Energy Storage: Technologies & Applications

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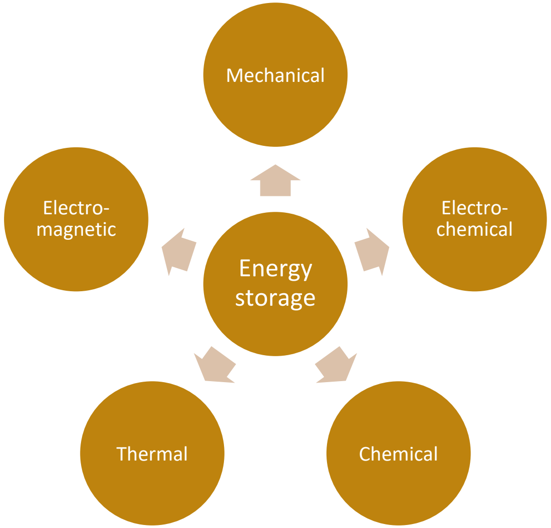
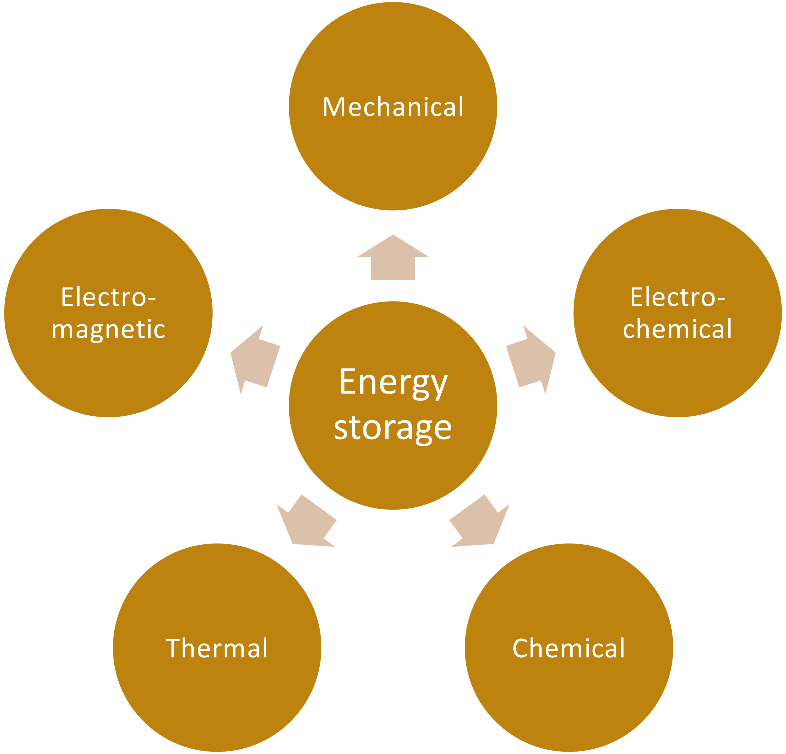
DrBinLu.com | Turning Science into Stories



Australian National University

Energy Storage Technologies



Category	Storage technology	Energy form in storage medium
Mechanical	Pumped hydro	Gravitational potential energy
	Solid gravity	Gravitational potential energy
	Compressed air	Elastic potential energy
	Liquid air	Thermal energy
	Flywheel	Kinetic energy
Electro-chemical	Lithium-ion battery	Chemical energy
	Lead-acid battery	Chemical energy
	Nickel-metal hydride battery	Chemical energy
	Sodium-sulfur battery	Chemical energy
	Flow battery	Chemical energy
	Gas battery	Chemical energy
Chemical	Hydrogen	Chemical energy
	Electro-fuels	Chemical energy
Thermal	Sensible heat	Thermal energy
	Latent heat	Thermal energy
	Thermochemical	Chemical energy
Electro-magnetic	Supercapacitor	Electromagnetic energy
	Superconducting magnetic	Electromagnetic energy

Pumped Hydro Energy Storage (PHES)

History

- First projects: 1890s → major growth during 1960s–80s in Europe, USA, Japan
- Supported inflexible nuclear & coal, balancing loads
- Today: renewed interest with rapid solar & wind growth

Key functions

- Large-scale energy time-shifting, 80% round-trip efficiency
- Ancillary services, e.g., frequency regulation

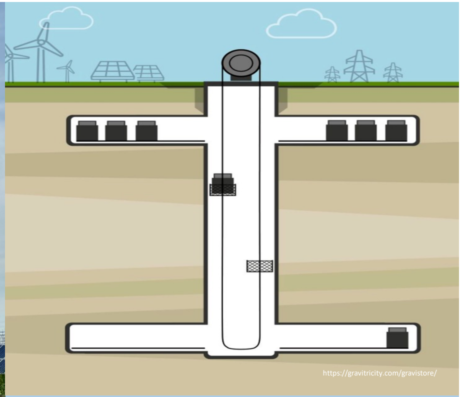
Conventional on-river PHES

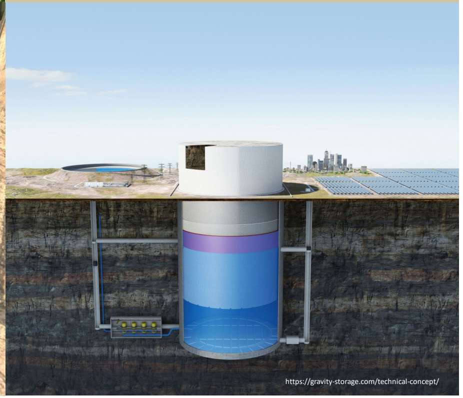
- Limited by rivers & environmental impact
- Low hydraulic head in river valleys

Short-Term Off-River Energy Storage (Lu, 2019)

- Flexible siting, vast potential
- Artificial reservoir near a water body, e.g., river, lake, sea
- Twin artificial reservoirs, filled by creeks & groundwater
- Converted mine pits

Solid Gravity Energy Storage (SGES)





Principle

- Converts electricity into gravitational potential energy
- Storage medium: solid mass (e.g., concrete 2.5x, iron 8x) instead of water

Implementation

- Tower structure, e.g., Energy Vault, USA
- Underground shaft, e.g., Gravitricity, UK
- Natural terrain, e.g., Advanced Rail Energy Storage, USA
- Hydraulic piston, e.g., Gravity Storage, Germany

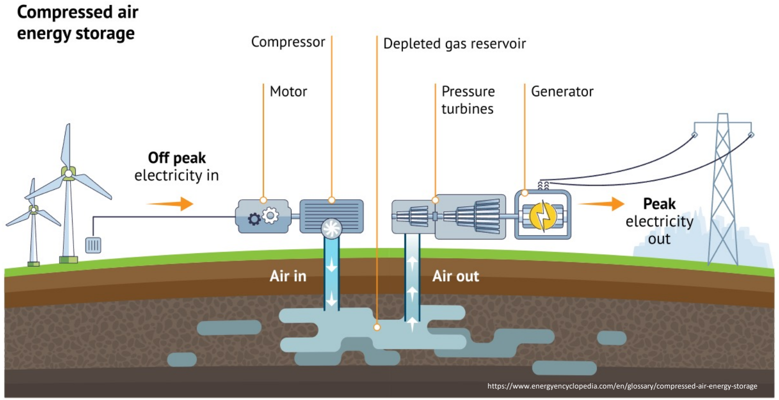
Key features

- Round-trip efficiency: 80–90%
- Construction time 1–2 years, lifetime >30 years
- Modular design: MWh to GWh scale

Projects

- Gravity blocks (China, 2024): 25 MW x 4 h, efficiency 80%
- ARES (USA, under construction): 50 MW x 0.25 h, 90%

Compressed Air Energy Storage (CAES)



Principle

- Charging: air is compressed into a high-pressure space, e.g., underground salt cavern.
- Discharging: air expands to drive a turbine and generate electricity.

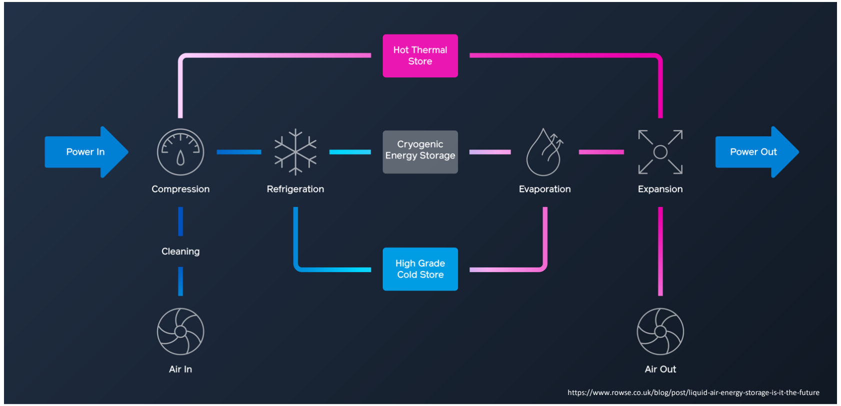
Types of CAES

- Diabatic: heat not stored, needs natural gas → 40–50% round-trip efficiency, e.g., Huntorf, Germany (1970s); McIntosh, USA (1990s)
- Adiabatic: heat stored & reused → 60–70% efficiency, e.g., Yingcheng, China (2024)
- Isothermal: water spray/foam for heat transfer → up to 80% efficiency
- Isobaric: constant-pressure container (e.g., underwater air bags)

Key features

- GWh-scale storage capacity, synchronous inertia
- Round-trip efficiency lower than batteries and pumped hydro
- Requires underground salt caverns, geographic constraints

Liquid Air Energy Storage (LAES)



Principle

- Charging: air is compressed & liquefied into low-pressure, insulated tanks.
- Discharging: liquid air is re-gasified & expanded to drive a turbine and generate electricity
- Storage medium: liquid air/nitrogen

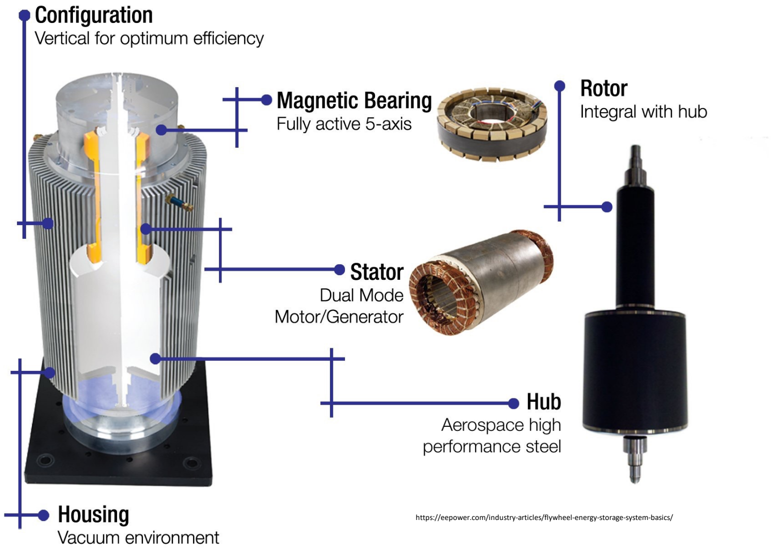
Key features

- No geographic constraints, small environmental impact
- Outputs both electricity and cooling (from re-gasification & expansion)
- Heat & cold storage → round-trip efficiency up to 60%
- Projects: 300 MWh project under construction (Manchester, UK); 2500 MWh project planned (Scotland, UK)

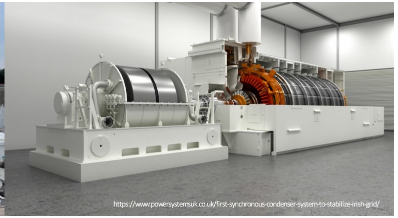
LAES versus CAES

- LAES: low-pressure insulated tanks, flexible siting
- CAES: high-pressure caverns, low cost (~US$200/kWh)

Flywheel Energy Storage System (FESS)



https://eepower.com/industry-articles/flywheel-energy-storage-system-basics/



Principle

- Charging: electricity → rotational kinetic energy in flywheels
- Discharging: rotational motion → electricity
- Operates in vacuum with magnetic bearings to minimise friction and air resistance

Technology advantages

- High power output in milliseconds to support grid stability
- Round-trip efficiency: 85–90%
- Projects: Hazle, USA (200 flywheels x 100 kW each); Dinglun, China (120 flywheels x 250 kW each)

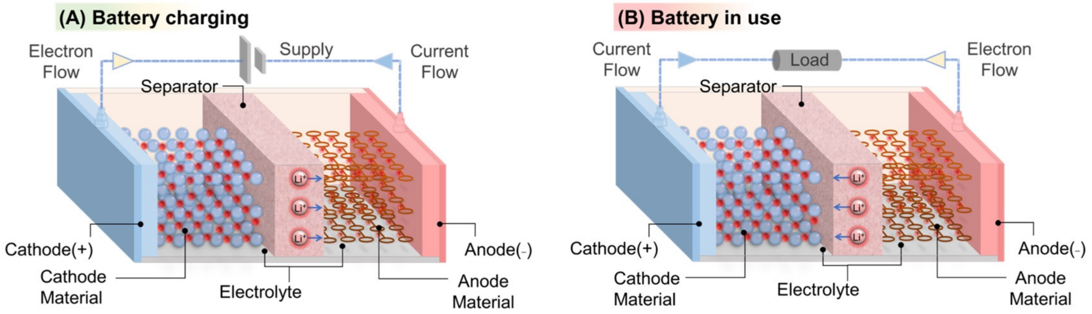
Limitation

- High self-discharge (standing loss): 5–20% per hour

Grid support (with synchronous condensers)

- Provides frequency control, voltage support, and fault strength
- Project: Moneypoint, Ireland (130-t flywheel + 66-t condenser = 4 GW·s inertia)

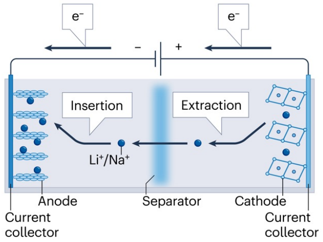
Battery Energy Storage System (BESS)



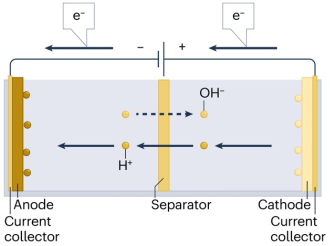
https://doi.org/10.3390/en18020342

Battery type	Cathode (+) | Anode (-) | Electrolyte
Lithium-ion battery	Cathode: $LiCoO_2 \rightleftharpoons Li_{1-x}CoO_2 + xLi^+ + xe^-$ | Anode: $C_6 + xLi^+ + xe^- \rightleftharpoons LixC_6$ | Electrolyte: Organic (e.g., $LiPF_6$ in carbonate solvents)
Lead-acid battery	Cathode: $PbSO_4 + 2H_2O \rightleftharpoons PbO_2 + 4H^+ + SO_4^{2-} + 2e^-$ | Anode: $PbSO_4 + 2e^- \rightleftharpoons Pb + SO_4^{2-}$ | Electrolyte: H_2SO_4 solution
Nickel-metal hydride battery	Cathode: $Ni(OH)_2 + OH^- \rightleftharpoons NiO(OH) + H_2O + e^-$ | Anode: $M + H_2O + e^- \rightleftharpoons MH + OH^-$ | Electrolyte: KOH solution
Sodium-sulfur battery	Cathode: $Na_2S \rightleftharpoons 2Na^+ + S + 2e^-$ | Anode: $Na^+ + e^- \rightleftharpoons Na$ | Electrolyte: Solid β″-Al_2O_3
Flow battery (e.g., Vanadium)	Cathode: $VO^{2+} + H_2O \rightleftharpoons VO_2^+ + 2H^+ + e^-$ | Anode: $V^{3+} + e^- \rightleftharpoons V^{2+}$ | Electrolyte: H_2SO_4 solution
Gas battery (e.g., Nickel-hydrogen)	Cathode: $Ni(OH)_2 + OH^- \rightleftharpoons NiO(OH) + H_2O + e^-$ | Anode: $2H_2O + 2e^- \rightleftharpoons H_2 + 2OH^-$ | Electrolyte: KOH solution

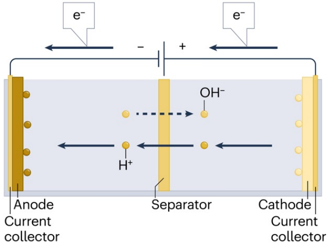
Battery Energy Storage System (BESS)



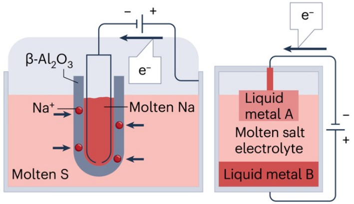
Lithium-ion battery



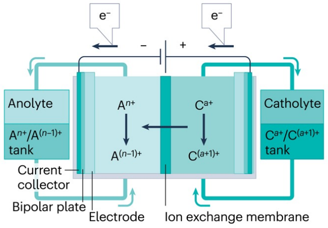
Lead-acid battery



Nickel-metal hydride battery

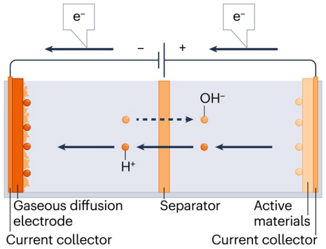


Sodium-sulfur battery



Flow battery

https://doi.org/10.1038/s44359-025-00067-9



Gas battery

Lithium-ion battery

- High energy density (160–200 Wh/kg), high efficiency (85–95%), long cycle life (up to 10,000 cycles)
- EVs, consumer electronics, grid storage

Lead-acid battery

- Low cost, highly recyclable, efficiency 75–85%
- Car batteries for starting, uninterruptible power supply (UPS)

Nickel-metal hydride battery

- Tolerates –40 to 50 °C, efficiency 80–90%
- Older electronics/aerospace, AA/AAA rechargeable batteries

Sodium-sulfur battery

- High energy density (150–300 Wh/kg), low self-discharge, efficiency 80–90%
- Requires high operating temperature, e.g., 300–350 °C

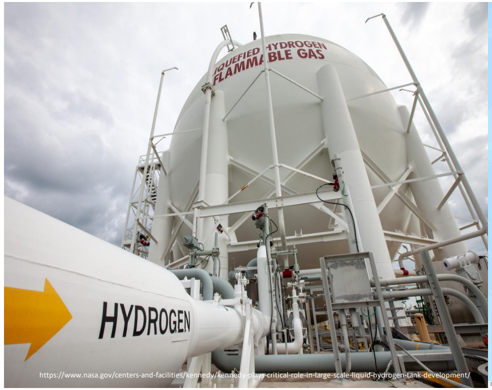
Vanadium redox flow battery

- Long cycle life (up to 20,000 cycles), independent power & energy, efficiency 65–75%
- Grid integration in China, Japan, Europe

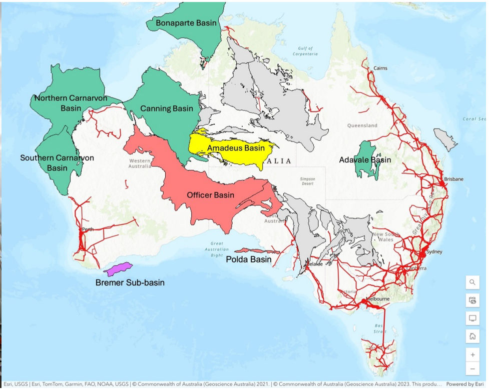
Nickel-hydrogen gas battery

- Very long cycle life (up to 30,000 cycles), operates –40 to 50 °C, efficiency 80–90%
- Space applications: satellites, space stations

Hydrogen



https://www.nasa.gov/centers-and-facilities/kennedy/kennedy-plays-critical-role-in-large-scale-liquid-hydrogen-tank-development/



Green ammonia production

https://chemistry.berkeley.edu/news/big-step-toward-green-ammonia-and-greener-fertilizer

Green steelmaking

https://ieefa.org/resources/green-steelmaking-will-need-technology-and-mining-advances

Green fuel manufacturing

https://www.lufthansagroup.com/en/responsibility/climate-environment/sustainable-aviation-fuel.html

Compressed gaseous hydrogen

- Density: 7.8 kg/m^3 at 100 bar → 40 kg/m^3 at 700 bar
- H_2 storage efficiency: 82–95% (storage only, not round-trip efficiency!)
- Storage options: vessels (flexible siting, costly), salt caverns (cheap, site-limited)
- Example: Clemens Dome, USA >2000 t

Liquid hydrogen

- Density: 70 kg/m^3 at –253 °C
- H_2 storage efficiency: <75% today → up to 85% as technology advances
- Example: NASA Kennedy Space Center, 200–300 t/tank

Australia

- Salt caverns in Amadeus, Canning, Officer, Adavale, offshore basins, but mostly far from main grid
- Future: hydrogen use in green industries, e.g., green ammonia, steel, synthetic fuels

Electro-fuels

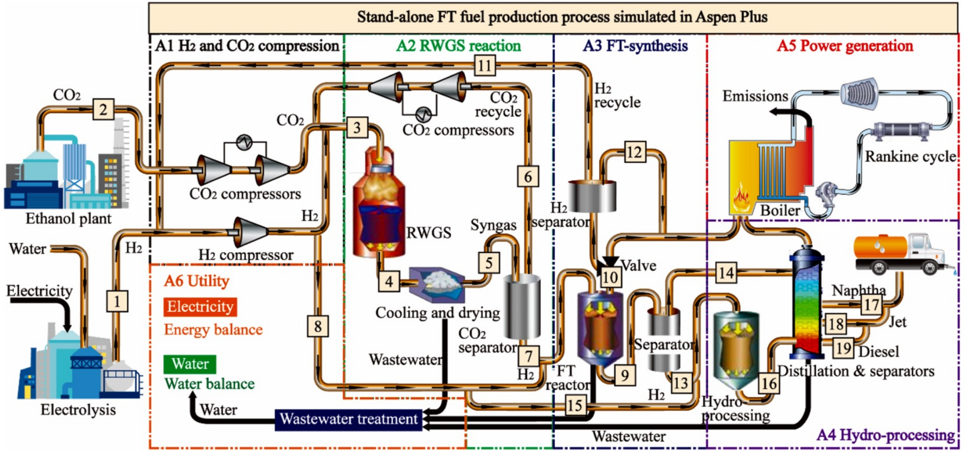


Fig. 1. System flowchart for liquid fuel production from H_2 and CO_2 based on the FT process.

https://doi.org/10.1016/j.jcou.2021.101459

E-fuel applications

- Drop-in fuels: aviation, shipping, long-distance heavy transport
- Feedstocks for chemical & metal industries

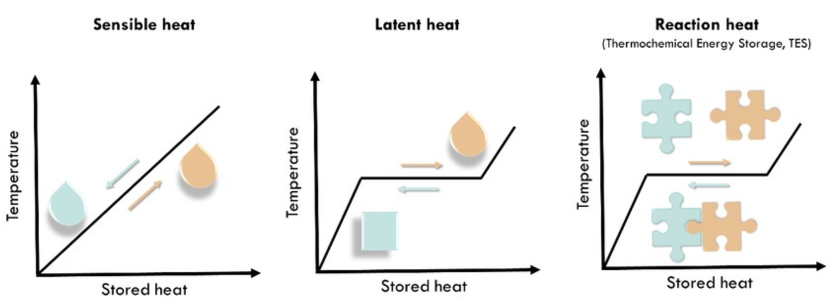
Typical routes

- Fischer-Tropsch: H_2 + CO (CO_2) → jet fuel, diesel
- Haber-Bosch: H_2 + N_2 → ammonia
- Sabatier reaction: H_2 + CO_2 → methane
- Methanol synthesis: H_2 + CO_2 → methanol

Efficiency & cost

- Highly energy intensive: H_2 from water electrolysis + CO_2 from industries or the atmosphere, both powered by renewable energy
- Current cost: €7–9/kg synthetic jet fuel (10x fossil)
- Future: ultra-low-cost solar cuts production costs, enabling cost parity.

Thermal Energy Storage (TES)



https://doi.org/10.3390/su15086567

Sensible heat storage

- Stores heat by raising material temperature
- Materials: water (<100 °C), steam (>100 °C), sand (~500 °C), molten salts (150–560 °C)
- Low-cost (<US$1–30/kWh), high technology maturity
- Examples: hot water tanks, sand battery, CSP molten salt

Latent heat storage

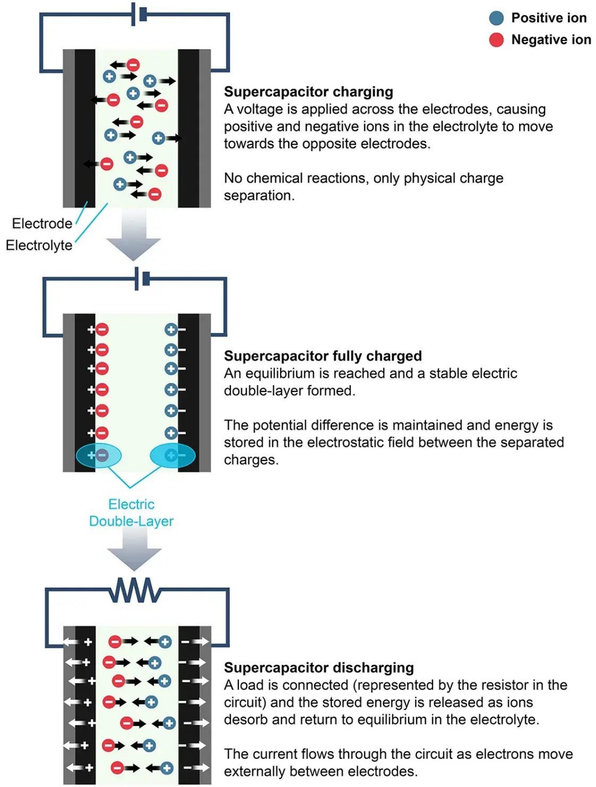
- Stores heat via phase change, higher energy density (2–4x sensible)
- Low-temperature materials (<200 °C): ice, paraffin, fatty acids, salt hydrates
- High-temperature materials (hundreds–1000 °C): inorganic salts, metals

Thermochemical storage

- Stores heat in reversible chemical reactions (chemical bonds)
- Wide operating range (100–1000+ °C), but still early R&D

Supercapacitor Energy Storage (SCES)

https://www.skeletontech.com/skeleton-blog/whats-the-difference-between-an-ultracapacitor-and-a-supercapacitor



https://www.skeletontech.com/skeleton-blog/understanding-how-supercapacitors-work

Principle

- Stores energy in an electric field between electrodes
- Supercapacitors: capacitance (F) orders of magnitude higher than normal capacitors (µF)

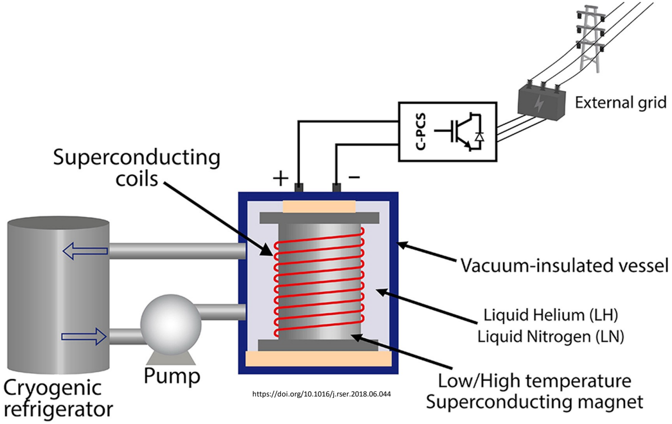
Types of SCES

- Electrochemical double-layer capacitors: physical charge separation, fast & long life (~1 million cycles), but low energy density (<8 Wh/kg)
- Pseudocapacitors: redox reactions at electrodes, higher energy density (>10 Wh/kg), but shorter life (~0.2 million cycles)

Applications

- Millisecond response, high power bursts, round-trip efficiency >90%
- Medical: defibrillators
- Industrial: cranes, forklifts
- EVs & trams: acceleration, regenerative braking, quick charge
- Grid: FACTS, microgrids
- New application in AI data centres to absorb GPU power spikes

Superconducting Magnetic Energy Storage (SMES)



https://doi.org/10.1016/j.rser.2018.06.044

https://www.furukawa.co.jp/review/fr043/fr43_03.pdf

Principle

- Stores energy in a magnetic field sustained by superconducting current
- Certain materials reach a superconducting state at cryogenic temperatures (e.g., Nb–Ti at –264 °C), with zero resistance.

Technology advantages

- Very high round-trip efficiency >95%
- Very high power density ~4000 W/L
- Millisecond response, full discharge within <1 min

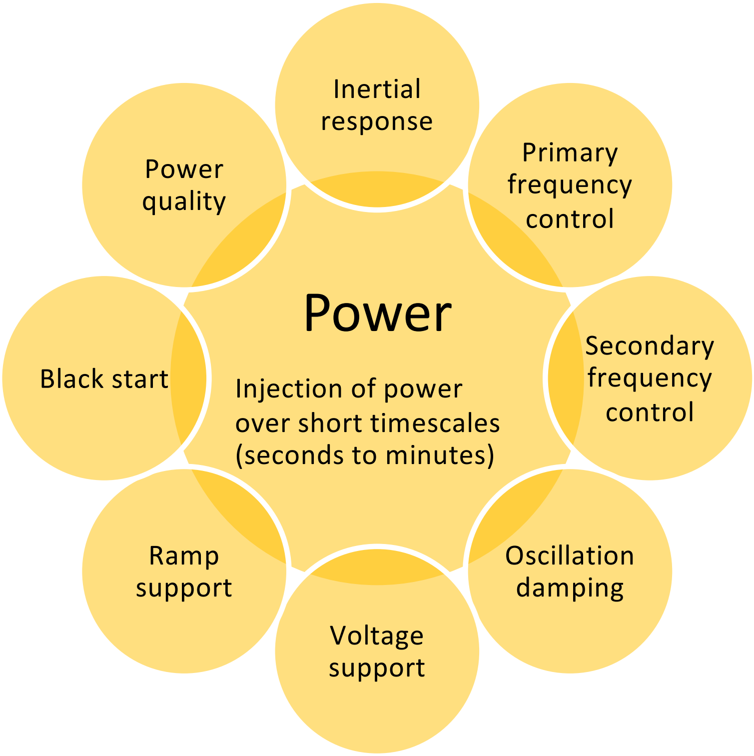
Limitations

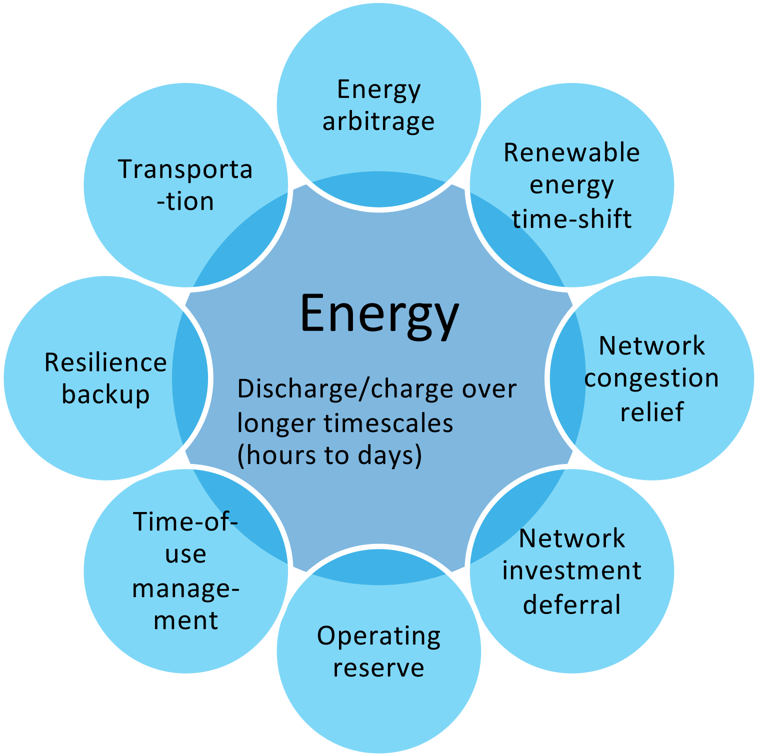
- Requires cryogenic cooling → 10–15% daily energy loss
- Very high cost ~US$10,000/kWh

Applications

- Japan & USA: MW-scale facilities for power quality
- NASA: exploring space applications (e.g., lunar craters at <–200 °C)

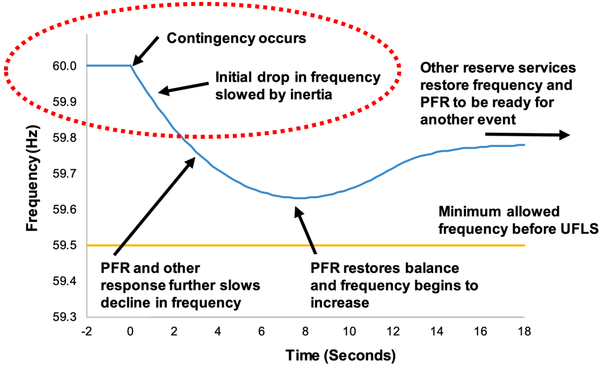
Energy Storage Applications





Inertial Response

Storage technology	Applicability
Pumped hydro	High
Solid gravity	
Compressed air	High
Liquid air	High
Flywheel	Very high (with sync condensers)
Lithium-ion battery	
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	
Superconducting magnetic	



https://docs.nrel.gov/docs/fy20osti/73856.pdf

Concept

- Stored kinetic energy in large rotating machines
- Synchronous generators: coal & hydro (2–6 s), gas (4–12 s)
- Inverter-based renewables (e.g., solar, wind): no synchronous inertia

Contribution to grid stability

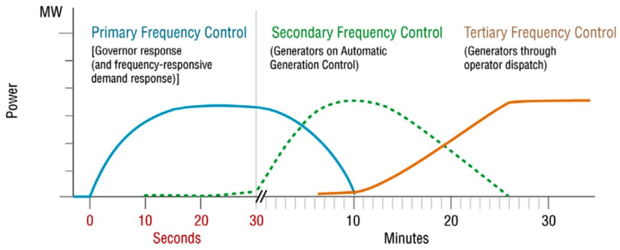
- Provides instantaneous support to frequency stability
- High inertia → low RoCoF (RoCoF 0.5 Hz/s = 2 s to drop from 50 Hz to 49 Hz; RoCoF 0.1 Hz/s = 10 s)

Inertia sources

- Storage with synchronous machines, e.g., pumped hydro, CAES
- Synchronous condensers: 1–3 s (~10 s with flywheels)
- Emerging trend: synthetic/virtual inertia from inverters

Frequency Control

Storage technology	Primary	Secondary	Tertiary
Pumped hydro		High	Very high
Solid gravity		High	High
Compressed air		High	High
Liquid air		High	High
Flywheel	Very high	High	
Lithium-ion battery	High	High	High
Lead-acid battery			
Nickel-cadmium/MH battery			
Sodium-sulfur battery		High	High
Flow battery		High	High
Gas battery			
Hydrogen			Very high (one-way)
Electro-fuels			Very high (one-way)
Sensible heat			High (one-way)
Latent heat			High (one-way)
Thermochemical			High (one-way)
Supercapacitor	Very high	High	
Superconducting magnetic	Very high	High	



https://www.aemo.com.au/-/media/files/electricity/nem/security_and_reliability/reports/2017/20170310-ge-ffr-advisory-report.pdf

Primary control (seconds)

- Automatic response via governors (e.g., droop control)
- Example: 5% droop = 50 Hz → 47.5 Hz, 0 → 100% output

Secondary control (seconds to tens of seconds)

- Automatic Generation Control (AGC) by system operator
- Adjusts generator output: regulation up/down

Tertiary control (minutes to hours)

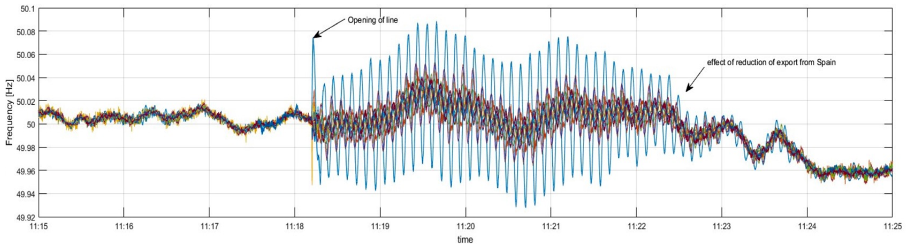
- Re-dispatch of generators & reserves
- Operating reserves: spinning (online), non-spinning (offline)

Case study: Australian FCAS market

- Regulation markets: regulation up/down
- Contingency markets: fast responses in 1s, 6s, 60s, 5 min

Oscillation damping

Storage technology	Applicability
Pumped hydro	
Solid gravity	
Compressed air	
Liquid air	
Flywheel	Very high
Lithium-ion battery	High
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	High
Flow battery	
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	Very high
Superconducting magnetic	Very high



https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Regional_Groups_Continental_Europe/2017/CE_inter-area_oscillations_Dec_1st_2016_PUBLIC_V7.pdf

Concept

- Large electricity grids can experience inter-area oscillations, when generators in different regions fall out of sync.
- Typical oscillation range: 0.1–1.0 Hz
- Phasor measurement units (PMUs) provide remote frequency signals for damping control.

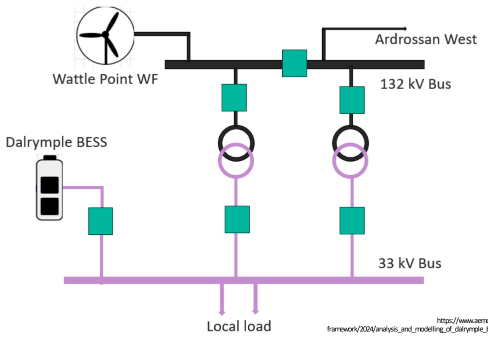
Role of energy storage

- Power injection from energy storage at multiple grid nodes, creating counteracting interference
- Inverter-based storage responds within milliseconds
- Benefits: lower oscillation amplitude, faster frequency stabilisation

Voltage Support

Storage technology	Applicability
Pumped hydro	Very high
Solid gravity	High
Compressed air	High
Liquid air	High
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	High
Flow battery	High
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	
Superconducting magnetic	

Figure 1 Dalrymple BESS and Wattle Point Wind Farm network



https://www.aemo.com.au/-/media/files/initiatives/engineering-framework/2024/analysis_and_modelling_of_dalrymple_bess_performance_december_2023_events.pdf

Concept

- Voltage stability depends on reactive power balance
- Reactive power shortage: voltage drop or even collapse
- Reactive power excess: over-voltage risk

Sources of voltage support

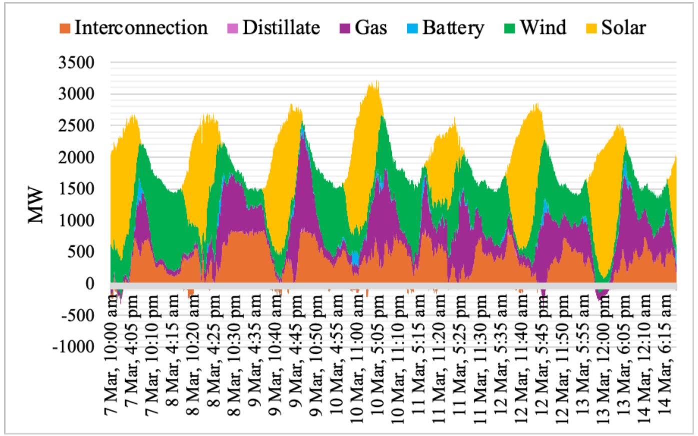
- Synchronous generators, synchronous condensers, capacitors
- Storage with synchronous machines
- Storage with grid-forming inverters (operate as voltage sources)

Case study: Dalrymple Battery, South Australia

- Lightning trip → 33 kV bus voltage fell below 80%
- Battery injected reactive power → voltage stabilised
- Formed an islanded grid with wind power until resync with main grid

Ramp Support

Storage technology	Applicability
Pumped hydro	Very high
Solid gravity	High
Compressed air	High
Liquid air	High
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	High
Flow battery	High
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	
Superconducting magnetic	



Data source: Open Electricity

Concept

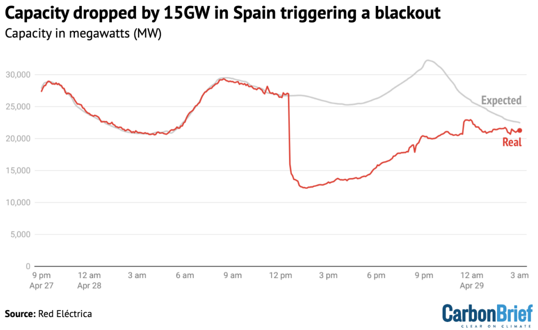
- Load rises/falls quickly during morning & evening peaks
- Ramp rate = % of rated power per minute, e.g., gas turbine 20%/min
- Solar output drops sharply at sunset, while demand climbs towards evening peak

Role of energy storage

- Most storage technologies ramp faster than gas turbines
- Case study: Batteries in South Australia provided morning & evening ramping support

Black Start

Storage technology	Applicability
Pumped hydro	Very high
Solid gravity	
Compressed air	
Liquid air	
Flywheel	
Lithium-ion battery	High
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	
Superconducting magnetic	



Concept

- Restarting the grid after a complete blackout and gradually restoring supply
- Hydropower & gas turbines can restart with little external input.
- Startup energy supplied by diesel generators or batteries
- Iberian blackout (2025): recovery from hydro, gas, interconnections with France and Morocco

Challenges

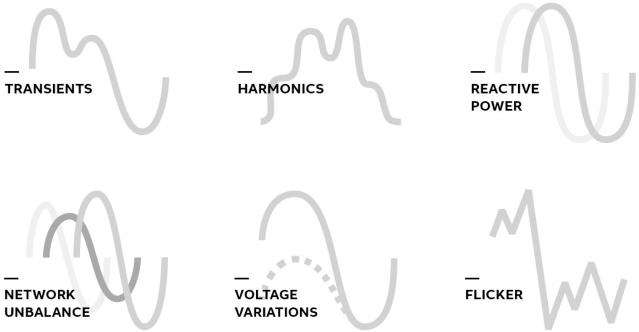
- Large frequency deviations during generator startup
- Generators require minimum stable load.

Role of energy storage

- Provides startup energy for hydro/gas turbines
- Balances generation and load during generator startup

Power Quality

Storage technology	Applicability
Pumped hydro	
Solid gravity	
Compressed air	
Liquid air	
Flywheel	High
Lithium-ion battery	
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	Very high
Superconducting magnetic	Very high



https://new.abb.com/news/detail/79505/how-poor-power-quality-is-damaging-system-performance

Concept

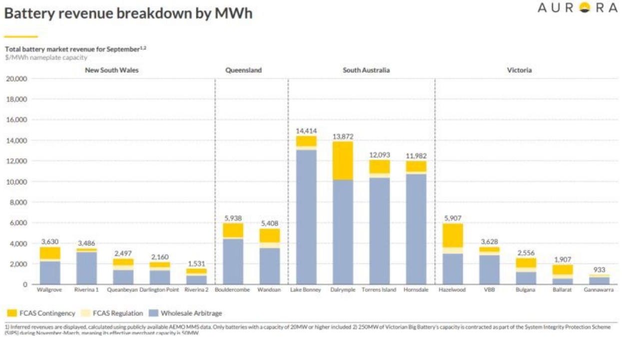
- IEEE definition: "the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment".
- Common issues: voltage dips, surges, harmonics
- High power quality requirements for microprocessor-based controls, sensitive electronic devices

Role of energy storage

- Storage with smart inverters improve power quality
- Very fast response (milliseconds to seconds) on the user side

Energy Arbitrage

Storage technology	Applicability
Pumped hydro	High
Solid gravity	
Compressed air	
Liquid air	
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	
Superconducting magnetic	



Concept

- Buys electricity when prices are low & sells it when prices are high
- Captures price difference as profit

Competitive electricity markets (e.g., Australia's NEM)

- Prices set every 5–30 minutes based on supply-demand balance
- When supply is tight, gas peakers set the price → very high spikes
- Example: natural gas sets 97% of trading intervals in UK

Key factors

- Price volatility: more fluctuations = more opportunities
- Round-trip efficiency: must be high for effective arbitrage

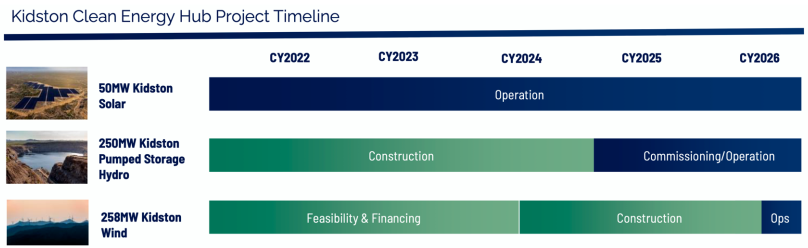
Case study: Battery storage in Australia

- Main revenue from energy arbitrage, especially in South Australia

Energy arbitrage model: Weber & Lu (2024), 10.3390/en17010013

Renewable Energy Time-Shift

Storage technology	Applicability
Pumped hydro	Very high
Solid gravity	
Compressed air	
Liquid air	
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	
Gas battery	
Hydrogen	
Electro-fuels	
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	
Superconducting magnetic	



https://genexpower.com.au/wp-content/uploads/2023/07/230707_Kidston-Fact-sheet-June-23_v1_FINAL.pdf

Concept

- Renewable generation fluctuates across minutes, hours, days, and months.
- Stores excess energy at peaks & releases it at low outputs
- Delivers reliable 24/7 clean power

Benefits

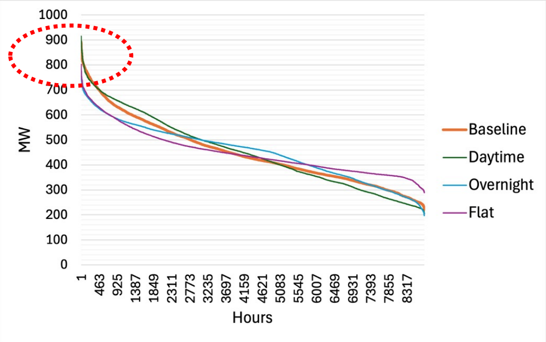
- Energy storage turns variable renewables into stable power
- Leverages existing infrastructure

Example: Kidston Clean Energy Hub, Australia

- Renewables: 50 MW solar + 250 MW wind
- Storage: 250 MW x 8 h pumped hydro (repurposed gold mine, existing infrastructure and water resources)

Network Investment deferral

Storage technology	Applicability
Pumped hydro	High
Solid gravity	
Compressed air	
Liquid air	
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	High
Gas battery	
Hydrogen	High (one-way)
Electro-fuels	High (one-way)
Sensible heat	High (one-way)
Latent heat	High (one-way)
Thermochemical	High (one-way)
Supercapacitor	
Superconducting magnetic	



Lu et al. (2025), 10.1016/j.renene.2025.123920

Concept

- Load growth → need for network upgrades (lines, transformers)
- Storage smooths short peaks → avoids or delays costly upgrades
- Deferral lowers investment net present value → lower electricity bills

Case study: All-electric ACT

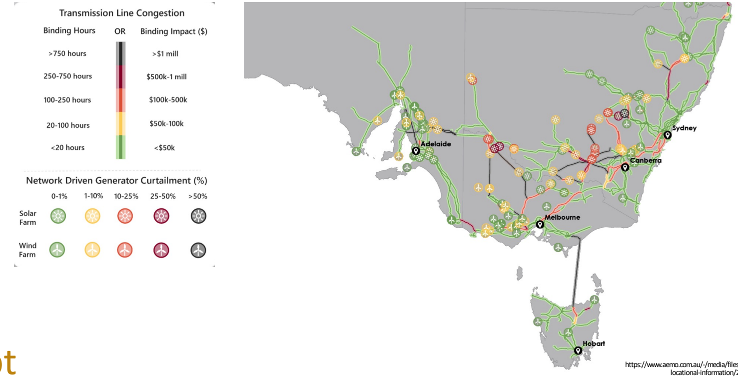
- Top 10% of loads last only 60 h/year
- Shifting these peaks could cut grid investment by 10%

Example: Nantucket Island, USA

- Planned: third submarine cable, US$200 million
- Storage integration: 6 MW x 8 h battery, US$80 million
- Battery effectively delayed the need for new submarine cable.

Network Congestion Relief

Storage technology	Applicability
Pumped hydro	High
Solid gravity	
Compressed air	High
Liquid air	
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	High
Gas battery	
Hydrogen	High (one-way)
Electro-fuels	High (one-way)
Sensible heat	High (one-way)
Latent heat	High (one-way)
Thermochemical	High (one-way)
Supercapacitor	
Superconducting magnetic	



https://www.aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/enhanced-locational-information/2025/2025-enhanced-locational-information-report.pdf

Concept

- Grid bottlenecks occur when power cannot reach demand
- Transmission networks: large solar & wind farms
- Distribution networks: rooftop solar
- Different from network investment deferral (load growth issue)

Example: Southern NSW & Northern Victoria

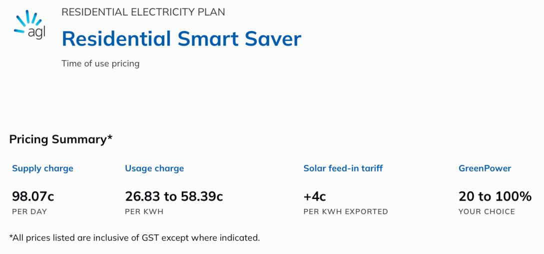
- 2024: 10–25% curtailment at some solar farms
- AEMO forecast: 20–35% curtailment in Victoria; >50% at some South Australian sites, if nothing changes

Role of energy storage

- Absorbs renewable peaks → fewer congestion hours
- Releases energy later → less curtailment

Time-of-Use (TOU) Management

Storage technology	Applicability
Pumped hydro	
Solid gravity	
Compressed air	
Liquid air	
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	
Gas battery	
Hydrogen	High (one-way)
Electro-fuels	High (one-way)
Sensible heat	High (one-way)
Latent heat	High (one-way)
Thermochemical	High (one-way)
Supercapacitor	
Superconducting magnetic	



Concepts

- Time-of-Use: different rates for peak, shoulder, and off-peak hours
- Demand pricing: charges designed to capture peak demand
- Net metering: selling excess solar back to the grid to offset usage (buy/sell rates differ)

Smart strategies

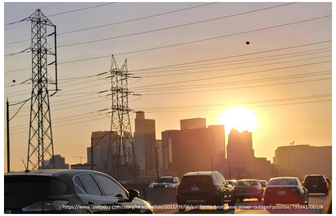
- Shift high-energy appliances (washer, dryer, dishwasher, pool pump) to off-peak hours
- Use batteries and hot water storage for load shifting, no lifestyle changes needed

Example: AGL Time-of-Use Plan

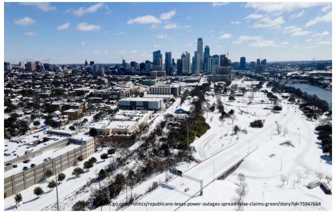
- Peak: 2–7 pm weekdays → 58.39 ¢/kWh
- Shoulder: 7 am–1 pm & 8–9 pm weekdays; 7 am–9 pm weekends → 33.15 ¢/kWh
- Off-peak: 10 pm–6 am → 26.83 ¢/kWh

Resilience backup

Storage technology	Applicability
Pumped hydro	Very high
Solid gravity	High
Compressed air	High
Liquid air	High
Flywheel	
Lithium-ion battery	High
Lead-acid battery	
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	High
Gas battery	
Hydrogen	High (one-way)
Electro-fuels	High (one-way)
Sensible heat	High (one-way)
Latent heat	High (one-way)
Thermochemical	High (one-way)
Supercapacitor	
Superconducting magnetic	



California's rolling blackouts (2020)



The Great Texas Freeze (2021)

Victoria's catastrophic storm (2024)

Concept

- IEEE definition: "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event".

Low-probability, high-impact events

- Extreme weather conditions, natural disasters, cyberattacks
- More frequent and severe with climate change, e.g., California (2020), Texas (2021), Victoria (2024)

Role of energy storage

- During disruptive events: absorb shocks, reduce immediate impact
- After disruptive events: backup supply, speed recovery

La Niña effect: Roberts, Lu & Catchpole (2022), 10.1109/ISGTAsia54193.2022.10003637

Transportation

Storage technology	Applicability
Pumped hydro	
Solid gravity	
Compressed air	
Liquid air	
Flywheel	
Lithium-ion battery	Very high
Lead-acid battery	Very high
Nickel-cadmium/MH battery	
Sodium-sulfur battery	
Flow battery	
Gas battery	
Hydrogen	High
Electro-fuels	High
Sensible heat	
Latent heat	
Thermochemical	
Supercapacitor	High
Superconducting magnetic	

Lithium-ion batteries

- High energy density, dominant in EVs
- Global EV sales: ~20 million (2025) → annual battery additions at TWh scale

Lead-acid batteries

- Low cost, safe, widely used in car starter batteries

Hydrogen fuel cells

- High energy density, used in EVs and rail transport
- Market share remains marginal compared with lithium-ion batteries

Electro-fuels

- Drop-in fuels, compatible with existing engines
- Key for aviation, shipping, long-distance heavy transport

Supercapacitors

- High power density, fast charge/discharge for acceleration & regenerative braking
- Applications in cars, buses, and trams

Energy Storage – Summary

Diverse storage technologies

- Mechanical, electrochemical, chemical, thermal, and electromagnetic
- Each brings unique strengths and trade-offs in efficiency, response speed, energy density, and scalability.

Wide-ranging storage applications

- Power applications deliver fast responses, e.g., inertia, frequency, voltage, ramping, black start, and power quality.
- Energy applications deliver sustained support, e.g., arbitrage, time-shift, network congestion relief, investment deferral, time-of-use, and resilience backup.

System integration: no silver bullet

- Renewable energy futures build on a portfolio of storage technologies, bridging variable renewables with stable electricity supply.

Questions?

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