Integrating Solar and Wind in Southeast Asia

Status and outlook for secure and efficient strategies

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Abstract

Southeast Asia is experiencing one of the fastest electricity demand growths globally, with consumption set to double by 2050. While renewable deployment has accelerated in recent years, the region's growing reliance on imported fossil-fuels for electricity generation, exposes countries to volatile fuel prices, potential supply disruptions and rising emissions. At the same time, the region possesses vast and diverse renewable resource potential.

Variable renewable energy (VRE) - solar and wind - are now among the most cost-competitive generation options and are playing an increasingly important role in the region's power sector. VRE presents an opportunity for the region to meet rising demand, support energy security, affordability and climate goals. However, integrating higher shares of VRE can present technical and regulatory challenges that require changes to system operation and planning.

This report provides a comprehensive assessment of the readiness of Southeast Asia's power sector to integrate higher shares of VRE - identifying opportunities and key considerations. It reviews technical and regulatory measures that are being implemented and applies the IEA's six-phases of VRE integration framework to assess potential challenges within the context of each country's power system.

Drawing on this assessment, the report outlines practical actions for policymakers, regulators, utilities and regional entities from 2025 to beyond 2030, corresponding to different phases of VRE integration and readiness.

Foreword

Southeast Asia's energy demand has surged over the past decade, driven by rapid urbanisation, economic development and population growth. The region stands at a pivotal moment for its energy future. With rapidly rising electricity demand, there is a narrow but vital window to shape a secure, affordable and sustainable energy future.

Today, eight of the ten ASEAN member states have set net zero or carbon neutrality targets. Solar PV and wind, now among the most cost-competitive electricity sources in the region, could be central to this transformation. The region's combined technical potential for utility-scale solar PV and onshore and offshore wind exceeds 20 terawatts – roughly 55 times the current regional generation capacity from all sources. Realising even a fraction of this potential presents an opportunity to diversify energy supply, harness domestic resources, reduce fossil fuel import reliance and curb emissions.

Yet challenges remain. The region's growing dependence on fossil fuel imports exposes countries to price volatility and supply disruption risks. Integrating variable renewable energy (VRE), especially solar and wind, is therefore both urgent and essential. Over the coming decade, renewable energy is expected to meet over one-third of Southeast Asia's electricity demand growth. Achieving this will require investments in system flexibility, grid modernisation, interconnections and well-aligned market and policy frameworks. Southeast Asia has an opportunity to accelerate VRE integration by learning from two decades of global experience. Building on the biennial *Southeast Asia Energy Outlook*, this report outlines regional dynamics and insights to accelerate VRE integration while ensuring secure and efficient power systems.

Recognising Southeast Asia's crucial role in shaping global energy trends, the International Energy Agency (IEA) recently opened the IEA Regional Cooperation Centre based in Singapore. This marks the first IEA office outside its Paris headquarters.

This report was carried out jointly by experts in the IEA Regional Cooperation Centre and Paris headquarters. We thank our regional partners for their insights and hope this work will inform practical action to unlock the region's renewable potential for a secure, affordable and sustainable energy future.

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Acknowledgements, contributors and credits

This study was prepared by the Renewable Integration and Secure Electricity (RISE) Unit in the Directorate of Energy Markets and Security (EMS) in co-operation with the Regional Cooperation Centre in Singapore and other directorates and offices of the International Energy Agency (IEA). The study was led and co-ordinated by Rena Kuwahata, Energy Analyst Power System Transformation, and Peerapat Vithayasrichareon, Senior Energy Analyst – Power and System Integration, under the guidance of Pablo Hevia-Koch, Head of RISE Unit and Sue-Ern Tan, Head of IEA Regional Cooperation Centre - Singapore.

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Other contributions from across the agency were from: Federico Callioni (peak demand analysis), Reine Mceben-Nornormey (affordability), Yinglun Teng (finance) and Hazel Yeo (renewables integration policies).

Hyejeong Lee and Adrian Gao provided essential support.

Elspeth Thomson carried editorial responsibility.

Several colleagues across the IEA provided valuable input to this study, including: Piotr Bojek, Eren Çam, Jack Gregory, Augustin Lorne, Edward McDonald, Brendan Reidenbach, Frederick Ritter, Simon Rolland, Max Schoenfisch, Mamiko Shimizu, Renee Stephens, Vrinda Tiwari, Ari Ugayama, Floris Van Dedem, Mike Waldron and Adam Ward.

Valuable comments and feedback were provided by other senior management and numerous other colleagues within the IEA. In particular, Keisuke Sadamori, Tim Gould, Dennis Hesseling, Cecilia Tam and Brent Wanner.

Thanks go to the IEA's Communications and Digital Office for their help in producing the report and website materials, particularly to Jethro Mullen, and Astrid Dumond, Wonjik Yang, Liv Gaunt and Poeli Bojorquez provided essential support to the production process.

IEA's Office of the Legal Counsel, Office of Management and Administration and Energy Data Centre, provided assistance throughout the preparation of the report. We also thank Einar Einarsson for his assistance on setting up the peer review.

Many senior government officials and international experts provided input and reviewed preliminary drafts of the report. Their comments and suggestions were of great value. They include (in alphabetical order of the institution):

Tharinya Supasa (ASEAN Centre for Energy), Ernst Kuneman, Supawan Saelim, Mentari Pujantoro (Agora Energiewende), John Ward (Commonwealth Scientific and Industrial Research Organisation), Eric Shumway (Delphos International), Mats de Ronde (DNV), Électricité du Laos, Electricity Generating Authority of Thailand, Danita Setyawati (Ember), Chanchai Amornvipas (Energy Regulatory Commission of Thailand), Eckehard Troester (Energynautics), Nuki Agya Utama (Economic Research Institute for ASEAN and East Asia), Sascha Oppowa, Chatchanis Kasemwong, Yunus Boehm, Lars Allerheiligen (German Agency for International Cooperation), Randi Kristensen (Glasgow Financial Alliance for Net Zero), Liming Qiao (Global Wind Energy Council Asia), Shanmugam Thoppalan, Rofidah Binti Mohamed (Grid System Operator Malaysia), Harmeet Bawa, Michael Drtil (Hitachi Energy), Dany Pudjianto (Imperial College), Arjon Valencia (Independent Electricity Market Operator of the Philippines), Fabby Tumiwa (Institute for Essential Services Reform), Yu Nagatomi (Institute of Energy Economics, Japan), Tasuku Nakanishi (Ministry of Economy, Trade and Industry of Japan), Ministry of Electric Power Myanmar, Shirley Sikun (Ministry of Energy, Brunei Darussalam), Homernico Mari B. Palma, Redi Allan B. Remoroza (National Grid Corporation of the Philippines), Karin Wadsack (National Renewable Energy Laboratory), Doug Arent (NREL Foundation), Norhasbi bin Abdul Wahah (TNB), Thu Vu (Transition Zero), Matthew Wittenstein (United Nations Economic and Social Commission for Asia and the Pacific), Dimas Fauzi (United Nations Office for Project Services – Energy Transition Partnership), Shinya Nishimura (World Bank), Grayson Heffner and Zoe Hungerford.

Table of Contents

Executive summary

Southeast Asia stands at a pivotal moment to leverage abundant renewable resources and meet growing demand

Electricity demand in Southeast Asia is rising at one of the fastest rates globally, highlighting the importance for all countries to diversify their energy sources. Driven by rapid urbanisation, population growth, industrialisation and rising living standards, demand growth exceeded 7% in 2024 - nearly double the global average. While the Association of South East Asian Nations (ASEAN) member states are becoming increasingly reliant on imported coal and gas for power generation, the recent global energy crisis underscored the risks that this dependence poses through fuel price volatility and supply disruptions. Meeting electricity demand growth securely, affordably and sustainably requires co-ordinated policy measures and actions from policymakers, regulators and utilities.

Southeast Asia has vast potential to leverage a diverse array of renewable energy resources – including solar, wind, hydropower, geothermal and biomass – offering a significant opportunity to secure its energy future. With 20 terawatts of untapped variable renewable energy (VRE) - solar and wind - technical potential (roughly 55 times the region's current total generation capacity), Southeast Asia is well positioned to meet surging demand whilst reducing dependence on fossil fuels. Solar and wind are now among the most cost-competitive sources of new electricity generation, with solar PV costs falling by 90% since 2010. Harnessing even a fraction of the available renewable resources would enhance energy independence, reduce import costs, and increase sustainability.

The ASEAN Vision 2045 and regional targets place strong emphasis on renewable energy, putting a spotlight on integration measures to ensure its cost-effective and secure deployment. Eight of the ten ASEAN member states have announced carbon neutrality and net zero emissions targets, with many countries already implementing policy measures to scale up renewables, including competitive auctions, direct power purchase agreements and feed-in tariffs. The 2025 renewal of the 5-year ASEAN Plan of Action for Energy Cooperation (APAEC) is expected to reinforce the regional commitment to progress deployment of renewables until 2030.

Near-term VRE integration challenges in Southeast Asia are manageable with proven, low-cost measures

Growing solar PV generation will create new flexibility demands, but most ASEAN member states can integrate higher VRE shares through 2030 by applying proven measures and without major system overhauls. Today, all ASEAN countries except Viet Nam operate in VRE integration phases 1-2 where VRE has minor to moderate impact on the power system. Most countries are expected to remain in these phases until 2030. At these low phases, integration challenges are manageable. Key integration measures include unlocking flexibility of existing conventional power plants, improving forecasting systems, making dispatch decisions closer to real time and at higher granularity, updating grid codes for renewable connections and modernising grid monitoring and control capability. Critically, these measures do not require significant investment or restructuring of power systems or markets. Countries can implement them progressively, adapting to specific challenges as VRE shares increase. By 2035 some ASEAN countries could reach VRE integration phases 3-4, with power systems facing greater flexibility needs due to changes in net load patterns, driven by variable output of solar PV. This is a similar situation that is already managed by many countries in phase 3 today, such as Japan and Australia, through a combination of flexible resources, including thermal and hydropower plants, demand response, interconnection and energy storage.

Southeast Asia has substantial flexibility resources to integrate growing VRE, though these remain underutilised without price signals and digital infrastructure. Today most system flexibility comes from thermal and hydropower plants, with 80% in Indonesia supplied by coal and gas. While these plants could technically operate more flexibly, ramping up and down faster and operating at lower minimum levels, they are constrained by long-term, inflexible power purchase and fuel supply contracts subject to take-or-pay obligations. Demand response can also facilitate VRE integration and benefit consumers through energy bill savings. The potential for demand response is enhanced by more flexible technologies like smart air-conditioners, electric vehicle charging, and battery energy storage, which could be actively supported through targeted policies and incentives. To unlock this potential, price signals should create incentives through arbitrage opportunities and remuneration for providing system services as well as changing consumer behaviour to support grid flexibility.

Modern grids and regional interconnection are essential for secure and affordable integration of renewables

Modernising grids and interconnecting the region’s power systems enables secure electricity supply, facilitates VRE integration and supports power

trade. Grid infrastructure must evolve in sync with growing demand, increased VRE penetration, and expanding regional power trade to maximise these benefits. This transformation requires coordinated action at both national and regional levels to deliver secure, affordable electricity while supporting the region's clean energy ambitions.

Timely reinforcement and modernisation of national grids is critical. Without it, power systems face mounting risks including grid congestion, lengthy connection queues for new projects and costly redispatch of generation. In a scenario where countries globally get on track for their national energy and climate pledges, grid investments would need to double by 2035 to deliver secure electricity to meet rapidly growing demand. Beyond supporting renewables integration, modern grids deliver important co-benefits including energy access for underserved communities, improved power quality and strengthened resilience, all of which aligns with the region's key priorities.

Cross-border interconnection delivers efficiency and security gains at regional scale. Regional initiatives such as the ASEAN Power Grid can bring benefits by leveraging complementary needs and resource endowments, as illustrated by the Lao PDR-Thailand-Malaysia-Singapore Power Interconnection Project. Peak demands rarely occur at the same time across ASEAN countries, creating opportunities for sharing resources and reducing the need for standby generation. Drawing on a larger pool of generation assets across a wider geographic area helps smooth out renewable energy variability and better balance supply and demand. Shared reserves, balancing services and flexibility resources also reduce the investment burden on individual countries by fully optimising assets across the region. Cross-border power trade helps address affordability concerns by allowing countries to access low-cost renewable resources and shared infrastructure. Realising these benefits requires strong regional co-ordination and robust governance frameworks to ensure the costs and benefits are distributed fairly across countries.

Balancing grid infrastructure investment needs with affordability is essential for maintaining public support and political feasibility. Rising grid costs create pressure to raise electricity prices, while many households already spend a significant share of their income on electricity bills. Countries can manage these cost pressures through strategic approaches: optimising existing assets, implementing competitive procurement, diversifying financing sources, and judicious cost allocation between governments and consumers. Additionally, dedicated funding pools for interconnectors and regional priority projects can unlock cross-border infrastructure that benefits multiple jurisdictions.

Decisive action now can deliver resilient, affordable and sustainable power systems

Countries have clear implementation pathways aligned with their readiness levels and 2030 ambitions. Readiness levels are assessed based on the implementation of technical and regulatory measures to support VRE integration. It reflects differences in grid infrastructure, system operation practices and market frameworks. Countries should prioritise different types of actions based on their current readiness level. Strategic sequencing from foundational to transformational actions is crucial to minimise costs and maximise system benefits. Early-stage readiness countries like Cambodia, Lao PDR and Myanmar should focus on foundational actions in the near term by enhancing energy efficiency regulations, establishing grid codes, building basic forecasting capabilities and co-ordinating government-utility planning. Mid-stage readiness countries – including Indonesia, Malaysia and Thailand – can develop flexibility procurement mechanisms, foster investment in a broader range of flexibility resources, enhance grid infrastructure, and reform system planning. High-readiness countries including the Philippines and Singapore can prepare for deeper system transformation, including flexibility deployment roadmaps, advanced grid services, market and regulatory reform, and cross-sector planning.

Delayed or misaligned action risks higher costs and lock-ins, while timely action secures long-term gains. Countries building coal plants today face long-term commitments to assets that may become increasingly uncompetitive over time as renewable energy costs, particularly solar PV and wind, continue to fall. Without proactive grid reinforcement, renewable projects may face connection delays just as deployment accelerates. Implementing appropriate integration measures can reduce system costs, lower the risk of renewable curtailment and enhance system stability. The region benefits from two decades of global VRE integration experience, with proven solutions readily available to avoid the pitfalls seen elsewhere.

Co-ordinated implementation across key dimensions is essential to position the region as a leader. Success depends on co-ordinated progress across technical, regulatory, and market dimensions, with clearly defined roles for stakeholders. Energy ministries provide direction through targets, regulators update frameworks, utilities modernise operations, and regional bodies facilitate cross-border trade. By drawing on global experience while electricity demand rises rapidly, Southeast Asia can avoid common development pitfalls and build power systems that deliver secure, affordable electricity while advancing economic prosperity and climate goals.

Introduction

Southeast Asia stands at a pivotal moment for its energy future. With abundant renewable resources at hand and electricity demand growth second only to India globally, the region must make some momentous decisions in order to shape a secure, affordable and sustainable energy future. The region's combined technical potential for utility-scale solar PV and onshore and offshore wind exceeds 20 terawatts (TW), roughly 55 times the current regional generation capacity from all sources of 361 gigawatts (GW), of which 40 GW is solar PV and wind. Recent cost reductions have also made these technologies among the most competitive sources of new electricity generation.

This report assesses the opportunities and readiness of Southeast Asia's power sector to integrate variable renewable energy (VRE) – solar and wind – at scale and identifies ways to unlock this potential. It also provides actionable steps for policy makers, regulators, utilities and other key stakeholders to support a secure, affordable and sustainable power system.

Variable renewables integration: challenges and solutions

VRE integration requires co-ordinated technical, market and policy changes to electricity systems originally designed around controllable, dispatchable generation. Traditional electricity systems relied on the principle of such generation that could be ramped up or down to match electricity demand in real-time. This approach used a portfolio of baseload, intermediate and load-following peaking plants, each with different economics and operational characteristics. For example, baseload plants such as coal have relatively high capital costs and low operating costs (especially when there is no carbon price) and typically require long construction times.

VRE changes this system design by introducing generation that produces power when solar and wind resources are available, regardless of electricity demand. Solar and wind power plants can be deployed relatively quickly and have close to zero operating costs without fuel costs. However, their weather-dependent output creates challenges for maintaining supply-demand balance that load-following plants previously managed through demand-responsive adjustments.

There are three key VRE integration challenges which will gradually increase over time as VRE penetration expands and plays a larger role in the power system.

First, the variability and uncertainty of solar and wind generation increase flexibility requirements across multiple timescales. Systems where VRE plays a limited role, as in most Southeast Asian countries, are unlikely to experience acute system operation challenges from VRE in the near term.

Second, when countries reach a state at which VRE has a more tangible influence on shaping system operations, they need to consider more enhanced integration measures such as reinforcing grid infrastructure. Utility-scale solar and wind typically have little flexibility in siting choices and often require transmission extension, while smaller assets connecting at lower voltage impact distribution grids. Grid extensions can help connect resource-rich areas to demand centres.

In the early stages of VRE integration, countries can optimise existing infrastructure before considering grid extension. However, given the strong and sustained electricity demand growth in the region, countries will need grid infrastructure upgrades and extensions regardless of VRE development. This creates an opportunity to strengthen grids today to prepare for smooth VRE integration later.

Third, the legacy market and operational frameworks, designed primarily around dispatchable energy resources, neither adequately incentivise flexibility nor provide system services to respond to system needs. Both become increasingly necessary in systems with high shares of VRE.

Structure of this report

- Chapter 1 establishes the regional context and outlook, examining the growing electricity demand, the potential for power mix transformation, the geographic distribution of domestic resources and an assessment of the ASEAN member states' readiness to integrate higher shares of VRE.

- Chapter 2 highlights opportunities and considerations for VRE integration in the region. It identifies opportunities to unlock flexibility from underutilised existing resources as well as emerging new options. It explores how grid modernisation enables power system transformation and regional trade, examines strategic financing to balance affordability with investment recovery and highlights the role of increased regional interconnection like the ASEAN Power Grid.

- Chapter 3 provides a practical roadmap for policy makers, regulators, utilities and regional entities with time-sequenced priority actions for different stakeholders over the near term (2025-28), medium term (2028-30) and long term (post 2030).

Chapter 1. Local Context and Outlook

Southeast Asia is experiencing rapid electricity demand growth and has a major opportunity to transform its power systems. While fossil fuels remain the dominant energy source, renewables – particularly solar PV and wind – are emerging as cost-competitive, sustainable alternatives. The region has abundant renewable energy resources. Harnessing even a portion of this potential could diversify energy supply, reduce fossil fuel imports and lower emissions, while expanding electricity supply across the region and enabling governments to raise living standards and boost economic development.

This chapter establishes the foundation for understanding this opportunity by examining three fundamental elements: rapidly growing electricity demand and the current energy mix; the region's renewable energy potential and evolving policy frameworks; and each ASEAN member state's readiness to integrate higher shares of VRE through regulatory, policy and technical measures.

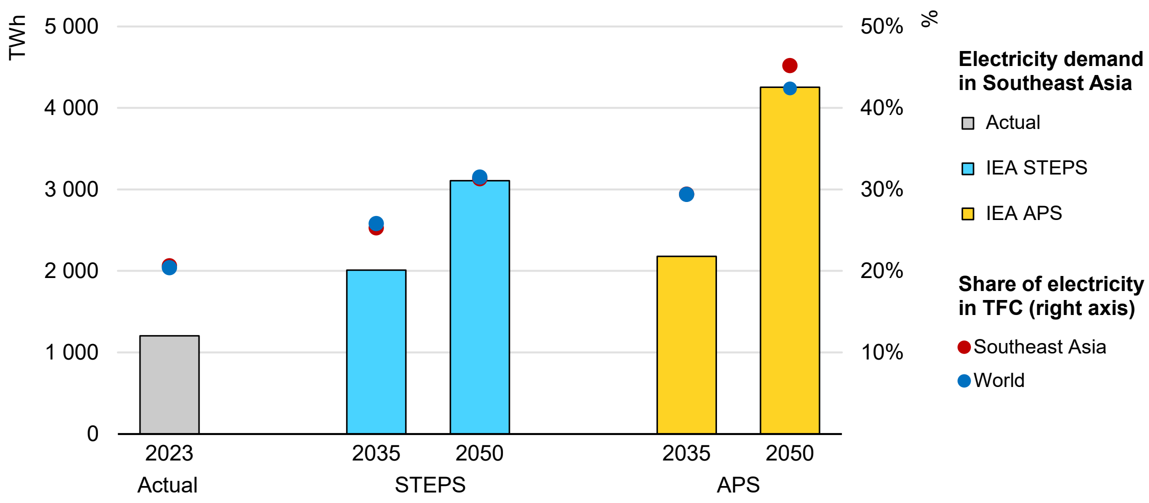
While the ASEAN member states are at varying stages of readiness, most can accommodate higher VRE levels in the near term without major system upgrades. However, meeting the region's ambitious renewable energy goals will require sustained political will, targeted investment in grid infrastructure and better alignment between targets and enabling policies.

Southeast Asia's electricity demand and supply mix

Regional electricity demand is surging

Southeast Asia's electricity demand growth significantly outpaces the global average, with 2024 growth exceeding 7% compared to approximately 4% worldwide. Electricity demand in Southeast Asia has tripled over the past two decades, with this growth heavily concentrated in Indonesia and Viet Nam. This trajectory is expected to continue, with annual regional demand projected to grow at 5% through 2027, compared to about 4% globally. Under current policies, Southeast Asia's electricity demand could double between 2023 and 2050, driven by economic growth, industrialisation, population growth, rising living standards, urbanisation, increasing air conditioning usage and data centre construction. If announced pledges and targets are fully implemented, the region's electricity demand could surge even higher as electrification accelerates across end uses.

Electricity demand in Southeast Asia by scenario and the share of electricity in total final consumption, 2023-2050



Notes: "TFC" = total final consumption. "STEPS" = Stated Policies Scenario, "APS" = Announced Pledges Scenario.
Source: IEA (2024), Southeast Asia Energy Outlook 2024.

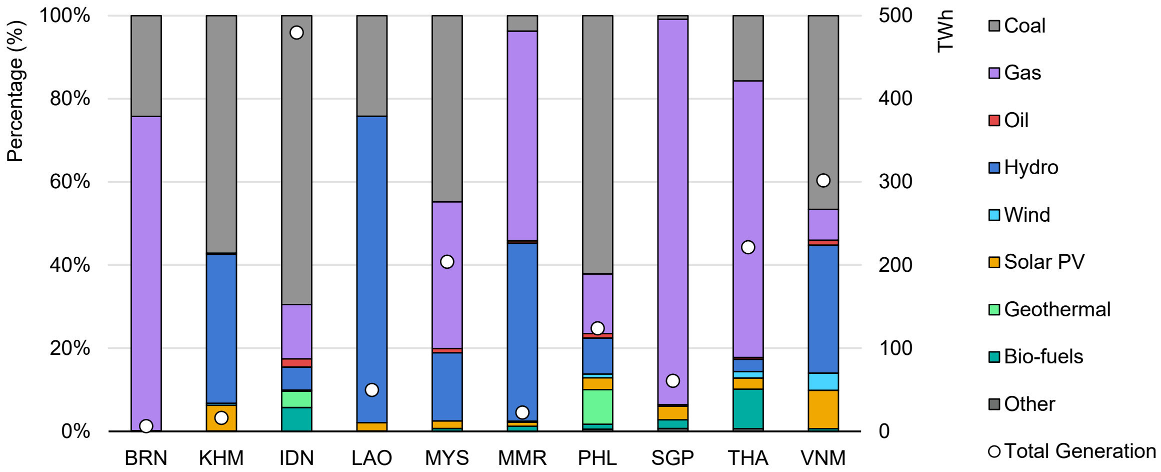
Alongside this surge in electricity demand, renewable generation is also expanding rapidly in the region. Renewables present an opportunity to meet this demand in an affordable and sustainable way. Led by solar PV, renewables are set to enter a period of rapid expansion, supplying over 50% of Southeast Asia's electricity by 2050 under current policy settings and nearly 90% if announced pledges and targets are achieved as in the APS.

Renewables are expanding in the region, but fossil fuels remain the dominant source of supply

Southeast Asia's increasing use of renewable energy – driven by climate commitments, supportive policy frameworks and the falling costs of clean energy technologies – coexists with continued growth in the use of fossil fuels. The average age of coal plants in the region is only 15 years and coal remains the dominant energy source, accounting for 47% of the region's generation mix in 2024. Despite growing renewable energy commitments, some countries, including Indonesia, continue to plan new coal capacity additions in the near term, reflecting the challenge of balancing energy security (and sometimes affordability) with decarbonisation goals. The region's coal consumption rose by almost 8% in 2024, driven by Indonesia, the Philippines and Viet Nam. The region's gas-fired power generation also continues to grow at just below 5% year-on-year.

While coal dominates the power generation mix of Indonesia, the Philippines and Viet Nam, gas is the main source in Thailand, Singapore and Brunei Darussalam. Hydropower accounts for more than 70% in Lao PDR and contributes significantly in Cambodia, Myanmar and Viet Nam.

Power generation mix by fuel in ASEAN member states, 2024



Notes: “Other” includes manufacturing gases, chemical heat, industrial waste, non-renewable municipal waste and any other non-specified. Three-letter country codes: “BRN” = Brunei Darussalam; “KHM” = Cambodia; “IDN” = Indonesia; “LAO” = Lao PDR; “MYS” = Malaysia; “MMR” = Myanmar; “PHL” = Philippines; “SGP” = Singapore; “THA” = Thailand; “VNM” = Viet Nam.

Between 2000 and 2023, the share of renewables in the region’s electricity generation mix nearly tripled, with VRE showing rapid growth in recent years. However, other than in Viet Nam, the share of VRE is still less than 5% of electricity generation in all ASEAN member states. While grid stability and supply reliability considerations become important at higher phases of VRE integration, most ASEAN member states remain in low phases, allowing the focus to remain on scaling deployment rather than managing complex integration challenges (see Chapter 2). Solar and wind have increased rapidly in recent years, however the region’s renewable energy supply remains dominated by modern bioenergy, geothermal energy and hydropower, which account for 96% of total renewable energy supply. Despite this renewable capacity growth, the absolute volume of fossil fuel generation continues to rise due to the pace of demand growth. While renewables are meeting a growing share of new electricity demand, they have not yet begun to displace existing fossil fuel generation at scale.

Renewables offer a secure, affordable and sustainable option for meeting growing electricity demand

The continued fossil fuel dependence creates significant vulnerabilities for the region. Several ASEAN member states, including Malaysia, Singapore, Thailand

and Viet Nam, rely on fossil fuel imports for power generation and the region is set to become a net importer of natural gas. ASEAN's growing reliance on fossil fuel imports exposes the power sector to external risks such as global commodity price volatility, geopolitical tensions affecting supply security and supply disruptions. These risks can translate into rising import bills which can impact affordability, potentially requiring government support to maintain affordable electricity for consumers.

Energy security risks of fossil fuels in 2022

When record-high coal and gas prices drove up generation costs across Southeast Asia in 2022, the region's fossil fuel consumption subsidies soared to a record USD 105 billion – nearly 60% above the previous peak.

Fuel supply shortages in 2022 also impacted the reliability of power systems. Viet Nam, for example, had to grapple with coal shortages, a doubling of coal import bills, as well as difficulty in securing LNG supply contracts. Meanwhile a drop in domestic gas production and difficulty sourcing additional coal exacerbated an electricity supply crunch in the Philippines. Though Indonesia has abundant coal resources, a temporary export ban and other measures were put in place in 2022 to ensure sufficient domestic supply. Coal is also expected to contribute around 80% of power sector emissions in the region.

Despite the energy security risks, reliance on fossil fuel imports continues to grow in the region. In 2024, Viet Nam, for example, saw thermal coal imports increase by 31%, largely driven by an expanding manufacturing sector. The growing vulnerabilities coincide with renewable energy reaching economic competitiveness in many countries, positioning clean technologies as both a climate solution and a strategic response to energy security risks by diversifying energy supply sources.

While some countries in the region, such as Indonesia, have turned to domestic fuels to hedge against import risks, renewables offer a more sustainable path to energy independence. The falling costs and vast untapped potential of renewables, solar in particular, provide an opportunity to diversify energy supply using borderless resources that do not deplete over time. Globally, the levelised costs of electricity from newly-commissioned utility-scale solar PV and onshore wind projects fell by 90% and 70%, respectively, between 2010 and 2023.[1]

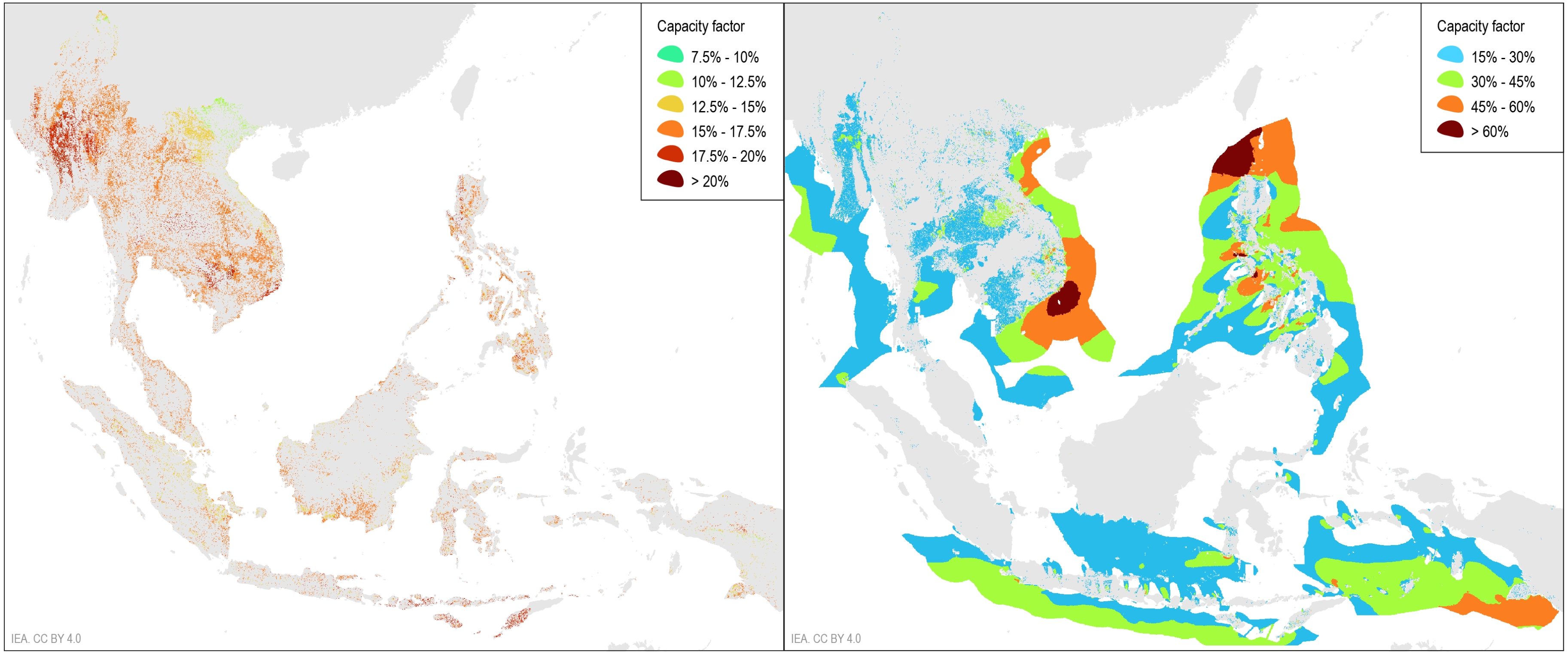
While renewable technology costs in Southeast Asia remain higher than international benchmarks due to smaller markets and higher financing costs, solar and wind are becoming increasingly cost-competitive with new coal and gas across the region (particularly in the absence of fuel price subsidies). In many Southeast Asian countries, solar PV is now among the most affordable options for new power generation and the costs appear to be continuing to fall. The scalability, modularity and declining costs of solar PV technology make it a practical and cost-effective option for both grid-connected and off-grid applications. As markets and manufacturing capacity for solar PV and wind continue to grow in the region, the costs of these technologies are expected to decline closer to global averages. Building domestic supply chains is also important since import dependencies for critical minerals and technologies needed for solar, batteries and other renewables supply chains are heavily dominated by a single supplier – People's Republic of China (hereafter: "China").

There is a rich untapped potential for renewables across the region

Southeast Asia is endowed with diverse renewable energy resources, including solar, wind, hydropower, geothermal and biomass, yet most remains largely untapped. Solar potential is widespread across the region, particularly in countries with pronounced dry seasons like Cambodia, Lao PDR, Myanmar, Thailand and Viet Nam. Wind resources are more location-specific, with excellent offshore potential in the Philippines and Viet Nam and onshore wind potential in Cambodia, Myanmar, Thailand and Viet Nam close to urban centres. Southeast Asia's combined technical potential for utility-scale solar PV, onshore and offshore wind exceeds 20 terawatts. The region also has significant hydropower potential: Lao PDR produces more than 70% of its electricity supply from hydropower and is the largest clean electricity exporter in the region. The country also plans to retrofit many existing hydropower plants into pumped storage hydropower – a key flexibility resource. Harnessing even a fraction of the region's vast renewable energy potential could significantly reduce its reliance on fossil fuels while meeting the growing electricity demand.

[1] Levelised cost of electricity (LCOE) is a widely used metric to compare the costs of different generation technologies, representing the average lifetime cost for providing a unit of output (kWh). However, the LCOE does not capture some important aspects of power generation, particularly for VRE, since it does not consider indirect costs incurred when integrating VRE into the system, such as grid and balancing cost as well as the value that they provide to the power system.

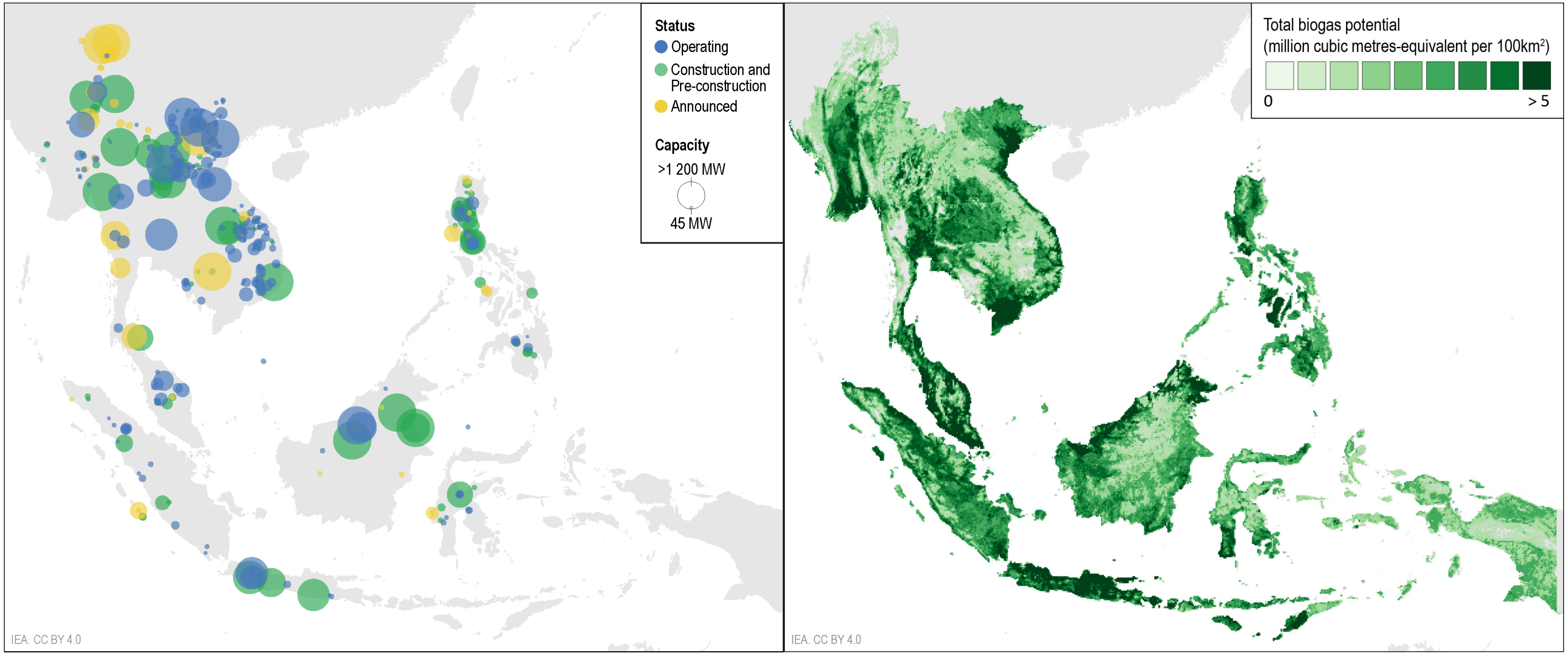
Utility-scale solar PV and wind power capacity factor in the region



Note: These maps show the distribution of wind and solar energy potentials in the region, quantified as the energy yield by the capacity factor, meaning the electricity produced from one unit capacity of solar PV or wind turbine in an average year. Only areas technically suitable for the deployment of renewables and not otherwise used or restricted are included. Offshore wind resources with a capacity factor below 20% are not included.

Source: IEA (2024), Southeast Asia Energy Outlook 2024.

Operating and planned hydro power capacity and biogas potential in the region



Note: "Operating": The project has been formally commissioned and commercial operation has begun, "Construction": Site preparation and equipment installation are underway, "Pre-construction": Projects actively moving forward in seeking governmental approvals, land rights, or financing, "Announced": Proposed projects described in corporate or government plans but not yet taking concrete steps such as applying for permits.

Source: IEA (2025), Outlook for Biogas and Biomethane, and IEA analysis based on data from GEM Wiki.

Evolving policy measures

Unlocking the region's huge renewable energy potential will require sustained political commitment and robust policy and regulatory frameworks to attract investment. Although progress on renewables has been slow, most ASEAN member states have now set ambitious targets and are advancing supportive policy measures. Increasing commitments to reduce reliance on fossil fuels also sends important market signals that could drive greater investment in renewables.

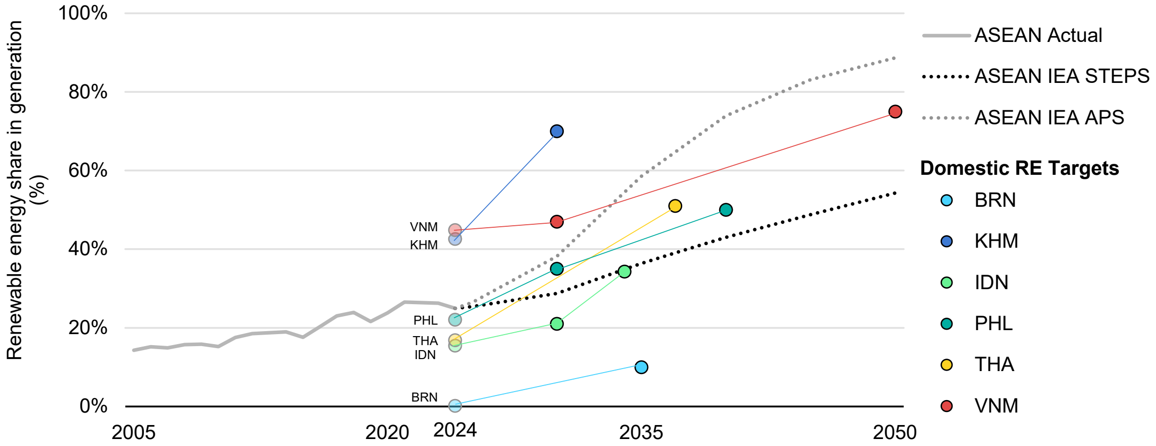
The region has ambitious targets for renewables

Renewable and climate targets provide a high-level policy signal to encourage investment. Eight of the ten ASEAN member states have announced carbon neutrality and/or net zero emissions (NZE) targets.

In Indonesia, the new Rencana Umum Perencanaan Tenaga Listrik (RUPTL) 2025-34 (Electricity Supply Business Plan 2025-34) includes a target to construct 69.5 GW of additional generation capacity by 2034, with 17.1 GW of solar PV and 11.7 GW of wind. Malaysia has set a bold target to reach a 70% share of renewables in the power capacity mix by 2050, up from 17% in 2024. Thailand's draft Power Development Plan 2024 states an ambitious target of at least 50% of electricity generation from renewables by 2037, up from 16% in 2024. Singapore is targeting up to 6 GW of low-emissions electricity imports by 2035. This is driving the development of large-scale renewable projects in neighbouring countries. Viet Nam's revised PDP8 2025, increases its 2030 solar capacity targets sixfold, aiming for renewables (excluding large-scale hydro) to contribute 28-36% of generation by 2030 and 74-75% by 2050.

At the regional level, initiatives like the ASEAN Power Grid (APG) are facilitating cross-border renewable energy trade. The ASEAN Plan of Action on Energy Cooperation (APAEC) 2016-2025 Phase II aims for a 23% share of renewables in the total primary energy supply (TPES) and a 35% share in installed power capacity by the end of 2025. The renewables share in TPES may not be met, but in the AMS Targets Scenario, installed renewables capacity is projected to reach 39% by 2025, exceeding the 35% APAEC target. We also anticipate that the region will announce even higher ambitions in the upcoming APAEC 2026-2030, which takes into consideration the ASEAN Community Vision 2045.

Domestic renewable energy targets in Southeast Asia and IEA scenarios (STEPS/APS), 2005-2050



Sources: IEA analysis based on BRN: Brunei Darussalam's Intended Nationally Determined Contribution (INDC); KHM: Government announcement, the target may account for imported electricity; IDN: National Electricity Business Plan 2025–2034 (RUPTL); PHL: Clean Energy Scenario, Philippine Energy Plan 2023–2050; THA: the draft Power Development Plan (PDP) 2024; VNM: Revised Power Development Plan 8 (PDP8).

Support measures are driving VRE deployment in Southeast Asia

The ASEAN member states are implementing diverse policies to support renewable development. These include regulated pricing instruments such as feed-in tariffs (FiTs) and net metering, as well as market-based approaches like direct or corporate power purchase agreements (PPAs)[2] and competitive auction schemes. These pricing instruments are complemented by fiscal incentives such as tax exemptions and subsidies to attract investment.

Regulatory mechanisms to drive early-stage VRE deployment

FiTs, which offer a premium price over a fixed period to de-risk investment, have played a key role in driving early-stage VRE deployment (initial market development) in Malaysia, the Philippines, Thailand and Viet Nam. In Viet Nam, FiTs were a key instrument in driving the unprecedented growth in solar PV and wind generation capacity, raising their share in the electricity generation mix from less than 1% before 2019 to around 15% in 2022. However, this unprecedented growth also exposed challenges in grid congestion, curtailment, system planning

[2] Direct or corporate PPAs are typically structured in two main types: physical and financial (virtual) PPAs. A physical PPA is the actual delivery of electrical energy from generators (e.g. wind, solar plants) to a corporate buyer through a national grid. A financial (virtual) PPA, does not involve physical delivery of electricity to the buyer. It is a contract for difference. The corporate buyer continues to purchase electricity from the grid but enters a financial arrangement with the generator to hedge price risk and receive Renewable Energy Certificates (RECs).

and policy uncertainty following the expiration of the FiTs which resulted in a bust in the deployment cycle. Viet Nam and several ASEAN member states have updated FiTs while introducing market-based mechanisms.

Alongside FiTs, regulated green electricity tariff programmes have emerged to allow consumers to purchase renewable electricity along with Renewable Energy Certificates (RECs) at a premium. Malaysia introduced a green electricity tariff (GET) in 2022, which is now available for residential and non-residential customers. Thailand launched the utility green tariff (UGT) scheme in 2025 targeting commercial and industrial consumers, allowing large energy users to procure green energy.

Another regulated mechanism which is commonly used in Southeast Asia is net metering and net billing to promote distributed energy resources, particularly rooftop solar, by allowing prosumers to manage their excess generation. Net metering, used in Brunei Darussalam, Malaysia and the Philippines, enables customers to offset electricity bills with excess energy exported to the grid, while net billing compensates electricity exports at a rate below the retail price, as adopted in Thailand.

Market-based mechanisms to accelerate the growth of VRE

Market-based mechanisms can help scale up renewables. These mechanisms, including direct or corporate PPAs and competitive auction schemes, are becoming the primary drivers of renewable investment growth in Southeast Asia.

Direct PPAs (DPPAs) allow businesses to purchase renewable electricity directly from generators, bypassing traditional utility models and are gaining traction in Malaysia, Singapore, Thailand and Viet Nam as alternatives to FiTs. In Singapore, corporate buyers can enter into PPAs, coupled with RECs, with licensed retailers allowing them to contract for renewable power indirectly via the grid. Viet Nam officially launched at DPPA scheme in 2024 to accelerate renewable deployment, which consists of two models: a physical and virtual DPPA. Malaysia introduced the Corporate Green Power Programme (CGPP) in the form of a financial PPA, which enables the corporation to enter virtual PPAs, where TNB (Malaysia's utility company) handles wheeling of electricity and buyers receive RECs for the solar energy produced. Thailand introduced a DPPA pilot of up to 2 GW to attract new foreign direct investment where large consumers (e.g. data centres) can purchase renewable energy through a third-party access framework.

In parallel, several ASEAN member states are moving towards competitive auctions for larger-scale renewable projects. The Philippines has undergone three rounds of Green Energy Auctions (GEA) from 2022 to 2025. Malaysia adopted solar auctions with quotas to award large-scale solar (LSS) projects with long-term PPAs while Viet Nam is developing an auction system to replace FiTs.

These national market mechanisms are being complemented by emerging regional cooperation initiatives, such as cross-border renewable energy trading frameworks and the development of regional REC systems to support broader market integration. The ASEAN member states are now working to adopt harmonised standards for RECs and to align cross-border power trade regulations to facilitate REC trading and help Southeast Asia function more like a unified energy market.

Growing commitments to reduce reliance on fossil fuels

Policies supporting renewable deployment are being accompanied by growing momentum to reduce dependence on fossil-fired generation, particularly coal. Southeast Asia has a large and relatively young fleet of coal-fired power plants. As the average age of its coal plants is only about 15 years, the region faces a unique challenge in balancing economic value from existing plants with a transition away from coal generation to achieve decarbonisation targets. While some ASEAN member states continue to build new coal power plants, measures including coal phase-out targets, the adoption of co-firing technologies and restrictions on new coal plant development are also being considered. Brunei Darussalam, Cambodia and Malaysia have announced that they will no longer pursue the development of greenfield coal-fired power plants. These efforts signal political commitment to a decarbonised power sector and could encourage further private sector investment in renewable deployment.

Indonesia is planning for new coal power plant development until the early 2030s and then a gradual reduction from the mid-2030s. Its roadmap includes accelerating the early retirement of coal power plants – conditional upon factors such as availability of international support and system affordability and reliability – and completely phasing out unabated coal-fired generation to achieve the NZE target by 2060. These phase-out plans primarily target grid-connected capacity, while co-firing with biomass and retrofitting with carbon capture and storage technology are considered as part of managed phase-out strategies under the recent RUKN 2024-60.

The Philippines, despite its moratorium on new coal projects, remains heavily reliant on coal, which accounted for 62% of the generation mix in 2024. To help address this challenge, the country is exploring innovative options such as transition credits where carbon credits could be issued for early coal retirement. Viet Nam has banned any new coal projects not already under construction and plans to retire or repurpose all existing coal plants by 2050.

With ambitious targets, supporting policy frameworks and abundant renewable potential, preparing regional power systems to accommodate much higher shares of renewables can help to accelerate this transformation. See Annex A for more details on current policy ambitions.

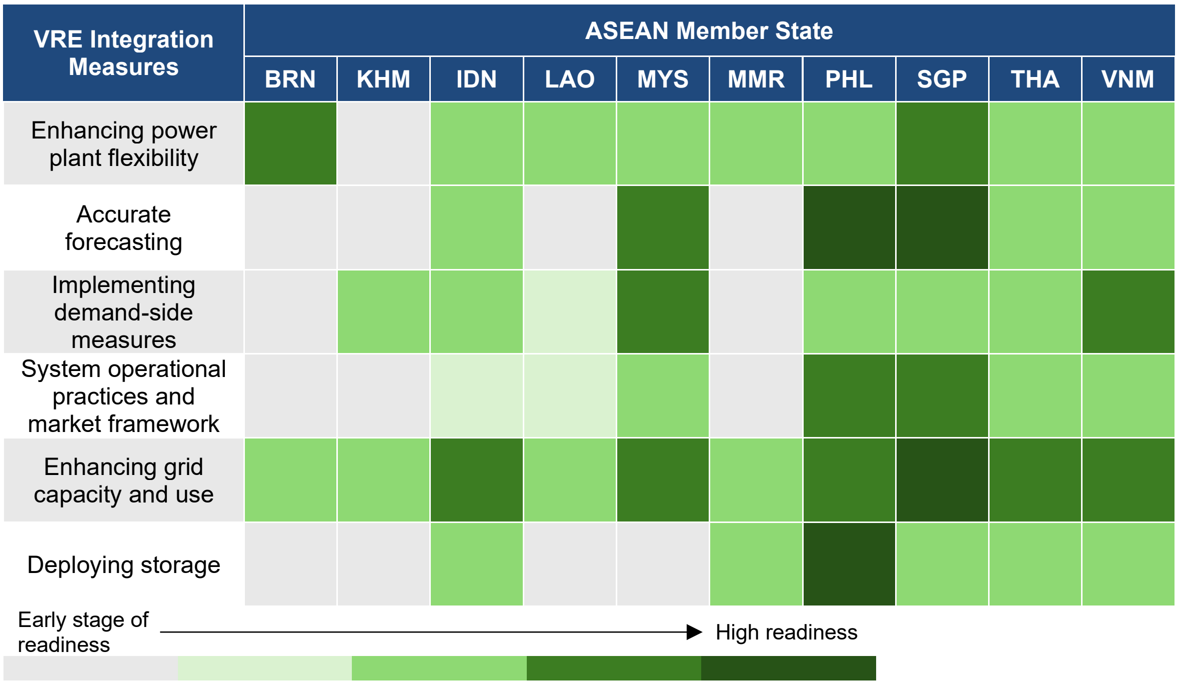
Readiness to manage the power system transformation

The current power system infrastructure and market frameworks in most of the ASEAN member states were designed with limited system flexibility, primarily based on the paradigm of centralised bulk generation with one-way transmission to demand centres where supply adjusts to follow demand.

Today, most Southeast Asian countries' power systems face manageable VRE integration challenges, though this varies by location depending on grid infrastructure, load patterns and existing flexibility resources. While many challenges can be managed by adjusting existing system assets and operational practices, some parts of the region with high VRE concentrations or weak grid infrastructure may already require more comprehensive measures. As the ASEAN member states move towards systems with higher impacts from VRE, more comprehensive integration measures will be needed to ensure the security of supply, efficient market operation and investment signals for flexibility resources.

To assess the ASEAN member states' readiness to integrate higher shares of VRE, we examined the extent to which key VRE integration measures have been implemented in each country. These integration measures include enhanced power plant flexibility, forecasting, demand-side measures, system operation practices and market frameworks, enhanced grid capacity and storage options. Each measure consists of a set of technical and regulatory components – see Annex C. ASEAN countries are at varying stage of readiness. The Philippines and Singapore are considered to have a high level of readiness with advanced forecasting, system operation practices and rules, and market frameworks in place. Indonesia, Malaysia, Thailand, and Viet Nam are at the mid stage of readiness, having implemented several integration measures but requiring further enhancements to manage increasing VRE penetration. The remaining ASEAN member states are at an early stage of readiness, with many integration measures yet to be implemented.

Stage of VRE integration readiness in each ASEAN member state



Notes: VRE integration measures and the approach to reaching the readiness assessment is explained in Annex C. Three-letter country codes: “BRN” = Brunei Darussalam; “KHM” = Cambodia; “IDN” = Indonesia; “LAO” = Lao PDR; “MYS” = Malaysia; “MMR” = Myanmar; “PHL” = Philippines; “SGP” = Singapore; “THA” = Thailand; “VNM” = Viet Nam.

Enhancing power plant flexibility

Thermal generation could transition from serving as baseload power to playing a more flexible, supportive role in the energy system, enabling greater integration of VRE as power systems evolve. Currently, coal and gas-fired power plants are the predominant source of flexibility in Southeast Asia, supported by hydropower plants in providing short and medium-term flexibility. International experience has shown that the flexibility of conventional power plants can be improved through targeted retrofits and adjustments in operational practices. For instance, coal plant retrofits are a central component of China's strategy to increase the flexibility of its electricity system.

Several countries including Indonesia, the Philippines and Thailand have been exploring retrofitting options to lower minimum generation levels, increase ramp rates and shorten start-up times of existing thermal plants. Thailand launched a power plant flexibility pilot project to accommodate the uptake of VRE. However, across several countries, existing contractual structures – including long-term fuel contracts and PPAs - are inflexible, posing significant challenges to improving power plant capability. The role of thermal power plants in providing flexibility is discussed in more detail in Chapter 2.

Forecasting VRE output

ASEAN member states, including Indonesia, Malaysia, Singapore, Thailand and Viet Nam, are at different stages of implementing VRE forecasting systems. High quality forecasts that accurately predict VRE generation are essential for cost-effective and secure system operation. Regularly updated forecasts closer to real time help optimise reserve requirements and the use of system services which improve system stability.

In Peninsular Malaysia, the grid system operator (GSO) currently uses 1-hour solar forecasts to support system operations. As for Indonesia, VRE plants submit daily forecasts at 15-minute intervals that are updated every six hours. In Thailand, the Electricity Generating Authority of Thailand (EGAT) has established the Renewable Energy Forecast Centre, which uses artificial intelligence to forecast generation out approximately 6 hours in advance to support real-time dispatch. In Viet Nam, the National Power System & Market Operator has developed centralised day-ahead and intraday VRE forecasting systems with ongoing efforts to reduce forecast errors. Singapore uses real-time high-resolution solar forecasting up to one hour ahead. Similarly, the Philippines incorporates day-ahead VRE forecasts in market projections for each of the dispatch intervals (5 min) and updates these once every dispatch interval. VRE plants submit daily forecasts at 15-minute intervals that are updated every six hours.

Demand-side measures

Demand response programmes across Southeast Asia demonstrate varying capabilities to suppress peak demand and smooth consumption patterns, regardless of VRE penetration levels. As the share of VRE increases, so too does the value of demand-side measures for the flexibility that they offer. They can help to smooth consumption curves through mechanisms such as load shifting or load shedding and they can limit the impact of peak demand on generation and grid congestion.

Demand response programmes are being actively explored in Singapore, Viet Nam and to some extent in Thailand. Most of Southeast Asia has more limited programmes such as those in the Philippines, mainly targeting large consumers in the case of power shortages. Several countries in the region (where systems allow) have time-of-use pricing which encourages consumers to shift demand based on market signals.

Electric vehicles (EVs) show promise for consumption smoothing through smart charging, while their potential contribution to grid stability through vehicle-to-grid (V2G) connections remains much more challenging to realise. V2G deployment faces significant hurdles, requiring comprehensive policy, regulatory and market frameworks that are not yet established in the region, alongside substantial infrastructure development including specialised connection points, monitoring and control systems and sophisticated optimisation platforms with advanced algorithms and communication networks. Although pilot projects are underway in the Philippines, Singapore and Thailand, more immediate benefits are likely to emerge from co-ordinated EV charging strategies that help reduce peak demand - an approach that can be implemented more readily using existing grid infrastructure.

System operation practices and market framework

The range of power sector institutional structures across Southeast Asia produces varying dispatch practices. Key market framework and system operational practices to integrate VRE include least-cost dispatch, faster scheduling, short dispatch intervals and the procurement of system services, either through market mechanisms or regulatory frameworks, depending on the structure of the electricity market.

Power sector structures in Southeast Asia range from vertically integrated utilities to liberalised markets, creating different implications for power system operation. Most ASEAN member states apply least-cost/merit order dispatch principles. However, the implementation and transparency vary depending on market structure and are subject to technical and contractual constraints. Some countries including Thailand, Indonesia and Viet Nam face contractual obligations from both PPA and fuel off-take contracts resulting in over-supply situations that can lead to uneconomic VRE curtailment.

The Philippines and Singapore have competitive market-based bidding systems with 5-minute and 30-minute dispatch intervals, respectively, and gate closure close to real time. Both countries have mechanisms to procure ancillary services.[3] For example, the Philippines launched the ancillary service market in 2024 in addition to the contracted capacity via the Ancillary Service Procurement Agreement (ASPA).

The market structure, procurement of system services, dispatch interval and gate closure of countries are provided in Annex A.

Mechanisms to enhance grid capacity

The ASEAN member states are deploying diverse grid enhancement technologies and planning mechanisms to enhance grid capacity and stability. The Philippines introduced Competitive Renewable Energy Zones (CREZ) in 2020 to steer

[3] The National Grid Corporation of the Philippines (NGCP) procures five ancillary service products via competitive contracts based on the reserve requirements (three for frequency control, one for voltage control and one for system restoration). In Singapore, ancillary services are procured through co-optimised markets and long-term contracts.

renewable investment in areas with high resource potential, aligning transmission expansion with these zones. However, implementation faces challenges including securing regulatory approval for transmission projects and completing transmission backbone infrastructure ahead of aggressive VRE grid connection targets. VRE proposals in areas outside the CREZ also require grid expansions, highlighting the need for prioritised planning to better align transmission and generation development. Thailand has deployed grid support devices such as static var compensators, shunt capacity and special protection schemes to strengthen grid capacity. Malaysia, Thailand and Viet Nam are also exploring dynamic line rating[4] to maximise the use of existing grids through accurate assessment of real-time capacity, with Malaysia particularly focusing on rapid growth areas. Some countries in the region, such as Indonesia, are rolling out smart grids to enhance future grid capacity.

Deploying storage options

Pumped storage hydro (PSH) currently dominates the storage landscape in Southeast Asia, though battery energy storage systems (BESS) are rapidly emerging as costs decline. Storage technologies can help store excess VRE generation and limit the need for backup generation. Thailand and the Philippines are already operating PSH and actively pursuing expansion, while Indonesia and Viet Nam are constructing their first PSH projects. Cambodia, Lao PDR, Malaysia and Thailand are in the early stages of PSH development. In 2025, a new USD 1 billion PSH project was announced in Cambodia which could reach a maximum generating capacity of 1 GW.

BESS are quickly maturing in the region and will be an important driver of flexibility as systems enter higher phases of VRE integration. Notable large-scale projects are emerging for example in Malaysia, the Philippines, Singapore and Thailand.

[4] Dynamic line rating calculates the capacity of transmission lines closer to real time by taking into account actual operating and ambient conditions instead of assuming a fixed capacity.

Chapter 2. Opportunities and Considerations

Southeast Asia can accelerate renewable energy adoption by applying proven international approaches and unlocking existing system flexibility. By drawing on decades of international experience and tailoring solutions to local contexts, countries can integrate VRE more efficiently and affordably. This chapter focuses on three key areas: learning from global experience with VRE integration, unlocking underutilised system flexibility, and modernising grid infrastructure. It sets the foundation for the practical implementation framework in Chapter 3, offering guidance on sequencing actions and aligning policy, technical, and investment priorities for effective VRE integration.

Outside of Viet Nam, most Southeast Asian countries generate less than 5% of their electricity from VRE and face challenges typical of low integration phases. These countries can therefore draw on proven international solutions whilst focusing on deployment in parallel, avoiding costly trial-and-error approaches that constrained earlier adopters. The chapter references the IEA's six-phase VRE integration framework, where phases 1-3 represent low integration levels and phases 4-6 represent high integration levels.

Solar PV deployment will create substantial flexibility needs over the next decade. However, significant untapped flexibility exists within current systems that can be mobilised before major investments in new infrastructure such as battery storage become necessary. This untapped system flexibility offers a cost-effective pathway for managing increased renewable penetration.

Large investments in grid infrastructure will be needed to support electricity demand growth, supply diversification and regional interconnection. These investments deliver long-term socioeconomic benefits, but financing approaches need careful consideration to prevent undue consumer burden.

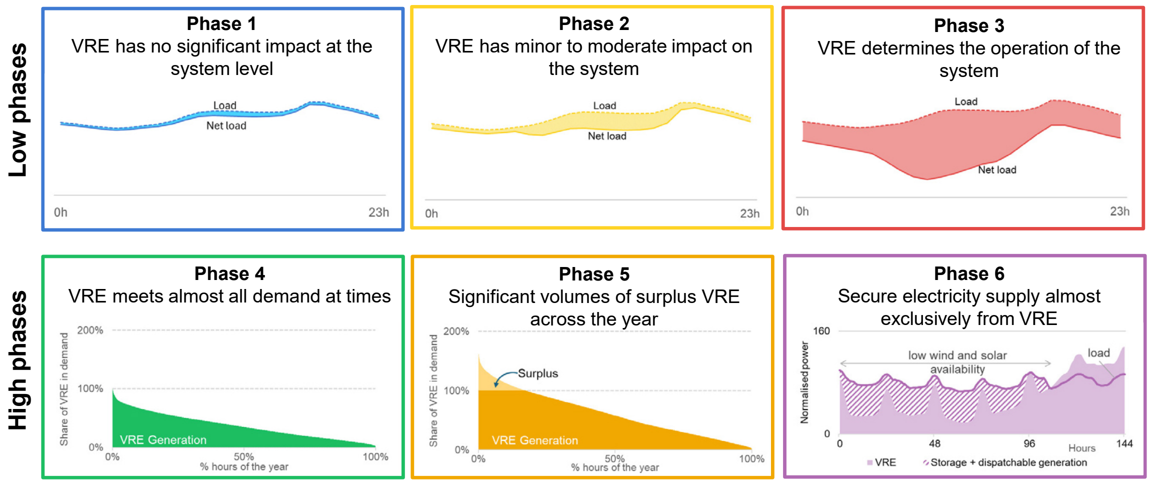
Learning from global experience

Most Southeast Asian countries operate in low phases of VRE integration

Based on the IEA's six-phases of VRE integration framework, most of the ASEAN member states currently operate in low phases of VRE integration, between phases 1 to 3. The framework illustrates the increasing impact of solar PV and wind on power systems, noting that radical changes to manage greater variability are generally not required until phase 3.

Phases 4 to 6 are considered high phases of VRE integration. These reflect growing VRE influence on system operations and require fundamental transformations in power system planning and operation. Globally, only a few countries and sub-systems such as Denmark and South Australia are classified in phase 5. Countries address these challenges by encouraging flexible operation of existing generation, building strong regional interconnections and investing in new devices across energy sectors. These measures help maintain system stability and manage renewable generation surpluses and deficits. Phase 6 remains largely theoretical and should not be regarded as the target to aim for to decarbonise power systems. It is rather a niche phase for smaller systems (such as some island systems) with extremely high or near complete reliance on VRE.

IEA's Phases of VRE integration framework



Notes: A description of the challenges experienced at each phase is given at https://www.iea.org/reports/integrating-solar-and-wind/infographic-six-phases-of-variable-renewables-integration
Source: IEA (2025) Carbon-Free Electricity in G20 Countries

The framework has limitations for power systems with multiple sub-national grids. It analyses supply-demand profiles at the national level, but many Southeast Asian power systems consist of multiple sub-national grids with varying interconnection levels. Archipelagic nations such as the Philippines and Indonesia often have isolated island systems or limited transmission capacity between islands. Areas with weak grid infrastructure, particularly rural and remote regions, also face similar constraints. Both types of systems may experience localised challenges when solar PV uptake increases rapidly, including voltage control and low system inertia that require immediate technical solutions. Whilst addressing these grid issues remains essential for maintaining reliable electricity supply, the solutions typically involve targeted technical interventions rather than comprehensive national policy or regulatory reforms. This report therefore focuses on system-level integration measures that support broader VRE deployment. Readers seeking archipelagic-specific solutions such as inter-island high-voltage direct current (HVDC) and microgrid strategies may consult additional IEA technical resources.

Countries progress through phases at different rates until 2035

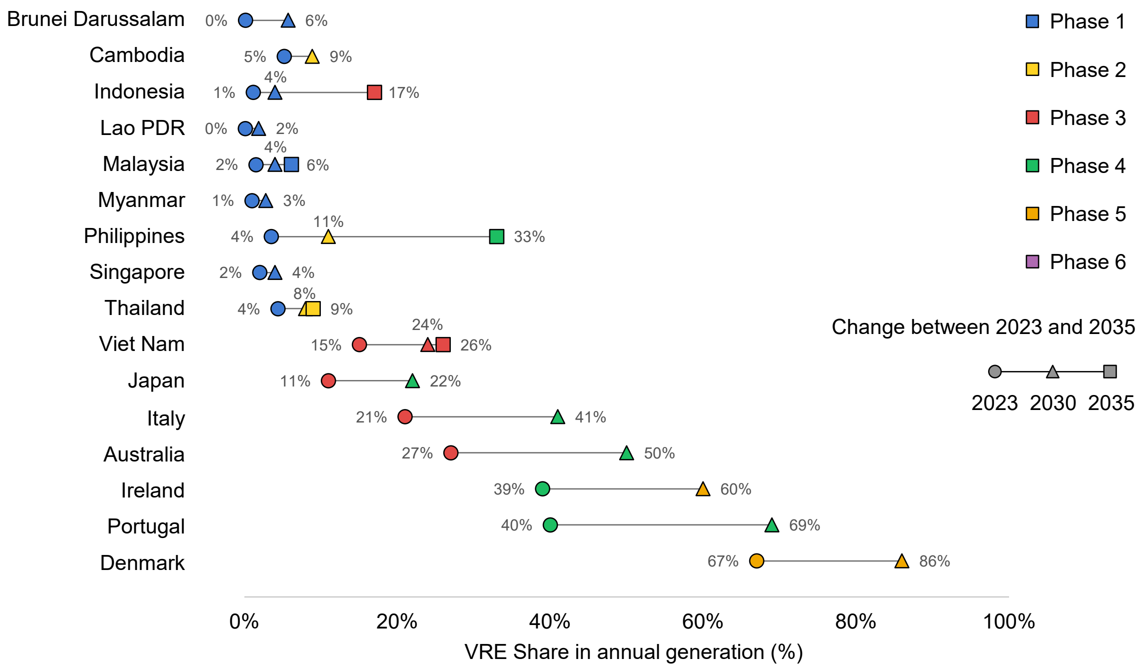
Today, all ASEAN member states stand in low phases of VRE integration. Nine out of ten currently operate in phase 1, where VRE integration has no significant impact at the system level. By 2030 most countries will stay in phase 2, where challenges at the system level are well understood and easily manageable. These require measures such as faster and more frequent ramping of generators.

Countries are progressing through this framework at different rates. Viet Nam already operates in phase 3 today. This means that greater swings in the supply-demand balance prompt the need for a systematic increase in flexible operation that often goes beyond what can be readily supplied by existing assets and operational practice. This includes significant enhancement of transmission capacity for Viet Nam, particularly to address persistent structural grid congestion along the north-to-south corridor. Indonesia could also reach this phase from 2035, based on the new Rencana Umum Perencanaan Tenaga Listrik (RUPTL) 2025-34 (Electricity Supply Business Plan 2025-34).

Only the Philippines is classified in one of the higher phases (phase 4) by 2035. According to current plans, the Philippines aims to expand its VRE generation, achieving more than 30% VRE penetration in 10 years. At that horizon, the power system may experience steep net load ramps and high instantaneous VRE penetration, reduced system inertia and lower short-circuit current levels, particularly during high solar generation output. These are all characteristics typical of a system entering phase 4.

Future considerations include frequency and voltage stability concerns. These are primarily relevant for systems with very high VRE penetration, which is not expected until beyond 2035 in Southeast Asia. These may eventually emerge if grids become weaker as conventional generation is displaced by renewable resources. Preparing for these future requirements involves ensuring that existing conventional plants continue to deliver essential grid support services for frequency response and voltage control, whether through explicit contracts or regulatory requirements. This also requires transitioning inverter-based resources from grid-following to grid-forming capabilities to provide active voltage and frequency support. Strategic grid strengthening and deployment of advanced grid-forming technologies can ensure continued system stability as power systems evolve.

Phase assessment of VRE integration in SEA countries, with comparison to higher-phase systems (2023, 2030 and 2035)



Notes: The phase assessments for 2030 are based on VRE forecasts (main case) from the IEA Renewables 2024 report. The phase assessments for 2035 are based on each country's national power development plans and publicly available data at the time of the writing of this report. These assessments are not based solely on VRE share in annual generation (see Annex B). For Indonesia, the future VRE shares are calculated based on the on-grid Java-Bali-Sumatra system (captive plants are not included) and is based on RUPTL numbers.

Proven low-phase integration measures can be deployed while preparing for future challenges

Southeast Asian countries can strategically select measures that have already demonstrated success in similar contexts. Unlike early adopters who pioneered integration solutions through costly trial and error, the region can adapt proven approaches. The IEA's 2024 report, "Integrating Solar and Wind: Global Experience and Emerging Challenges" catalogues a suite of commonly adopted and effective measures that countries worldwide have successfully used to integrate similar levels of VRE and provides comprehensive analysis of these approaches and their application across different system types.

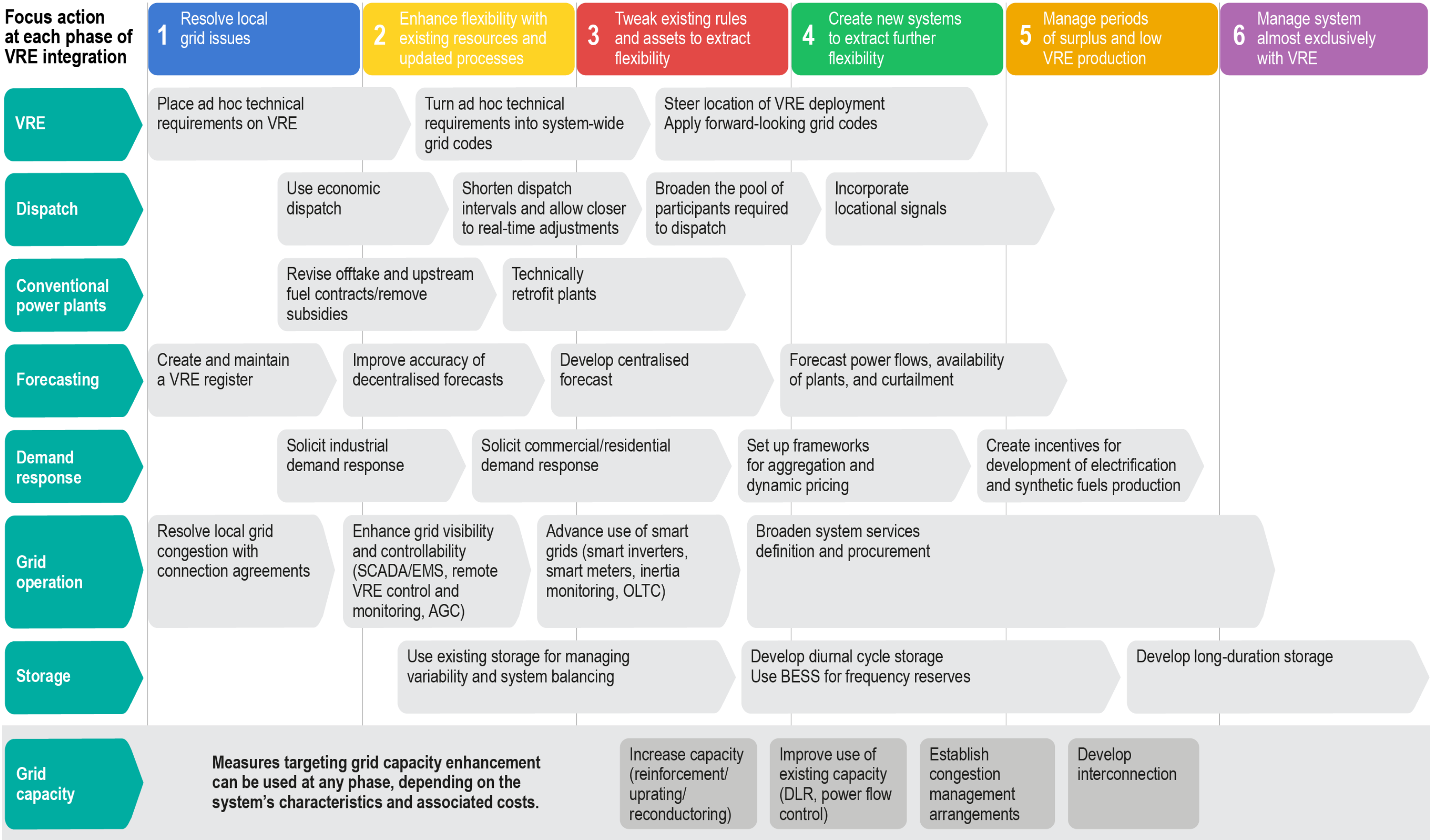
The economic implications of choosing the right integration sequence are substantial. Early VRE adopters often invested in expensive infrastructure solutions before discovering more cost-effective operational approaches. Southeast Asia can reverse this sequence by implementing low-cost operational measures first whilst strategically planning infrastructure investments.

Countries can apply proven solutions based on their system characteristics. Those with significant thermal generation can apply operational flexibility measures that countries like Denmark and China have successfully implemented. Hydro-rich nations can leverage balancing strategies developed by Brazil. Nations with growing industrial sectors can implement demand response programmes proven effective in Australia and the Netherlands. Those with advanced grid infrastructure can implement system operation improvements that have worked in Germany and Japan. Countries like India demonstrate this approach, retrofitting existing thermal plants and improving forecasting systems to accommodate renewables before building new storage infrastructure.

More critically, this global experience shows that low-phase VRE integration relies primarily on unlocking flexibility within existing power systems before building new infrastructure. Southeast Asia possesses significant untapped flexibility from underutilised thermal plant operational flexibility (including ramping capabilities, start-up times and minimum generation levels) and demand response potential across its rapidly industrialising economies.

This represents Southeast Asia's fundamental strategic opportunity in applying recent decades of global learning to its unique regional context, achieving affordable and reliable VRE integration at unprecedented speed.

VRE integration measures from recent decades of global experience organised by phase



Notes: The proposed set of focus actions by phase represents a timeline of priorities, though specific system contexts may require adjustments to address their particular challenges. AGC = automatic generation control; DLR = dynamic line rating; EMS = energy management systems; OLTC = on-load tap changers; SCADA = supervisory control and data acquisition; VRE = variable renewable energy.

Unlocking flexibility resources to meet system needs

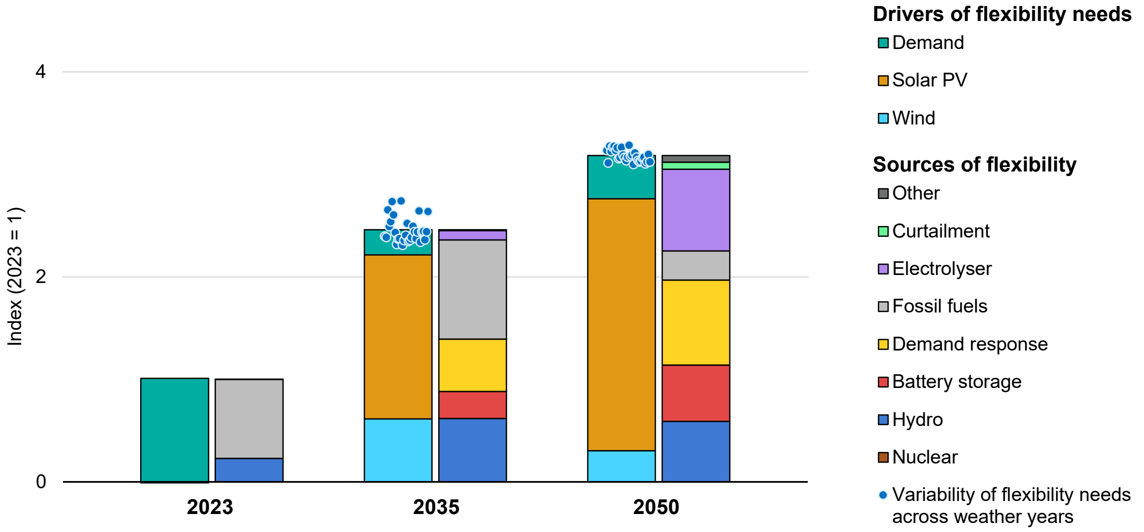
Steadily expanding power production from solar PV will drive hourly and daily flexibility needs in the region by 2030

Solar PV expansion will increasingly create flexibility challenges across Southeast Asia in the coming years. With abundant solar potential across the region, Southeast Asia has made initial progress in solar PV adoption, with over 35 GW installed at the end of 2024. Viet Nam has emerged as the regional leader in solar PV, representing 61% of the total regional capacity, followed by Thailand (11%) and the Philippines (10%). By 2030, this regional capacity is set to more than double to reach 81 GW. Viet Nam's solar production already represents around 10% of its generation mix, a level comparable to leading solar markets such as Japan and Italy, which are in phase 3 of VRE integration. Between 2024 and 2030, supported by the policy measures previously outlined, close to 20 GW of distributed solar PV and 30 GW of utility-scale solar PV projects are set to be added in the ASEAN region in the IEA Renewables main case.

Solar PV introduces characteristic ramping challenges as production peaks during midday and decreases at sunset. While today, short-term (sub-hourly, hourly, daily) flexibility needs are mainly driven by changing consumption of electricity throughout the day, solar PV will become the primary driver across the region. By contrast, wind power development will be more limited and concentrated in specific areas. Wind does not bring the same challenges as solar PV because its output is typically less correlated across time and location, and its generation profile does not create the same steep ramps.

Existing dispatchable plants can meet near-term ramping needs through 2030 with only minimal operational adjustments, such as faster upward and downward response. However, beyond 2030, ramping requirements associated with solar PV will become more pronounced, requiring additional solutions. These include greater use of demand-side flexibility to shift consumption and expand capacity to store surplus electricity for use when solar output declines.

Short-term flexibility needs and supply by technology in Indonesia in the Announced Pledge Scenario, 2023-2050

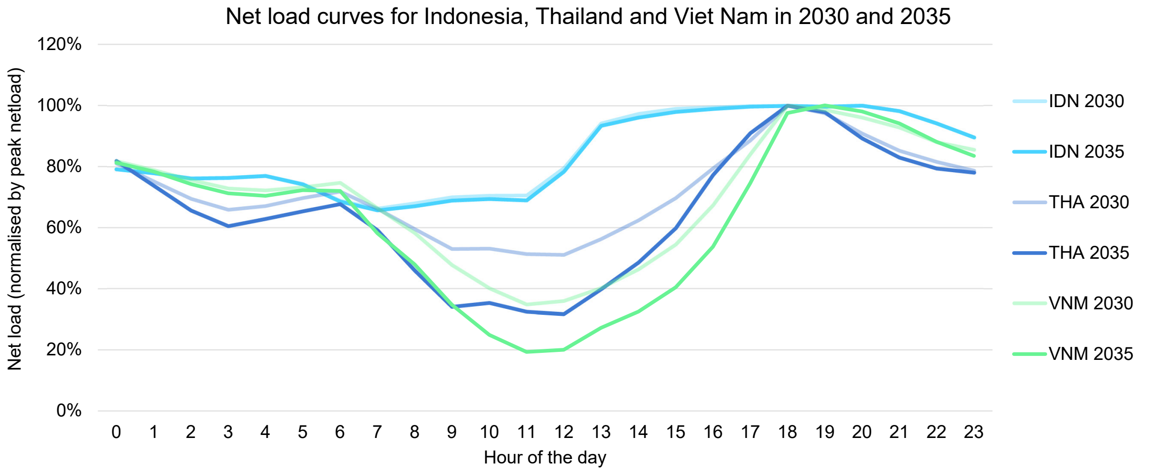


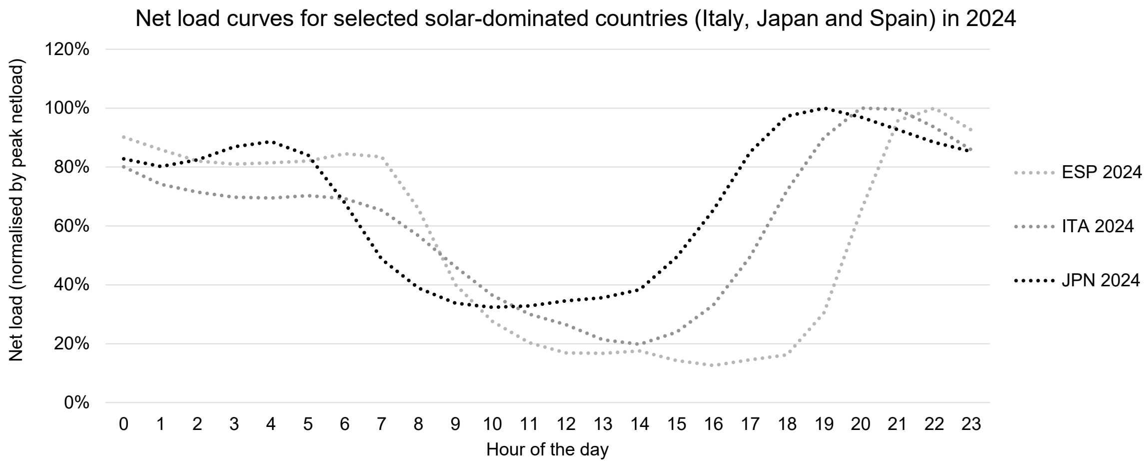
Source: IEA (2024), Southeast Asia Energy Outlook 2024.

Solar PV creates duck curves and ramping challenges

With its characteristic production pattern, solar PV introduces steep ramping requirements when production peaks in the afternoon and decreases at sunset, while demand often peaks in the evening. This creates greater challenges for maintaining the balance between supply and demand, as the net load - the electricity demand that remains after subtracting variable renewable production - becomes much more variable. In systems with already high shares of solar PV, this results in the well-known "duck curve", characterised by steep ramp rates as the sun rises and sets, and a low net load during midday when solar output is highest. Steep ramping requirements and large gaps between net daily minimum and peak demand present challenges that California, Italy and Japan have successfully addressed through different strategies, including enhanced thermal plant flexibility, use of storage and operational improvements.

Net load curves for SEA countries in 2030 and 2035 and selected solar-dominated systems, 2024





Notes: Net load curves on the day with the highest 3-hour ramp-up change in the year. Values are normalised based on the system's hourly peak net load on that day. Curves for Indonesia represent the Java-Bali system for 2030 and Java-Bali-Sumatra system for 2035. Three-letter country codes: "ESP" = Spain; "ITA" = Italy; "JPN" = Japan.

Challenges will be comparable to those currently managed by advanced markets

Our detailed analysis examines Viet Nam, Thailand and Indonesia as representative of the region's diverse solar integration pathways. It compares the solar PV-related challenges of these three countries by 2030 and 2035 with those of some current leading solar PV systems.

Viet Nam, reaching around 10% solar generation share by 2030, will face similar integration requirements to Japan and Italy today, with these countries experiencing minimum net load levels between 10-17% of peak demand. Thailand with a 6% solar share by 2030 will have more moderate challenges, while Indonesia with a 3% share will face less severe variations. Overall, by 2035, the scale of flexibility challenges in Viet Nam and Thailand will be comparable to those currently managed by advanced solar markets.

Ramp rate challenges will vary significantly across the region but remain manageable. The ramp rate challenges, measuring how quickly the system must adjust as the net load curve changes, will vary across the region. Viet Nam is projected to experience maximum three-hour ramp rates of 31% of peak load by 2030, comparable to Italy's 36% today. Thailand and the projected Java-Bali-Sumatera system in Indonesia will experience more moderate ramp requirements at 17% and 25%, respectively.

These comparisons demonstrate that Southeast Asia's projected solar integration challenges beyond 2030 fall well within the range of what advanced markets are currently managing successfully.

Comparison of selected characteristics for SEA countries (2030) with current leading solar PV systems (2024)

Country	Annual PV generation share (%)	Utility-scale systems (%)	Distributed systems (%)	Maximum 3h ramp rate /Peak load (%)	Minimum net load /Peak load (%)
Indonesia 2030	3%	67%	33%	25%	62%
Thailand 2030	6%	65%	35%	17%	25%
Viet Nam 2030	10%	45%	55%	31%	17%
Italy 2024	13%	23%	77%	36%	10%
Japan 2024	10%	43%	57%	30%	13%
Spain 2024	18%	73%	27%	53%	-1%

Notes: Distributed systems refer to solar PV assets with a capacity below 1 MW, while utility-scale systems have a capacity higher than 1MW. Maximum 3-hour ramp rates are calculated as the maximum 3-hourly ramp observed in the year (MW) and are normalised by the yearly peak load (MW). Minimum net load refers to the annual minimum net load and peak load refers to the annual peak load.

Distributed solar adds operational complexity

Distributed solar installations, located behind-the-meter, create additional operational challenges for grid operators. These assets offer no or limited visibility to the system operator in the absence of smart meters, advanced inverters, or aggregators. This makes it more difficult to forecast and results in reduced observed demand during midday hours for the system operator. Moreover, high penetration of distributed solar can create stress on local distribution grids, such as reverse power flows causing overvoltage, highlighting the need for grid upgrades and local solutions. Remuneration models encouraging self-consumption and demand-side measures to encourage load shifting and aggregation can be considered to mitigate these issues.

Managing large 3-Hour ramps in Japan's power system

Japan experiences exceptionally large net load ramps compared to its peak demand, facing one of the world's most challenging solar variability situations. On 14 January 2024, the country faced an upward ramp of around 50 GW over 3 hours, representing 30% of its annual peak demand. Such a magnitude is comparable only to those in China and India, where the largest 3-hour ramps are 265 GW (in 2022) and 49 GW (in 2024) respectively, corresponding to around 18% and 20% of their respective annual peak demands. During 2024, Japan experienced 3-hour ramps higher than 25% of its annual peak demand for 5% of the year, while ramps higher than 20% were observed for 28% of the year. In comparison, India reached a 3-hour ramp higher than 20% only once in the same year. The steepest upward net load ramp results when a typical evening surge in electricity demand coincides with decreasing solar PV output. In Japan, the challenge to meet this net load variability is further intensified by its isolated grid characteristics.

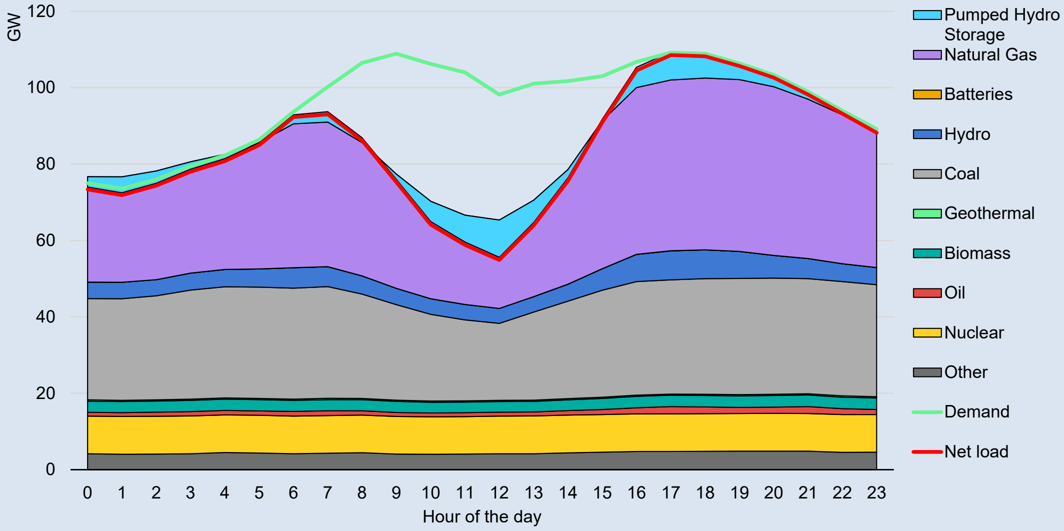
Incredibly, Japan successfully manages such extreme ramps on a regular basis. This is done through co-ordinated dispatch of controllable generation across nine sub-regional control areas.[5] In 2024, the country's electricity generation mix provided a variety of flexible resources, including hydro at around 8%, gas at 29%, and coal at 28% of its annual electricity generation. BESS installation is expanding, but remains limited to 0.3 GW of storage capacity, expected to grow in the next years up to 2.6 GW, compared to around 27 GW of pumped hydro capacity. Therefore, 3-hour upward ramps were primarily met by dispatchable generation. During this period, gas, hydro, and coal, increased their outputs compared to pre-ramping output levels[6] by 18 GW, 14 GW[7]and 7 GW, respectively.

Analysis across the nine sub-regional control areas reveals significant variation in how each of them manage ramping events, reflecting their diverse resource portfolios. For example, Shikoku relied primarily on coal generation, increasing its output by 26% over the 3-hour ramping period. Chubu increased its gas power output by 34 %, while Chugoku increased its hydropower output by 22% in response to the ramp-ups of its local net loads.

[5] Japan system consists of 10 sub-regional control areas, 9 of which are interconnected.
[6] These percentages are calculated using data from 25/11/2024, when fuel source and regional breakdowns were available. The 3-hour ramp rate on this day was 40.6 GW.
[7] The number describes the increase of hydro plus pumping hydro at country-level. During pre-ramping, pumped storage hydro was replenishing via reverse-mode the reservoirs, absorbing 10% of the generation.

This decentralised management approach handles solar PV variability by splitting the system into smaller control areas for intervention, while aiming for optimal system-level efficiency. The approach breaks down large system-wide ramping challenges into manageable sub-regional components, allowing each area to respond to net load variations separately. A co-ordinating agent (OCCTO[8]) manages the flow of electricity between the sub-regions to optimise system-wide supply-demand balance and ensure efficient resource allocation across sub-regional control areas. This decentralised approach, combined with diverse supply sources, provides resilience against the full range of challenges from solar variability to external hazards common in Japan, such as earthquakes, heatwaves, floods and typhoons. The US, China, and India similarly use regional sub-systems for co-ordinating balancing operations. However, compared to Japan, they benefit from international and larger domestic interconnections that provide additional operational flexibility. This highlights that there is potential for enhanced interconnection and use of domestic links between areas in Japan.

Hourly power generation by fuels, demand and net load on a severe ramping day in Japan, 2024



[8] OCCTO - Organization for Cross-regional Coordination of Transmission Operators is the entity responsible for developing the overall power distribution network necessary for wide-area utilisation of power sources, and for strengthening supply and demand adjustment functions nationwide during normal and emergency times. Its main duties are to establish rules, adjust supply and demand and manage interconnection lines during times of tight supply and demand, draft a development plan for wide-area interconnection systems and collect a balanced supply plan, and consider the state of adjustment and reserve capacity.

Seasonal flexibility needs emerge in higher VRE phases

Longer-term flexibility needs will emerge as VRE penetration reaches higher phases. As the penetration of wind and solar power increases significantly, periods of system surpluses and deficits extend from hourly and daily to seasonal and interannual timescales. Managing seasonal variability requires flexibility resources that can respond across the year, extending over weeks or months. These challenges are characteristic of phase 5 of VRE integration, which most countries do not reach until VRE penetration becomes very high.

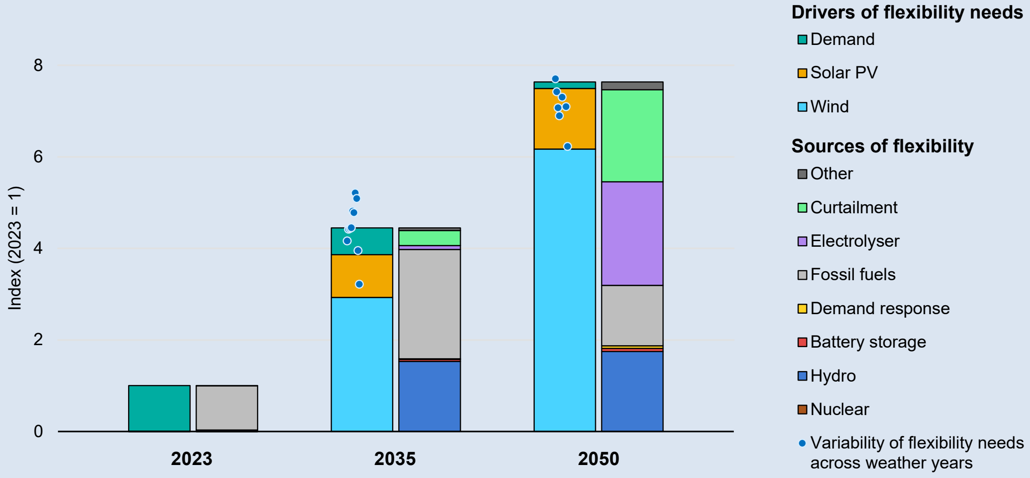
The transition to higher VRE penetration fundamentally changes how thermal plants operate. Dispatchable power plants become the key sources for seasonal variability management, but these assets are used only to meet occasional needs, with annual operating hours significantly below current global average of 4,000 hours in phase 5 systems. This underscores the need to manage the transition of thermal plants from constant generation to flexibility provision, ensuring they remain economically viable whilst operating fewer hours. Addressing seasonal variability in long-term system planning is therefore essential to maintain the reliability of the system as VRE penetration increases.

Southeast Asia's natural advantages for seasonal flexibility

Southeast Asia’s tropical climate leads to relatively flat seasonal electricity demand across the year and the availability of dispatchable hydropower, along with complementarity between solar, wind and hydro, helps ease VRE integration on a seasonal timescale.

Hydropower is the second most important source of seasonal flexibility after thermal generation and many hydropower plants in the region can be upgraded to provide greater balancing services. However, hydropower is vulnerable to interannual variations due to changes in precipitation and prolonged dry spells, which may lead to consecutive years of above or below average generation. Since multi-year deficits cannot be fully offset through reservoir management, generation shortfalls may occur if hydropower’s interannual variability is not considered as part of the overall power system planning.

Seasonal flexibility needs and supply by technology in Indonesia in the Announced Pledges Scenario, 2023-2050



Source: IEA (2024), Southeast Asia Energy Outlook 2024.

In Indonesia, thermal power plants currently provide nearly all of the seasonal flexibility required in the electricity system, with the remainder provided by hydropower plants. Across the seasons, thermal power plants, most notably fired with coal, remain the most important source of flexibility until well after 2030. By 2050, they are mostly displaced in that role by additional hydro and the flexible operation of grid-connected electrolysers in the APS. The curtailment of surplus solar PV or wind generation becomes an increasingly important tool to manage seasonal variations and balance the system in a cost-effective manner.

Abundant existing flexibility resources remain underutilised

Thermal and hydro plants already provide most system flexibility

Today, flexibility needs across the region are met mostly by thermal power plants and hydropower. For example, in Indonesia, coal- and gas-fired power plants currently provide around 80% of short-term flexibility with the remainder supplied by hydropower. These existing assets demonstrate that Southeast Asia already has a substantial foundation of flexible resources operating within current power systems. Thermal plants adjust their output to match demand variations throughout the day, whilst hydropower plants provide balancing services that help maintain system stability.

Many existing Southeast Asian power systems have latent technical flexibility that can be unlocked through proven approaches applied elsewhere.

Contractual barriers prevent full utilisation of existing assets

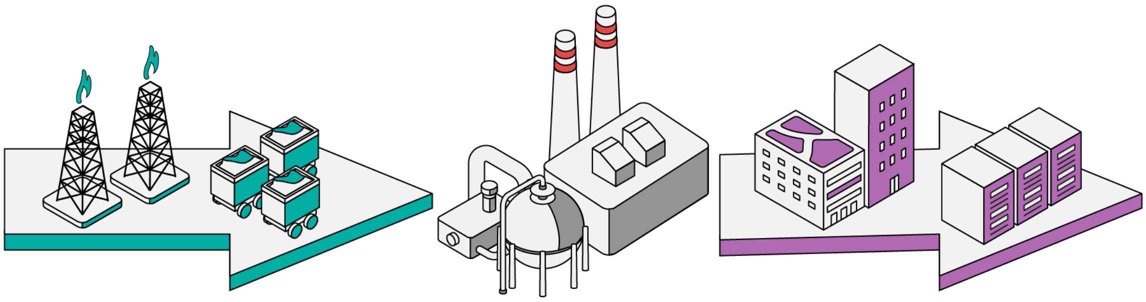
Contractual arrangements often prevent existing assets from providing their full flexibility potential. Barriers such as long-term PPAs and fuel supply contracts with minimum take-or-pay obligations can restrict access to operational flexibility by requiring plants to operate at fixed levels or purchase minimum fuel quantities regardless of system needs, leading to higher system costs.

For example, past IEA analysis has shown that Thailand's power system has substantial untapped technical flexibility and high reserve margins from its hydro and thermal generation fleet, which would allow the system to integrate up to 15% VRE by 2030 without additional investments. With high minimum-take obligations in PPAs, the Thai system has significant amounts of over-contracted volumes, especially in off-peak periods and when renewables are producing at high levels, leading to curtailment and higher operating costs and emissions.

Similarly, gas contracts with take-or-pay obligations introduce inflexibility by preventing the use of otherwise available and cost-optimal resources in the system, as gas becomes a sunk cost and moves down the merit order in line with renewables where the fuel is free.

Recommendations on fuel and power purchase contracts

Recommendations for fuel contracts			
Terms	**Quantity**	**Pricing and settlement**	**Delivery and transport**
• Ensure diversification of contract durations in supply portfolio with long- and short-term contracts to increase the flexibility • Include reopener or review clauses triggered by market or system changes • Extend take-or-pay (ToP) 'observation periods' for more flexibility in offtake of contracted volumes with the opportunity to roll over to the next contractual period	• Allow greater upward/ downward quantity adjustments within contract periods • Renegotiation of take-or-pay volume • Enable early or late volume nominations	• Implement incentive pricing structures to ensure fuel availability during system stress periods • Consider pricing structure according to risk allocation such as higher prices for offtakes longer observational periods for the ToP obligation	• Provide flexible delivery locations to adapt to constraints. • Allow adjustments to delivery timing and transport responsibilities (DAP or FOB) as needed



Recommendations for power purchase contracts			
Terms	**Capacity**	**Pricing and settlement**	**Operation**
• Reduce minimum-take obligations; allow flexible contract durations and renegotiation provisions in PPAs • Allow early termination clauses to accommodate market or system changes • Consider auction-based mechanism for restructuring or buyout firm contracts	• Design capacity obligations considering plant operating conditions and planned outages • Reassess contractual operational characteristics including lower minimum stable levels; higher ramp rates; faster startup/shutdown times; and more frequent startups/shutdowns	• Align capacity payments with the value of flexible, responsive capacity rather than just installed capacity • Link energy payments to market signals, including by peak/off-peak and scarcity periods • Align settlement periods with dispatch interval • Establish remuneration mechanisms for ancillary services, including frequency response and reactive power	• Allow generation output adjustments during grid constraints, with transparent compensation mechanisms • Establish optional standby conditions to enable quick start during system contingencies • Integrate digital interface standards such as EMS and SCADA to provide visibility and enable real-time dispatch • Allow maintenance schedule adjustments with grid needs • Mandate flexible operation tests

Notes: The abbreviations are explained as follows: ToP = Take-or-Pay; DAP = Delivered at Place; FOB = Free on Board; PPA = Power Purchase Agreement; EMS = Energy Management System; SCADA = Supervisory Control and Data Acquisition.

Enhancing operational flexibility and incentivising the use of more cost-efficient and low-carbon resources will require reforming these contracts with careful management of the potential legal and commercial implications whilst shifting away from operating plants at constant output levels to flexible operation patterns.

Significant demand response potential remains untapped

Beyond power generation assets, significant demand response potential exists among industrial and commercial consumers across the region. Large energy users such as manufacturing facilities and commercial buildings can shift energy-intensive processes to align with solar production peaks, providing valuable grid balancing services whilst reducing their electricity costs.

Emerging resources and approaches unlock system flexibility

Beyond existing flexibility sources, emerging technologies will provide additional flexibility as the region's renewable energy deployment accelerates. These resources will diversify the flexibility portfolio and distribute capabilities across the power system, from large-scale batteries to small end-users.

Air conditioning (AC) and EVs represent rapidly growing sources of electricity demand across Southeast Asia. AC consumption continues to rise in the region's tropical climate, with the IEA projecting AC stock to surge from 40 million units in 2017 to 300 million by 2040. This growth could account for up to 30% of peak electricity demand if energy efficiency measures are not adopted. The EV market is expanding with the IEA projecting EVs will make up 30% of vehicle sales in Southeast Asia by 2030. National governments are scaling up charging infrastructure and battery swapping stations with policy incentives like tax breaks and local manufacturing support in Malaysia, Thailand, and others.

BESS deployment is also accelerating. In the IEA's Announced Pledges Scenario, batteries provide around 11% of Indonesia's short-term flexibility by 2035 and around 17% by 2050. IEA analysis for Thailand shows that a portfolio combining BESS, smart EV charging and flexible thermal generation is the most cost-efficient option to achieve the country’s 2037 climate targets.

Price signals and digitalisation enable flexibility deployment

Price signals and digitalisation are essential to activate flexibility from both existing and emerging resources. Without them, the technical potential remains untapped.

Price signals can effectively guide when and how flexibility resources operate to support the grid. Dynamic tariffs encourage large energy consumers seeking to optimise their production costs to shift energy-intensive processes. In liberalised markets, flexibility providers can gain revenue through competitive system services (e.g. frequency and voltage regulation) and energy arbitrage opportunities in wholesale markets based on price signals. However, these market-based models do not exist in all Southeast Asian countries. The Philippines introduced an alternative model through auctions for BESS combined with solar PV, offering 20-year contracts with minimum four hour storage duration requirement. As power markets evolve in the region, regulators must first recognise the value of flexibility services, then establish mechanisms that provide appropriate price signals and adequate compensation on a level playing field.

Digitalisation makes distributed energy resources visible and controllable. Large industrial and commercial consumers use digital tools to identify, monitor and control energy-intensive processes that can be shifted in time. Smaller residential consumers need smart meters to make BTM devices such as EVs, air conditioners and hot water tanks visible to system operators. These tools enable aggregation of small resources to provide system services. The IEA developed an in-depth analysis of efficient grid-interactive buildings in ASEAN, including how distributed energy resources in the region can contribute to system flexibility.

Diverse flexibility portfolios ensure system reliability

Not all flexible resources can provide the same system services. Their effectiveness depends on factors like response time and service provision duration capabilities. Countries should prioritise the most cost-effective flexibility options available to them based on their existing asset base and local conditions, while system planners must combine their complementary capabilities to maintain all necessary grid services throughout the energy transition.

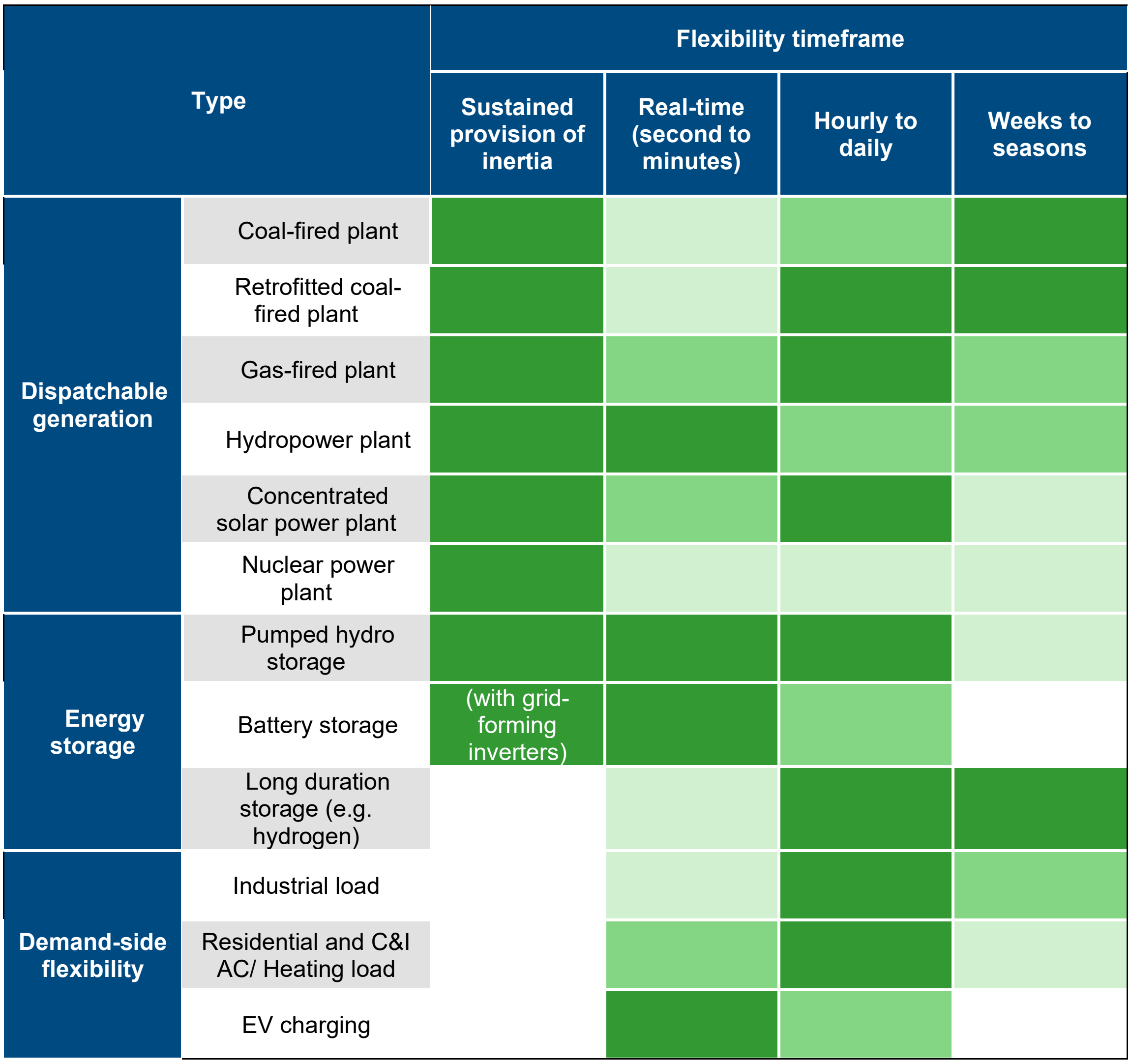
Amongst thermal assets, gas-fired power plants generally provide the most responsive flexibility. They ramp up and down faster and have shorter start-up times compared to coal-fired plants. However, their levelised cost of electricity varies significantly with local natural gas availability, infrastructure and fuel supply arrangements. This affects their economic competitiveness across countries.

Coal-fired generation flexibility depends on age and technology. Modern or retrofitted plants offer better ramping and lower minimum operating levels than standard older plants. Retrofits can reduce start-up times, enabling more frequent cycling, but are often quite costly. Before making major investments, priority should go to removing contractual barriers to flexibility, such as inflexible fuel or offtake contracts and dispatch rules. Further considerations can be given to solar-plus-storage combinations that are becoming increasingly cost-competitive, as demonstrated by projects like Terra Solar in the Philippines.

Emerging technologies can shift demand to moderate system impacts from solar PV production. Smart air conditioning systems can adjust cooling with intelligent controls during peak solar production periods whilst maintaining comfort levels. Similarly, smart charging can shift EV demand by scheduling charging during high solar PV production for both individual charging points and battery swapping stations. Beyond 2035, electrolysers are expected to provide additional short-term flexibility by adjusting the timing of hydrogen production. Where time-based pricing exists, this reduces costs for users whilst helping manage duck curve impacts.

BESS offers multiple flexibility services beyond absorbing excess power production. It enables energy arbitrage and fast-response services, reacting within seconds to frequency deviations. Demand response can also technically provide rapid response. When equipped with modern, grid-forming inverters, BESS, VRE and HVDC converter stations can deliver system services like synthetic inertia. BESS and demand response are less suited for weekly to seasonal flexibility, which thermal and long duration energy storage can provide more effectively.

Suitability of flexible resources for system services



Notes: The darker shade of green means that the resource is more adapted to this timeframe of management.
"Realtime" refers to system services such as frequency regulation, voltage support, fast ramping and reserve activation.
"Hourly to daily" refers to system services such as load shifting, peaking generation, day-ahead unit commitment and storage cycling.
"Weekly to seasonal" refers to system services such as capacity adequacy, seasonal storage and maintenance scheduling.
C&I = commercial and industrial.

Grid modernisation and regional integration

Grid modernisation and reinforcement enable power system transformation and regional power trade across Southeast Asia, unlocking substantial benefits for energy security, economic development and renewable energy integration. However, many existing grid systems were designed for lower demand, centralised generation and domestic operation rather than regional co-ordination. This creates significant opportunities for upgrading transmission capacity, strengthening distribution grids, deploying modern grid management technologies and enhancing cross-border connectivity. These measures can enhance system reliability, reduce outages, support renewables integration, enable shared energy resources across borders and lower system costs. Since these improvements require significant investment and affordability remains a concern in several countries across the region, efficient grid deployment and utilisation become critical. This requires strategic co-ordination and optimised planning to maximise value from infrastructure investments.

Modern grids unlock economic and social benefits, and provide a pathway to regional power trade

Modern grid infrastructure delivers system-wide benefits beyond basic electricity delivery through enhanced efficiency, flexibility and resilience. Strategic investments in national and cross-border grid infrastructure support reliable energy access and broader economic, social and environmental goals. Grid modernisation improves system reliability by strengthening infrastructure to withstand extreme weather and changing demand patterns. Upgraded transmission lines, smart grid technologies and enhanced monitoring systems enable faster fault detection and isolation, reducing outage duration and extent.

These investments improve power quality and reliability for households, schools, healthcare facilities and businesses, while stimulating employment in construction, engineering and digital infrastructure sectors. Reliable power supply attracts investment that creates broader economic opportunities. Translating these economic benefits into policy action requires sector-specific business cases tailored to local priorities and circumstances.

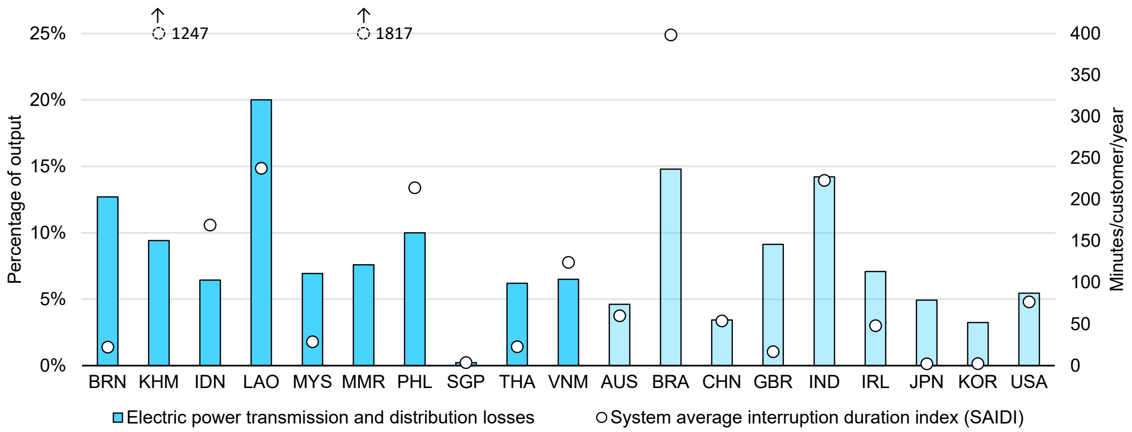
Enhanced grid infrastructure enables countries to share energy resources and complement generation capabilities and reduces costs. As political, regulatory and institutional frameworks mature, regional integration can unlock mutual benefits across Southeast Asia while supporting energy security and decarbonisation goals.

Strengthening grid infrastructure enables the delivery of secure electricity as demand grows

The current grid systems need strategic enhancement to serve Southeast Asia's growing electricity demand and more diverse generation sources, irrespective of the energy supply mix. These enhancements include immediate operational improvements and the deployment of modern grid technologies to address evolving electricity system requirements.

Operational improvements can address immediate performance constraints across the region. Technical grid losses and power outage durations vary significantly across the ASEAN member states. Countries such as Myanmar, Cambodia, Brunei Darussalam and the Philippines experience losses above global averages. Myanmar and Cambodia experience long outage durations. Grid capacity constraints limit efficient electricity delivery as demand grows and distribution grids require strengthening to accommodate distributed energy resources and bidirectional power flows. Enhanced national connectivity represents another infrastructure need across several countries, with archipelagic nations like Indonesia and the Philippines and countries with challenging terrain like Lao PDR, Cambodia and Myanmar still working to achieve comprehensive domestic grid integration. Better co-ordination between infrastructure development and system needs can optimise investment value and prevent constraints from emerging.

Transmission and distribution grid losses (2023) and SAIDI (2019) in each ASEAN member state and in selected regions



Notes: The system average interruption duration index (SAIDI) is the average total duration of outages (in minutes) experienced by a customer in a year. The index is computed based on the methodology in the World Bank Doing Business studies (2016–2020). KHM and MMR are not shown as they are beyond 400 minutes. Country codes for light blue bars are as follows: "AUS" = Australia, "CHN" = China, "GBR" = the United Kingdom, "IND" = India, "IRL" = Ireland, "JPN" = Japan, "KOR" = Korea and "USA" = the United States.

Modern grid technologies can unlock greater system flexibility potential through improved grid management and planning. Smart grid technologies like SCADA and Energy Management System (EMS)[9] can enhance grid visibility and control of transmission and distribution assets. Digitalisation and automation can improve the communication with all connected devices, from transmission-connected generation to BTM resources, improving the ability to identify and activate flexibility resources.

Integrated planning approaches that co-ordinate generation, transmission and distribution development can optimise multi-year infrastructure investments and system performance. Co-ordinated planning is particularly critical given that renewable energy projects typically have shorter development cycles than transmission infrastructure, making timing alignment essential to avoid grid connection bottlenecks. This integrated approach allows grid planners to evaluate whether it is more cost-effective to extend or reinforce grid infrastructure to accommodate new generation and demand, or whether incentivising the relocation of these resources closer to existing grid capacity would be more economical.

Strategic power system investments deliver both affordability and energy security

Directing power system investments towards renewable energy-based systems delivers multiple benefits, including reduced dependence on fuel imports, opportunities to export fossil fuels, protection from volatile global energy prices that strain national budgets, enhanced energy security through distributed generation and long-term operational cost savings. Grid investments spanning local reinforcements, modernisation technologies, inter-regional connections and cross-border transmission can enable renewable resources to supply growing demand while ensuring system reliability.

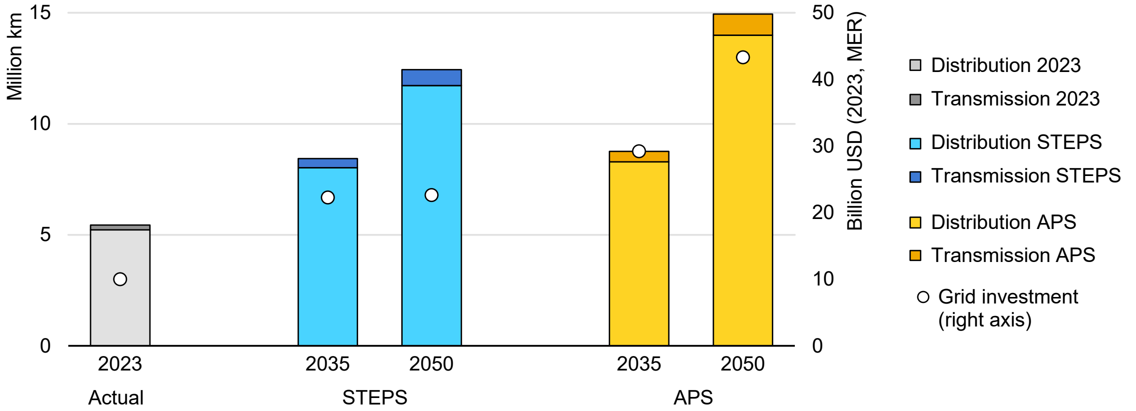
International experience provides useful context for understanding grid modernisation timelines and investment requirements, though Southeast Asia's unique geography, economic conditions and development stages require tailored approaches. Europe's grid infrastructure development over several decades - including post-war reconstruction (1950s-70s), market integration (1990s-2000s) and renewable integration (2000s-present) - required sustained investments of USD 40-60 billion per year over the last two and a half decades. While this

[9] SCADA (Supervisory Control and Data Acquisition) and EMS (Energy Management System) are industrial control systems used to monitor, control and optimise infrastructure operations, with SCADA handling real-time data collection and remote control while EMS performs higher-level analysis and optimisation, particularly in electrical power grids. In addition, there are WAMS (Wide Area Monitoring System which assists transmission system operators in daily operations, even prevents widespread blackouts, and assists system restoration), DMS/ADMS (Distribution/Advanced Distribution Management Systems) and DERMS (Distributed Energy Resource Management Systems).

demonstrates both the scale of investment required and the long-term nature of grid transformation, Southeast Asia has opportunities to avoid some of Europe's inefficiencies by learning from this experience and leveraging modern technologies to accelerate development timelines.

Southeast Asia faces significant challenges in meeting the high capital requirements of transmission and distribution modernisation. From a level of USD 10 billion annual investment in grids in 2023, requirements are expected to more than double by 2035 and grow further towards 2050. These investment needs must be balanced against the current purchasing power of populations across the region. Except for Singapore and Brunei Darussalam, purchasing power parity (GDP per capita) remains well below that of advanced economies, making electricity affordability a critical social and economic concern, with many households already spending a large share of their incomes on electricity bills.

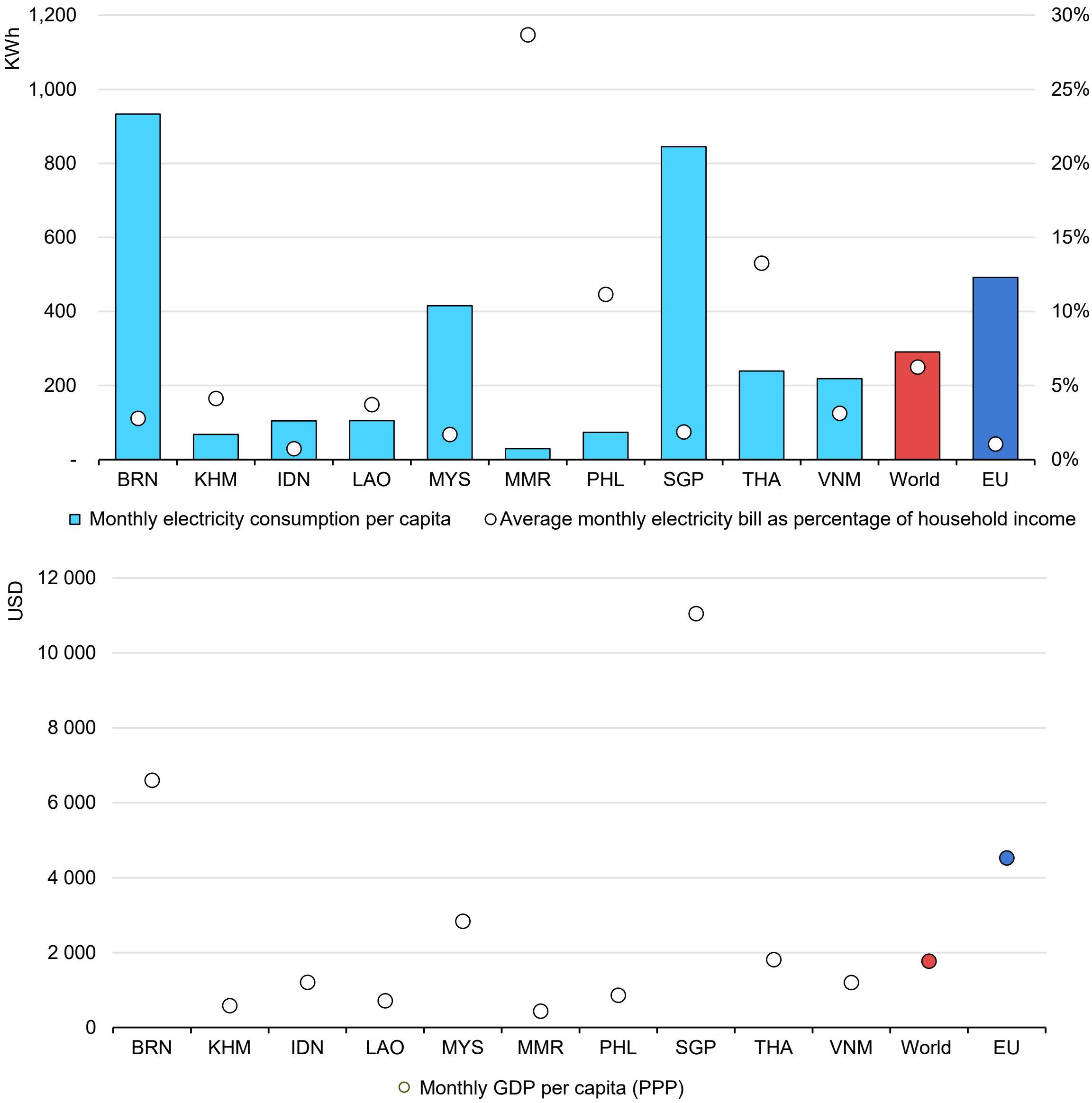
Installed transmission and distribution line length and annual average investment in grids by scenario for Southeast Asia, 2023-2050



Notes: MER (Market Exchange Rates) refers to the conversion of national currencies using market exchange rates.
Source: IEA (2024), Southeast Asia Energy Outlook 2024.

While GDP per capita is positively correlated with electricity consumption and negatively with electricity affordability, significant social inequality and uneven electricity access between urban and rural areas mean that national averages mask important disparities. Other factors like the state of the electricity infrastructure and cost allocation of electricity upgrades can further exacerbate affordability challenges. In the case of Myanmar and the Philippines, per capita electricity consumption is significantly lower than the regional average but electricity bills are very high relative to income.

GDP per capita and monthly electricity bills as a percentage of average household income (2024)



Sources: GlobalPetrolPrices (2025), Electricity prices; World Bank (2025), World Bank Database- World Development Indicators; WorldData (2025), Average income by country.

This affordability challenge is particularly acute in countries where infrastructure constraints drive up costs. Myanmar exemplifies this challenge, where weak transmission and generation assets trigger regular load-shedding and heavy reliance on costly diesel generators. The substantial expense of rehabilitating the grid translates into high electricity tariffs borne by end users. Similarly, the Philippines faces high costs due to its archipelagic geography and aging distribution network, requiring extensive upgrades alongside continued dependence on expensive oil-fired peaker plants, with utilities recovering these capital outlays through higher tariffs. These cases demonstrate that infrastructure constraints can create a vicious cycle where countries with the greatest need for power system investment face the steepest affordability challenges.

This challenge is compounded by the high costs of capital in most Southeast Asian countries. The cost of capital for solar PV and storage projects in emerging markets, including Indonesia and Viet Nam, is over twice the average in advanced economies, significantly impacting project economics and deployment pace.

Diverse financing approaches offer ways to address affordability concerns

Traditional financing approaches create affordability constraints for grid investment across Southeast Asia. Utilities rely heavily on state-owned enterprise (SOE) balance sheets and regulated electricity tariffs for cost recovery, with financing capacity directly linked to SOE creditworthiness rather than project characteristics. Electricity tariff structure represents an important aspect of grid investment bankability, as investment costs are often recouped through regulated tariffs. Tariff structures can help improve the financial health of utilities, as well as their ability to finance infrastructure on balance sheets in the future. Tariff levels involve complex trade-offs between consumer affordability and utility financial sustainability, and where tariffs cannot reflect full investment costs, fiscal support from governments may be required.

Private sector involvement can reduce public financial burdens and improve cost efficiency. Public-private partnership models enable governments to attract private investment while transferring project risks. Brazil's experience with almost 350 independent power transmission projects demonstrates this approach, where private sector competition secured nearly USD 4 billion in transmission rights at an average of 40% below maximum prices the regulator was willing to pay. However, implementation depends on each country's regulatory and legal environment.

Public and international support mechanisms can provide financing support, including concessional financing and cost-sharing solutions. Development finance institutions offer long-term financing and de-risking instruments that improve project affordability, as illustrated by the Asian Development Bank and Agence Française de Développement's support for Indonesia's West Kalimantan transmission development.

Southeast Asia has multiple channels available for recovering grid transformation costs, each with different implications for affordability and equity. Cost recovery can occur through four main channels: electricity tariffs paid by consumers, government budgets funded by taxation, foreign debt financing and private sector investment. The total cost burden can be reduced through efficiency measures such as competitive procurement mechanisms, optimised asset operation and market-based allocation of resources.

However, cost-reflective tariffs may not be feasible for all segments of society, particularly in Southeast Asia where many households already face affordability constraints. This creates a need to redistribute the cost burden across different recovery channels and consumer segments. International experience demonstrates the necessity of mixed cost allocation approaches, with countries employing various combinations of consumer tariffs, government subsidies and strategic planning mechanisms.

Approaches to managing grid costs in countries/regions with high VRE shares

Country / Region	Cost allocation approach
Germany	Subsidises electricity costs while passing some costs on to consumers, recognising affordability thresholds
Japan	Uses revenue cap mechanism for TSOs (since 2023) with cost recovery through consumer tariffs. Generation-side tariffs introduced in 2024 to share grid costs.
Netherlands / EU/ EU	Subsidises offshore grid construction and provides dedicated funding for cross-border projects
Australia / UK	Implements strategic integrated planning to control infrastructure costs

Southeast Asia, having in many cases not undergone electricity sector liberalisation, retains relatively more government control than in more mature economies over tariff-setting and cost- allocation decisions, which enables flexible approaches that balance cost recuperation through multiple channels. The region's experience with using state budgets to shoulder costs and reduce burdens on end consumers provides a foundation for ensuring equitable distribution of costs across society.

Together, these diverse financing options enable countries to tailor approaches to their specific fiscal circumstances while maintaining affordability and utility financial sustainability.

Regional interconnection offers strategic benefits for system optimisation

Given the substantial investment requirements and affordability challenges outlined above, regional interconnection provides a strategic approach to reduce overall system transformation costs while enhancing energy security and reducing fossil fuel dependency. Connecting different geographic areas within and across countries can moderate the financial burden on individual systems, optimise performance and strengthening energy resilience by enabling countries to share resources, reserves and flexibility services.

Regional grids provide access to a larger pool of assets that can respond to demand fluctuations, outages, or extreme weather events, reducing vulnerability to supply disruptions. Geographic complementarity, particularly non-coincidental demand patterns across countries, further enables cost reduction and system optimisation. These benefits, ranging from immediate cost savings and reliability gains to longer-term advantages in energy security and competitiveness, make regional interconnection a compelling option for Southeast Asia

Benefits of regional power system integration

Benefit category	General advantage	How it applies in Southeast Asia
Cost reduction	Shared transmission infrastructure and avoided redundant generation capacity reduce overall system costs	Reduces the need for expensive local flexibility investments and fossil fuel backup systems across the region
Energy security	Larger pool of generation and reserves provides backup during outages and extreme weather, reducing supply vulnerabilities	Allows systems to back each other up during periods of stress, lowering the risk of blackouts; diversified supply reduces diesel dependency in remote areas
Resource optimisation	Using existing generation more efficiently across regions to avoid building additional capacity; imports through interconnection may supply demand more efficiently than reinforcing domestic grids	Non-coincident demand peaks across countries, thereby reducing the total generation capacity investment needed; It is more efficient for Mekong hydropower to supply neighbouring countries than for them to build their own backup capacity
Environmental impact	Reduced carbon emissions, costs and global price exposure through lower fossil fuel dependency and enhanced renewable energy integration	Reduces reliance on expensive and volatile fossil fuel peaker plants for system balancing; enables countries to share abundant renewable resources
Regional integration	Cross-border interconnection builds regional solidarity and deepens economic ties between countries	Grid integration can deepen economic ties, connect underserved border communities and unlock mutual benefits across Southeast Asia
Technical flexibility	Access to diverse flexibility options for managing variability and sudden system changes across interconnected networks	Access to broader pools of flexibility options across borders from industrial load shifting to demand response mechanisms; enhanced ability to manage solar and wind generation variability
Economic Development	Job creation and industrial growth from infrastructure development and cross-border energy trade	Regional grid development stimulates employment in construction, engineering and digital infrastructure sectors; energy trade creates new business opportunities and industrial development

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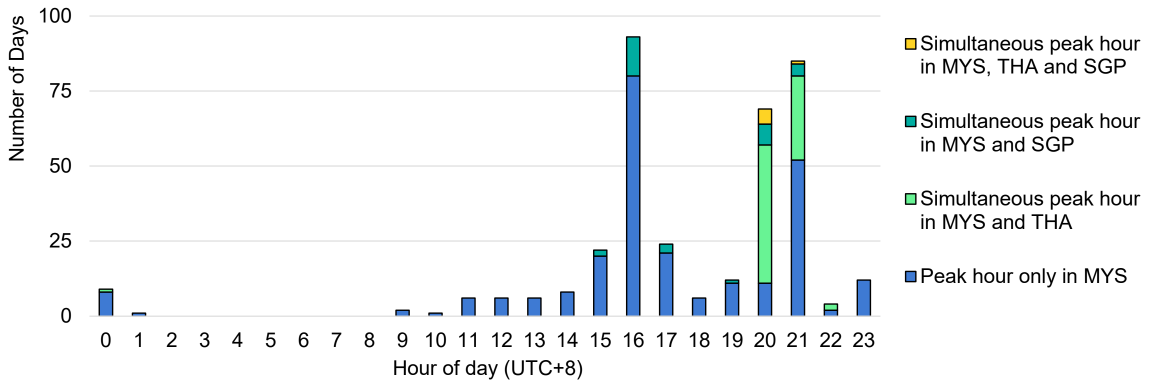
International examples demonstrate the proven effectiveness of leveraging geographic complementarity for renewable energy integration. For example, Brazil utilises its extensive north-south transmission network to balance solar power variability across diverse climatic regions with dispatchable hydropower from major river basins. This approach allows solar-rich northeastern states to complement hydropower-abundant regions in the north and southeast during different seasonal patterns. Similarly, South Australia has expanded interconnection capacity with neighbouring states, taking advantage of resource diversity between solar, wind and dispatchable generation across Australian regions to integrate high levels of VRE while maintaining system reliability.

Number of days when Malaysia's peak demand hour coincides with that of Thailand and Singapore in 2024



Notes: Number of days in 2024 when Malaysia's daily peak demand occurred at each hour, indicating the frequency of coincident peak demand hours with Thailand and Singapore (times aligned to co-ordinated universal time [UTC]+8).

Technical barriers to interconnection are manageable with modern grid technologies and co-ordinated protection systems. While countries in Southeast Asia have different grid characteristics and stability levels, this does not preclude successful interconnection. Modern grid technologies and co-ordinated protection systems enable safe interconnection between systems of varying strengths, as demonstrated by successful interconnections worldwide between grids with different technical specifications. Advanced grid technologies enable real-time monitoring and control of bidirectional power flows, managing solar and wind generation variability while maintaining system stability. The APG and bilateral interconnection initiatives represent substantial opportunities to capture these proven benefits while addressing the affordability constraints identified in previous sections.

The role of the ASEAN Power Grid (APG) to facilitate VRE integration

The APG has been one of the main pillars in the ASEAN Plan of Action for Energy Cooperation (APAEC) since its inception in 1997 as part of the ASEAN Vision 2020. With the goal to drive energy security, accessibility and sustainability in the region, APG is seen by the ASEAN member states as a tool to meet the rising electricity demand more efficiently and securely through regional integration.

The initiation and implementation of the first multilateral (uni-directional) power trade under the Lao PDR – Thailand-Malaysia-Singapore Power Integration Project (LTMS-PIP) was a key milestone of the APG which demonstrated the technical and institutional feasibility of cross-border trade in the region. This pilot, which has since been extended to be multidirectional, has shown the practical viability of regional power integration. Singapore's decarbonisation strategy relies heavily on such cross-border power trade, with the country actively developing multiple import projects to access regional renewable energy resources. Other multilateral initiatives, including the Brunei Darussalam-Indonesia-Malaysia-Philippines (BIMP-PIP), are also under development as part of the broader regional effort to advance cross-border trade capabilities.

The vision for the full development of the APG is discussed in the ASEAN Interconnection Masterplan Study (AIMS), with three editions completed to date (AIMS I-III), representing the co-ordinated efforts of the ASEAN member states to identify priority interconnections and advance APG.

The APG can play a critical role in facilitating the integration of high shares of VRE in the region, delivering not only environmental benefits, but also economic and operational advantages. By expanding the balancing areas, the APG can help to:

- **Leverage geographical complementarity:** By connecting diverse renewable resources and demand centres across the region, the APG can smooth out the variability of VRE generation and demand. APG would allow countries to export VRE surplus during periods of excess and import when local resources are insufficient to meet the demand
- **Support resource diversity and defer investment**: The APG would allow different jurisdictions to access a broader pool of generation and flexibility resource cross borders, reducing their need to invest independently in their own generation and flexibility resources, particularly storage. Full regional interconnection could potentially reduce the need for solar generation capacity by up to 0.6 TW and more than 15 TWh of electricity and hydrogen storage.

Despite these efforts, the APG remains only partially developed. Key barriers – including political will, regulatory and institutional arrangements, and grid financing – still need to be addressed to unlock its full potential. Additional challenges include establishing clear frameworks for renewable energy certificate (REC) accounting in cross-border renewable energy trade, which remains underdeveloped across the region. The finalisation of APAEC 2026–2030 and the renewal of the APG MOU in 2025 is expected to facilitate the development of APG by addressing these key challenges, particularly facilitating the development of protocols on regional institutions, market development and infrastructure planning. On financing, the establishment of a dedicated APG Financing initiative by the ADB and World Bank to expedite cross-border connections infrastructure by mobilising, arranging and deploying financing in collaboration with the ASEAN member states will be very advantageous.

Chapter 3. Policy and Regulatory Framework

Southeast Asia can successfully transform its power system to reliably and affordably meet growing electricity demand. This is possible with a progressive approach that aligns VRE integration measures with local contexts. It also involves building the technical and institutional capabilities to manage effectively higher VRE penetrations.

This chapter outlines a practical implementation roadmap with actionable steps for key stakeholders in Southeast Asia. These include policymakers, regulators, regional bodies and utilities. The roadmap draws on the regional opportunities identified in Chapter 2, global experience in navigating from low to higher phases of VRE integration and the current readiness assessment from Chapter 1.

The roadmap is organised around three types of actions that can build upon each other: **foundational actions** that establish basic policy and regulatory frameworks, **enabling actions** that implement systems and capabilities for effective VRE integration and **transformational actions** that drive advanced system transformation. These actions are structured across three time periods: near-term (2025-28) based on countries' current readiness and 2030 ambitions, medium-term priorities (2028-30) focused on progression towards stated goals and longer-term preparation (post-2030). Regional interconnection represents a parallel opportunity throughout, offering pathways to reduce costs and enhance energy security regardless of individual country phases.

Implementation priorities for different phases of VRE integration

Global experience shows that successful VRE integration works best when countries move through types of actions in sequence, corresponding to different VRE integration phases:

- **Foundational actions**: Establish core policy and regulatory frameworks and technical standards that create the institutional foundation for VRE deployment. These actions are essential for countries in phases 1-2 where the focus is on building basic capabilities and frameworks for initial VRE deployment.
- **Enabling actions**: Implement operational capabilities, market mechanisms and infrastructure to manage VRE effectively. These actions become critical

for countries entering phase 3, where VRE begins to require active system management and flexibility resources.

- **Transformational actions**: Deploy advanced technologies, cross-sector integration and sophisticated market designs that optimise high-VRE system performance. These actions are necessary for countries approaching phases 4 and beyond, where very high VRE penetration demands system transformation.

Implementation priorities by readiness level and expected phase of VRE integration

	Phase of VRE integration in 2030: 1-2	3	4+
High readiness	Any missing foundational + enabling actions	Focus on remaining enabling + some optimisation actions	Transformational actions + advanced measures
Mid-stage readiness	Focus on remaining foundational actions	Enabling actions (complete)	Enabling + transformational actions
Eary-stage readiness	Foundational actions (complete)	Foundational + some enabling actions	Foundational + Enabling + some transformational actions

Countries typically need to complete foundational actions before effectively implementing enabling actions and successfully deploying transformational actions. However, specific priorities of actions depend on both current readiness levels and 2030 ambitions, with some countries needing to accelerate through multiple action types simultaneously to reach their goals.

Based on our assessment from Chapter 2, the ASEAN member states are expected to progress through VRE integration phases at varying rates over the next decade, reflecting different starting points, resource endowments, policy frameworks and economic conditions. This varied timeline highlights the importance of tailored approaches whilst maintaining regional co-ordination for collective benefits.

Understanding each country's current readiness in relation to their 2030 and 2035 ambitions is crucial for mapping out implementation priorities. Countries with ambitious targets relative to their current readiness face the most intensive implementation efforts and require accelerated action across multiple fronts. Countries with conservative targets relative to their readiness may have opportunities to aim higher or focus on building robust foundations.

The ASEAN member states will face different levels of VRE integration challenges through 2030 depending on their current readiness to integrate VRE and expected phases based on renewables targets.

Early-stage readiness countries (Brunei Darussalam, Cambodia, Lao PDR, Myanmar) are expecting to be in phases 1-2 by 2030, requiring steady progress through foundational capabilities and frameworks and enabling actions to get their readiness to tackle future VRE challenges.

Mid-stage readiness countries (Indonesia, Malaysia, Thailand, Viet Nam) present more complex trajectories. Viet Nam, which is expected to be in phase 3 in 2030, is already experiencing phase 3 challenges today but lacks sufficient readiness, creating the urgency of implementing enabling measures. Indonesia, which is likely to remain in phase 1 in 2030, faces the steepest acceleration. It is expected to leap to phase 3 by 2035, but this is complicated by fragmented grids, with some islands already experiencing phase 2-3 challenges. Malaysia and Thailand have more manageable progressions and are expected to be in phases 1 and 2, respectively, by 2030, with both progressing to phase 2 by 2035. Given their mid-stage readiness, both countries can begin to consider enabling actions and potentially pursue more ambitious renewable energy targets.

High readiness countries (Singapore, the Philippines) present distinct challenges. The Philippines faces a triple challenge as it would undergo the transition from phase 2 in 2030 to phase 4 by 2035, while simultaneously managing multiple island systems, some of which are not interconnected, at different phases and navigating the steepest system transformation requirements. Singapore presents a unique case as it would remain in phase 1 by 2030, despite high readiness, reflecting limited domestic VRE growth rather than technical constraints. Singapore plans to increase the share of VRE through imports, which requires efforts to build strong importing capability including physical infrastructure and regulatory frameworks and regional co-ordination. Singapore actively supports regional electricity trade within ASEAN, leveraging its advanced system capabilities.

This varied landscape highlights the importance of tailored approaches whilst maintaining regional co-ordination for collective benefits.

Priority action by country readiness level and time period

Country group	Primary focus	Key recommendations	Implementation priority
Early-stage readiness (BRN, KHM, LAO, MMR)	Foundational actions	R1: Set policy frameworks to support ambitious VRE targets R2: Enhance energy efficiency regulations R3: Establish grid codes, compliance frameworks and build basic operational capabilities R4: Co-ordinate government-utility grid infrastructure planning	Near-term (2025-2028)
Mid stage readiness (IDN, MYS, THA, VNM)	Enabling actions	R5: Develop flexibility procurement mechanisms R6: Foster investment in diverse flexibility resources R7: Enhance power system infrastructure and operation practices R8: Enable flexible operation of conventional power plants R9 Reform system planning and adequacy assessment	Near to medium-term (2025-2030)
High readiness (SGP, PHL)	Transformational actions	R10: Map out policies to mobilise power system transformation R11: Reform markets and tariff structures R12: Build capabilities to handle complexities of a future power system R13: Deploy advanced system transformation capabilities	Medium to long-term (2028-post 2030)
All Countries	Regional co-ordination	R14: Strengthen regional co-ordination platforms R15: Sustain regional implementation progress R16: Develop roadmaps to harmonise trading	Continuous parallel process

Implementation priorities for systems in phases 1-2 (Foundational actions)

Foundational actions establish the basic institutional, policy and technical frameworks that create the foundation for successful VRE integration. These actions are essential for all countries but represent the near-term priority for countries in phases 1-2 where the focus is on building basic capabilities and frameworks for initial VRE deployment.

R1: Set policy frameworks that support a clear path to achieve VRE integration targets

Establish clear policy frameworks that enable continued VRE deployment and investment confidence. Investment decisions, technology choices and infrastructure planning all depend on policy certainty over multi-year timeframes. Specifically, ambitious VRE targets with supporting policy measures provide a coherent roadmap, giving confidence to investors.

Competitive procurement mechanisms are increasingly driving the most cost-effective VRE deployment while Southeast Asia relies on regulated approaches. Almost 84% of global renewable utility-scale capacity growth projected between 2024 and 2030 is policy-driven deployment. Excluding China, auctions and tax credits serve as the primary drivers of utility-scale solar and wind growth. Although many ASEAN member states are introducing competitive mechanisms such as corporate PPAs and auction schemes, the operational frameworks to execute them remain weak compared to regulated approaches like FiTs and net metering. Southeast Asia accounts for only 2% of global clean energy investment, highlighting significant potential for growth through more effective policy measures.

Successful regional examples demonstrate competitive approaches' effectiveness, but require government co-ordination for implementation. The Philippines' Green Energy Auction Programme demonstrates how competitive approaches can drive down costs and scale up renewable capacity. Countries including Malaysia, Singapore, Viet Nam and Thailand are moving towards corporate PPAs with third-party access to unlock renewable investment. Government co-ordination with regulators and utilities is essential for establishing transparent procurement processes, improving bankability of PPAs and creating regulatory clarity that reduces investment risks.

R2: Enhance energy efficiency regulations to reduce electricity demand, grid capacity requirements and enable future flexibility

Update appliance standards and building codes to reduce electricity demand and enable future grid integration. Energy efficiency, often called the "very first fuel", is a cost-effective, proven strategy to reduce electricity demand, lowering energy bills and reducing pressure on power systems. Most technologies are market-ready with large potential in the buildings and transport sectors. Updating appliance standards now offers the greatest opportunity for long-term impact, as appliances purchased today will remain in use for decades across Southeast Asia's rapidly electrifying economy. Embedding demand-response readiness in new standards prepares the foundation for grid-responsive capabilities that support VRE integration as grid infrastructure develops. Government action should focus on updating building codes, setting appliance efficiency standards and creating regulatory frameworks that enable future grid integration through co-ordination with regulators and utilities.

R3: Ensure technical standards and enhance operational capabilities for secure and efficient power systems

Develop updated grid codes with detailed VRE performance requirements to enable renewable integration that protects existing infrastructure. Grid codes must specify technical requirements for VRE plants including fault ride-through capability, voltage and reactive power control, and communication interfaces. These codes need to safeguard today's system whilst anticipating future requirements. Detailed technical requirements, implementation benefits and regional examples are provided in Annex D.

Establish compliance monitoring frameworks to ensure VRE installations meet safety and performance requirements throughout plant lifetime. Countries need compliance-testing procedures, certification processes for VRE equipment and ongoing monitoring frameworks. Regional examples include Malaysia's Guidelines for Large Scale Solar Plants and the Philippines' reactive power support standards, with more details available in Annex D.

Implement basic operational capabilities in forecasting and dispatch to create the foundation for initial VRE deployment and future operational enhancement. Basic VRE forecasting provides essential visibility for operational planning. Countries should incorporate forecasting into dispatch processes and implement hardware and software that enable dispatch optimisation. Applying economic dispatch principles ensures efficient utilisation of available generation resources. This creates foundations for the operational enhancements needed as VRE penetration increases.

R4: Establish co-ordinated grid infrastructure planning between government and utilities

Establish co-ordinated planning processes that align government policy frameworks with utility technical expertise. Grid plans become robust by testing them against scenarios for supply and demand trajectories, grid configuration options and regional interconnection possibilities. This provides the foundation for infrastructure investments that deliver value across different possible futures.

Energy ministries, regulators and planning authorities must work together to create grid development plans with clear timelines and technical specifications. The Philippines' Transmission Development Plan demonstrates this approach. The National Grid Corporation co-ordinates annually with the Department of Energy to align grid infrastructure with the country's Clean Energy Scenario and broader energy policy objectives. Australia's Integrated System Plan and the UK's Future Energy Scenarios provide examples of testing transmission scenarios against different renewable energy and demand futures to identify priority infrastructure investments with clear timelines. Co-ordinated planning between government renewable energy targets, utility grid development capabilities and VRE deployment timelines ensures that renewable energy investments can be fully utilised while maintaining system reliability and security.

Implementation priorities for systems in phase 3 (Enabling actions)

Enabling actions implement the operational capabilities, market mechanisms and infrastructure systems that allow countries to effectively manage variable renewable resources. These actions become critical for countries moving through phases 1-3 and are essential for phase 3, where VRE variability begins to require active system management and flexibility resources.

R5: Develop mechanisms to procure flexibility and create viable business cases for flexibility services

Establish clear incentive mechanisms and update regulatory frameworks to value and procure essential system services, tailored to each country's market structure. This requires defining and quantifying specific system services needed to support grid stability and reliability. Countries should establish transparent procurement processes and provide valuation mechanisms that enable service providers to build viable business cases. Countries can define specific technical requirements for system services such as frequency response or ramping products. Establishing competitive processes for procuring these services provides market-based price discovery. Compensation mechanisms such as availability payments for being ready to provide services plus performance payments for actual delivery are essential to create viable revenue streams.

Create transparent procurement processes and market rules that facilitate fair competition among flexibility providers. Regulatory frameworks should also establish rules and licenses for emerging business models such as EV smart charging, BESS grid codes and connection rules, and distributed energy resource aggregator licenses. They should also create data-sharing protocols between utilities to remove barriers for new flexibility services. Flexibility procurement mechanisms should consider all available resources, including existing dispatchable plants and demand response, to optimise system flexibility.

The Philippines demonstrates this approach through both the Reserve Market and the Ancillary Services Procurement Agreement (ASPA) contracting framework. The reserve market, which entered full commercial operation in January 2024, co-optimises energy and reserve offers to determine the most cost-effective mix of energy and ancillary services. These mechanisms have encouraged greater private sector participation and stimulated investment in flexibility resources, particularly BESS.

R6: Establish stable investment signals for diverse flexibility providers

Remove regulatory barriers and create supportive policy environments that unlock private sector investment in flexibility resources. As renewable energy shares grow, power systems need diverse flexibility options that private sector can deliver, including distributed energy resources, BESS, gas turbines, virtual power plants and aggregator services. Removing regulatory barriers means establishing fair market access rules, allowing market participation of new flexibility resources, and ensuring different flexibility providers can compete on equal terms. Supportive policy environments include setting specific distributed energy resource targets in national power development plans, updating procurement policies to favour integrated solutions like solar-plus-storage projects, and implementing tariff reforms such as modernised time-of-use rates that provide appropriate price signals for flexibility deployment.

Co-ordinated policy development across government departments provides consistent signals about market opportunities to unlock private investment in flexibility technologies. When energy ministries, finance departments, and planning agencies align their policies, private companies gain confidence to make long-term investments in flexibility technologies. This co-ordination becomes essential when flexibility resource development must align with renewable energy targets and grid infrastructure plans to ensure integrated system planning that maximises benefits from both public and private investments.

R7: Enhance power system infrastructure and operational practices

Ensure timely grid capacity development and digitalisation to meet growing electricity demand and support effective VRE integration. Grid capacity development is primarily needed to cater for growing electricity demand, whilst digitalisation provides real-time visibility into grid conditions and control over transmission assets. Dynamic Line Rating technology can maximise transfer capacity of existing transmission lines without major new investments, providing cost-effective enhancement of grid capacities as both demand and VRE penetration increase.

Update grid codes regularly to reflect evolving system needs while balancing performance requirements with provision costs. As VRE penetration increases, their operational requirements evolve. Connection standards and compliance frameworks must maintain system security whilst enabling efficient VRE integration. Regular updates ensure grid codes remain aligned with system capabilities and requirements.

Enhance operational procedures to respond more quickly to system changes. This requires improved VRE and demand forecasting capabilities - while many countries including the Philippines, Singapore, Malaysia and Thailand have established VRE forecasting systems, though most only forecast days to six hours ahead. Countries should implement faster decision-making systems with shorter time intervals, as demonstrated by Philippines with 5-minute dispatch intervals. Real-time monitoring capabilities track actual system conditions against forecasts and schedules, enabling automated dispatch optimisation and continuous adjustments through advanced hardware and software systems. Additional details on forecasting system capabilities and operational improvements across the region are provided in Annex D.

R8: Enable flexible operation of conventional power plants

Co-ordinate improvements across plant performance, market operations and system control capabilities to enable flexible operation of conventional power plants. Countries can retrofit existing power plants to operate more flexibly to respond to changing electricity demand by lowering minimum generation levels, increasing ramp rates and shortening start-up times. Studies in Thailand, Viet Nam and Indonesia indicate the technical and economic feasibility of enhancing thermal plant flexibility, though implementation strategies vary by country.

Many countries including Indonesia, Thailand, Viet Nam, Lao PDR and the Philippines face limitations from inflexible long-term PPAs that hinder VRE integration. Traditional PPAs typically focused on energy delivery and capacity availability, but modern flexible contracts include ramping requirements, part-load efficiency standards, or payments for ancillary services. Incorporating flexible operation requirements when negotiating new contracts ensures future assets can respond to system needs. Countries can prioritise operational flexibility improvements at existing utility-owned thermal plants to avoid contractual complications.

R9: Reform system planning and adequacy assessment

Adapt system adequacy assessment methods to account for variability and uncertainty of demand and supply. With rising VRE penetration and growing uncertainty on both the supply and demand side, system adequacy assessments must evolve beyond traditional deterministic methods. Malaysia, Thailand and Viet Nam have moved from traditional reserve margin approaches towards more sophisticated, probabilistic assessments such as LOLP, LOLE and EENS[10] that better capture the uncertainty of power systems. As Southeast Asia is highly exposed to severe weather events including typhoons, floods and extreme heat, integrating the risk of climatic events into planning is essential to ensure system security. Internationally, many system operators have been using stochastic metrics in adequacy assessments to ensure a reliable system such as the Electric Reliability Council of Texas, Australian Energy Market Operator and European Network of Transmission System Operators for Electricity.

Systems preparing for a high VRE future at phase 4 and above (Transformational actions)

Transformational actions deploy advanced technologies, cross-sector integration and sophisticated market designs that optimise high-VRE system performance. These actions are necessary for countries approaching phases 4-5, where very high VRE penetration demands comprehensive system transformation and advanced operational capabilities.

R10: Map out policies needed to mobilise the power system transformation

Develop comprehensive flexibility deployment roadmaps to guide when and how different flexibility resources will be needed as countries approach high phases of VRE integration. These roadmaps should quantify flexibility needs, indicate deployment timelines and consider procurement methods for different flexibility options including demand response programs, large-scale storage systems and flexible generation resources. Creating flexibility deployment roadmaps helps countries understand the scale and timing of investments needed to support high VRE penetration levels.

Establish streamlined permitting processes and co-ordinate VRE and demand development locations to enable system-friendly deployment at scale. As VRE deployment increases, ensuring that new projects are developed in locations and configurations that support grid integration becomes essential for efficiently maintaining system security. The Philippines has introduced Competitive Renewable Energy Zones (CREZ), which are designated areas with high renewable resource potential and streamlined permitting processes, demonstrating how co-ordinated planning can facilitate grid-compatible renewable

[10] LOLP (Loss of Load Probability): probability that demand exceeds available generation capacity; LOLE (Loss of Load Expectation): expected number of periods per year when supply is inadequate; EENS (Expected Energy Not Served): expected amount of energy not supplied due to generation shortfalls.

development. Countries can establish similar approaches that consider grid constraints, transmission capacity and system requirements to ensure large-scale VRE deployment enhances rather than challenges system stability.

R11: Align and map market and regulatory reforms with power system transformation

Implement targeted market and regulatory reforms that work within current frameworks rather than requiring complete restructuring. These reforms should include transparent mechanisms to value and procure system services, focusing on incremental adjustments that enable higher renewable integration. Regulatory frameworks must evolve to accommodate new technologies like BESS and advanced grid enhancing devices while providing clear incentive mechanisms for flexible power plants and demand response providers to deliver essential system services.

Reform electricity tariff structures to support grid investments while maintaining affordability for consumers. High renewable penetration requires grid upgrades and new flexibility resources, creating cost recovery challenges. As many households across Southeast Asia already spend a considerable share of their income on electricity bills, tariff reforms must carefully balance the need to recover infrastructure investment costs with affordability. Options for managing these costs include shifting some infrastructure investments to government budgets, recognising that grid modernisation drives economic growth and long-term energy supply cost savings that benefit the broader economy.

Expand green finance eligibility to include grid infrastructure investments essential for VRE integration. Creating green taxonomies that include transmission lines, storage systems and grid modernisation investments could open access to green and sustainable finance from banks and development institutions. ASEAN member states can build on existing frameworks such as the ASEAN Taxonomy for Sustainable Finance to ensure that grid investments needed to support renewable integration receive appropriate recognition in sustainable finance classifications. Clear definitions help investors understand which grid projects qualify for green financing, while transparent criteria ensure that infrastructure investments genuinely support renewable energy deployment.

R12: Build capabilities to deal with the complexities of a future power system

Build comprehensive operational capabilities to manage increasing power system complexity. This entails the establishment of forecasting capabilities that can handle greater uncertainty and variability across generation, demand and grid operations as the system evolves with electrification and digitalisation. It also requires real-time operational capabilities to co-ordinate diverse flexible resources including storage, demand response and distributed generation across transmission and distribution networks. Investments in workforce development for data science, power system analytics and cross-sector energy planning is critical, supported by partnerships with technology providers and research institutions to access emerging grid management solutions and operational expertise.

Assess system-level grid stability requirements and ensure adequate sources to provide essential functions as conventional generation is displaced by VRE. Countries need to evaluate what grid stability services are required across their power system and consider implementing solutions such as synthetic inertia, reactive power support, and grid-forming capabilities based on their specific needs. This may involve deploying monitoring systems such as Phasor Measurement Units (PMU) and Wide Area Monitoring Systems (WAMS) to track system conditions in real-time. Response plans including advanced operational capabilities and emergency protocols should be developed based on system requirements. These capabilities, combined with power flow forecasting for advanced operational planning, enable system operators to maintain reliability and security with very high renewable penetration levels.

Implement practical approaches to address supply chain and climate resilience challenges for grid infrastructure deployment. Transmission lines, substations and interconnectors face significant logistics challenges that can delay projects and increase system costs, particularly when connecting utility-scale solar and wind projects in remote areas. Strategic approaches include adopting modular and scalable grid components that facilitate transport and assembly, implementing supplier-managed inventory models that reduce procurement bottlenecks and establishing regional manufacturing or assembly hubs that shorten delivery times whilst building local technical capacity.

R13: Deploy advanced system transformation capabilities

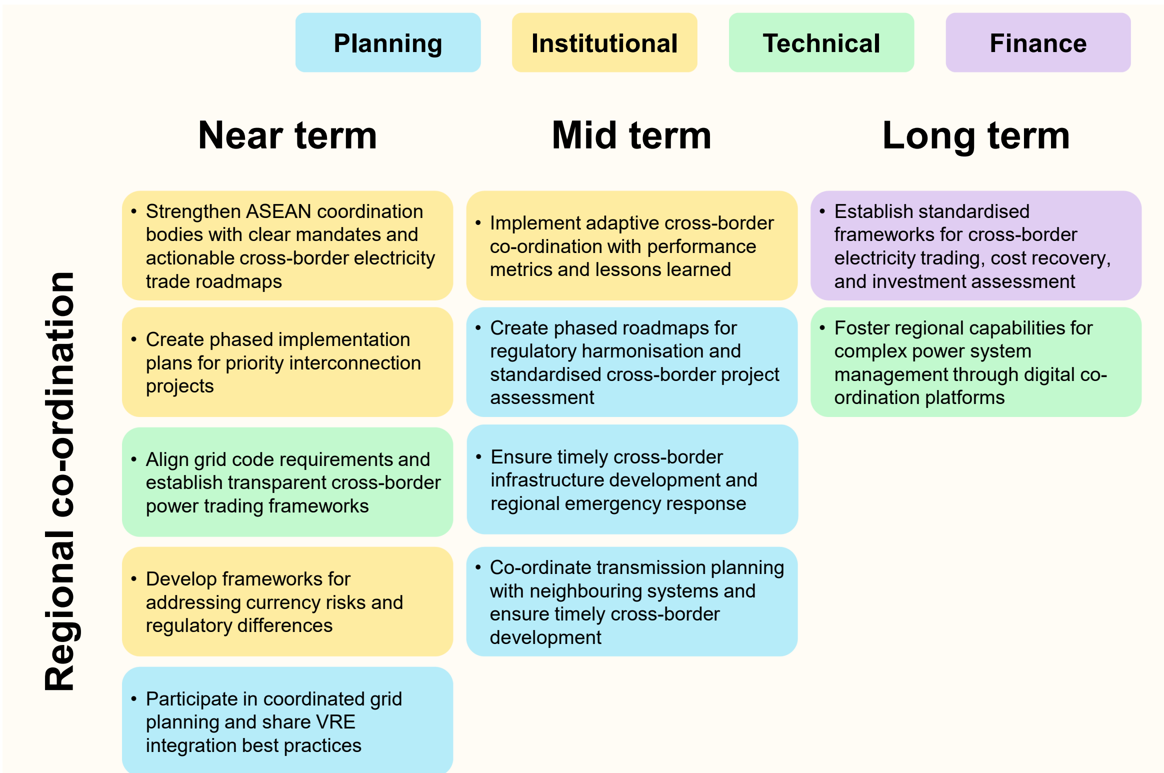
Develop comprehensive power system transformation roadmaps to guide co-ordinated planning of multiple resources. These roadmaps outline the staged deployment of flexibility providers including BESS, pumped hydro storage, long-duration energy storage, vehicle-to-grid services and power-to-hydrogen, while accounting for transmission infrastructure development.

Integrate planning across different sectors to align power system development with decarbonisation and regional energy security objectives. As electrification of transport, heating and industry accelerates, integrated and co-ordinated planning can align grid expansion and flexibility resource deployment with changing demand patterns. Countries approaching high VRE phases need to consider how electricity system transformation interacts with broader economic decarbonisation, ensuring that power system development supports rather than constrains overall decarbonisation efforts.

Regional interconnection

Regional interconnection offers strategic benefits for system optimisation as presented in Chapter 2. While countries pursue individual VRE integration at different paces, regional interconnection runs as a parallel track requiring sustained multilateral effort. The APG initiative provides the institutional framework for this co-ordination, aiming to enhance regional energy security and optimise resource sharing across the region. The inherently cross-border nature of regional interconnection means that progress depends on collective commitment and co-ordinated action rather than individual country readiness. This framework identifies priority actions across near-term (2025-28), medium-term (2028-30) and long-term (beyond 2030) timeframes to build the institutional capabilities, technical standards and cross-border frameworks needed for successful regional integration.

Recommendations regional power interconnection and integration time period



Strengthen regional co-ordination platforms for cross-border electricity trade in the near term (2025-28)

Enhance existing co-ordination platforms to be more effective in planning and implementing large-scale infrastructure for interconnectors with clear mandates, deliverables and timelines to ensure sustained progress in regional integration. These platforms should go beyond high-level dialogues and be structured as working groups or steering committees that enable actionable implementation rather than just policy discussions. Existing ASEAN energy co-ordination bodies like the ASEAN Secretariat, ASEAN Centre for Energy, ASEAN Power Grid Consultative Committee, ASEAN Energy Regulators' Network and Heads of ASEAN Power Utilities/Authorities provide the foundation that can be further strengthened through mechanisms for regular progress reviews and adaptation of strategies. Co-ordination platforms should balance the representation of all participating countries and establish equitable benefits to maintain long-term commitment and political support. Setting a consistent cross-border power trading framework, starting from bilateral trading in the near term, provides the foundation for broader regional market development, as demonstrated by initiatives like the Lao PDR-Thailand-Malaysia-Singapore Power Integration Project.

Developing actionable roadmaps for cross-border electricity trade requires identifying priority interconnection projects based on regional system assessments that consider technical, economic and strategic factors. Establishing phased implementation plans with clear milestones and responsibilities enables the tracking of progress and identification of bottlenecks, as demonstrated by the ASEAN Power Grid Advancement Programme approach to structured regional co-operation. Creating frameworks for addressing the unique challenges of cross-border investments, including currency risks, regulatory differences and cost and risk allocation between participating countries, can help resolve institutional challenges that often delay regional projects. Regional or multilateral institutions can play important roles in facilitating these complex negotiations.

Sustain regional implementation progress through adaptive co-ordination in the medium term (2028-30)

Implement adaptive management approaches that sustain progress in cross-border integration through continuous learning and adjustment. Regional integration requires ongoing co-ordination that can adapt to changing circumstances and emerging challenges. Regular reviews of implementation progress against established milestones enable regions to apply lessons learned and recalibrate approaches and timelines as needed to maintain momentum. Developing performance metrics to track the effectiveness of regional integration efforts, whilst co-ordinating among all stakeholders and related initiatives, helps regions progress towards a common goal. For example, the Agency for the Cooperation of Energy Regulators in Europe demonstrates this adaptive approach through annual monitoring reports that track cross-border capacity utilisation and market integration progress, regularly updating methodologies and recommendations based on emerging challenges such as rising congestion costs and delays in implementing market design changes.

Ensure timely development of grid infrastructure that delivers secure electricity to the growing demand. While grid planning in Southeast Asia currently remains primarily domestic or bilateral, regional bodies can work to co-ordinate and align grid development plans gradually based on evolving regional needs, adjusting timelines and priorities as renewable deployment accelerates and demand patterns change. This ongoing planning process involves continuing efforts to harmonise technical aspects such as grid codes, operating procedures and trading rules to enable secure electricity trade across borders. Even with adaptive planning and technical alignment, securing and optimising funding for priority interconnection projects remain challenging due to complex co-ordination requirements between several parties and many financiers which are not typically set up for this type of investment. National laws and regulations in Southeast Asia are generally not set up to encourage this type of investment and green taxonomies are not typically inclusive of grid-to-grid investments. Australia's "Rewiring the Nation" programme demonstrates how dedicated financing mechanisms can address these challenges, providing finance at concessional rates through the Clean Energy Finance Corporation (CEFC) to minimise the costs of critical grid investments and enable projects that might otherwise struggle to secure funding. Although such fiscal resources may not be readily available in emerging market and developing economies, this model highlights the need for alternative financing mechanisms.

Develop roadmaps to harmonise trading across interconnected borders (beyond 2030)

Establish regional frameworks to enable cross-border trade across different electricity market structures. Fundamental to this are regional co-ordination mechanisms that create compatible trading interfaces between different national electricity systems, harmonise grid codes, align operating standards and co-ordinate transmission planning practices. Where power transits through third countries, there must be consistent wheeling charge methodologies to ensure fair cost allocation for shared infrastructure use. This framework must accommodate both liberalised markets and state-controlled utilities by establishing standardised cross-border operational procedures – including common scheduling timelines, settlement mechanisms and data exchange protocols – that enable different national systems to trade effectively while providing the business case for cross-border transmission infrastructure investment.

Establish common transmission cost recovery principles for investment recovery and regulatory harmonisation. The ASEAN member states will need phased roadmaps for regulatory harmonisation and grid code alignment that enable cross-border electricity trade while respecting national sovereignty and regulatory autonomy, using incremental approaches where grid codes and trading rules are progressively revised and adapted to achieve higher levels of regional integration through step-by-step implementation. In parallel, they must establish regionally-agreed principles for transmission cost recovery that address cases where transmission investments benefit not only the country where the investment takes place but also its neighbours, in a manner comparable to the EU's cross-border cost allocation mechanism. These principles can be implemented domestically according to each country's institutional structure, whether through market mechanisms, regulated tariffs, or government budgets. Standardised approaches for cross-border project assessment and financing that work across different regulatory frameworks must be agreed upon; where power transits through third countries, consistent methodologies for cost allocation and wheeling charges that support bankable investment cases for interconnector development are needed.

Annexes

Annex A. ASEAN member state market frameworks and policy ambitions

Market frameworks and key system operation practices of the ASEAN member states

	Market structure	Procurement of system services	Dispatch interval	Gate closure
Brunei Darussalam	Vertically integrated	No formal market	60-min	N/A
Cambodia	Single buyer	No formal market	60-min	N/A
Indonesia	Single buyer	No formal market	60-min	N/A
Lao PDR	Single buyer	No formal market	60-min	N/A
Malaysia	Single buyer	No formal market	30-min	N/A
Myanmar	Single buyer	No formal market	60-min	N/A
Philippines	Liberalised market	Market + contract	5-min	9-min ahead
Singapore	Liberalised market	Market + contract	30-min	65-min before dispatch
Thailand	Single buyer	No formal market	30-min	N/A
Viet Nam	Single buyer + retail competition	No formal market	30-min	N/A

Notes: Dispatch interval refers to a given time interval in which generators are scheduled to operate. For market-based systems, the dispatch interval determines how often the market operator clears bids and schedules generation. In non-liberalised markets, the dispatch interval refers to the period during which system operators issue dispatch instructions to generators. However, they may re-dispatch at any desired time according to system needs. Gate closure timing is only applicable to liberalised markets. N/A – Not applicable.

Targets and policy measures to support the development of renewable energy in the ASEAN member states

	Renewable target	Carbon neutrality / NZE	Policy measures for renewable energy deployment	Fossil fuel transition
Brunei Darussalam	30% share of renewables in installed capacity by 2035	NZE by 2050	Net metering	Ceasing new permits for and construction of unabated coal-fired generation
Cambodia	70% share of renewables in total installed capacity by 2030	Carbon neutrality by 2050	Tax holidays	

	Renewable target	Carbon neutrality / NZE	Policy measures for renewable energy deployment	Fossil fuel transition
Indonesia	34% share of renewables in total installed capacity by 2034 and 73% by 2060	NZE by 2060	Net metering, tax exemptions	No development of new coal power plants, except for plants that were already included in the RUPTL pipeline.
Lao PDR	30% share of renewables in total energy consumption by 2025 (without large hydropower).	NZE by 2050.	Tax holidays	
Malaysia	30% share of renewables in total installed capacity by 2030, 70% of RE by 2050.	NZE by 2050.	FiT, Green energy tariffs (GET), corporate PPA, solar auctions	No new greenfield coal-fired power plants, accelerating coal phase out by 2045.
Myanmar	9% share of renewables in total installed capacity by 2030, 38% of hydropower in total installed capacity by 2030.	Partial NZE from LULUCF[11] by 2040.	Tax waiver on production and distribution of renewable energy.	
Philippines	35% share of renewables in electricity generation by 2030 and 50% by 2040		FiT, Net metering, green energy auction	Coal moratorium
Singapore	30% of renewables (import) in electricity supply by 2035	NZE by 2050	Corporate PPAs	
Thailand	51% share of renewables in electricity generation by 2037 (based on draft PDP 2024).	Carbon neutrality by 2050, NZE by 2065	FiT, net billing, utility green tariff (UGT), direct PPA (pilot)	No new coal-fired power plants after 2030.
Viet Nam	28-36% of renewables in electricity generation by 2030 and 75% by 2050 (excluding hydro)	NZE by 2050	FiT, Direct PPA	No new coal-fired power plants after 2030.

[11] Land Use, Land-Use Change and Forestry (LULUCF) refers to human activities impacting the carbon cycle of terrestrial ecosystems.

Annex B. Technical note on the phase assessment framework

Overview

This technical note outlines the methodology used to assess the integration of VRE into power systems, as part of the IEA's phases of VRE integration assessment framework. The framework is designed to identify the operational challenges arising from increasing shares of solar PV and wind generation and to support tailored responses across different power system contexts. At the core of these challenges lies the need to maintain a continuous balance between electricity demand and supply - across all time scales, from seconds to minutes, hours and days.

VRE technologies, due to their variable and non-dispatchable nature, introduce fundamental changes to power system operations. Unlike conventional generators, they do not intrinsically provide essential ancillary services such as inertia, short-circuit current and voltage control.[12] At the same time, demand patterns are also evolving due to the electrification of transport and heating, rising cooling loads and the expansion of data centres. Therefore, although the phase assessment focuses on the implications of increasing VRE shares, it also captures the growing impact of changes in electricity demand profiles.

Importantly, the framework concentrates solely on system-level impacts. It does not account for localised issues at specific points of interconnection. The intent is not to offer a prescriptive or exhaustive list of conditions and responses, but rather to serve as a guiding tool to help identify the most likely challenges and corresponding solutions at different stages of VRE integration. Consequently, certain challenges associated with a particular phase may also be observed in systems classified under other phases.

Rather than relying solely on the share of VRE, the assessment considers a wide range of system characteristics such as generation mix, demand profiles, system flexibility and resilience to disturbances. It offers a structured, yet flexible, approach to benchmarking progress and identifying integration priorities, particularly as systems transition towards higher levels of VRE penetration.

In more advanced phases, the assessment also examines the frequency and magnitude of VRE generation surpluses and deficits, i.e. periods when generation either exceeds or falls short of demand. Additional factors influencing the phase classification include ramping needs, load and generation variability, behind-the-

[12] VRE is able to provide ancillary services, such as voltage control and inertial response, if paired with advance controls.

meter (BTM) storage, demand-side response and interconnection capabilities. Notably, at low levels of VRE penetration, modest increases in generation may trigger a phase shift. Conversely, at higher VRE shares, more substantial increases are required, as other system attributes become more significant. The main objective of the framework is to identify system impacts that stem from the integration of VRE.

Rationale

The primary aim of the framework is to identify system-level impacts resulting from the integration of solar PV and wind generation. The framework comprises six phases, each associated with specific operational challenges and corresponding solutions. By situating a system within a particular phase, the framework supports the identification of priority integration measures and fosters knowledge exchange between systems in similar circumstances.

The framework focuses on identifying broader system-level impacts, rather than isolated local incidents. It emphasises net load (load minus VRE generation) dynamics and incorporates contextual factors, such as generation mix and system size. The framework does not prescribe fixed thresholds to denote that a power system is in a particular phase. While the annual share of VRE serves as one of several indicators, short-term variability and system balancing challenges are also considered.

Data sources

For historical assessments, real-time data on electricity demand, solar PV and wind output generation and generation from all other sources are gathered from publicly available sources, typically market or system operation application programming interfaces. In addition, IEA's own modelling outputs – such as demand forecasts, capacity expansion scenarios and simulated hourly operation – are also considered where relevant.

While the assessment is based on a quantitative analysis, it also considers qualitative system characteristics, including policy frameworks, market design and operational practices.

Phase assessment process and considerations

The assessment is primarily quantitative, centred on a set of indicators that evaluate a power system's ability to balance demand and generation across multiple timescales. This includes analysis of hourly and sub-hourly (when available) demand and generation profiles by technology, system ramp rate requirements (i.e. rate at which power output must be increased or decreased) and annual statistics such as total energy consumption and generation by source.

Recognising the evolving nature of electricity usage – driven by the electrification of transport, heating, cooling and industrial processes – the framework also accounts for shifts in demand profiles. Beyond VRE penetration, the phase assessment incorporates broader system characteristics, including the generation mix (e.g. offshore/onshore wind, utility-scale and distributed solar PV), the correlation between VRE output and load patterns, system flexibility across timeframes and resilience to disturbances, particularly those affecting frequency control and system inertia.

For higher phases, the evaluation includes the extent and timing of VRE generation surpluses or deficits (periods when generation exceeds demand or falls short), ramping needs and variability in both load and generation output, impact of BTM generation and storage and demand-side flexibility.

Assessment approach

The phase assessment evaluates system-level challenges across short-term and longer-term intervals. The following key indicators are assessed:

- comparison of demand, solar and wind generation and net demand (demand minus VRE generation)
- ramp rates (hourly and multi-hour ramp rates) and daily flexibility requirements
- peak load versus peak net load, including their respective timing
- large shifts in system inertia due to changes in dispatch on the supply side
- indicators of daily ramping required from dispatchable, non-VRE generation
- estimated curtailment volumes
- incidences and durations of VRE surpluses exceeding local demand
- frequency and duration of VRE deficits, periods where VRE generation is lower than local demand.

These indicators help identify the degree and type of potential operational stresses introduced by increasing the penetration of VRE integration and inform the development of necessary flexibility and operational strategies to ensure a reliable power system.

Annex C. Approach to assess VRE integration readiness

The readiness of each ASEAN member state to integrate variable renewable energy (VRE) was assessed on the basis of key policies and regulatory and operational measures essential to ensure the security and cost-effectiveness of the power system. The assessment considers six main VRE integration measures, each of which consists of a set of specific factors. Each factor was evaluated in the context of each ASEAN member state based on its current policy and regulatory settings to develop a readiness score for each of the six measures.

In our analysis, we evaluated measures and policies in place for the specific country based on publicly available information and inputs from key stakeholders, including government agencies, regulatory bodies, utilities, private sector actors and local experts. Insights were gathered through consultation and targeted surveys.

The measures and the factors considered are outlined below:

Enhancing power plant flexibility: This measure evaluates the flexibility of conventional generation to accommodate VRE. Key factors include:

- retrofitting existing conventional plants,
- flexible fuel contracts and power purchase agreements (PPAs),
- increasing VRE technical requirements.

Accurate forecasting: Accurate forecasting with appropriate time granularity is key to managing uncertainty and variability of VRE generation output and maintaining system stability. The factors assessed include the ability to forecast:

- VRE generation,
- conventional power plants netload,
- power flows.

Implement demand-side measures: Demand-side flexibility plays a vital role in unlocking the full value VRE generation potential. Key factors include:

- industrial, commercial and residential demand response,
- new EV technologies such as smart charging and vehicle-to-grid (V2G),
- planned geographical distribution of VRE generation units.

System operation practices and market framework: This measure focuses on market and operational mechanisms to support VRE integration. Factors include:

- ancillary and balancing services mechanisms,
- VRE curtailment,
- least cost dispatch with short intervals (i.e. sub-hourly) subject to must-run,
- close to real-time gate closure,
- enhancing the use of interconnection.

Mechanisms to enhance grid capacity and use: To enhance grid capacity, there are several factors to be considered, including:

- **Physical capacity expansion:**
  - grid reinforcement and uprating – Increase thermal limits of existing transmission lines,
  - new AC interconnections, grid redundancy and mesh networks – Provide alternative power flow paths and reduce bottlenecks,
  - HVDC transmission – Enable long-distance, high-capacity transfer with lower losses and no stability limits.
- **Technology-enabled capacity optimisation:**
  - FACTS (Flexible AC Transmission Systems) devices (e.g. Static Synchronous Compensator, Synchronous Condenser, Thyristor-Controlled Series Capacitor) – Control power flow and enhance stability to increase transfer capacity,
  - dynamic line rating systems – Increase usable capacity based on real-time thermal conditions,
  - power flow control and congestion management – Optimise utilisation of existing transmission capacity.
- **Operational capacity management:**
  - VRE zoning – Optimise renewable placement to minimise grid constraints,
  - strategic VRE curtailment – Prevent overloading during peak generation periods.

Ways to support the integration of VRE: storage options can support VRE grid integration. This measure considers the deployment and use of pumped storage hydropower and battery energy storage systems (BESS).

Emerging measures: We collected information about emerging measures in the region. We considered pilot projects, announced plans and measures underway. Our results highlight active areas for VRE policy improvements.

Emerging measures for VRE integration in Southeast Asia

VRE Integration Measures	Emerging measures
Enhancing power plant flexibility	Initial
Accurate forecasting	Active
Implementing demand-side measures	Initial
System operational practices and market framework	Initial
Enhancing grid capacity	Initial
Deploying storage	Active

Legend: Initial; Active

Annex D. Priority technical standards and operational improvements

Priority technical standards and operational improvements

Technical area	Key Requirements	Implementation Benefits	Regional Status & Examples
Generation Connection Standards	• Fault ride-through during disturbances • Voltage and reactive power control • Communication interfaces (IEC 61850 standard) • Grid codes regularly reviewed and updated to reflect evolving system needs	• Supports grid to maintain stability • Enables VRE plants to provide grid services • Effective co-ordination and control between VRE plants and system operators • Protects current system while preparing for future needs	• Malaysia: Guidelines for large-scale solar plants with voltage control, frequency range, fault ride-through • Thailand: Requirements for solar and wind including BESS • Philippines: Reactive power support and power quality standards for renewable energy facilities • Brunei: Code of Practice for Large Scale Solar PV Plant Connection to Distribution Grid, Code of Practice for Small Scale Photovoltaic System Connection to Low Voltage Network, National Grid Code for Grid Code Requirements and Electrical Installation Regulation (EIR) • International reference: IEEE-2800 standard provides framework for grid interconnection technical requirements
Compliance and Monitoring	• Compliance-testing procedures • Certification processes for VRE equipment • Ongoing monitoring frameworks to ensure continued compliance	• Ensures installations actually meet safety and performance standards • Maintains required performance throughout plant lifetime • Verifies ongoing compliance with grid code requirements	• Limited specific regional examples of comprehensive compliance frameworks • Need for standardised testing and certification processes across the region • Ongoing compliance monitoring throughout plant lifetime required

Technical area	Key Requirements	Implementation Benefits	Regional Status & Examples
VRE Forecasting Systems	• Multi-timeframe forecasting (days to minutes) • Enhanced time resolution capabilities • Integration with dispatch systems	• Reduces operational uncertainty • Optimises existing plant dispatch • Minimises system balancing costs	• Philippines, Singapore, Malaysia and Thailand have established systems • Room for improvement: Most systems only forecast days to 6 hours ahead • Example: Malaysia: Guidelines require only day-ahead forecasts at 15-minute resolution
Real-time Monitoring	• Wide Area Monitoring Systems (WAMS) • Dynamic Line Rating (DLR) • Flexible AC Transmission Systems (FACTS) • Real-time grid monitoring systems	• Maximise transfer capacity of existing transmission lines • Provides real-time system visibility	• Cost-effective technologies available • Can maximise existing transmission capacity without major new investments
Contract Flexibility	• Embedding flexibility requirements in new contracts • Avoid rigid take-or-pay obligations • Incentives for ramping and part-load capabilities	• Enables response to system variability • Reduces long-term system costs • Avoids limitations from inflexible agreements	• Issues include fuel cost pass-throughs and limited operational flexibility • Indonesia, Thailand, Viet Nam, Philippines, Lao PDR face limitations from inflexible contracts • Hydropower plants that are inherently flexible are underutilised due to rigid PPAs and competing water management priorities • Thailand: Daily take-or-pay gas supply obligations limit flexibility • Issues include fuel cost pass-throughs combined with dispatch not based on marginal costs and low reserve margins causing coal plants to run continuously, reducing incentives for efficient fuel procurement • Pilot approach: Design pilot projects for utilities to test flexible operations with select plants (as demonstrated in India) to build experience and calibrate contractual terms

Annex E. Detailed recommendations by action type

Foundational actions (recommendations R1-R4)

Nr.	Recommendation	Target countries	Key action	Expected outcomes
R1	Set policy frameworks for continued VRE growth (targets and procurement)	All countries (Priority: Early stage)	• Set ambitious VRE targets with milestones • Implement competitive procurement (auctions, corporate PPAs) • Remove VRE deployment barriers • Establish policy continuity mechanisms	• Clear investment signals • Cost-effective deployment • Sustained policy support
R2	Set energy efficiency policies and demand response ready standards	All countries (Priority: Early stage)	• Establish energy efficiency standards to reduce electricity consumption • Update appliance standards and building codes with demand response ready features	• Peak demand reduction • Grid-response ready BTM equipment
R3	Build basic operational capabilities	All countries (Priority: Early stage)	• Implement VRE forecasting • Apply economic dispatch principles • Install optimisation hardware/software • Train operational staff	• Efficient resource utilisation • Operational foundations • Readiness for higher phases
	Establish technical standards, grid codes and compliance frameworks	All countries (Priority: Early stage)	• Specify VRE technical requirements • Align with international standards • Establish compliance monitoring • Create certification processes	• Secure VRE integration • Standardised equipment • Regional interoperability
R4	Co-ordinate grid infrastructure planning	All countries (Priority: Early stage)	• Active government-utility co-ordination • Scenario-based grid planning • Clear development timelines • Regional interconnection consideration	• Robust infrastructure investment • VRE-compatible grid development • System reliability maintained

Enabling actions (recommendations R5-R9)

Nr.	Recommendation	Target countries	Key action	Expected outcomes
R5/R6	Develop flexibility procurement mechanisms	Mid to high readiness (Essential: Phase 3)	• Create investment signals for flexibility • Design competitive procurement • Enable new business models • Attract private sector participation	• Diverse flexibility sources • Cost-effective solutions • Private investment mobilised
R7	Enhance grid infrastructure and digitalisation	Mid to high readiness (Essential: Phase 3)	• Implement grid capacity expansion • Deploy real-time monitoring • Upgrade operational procedures and grid codes • Enable higher granularity dispatch	• System flexibility is visible and accessible • Operational responsiveness • VRE provides system support
R8	Enable flexible operation of conventional power plants	Mid to high readiness (Essential: Phase 3)	• Set contract conditions that do not discourage flexible operation • Retrofit power plants to enhance flexible operation capabilities	• More flexibility extracted from conventional power plants
R9	Reform system adequacy assessments	Mid to high readiness (Essential: Phase 3)	• Adopt stochastic approaches • Consider flexibility resources • Include demand-side options • Update planning criteria	• Accurate system planning • Optimised capacity mix • Cost-effective adequacy

Transformational actions (recommendations R10-R13)

Nr.	Recommendation	Target countries	Key action	Expected outcomes
R10	Map out policies for power system transformation	High readiness (Essential: Phase 4+)	• Develop comprehensive flexibility deployment roadmaps • Quantify flexibility needs and deployment timelines • Consider procurement methods for different flexibility options	• Co-ordinated flexibility deployment
	Steer VRE development with grid planning	Mid to high readiness (Essential: Phase 3)	• Co-ordinate VRE siting decisions • Streamline permitting processes • Consider grid constraints • Enable system-friendly deployment	• Grid-compatible development • Reduced integration costs • Enhanced system stability

Nr.	Recommendation	Target countries	Key action	Expected outcomes
R11	Align market and regulatory reforms with system transformation	High readiness (Essential: Phase 4+)	• Implement targeted market reforms within current frameworks • Create transparent mechanisms to value system services • Accommodate new technologies (BESS, grid enhancing devices)	• Efficient market mechanisms • Clear regulatory frameworks • Technology integration support
	Reform markets and tariff structures	High readiness (Essential: Phase 4+)	• Value system services transparently • Reform tariff structures • Balance cost recovery with affordability • Enable sustainable finance access	• Efficient price signals • Sustainable financing • Consumer protection
R12	Build advanced operational capabilities	High readiness (Essential: Phase 4+)	• Develop forecasting for complex systems • Co-ordinate diverse flexible resources • Integrate planning across sectors • Build workforce capabilities	• Complex system management • Operational excellence • Future-ready capabilities
	Ensure adequate grid stability services	High readiness (Essential: Phase 4+)	• Assess system-level grid stability requirements • Implement synthetic inertia and reactive power support • Deploy monitoring systems (PMU, WAMS) • Develop response plans and emergency protocols	• Maintained system reliability • Grid stability with high VRE • Real-time monitoring capabilities
	Develop supply chain resilience	High readiness (Essential: Phase 4+)	• Adopt modular grid components • Implement inventory management • Establish regional manufacturing • Build climate resilience	• Reliable project delivery • Reduced logistics costs • Regional capacity building
R13	Deploy advanced system transformation capabilities	High readiness (Essential: Phase 4+)	• Integrate planning across different sectors • Align with decarbonisation and energy security objectives • Enable cross-sector integration	• Co-ordinated multi-resource planning • Cross-sector integration • Comprehensive decarbonisation support

Regional co-ordination (recommendations R14-R16)

Nr.	Recommendation	Target countries	Key action	Expected outcomes
R14	Strengthen regional co-ordination platforms	All ASEAN countries	• Enhance existing co-ordination bodies • Create actionable working groups • Develop progress tracking • Ensure equitable participation	• Effective regional co-operation • Sustained implementation • Collective benefits
R15	Develop cross-border trading frameworks	All ASEAN countries	• Start with bilateral trading • Address investment barriers • Secure project financing • Build technical capabilities	• Regional market development • Enhanced energy security • Cost optimisation
R16	Harmonise technical standards progressively	All ASEAN countries	• Align grid codes gradually • Establish cost recovery principles • Create compatible interfaces • Respect national sovereignty	• Seamless regional integration • Fair cost allocation • Market harmonisation

Abbreviations and acronyms

AC	Alternating Current
ACE	ASEAN Centre for Energy
ADMS	Advanced Distribution Management Systems
AERN	ASEAN Energy Regulators Network
AGC	Automatic Generation Control
AIMS	ASEAN Interconnection Masterplan Study
AMS	ASEAN Member States
APAEC	ASEAN Plan of Action on Energy Cooperation
APG	ASEAN Power Grid
APGCC	ASEAN Power Grid Consultative Committee
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
ASPA	Ancillary Service Procurement Agreement
ATS	ASEAN Targets Scenario
BAS	Baseline Scenario
BESS	Battery Energy Storage Systems
BIMP-PIP	Brunei Darussalam-Indonesia-Malaysia-Philippines Power Integration Project
BRN	Brunei Darussalam
BTM	Behind-the-Meter
C&I	Commercial and Industries

CEFC	Clean Energy Finance Corporation
CGPP	Corporate Green Power Programme
CNS	Carbon Neutrality Scenario
CREZ	Competitive Renewable Energy Zones
DAP	Delivered at Place
DERMS	Distributed Energy Resource Management Systems
DLR	Dynamic Line Rating
DMS	Distribution Management Systems
DPPA	Direct Power Purchase Agreement
EENS	Expected Energy Not Served
EGAT	Electricity Generating Authority of Thailand
EIR	Electrical Installation Regulation
EMS	Energy Management Systems
ESP	Spain
EV	Electric Vehicle
FACTS	Flexible AC Transmission Systems
FiT	Feed-in Tariff
FOB	Free on Board
GBR	Great Britain
GEA	Green Energy Auction
GET	Green Electricity Tariff
GSO	Grid System Operator
HAPUA	Heads of ASEAN Power Utilities/Authorities
HVDC	High Voltage Direct Current
IDN	Indonesia
IEA	International Energy Agency
IND	India
IRL	Ireland
ITA	Italy
JPN	Japan
KHM	Cambodia
KOR	Korea
LAO	Lao PDR
LCOE	Levelised Cost of Electricity
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
LSS	Large-Scale Solar
LTMS-PIP	Lao PDR-Thailand-Malaysia-Singapore Power Integration Project
LULUCF	Land Use, Land-Use Change and Forestry
MER	Market Exchange Rates
MMR	Myanmar
MYS	Malaysia
NGCP	National Grid Corporation of the Philippines
NZE	Net Zero Emissions
OCCTO	Organisation for Cross-regional Coordination of Transmission Operators

OLTC	On-Load Tap Changers
PDP	Power Development Plan
PDR	People’s Democratic Republic
PHL	Philippines
PMU	Phasor Measurement Unit
PPA	Power Purchase Agreement
PSH	Pumped Storage Hydropower
PV	Photovoltaic
RAS	Regional Aspirational Scenario
RE	Renewable Energy
REC	Renewable Energy Certificate
RUKN	National Energy General Plan (Indonesia)
RUPTL	Rencana Umum Perencanaan Tenaga Listrik (Indonesia's National Electricity Business Plan)
SAIDI	System Average Interruption Duration Index
SCADA	Supervisory Control and Data Acquisition
SGP	Singapore
SOE	State Owned Enterprise
STEPS	Stated Policies Scenario
TFC	Total Final Consumption
THA	Thailand
TNB	Tenaga Nasional Berhad
ToP	Take or Pay
TPES	Total Primary Energy Supply
UGT	Utility Green Tariff
USA	United States of America
V2G	Vehicle-to-Grid
VNM	Viet Nam
VRE	Variable Renewable Energy
WAMS	Wide Area Monitoring Systems

Glossary

GW	gigawatt
GWh	gigawatt hour
kW	kilowatt
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour
TW	terawatt
TWh	terawatt hour
USD	United States Dollar

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Typeset in France by IEA - September 2025
Cover design: IEA
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