

8. Variable renewable electricity: challenges and integration costs

Decarbonisation requires adding vast amounts of non-carbon emitting power sources. In particular, solar photovoltaics (PV) and wind have been expanding significantly in recent years as their costs have come down considerably with progress in technology and economies of scale. Expectations for continued expansion of solar PV and wind remain high, and IEEJ Outlook 2026 projects that electricity generated from variable renewable energy will expand by about five times between now and 2050 in its Reference Scenario and by about seven times in its Advanced Technologies Scenario.

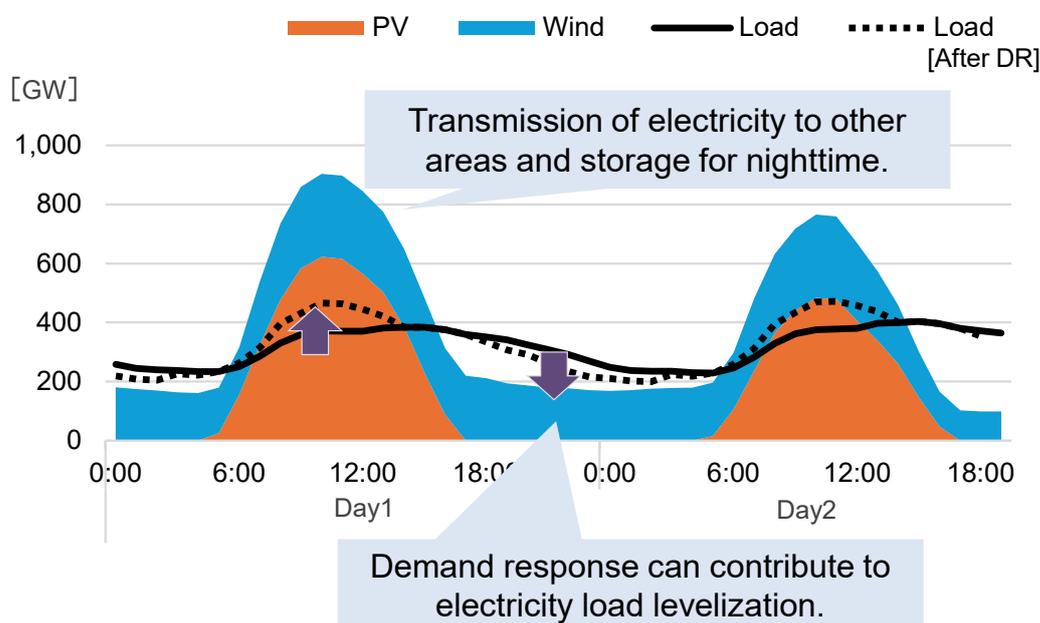
Solar PV and wind are sometimes referred to as variable renewable energy (VRE) as their power output is affected by natural conditions. As VRE deployment increases, there is a need for the electricity and energy systems to adapt to the increase in VRE. The costs necessary for this adaptation are called integration costs. This chapter describes the idea of integration costs as a challenge associated with the expansion of VRE and presents examples of analysis.

8.1 Challenges of VRE expansion

Response to output fluctuations and stable supply of electricity

As the power output from VRE fluctuates based on natural conditions, it is important to predict output and respond to changes in real time to maintain a stable supply of electricity. For example, in some countries and regions today (such as the Kyushu region of Japan), some power plants are subject to output curtailment during periods when VRE electricity supply is in surplus. Occasional electricity supply-demand tightness has also occurred when natural conditions caused VRE output to plunge and backup thermal power plants experienced unplanned shutdowns. As such, when introducing large amounts of VRE, it is essential to operate conventional power sources like thermal power generation flexibly to ensure the stable functioning of the power system. In addition, the use of technologies capable of instantly restoring the power supply-demand balance, such as power interchanges with other regions via transmission networks, demand-side load balancing (demand response) and storage batteries is being considered (Figure 8-1).

Figure 8-1 | An illustrative example of mass introduction of VRE and response by power systems



Source: IEEJ Outlook 2025

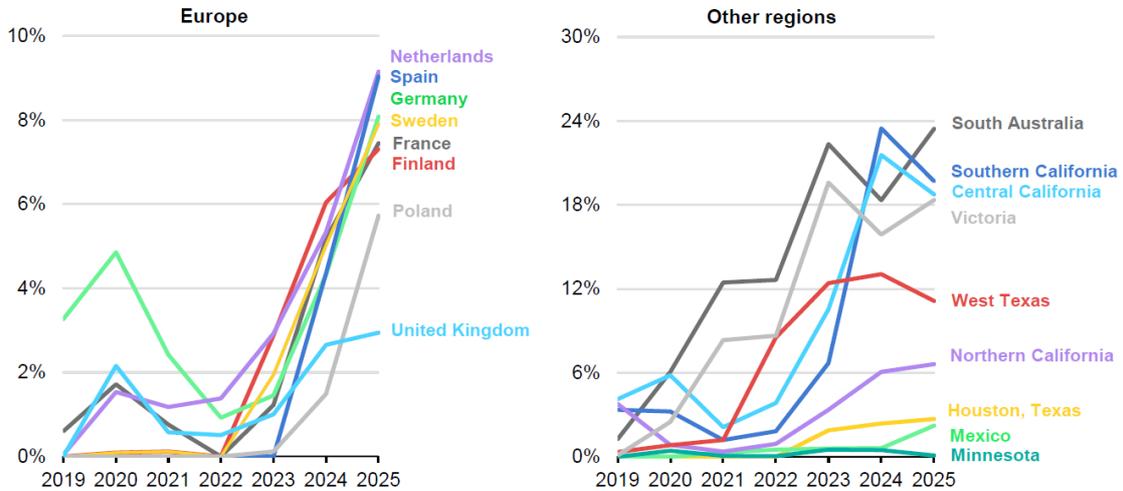
Shortage of power system flexibility and impact on the electricity market

One impact of VRE expansion is the effect on the electricity market. A notable example is negative pricing, in which wholesale electricity market prices become negative. According to the International Energy Agency (IEA) (2025), negative prices in wholesale electricity markets are still relatively rare on a global basis but have been increasing in some regions in recent years.

For example, in South Australia, which had an annual VRE share of around 65% in 2023, prices were negative for around 25% of the annual trading time in the wholesale electricity market. Similarly, in Texas, where the annual share of VRE was around 33% in 2023, prices were negative for around 10% of the annual trading time. While negative market prices do spur electricity consumption and urge consumers to utilise load balancing in situations of excess electricity supply, they are also known to worsen market revenues and in turn negatively impact investments in power sources.

IEA (2025) noted that negative prices are a result of wider fluctuation ranges in wholesale prices caused by insufficient system flexibility. It also noted that to respond to VRE output fluctuations, it is important to ensure power system flexibility by utilising thermal power generation and demand-side load balancing.

Figure 8-2 | Cases of negative prices in the wholesale electricity markets around the world



IEA. CC BY 4.0.

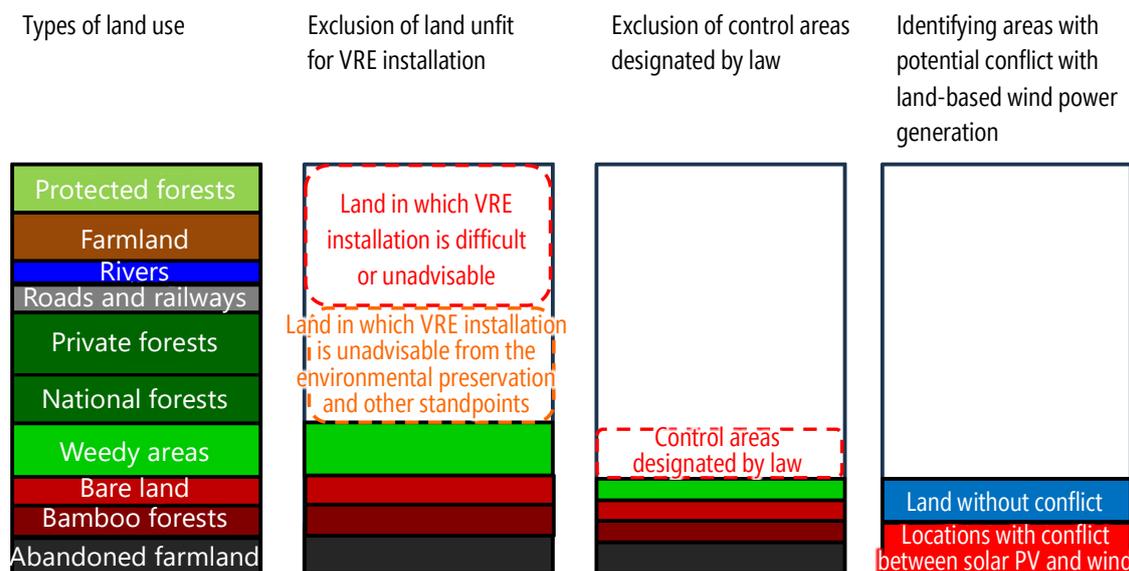
Source: IEA (2025), *Electricity Mid-Year Update 2025*, IEA, Paris <https://www.iea.org/reports/electricity-mid-year-update-2025>, Licence: CC BY 4.0

Constraints on resource development and land use

The availability of renewables, not limited to VRE, is affected by natural and land conditions. Regions with favourable conditions and a high energy supply potential tend to be concentrated in nature-rich areas. For instance, much of the supply potential for wind power generation is found in mountainous regions and offshore areas with favourable wind conditions that are often located far away from demand centres such as cities. This makes it necessary to build new power systems when developing these resources.

Furthermore, because developing this supply potential can disrupt harmony with the natural environment and other land uses (Figure 8-3), these factors must be considered when assessing supply potential to achieve sustainable renewable energy development. Renewable energy development usually starts in locations that are relatively easy to access from a regulatory perspective, and such sites become scarcer as projects advance. As a result, additional costs, such as those for power grid construction and environmental protection, tend to increase with time.

Figure 8-3 | Sample method for evaluating VRE plant locations



Source: 67th meeting of the Large-scale Renewable Energy Introduction and the Next-Generation Power Network, Committee on Energy Efficiency and Renewable Energy/Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy, Material 3; explanatory material by the IEEJ/Yokohama National University (2024)

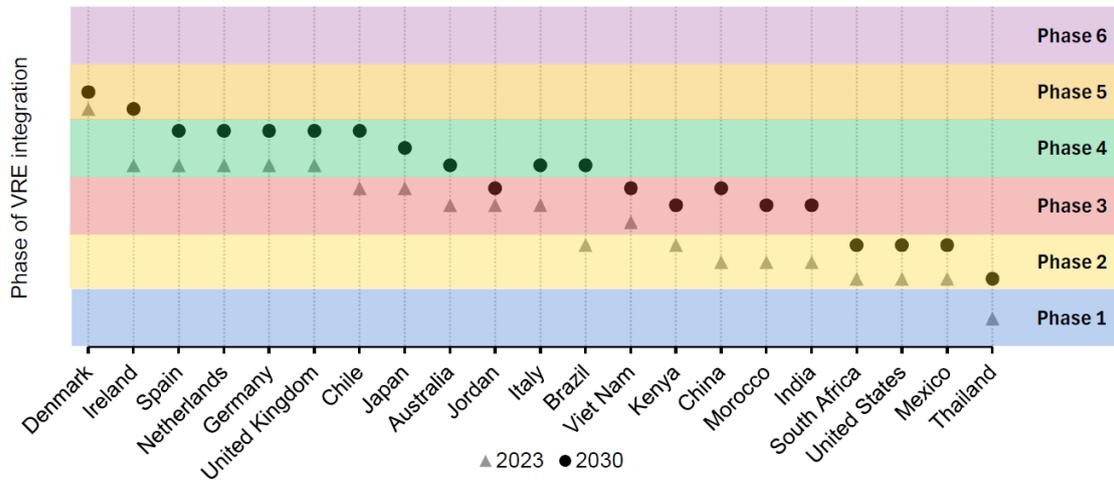
VRE grid integration challenges

IEA (2024) classifies countries by phase based on their progress in introducing VRE and other renewables, taking into account the stable supply capability of their power systems, market impact and other factors. For example, Denmark is categorised in Phase 5, an advanced phase of VRE introduction, because it can cover its electricity demand with VRE (especially wind) for almost all hours of the year. Meanwhile, Japan is lower than Denmark in Phase 3 and is expected to move up to Phase 4 in 2030 as more VRE is introduced.

The IEA expects that countries will move up in phases and notes that the measures required for their power systems will change depending on the phase.

In addition to technological and institutional measures, cost-related measures will be important going forward. The costs required for integrating a power source into the power system are essential, and these costs are referred to as integration costs. In introducing VRE, it is important to identify the integration costs as a metric that accounts for the nature of each power source, and integration costs are increasingly recognised as a challenge for the wider adoption of VRE.

Figure 8-4 | Phases of variable renewable energy introduction



IEA. CC BY 4.0.

Note: The phase assessments for 2030 are based, among other factors, on VRE forecasts that will be presented in the upcoming Renewables 2024 report.

Source: IEA (2024), *Integrating Solar and Wind*, IEA, Paris <https://www.iea.org/reports/integrating-solar-and-wind>, Licence: CC BY 4.0

8.2 Integration costs

Power system integration costs

In addition to the costs associated with power sources themselves, the Organisation for Economic Co-operation and Development (OECD)³⁷ notes that the following integration costs will be necessary.

- **Profile costs:** The costs for changing the operations of dispatchable power stations to address a supply-demand mismatch resulting from a deviation of power station output from the plan.
- **Balancing costs:** The costs arising from operating dispatchable power stations in grid-balancing mode to address brief output prediction errors lasting for a few seconds to a few minutes and brief output fluctuations.
- **Grid-related costs:** The costs for building core transmission networks connecting power plant locations and demand areas, and for installing power cables connecting power plants with the electric power grid.

Various approaches are being studied for analysing the power system integration costs based on these cost classifications, as shown in Table 8-1. The approaches have different focuses, such as the change in overall costs of the power system and the value of a power source in the market, thereby ensuring that integration costs are assessed from a variety of perspectives.

³⁷ OECD/NEA (2018) "The Full Cost of Electricity Provision"

Table 8-1 | Integration cost-related indicators and examples of analysis methods

Indicator	Description	Example of analysis
Integration cost, system cost	The cost obtained by subtracting the amount proportional to the levelised cost of electricity (LCOE) from the total cost of the power sector. There are many cases of evaluation for various regions around the world.	
System value	An indicator for evaluating the contribution of each power source to the power market. It is advocated in the IEA report "Next Generation Wind and Solar Power" (2016).	IEA
Levelised avoided cost of electricity (LACE)	An indicator proposed by the U.S. Department of Energy (DOE) and the Energy Information Administration (EIA). LACE indicates the economic advantage of a certain technology by considering the costs that would be avoided when a certain power source is introduced into the power system.	U.S. DOE/EIA, Levelized Costs of New Generation Resources in the Annual Energy Outlook (annual editions)
Enhanced levelized cost/wider system impact	This indicator expands the traditional LCOE to incorporate the marginal costs of a power source. Rather than a simple cost comparison, it enables evaluations that incorporate the impact on the power market.	Department for Business, Energy and Industrial Strategy (BEIS), Electricity Generation Costs 2020, etc.
System LCOE	This indicator is based on the marginal cost of each power source and is known to be effective for evaluating the impact of increasing new renewable capacities on the power market. By adding on the difference between marginal unit prices of each power source and demand to LCOE, the impact on the overall power system is incorporated more accurately.	Hirth et al., 2016 and others
Marginal system LCOE	This is an indicator that is based on the marginal cost of each power source and is used to compare and analyse certain power sources. It is used especially to compare two types of technologies in terms of relative economic efficiency.	Ueckerdt et al., 2013; Reichenberg et al., 2018 and others

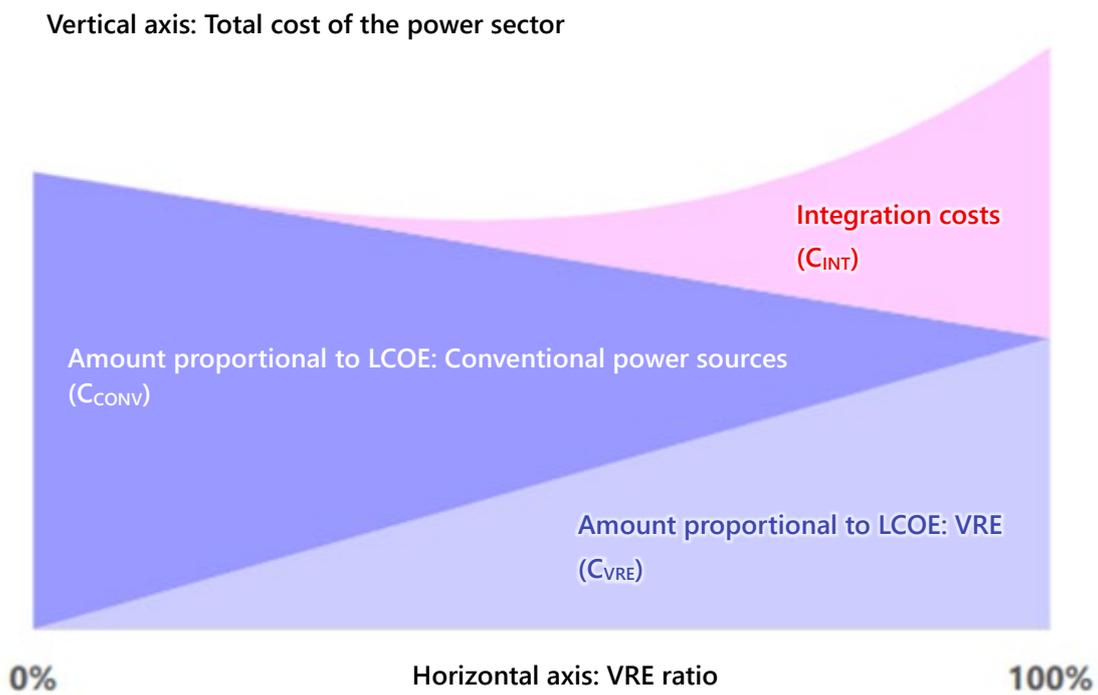
Indicator	Description	Example of analysis
Relative marginal system LCOE/ average system LCOE	This indicator evaluates the integrability of a power source and its value in the market based on its marginal cost and average cost.	Matsuo and Komiyama, 2021

Source: Created based on Matsuo (2021), Assessment of costs by power source with a focus on OECD/NEA and IEA reports

Optimal power generation mix integration costs

In considering the future power generation mix and evaluating its economic efficiency, it is important to assess total system costs including integration costs, in addition to the costs of each power source itself. Matsuo (2025) notes that when including the costs for integrating a power source into the power system (integration cost) in the evaluation, there is an optimal combination of power sources in terms of costs (Figure 8-5).

Figure 8-5 | Conceptual diagram of power generation costs (LCOE) and integration costs



Source: First meeting of the Power Generation Cost Verification Working Group, Material 1, Material 5 Overview of Assessment by Power Generation Cost Verification Working Group (material submitted by Committee Member Matsuo (2024)

With technological progress, the generation cost of renewables per 1 kWh of output (LCOE) is now lower than that of conventional power sources. As such, there are high expectations for replacing conventional power sources with new renewable capacities on cost-competitiveness grounds. This means that C_{CONV} will be gradually replaced by C_{VRE} as shown in Figure 8-5.

Meanwhile, additional costs for installing battery systems and reinforcing the grid will arise as VRE is introduced in large amounts. As a result, costs represented by C_{INT} in Figure 8-5 will be necessary for some power sources in addition to their development costs.

8.3 Power generation including integration costs

Assessing the power generation mix with integration costs

To analyse the integration costs with incremental amounts of variable renewable energy (VRE), we identified the power generation mix that produces the smallest energy system costs for the Association of Southeast Asian Nations (ASEAN) as a whole using a model that analyses the entire energy system.

For the analysis, the NE_ASEAN model³⁸, a linear planning model co-developed by the IEEJ and the Otsuki Group at Yokohama National University based on the NE_Japan model developed by the Otsuki Group, was used. The amount of VRE capacity to be introduced by 2060 and its integration costs were analysed based on the assumption that each country will reduce greenhouse gas (GHG) emissions in line with the Nationally Determined Contributions (NDCs).

Analysis of power generation mixes including integration costs

For nations to reduce their GHG emissions in line with their NDCs, introducing decarbonised energies is essential. Based on the conditions of this estimation, ASEAN's energy system costs are estimated to be the lowest in 2060 when the VRE share is around 30%. Using this result as the baseline, we charted the system costs for higher and lower shares of VRE.

Facility and fuel costs for conventional power generation decrease as VRE increases from the baseline. On the other hand, the costs for introducing VRE itself increase, along with additional costs for integration, such as those for storage batteries (Figure 8-6). For example, when the share of VRE is raised to 60% for ASEAN as a whole, the costs would increase by 300 billion dollars between 2030 and 2060, as opposed to a much greater increase of \$1.3 trillion if the share is raised to 80%.

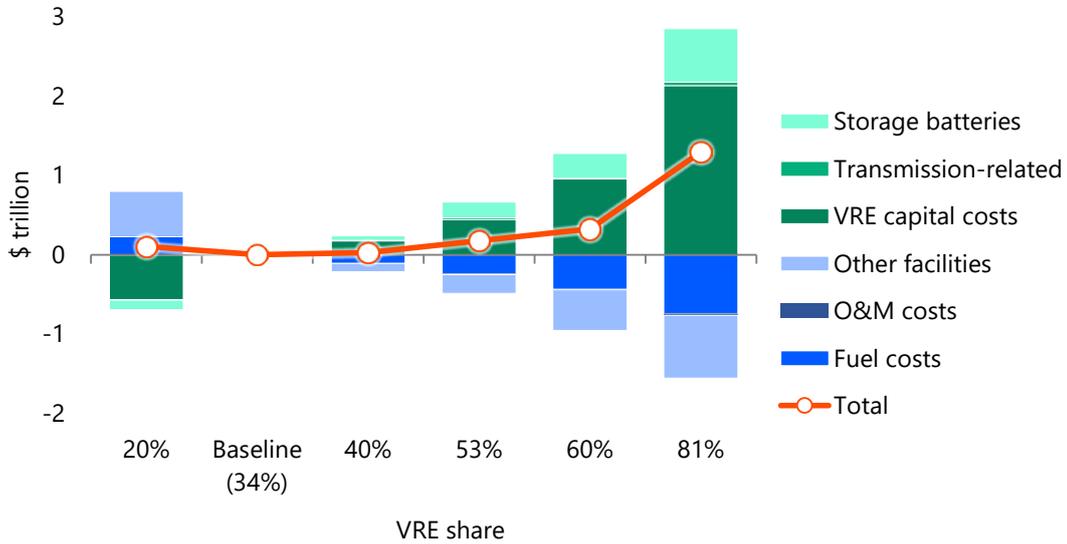
To promote the energy transition required to decarbonise the ASEAN region, ASEAN-wide collaboration and cooperation are essential, alongside strengthening efforts within each country. Meanwhile, attention must be paid to the potentially significant differences in additional costs between countries. Behind these gaps lie variations in geographical and natural conditions and the availability of infrastructure, between the ASEAN nations, resulting in major disparities in their abilities to add more VRE (Figure 8-7). The impact of the cost increase associated with adding VRE is particularly significant in Indonesia, Viet Nam and Thailand, which have large populations and economies.

Here we present an analysis of different shares of VRE and integration costs. Some ASEAN nations are rich in non-VRE renewables, such as hydro and geothermal resources. Meanwhile, the ability to bear additional costs associated with reaching carbon neutrality varies between nations depending on their economic circumstances and national scale. To utilise VRE and other

³⁸ The IEEJ-NE_ASEAN model analyses the combination of energy technologies, including power generation and storage facilities, that minimises the overall cost of the energy system. See below for an overview of the model and an example analysis. IEA (2023), *Decarbonisation Pathways for Southeast Asia*, IEA, Paris <https://www.iea.org/reports/decarbonisation-pathways-for-southeast-asia>, Licence: CC BY 4.0

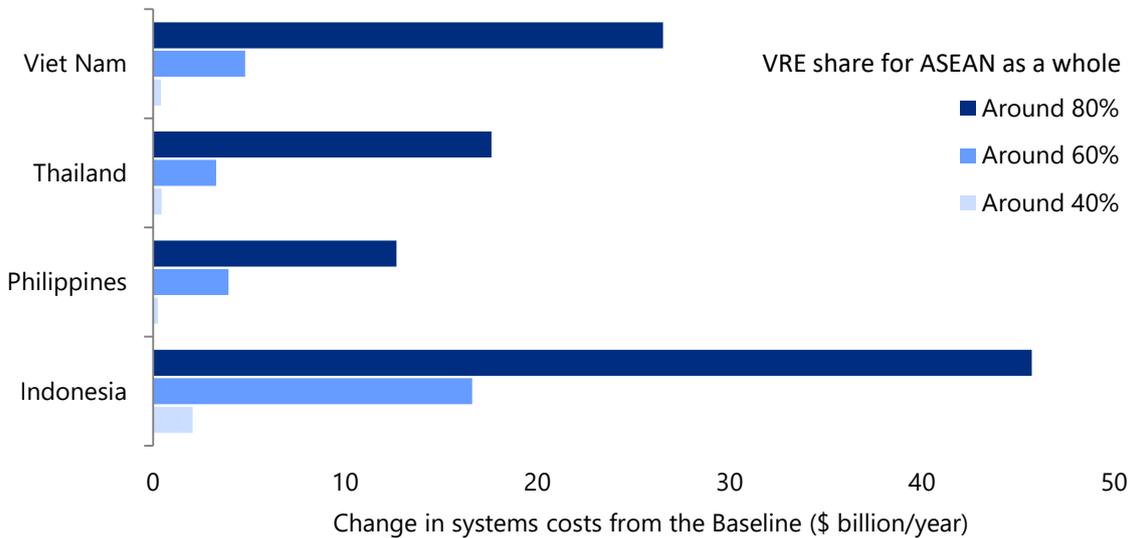
renewable energies even further, alongside cross-border cooperation, it is essential for each country to decarbonise through a pathway that suits its individual circumstances.

Figure 8-6 | VRE shares and system costs in ASEAN [total for 2030–2060]



Notes: The assumptions for international and other key transmission lines are based on the maximum scale of grid development being considered under the ASEAN Power Grid initiative. All numbers are in real terms; 2017 prices.

Figure 8-7 | VRE shares and system costs in ASEAN [2060]



Notes: The assumptions for international and other key transmission lines are based on the maximum scale of grid development being considered under the ASEAN Power Grid initiative. All numbers are in real terms; 2017 prices.