Stabilising 100% Renewable Grids: The Integrated FIRM Strategy

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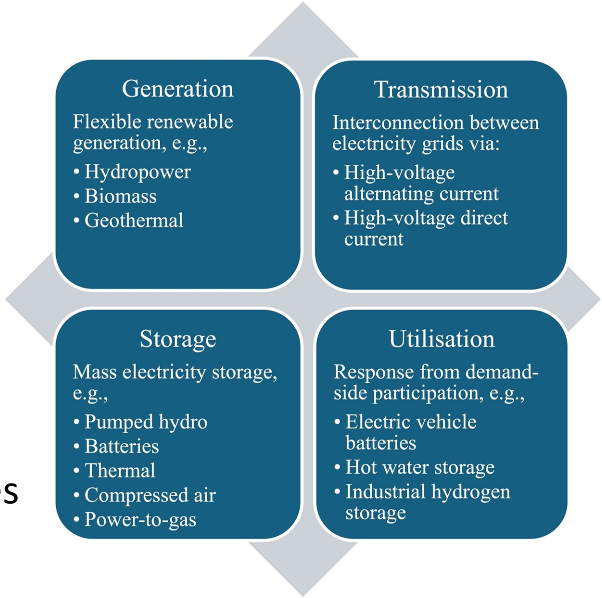
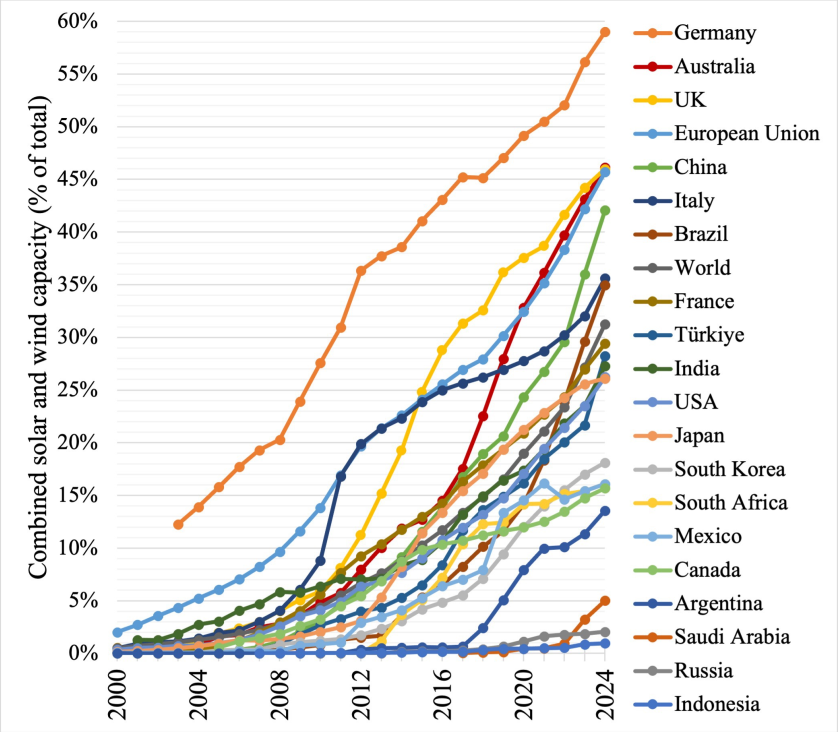


Australian National University

Global Renewable Energy Growth



Growth of solar and wind share in generation capacity, G20 economies. Data source: IRENA (2025).

Global

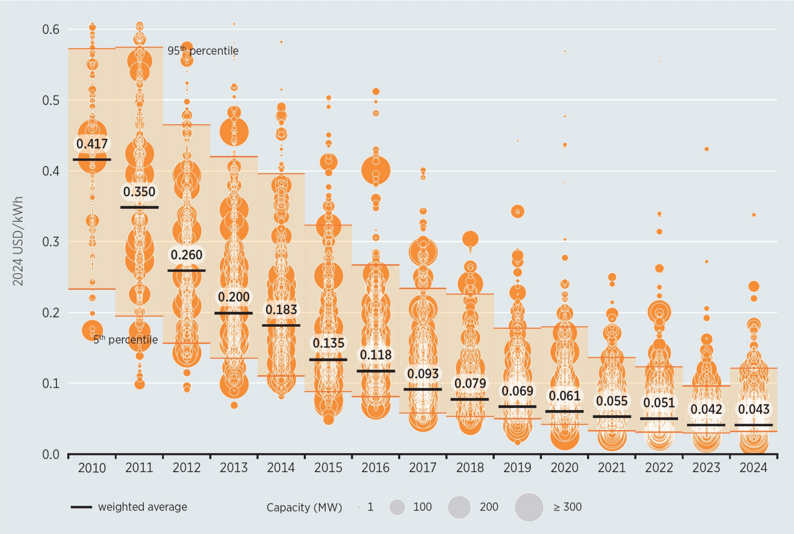
- Solar + wind > 3000 GW, ~30% of global power generation capacity.
- Leaders: Germany (59%); Australia, UK, EU (46%).
- Top emitters: China (42%), USA (26%), India (27%).

Australia

- Renewables (excl. hydropower) = 55 GW (40 GW solar, 15 GW wind).
- Target: 82% renewables in the National Electricity Market by 2030.
- Capacity Investment Scheme: +40 GW by 2030.

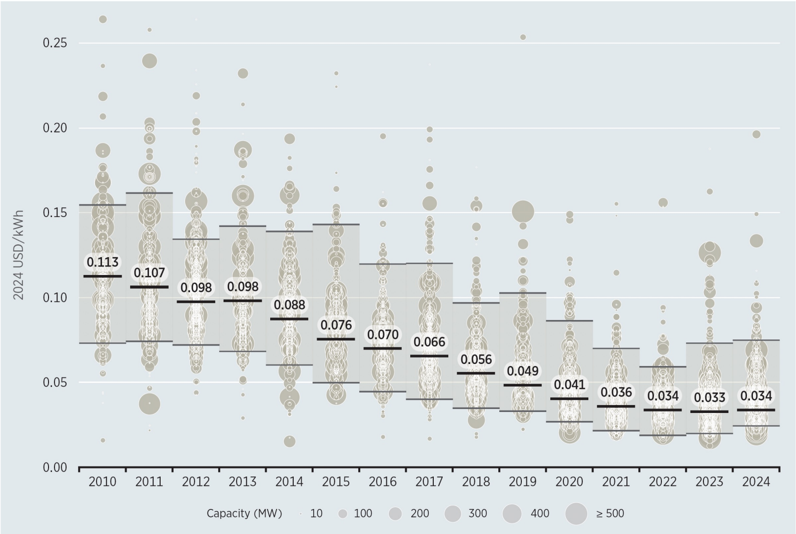
Falling Costs of Renewables

Figure 3.8 Global utility-scale solar PV project LCOE and range, 2010–2024



Notes: kWh = kilowatt hour; MW = megawatt; USD = United States dollar.

Figure 2.14 LCOE of onshore wind projects and global weighted average, 2010–2024



Notes: kWh = kilowatt hour; MW = megawatt; USD = United States dollar.

Source: IRENA (2025).

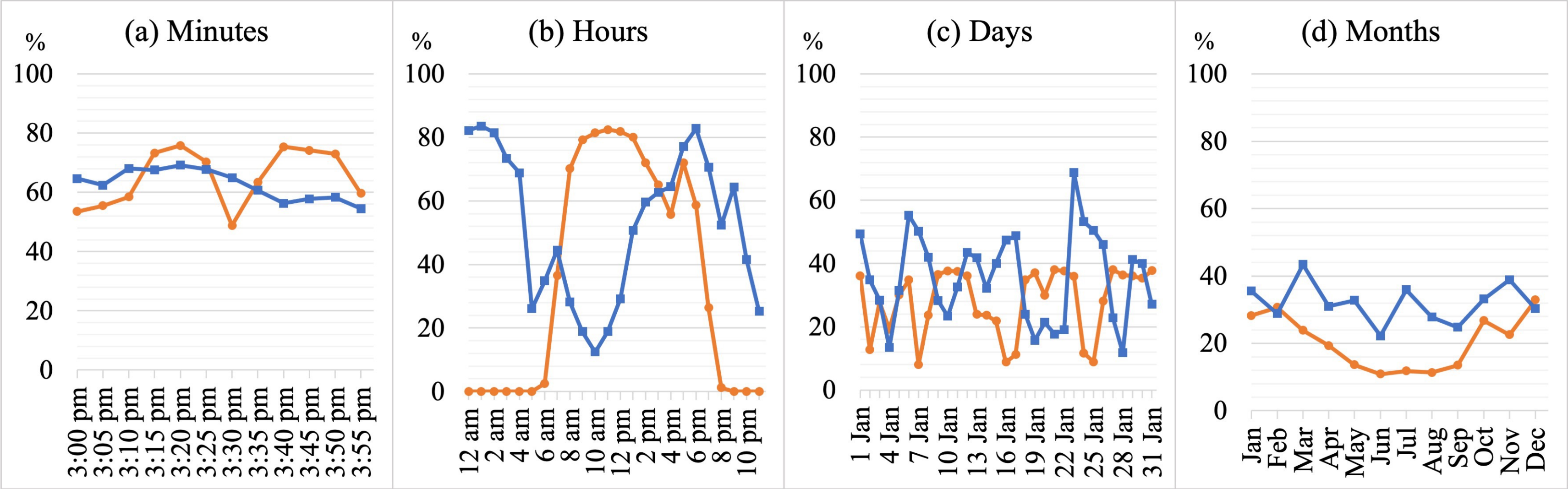
Solar PV

- Cost fell by 90% (417 → 43 US$/MWh, 2010–2024)
- Australia's 30-30-30 goal: 30% efficiency, 0.30 AU$/W, by 2030

Wind

- Onshore: cost fell by 70% (113 → 34 US$/MWh, 2010–2024)
- Offshore: cost fell by 62% (208 → 79 US$/MWh , 2010–2024)

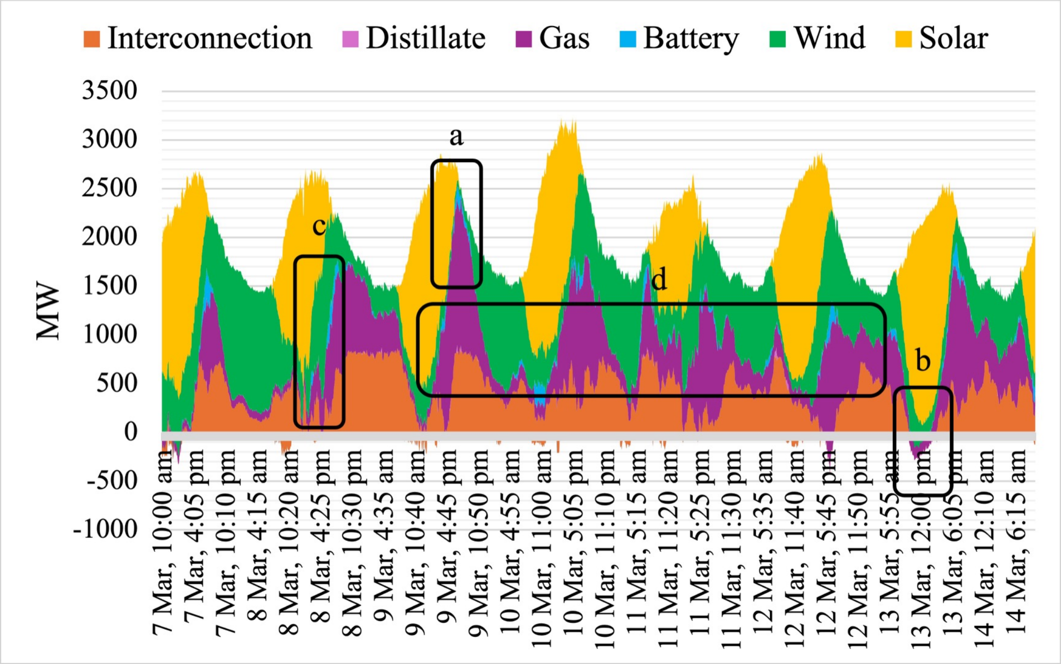
Solar & Wind Characteristics



Power output (% of rated capacity) from Darlington Point Solar Farm (orange) and Coopers Gap Wind Farm (blue).
Source: Lu (2025), *Net Zero*.

- Solar & wind: weather-dependent, variable and uncertain (not a bug, but a feature!)
- Capacity factors: solar <30%, wind ~33% on average (Australia)
- Variability occurs at multiple timescales: minutes, hours, days, months.

Challenges of High Renewables



South Australia's generation mix (7–14 March 2025) highlighting challenges of high renewable energy penetration. Source: Open Electricity.

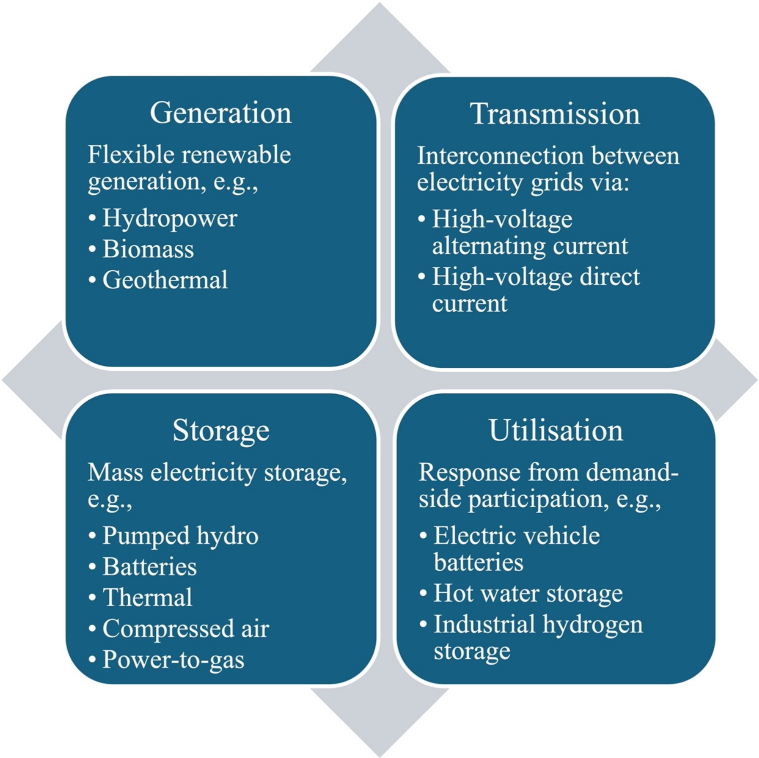
a. Capacity inadequacy: little/no solar & wind → insufficient supply

b. Low minimum generation: excess renewables force thermal units near technical limits

c. High ramping: rapid solar drop + evening peak → fast ramping by gas turbines

d. Frequent cycling: thermal generators switched on/off, ramped up/down more frequently

FIRM Strategy



FIRM strategy to unlock system-wide flexibility across the electricity supply chain. Source: Lu (2025) *Net Zero*.

Flexible renewable generation

- Hydropower & bioenergy provide operational flexibility

Interconnection between electricity grids

- Electricity flows across regions, smoothing out renewable variations

Response from demand side

- Smart energy systems empower consumers to support grid balancing

Mass electricity storage

- Energy shifts day/night, windy/windless periods

Flexible Renewable Generation

Hydropower

- Storage dams, run-of-river
- Fast ramping to stabilise the grid
- 1400 GW worldwide (one third of renewables)
- Constrained by resource limits and environmental impacts

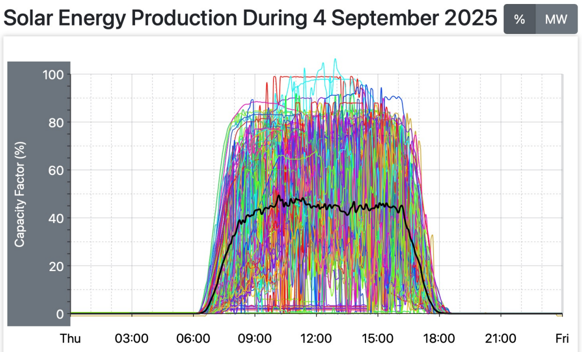
Bioenergy

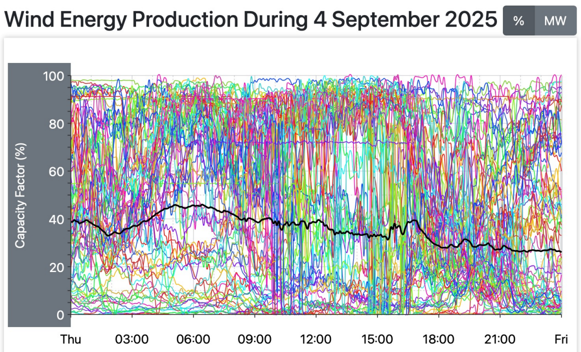
- Crops, residues and waste for power, heat, and fuels
- Potentially carbon neutral, but emits pollutants and particulates
- 150 GW worldwide
- Land-use competition with food, feed and materials

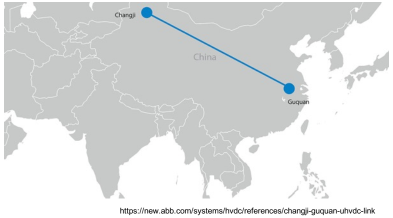
Geothermal

- Heat from Earth's crust
- High capacity factor (e.g., > 80%) for 24/7 baseload power
- Geographically constrained, e.g., Pacific Ring of Fire

Interconnection of Grids







Changji-Guquan HVDC link (China)

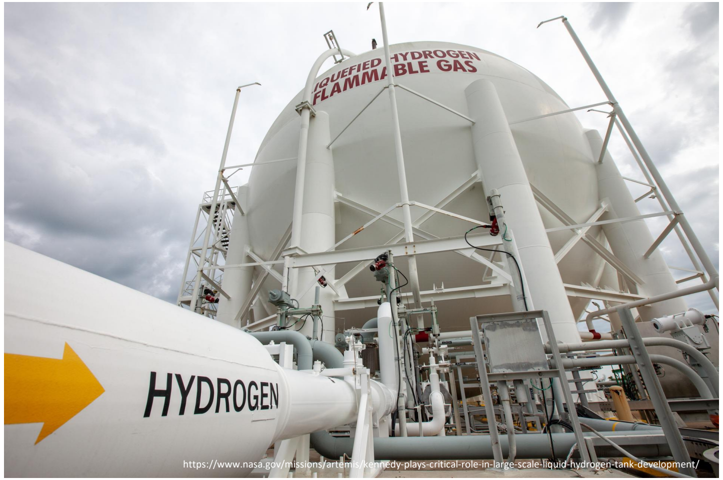
North Sea Link (Norway–UK)

Grid interconnection aggregates solar and wind across regions, creating a smoothing effect.
Source: Aneroid Energy.

High-voltage alternating current (HVAC)	High-voltage direct current (HVDC)
Easy voltage conversion with transformers	Needs converter stations (power electronics)
Higher losses (reactive power, skin effect, frequency-related)	Lower losses (~3% per 1000 km)
Low terminal cost, high line cost	High terminal cost, low line cost
Dominant for national and regional grids	Cost-effective for very long -distance and undersea links
Grids are synchronously coupled: faults can spread	Grids are decoupled: faults remain isolated

Response from demand side

From homes to industries, demand-side storage is a powerful buffer for renewables.
More: Lu et al. (2025) *Renewable Energy*, 123920.



Residential & commercial

- EV batteries, hot water tanks, home batteries
- Embedded in local grids, close to final consumption
- Reduce grid pressure by shifting loads
- Flexibility without behaviour change

Industrial

- Hydrogen & e-fuel production as large flexible loads
- Ramp up/down with renewable availability
- Flexibility from minutes to months

Mass Electricity Storage

The energy future will be built on a mix of diverse, complementary storage solutions.

Pumped hydro	Batteries	Thermal storage	Compressed air
80% round-trip efficiency	85–95% round-trip efficiency (lithium-ion)	40–55% round-trip efficiency	60–70% (adiabatic CAES)
50–100 year lifetime	10–20 year lifetime	30–40 year lifetime	30–40 year lifetime
Needs suitable geography, geology & hydrology	Can be built almost anywhere	Can be built almost anywhere	Needs high-pressure environment, e.g., underground salt caverns
Cost: tens–hundreds USD/kWh	Cost: hundreds USD/kWh, falling fast, modular design	Cost: tens USD/kWh	Cost: hundreds USD/kWh
Ramps in minutes, provides inertia	Responds in seconds, fast response	Ramps in minutes–hours, provides inertia	Ramps in minutes, provides inertia

Source: Lu (2019) Short-Term Off-River Energy Storage.

Energy Balance Modelling

Energy balance modelling can provide insight into the energy reliability and affordability of high-renewable scenarios.

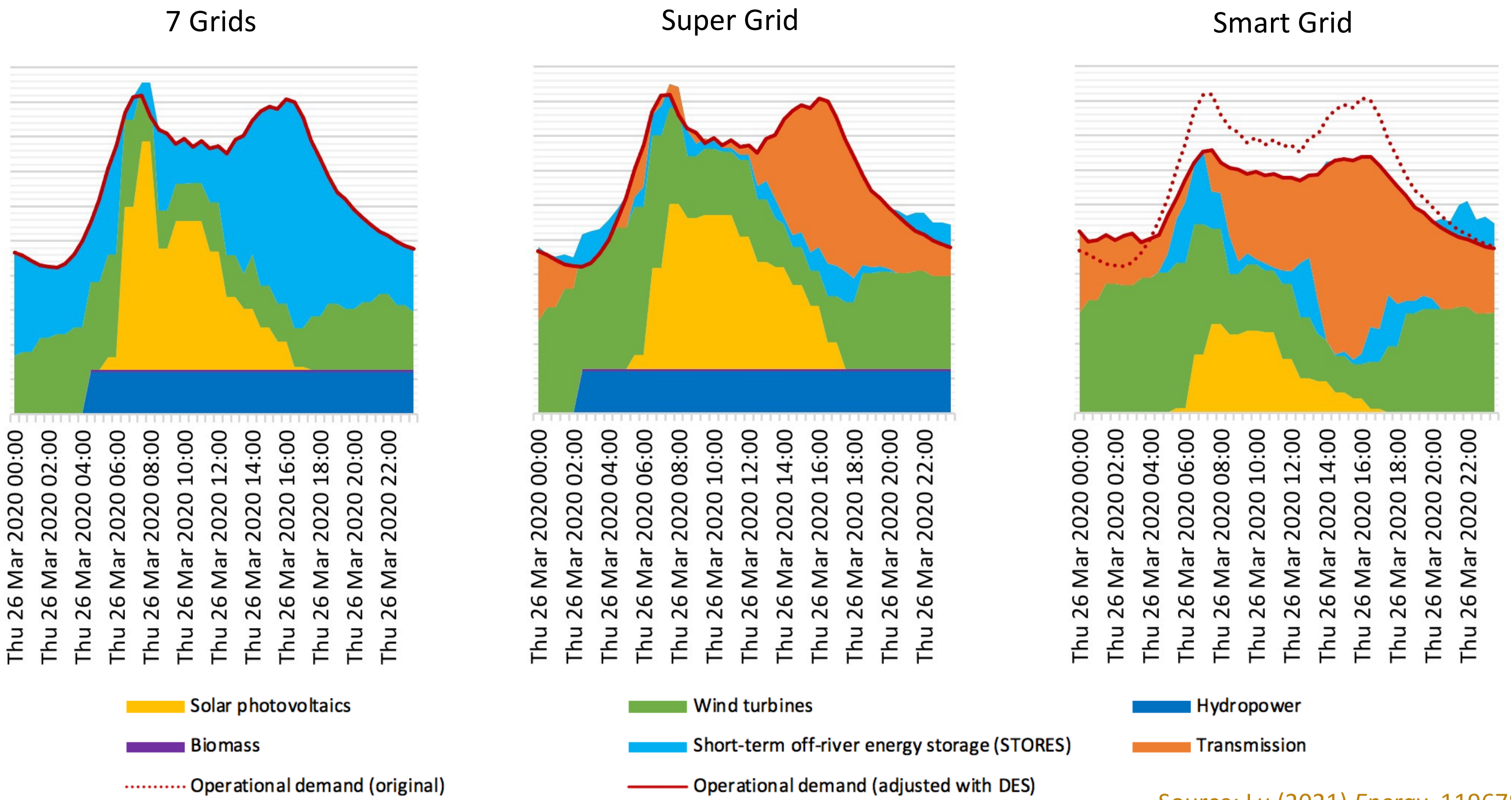
Can do

- Develop various strategies for balancing variable renewable energy resources
- Investigate trade-offs between energy storage (energy time-shifting) and electricity grid interconnection (energy geo-shifting)
- Identify most challenging periods when renewable energy is constrained while electricity demand is high

Cannot do

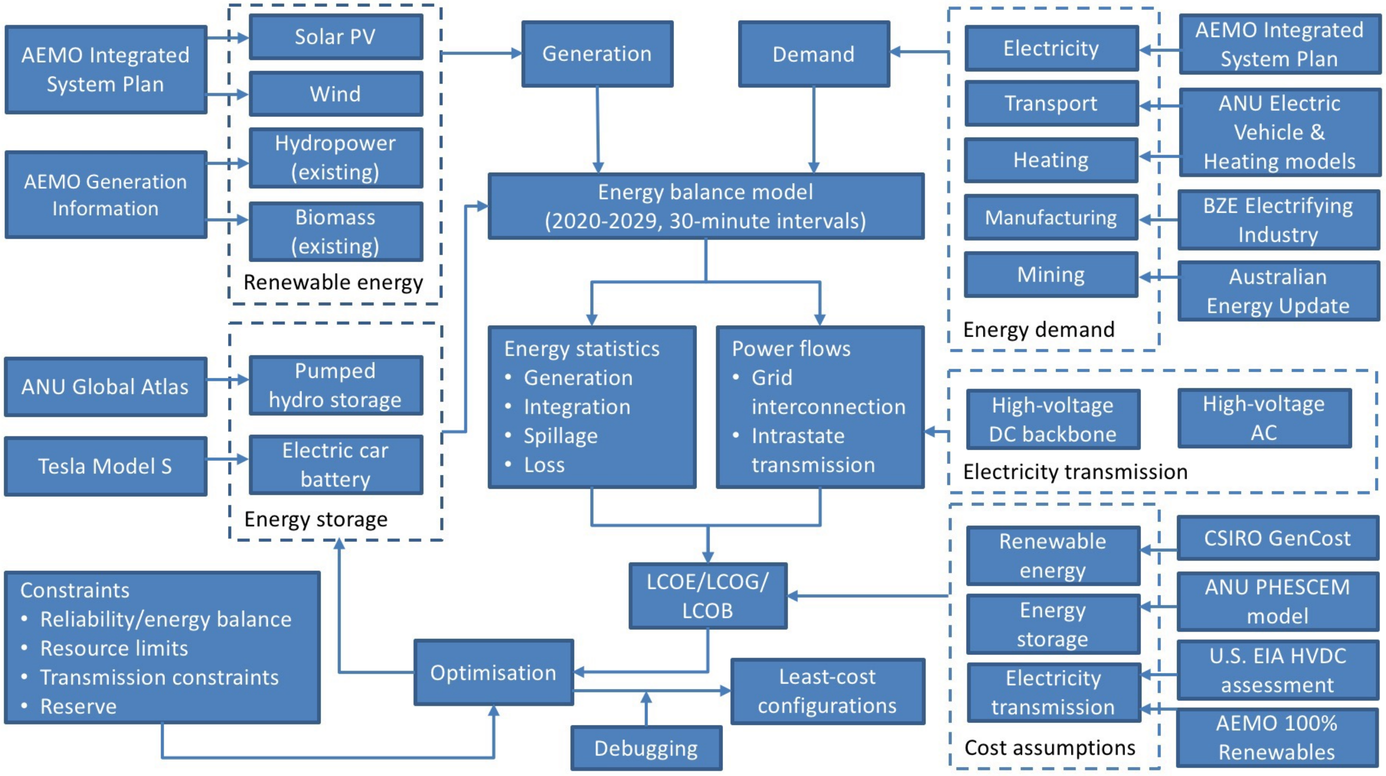
- Power system stability analysis (subseconds to minutes)
- AC network modelling (reactive power flows)

Simulation Snapshots



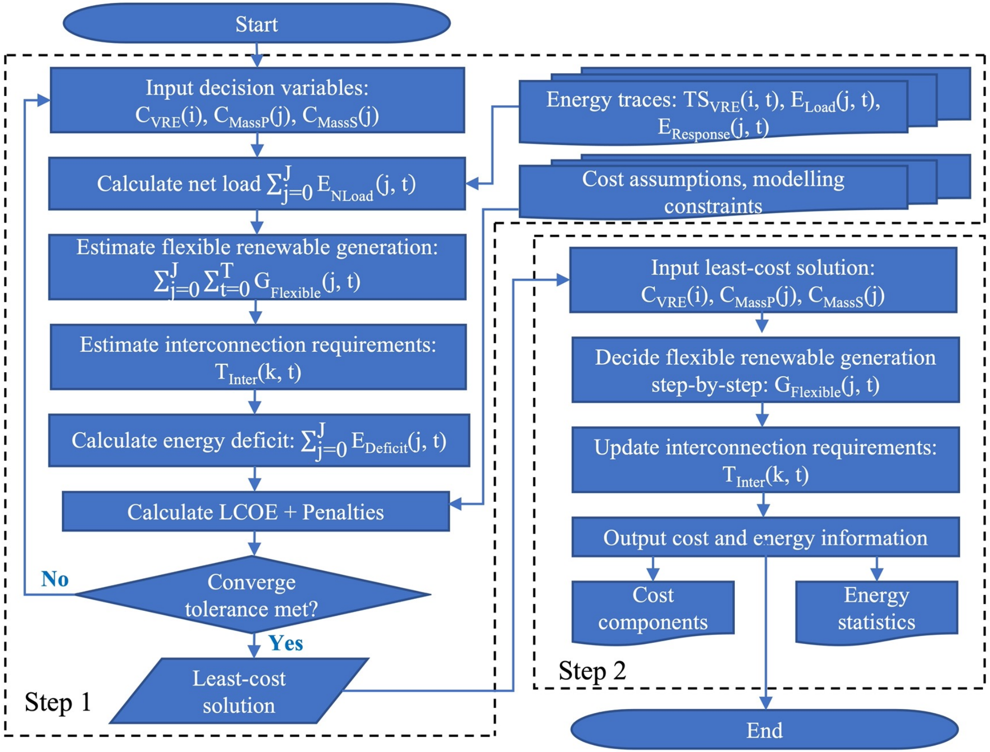
Source: Lu (2021) *Energy*, 119678.

FIRM Modelling Framework



Source: Lu (2021) *Energy*, 119678.

Two-Step Modelling Approach

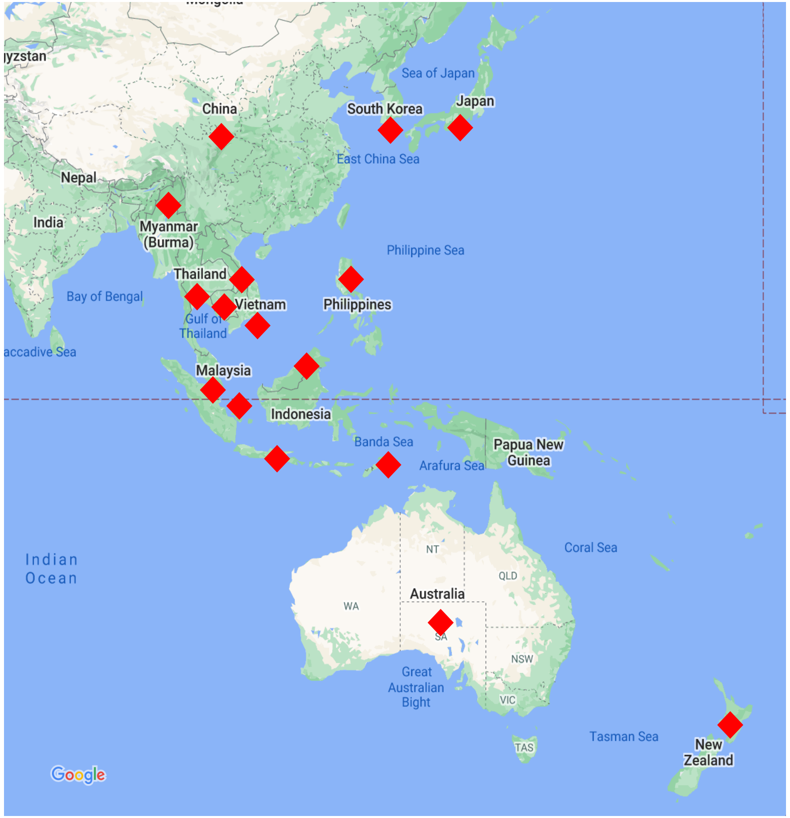


Source: Lu (2025) *Net Zero.*

The advantage of this two-step modelling approach is that it separates the time-consuming scheduling (Step 2) from heuristic optimisation (Step 1).

- Co-optimise generation, storage and transmission using high-resolution, chronological data.
- Integrate diverse strategies to support high shares of solar and wind.

FIRM Model Applications



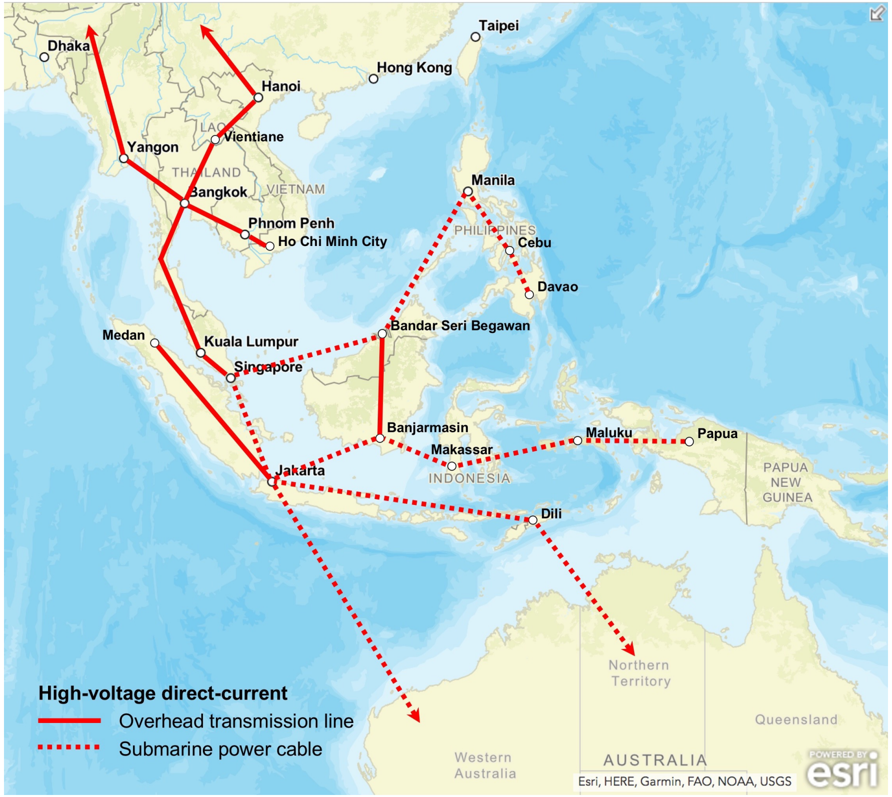
Research coverage

- Australia, New Zealand
- Southeast Asia: ASEAN-10 + Timor-Leste
- Northeast Asia: China, Japan, Korea

Key findings

- FIRM strategy makes high-renewable grids reliable, affordable & resilient.
- Transition to 100% renewables delivers substantial energy, economic & environmental benefits.

ASEAN Study

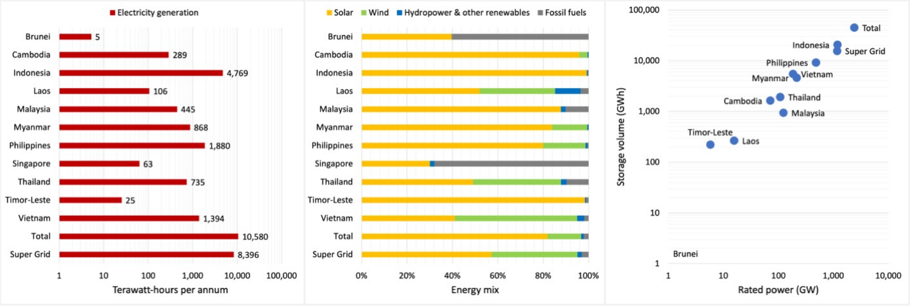


Q1. Is a Super Grid technically and economically viable?

- Yes – Technically feasible with HVDC technology
- Yes – Cost-competitive versus isolated national markets

Q2. Benefits for ASEAN?

- 20% fewer electricity generation capacity
- 70% more wind energy integration
- 65% low energy storage needs



Source: Lu (2021) *Energy*, 121387.

Questions?

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