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# **Evaluating the Integration Cost and Deployment of Variable Renewable Energy**

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# Challenges and Costs Associated with Large-Scale Integration of Variable Renewable Energy

- ✓ Geopolitical risks are increasing the need for energy self-sufficiency, driving greater use of solar, wind, and nuclear power as domestic energy resources.
- ✓ Large-scale VRE deployment raises concerns about rising system-wide integration cost.

## Variable Renewable Energy and the Resulting System-Wide Integration Cost

### Profile Cost

Variability due to natural conditions

Costs arising from temporal mismatches between generation and demand patterns



### Grid-related cost

Geographical constraints of resources

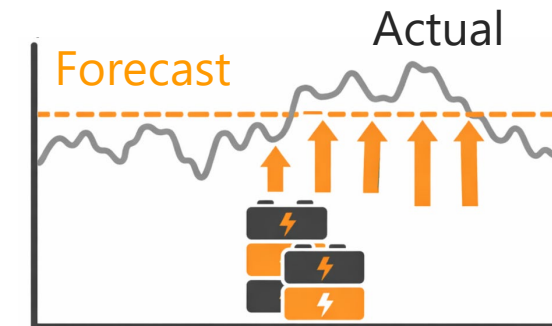
Costs associated with grid expansion and new infrastructure development



### Balancing cost

Uncertainty in output forecasting

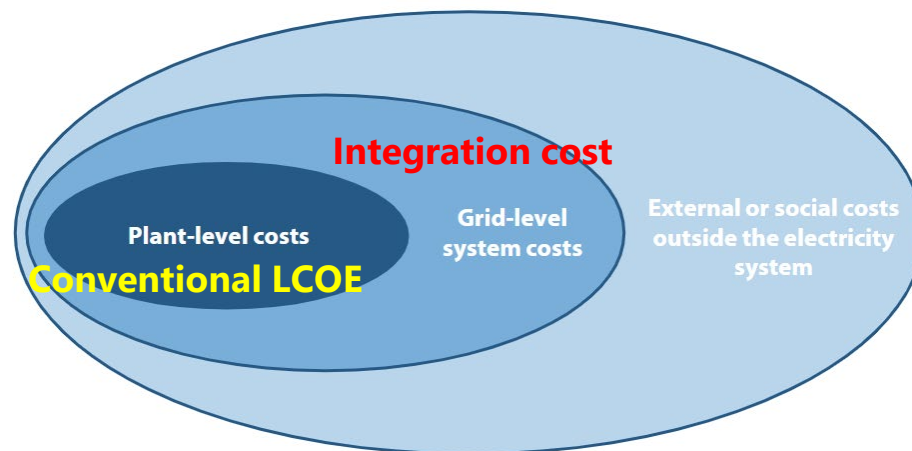
Costs for supply–demand balancing to address forecast errors



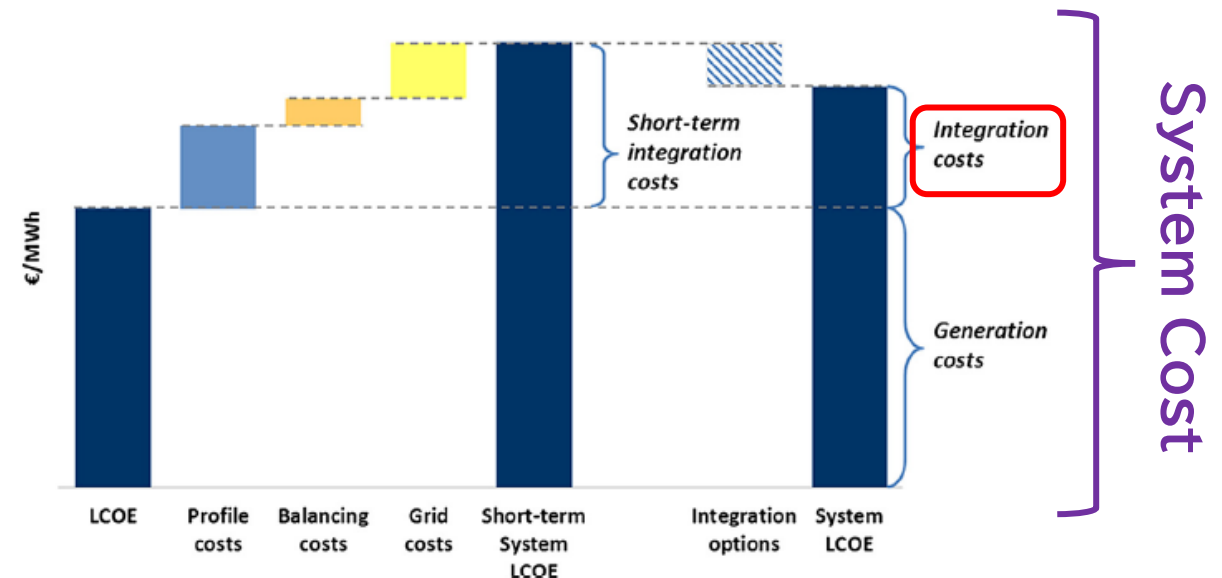
# System Cost and Integration Cost

- ✓ OECD/NEA studies define system cost as LCOE plus system-level integration costs, covering both technology-specific generation costs and grid-level impacts.
- ✓ Power system design aims to minimize total system cost, balancing generation and integration cost rather than treating integration cost alone as the target.

## Characteristics of Variable Renewable Energy and the Resulting System-Wide Cost



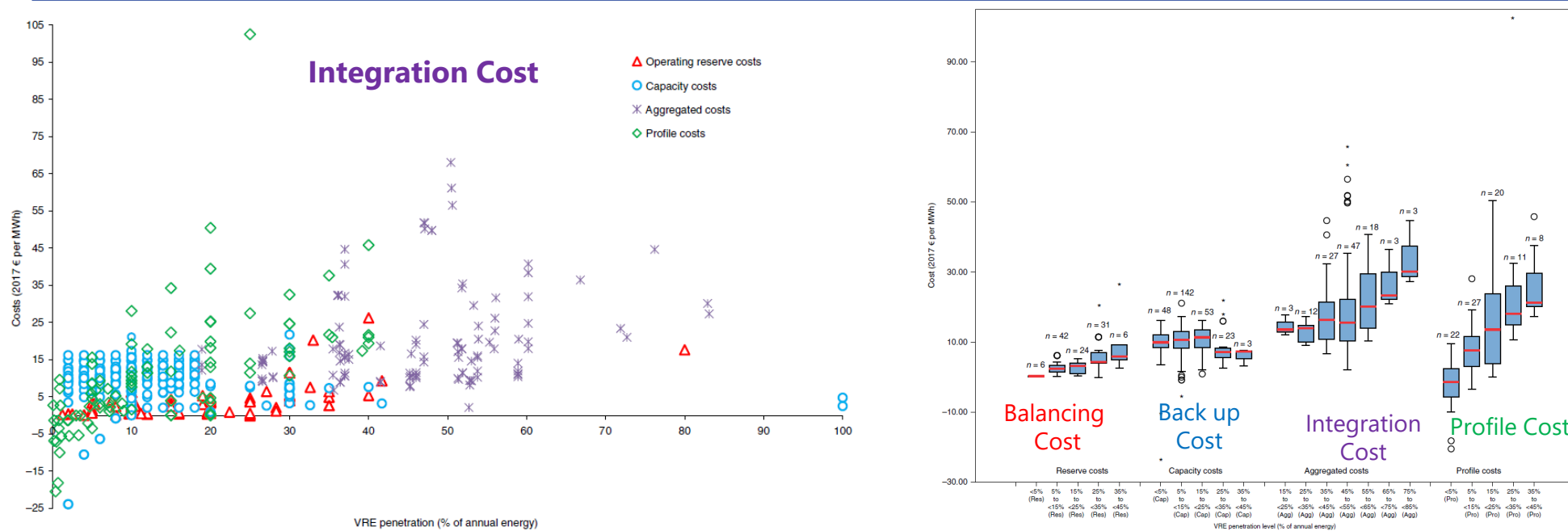
Source: NEA, 2012b.



# System Cost Analysis in Academic Research

- ✓ A major review of system costs stresses that minimizing the total cost of power-sector decarbonization matters more than examining individual integration-cost components.
- ✓ Accordingly, effective VRE deployment requires power-system designs that minimize overall system cost, not just specific cost elements.

## Review of estimated values for each component of integration costs by VRE share

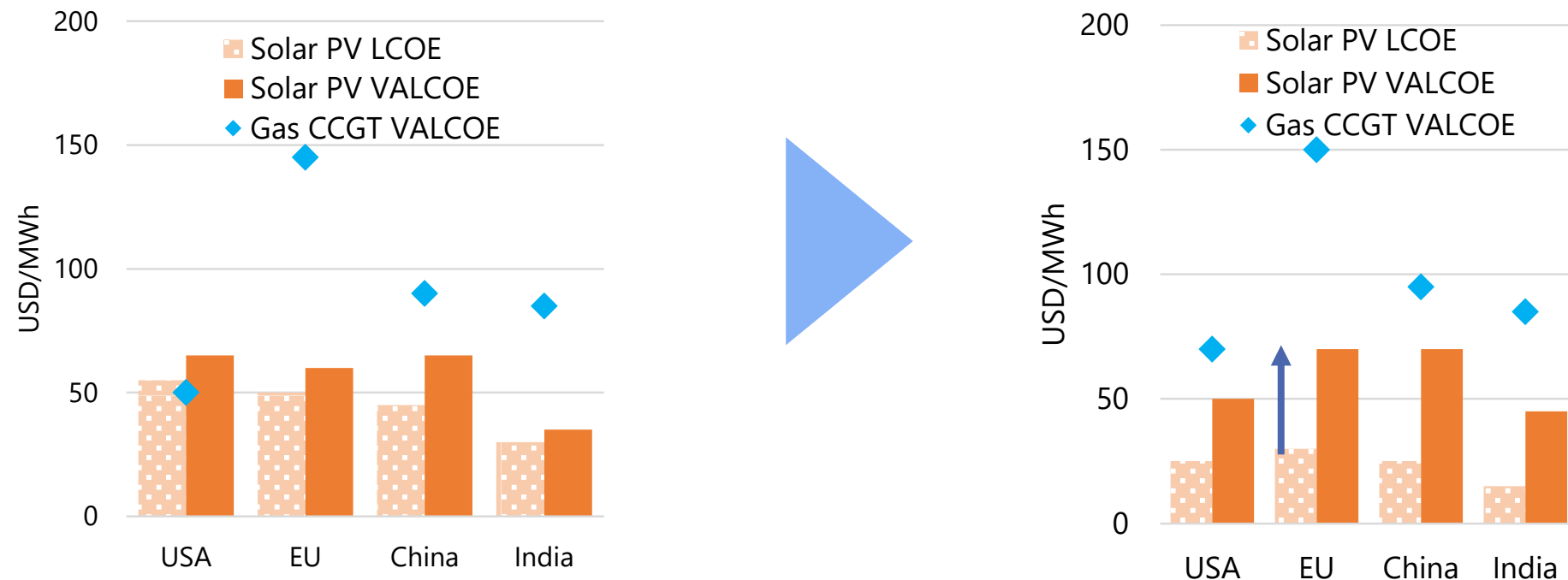


- [Source] Heptonstall, Philip J., and Robert J. K. Gross. (2021). "A Systematic Review of the Costs and Impacts of Integrating Variable Renewables into Power Grids." *Nature Energy* 6 (1): 72–83.
- In the same paper, operating reserve costs are defined as the costs of securing reserve capacity, and capacity costs as the additional capacity costs required to ensure adequacy. By definition, both are included within profile costs.

# Value-adjusted LCOE (VALCOE) of IEA

- ✓ VRE impacts can be assessed through cost-based or value-based perspectives.
- ✓ Under the IEA's VALCOE framework, market value effects—such as the daytime wholesale price drop caused by PV's cannibalization effect—are incorporated into PV's assessed cost.

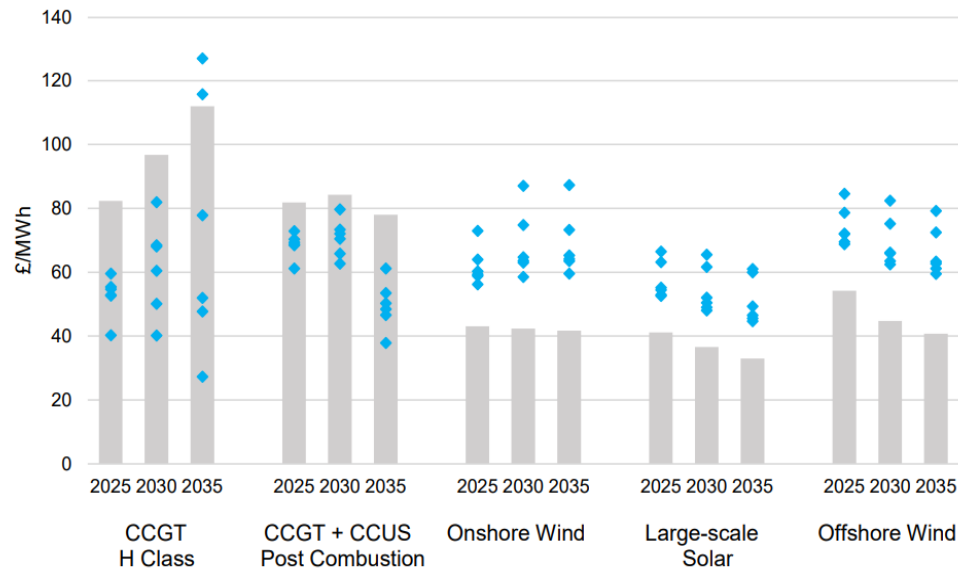
Cost comparison of PV (Left: in 2024, Right: in 2050)



# International Experience on LCOE and Policy Debate

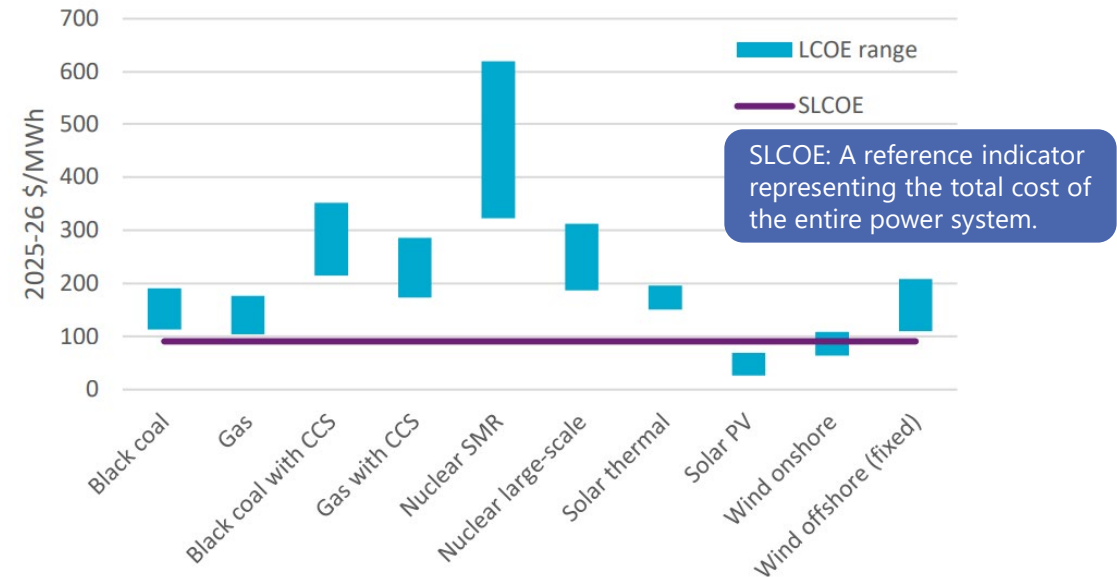
- ✓ Attempts to fold integration costs into LCOE have been made in many countries, but such metrics can distort policy debates because they depend heavily on modeling assumptions.
- ✓ In the UK, an “Enhanced LCOE” was proposed, but the latest 2025 cost assessment no longer evaluates integration costs separately by technology.

**LCOE (Grey bar) and Enhanced Levelized Costs (Light blue diamond) in the UK**



[Source] BEIS(2020)

**System levelized costs of electricity in Australia**

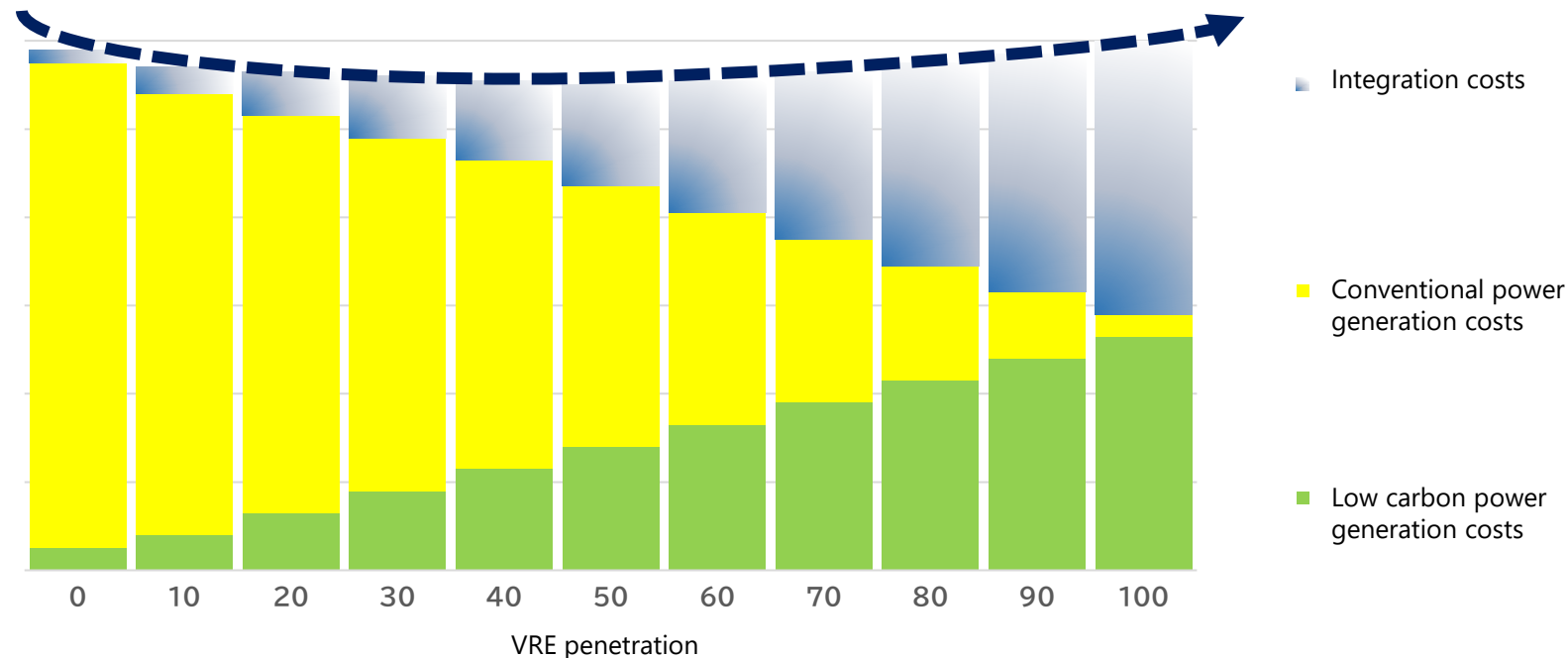


[Source] CSIEO(2018). Modified and supplemented by the author.

# VRE Deployment and the Evolution of Integration Cost

- ✓ Integrating a power source adds system-level costs beyond generation, including grid upgrades and storage.
- ✓ As VRE penetration grows, these integration costs rise, making it essential to evaluate total system cost to maintain an optimal mix

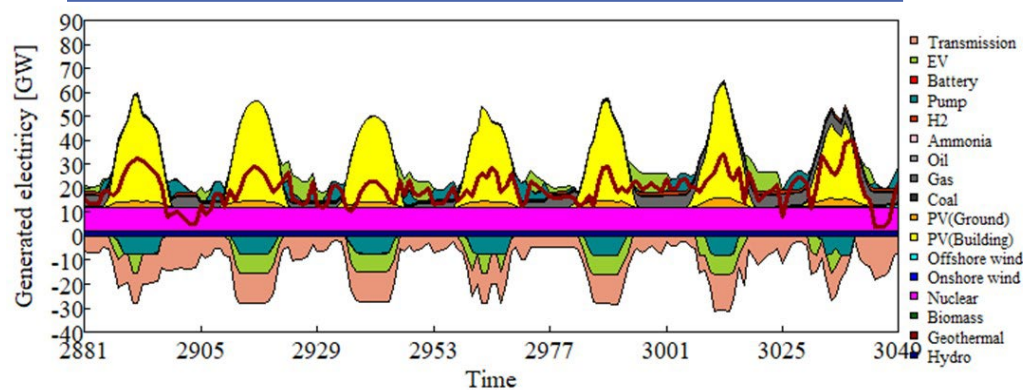
**Illustrative image: Growth in VRE deployment vs. system cost trajectory**



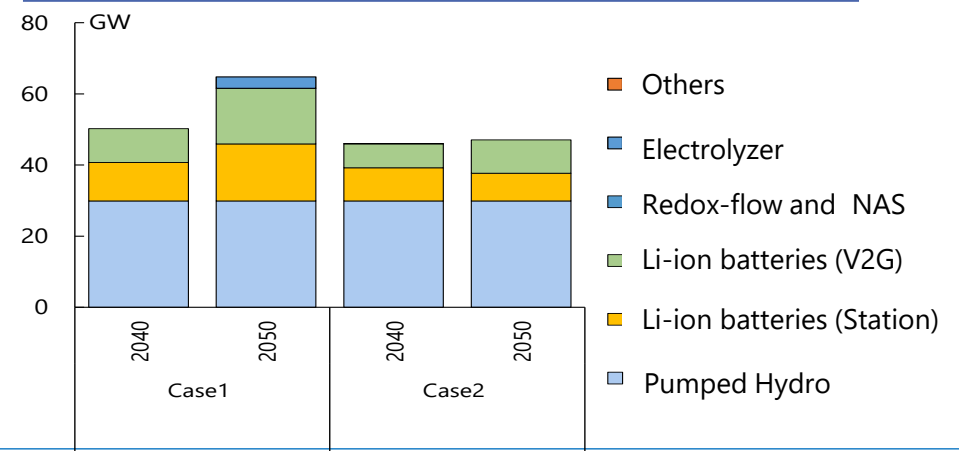
# Overview of the IEEJ Technology Selection Model (IEEJ-NE Model)

- ✓ 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 system 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)**



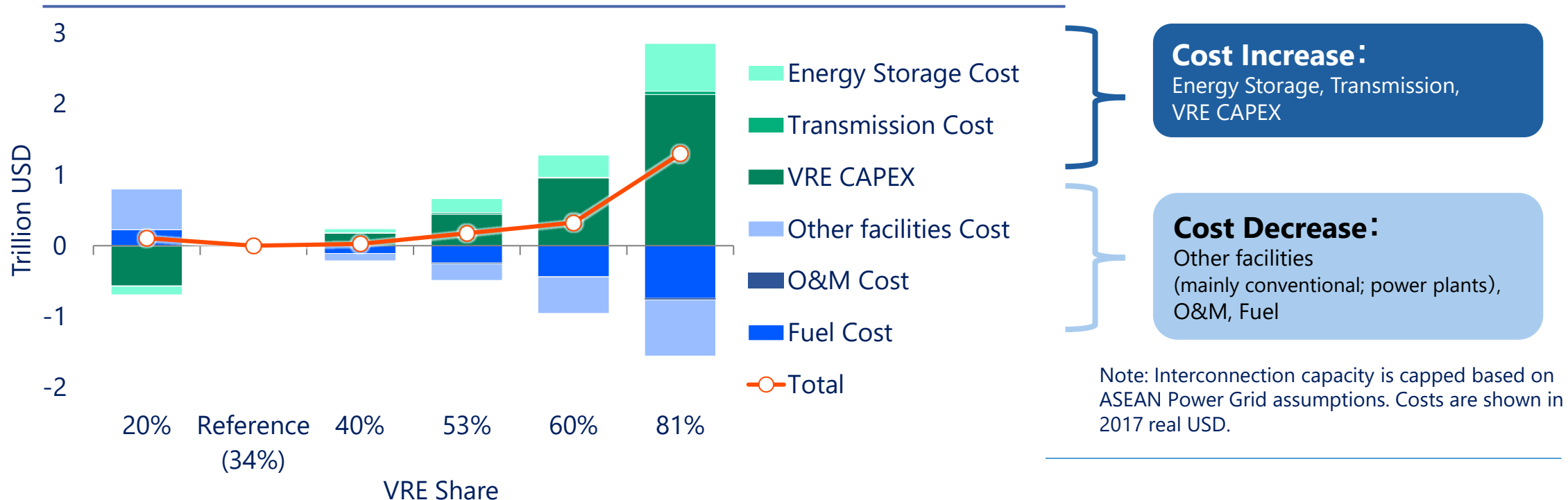
**Required storage capacity estimated**



# VRE Deployment and Changes in System Cost

- ✓ In ASEAN, the least-cost VRE share in 2060 is estimated to be around 34% as the reference.
- ✓ Increasing VRE reduces conventional generation CAPEX 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.

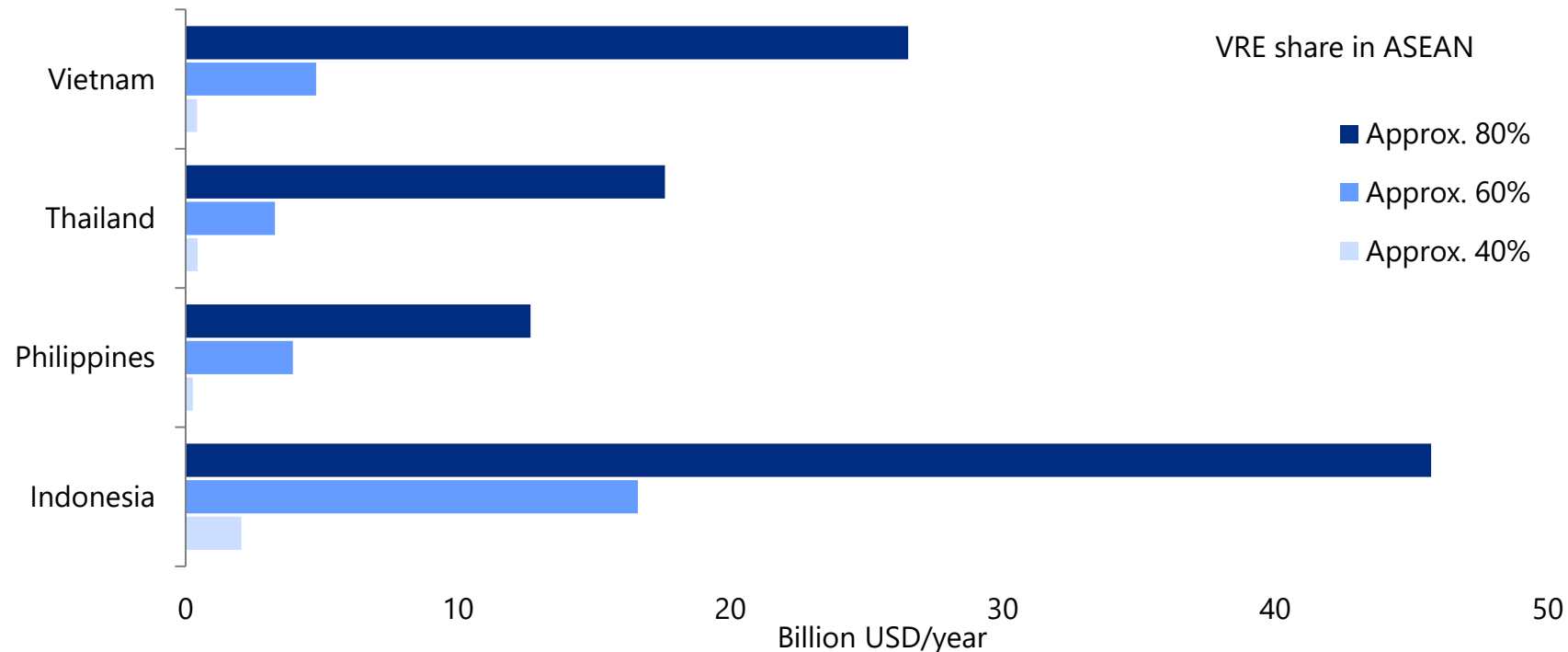
**Cumulative System Cost Change in ASEAN (2030–2060, vs. reference)**



# VRE Deployment and Country-Level System Cost Impacts

- ✓ The change in system cost for 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. reference)



# Summary

- ✓ In the decarbonization era, integration cost is increasingly seen as a key metric for evaluating energy costs, and a growing number of studies and analyses are focusing on them.
- ✓ With broader recognition and improved analytical methods, integration-cost metrics have the potential to support better and informed decision-making.
- ✓ 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.
- ✓ Additional deployment of VRE and associated costs vary by country, underscoring the need for diverse, country-specific decarbonization pathways is essential.