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IEEJ Outlook 2026
-Evaluating the Integration Costs and Deployment Potential of Variable Renewable Energy-

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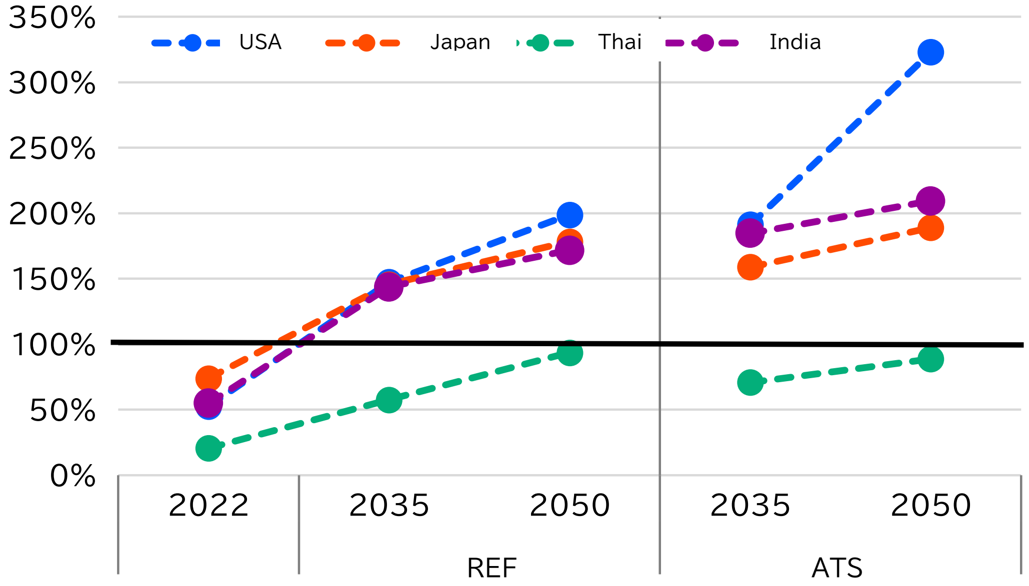
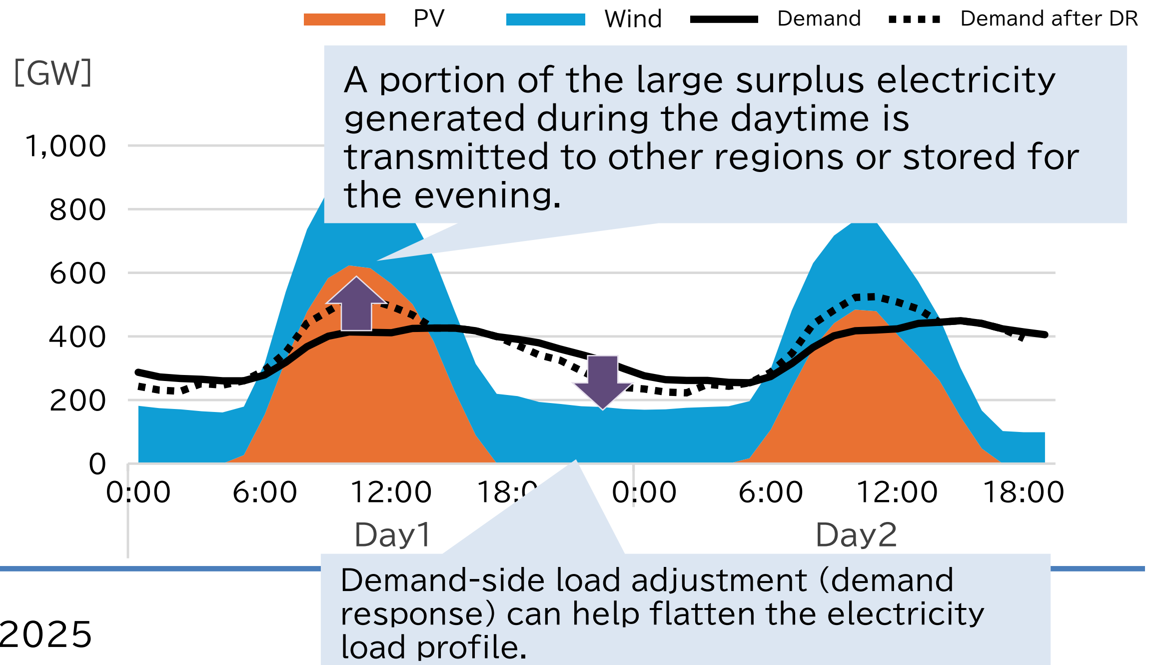
Rising VRE Penetration and the Changing Supply-Demand Balance in the Power System

- The IEEJ Outlook 2026 projects that under the Reference Scenario(REF), VRE power generation will increase approximately fivefold from current levels to 2050, rising to approximately sevenfold under the Advanced Technologies Scenario(ATS).
- As VRE scales toward decarbonization, the electricity supply–demand balance will shift significantly — as already seen in regions with high solar penetration, where daytime and nighttime conditions diverge sharply.
- Power systems must therefore be designed to manage VRE fluctuations through accurate forecasting, flexible operation of power generation, storage deployment, and grid reinforcement.

Ratio of Installed VRE Capacity to Average Annual Electric Load [GW]



Gap Between Solar/Wind Output and Power Demand (Illustrative) ATS– India, 2050 (August)



Source:IEEJ Outlook 2025

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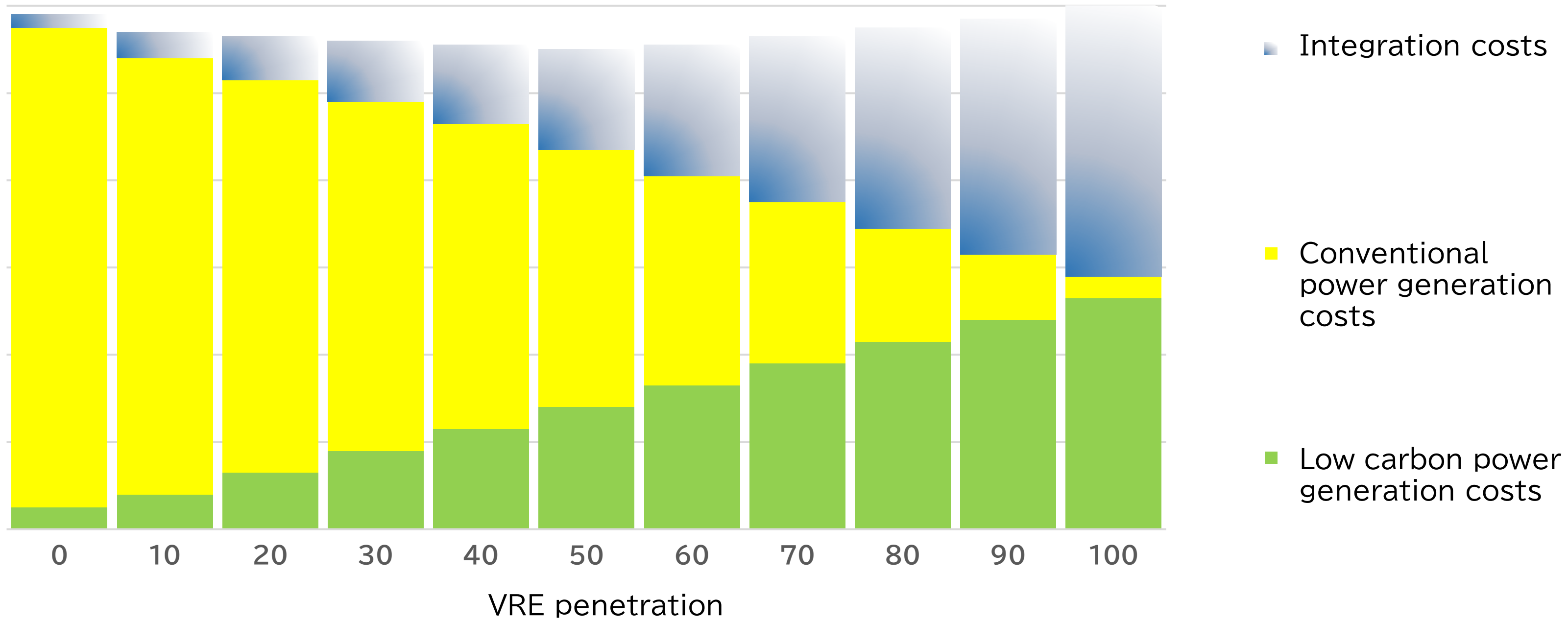
VRE Deployment and the Evolution of Integration Costs

- When integrating a power source, additional system costs beyond its generation cost — known as integration costs — are incurred. These include expenses for grid reinforcement and storage.
- As VRE penetration rises, it is crucial to account for these growing integration costs and assess the total system cost to achieve an optimal balance.

Illustrative image: Growth in VRE deployment vs. system cost trajectory



Source：Author, based on Matsuo (2021) and The Working Group on Power Generation Cost Verification (2025)

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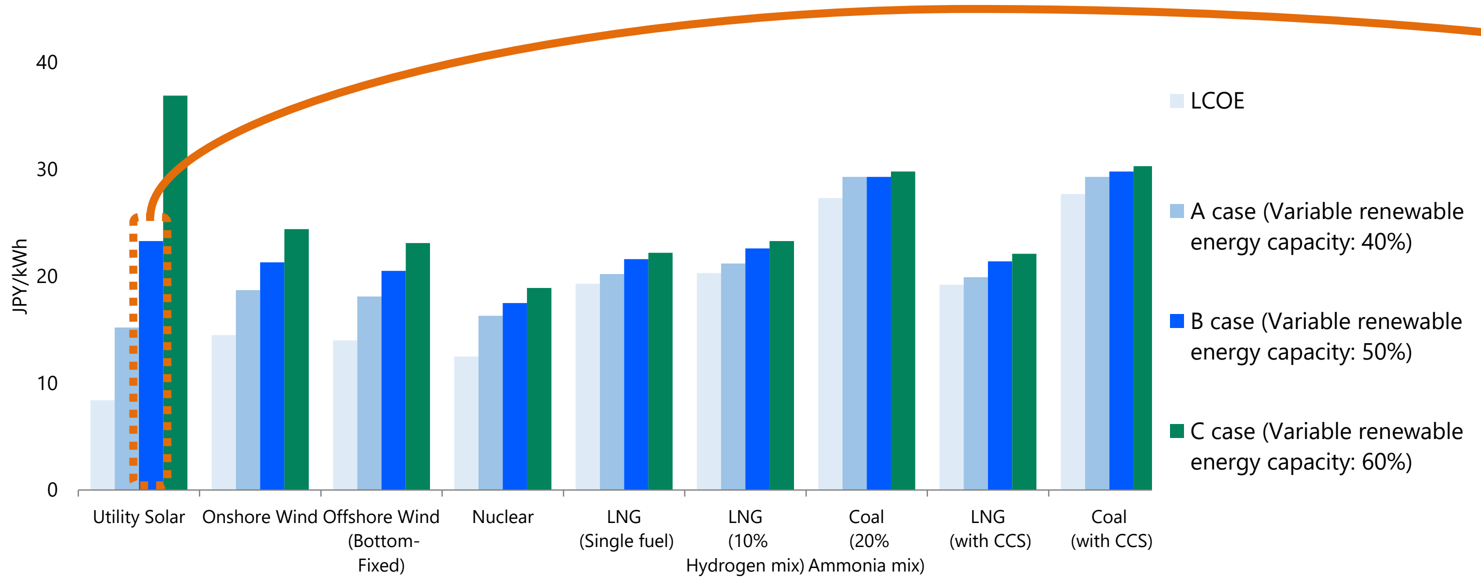
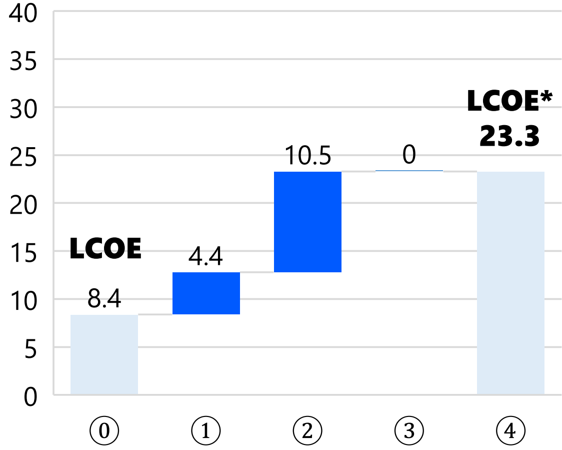
Example of the Study on Integration Cost:
The Working Group on Power Generation Cost Verification (2025)

- As VRE penetration increases, curtailment and storage losses grow, while the capacity factor of balancing plants declines — resulting in a much steeper rise in LCOE* for VRE compared with nuclear and thermal power.
- The right-hand side figure decomposes the gap between generation cost (LCOE: Levelized Cost of Energy) and adjusted LCOE (LCOE*), which incorporates part of the integration costs, showing that charging/discharging losses and curtailment have the largest impact.

Comparison of Generation Cost vs. Adjusted Generation Cost (including part of the integration costs)



Breakdown of Utility-Scale Solar PV Cost



Source：Author, based on The Working Group on Power Generation Cost Verification (2025)

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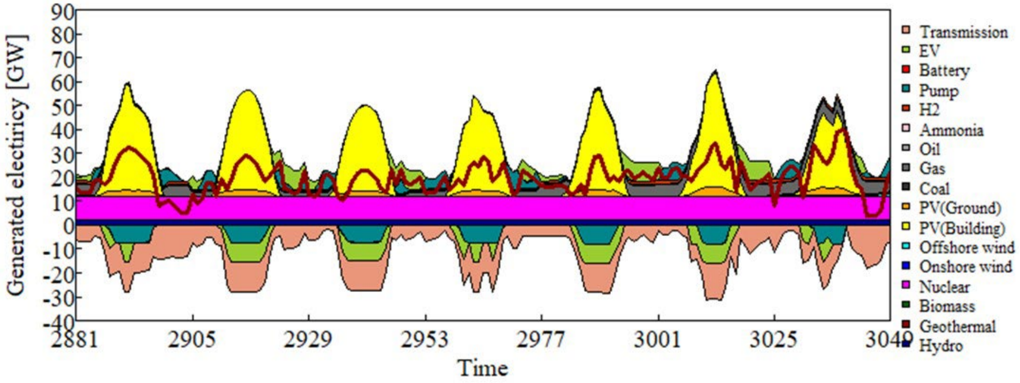
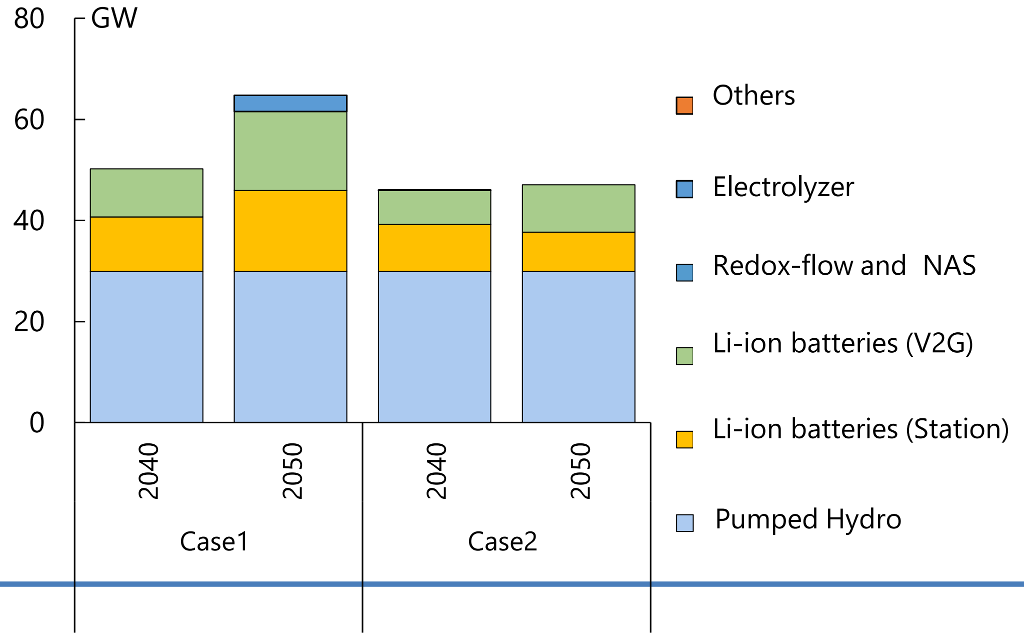
Overview of the IEEJ Technology Selection Model (IEEJ-NE Model)

- Using the IEEJ-NE model, we analyze the least-cost technology mix for ASEAN under varying levels of VRE deployment.
- The analysis assumes each country follows its NDC targets and evaluates VRE deployment and integration costs through 2060.
- IEEJ-NE Model Framework
  - ✓ Simulates annual power and hydrogen supply–demand on a time-step basis
  - ✓ Calculates required capacity for power generation and storage
  - ✓ Considers grid reinforcement and energy storage for power system balancing

Example of Power Supply–Demand (hourly)



Required storage capacity estimated by area



Technology list

Energy Storage	Pumped hydro, Li-ion batteries (grid-side and demand-side), NaS batteries, redox-flow batteries, hydrogen storage
(Demand Response)	Demand-side flexibility: EV charging, passenger EV V2G, and heat pump water heater load shifting

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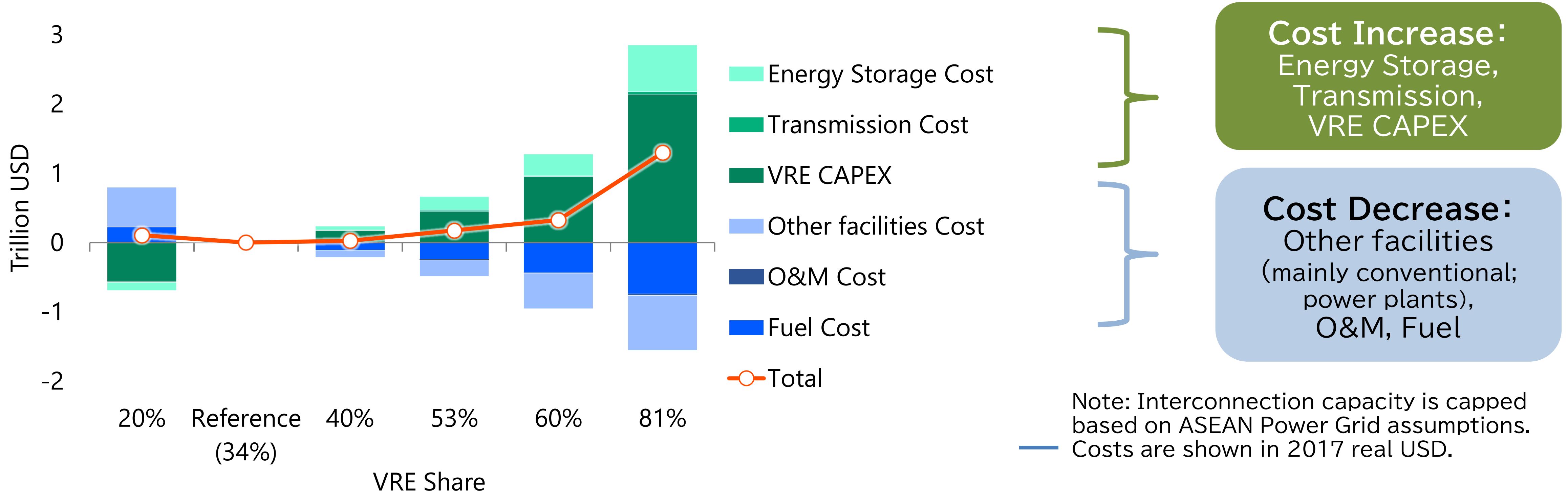
VRE Deployment and Changes in System Cost

- In ASEAN, the least-cost VRE share in 2060 is estimated to be around 30% — used here as the reference.
- Increasing VRE beyond this reference reduces conventional generation capital and fuel costs, but raises VRE installation costs and integration costs such as storage.
- At 81% VRE, cumulative system cost rises by approximately USD 1.3 trillion over 2030–2060 compared with the reference.

Cumulative System Cost Change in ASEAN (2030–2060, vs. baseline)



Note: Interconnection capacity is capped based on ASEAN Power Grid assumptions. Costs are shown in 2017 real USD.

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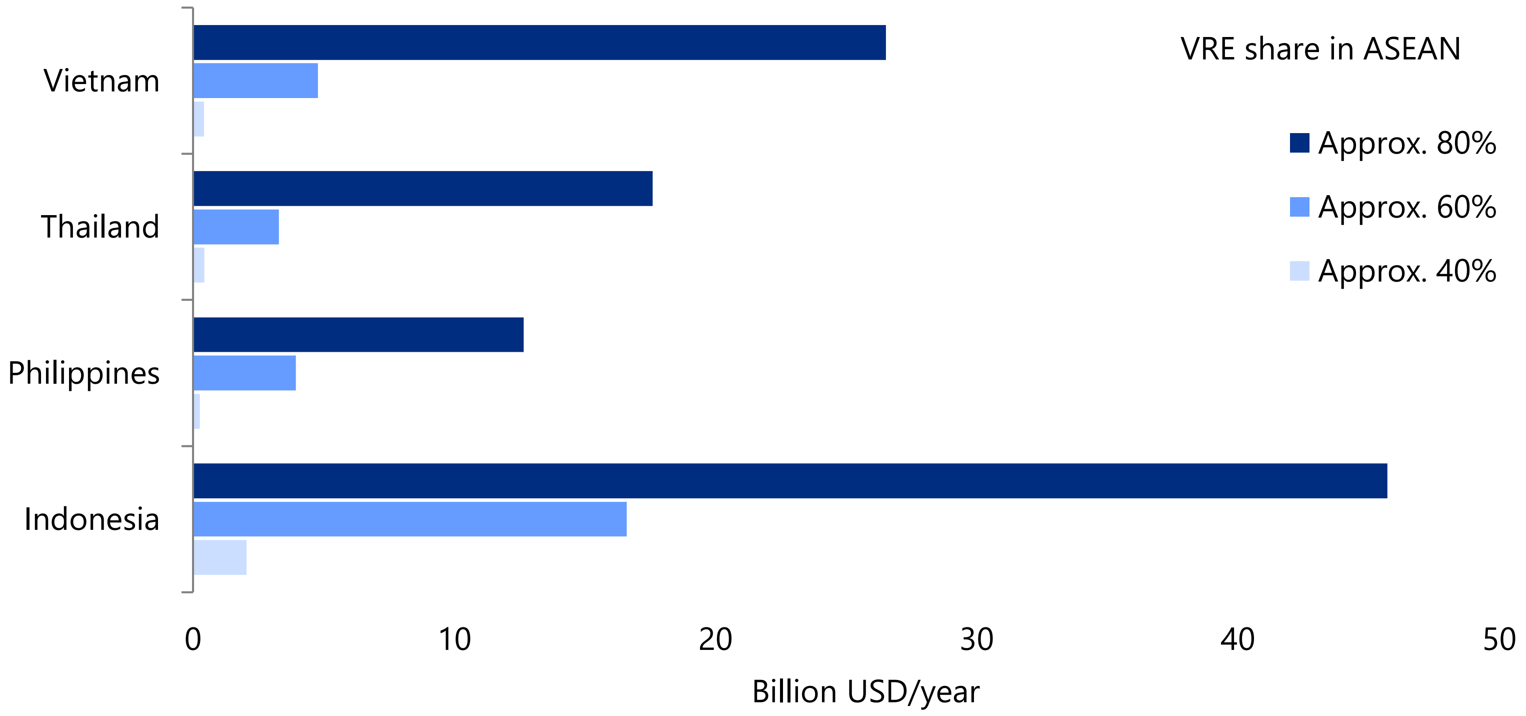
VRE Deployment and Country-Level System Cost Impacts

- The change in system cost from higher VRE deployment varies significantly by country.
- Indonesia, Vietnam, and Thailand — with large populations and economies — see the largest cost increases, including VRE capital costs.

Change in System Cost by Country in 2060 (vs. baseline)



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Summary

- As variable renewable energy (VRE) expands toward decarbonization, the future supply–demand balance of electricity will change significantly.

- In the decarbonization era, integration costs are increasingly seen as a key metric for evaluating energy costs, and a growing number of studies and analyses are focusing on them.

- This report analyzes VRE deployment and integration costs in ASEAN through 2060.

- When VRE is increased beyond the reference level, capital and fuel costs for conventional power are reduced — but VRE installation and integration costs rise, resulting in a net increase in total system cost.

- The cost and additional deployment potential of VRE vary by country, making it essential to pursue diverse and country-specific pathways to decarbonization.

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Appendix: Key Components of Integration Costs (Typical Classification)

Category	Item	Detailed item	Description	Considered in various analyses
Cost of managing forecast errors	Balancing costs		Short-term balancing costs from dispatchable plants responding to intra-day VRE fluctuations (seconds–minutes reserve).	
Grid reinforcement costs	Grid-related costs		Investment in transmission infrastructure and congestion management (e.g., redispatch) due to geographical mismatch between VRE generation and demand.	<u>This study</u>
Cost of supply–demand mismatch / adequacy	Profile costs/utilization costs	Cost of supply–demand mismatch / adequacy	Backup capacity required due to the low capacity value of VRE, especially during peak demand (e.g., thermal, flexible renewables, storage).	<u>This study</u> The Working Group on Power Generation Cost Verification
		Curtailment costs	Higher unit cost of electricity when VRE output exceeds demand and curtailment is needed.	<u>This study</u>、 The Working Group on Power Generation Cost Verification
		Reduced capacity factor of dispatchable plants	Increase in unit generation cost as baseload and mid-merit thermal plants operate fewer hours due to VRE.	The Working Group on Power Generation Cost Verification
		Increased cycling and start-up/shutdown costs	Additional costs from more frequent and unplanned ramping or cycling of dispatchable power plants.	The Working Group on Power Generation Cost Verification

Source：Author, based on Ueckerdt et al. (2013) and Matsuo (2021)

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