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Japan's Energy Scenarios Toward 2050 Strategies for Reducing Power System Costs

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Challenges of Large-Scale VRE Integration

- Even with declining Variable Renewable Energy (VRE) costs, large-scale deployment may increase **system-wide integration costs**.
- Reducing power system costs, including **integration costs**, is essential for large-scale VRE deployment.

Characteristics of VRE and Associated System Integration Costs

Output variability

Generation–demand mismatch
(**Profile costs**)



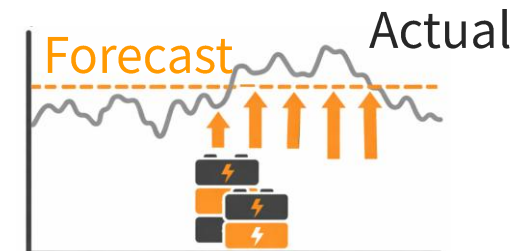
Geographic constraints

Grid expansion
(**Grid-related costs**)



Output forecast uncertainty

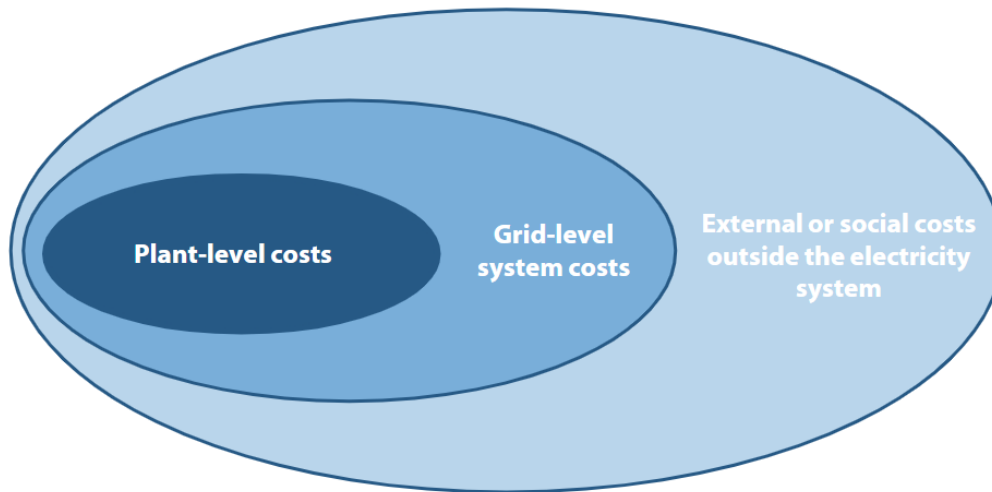
Balancing costs caused by forecast errors
(**Balancing costs**)



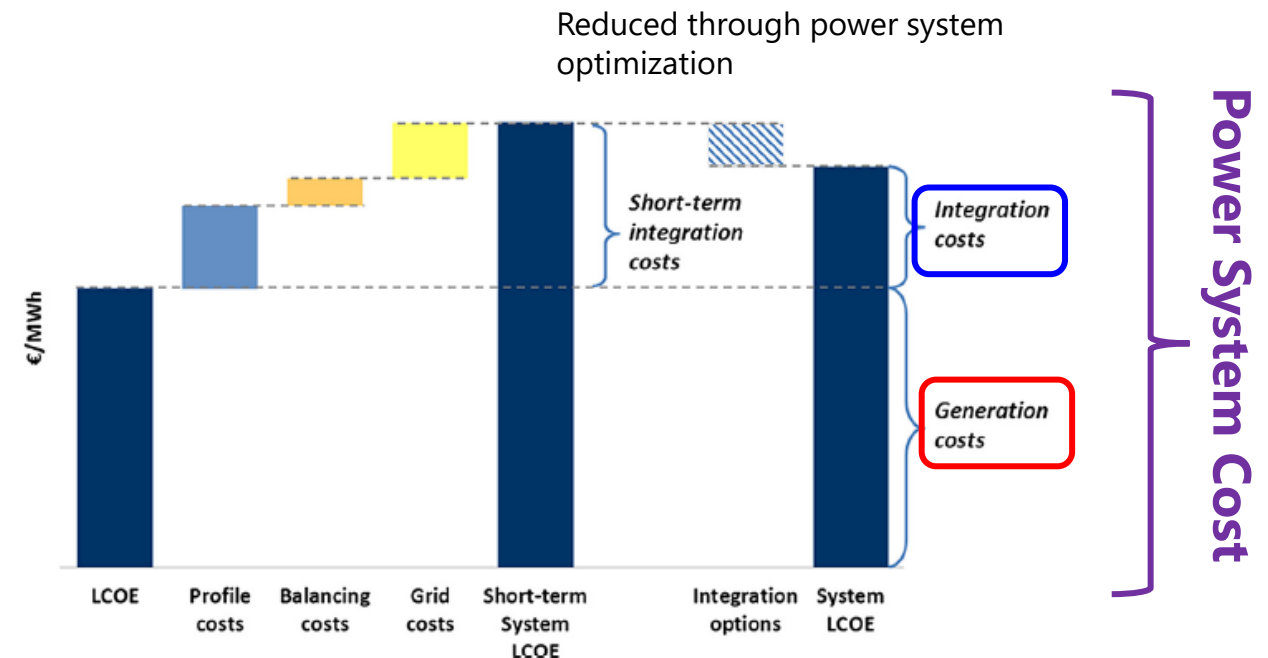
Definition of Power System Cost

- In this analysis, power system costs are defined as follows:
Power system costs = **LCOE** + **Integration costs**. (Based on OECD/NEA [2]–[4])
- Reducing power system costs, rather than LCOE alone, is essential for energy policy.

Cost Components of VRE Integration



Source: NEA, 2012b.



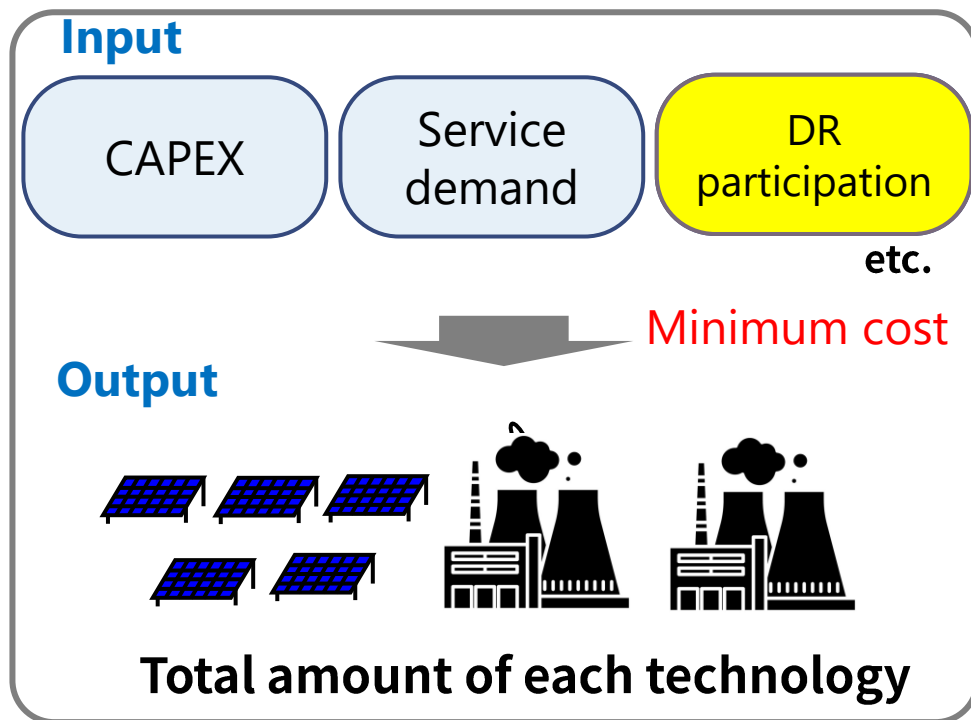
Source: Adapted from OECD/NEA [3] [4].

Source: Adapted from Ueckerdt et al. [1].

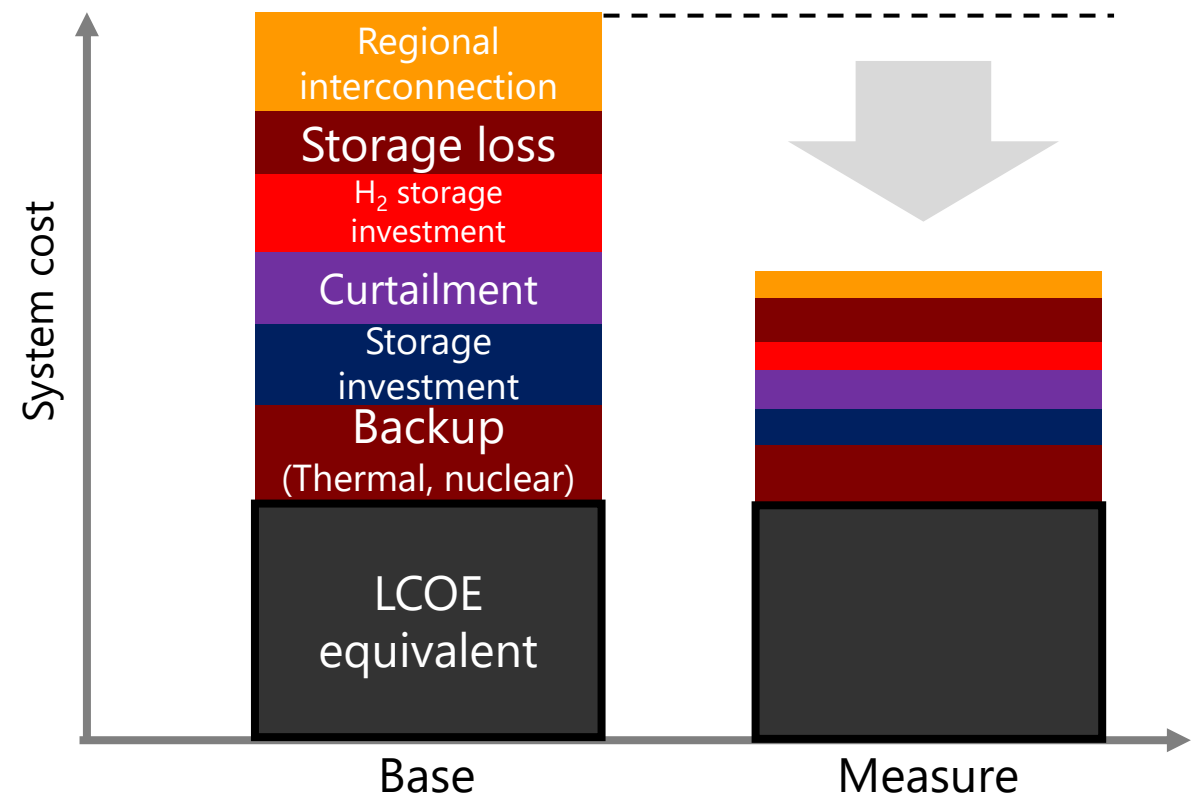
Objective

- This analysis assesses the impacts of flexibility and supply-side measures on power system costs.
- This analysis provides insights into measures to reduce integration costs.

System-wide optimization model



Power system cost



Integration Cost Components Considered in This Study

- This analysis accounts for selected components of integration costs.
- Some integration costs, such as intra-regional transmission reinforcement costs, are excluded, potentially leading to an underestimation of total integration costs.

Integration Cost Components Considered in This Study (Black: Included Gray: Excluded)

Profile Costs

Thermal backup capacity cost
Curtailment cost

Battery investment cost
Battery losses cost
Hydrogen storage investment cost
(Thermal start-up and shut-down costs)
(Thermal part-load operation costs)
(Penalty cost for unserved electricity)

(Thermal part-load standby costs)
(Efficiency losses from thermal Load-following operation)

Balancing Costs

Grid-related Costs

Interregional transmission expansion costs (Distribution network expansion costs)
(Substation expansion costs)

- Some cost components overlap across categories. Only the major cost components are shown.

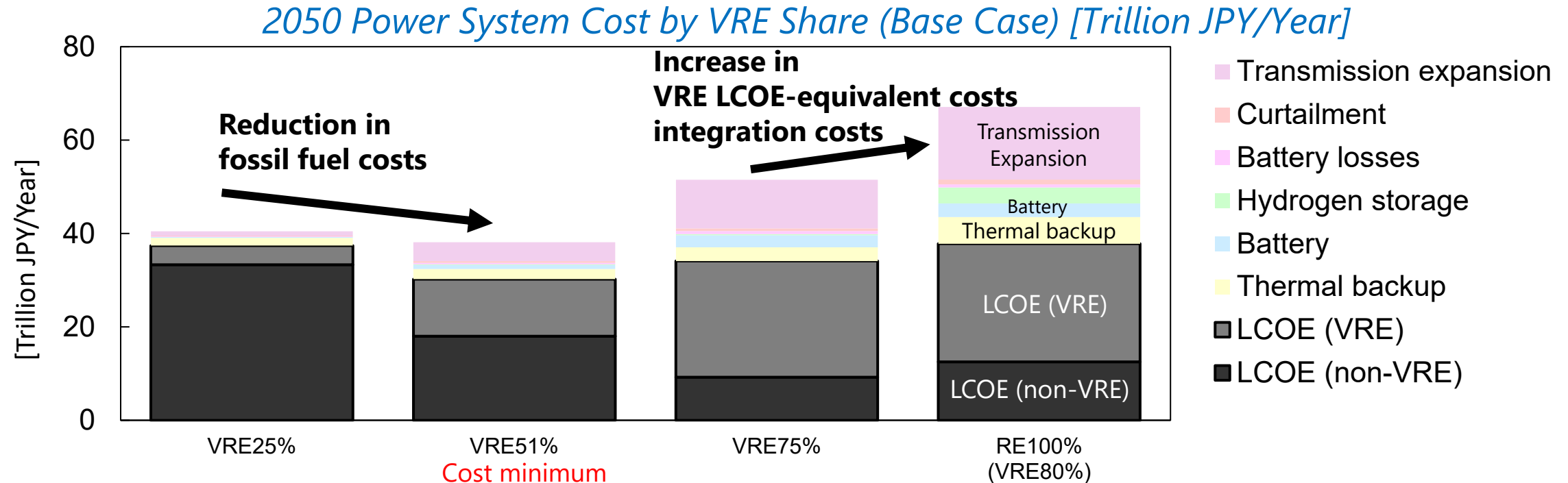
Scenario Settings

In addition to the Base Case for achieving **carbon neutrality** by 2050, four scenarios representing demand- and supply-side measures are analyzed.

	Description
Base Case	No additional measures.
EV Demand Response	26% of EVs participate in demand response (DR), based on the participation rates reported by Ofgem/FES [7].
Low-Cost Battery	Lower battery costs through technology improvements. Base: 33,800 JPY/kWh (NREL Mid Case [8]) Low-cost: 12,900 JPY/kWh (IEA NZE [9])
Expanded Nuclear	Maximum lifetime extension of existing plants and full operation of planned new reactors. Base: 27 GW Expanded: 41 GW
Combined Measures	All three measures are implemented.

Power System Costs at Different VRE Shares (Base Case)

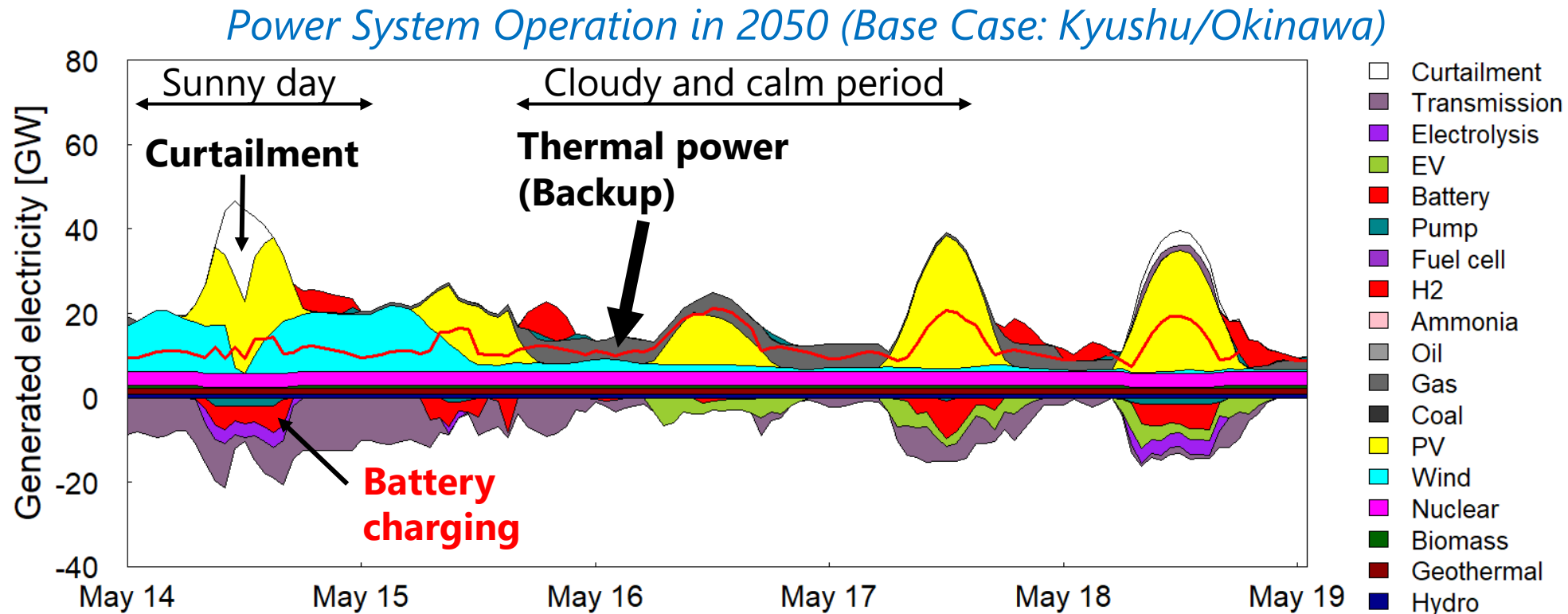
- In the Base Case, power system cost is minimized at a **51% VRE share**.
- Beyond the cost-optimal VRE share, **increases in VRE LCOE-equivalent costs** and **integration costs** outweigh the reduction in fossil fuel costs.



- The optimal VRE share depends on system flexibility and fuel prices.
- At 100% renewable electricity, thermal backup is provided by biomass and green hydrogen.
- Hydrogen-fired generation costs are included in LCOE (Non-VRE).

Power System Operation in 2050 (Base Case)

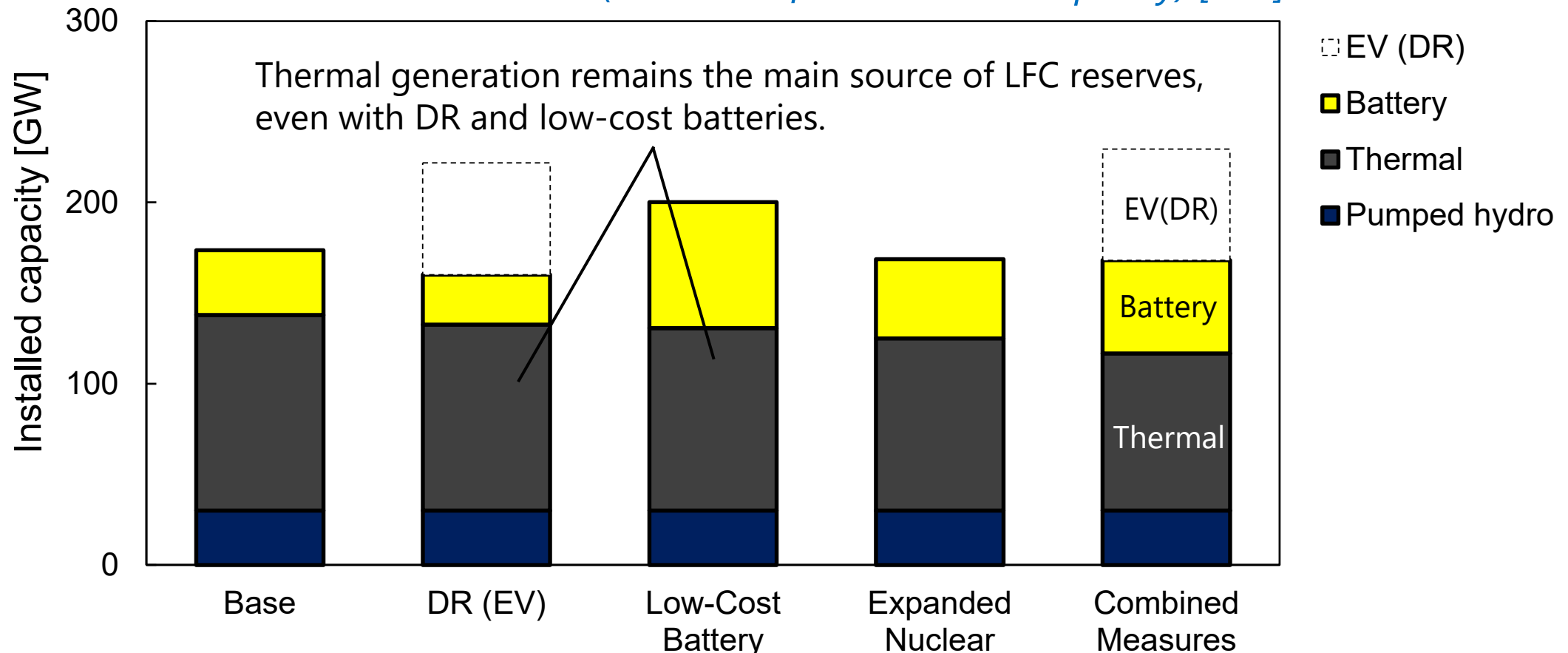
During prolonged periods of low wind and solar output, battery storage alone cannot balance supply and demand, requiring **backup thermal generation**.



LFC Reserves in 2050

- Even with the demand response (DR) using EVs and low-cost batteries, **thermal power plant** (with CCS) remains the primary source of LFC reserve capacity.

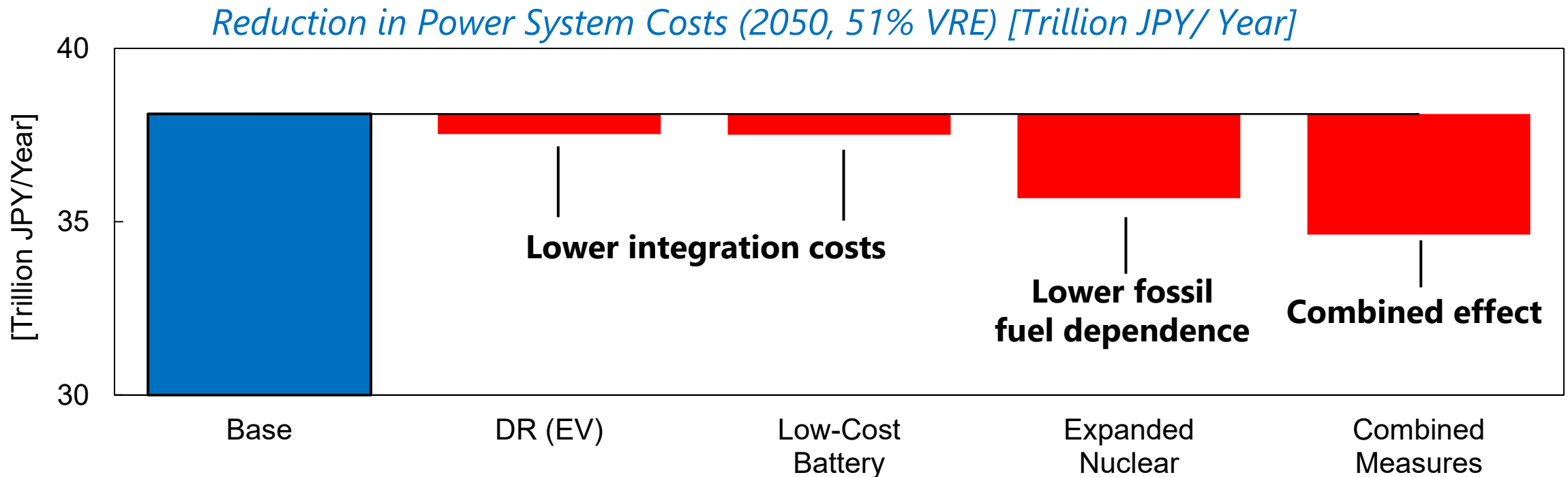
LFC Reserves in 2050 (Estimated from installed capacity) [GW]



- Thermal generation includes CCS gas, ammonia, hydrogen, and biomass.

Power System Cost Reduction in 2050 (51% VRE)

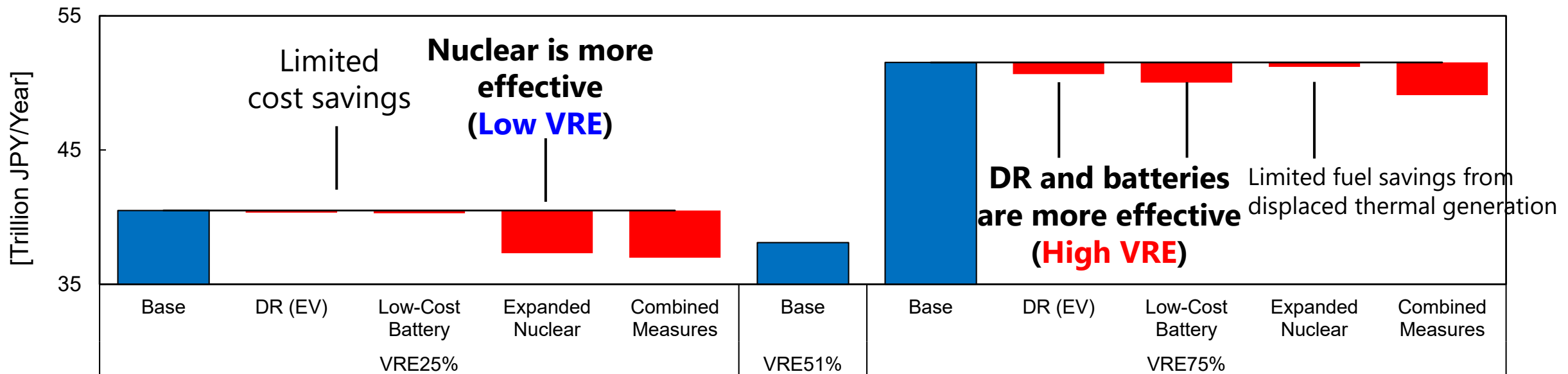
- At the optimal 51% VRE share, nuclear power reduces total system costs **by lowering fossil fuel use**.
- Demand response and low-cost batteries further **reduce integration costs**.



Cost Reduction at Different VRE Shares

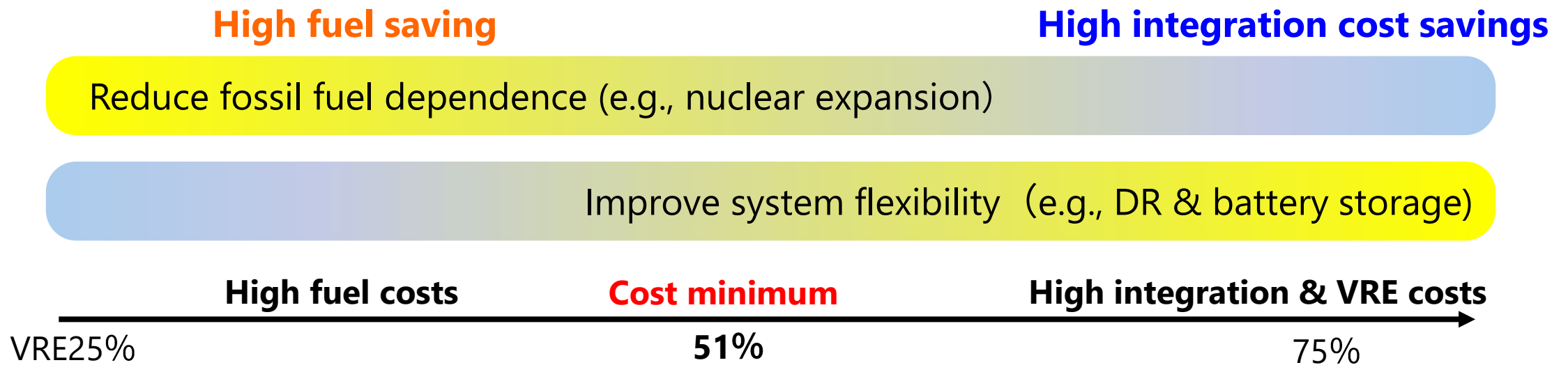
- At 25% VRE, **nuclear power** provides the largest cost reduction.
- At 75% VRE, **DR** and **low-cost batteries** become more effective.

Cost Reduction by VRE Share (VRE25% • 75%) [Trillion JPY/year]



Policy Implications

- In the Base Case, power system cost is minimized at a **51% VRE share**.
- The most effective measures for reducing power system costs **depend on the VRE penetration level**.
- A **phased transition strategy** is needed to balance energy security and cost reduction.



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Supplements

Components of Integration Costs

- Integration costs can be classified into **three categories** [1]*.
- Some cost components **overlap** across categories [2].

Profile Costs

Costs due to **generation–demand mismatch**

- Thermal backup capacity cost
- Curtailment cost
- Battery investment cost
- Battery losses
- Hydrogen storage investment cost
- Start-up / shutdown costs
- Part-load operation

Grid-related Costs

Costs due to **grid expansion**

- Interregional transmission expansion costs
- Distribution network expansion costs
- Substation expansion costs

Balancing Costs

Costs due to **forecast errors**

- Thermal part-load standby costs
- Efficiency losses from thermal Load-following operation

• Some studies treat capacity costs as a separate category [2]. In this study, they are included in profile costs.

Key Assumptions

Capital Cost	Based on the Procurement Price Calculation Committee [10]. For offshore wind: Base cost: 600,000 JPY/kW (2045) [11]. Adjusted for water depth and distance from shore [12].
Fuel Price	Based on 2022 CIF import prices and the IEA WEO 2024 NZE fuel price trend.
Interregional Transmission	Unit costs are based on the OCCTO Master Plan [13],[14]. No transmission capacity limit is assumed.
Maximum Renewable Energy Capacity	Residential rooftop PV : Roof orientation (S: 49.0 GW , E: 48.6 GW , W: 48.6 GW) [15]. Commercial rooftop PV : Building database (137.2 GW) [15]. Ground-mounted PV : Areas with limited local restrictions (52.3 GW) [15]. Agrivoltaics : All farms install up to 50 kW (41.9 GW) (based on [16]). Onshore wind : Areas with limited local restrictions (25.2 GW) [15]. Offshore wind : Water depth, capacity factor, and available area [12].

* Capacity limits may differ from Ref. [15] because existing renewable installations (e.g., in forests) are included.

Approaches to Reducing Power System Costs

- Power system costs can be reduced through demand-, supply-, and grid-side measures.
- However, their **effectiveness at different VRE penetration** levels remains unclear.

	Measure	Examples
Demand-side	DR (commercial EVs, industrial loads) Battery optimization Long-duration energy storage	Netherlands: Flex-e [17] California: SGIP [18] Massachusetts: Connected Solutions [19] UK: LDES [20]
Supply-side	Reduce fossil fuel dependence to improve energy security	France: Nuclear lifetime extension & new builds [21] UK: More renewables & nuclear to reduce gas dependence [22]
Grid-side	Transmission expansion	EU: Cross-border transmission expansion [23]

Nuclear Power Scenario Assumptions

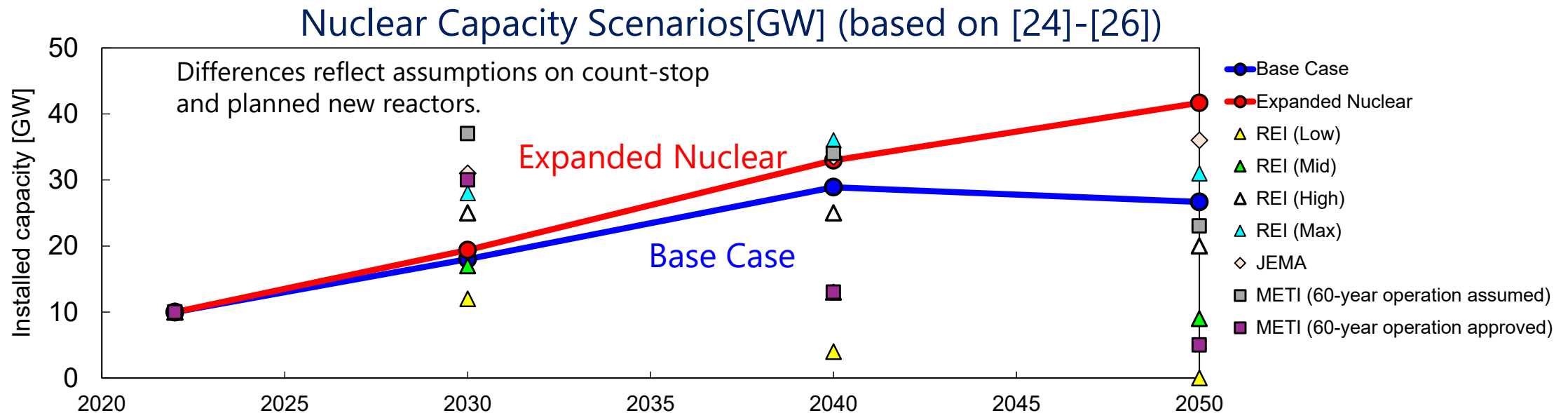
60-year lifetime assumed. Restart year by licensing status (March 2026):
Licensed: 2030, Under review: 2035, Not applied: 2040

Base Case

1970s reactors: retire by 2040. 1980s reactors: remain through 2050.
New builds: under construction only.

Expanded Nuclear

Existing reactors are fully utilized, including count-stop, and all restarted reactors remain in operation through 2050. Planned reactors are also included.



Reference: Count-Stop Policy

- Under the GX Decarbonized Power Source Act (2023, effective 2025), shutdown periods due to regulatory reviews or court orders can be excluded from the licensed operating period.
- However, reactors must pass aging management reviews every 10 years after 30 years of operation to continue operating.
- As reactor-specific count-stop periods are unavailable, this study applies a **uniform assumption**.