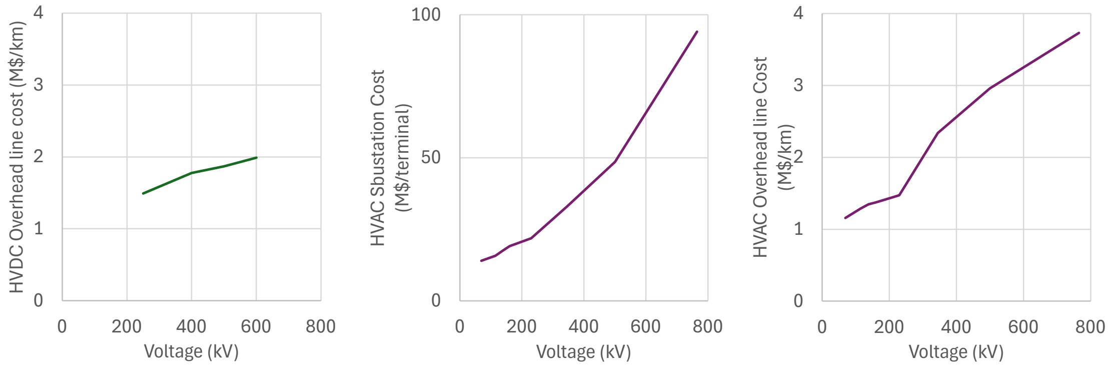
② Distance Assumptions

- Route distances were principally based on the planned values described in ACE documents.
- For routes including submarine sections, such as strait crossings, onshore and submarine distances were estimated using map-based information.
- When route distances were not explicitly provided, approximate distances were measured based on the start and end points shown in the route maps contained in the same documents.
- For routes passing through major urban areas (Routes No. 1 and No. 16), partial underground cable installation was assumed.
- In estimating cable installation costs, a 30% contingency factor was added to overhead and underground sections to account for additional route length arising from practical routing considerations such as detours.

[156] Reference: https://www.hitachienergy.com/jp/ja/news-and-events/customer-stories/nordlink (Accessed on June 3, 2026)
[157] Midcontinent Independent System Operator (MISO) (2025), Transmission Cost Estimation Guide for MTEP25 and accompanying MISO Transmission Cost Estimate Workbook for MTEP25, MISO,
Guide: https://cdn.misoenergy.org/MISO%20Transmission%20Cost%20Estimation%20Guide%20for%20MTEP25337433.pdf (Accessed on June 3, 2026)
Workbook:
https://cdn.misoenergy.org/MISO%20Transmission%20Cost%20Estimate%20Workbook%20for%20MTEP25547535.xlsx (Accessed on June 3, 2026)

Table6-1 Unit Cost Assumptions for Investment Cost Estimation[158]

Technology	**Item**		**Value**	**Unit**	**Source / Notes**
HVDC	Substation cost		323	USD/kW /terminal	MISO[159] / Assumed to be a VSC converter station installed only at both ends of the transmission line.
	Cable installation cost	Overhead line (up to 600 kV)	Figure 6-1 (a)	million USD/km	MISO
		Overhead line (large-capacity)	2.73	million USD/km	IET [160] / Applied to routes exceeding 6,000 MW.
		Underground cable	2.82	million USD/km	IET
		Submarine cable	4.0	million USD/km	Assumed based on IET and OCCTO[161] materials.
HVAC	Substation cost		Figure 6-1(b)	million USD /terminal	MISO / In this study, HVAC transmission lines were assumed to have a maximum transmission distance of approximately 200 km and to be constructed as overhead lines. Therefore, no intermediate substations were included, and only terminal substations at both ends were counted.
	Cable installation cost	Overhead line	Figure 6-1 (c)	million USD/km	MISO



(a) HVDC Overhead Transmission Line (b) HVAC Substation Facilities (c) HVAC Overhead Transmission Line

Figure 6-1 Unit Cost Assumptions Used in the Investment Cost Estimation

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

158 All cited cost figures were converted to constant 2024 USD values.

159 MISO (2025) , Transmission Cost Estimation Guide for MTEP25 and accompanying MISO Transmission Cost Estimate Workbook for MTEP25.

160 Institution of Engineering and Technology (IET) (2025), A Comparison of Electricity Transmission Technologies: Costs and Characteristics, https://www.theiet.org/media/axwkktkb/100110238_001-rev-j-electricity-transmission-costs-and-characteristics_final-full.pdf (Accessed on June 3, 2026)

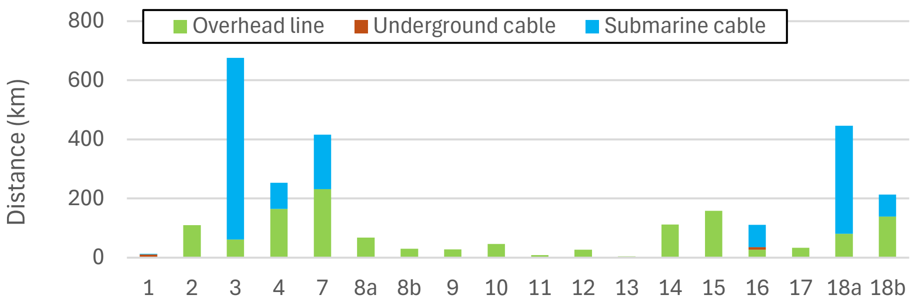
161 Organization for Cross-regional Coordination of Transmission Operators, Japan (OCCTO) (2024), "第 75 回 広域系統整備委員会 資料 1-3 東地域の広域連系系統に係る計画策定プロセス" (in Japanese), https://www.occto.or.jp/assets/iinkai/kouikikeitouseibi/2023/files/seibi_75_01_03.pdf (Accessed on June 3, 2026)

(2) Results and Discussion

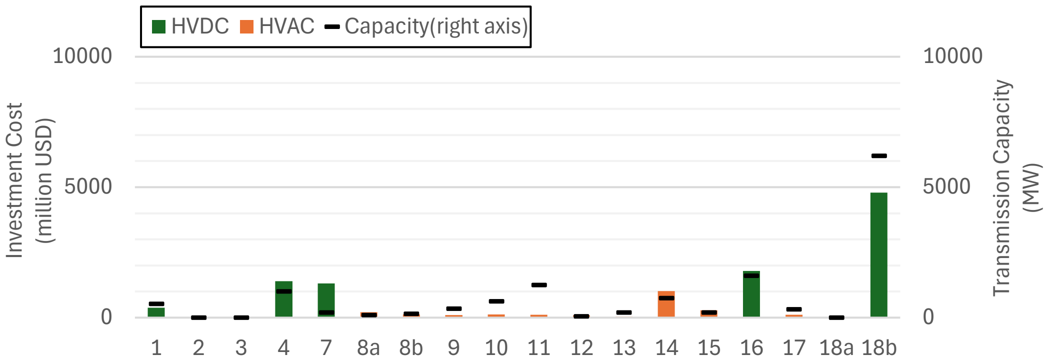
① Estimation Results

The estimated transmission line specifications and associated capital investment requirements under each scenario are presented in Figure 6-2. The analysis indicates that the total upfront investment required for the transmission projects categorized as "Planned" in ACE(2024)[162] is approximately USD 11.9 billion under the Updated PDP Scenario, USD 23.1 billion under the ASEAN RE Target Scenario, and USD 49.8 billion under the High RE Target Scenario. The investment requirement increases substantially in the High RE Target Scenario because the large-scale deployment of renewable energy necessitates the construction of high-capacity, long-distance transmission infrastructure[163]. These estimated investment requirements correspond to approximately 1.5–6.4% of total government expenditure across ASEAN in 2024.

1	Peninsular Malaysia – Singapore	8a	Sarawak – Brunei	12	Vietnam – Cambodia	17	Lao PDR – Myanmar
2	Thailand – Peninsular Malaysia	8b	Sarawak – Sabah	13	Lao PDR – Cambodia	18a	Kalimantan – Java
3	Sarawak – Peninsular Malaysia	9	Thailand – Lao PDR	14	Thailand – Cambodia	18b	Sumatera – Java
4	Peninsular Malaysia – Sumatera	10	Lao PDR – Vietnam	15	East Sabah – North Kalimantan		
7	Philippines – Sabah	11	Thailand – Myanmar	16	Singapore – Sumatera		



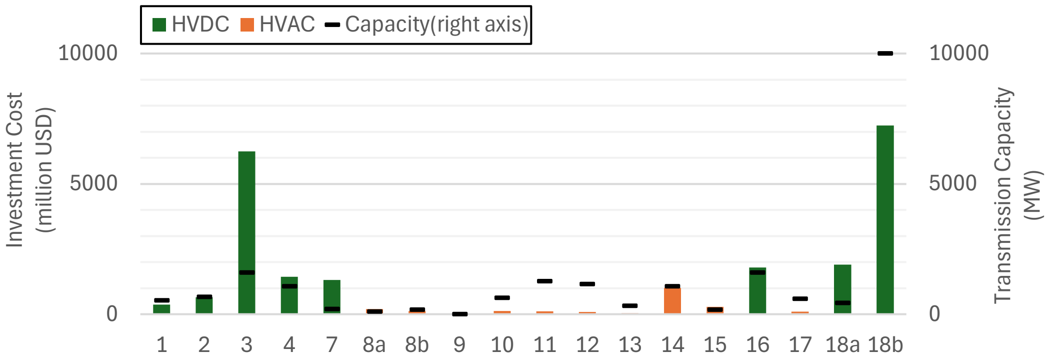
(a) Distance



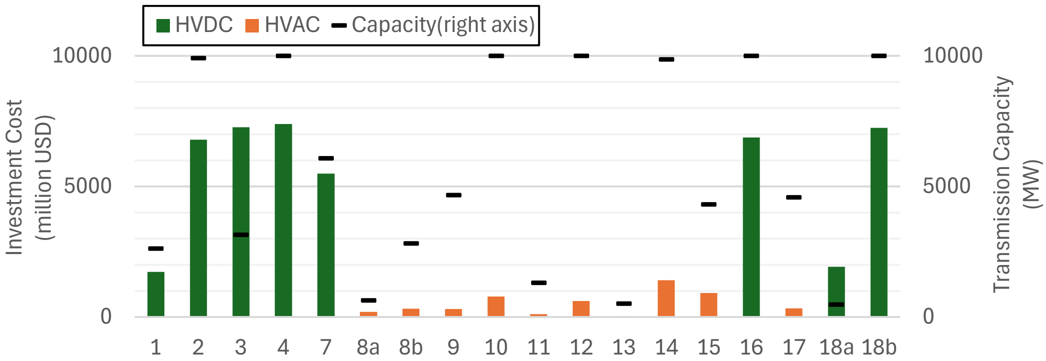
(b) Updated PDP Scenario

[162] ASEAN Centre for Energy (2024) ASEAN Power Grid Interconnections Project Profiles, https://storage.googleapis.com/aceweb-bucket-261225/files/publication/1766846405_ASEAN-Power-Grid-Interconnections-Project-Profiles.pdf (Accessed on May 20, 2026)

[163] The total investment requirement does not increase in proportion to the increase in aggregate transmission capacity because the project portfolio includes both HVDC interconnections—typically characterized by long transmission distance and/or submarine cable sections—and HVAC interconnections, which are generally shorter and consist entirely of overhead transmission lines. Since the latter require substantially lower investment than the former (typically by roughly an order of magnitude), increases in capacity associated with HVAC projects have only a limited effect on the overall investment requirement when aggregated with HVDC projects. As a result, the total investment requirement increases less rapidly than the total transmission capacity.



(c) ASEAN RE Target Scenario



(d) High RE Target Scenario

Figure 6-2 Assumptions and Results of the Investment Cost Estimation[164]

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

To provide a benchmark, IEA(2026)[165] estimates that approximately USD 27 billion of investment will be required to realize the ASEAN Power Grid (APG) under its reference case, which is based on an ASEAN RE Target-type scenario. Under broadly similar assumptions, the ASEAN RE Target Scenario developed in this study yields an estimated investment requirement of approximately USD 23.1 billion. Although the underlying assumptions are not identical, the results are of a comparable order of magnitude. It should be noted, however, that the IEA assessment also includes major upgrades to existing interconnections and transmission facilities beyond the officially designated 18 APG projects. Therefore, the scope of the two assessments is not fully aligned.

Investment requirements vary considerably across individual transmission projects (Figure 6-2(b), (c), and (d)). For projects assumed to utilize HVDC technology, investment costs tend to increase significantly when transmission distances are long and when submarine cable sections are required. In contrast, HVAC projects consisting primarily of relatively short overhead transmission lines generally exhibit lower capital costs. Under the ASEAN RE Target Scenario, estimated investment costs range from approximately USD 0.04–1.0 billion for HVAC projects and USD 0.4–7.2 billion for HVDC projects, demonstrating substantial variation depending on technology choice and route characteristics. In particular, large-capacity HVDC projects require extensive converter station facilities, making substation-related costs the dominant component of total investment.

Significant differences are also observed in investment costs per unit of transmission capacity across projects (Figure 6-3). This variation reflects not only differences in transmission capacity but also route-specific characteristics such as the presence of submarine sections, transmission distance,

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[164] Project No. 5 was excluded from the estimation because it has been integrated into Project No. 16 and constitutes a generation-to-grid connection. In addition, it has been suggested that the project will fall outside the scope of future AIMS IV transmission projects.
Project No.6 was also excluded because a 275 kV transmission line has already been constructed. The transmission capacities assumed in all scenarios remain within the standard capacity range of the line operating at this voltage level.

[165] International Energy Agency (IEA) (2025), “Financing the ASEAN Power Grid”, IEA, https://iea.blob.core.windows.net/assets/ae91a87e-275b-48b8-81b9-2eacadc8d28b/FinancingtheASEANPowerGrid.pdf (Accessed on May 20, 2026)

and the choice between HVDC and HVAC technologies. At the same time, several large-capacity projects exhibit lower investment costs per unit of capacity, suggesting the existence of economies of scale associated with larger transmission infrastructure.

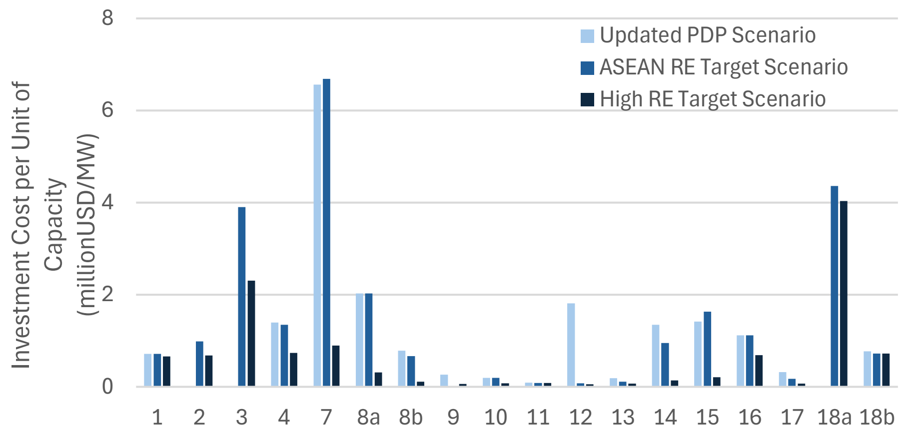


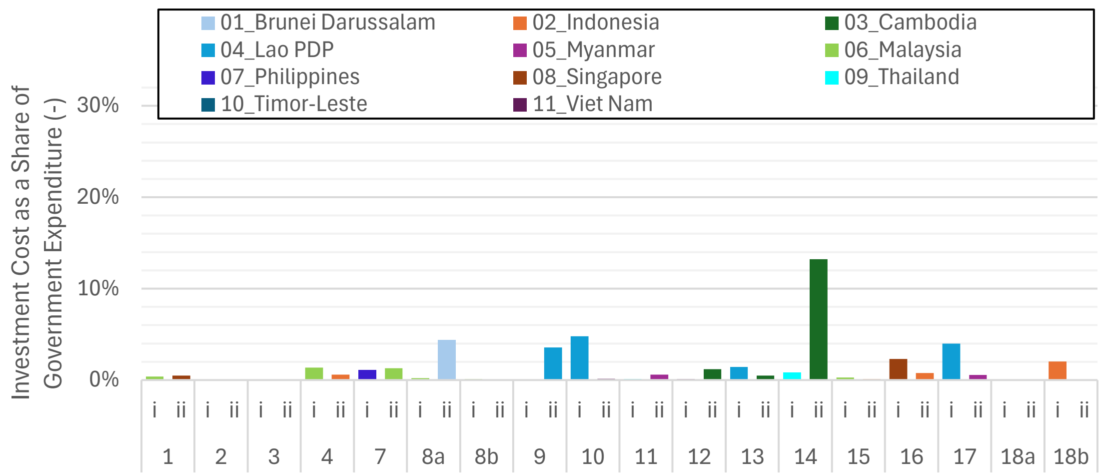
Figure 6-3 Investment Requirements Relative to Government Expenditure

Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

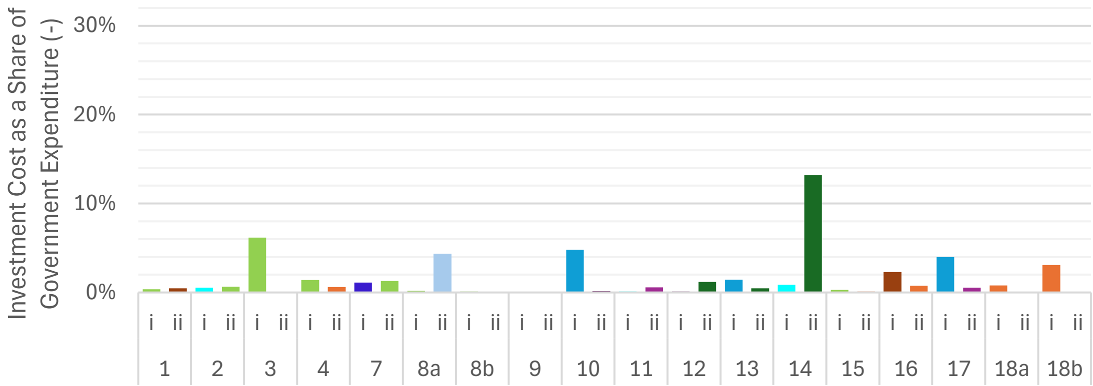
② Assessment of Investment Burden Through Comparison with Government Expenditure

To provide a simple indication of the financial burden associated with publicly financed transmission development, Figure 6-4 compares the investment cost of each project with the annual government expenditure of each of the two countries connected by the interconnection. The results show that even projects with relatively high investment requirements, such as Project No. 18b, may impose a relatively modest burden when measured against government expenditure because the participating countries have comparatively large fiscal capacities. Conversely, some HVAC projects with relatively low absolute construction costs exhibit higher expenditure ratios when the connected countries have smaller fiscal budgets. These findings indicate that the perceived burden of a project, when measured relative to government expenditure, does not necessarily correspond to its absolute investment cost.

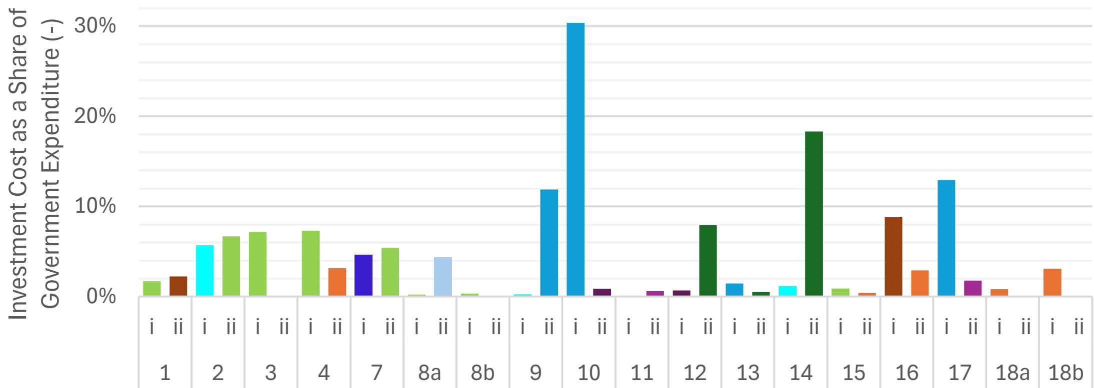
1	Peninsular Malaysia – Singapore	8a	Sarawak – Brunei	12	Vietnam – Cambodia	17	Lao PDR – Myanmar
2	Thailand – Peninsular Malaysia	8b	Sarawak – Sabah	13	Lao PDR – Cambodia	18a	Kalimantan – Java
3	Sarawak – Peninsular Malaysia	9	Thailand – Lao PDR	14	Thailand – Cambodia	18b	Sumatera – Java
4	Peninsular Malaysia – Sumatera	10	Lao PDR – Vietnam	15	East Sabah – North Kalimantan		
7	Philippines – Sabah	11	Thailand – Myanmar	16	Singapore – Sumatera		



(a) Updated PDP Scenario



(b) ASEAN RE Target Scenario



(c) High RE Target Scenario

Figure 6-4 Investment Requirements Relative to Government Expenditure

Note: For illustrative purposes, the investment cost of each project estimated in Figure 6-2 is divided by the government expenditure of the country shown on the left (i) and the country shown on the right (ii). Since future cost-sharing arrangements cannot be determined at this stage, the calculation assumes, hypothetically, that the full investment cost is borne by a single country.
Source: Compiled by The Institute of Energy Economics, Japan (IEEJ)

The analysis also reveals that, in some projects, differences of several percentage points or more were observed between the two participating countries. Such asymmetry in perceived financial burden could complicate negotiations regarding cost-sharing arrangements and project implementation frameworks. Consequently, the successful advancement of the APG may require institutional mechanisms that incorporate support from international financial institutions, third-country financing, and structured cost-sharing arrangements.

While this study focuses primarily on transmission infrastructure investment costs, a comprehensive assessment of the APG must also consider its potential benefits. As discussed in Chapter 3, these benefits include facilitating higher renewable energy integration, sharing balancing resources across countries, reducing reserve requirements, and lowering overall generation costs. Quantifying these benefits and evaluating projects from a cost-benefit perspective will therefore be an important next step.

Moreover, many of the benefits associated with the APG arise not only from individual interconnection projects themselves but also from broader changes in regional power system operation and electricity market dynamics across ASEAN. Accordingly, benefit assessments should incorporate system-wide power sector analyses that account for future generation mixes, electricity demand patterns, renewable energy deployment levels, and grid operation strategies. Developing such analytical frameworks remains an important area for future research.

This chapter has presented both the macro-level investment requirements of the ASEAN

Power Grid and a visualization of the fiscal burden that individual transmission projects may impose on participating countries. The latter perspective may be particularly useful in supporting a bottom-up approach to APG development by providing ASEAN member states with an objective understanding of each other's financial circumstances.

To advance the implementation of individual projects, it will be essential to identify the primary bottleneck associated with each transmission corridor. Depending on the project, the main challenge may be technical (e.g., submarine cable installation), financial (e.g., large upfront capital requirements), or institutional (e.g., differences in bilateral regulations and governance frameworks). Once these constraints have been identified, the technical, financial, and institutional measures discussed in Chapters 4 and 5 should be prioritized and applied according to the specific circumstances of each project.

7. International Interconnection Projects Beyond APG

(1) International Interconnection Projects Outside the ASEAN Region

① Australia–Singapore (SunCable Project)[166]

The SunCable project, which is widely recognized under this name, is an international interconnection initiative that plans to transmit electricity generated by solar power via a 4,300–4,500 km submarine cable from Darwin in northern Australia—an ASEAN non-member country—through Indonesian waters to Singapore (Figure 7-1). The planned transmission capacity is 1.75 GW, which could supply up to 15% of Singapore's electricity demand, given its limited domestic energy resources.

Figure 7-1 SunCable Project

Source: Adapted by The Institute of Energy Economics, Japan (IEEJ), based on G. Heynes (2024)[167].

② China–Greater Mekong Subregion (GMS)

International interconnection projects can also be observed between China and the GMS countries among the ASEAN Member States (AMS) (Figure 7-2).

First, there is the Lao PDR–China (Yunnan Province) route[168]. This project aims to expand electricity trade between the two countries and strengthen cooperation. The line is scheduled to commence operation in 2026, with a bidirectional transmission capacity of 1.5 GW, and is expected to supply 3,000 GWh of clean electricity annually.

Second, there is the Vietnam–China (Yunnan Province) route. Electricity trade cooperation

166 Astri Yoga P.R. (2025), "The ambitious SunCable project hinges on good neighbours and secure seas," https://www.lowyinstitute.org/the-interpreter/ambitious-suncable-project-hinges-good-neighbours-secure-seas (Accessed on March 19, 2026)

167 G. Heynes (2024), "SunCable lands approval for AAPowerLink project set to unlock 20GW of solar in Australia," https://www.pv-tech.org/suncable-lands-approval-for-aapowerlink-project-set-to-unlock-20gw-of-solar-in-australia/ (Accessed on April 3, 2026)

168 PowerTechnology (2025), "Laos-China 500kV power link to be complete by 2026," https://www.power-technology.com/news/laos-china-power-link/?cf-view (Accessed on March 19, 2026)

between Vietnam and China has been in place since 2004[169]. Vietnam Electricity (EVN) plans to increase electricity imports from China to 4,100 MW by 2027–2028 and is also considering purchasing an additional 3,000 MW[170].

Third, regarding the Myanmar–China (Yunnan Province) route, although no new large-scale projects have been confirmed, electricity trading from independent power producers (IPPs) in Myanmar to the grid in Yunnan Province, China, is already taking place[171]. In this way, power connectivity between China and ASEAN—particularly the GMS countries—has become increasingly close. A total of 16 cross-border interconnections at 110 kV or higher have been completed, enabling electricity trade exceeding 75,000 GWh, of which more than 90% consists of green electricity[172].

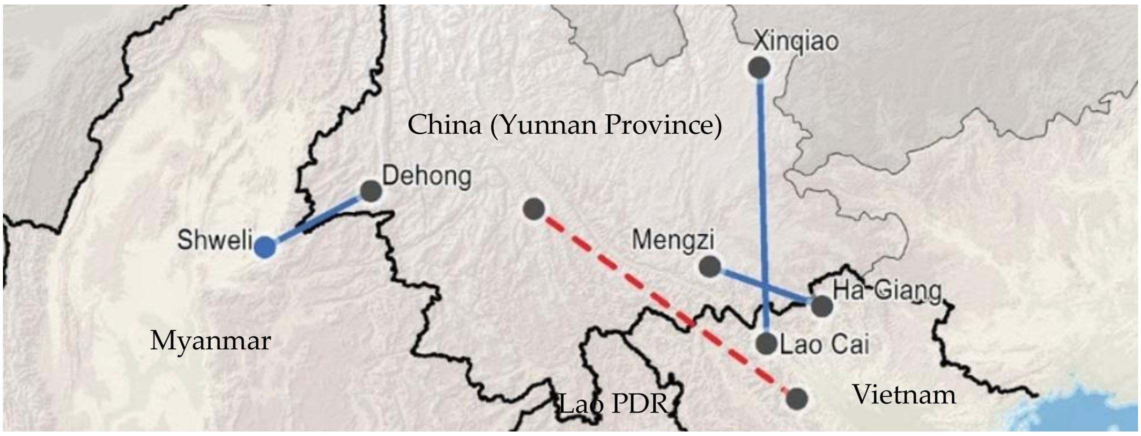


Figure 7-2 China–GMS Cross-Border Interconnection Lines
Note: The existing Laos–China (Yunnan Province) line is relatively small in scale at 115 kV and is therefore not shown on the map.
Source: Adapted by The Institute of Energy Economics, Japan (IEEJ), based on The Stimson Center (2017)[173]

③ Taiwan–Philippines[174]

To meet the electricity demand of energy-intensive industries in Taiwan, including semiconductor manufacturing, there are plans to construct a 250–350 km HVDC submarine cable to transmit power from the Philippines to Taiwan. While this could provide a potential and cost-effective solution to Taiwan's renewable energy needs, high upfront costs, bureaucratic barriers, and grid constraints are hindering onshore wind development on the Philippine side. Additionally, technical complexity, the risk of natural disasters, and geopolitical factors pose further risks to the project.

(2) Independent Interconnection Projects within ASEAN

① Vietnam–Singapore

The Energy Market Authority (EMA) of Singapore has conditionally approved the import of 1.2 GW of low-carbon electricity from Vietnam via a new 1,000 km submarine cable[175]. Subsequently,

[169] Vietnam Energy (2023), "CSG của Trung Quốc và EVN rà soát các hợp đồng mua bán điện (giai đoạn 4)," https://nangluongvietnam.vn/csg-cua-trung-quoc-va-evn-ra-soat-cac-hop-dong-mua-ban-dien-giai-doan-4-30767.html (Accessed on March 19, 2026)
[170] M. Hue (2025), "Vietnam plans to increase electricity imports from China, Laos by 2030, "https://theinvestor.vn/vietnam-plans-to-increase-electricity-imports-from-china-laos-by-2030-d14542.html (Accessed on March 19, 2026)
[171] H. Yu (2025), "Innovation of Technology and Market Mechanism to Promote Power Interconnection in Lancang-Mekong Region," https://www.unescap.org/sites/default/d8files/event-documents/Lancang-Mekong%20interconnection,%20Huang%20Yu,%20China%20Southern%20Power%20Grid.pdf (Accessed on March 19, 2026)
[172] CCTV News (2025), "China and ASEAN Build 16 Cross-Border Power Transmission Lines," https://www.newenergyera.com/news/china-and-asean-build-16-cross-border-power-transmission-lines.html (Accessed on March 19, 2026)
[173] The Stimson Center (2017), "Letter from the Mekong – MEKONG POWER SHIFT: EMERGING TRENDS IN THE GMS POWER SECTOR," https://mekong-cuulong.blogspot.com/2017/07/letter-from-mekong-mekong-power-shift.html (Accessed on April 3, 2026)
[174] B. Linssen (2025), "Cable to the Philippines? Dream vs reality," https://euroview.ecct.com.tw/category-inside.php?id=2265 (Accessed on March 24, 2026)
[175] MalayMail (2025), "Singapore and Vietnam ink deal to expand Asean power grid links,"

the governments of Singapore and Vietnam signed a Letter of Intent (LOI) to consider increasing imports of offshore wind-generated electricity to Singapore to 2 GW by 2035[176,177].

② Cambodia–Singapore[178]

Singapore's EMA has also granted conditional approval for importing electricity from Cambodia—generated from hydropower, solar, and potentially wind—through a submarine cable exceeding 1,000 km in length. A supply of 1 GW could provide electricity to all households in Singapore (approximately 1.4 million households) for one year. There is also potential for future expansion of the project to include renewable energy imports from Laos.

③ Malaysia (Sarawak)–Singapore

The Sarawak–Singapore interconnection project has received conditional approval from Singapore's EMA and aims to export 1 GW of renewable electricity from Sarawak to Singapore, with commercial operation targeted before 2035[179]. The project focuses on hydropower in Sarawak, and construction of the submarine cable is expected to begin by 2026[180].

However, while the above concepts represent international interconnection projects beyond the APG, it should be noted that these projects are not without challenges. They face significant financial risks as well as the potential for delays arising from competing national interests among the countries involved.

(3) Implications of Interconnection Projects Beyond APG for ASEAN's Energy and Economic Security

① Multilayering of Energy Security and Spillover Effects on the Mainstream APG Framework

From the perspective of energy security, international interconnection projects with regions outside ASEAN have the effect of significantly expanding the geographical diversification of supply sources and procurement routes. If ASEAN is viewed as a single block, the APG can be characterized as "inward-oriented grid resilience," enhancing energy self-sufficiency through the maximum utilization of intra-regional renewable energy resources. In contrast, interconnections with Australia and other external regions can be positioned as "outward-oriented grid resilience," as they structurally reduce supply variability risks by linking regions with differing weather patterns and resource distributions.

In particular, the substantial demand and financial mobilization capacity represented by Singapore—such as its plan to import up to 6 GW of low-carbon electricity by 2035[181]—has the potential to significantly strengthen ASEAN's energy supply structure. Historically, this structure has been vulnerable to fluctuations in fossil fuel prices, which have caused abrupt impacts on macroeconomic conditions and national finances. Access to diversified clean energy sources can therefore greatly enhance resilience.

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https://www.malaymail.com/news/singapore/2025/03/26/singapore-and-vietnam-ink-deal-to-expand-asean-power-grid-links/170940 (Accessed on March 25, 2026)

[176] MalayMail (2025), "Singapore and Vietnam ink deal to expand Asean power grid links," https://www.malaymail.com/news/singapore/2025/03/26/singapore-and-vietnam-ink-deal-to-expand-asean-power-grid-links/170940 (Accessed on March 25, 2026)

[177] Vietnam Energy (2025), "Vietnam-Singapore Cross-Border Power Grid Cooperation Towards the ASEAN Region," https://vietnamenergy.vn/vietnam-singapore-cross-border-power-grid-cooperation-towards-the-asean-region-34027.html (Accessed on March 25, 2026)

[178] C. Tan (2023), "Singapore to get 1GW of renewable energy from Cambodia in largest electricity import to date," https://www.straitstimes.com/singapore/singapore-to-get-1gw-of-renewable-energy-from-cambodia-in-largest-electricity-import-to-date (Accessed on March 25, 2026)

[179] Sarawak Energy (2025), "Sarawak-Singapore Interconnection Project Receives Conditional Approval from Energy Market Authority of Singapore to Proceed to Next Phase," https://www.sarawakenergy.com/media-info/media-releases/2025/sarawak-singapore-interconnection-project-receives-conditional-approval-from-energy-market-authority-of-singapore-to-proceed-to-next-phase (Accessed on March 25, 2026)

[180] J. Wong (2025), "Sarawak-Singapore cable work to start in 2026," https://www.thestar.com.my/business/business-news/2025/10/21/sarawak-singapore-cable-work-to-start-in-2026#goog_rewarded (Accessed on March 25, 2026)

[181] Ministry of Trade and Industry (2025), "Low-Carbon Electricity Import," https://www.mti.gov.sg/energy-and-carbon/energy-supply/low-carbon-electricity-import/ (Accessed on March 19, 2026)

Moreover, the spillover effects of these non-APG projects in supporting the realization of the APG itself should not be overlooked. In the process of implementing advanced projects such as HVDC submarine cables extending thousands of kilometers, "technological innovations" (e.g., reductions in long-distance transmission losses and deep-sea cable installation techniques) will accumulate. At the same time, "institutional innovations" will also be fostered, including the conclusion of multi-country PPAs, rules for the transfer of environmental value such as renewable energy certificates (RECs), and financial schemes to mitigate investment risks. The feedback of such technical and institutional know-how from non-APG routes into the APG framework is expected to significantly lower the barriers to multilateral coordination for grid integration across ASEAN as a whole.

② Economic Security Risks and the Importance of a "Hedging Strategy (Equidistant Diplomacy)"

From the standpoint of economic security, there is a need for vigilance and strategic responses to new dependencies on specific countries that may arise from large-scale energy infrastructure projects. Excessive reliance on a particular external country for capital and technology in the development of transmission networks entails the risk of having critical choke points of power infrastructure—often described as the "arteries" and "nervous system" of a nation—controlled by external actors.

In particular, core infrastructure systems become locked into the technological standards or black-boxed equipment of a specific country, which may significantly undermine national autonomy. Risks include cybersecurity threats during emergencies and the possibility of large-scale power outages triggered by intentional disruptions in supply chains.

Therefore, even for projects outside the official APG framework, ASEAN must apply its traditional diplomatic and security approach of a "hedging strategy (equidistant diplomacy)" to the procurement and construction of energy infrastructure. Avoiding excessive dependence on any single country and instead incorporating technologies and capital from multiple technologically advanced nations in a balanced manner is essential. Diversifying the technological portfolio in this way constitutes a necessary condition for truly establishing ASEAN's economic security.

8. Conclusion

This paper has examined the importance of the ASEAN Power Grid (APG) as a core piece of infrastructure supporting sustainable growth in ASEAN, as well as Japan's potential to contribute through a multifaceted approach, in an era where the significance of globalization and climate change mitigation is being questioned and geopolitical risks are rising.

As discussed, the challenges facing ASEAN extend beyond merely addressing climate change. Maximizing the use of unevenly distributed renewable energy across the region through wide-area interconnection represents a rational strategy for reducing excessive dependence on fossil fuels and stabilizing macroeconomic conditions. However, despite many years since its conception, full market integration has yet to be achieved due to a set of complex bottlenecks, including technical barriers related to long-distance transmission and grid stability, investment gaps stemming from state-owned monopolies and high risk premiums, and regulatory fragmentation across countries.

To overcome these accumulated challenges and make the APG a functioning infrastructure, Japan should deploy a distinctive package of support leveraging its strengths. As discussed in Chapter 4, Japanese companies—having overcome grid constraints unique to island nations and harsh natural environments—possess strong global market shares and operational expertise in "flexibility enhancing measures" such as HVDC, submarine cables, large-scale battery storage, and xEMS. Beyond the provision of hardware, a shift toward a "service-oriented" business model (koto-uri)", including maintenance and operational support through education and digital services that enable self-sustaining operations after installation, can reduce total costs while enhancing operational capacity in ASEAN. This represents a uniquely valuable technological contribution from Japan. Going forward, it will be necessary to examine the optimal combination of technologies in the short and medium-to-long term, while taking into account the status of domestic power grids and renewable energy deployment in each country.

At the same time, ensuring the social implementation of these advanced technologies requires innovative financial and institutional approaches, as outlined in Chapter 5. On the financial side, to reduce the risk premiums inherent in ASEAN markets, it is essential to build flexible risk-money supply schemes that leverage blended finance centered on public funds from institutions such as JICA and JBIC. These schemes should incorporate mechanisms such as two-step loans to recipient countries and technology-package leasing to attract private capital. On the institutional side, Japan can utilize frameworks such as AZEC and ERIA to promote the standardization of RECs by applying JCM-type MRV rules, while also sharing Japan's expertise in wide-area grid operation and institutional design—accumulated by OCCTO—through capacity development. This would strongly support the establishment of transparent rules and the development of ASEAN's autonomous regional grid operation capabilities.

Furthermore, Chapter 6 estimates the initial investment required for the entire APG at approximately USD 11.8–49.8 billion, depending on the scenario, and shows that the perceived fiscal burden of individual routes does not necessarily correspond to their absolute costs. Moving forward, in order to advance the concretion of individual transmission routes, it is necessary to identify whether the primary bottleneck in each case is technical, financial, or institutional, and then apply the measures discussed in Chapters 4 and 5 with appropriate prioritization. While this study analyzed the cost aspect in terms of initial investment, it would also be beneficial to estimate the benefit side and conduct a cost-benefit analysis of the APG as a whole or of each individual transmission route.

Moreover, as suggested in Chapter 7, the "grid resilience" sought by ASEAN entails more than simply strengthening physical transmission networks. It involves, on one hand, enhancing "energy security" by increasing resilience to external shocks through optimization of regional resources and diversification of procurement routes, including interconnections with external regions such as Australia; and on the other hand, establishing "economic security" by preventing lock-in to the core technologies of one country's infrastructure. These two dimensions are inseparable and must be pursued together.

Accordingly, the policy path Japan should take is not to position itself as the sole option. Rather, it is to offer an integrated package comprising advanced grid flexibility technologies—designed with transparent open architectures and cybersecurity frameworks that respect data sovereignty as safeguards against overdependence on any single partner—alongside flexible financial support such as blended finance, and rule-making assistance centered on AZEC. Through this approach, Japan can provide ASEAN with transparent and diversified options in terms of technology, financing, and institutional frameworks, thereby effectively responding to ASEAN's preference for maintaining diverse partnerships (a hedging strategy). This constitutes Japan's potential role as "one of the most important partners" that supports both dimensions of security while contributing to ASEAN's autonomous development.

The APG has its roots in the region's recovery from the Asian financial crisis, and current instability in fossil fuel supplies due to crises such as those in the Middle East could likewise serve as a powerful driving force to accelerate the effective use of regional resources. Whereas cross-border infrastructure in the past was often used to expand great-power influence or create debt dependency, the APG—based on ASEAN's endogenous demand—is fundamentally different. This is because its development process, which requires not only physical interconnection but also a high degree of institutional harmonization, functions as a cooperative platform that fosters multilateral dialogue.

Furthermore, by promoting technology transfer through support from Japan and encouraging the participation of local industries in this development process, the economic benefits generated by renewable energy development can be proactively ensured to be distributed equitably—not only to specific companies or urban areas, but across local communities as a whole. This, in turn, contributes to the realization of a "Just Energy Transition." By sharing clean energy and entrusting one another with a stable energy supply, regional solidarity will be strengthened. With Japan's partnership, the APG could become a historic example of sustainable international cooperation in an uncertain era.

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