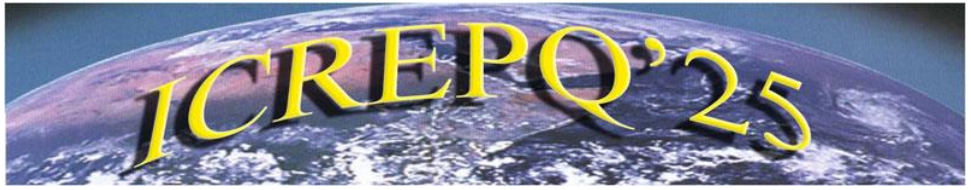

Energy storage: the flexible link between generation & demand

Antonio Gómez Expósito, *IEEE Life Fellow*

ENGREEN – Endesa Red Chair

June 25, 2025

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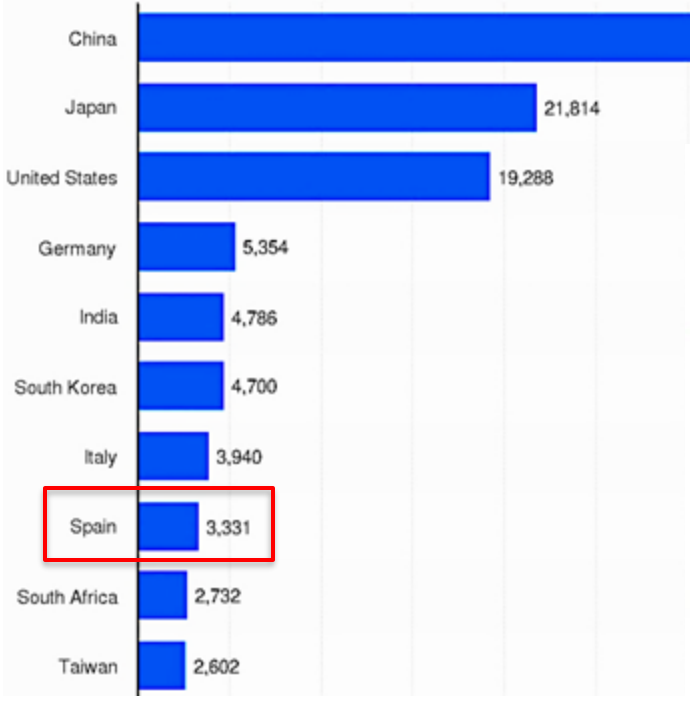
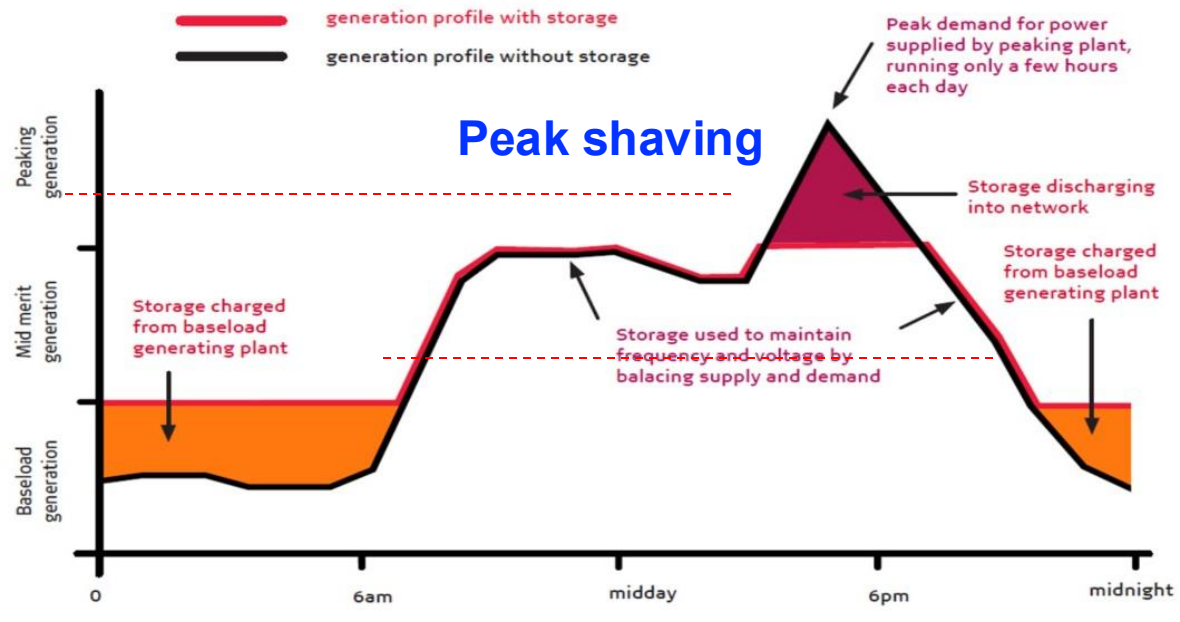
- Energy storage drivers: why now?
- Power system applications
- Winning technologies
- Looking forward

Historic driver: Nuclear stations deployment

Pumped-storage hydro power (80's & 90's): **Price arbitrage**

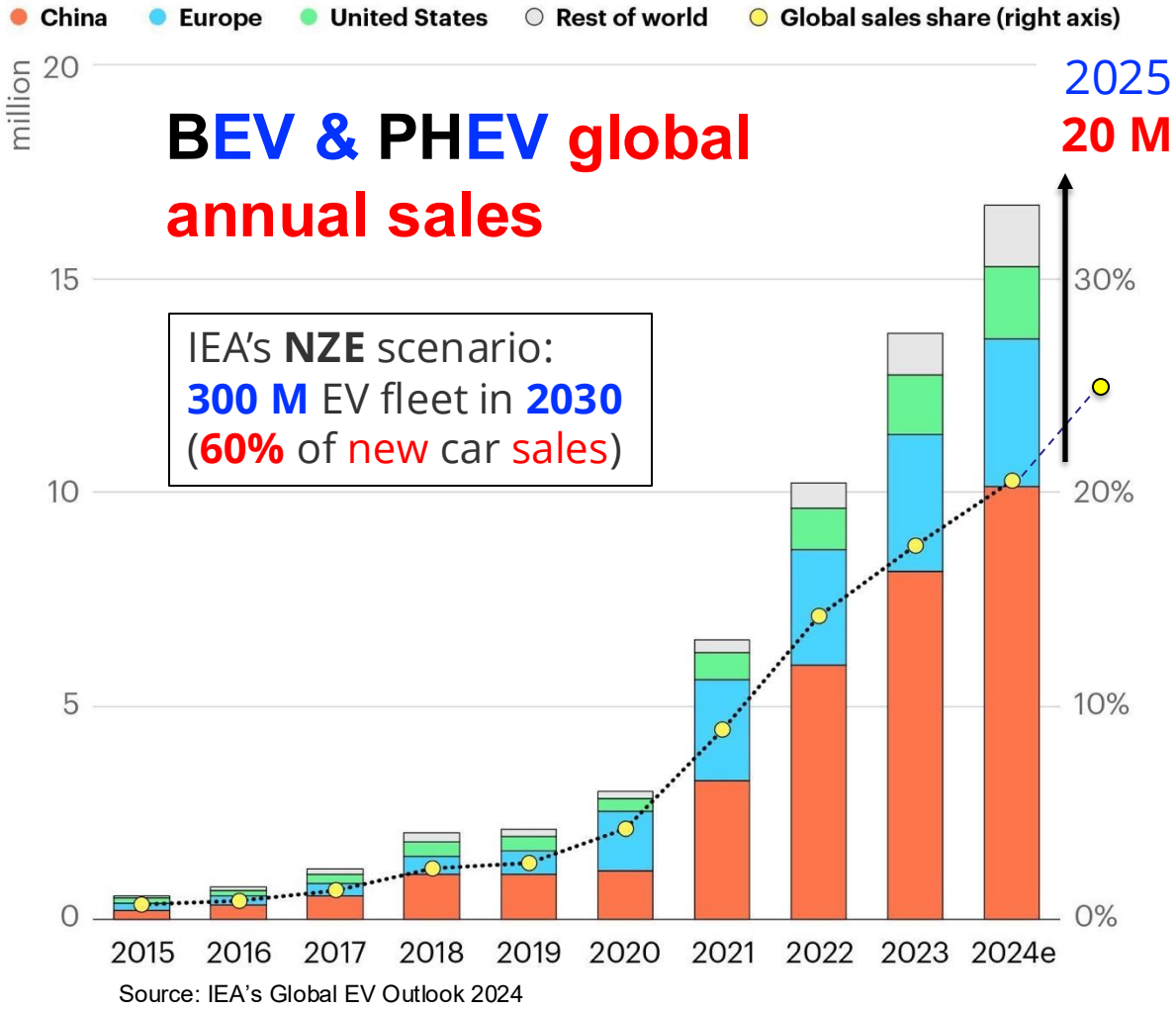


https://www.irena.org/Data/View-data-by-topic/Capacity-and-Generation/Country-Rankings



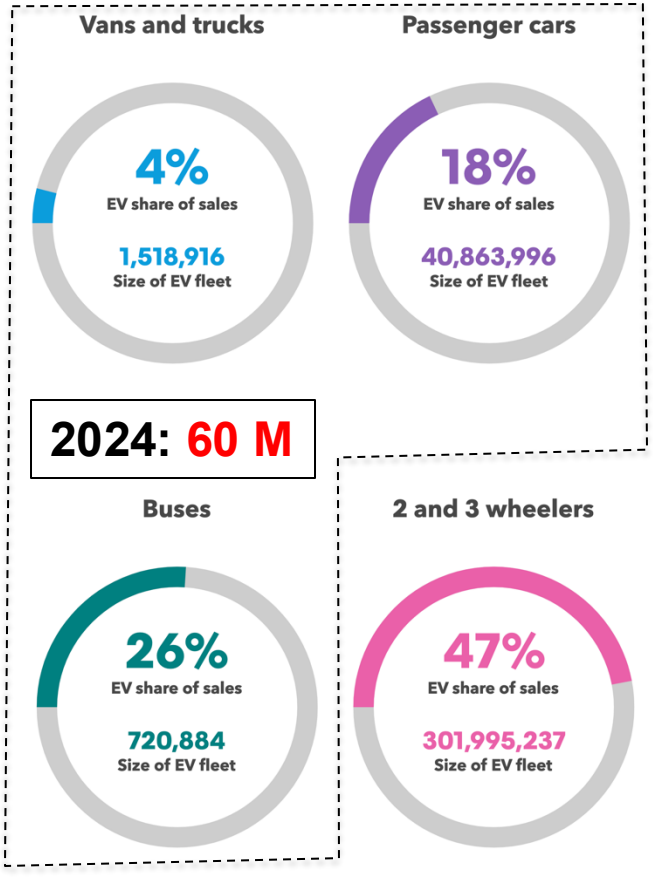
Inflexibility of generation to follow the demand

Current drivers: Electric mobility



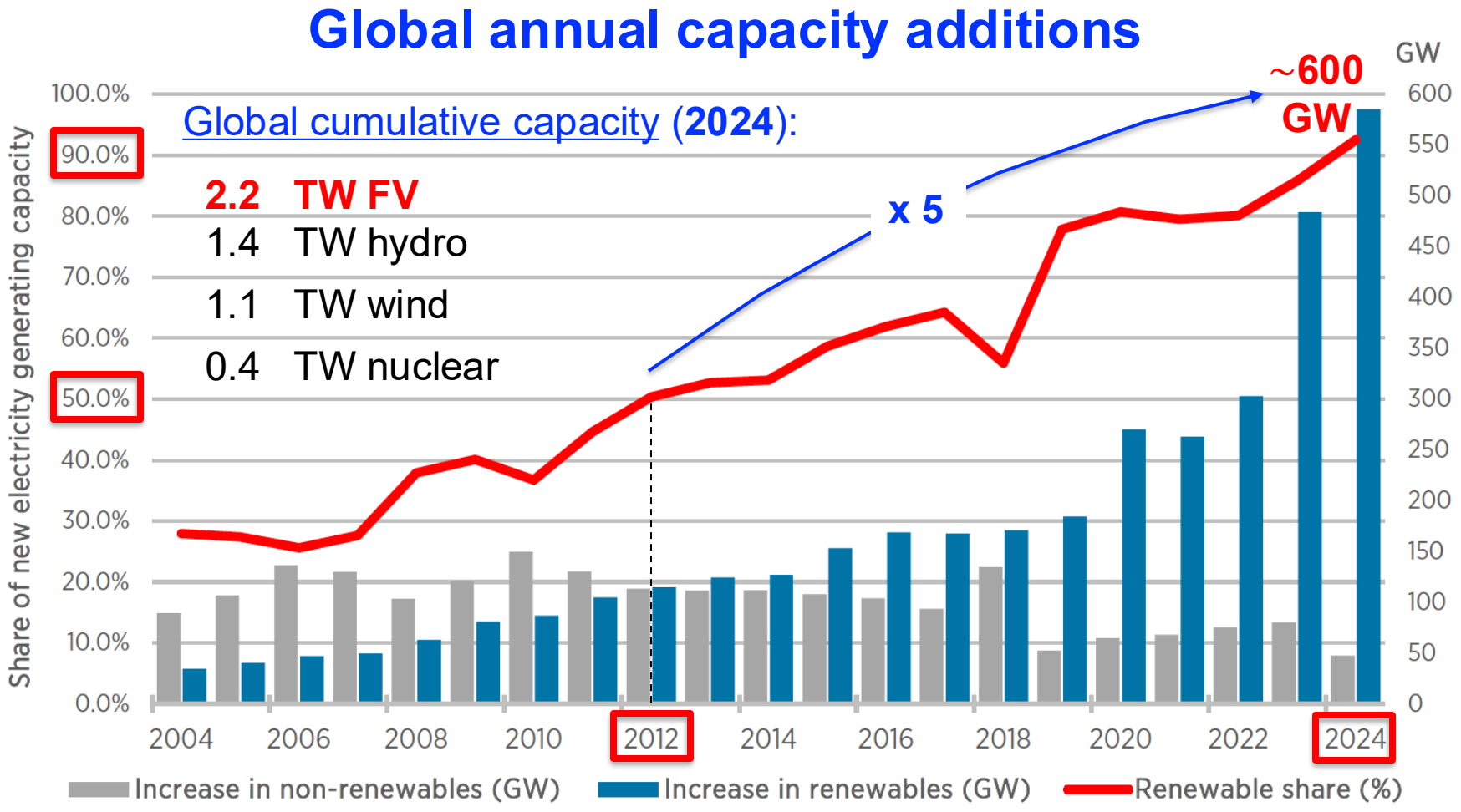
Source: IEA's Global EV Outlook 2024

Global stock (2023)



Source: https://about.bnef.com/electric-vehicle-outlook/

Current drivers: Increasing renewable capacity

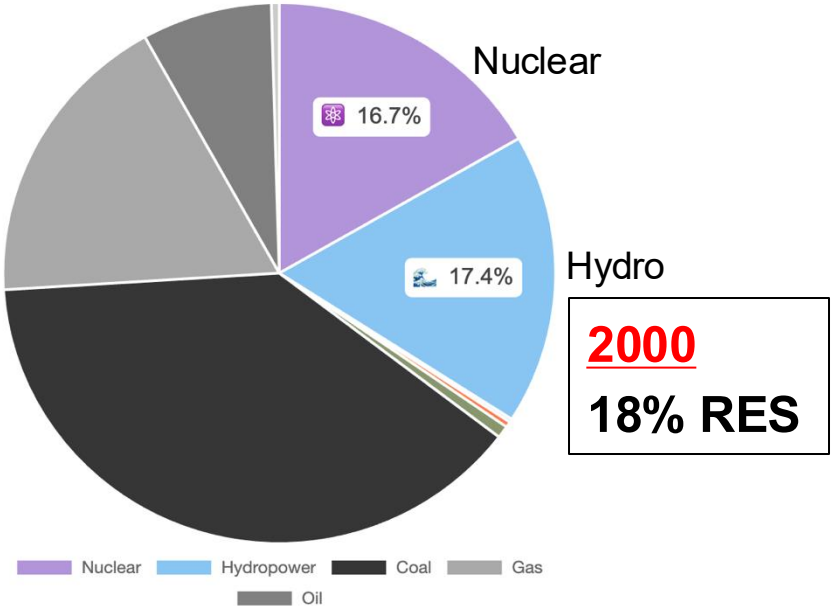


Source: https://www.irena.org/Data

Current drivers : Increasing renewable share

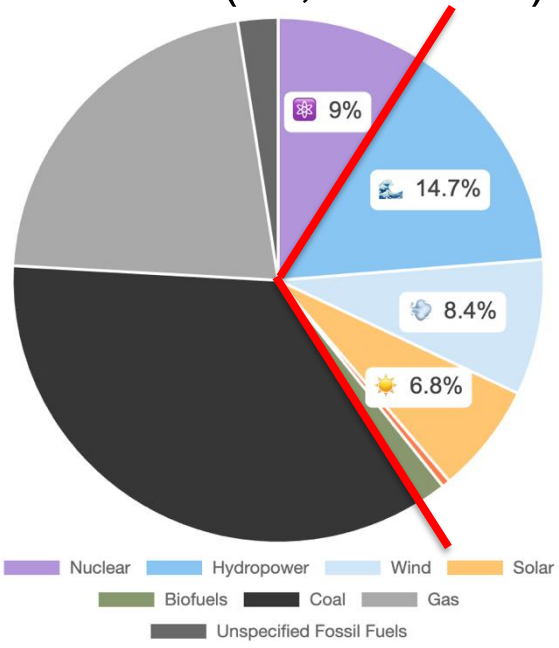
Global electricity mix

2000 (15,000 TWh)



2000
18% RES

2023 (30,000 TWh)



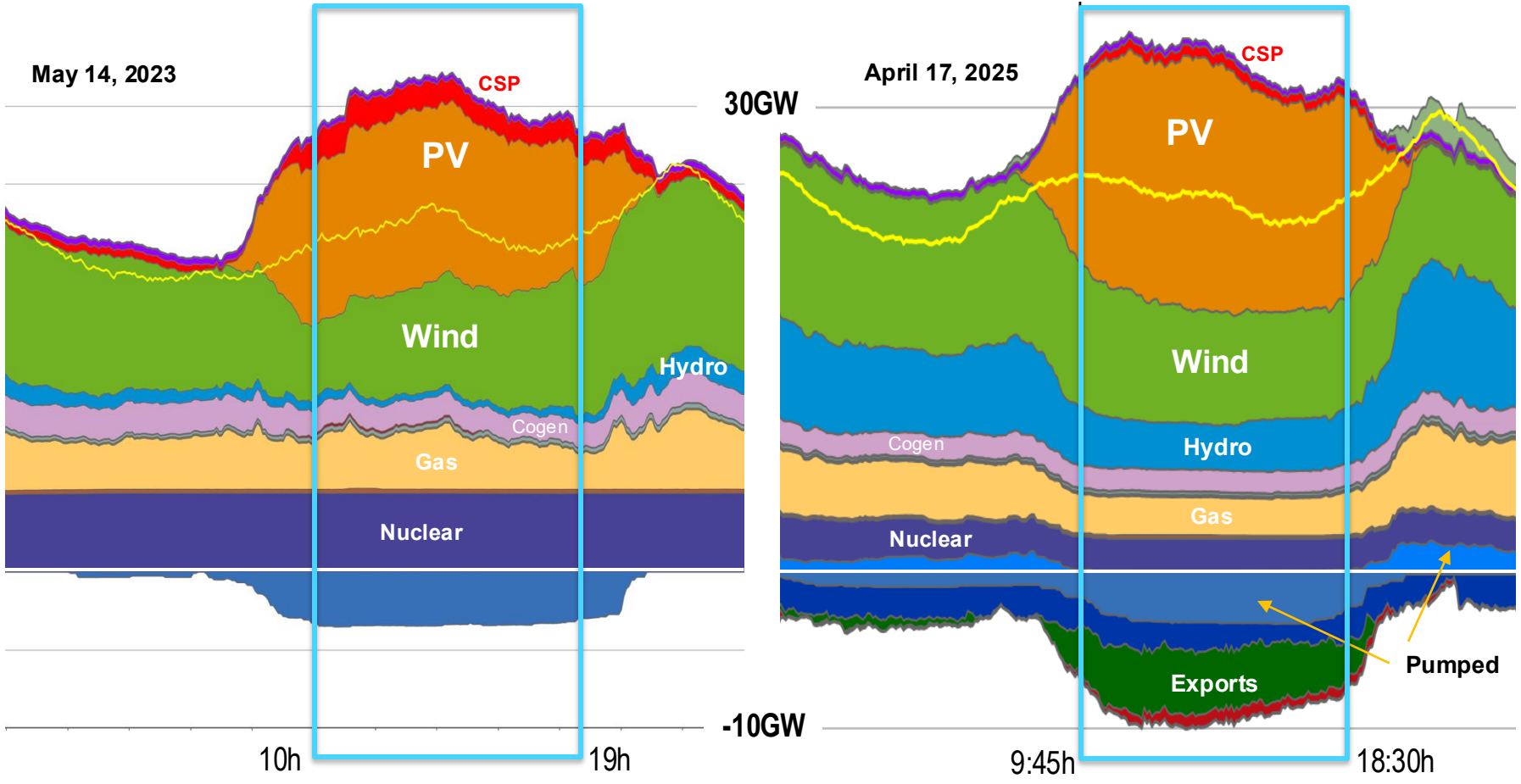
2024
31% RES

56% in Spain

Electricity: 21% of final energy (70% in 2050?)

Source: https://lowcarbonpower.org/

Example of RES penetration: Spain



Inflexibility of demand to follow the generation

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- Energy storage drivers: why now?
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Applications by time horizons

In a future with **>80-90%** share of renewables:

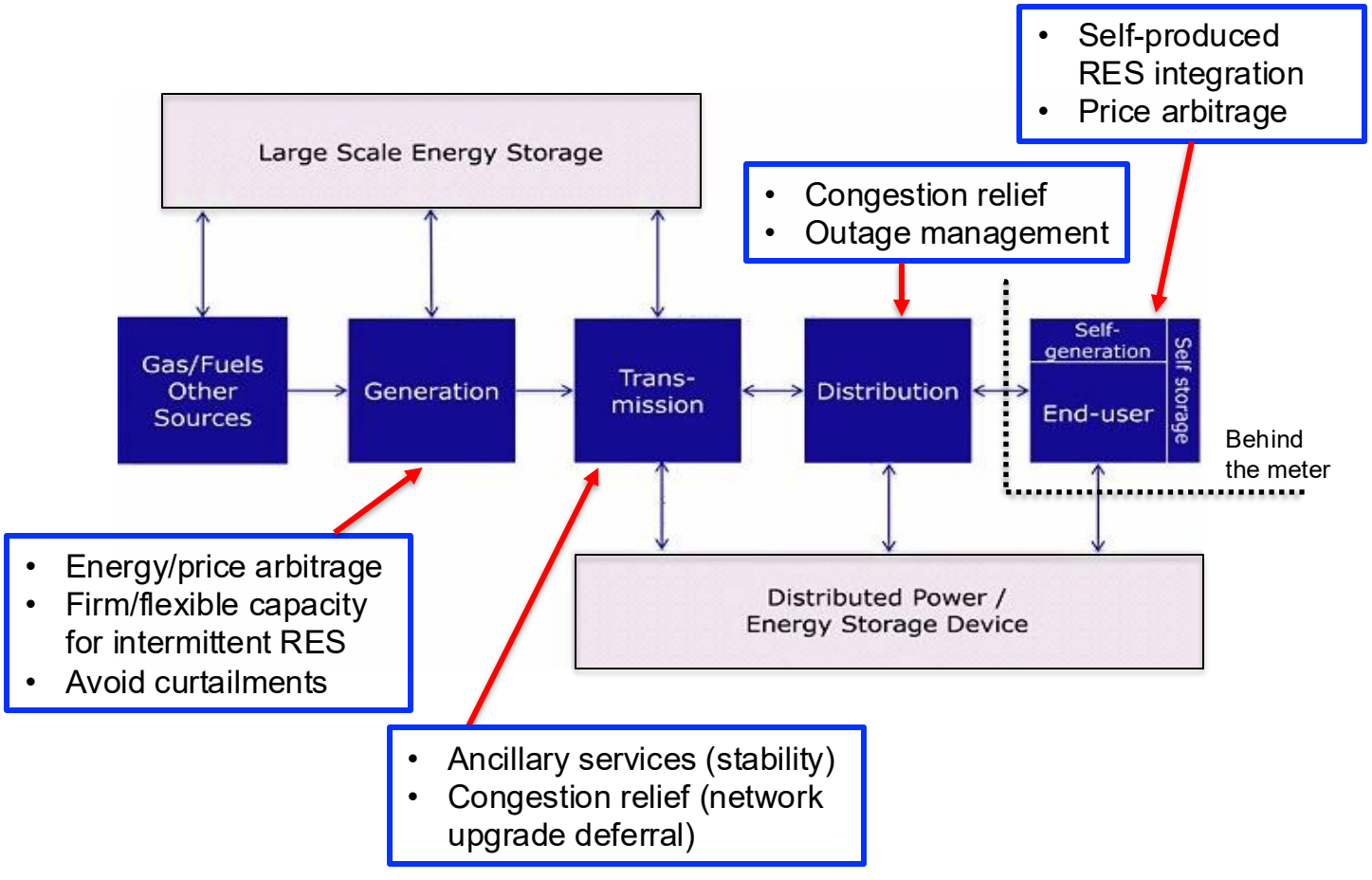
Real-time

Time horizons

Long-term

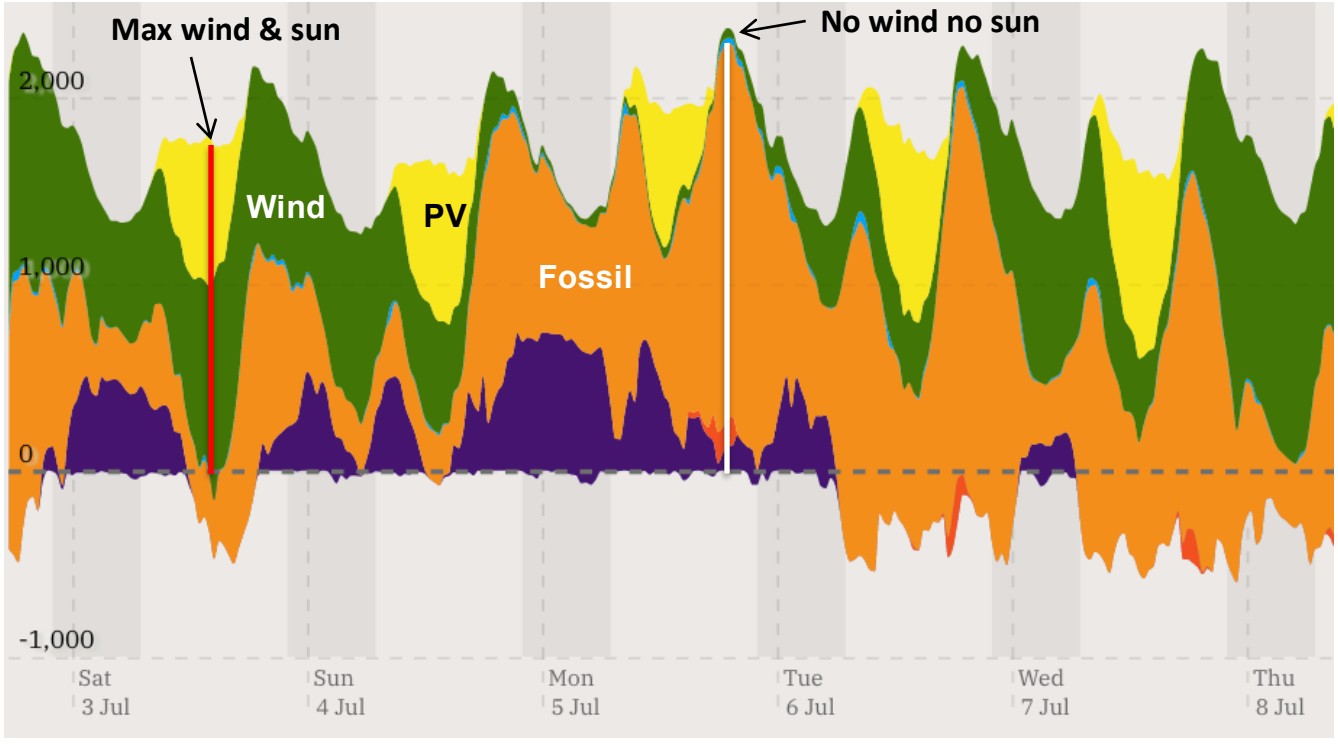
- Grid **stability** (inertia, frequency reg.)
  - Milisec to sec
- **Flexible** capacity (power gradients)
  - Minutes to hours
- **Firm** capacity (peak power, congestions)
  - Hourly to daily
- Energy & price **arbitrage** (time shift)
  - Daily to weekly **(seasonal ?)**

Applications by agents



Daily fluctuations

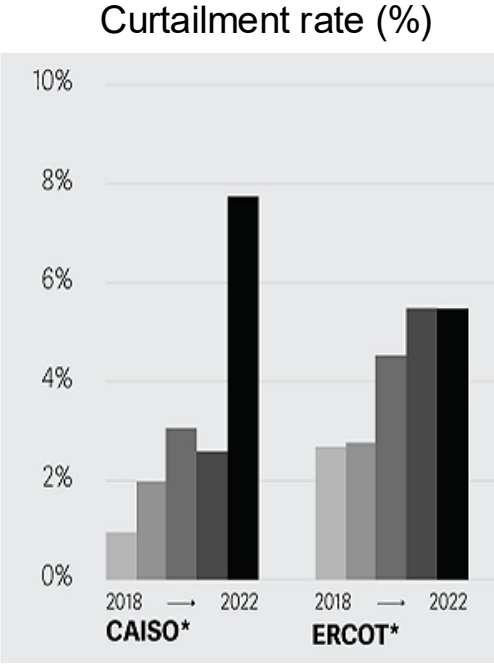
South Australia: July 3-8, 2021

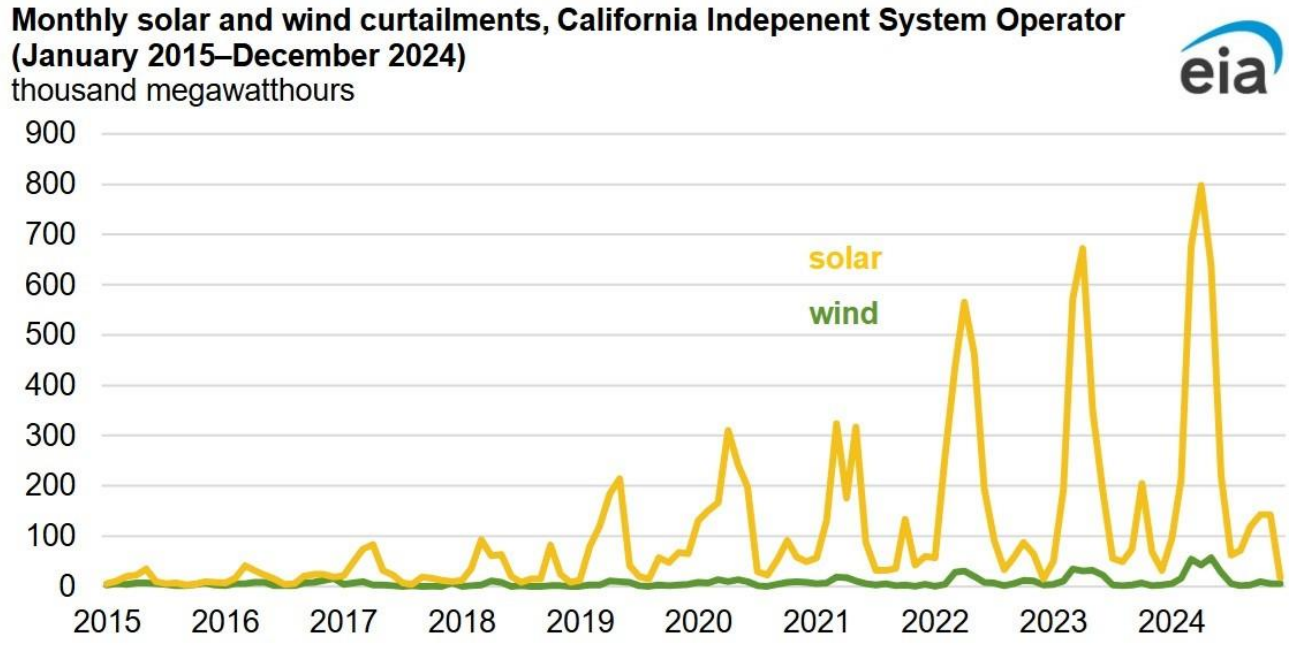


Source: openNEM (https://opennem.org.au/)

Daily & weekly storage will be crucial

RES curtailments: **USA**

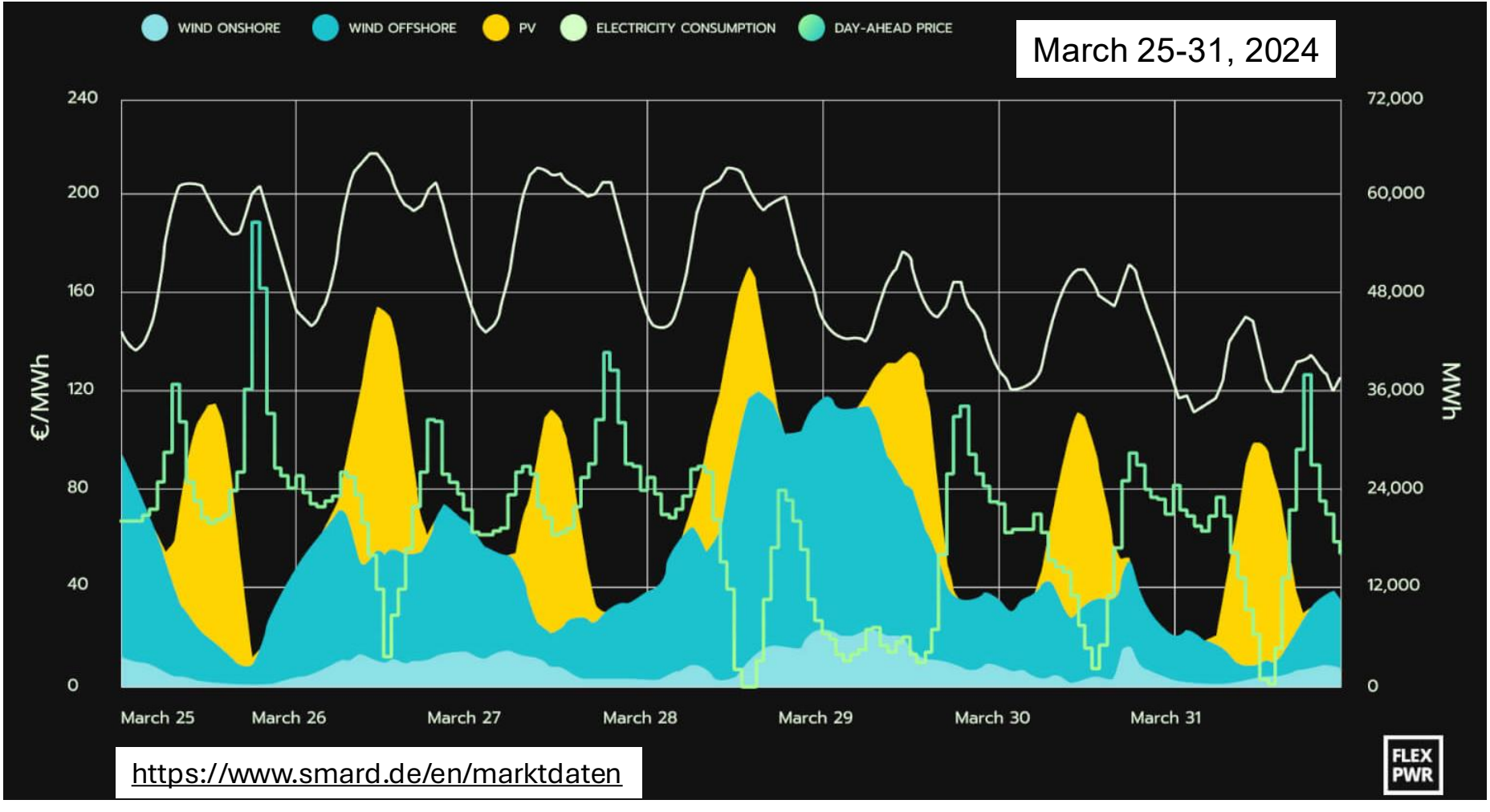




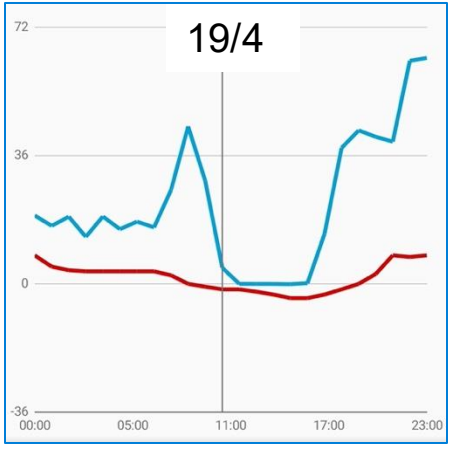
Source: https://www2.deloitte.com/us/en/insights/industry/power-and-utilities/battery-energy-storage-electric-grid.html

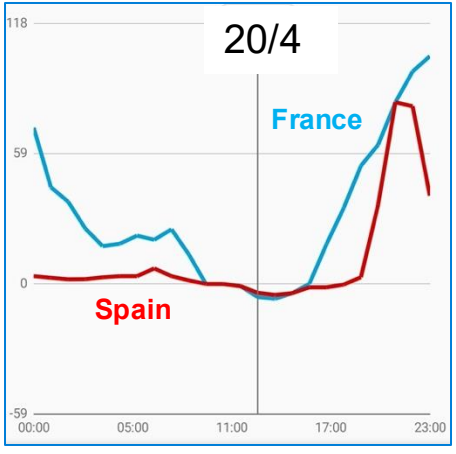
2024: China to relax the 5% limit to RES curtailments imposed in 2017

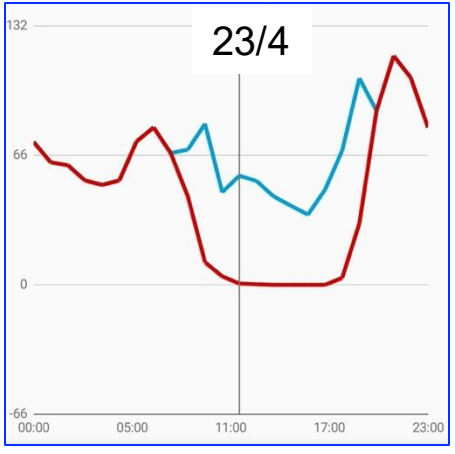
Energy & Price arbitrage: Germany

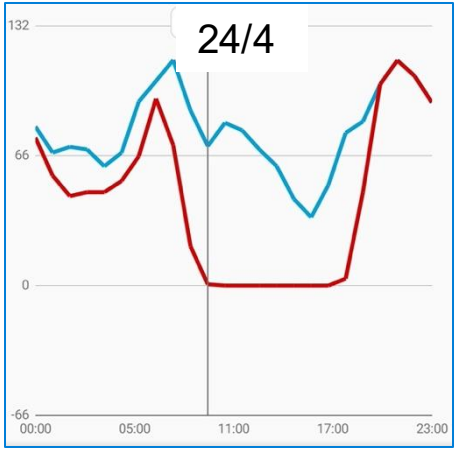


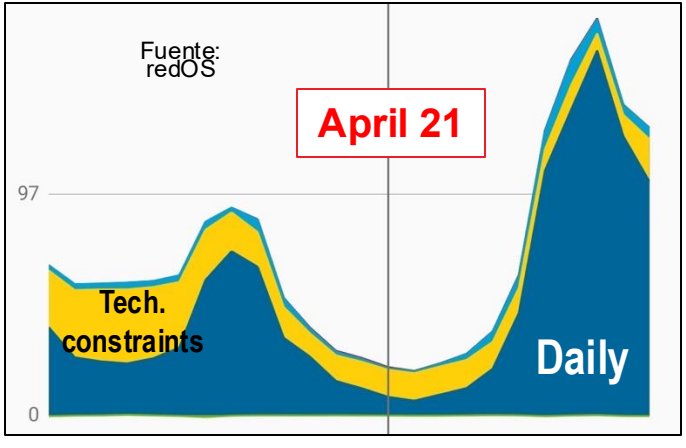
Cannibalization of prices: Spain

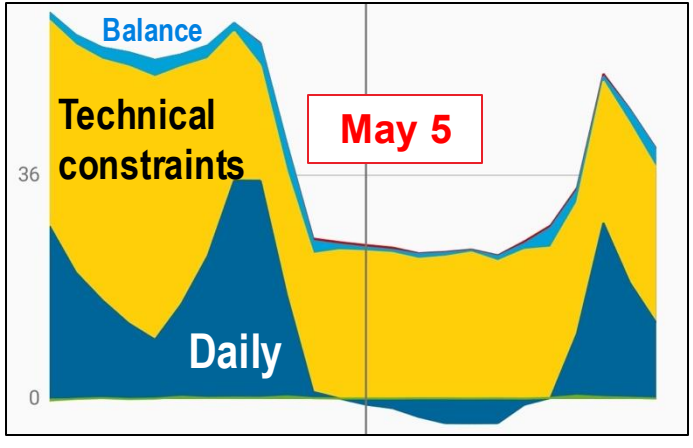






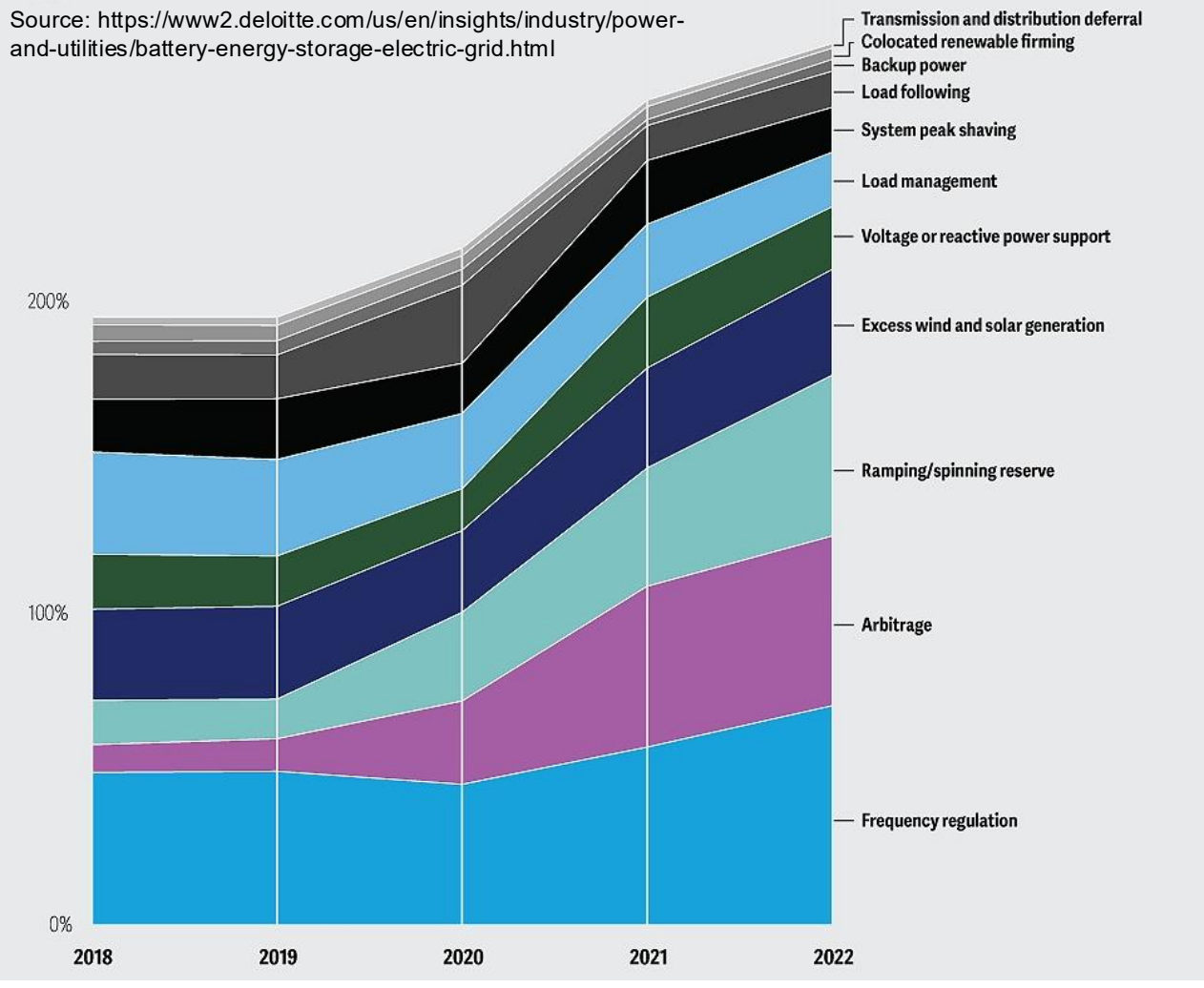






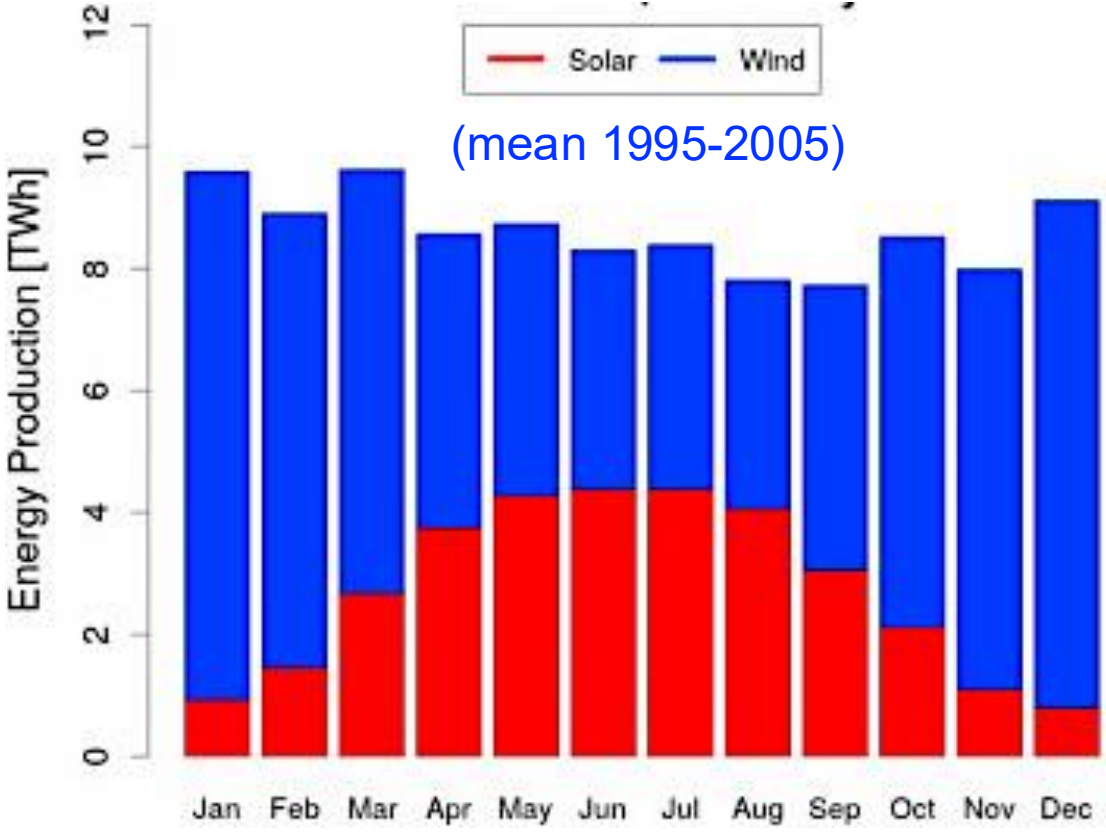
Major hurdle to secure return on investment

Energy Storage Applications: USA



Seasonal fluctuations (not so relevant)

Monthly RES production in Germany. With power installed in 2015



Source: J. Drücke, et. al. “Climatological analysis of solar and wind energy in Germany using the Grosswetterlagen classification”, Renewable Energy, vol. 164, pp. 1254-1266, 2021.

Contents

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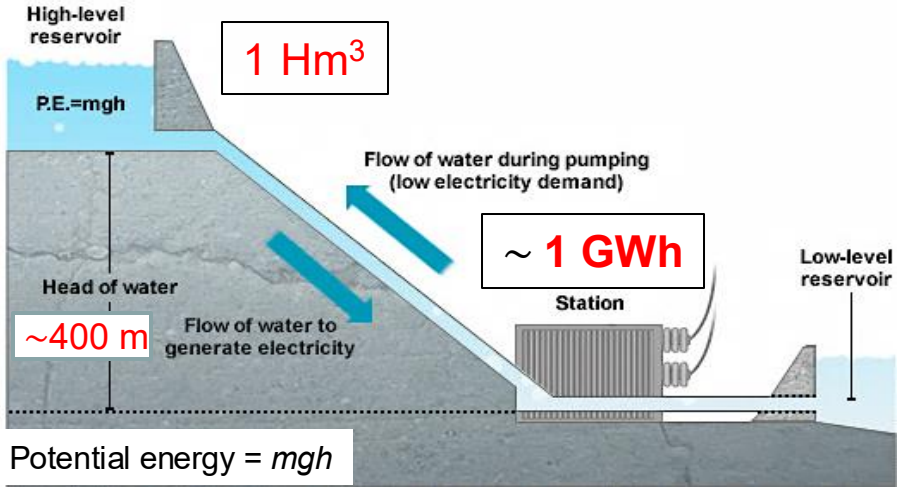
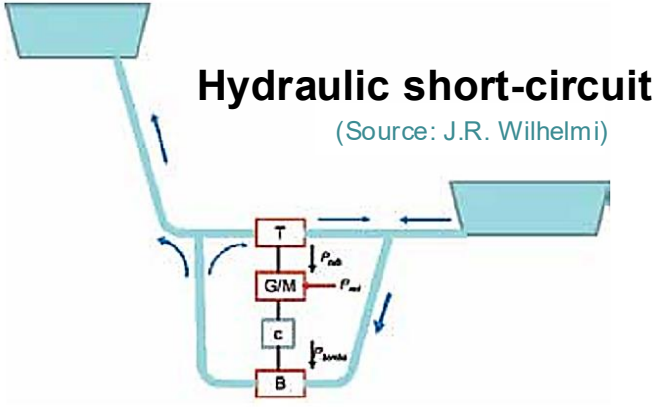
Hydro pumped storage





Technological improvements: efficiency, speed of response, flexibility

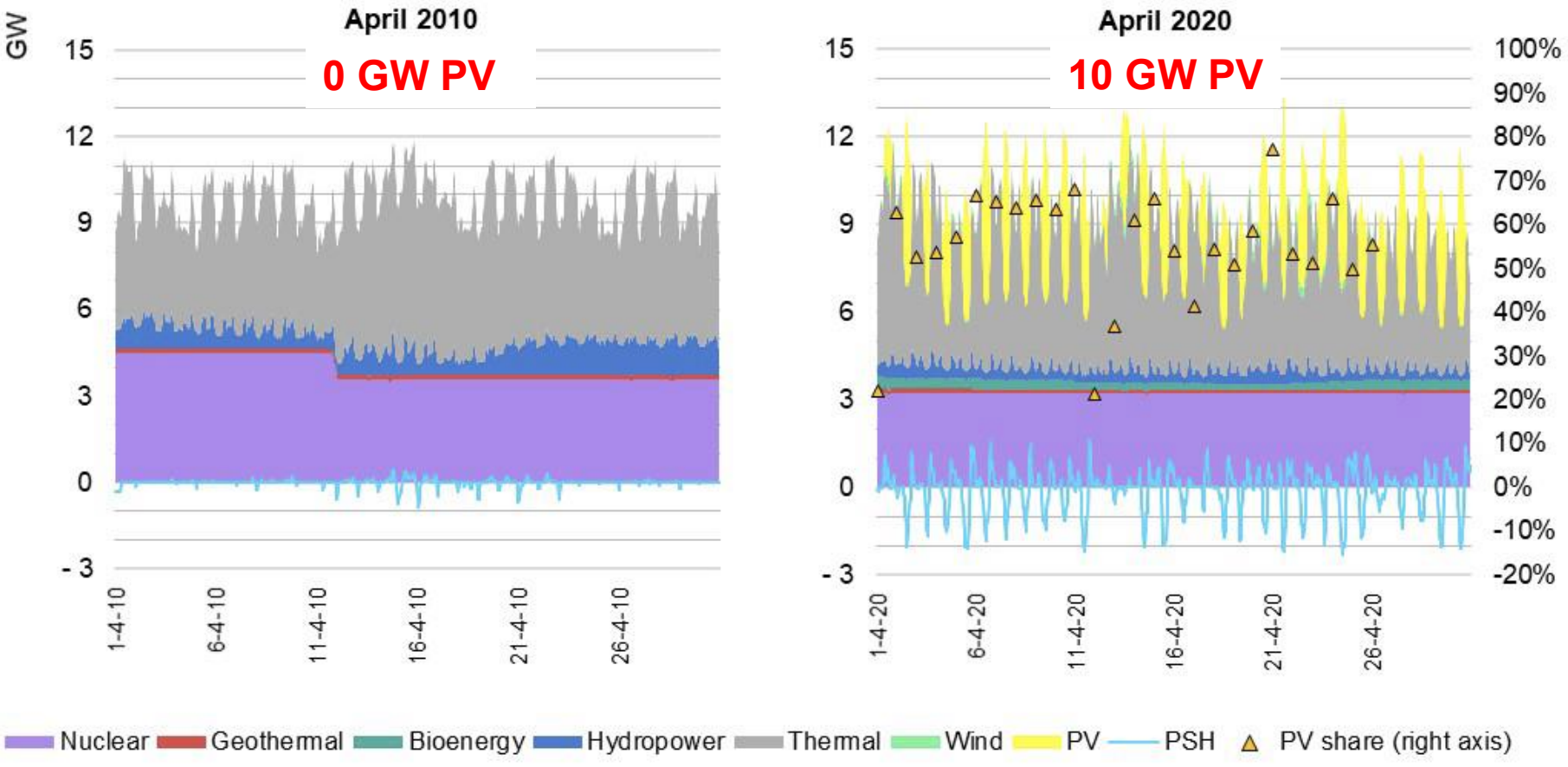
- Hydraulic short-circuit
- Variable speed drives (Japan)

Alternative sites:

- Ocean as lower reservoir (Japan limited experience)
- Alternative placements: underground (mines, salt caverns), underwater

Modify existing reservoirs (add pipes, gen-turbines sets): more power same energy

Pumped storage for PV integration: Kyushu (Japan)



Source: IEA, 2020. Based on Kyushu Electric Power Company data

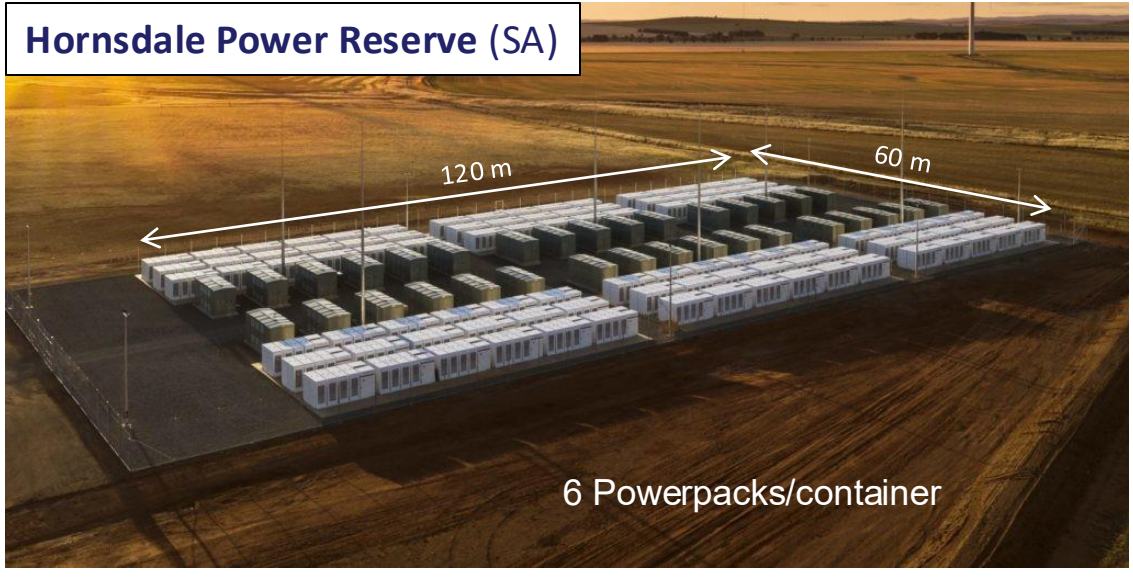
Electrochemical storage: **Li-ion batteries**

Tesla batteries family:

- Powerwall: 13.5 kWh
- Powerpack: 210 kWh
- **Megapack: 3 MWh** (2020)

  NMC/NCA → LFP (2021)

Hornsdale Power Reserve (SA)

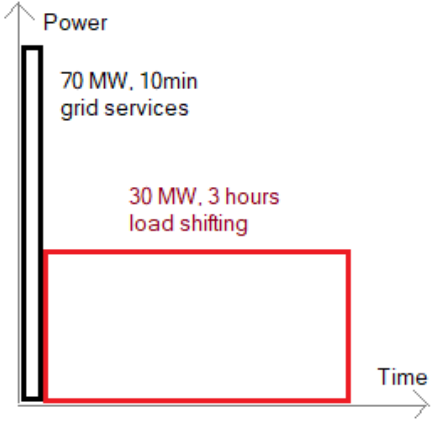


Phase I (100 MW) built in about 60 days

Pioneering Project:

100MW/129MWh (2017)
50MW/64.5MWh (2020)

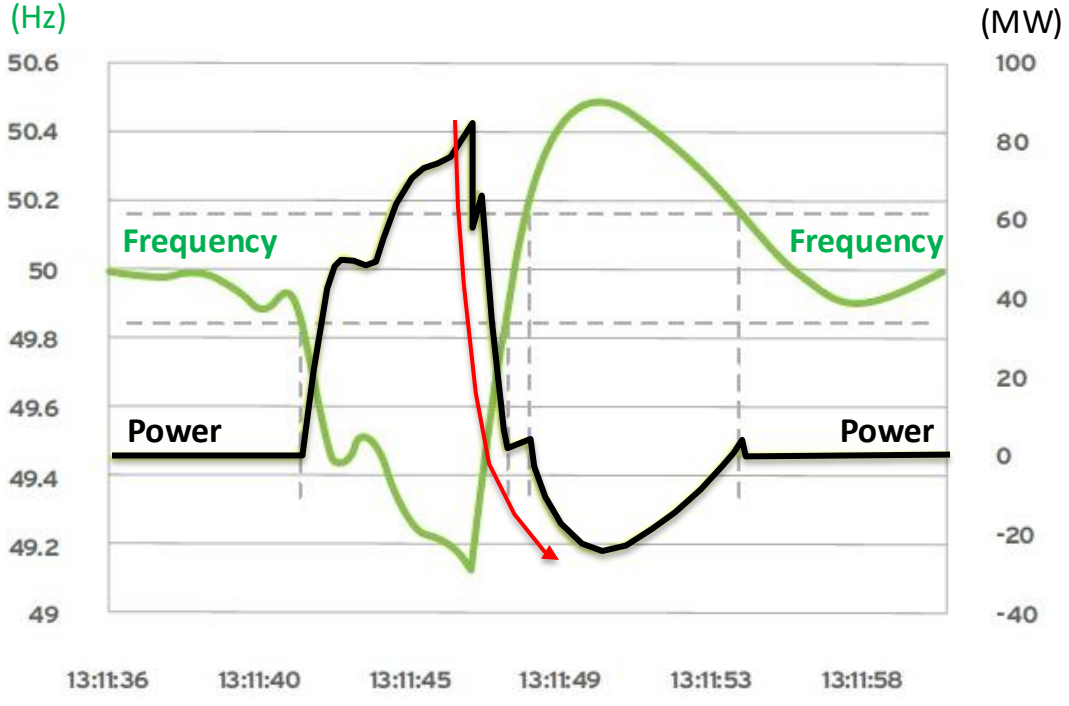
Total: **150MW/ ~200MWh**



Provision of ancillary services: S. Australia

Example: interconnection Queensland-NSW lost (August 25, 2018)

HPR TESLA BATTERY: **Discharge up to 100MW in under 1 sec.**

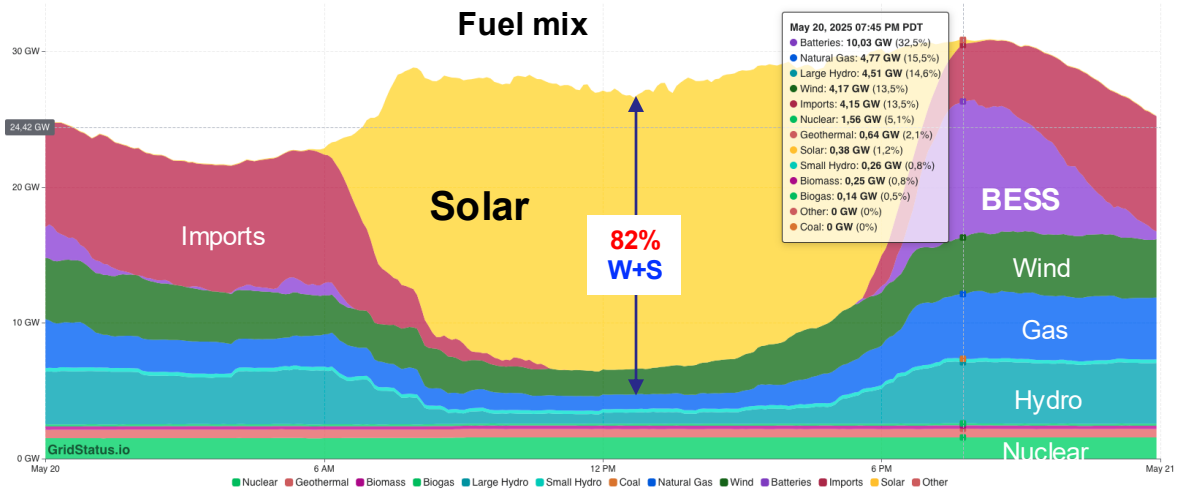


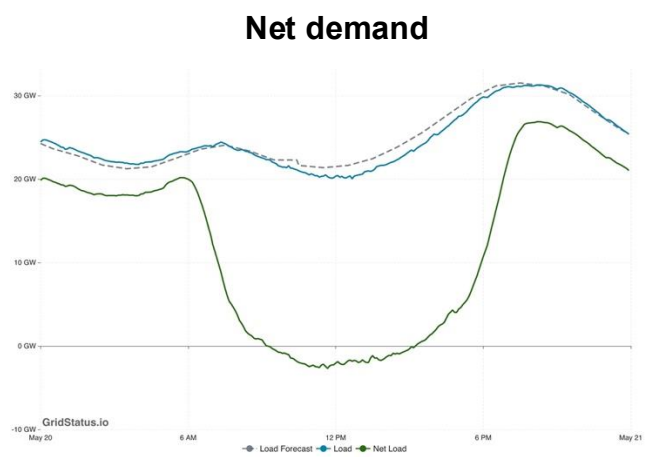
What do we need inertia or speed of response?

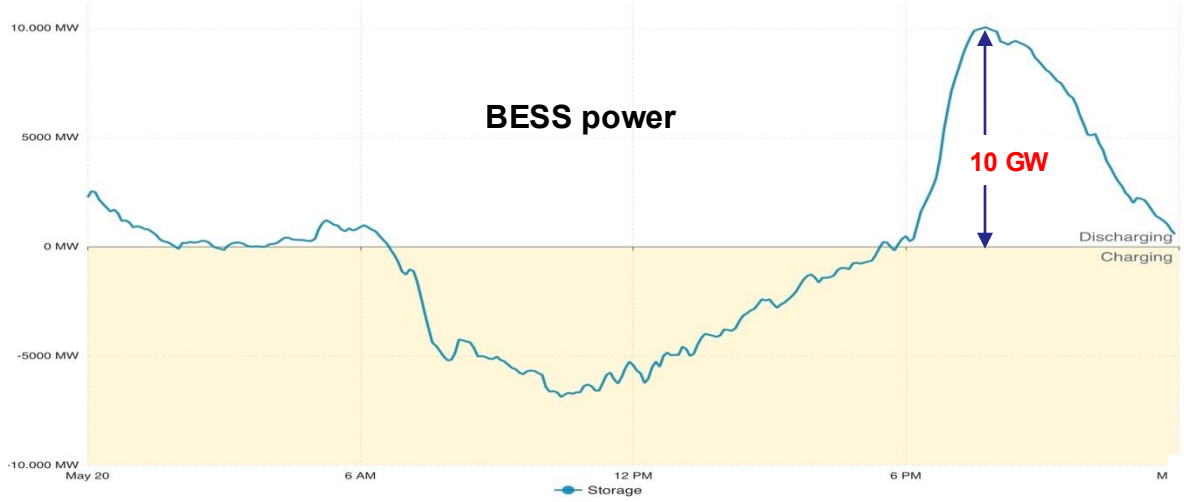
Its "speed and laser precision in response to system events has been encouraging,"

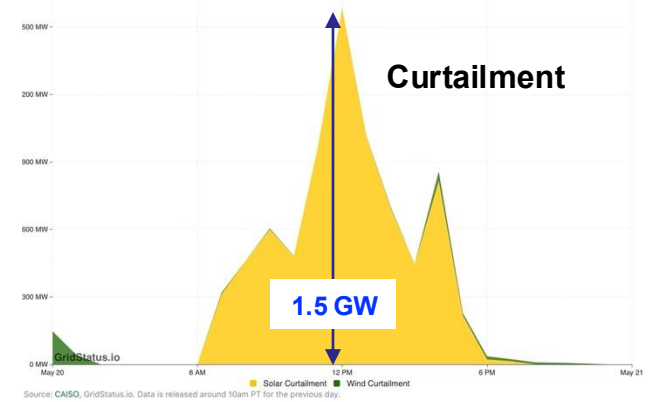
-- Australian Energy Market Operator

Provision of firm capacity: California (May 20, 2025)





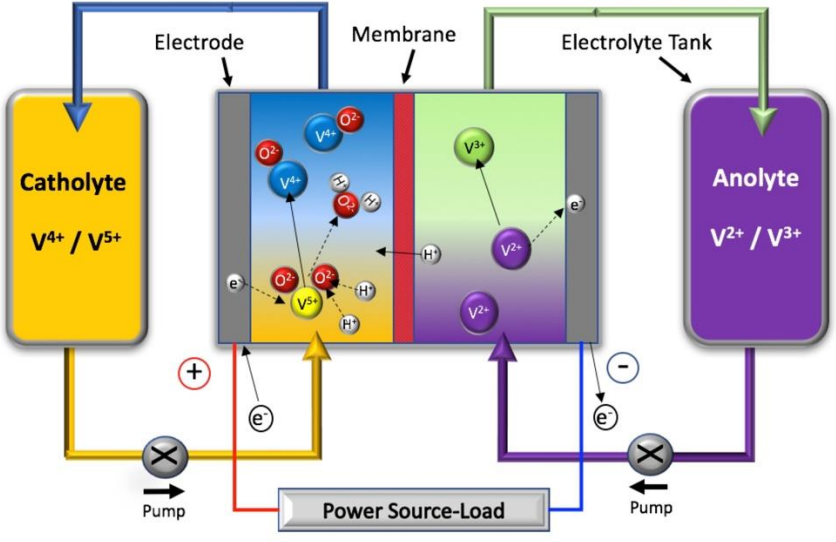




Source: https://www.gridstatus.io/live/caiso?date=2025-05-20

Electrochemical storage: **Flow batteries**

Vanadium Redox Flow Battery



Tanks capacity determines the rated energy of the flow battery

Source: http://impress-energystorage.com/redox-flow-battery/

Example: 200MW/800MWh Vanadium flow battery (China)

World's largest flow battery in Dalian, China (400 containers)

100MW/400MWh connected **2022**

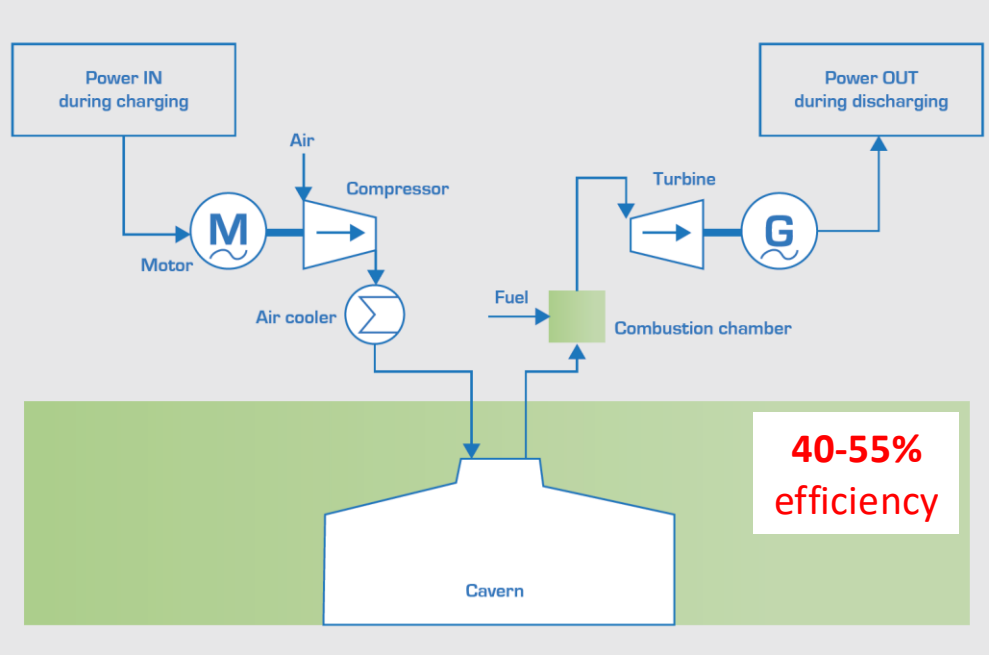
Rongke Power's gigafactory (opened in 2016)

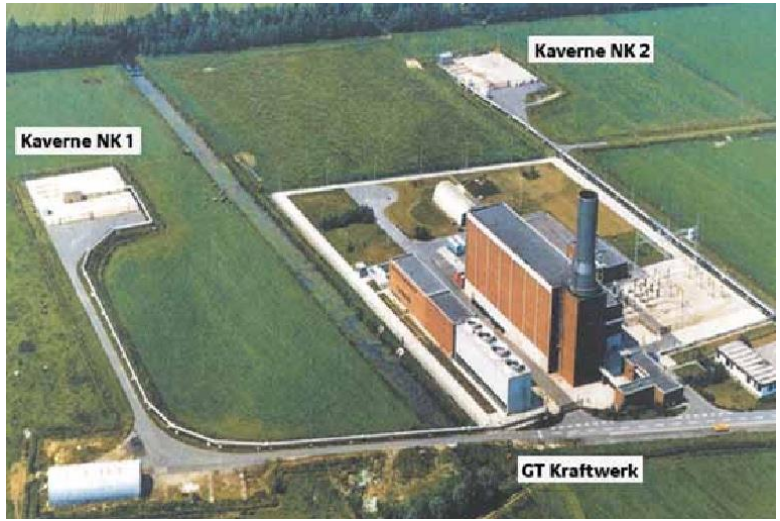
- Land occupation: **9 Ha**
- Response time: **10-20 ms**
- Efficiency: 65%-75%
- Expected lifetime: **15,000 cycles** (zero degradation 20 years)
- Functions: Peak load shifting & power supply for black start

https://www.bestmag.co.uk/worlds-largest-flow-battery-begins-operations-after-six-year-of-planning-and-building/

CAES

Diabatic Compressed-Air Energy Storage





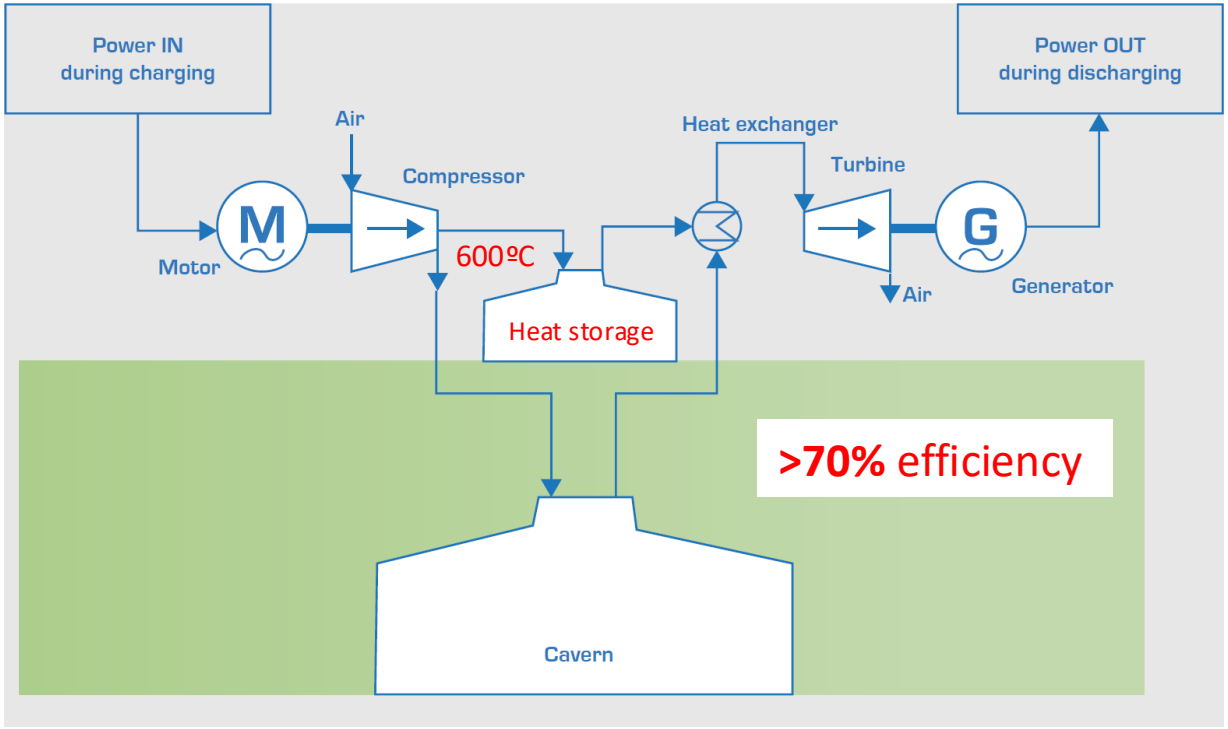
Kraftwerk Huntorf (Germany), 1978:
320 MW / 640 MWh
70 bar, 300,000 m^3

McIntosch (US), 1991:
110 MW / 2.86 GWh

Source: http://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_DCAES.pdf.

ACAES

Adiabatic Compressed-Air Energy Storage



ADELE Project (Germany): 300 MW, 1000 MWh (2013? Discontinued)

Source: http://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_ACAES.pdf.

ACAES

Largest ACAES plant: **Shandong Province (China)**

300 MW, 72% efficiency, 6 hours (1.8 GWh), US**$ 208 M**

Source: https://www.pv-magazine.com/2024/05/16/worlds-largest-compressed-air-energy-storage-project-comes-online-in-china

Gravitational storage

Energy Vault

Modular system:

2- 5 MW, 10-35 MWh

~ 40-story building

25 MW - 100 MWh

+35 years life, ~80% efficiency

Rudong (Shanghai)

Source: https://366solutions.com/14-/01-/2021/136-gravity-based-energy-storage-system/

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Further BESS improvements driven by EVs

- Battery energy densities increasing: 300 Wh/kg
- Alternative chemistries:
  - LFP cathodes (no critical metals): https://www.evlithium.com/LiFePO4-Battery/
  - Silicon anodes: https://alltechmagazine.com/silicon-anode-batteries
  - Cell design (Tesla 4680): https://www.evlithium.com/Blog/4680-battery-power-innovation.html
  - Solid-state Li-ion: https://spectrum.ieee.org/solid-state-battery-production-challenges
  - Sodium-ion (CATL): https://www.sciencedirect.com/topics/materials-science/sodium-ion-battery
  - Lithium-sulfur: https://www.sciencedirect.com/topics/engineering/lithium-sulfur-batteries
- Higher investment rates: from <200 GWh (2019) to over >1,200 GWh (2024)
- More ambitious Governments' targets & subsidies

Suggested reading: Frith, J.T., Lacey, M.J. & Ulissi, U.
A non-academic perspective on the future of lithium-based batteries.
Nat Commun **14**, 420 (2023), https://www.nature.com/articles/s41467-023-35933-2

6-hour BESS will become commonplace

Source: https://www.aa.com.tr/en/energy/solar/chile-launches-largest-solar-plant-with-battery-storage-in-latin-america/49429

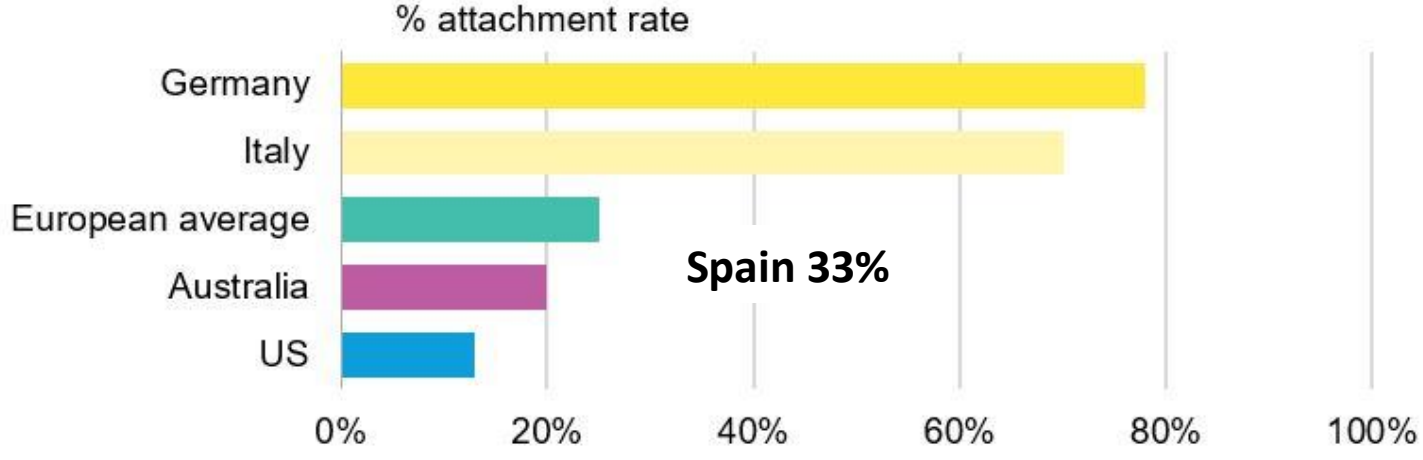
Distributed BESS: Germany showing the way

6 GW of home batteries (1,000,000 systems 6/2023)

Same capacity as pumped hydro

https://www.bves.de/en/energy-storage/households/

Figure 2: Share of residential solar installations with battery storage in 2023, selected markets

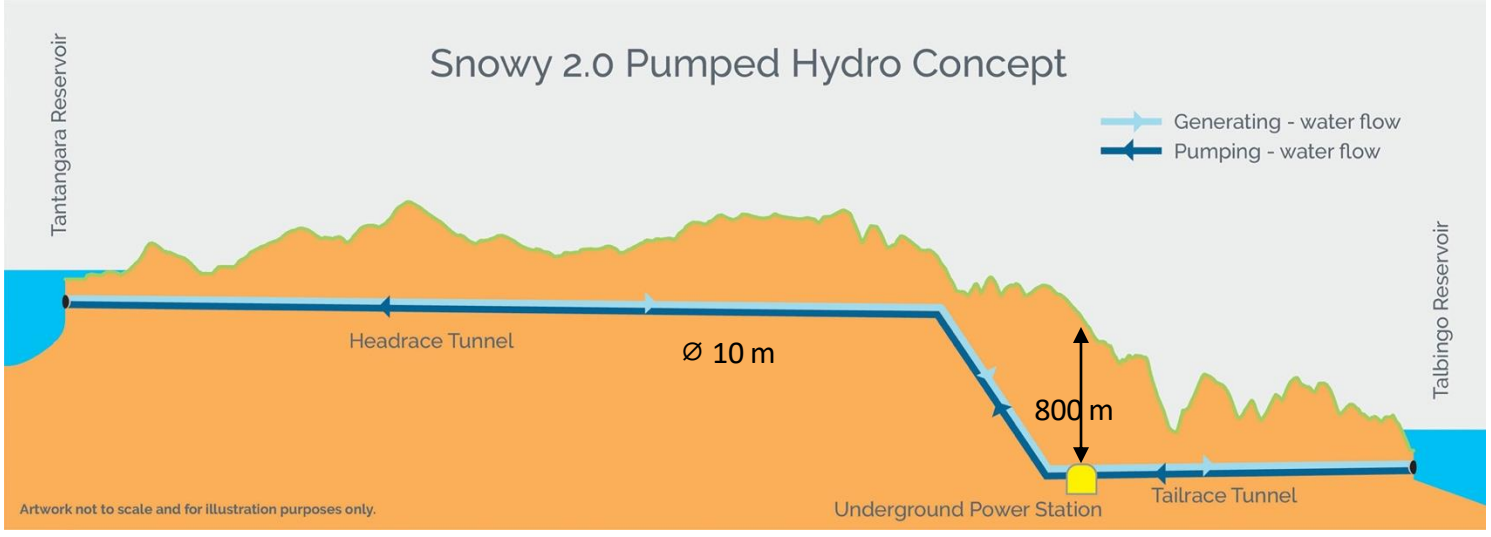


Source: BloombergNEF, LBL, Sunwiz, SolarPowerEurope, Otovo, ANIE, Enphase. Note:

Hydro pumped storage

Snowy 2.0 Project (Australia): 2 GW, 350 GWh (175h)

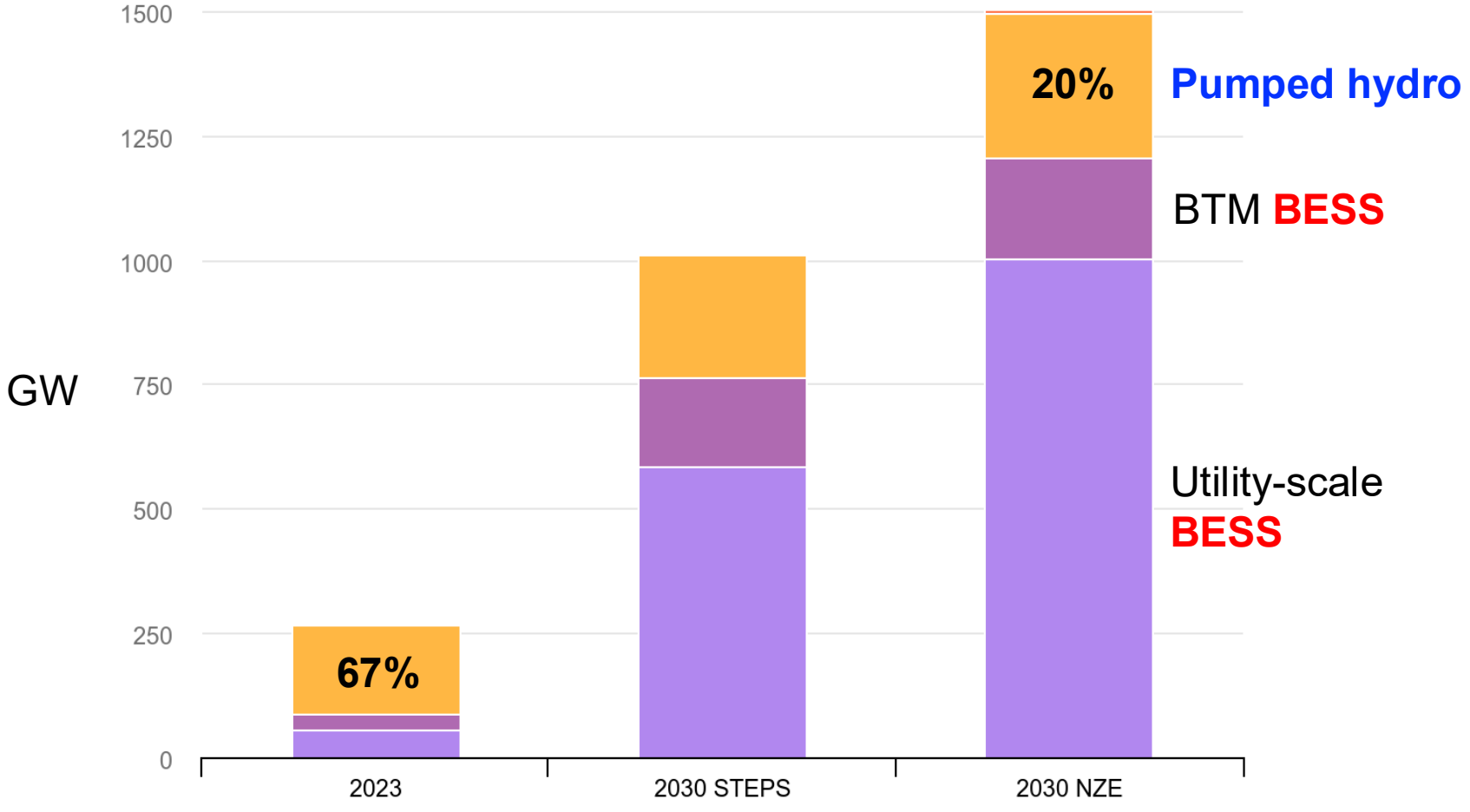
- Upgrade of two existing hydro stations (27 km tunnels)
- Six generators (Francis turbines)
- To be commissioned by 2025 (8 years): 2,500-3,000 M€ (**12,000 M€, 2029!**)



Machine hall: 240x30x50 m
Transformer hall: 200x20x50m

Source: https://www.snowyhydro.com.au/snowy-20/about/

Global cumulative storage capacity



Source: https://www.iea.org/data-and-statistics/charts/global-installed-energy-storage-capacity-by-scenario-2023-and-2030

Suggested reading

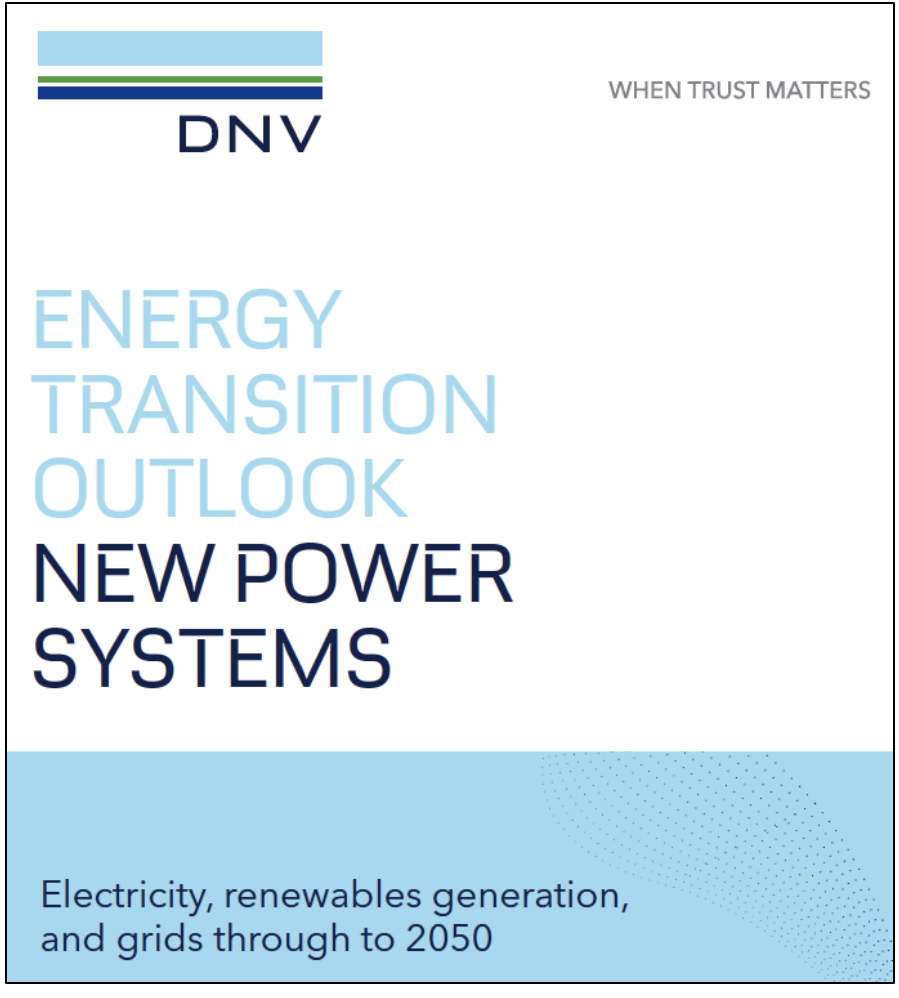
EMBER

EU battery storage is ready for its moment in the sun

1. EU countries could save €9bn in gas costs by capturing excess wind and solar
2. Solar surpasses 80% of demand at peak hours in 9 countries (8/2023 – 7/2024)
3. Germany could have avoided up to €2.5mn fuel costs in June alone with 2 GW (+20%) additional battery storage

Source: https://ember-climate.org/insights/research/eu-battery-storage-is-ready-for-its-moment-in-the-sun/

Suggested reading



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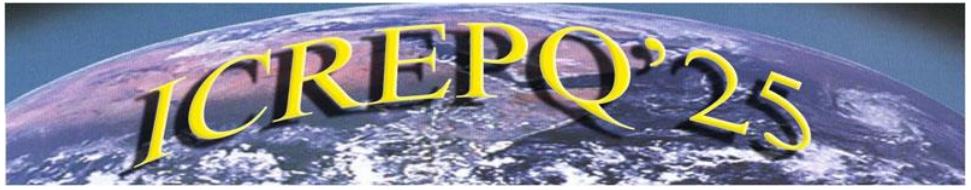
https://osloenergyforum.no/app/uploads/2024/06/DNV_ETO_New_Power_Systems_2024.pdf



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ENGREEN – Endesa Red Chair

June 25, 2025