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4 March 2025

Storing Energy

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The energy storage opportunity

Mobility energy storage

Utility energy storage

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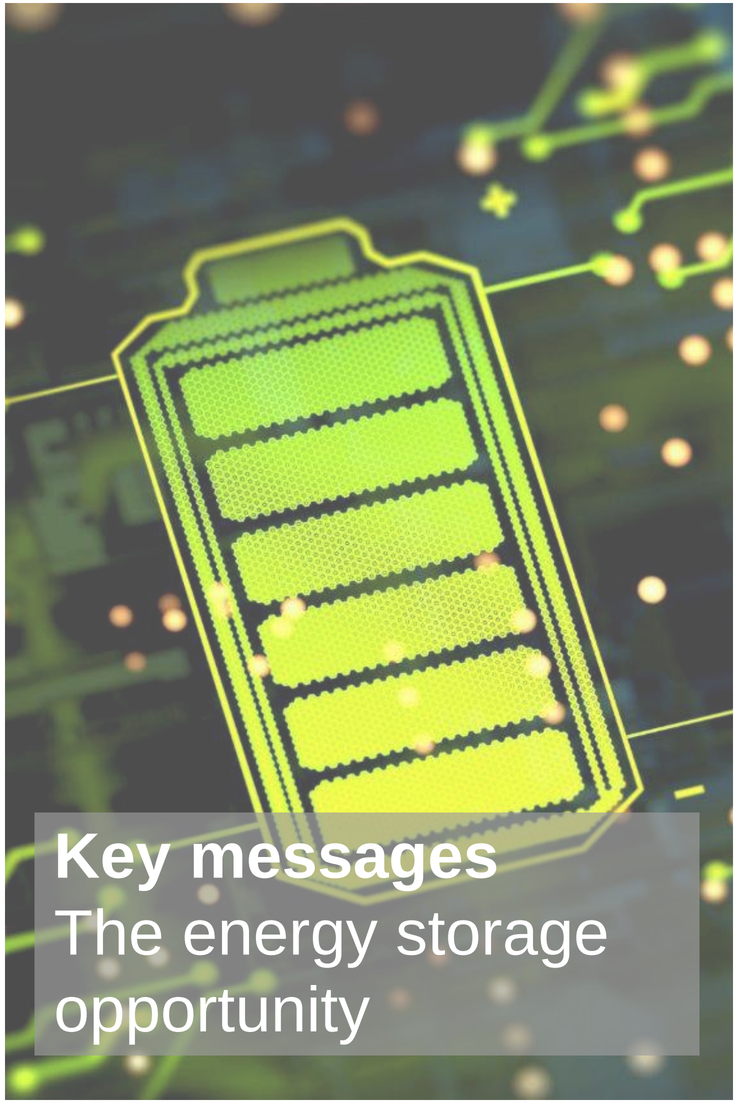
Executive Summary:
The energy storage opportunity



Energy storage plays a critical role in the transition to a clean and sustainable energy future, tackling the challenges of using intermittent renewable energy sources, improving grid stability and dispatchability, and powering electric vehicles (EVs).

Energy storage has the potential to abate up to **17 Gt of CO_2 emissions across sectors by 2050**, primarily by supporting renewable power and the electrification of transport.

Mobility: **EVs** are expected to reach **95% share in vehicle sales** by 2035 under the Net Zero Emissions (NZE) Scenario.

- The shift is expected to drive rapid growth in global EV battery demand, with capacity needs projected to exceed **20 TWh** by 2050.
- Demand will grow by **~23% annually** until 2035, driven by EV adoption and government policies before stabilizing as EV market penetration reaches saturation.

Utility: Renewables like solar and wind must grow twelvefold, with expected combined capacity of ~15 TW to achieve net zero by 2050.

- Energy storage is essential for supporting the growth of renewables, with global capacity projected to reach **1.5 TW by 2030**, mainly for front-of-the-meter applications.
- However, capacity growth so far is failing to keep pace with rapid solar and wind growth.

Innovations in battery storage have reduced costs and curtailment issues, enhancing economic competitiveness. However, timely grid infrastructure updates and storage deployment are critical to fully integrate renewables.

The energy storage system (ESS) plays three key roles: Providing stability, dispatchability, and portability

Stability

Improves reliability by reducing transmission constraints and providing grid stability services.

For instance, an ESS can provide frequency regulation to maintain a system's frequency at 60 Hz, which helps balance the network's load and the power generated.

Dispatchability

Enables electricity generated at one time to be used at a later time.

Demand for energy storage plays an increasingly important role in maintaining the balance between supply and demand as renewable energy sources (wind, hydroelectric, solar) expand and electricity becomes more decentralized.

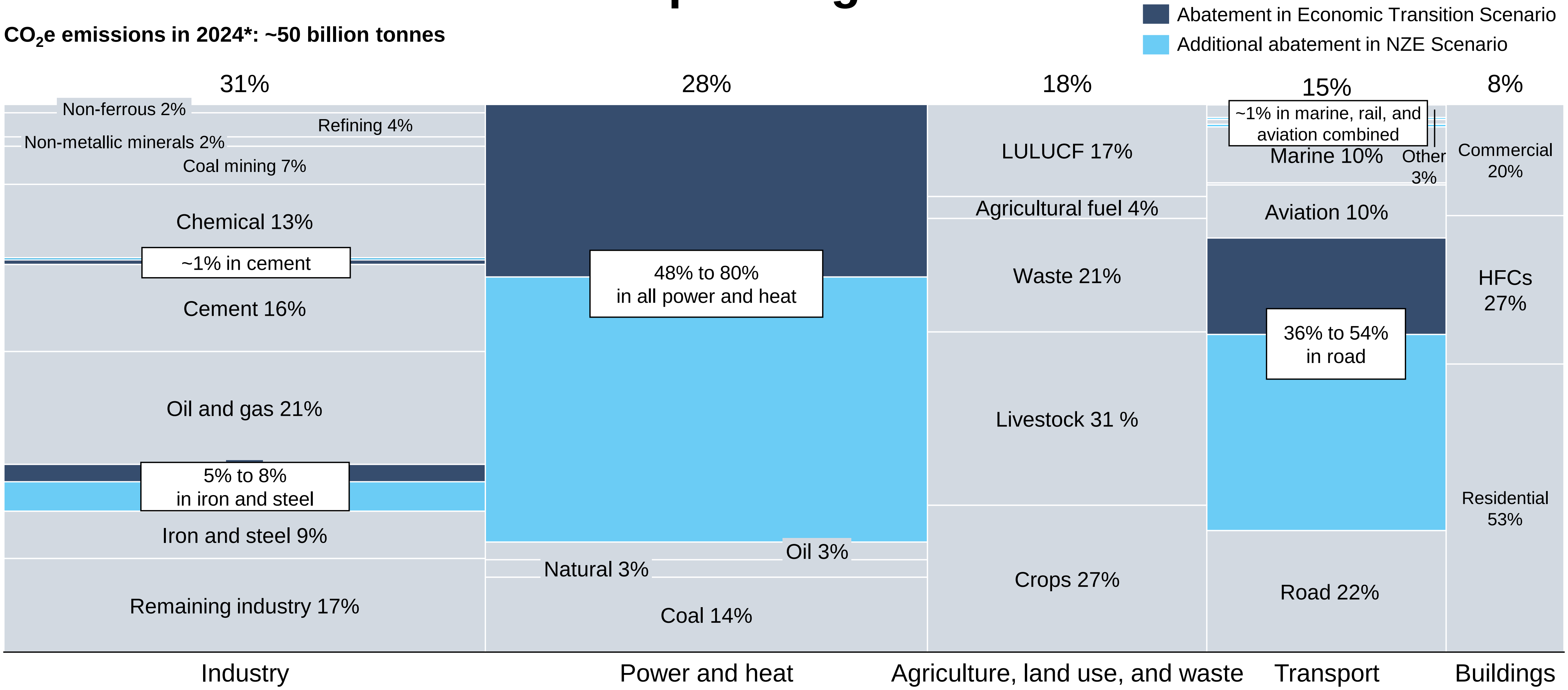
Portability

Allows EVs to be charged and used anywhere and at any time.

It controls the frequency of the AC power being sent to the motor, which directly influences an EV’s speed.

Sources: C3controls, Understanding Energy Storage Systems (2023); EVESCO, Battery Energy Storage; Renault Group, Rallying Heritage (2022); Drive Clean, Battery-Electric Cars.

Energy storage can help abate up to 17 Gt of CO_2e emissions by 2050 in select subsectors depending on the transition scenario



*2024 emissions based on projections.
Sources: Scope 1 emissions from Rhodium Group Climate Deck (September 2024); abatement estimates from BloombergNEF (2024), IRENA, and IEA (2023).
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Focus on energy storage technologies in mobility and utility sectors to identify future opportunities

Areas to explore

- Demand projections
- Characteristic by technology, including:
  - Maturity
  - Pros and cons
  - Market share
  - Cost projections
  - Growth opportunities

Mobility

Lithium iron phosphate (LFP)
Nickel cobalt manganese (NCM)
Nickel cobalt aluminum (NCA)
Solid state
Sodium ion
Nickel-metal hydride
Lead-acid
Ultracapacitors

Utility

Pumped-storage hydropower (PSH)
Compressed-air energy storage (CAES)
Battery
Thermal energy storage (TES)
Hydrogen
Flywheel

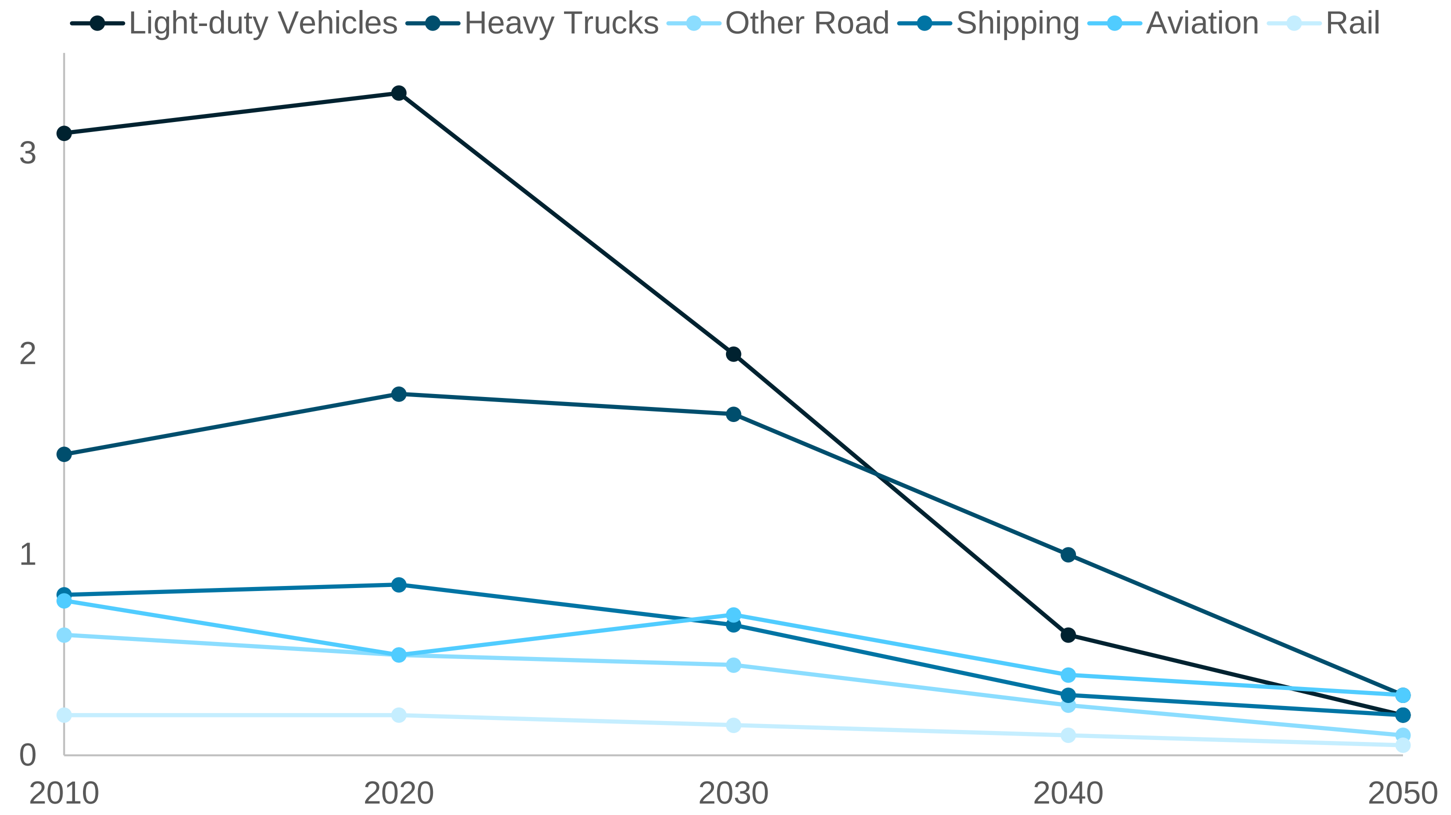
Technologies with the greatest potential are highlighted in forthcoming slides, based on:

- Current market share
- Growth potential
- Cost projections
- Uses in mobility and utility

Credit: Ashley Kim, Xiaodan Zhu, Devashri Mehrotra, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

CO_2 emissions from passenger vehicles could be largely eliminated by 2050

Global CO_2 transport emissions by mode, Gt



Observations

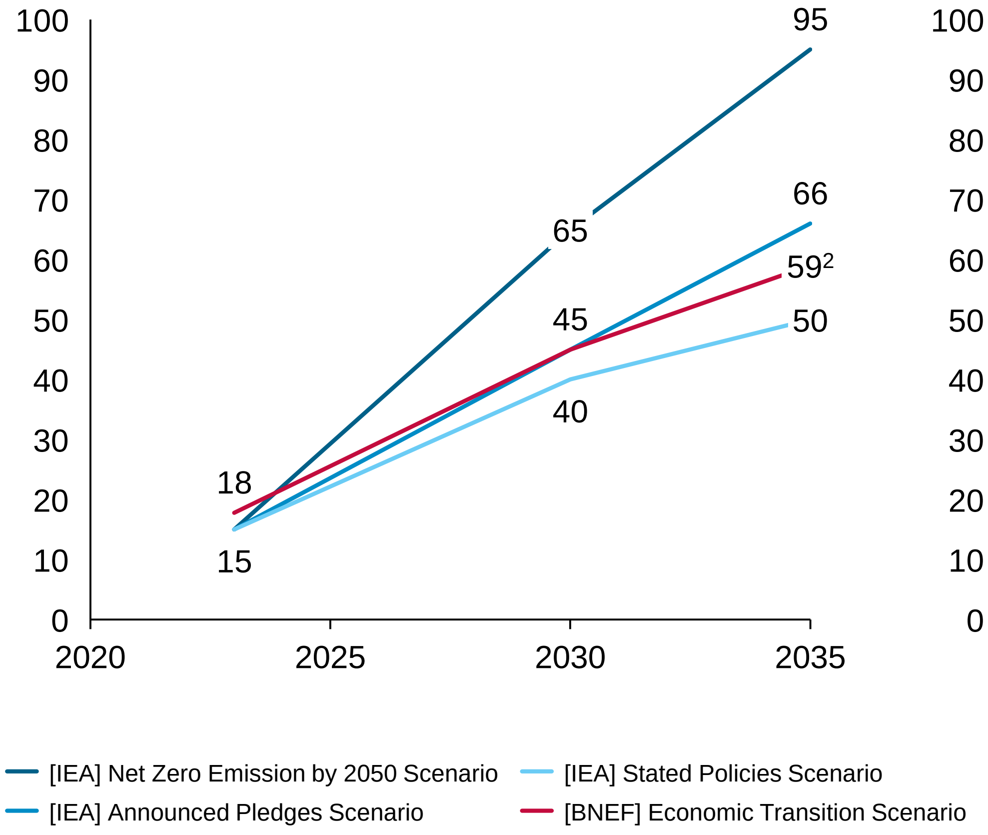
- CO_2 emissions from transport are projected to drop to ~0.7 Gt by 2050 based on the Next Zero Emissions Scenario.
- Despite this decline, **passenger travel is expected to almost double by 2050**, and freight activity will more than double from 2020 levels.
- **Electric vehicle adoption will be an important part of that shift**, with the quantity of battery-electric, plug-in hybrid, and fuel-cell-powered electric cars and vans rising from just 11 million in 2020 to 350 million by 2030 and approaching 2 billion by 2050.

Sources: IEA, Net Zero by 2050 (2021); IEA, Batteries and Secure Energy Transitions (2024).
Credit: Devashri Mehrotra, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

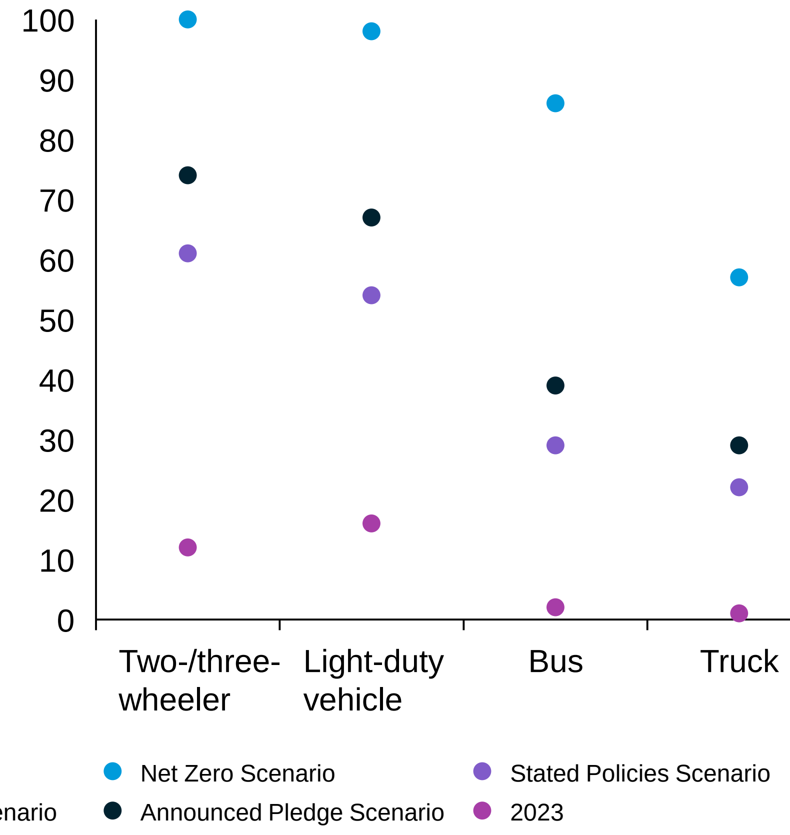
EVs to play an important role, with sales projected to increase to as much as 95% of vehicle purchases by 2035

Electric vehicle adoption rate by scenario

EV sales share by IEA and BNEF scenarios[1] (%)



EV sales share by mode and IEA scenario (%), 2035



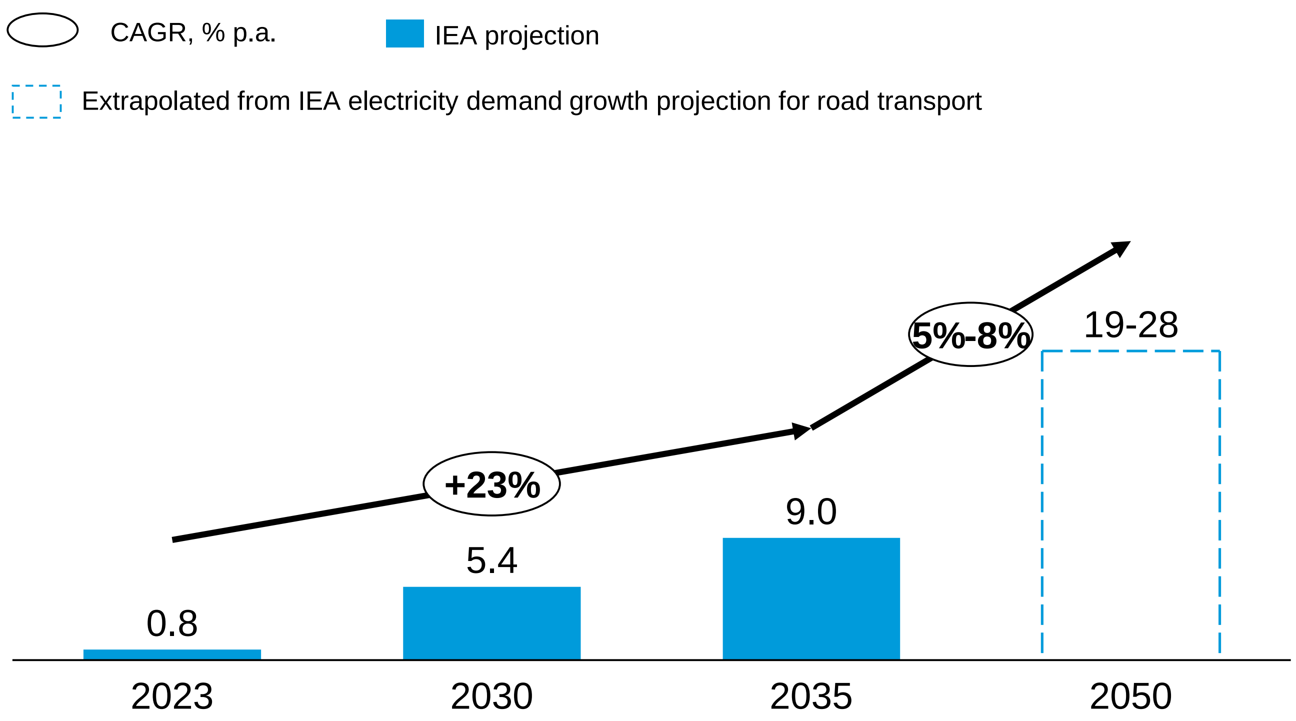
Observations

- In the **NZE Scenario**, **EV sales as a share of new vehicles** grow over the next few years, reaching about **65% in 2030** and **95% in 2035.**
- **Two-/three-wheeler and light-duty vehicles are expected to lead adoption** by 2035 with **60% to 100% adoption** across scenarios, while **trucks lag at 20% to 55% adoption.**
- However, the discrepancy between **policy implementation** and **announced ambitions continues to widen over time,** as many initiatives, including **the U.S. IRA, the EU Green Deal Industrial Plan, and China's 14th Five-Year Plan,** tend to prioritize short- to medium-term incentives.

1) IEA scenario: All EVs except two- and three-wheelers; BNEF scenario: Passenger EVs. 2) Assumed linear growth from 2030 to 2040.
Sources: IEA, Global EV Outlook 2024 (2024); BloombergNEF, Electric Vehicle Outlook (2024).
Credit: Ashley Kim, Devashri Mehrotra, Birru Pagi Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Global battery demand for EVs expected to reach >5 TWh in 2030

Global EV battery demand, TWh/year



Note: Projection until 2035 is based on the IEA Global EV Outlook for EV battery only. Projection for 2040 to 2050 is based on extrapolation from road transport electricity demand from IEA.

Observations

- Annual global demand for batteries will grow at a **rate of ~23% p.a. until 2035.**
- **The steep increase until 2035 will be driven by advancements in EV adoption, in places like:**
  - **Norway,** which continues to lead in EV deployment, with electric cars accounting for ~**93% of total sales in 2023.**
  - **China,** representing ~**60%** of all new electric car registrations worldwide in 2023.
  - **Canada,** targeting at least **60% of zero-emission vehicles by 2030.**
  - **The United States and European Union,** which recently implemented emissions standards for heavy-duty vehicles, paving the way for increased adoption of electric trucks and buses in the years ahead.
- Demand growth will subsequently slow to **5%-10% p.a. between 2040 and 2050,** as the **global EV sales share** is expected to reach **98% by 2035.**

Sources: IEA, Global EV Outlook (2024); IEA, Net Zero Roadmap (2023).
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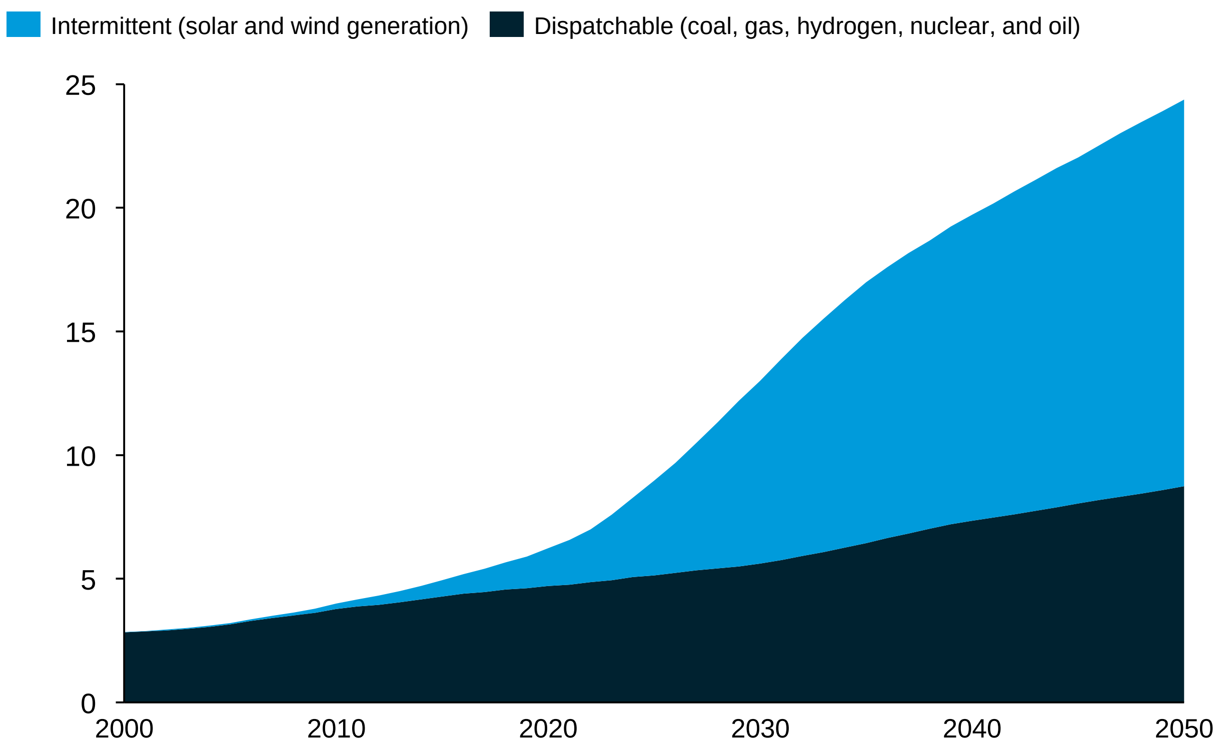
To achieve net zero, intermittent sources such as solar and wind must grow; energy storage is critical to enable integration

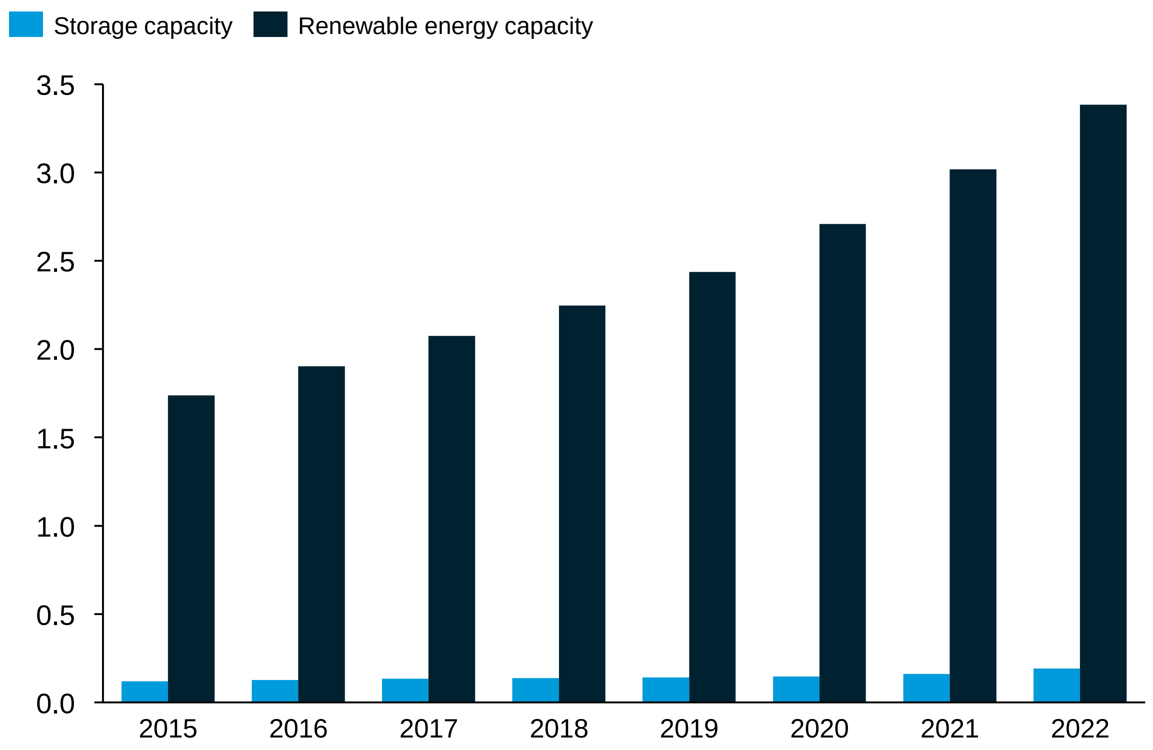
Energy storage will play a significant role, as solar and wind capacity is projected to reach ~15 TW by 2035

Global intermittent generation vs. dispatchable generation from 2000 to 2050, TW



However, energy storage is failing to keep pace with rapid renewable capacity growth

Installed capacity of storage compared to renewable energy, TW

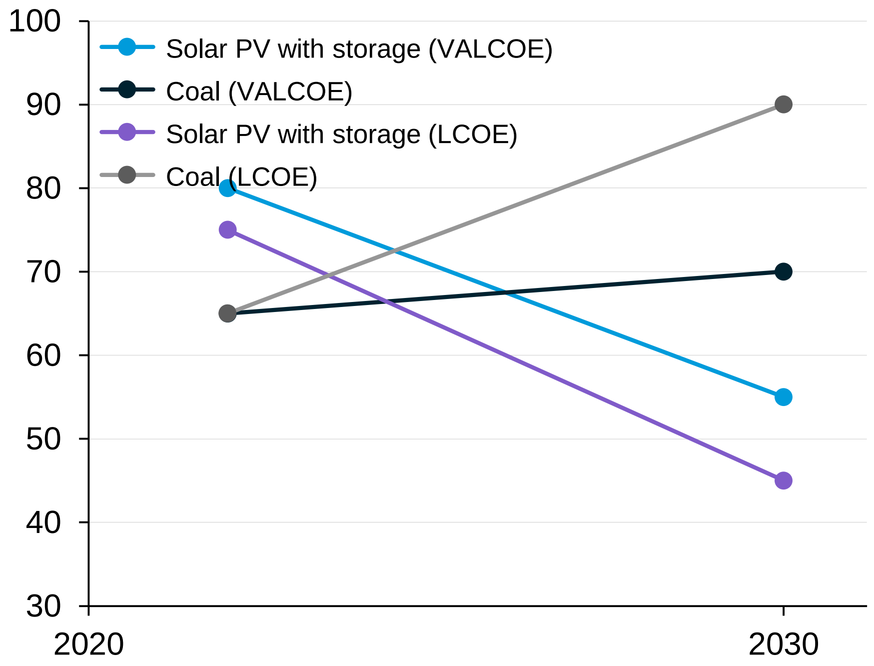


Source: BloombergNEF, New Energy Outlook (2024).
Credit: David Foye, Birru Lucha, Hyae Ryung Kim , and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

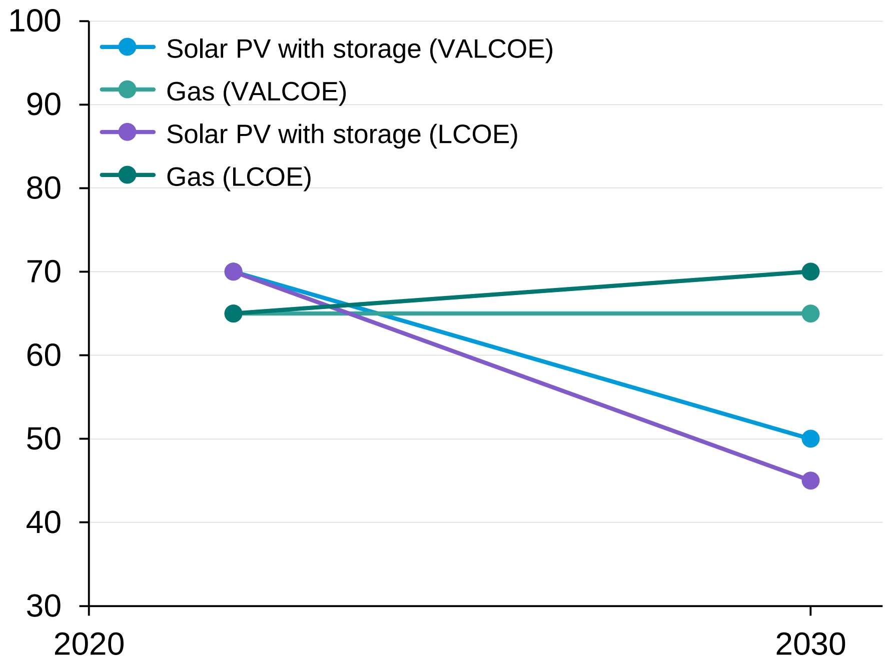
Integrating storage expected to gradually boost renewable energy economics relative to fossil fuels

LCOE and value-adjusted LCOE (VALCOE)[1] for solar PV plus battery storage,[2] coal, and natural gas for China and the United States, USD/MWh

China



U.S.



Observations

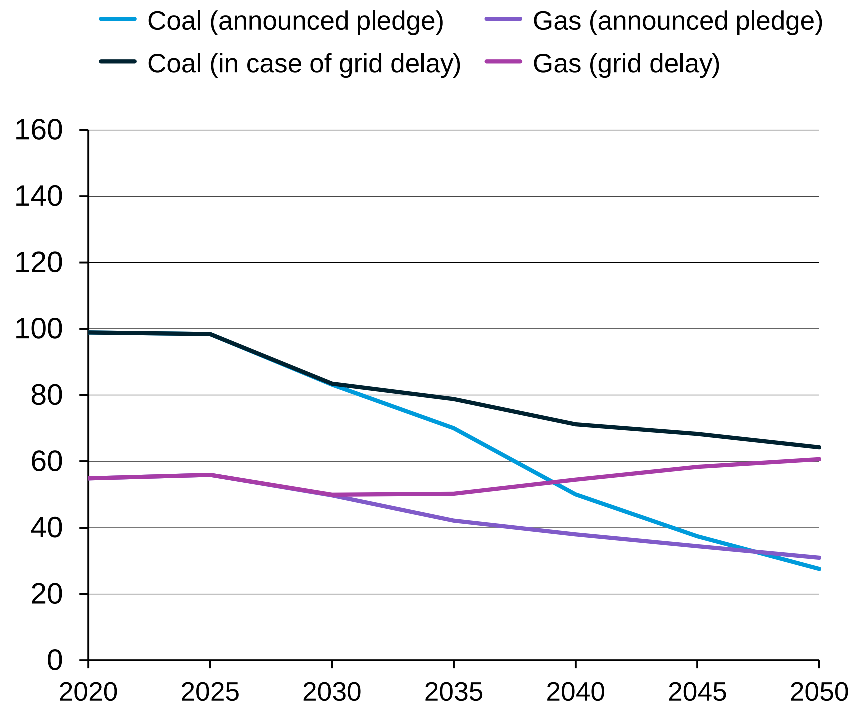
- Further innovations in battery chemistry and manufacturing are expected to lower the global average cost of lithium-ion batteries by 40% between 2023 and 2030.
- **The competitiveness of solar PV combined with batteries compared to new coal- and natural gas-fired plants varies:**
  - In India, the current cost is already competitive.
  - In China and the US, the cost will be competitive before 2030.

1) Solar PV installation paired with four-hour duration battery storage; 2) **VALCOE** is value-adjusted LCOE. That includes both the cost of the electricity and the value to the electricity system.
Source: IEA, Batteries and Secure Energy Transitions (2024).
Credit: David Foye, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

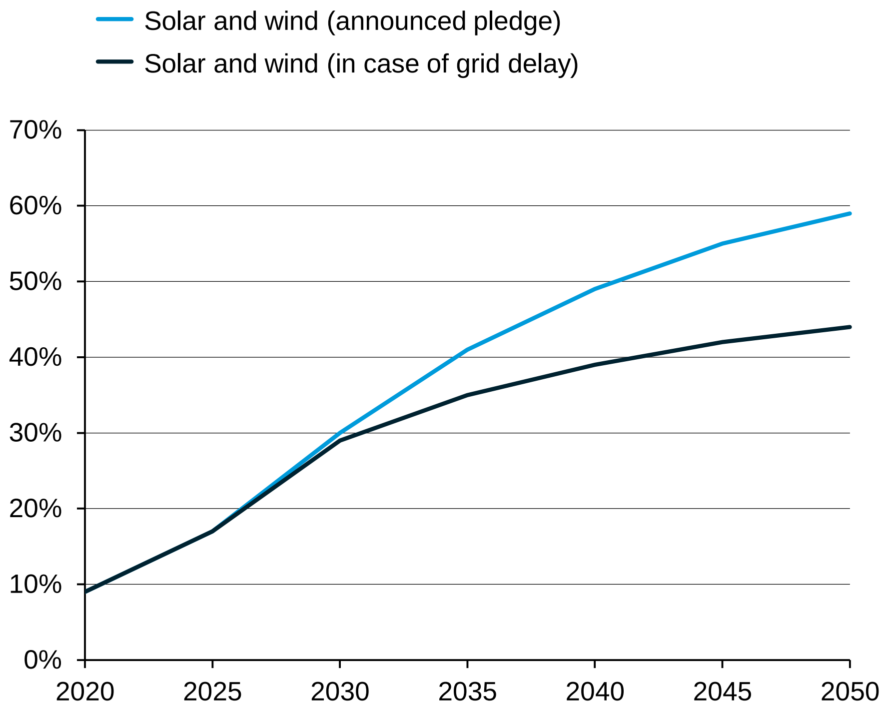
Delays in grid upgrades and energy storage deployment to slow transition from fossil-based sources to renewables

Grid delay inhibits transition from coal and gas by ~37 and ~31 EJs, respectively, while reducing renewable energy power generation by ~15% in 2050 vs. pledges

Coal and gas transition, EJ[1]



Share of solar and wind in total generation capacity, %



Observations

- **Energy storage** is essential to achieving significant reductions in fossil fuel use by enabling greater integration of renewable energy sources.
- Energy storage can help balance the variability of renewable energy by **storing** excess energy and **releasing** it when needed.
- Grid operators must invest in modernizing grid infrastructure to handle the **intermittent nature of renewable energy**, **reduce congestion**, and **improve grid flexibility.**
- Timely updates to grid infrastructure and energy storage deployment **are essential for reducing dependency on coal and natural gas.**

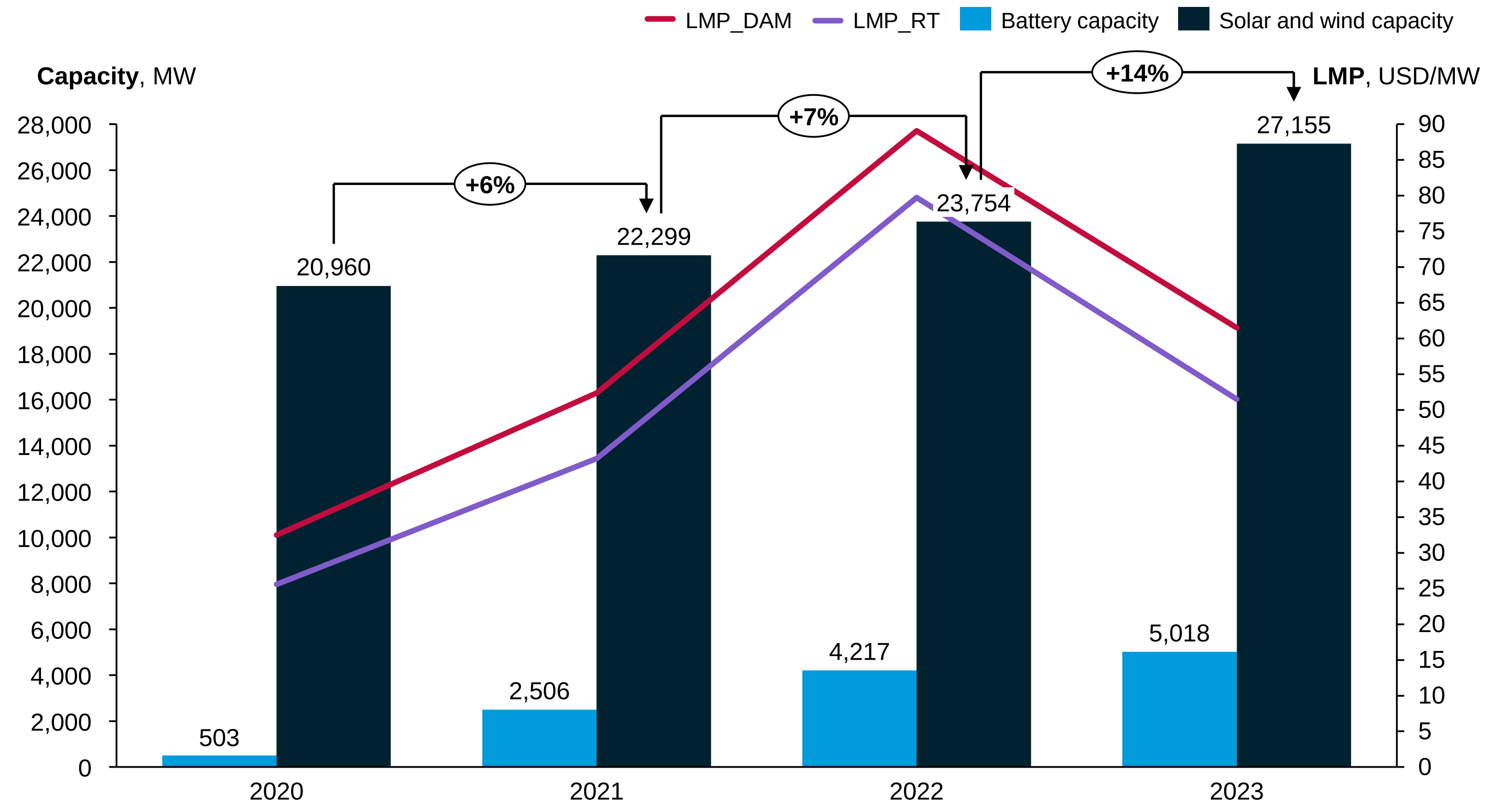
1) EJ = exajoules, a unit of measurement for energy; 1 exajoule is 277.7 TWh

Sources: IEA, Electricity Grids and Secure Energy Transitions (2023); McKinsey, How grid operators can integrate the coming wave of renewable energy (2024).

Credit: David Foye, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Growth in battery storage capacity has reduced curtailment and stabilized electricity pricing in California

Cumulative CAISO intermittent capacity plus battery storage capacity vs. LMP, MW, USD/MW



Observations

- California's Independent System Operator **(CAISO) experienced a notable increase in renewable energy capacity**, challenging the grid's ability to integrate this supply.
- The surge in renewable energy led to **higher levels of curtailment, wasting excess energy and driving up locational marginal pricing (LMP)** in both the day-ahead market[1] and real-time market.[2]
- **LMP** provides a method for wholesale electricity prices to represent the value of electric energy at **various locations**, considering **load patterns, generation, and the physical constraints of the transmission system.**

1) The day-ahead market is made up of three market processes that run sequentially (market power mitigation test**,** integrated forward market, and residual unit commitment process. 2) The real time is a spot market in which utilities can buy power to meet the last few increments of demand not covered in the day-ahead market.

Sources: California Energy Commission, Electric Generation Capacity and Energy; CAISO, Special Report on Battery Storage (2023), CAISO LMP (2024); ISO New England.

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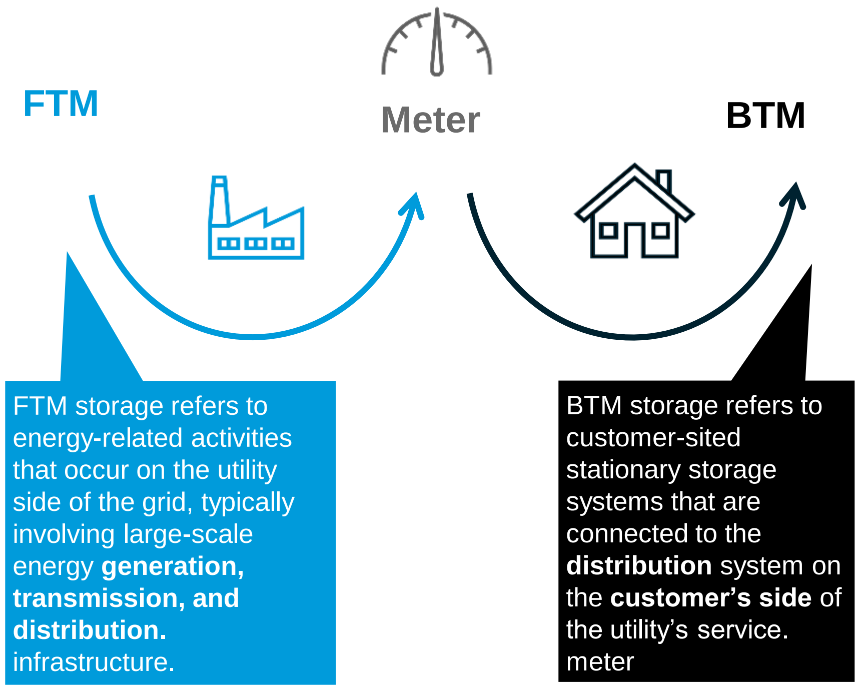
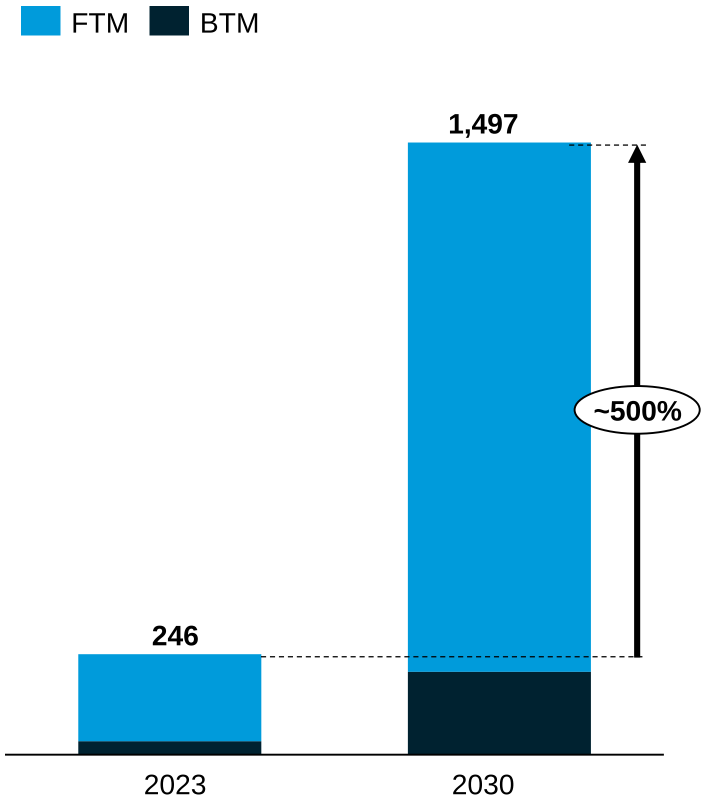
Global installed energy storage capacity projected to grow 5x by 2030, and >80% at front-of-the-meter

Front-of-the-meter (FTM) vs. behind-the-meter (BTM) energy storage



Global installed energy storage capacity, GW



Observations

- **Front-of-meter storage** will continue to grow, driven by the need for **large-scale grid support and renewable energy integration.**
- These operations are largely managed by **utility** companies and aim to address the energy needs of diverse consumers.
- **Behind-the-meter** storage will grow as well, due to the adoption of renewable energy in **residential and commercial settings.**
- BTM, combined with distributed generation and other grid assets implemented at the distribution level, is broadly known as **distributed energy resources (DERS).**
- BTM storage differs from FTM, depending on the ownership of the systems**, their installation locations**, as well as the **size and number** of systems deployed.

Source: IEA, Batteries and Secure Energy Transitions (2023).
Credit: David Foye, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

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Technology landscape

Opportunities and unlocks

Case study

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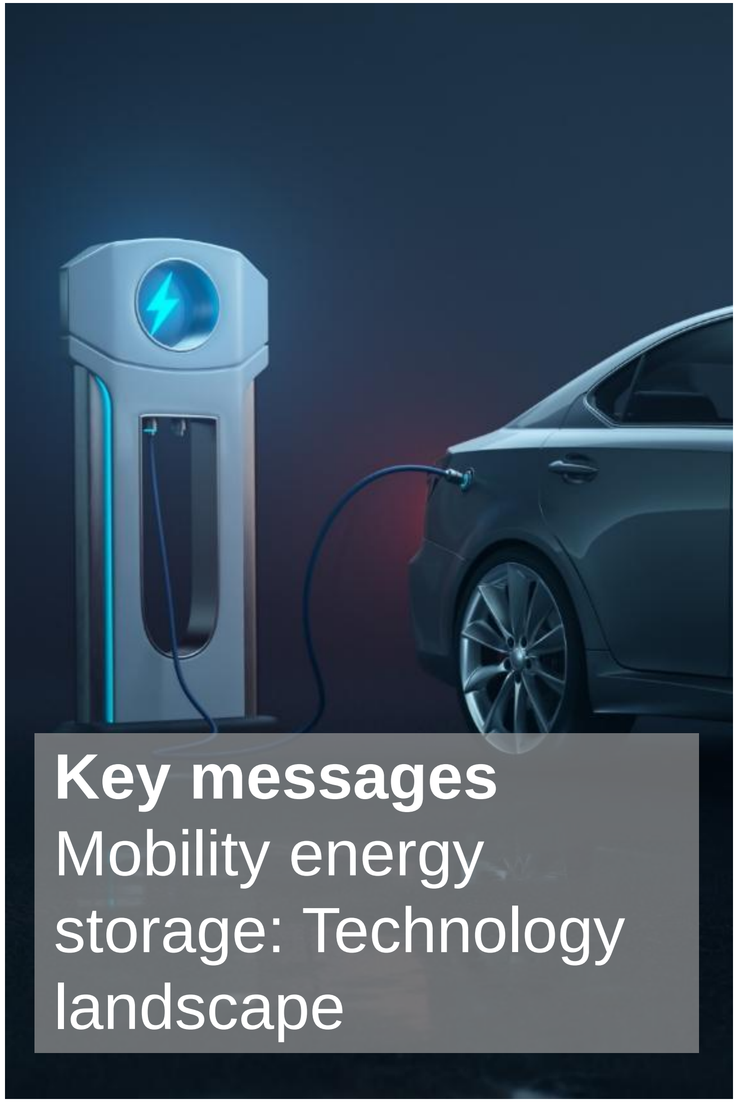

Key messages
Mobility energy storage: Technology landscape

Various storage technologies are available for electric vehicles, with **lithium-ion batteries** being the most prevalent due to their high energy density and reliable performance. LiBs consist of diverse chemistries, including LFP, NCM, NCA, and solid-state batteries.

Market trends: **NCM** led the EV battery market with a **60%** share in 2023, due to its superior energy density. However, **LFP** has been gaining momentum of late, driven by Chinese OEMs and concerns about cobalt and nickel availability.

Future scenarios: We expect LFP to surpass NCM in market share over the next five to 10 years, driven by advancements in energy storage, with other chemistries also entering the mix. For these technologies to gain market share:

- **LFP** should improve energy density (e.g., through lithium manganese iron phosphate or LMFP, a promising new cathode material) while decentralizing capacity across regions.
- **NCX** will need to resolve issues with thermal runaway while ensuring critical mineral supply availability.
- **Li-S/Air** will require sufficient investment in R&D to realize the theoretical level of energy density and efficiency.

Sodium-ion batteries, an emerging battery chemistry**,** are a lower-cost alternative to LiBs due to the abundance of sodium resources. They are also safer and made with similar manufacturing processes. However, challenges remain to achieve an energy density comparable to that of LiB.

1) LFP = lithium iron phosphate; NCM = nickel cobalt manganese; NCA = nickel cobalt aluminum; NCX = NCM and NCA variants

LiBs dominate the market due to high energy density and strong track record; SiBs ramping up as an alternative

Non-exhaustive	**Lithium-ion battery (LiB)**				**Sodium-ion battery (SiB)**
	LFP	**NCM**	**NCA**	**Solid-state battery**	
Description	**Uses lithium iron phosphate as cathode**	**Uses nickel cobalt manganese as cathode**	**Uses nickel cobalt aluminum oxide as cathode**	**Li-ion battery with solid electrolyte**	Transfers energy through the **movement of charged sodium ions** between the cathode and the anode during charge and discharge cycles
Pros and cons	⊕ Low cost due to **relatively inexpensive critical raw materials** ⊕ **Safer** with thermal stability ⊖ **Lower energy density** (175-425 Wh/kg) **shortens driving range** ⊖ Reduced capacity and power output in **low temperatures**	⊕ **Higher energy density** (340-420 Wh/kg), **increasing driving range** ⊖ Uses nickel and cobalt, two **relatively expensive raw materials**	⊕ Aluminum oxide allows for **faster charging** capabilities ⊖ **Costly** due to **limited supply of cobalt and nickel**	⊕ Enables **packing more energy into less space** ⊕ **Pushes cell-level energy density up to 500 Wh/kg** ⊕ **Safer** due to non-flammable electrolytes ⊖ **Sensitive to contaminants** and therefore requires **large volumes of high-quality materials**	⊕ **Saves manufacturing time by ~50%** and **reduces plant CapEx by ~30% compared to LiBs**, as it doesn't require formation ⊕ **Inherently safer** with **no risk of thermal runaway** ⊕ **Significantly more cost effective,** with sodium hydroxide as a key raw material ⊕ **Suitable for a broader range of applications** given its **adaptability to varying temperatures** ⊖ **Lower energy density** (130-160 Wh/kg) suitable for only two-/three-wheelers or stationary batteries
Global average cell cost*, USD/KWh ● 2020 ● 2030F	-10% p.a.; 101 → 35	-7% p.a.; 105 → 52	-6% p.a.; 112 → 58	Not yet commercialized	Data not available

*Adjusted based on 2020 CPI; cell cost of NCM 811 is used for NCM.

Sources: IEA, Global EV Outlook (2024); Drive Electric Tennessee (2023); Wood Mackenzie, LFP cathode supply (2023); Journal of Energy Storage (2024); BloombergNEF, Top 10 Energy Storage Trends (2023). Credit: Ashley Kim, Devashri Mehrotra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

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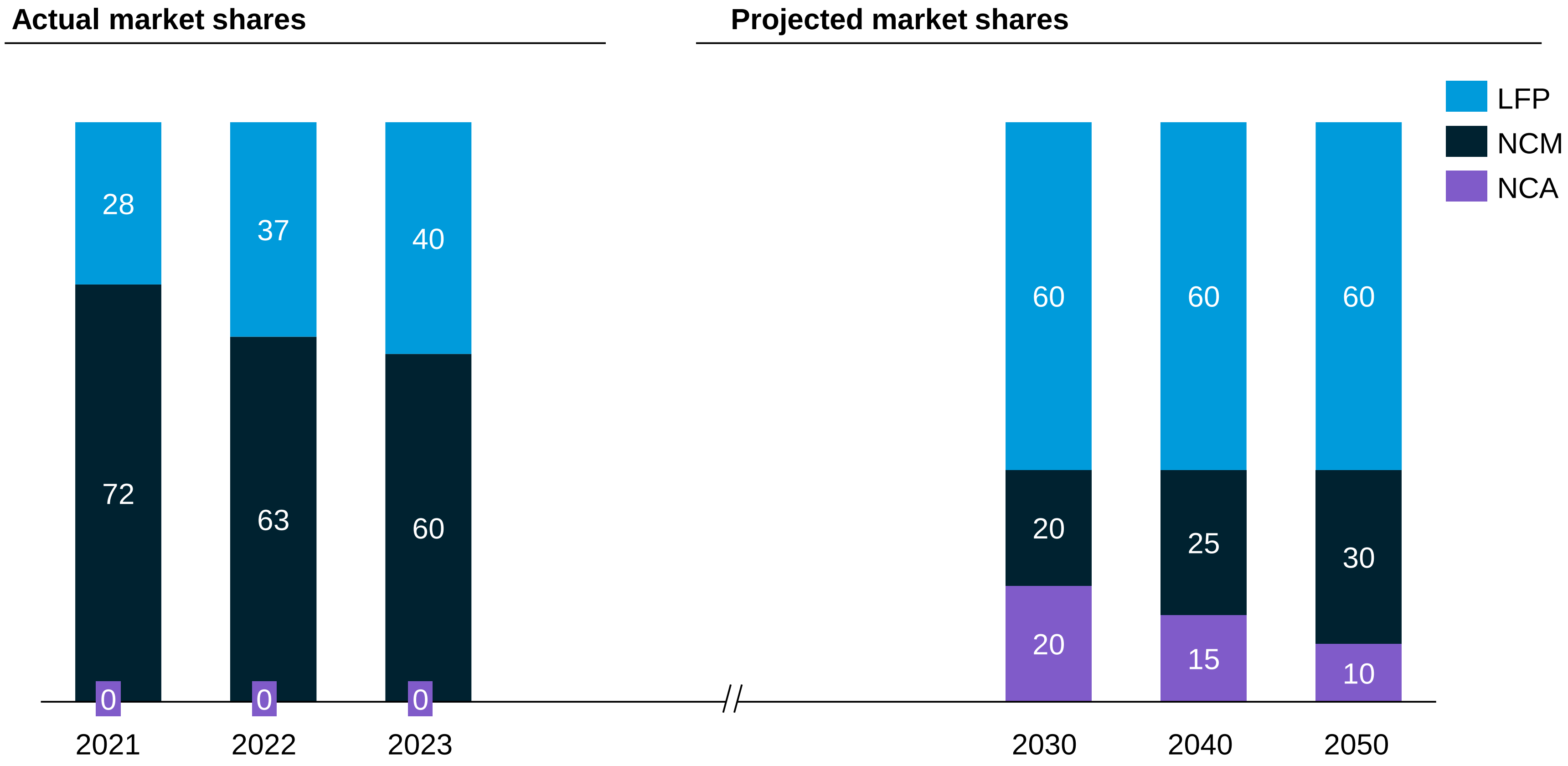
Other batteries used for more limited or complementary applications

Non-exhaustive	**Nickel-metal hydride (NiMH)**	**Lead-acid**	**Ultracapacitor**
Description	Uses **nickel hydroxyl oxide** as cathode material and **a hydrogen-absorbing alloy** as anode	Consists of an anode made of **spongy or porous lead,** a cathode made of **lead dioxide,** and an electrolyte composed of **sulfuric acid**	Double-layer capacitors that store **polarized liquid between an electrode and an electrolyte**
Pros and cons	⊕ **Lasts longer than a Li-B** and is **safe to use** ⊕ **Can be operated across a broad temperature range** (below -30°C and above 100°C) ⊖ **Expensive** to produce ⊖ Generates a lot of **heat at high temperatures** ⊖ Has a **high discharge rate**	⊕ **Inexpensive** and **safe to use** ⊖ Relatively **short life** ⊖ **Worse** performance in **cold weather** ⊖ **Heavy and less durable** than nickel and lithium-based systems **when deep-cycled**	⊕ Can be charged multiple times **with almost no battery degradation** ⊕ **Higher power density** than batteries makes it more suitable for high-drain applications ⊖ **Lower energy density** than batteries, so it is less suitable for long-range EVs
Applications	• **Typically used in hybrid vehicles,** where a gasoline engine operates alongside electric motors and recharges the onboard battery • While mostly altered by Li-B, **a few Indian motor companies and Toyota still favor NiMH** for some applications (e.g., hybrid-electric vehicles)	In EVs, it cannot independently power the electric motor but is primarily used to **assist auxiliary features,** such as providing backup power for power steering, brake boosting**,** and safety features	• Serves as **secondary storage devices,** aiding in load balancing for **lithium-ion battery packs** • **Provides EVs an extra boost of power for acceleration**

Sources: Encyclopedia of Electrochemical Power Sources (2009); Solar Energy Materials and Solar Cells (2014); Green Cars (2024); Mobility Engineering Tech (2023).
Credit: Ashley Kim, Devashri Mehrotra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

LFP chemistries increasing in market share compared to NCX chemistries, with 2030 forecasts indicating majority share

Battery market share (based on capacity) by cathode type, %



Observations

- **NCM** has been dominating the market for EV batteries due to the **high energy density.**
- The recent shift to **LFP** is driven by **fierce cost competition**, with Chinese OEMs spearheading this expansion.
- **Future market share among battery chemistries is still uncertain** given the continuously evolving technology. However, recent capacity expansions in LFP suggest a large share in LFP.
  - Once cost reductions saturate across chemistries, **achieving further performance improvements** may be necessary to achieve dominance in the field.
- These scenarios will **affect raw material demand** and necessitate a further review of **reserve availability.**

1) NCM refers to Li-based batteries with nickel-cobalt-manganese based cathode; NCA refers to Li-based batteries with nickel-cobalt-aluminum based cathode.
Sources: IEA, Global EV Outlook (2024); Argus, NMC to LFP transition (2023); Nature, Future material demand for automotive Li-based batteries (2020); Focus Distribution, Forecasting demand for batteries (2022).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

NCM and LFP currently the leading technologies in battery systems; room for further technological development exists

How the different Li-ion battery technologies rate on key features

Performance: Low | Moderate | High

	NCM	NCA	LFP	Li-S/air
Safety	Thermal runaway at > 210°C	250°C	270°C	190°C (All solid-state Li-S)
Energy density[1]	2,400 Wh/kg	2,400 Wh/kg	1,100 Wh/kg	2,600-11,140 Wh/kg
Price[2]	\$95-\$100/kWh	\$95-\$100/kWh	\$70-\$75/kWh	N/A (not commercialized yet; expected to be cheaper given that sulfur is \$0.10-\$0.15/kg vs. cobalt at \$33-\$35/kg)
Lifespan (Endurance)	500-1,500 cycles	500-1,500 cycles	>2,000 cycles	<1,000 cycles
Service time per charge	0.7-1C	0.7C	Charging c-rate of 1C	3C

Observations

- As of 2022, ~50% **of EV makers relied on NCM batteries because their high energy density is crucial for maximizing driving range.**
- NCM battery and EV makers have adjusted **cathode active material components to improve energy density and manage raw material risks**, increasing nickel content.
  - LG supplied NCM 811 batteries (80% nickel, 10% cobalt, and 10% manganese) for Tesla's Model 3S in China.
  - Tesla, VW, and others are developing high-nickel batteries for larger vehicles.
- Starting in 2023, **price and safety** are increasingly critical factors, as driving range requirements are largely being met.
  - LFP is becoming more popular because of qualities like its competitive cost and relative safety. LFP technology has also advanced to overcome its inferior driving range.
  - NCX is being modified to cut costs by lowering cobalt content and enhance safety by decreasing nickel content and increasing manganese content.
- **NCA,** deployed by Tesla, Samsung SDI, and Panasonic, **has innate limitations because it doesn't use manganese, a crucial safety element. Reducing cobalt content for cost saving in NCA has been difficult,** since it plays a key balancing role.
- Despite offering **energy density that is potential higher** than conventional Li-ion batteries like NCM/NCA/LFP**, Li-S batteries must overcome multiple technical challenges** before they are ready for commercialization.

1) Compared to theoretically achievable cell-level energy density, Li-S has achieved 450 Wh/kg and Li-air has achieved 610 Wh/kg for practical applications. 2) Cell costs as of 2023, adjusted to 2020 CPI. For NCM, the cell cost is weighted by the 2023 market share distribution across NCM 111, 532, 622, 811, and 955.

Sources: IEA, Net Zero by 2050 (2021); IEA, Batteries and Secure Energy Transitions (2024); One Charge (2023); Flash Battery (2022); Energies (2019); Volts (2021); S&P Global, Gas and Power; Journal of Energy Storage (2023); Materials for Renewable and Sustainable Energy (2022); SmartMat (2023); ArenaEV (2022); Joule (2022); Lyten (2022); Chemistry Europe (2018).

Technological advancements, raw material supply chains, and market adoption to determine which chemistries lead in the future

Key conditions to be satisfied for individual chemistries to achieve dominance

Level of difficulty: L Low; M Moderate; H High

	NCX	LFP	Li-S/air
Technological advancement	M **Resolve technical shortcomings,** including **safety issues** like greater risk of thermal runaway and **shorter battery lifespan**	M **Improve energy density at cell level** (e.g., LMFP) **and pack level** (e.g., advanced **cell-to-pack technology)**	H Overcome **technical challenges** to **achieve theoretical energy density and efficiency levels** that provide an advantage over conventional LiBs
Supply chain, including raw material supply	M Need for a stable, cost-effective, and circular **supply of nickel** and a **shift away from cobalt**	H More investment needed in **LFP supply outside of China (**both upstream and downstream)	N/A
Market adoption	N/A	L Increasingly being adopted in **light-duty vehicle market**	H **Investments needed in R&D** to overcome technical challenges

Sources: Nature, Material demand for lithium-based batteries (2020); S&P Global, Lithium-ion battery capacity (2023); S&P Global, Lower lithium prices (2024); Argus, NMC to LFP transition (2023); Forbes, Lithium Iron Phosphate (2023); Journal of Energy Storage, Deploying lithium sulfur batteries (2023).

Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

While dominant today, NCX must resolve safety issues and improve battery lifespan to stay on top

	Bottlenecks	Potential solutions and level of difficulty
Technological advancements required (M)	**Safety:** Physically damaged batteries or those with manufacturing defects are **more prone to thermal runaway**, with six recalls in the past three years (e.g., Chevrolet Bolt). • The release of oxygen from the nickel-cobalt mixture during an internal short circuit can increase heat and raise safety issues.	• Battery enhancement options include additives to active materials, improvements in separators, and external measures such as **battery management systems, cooling, and cell balancing.** However, they tend to come **at the expense of energy density, power, and charging time.** • **Solid-state batteries** could provide better stability without losing the advantages of NCM. • **Reducing nickel content and increasing manganese** could also help prevent NCM thermal runaway.
	Lifespan: NCM batteries degrade fast, lasting just **800 to 2,000 cycles,** or **three to four years. LFP batteries** are more durable, lasting **~3,000 cycles,** or **seven to eight years.**	• **A battery thermal management system**, along with **CAM improvements such as the introduction of a single crystalline structure, efficient current distribution**, and **optimal electrode configurations** can extend the battery's lifecycle. However, **NCX's battery chemistry means its upper cycle threshold will typically be lower than for LFP.**
Supply chain, including raw material (M)	**Nickel (Ni) and cobalt** (**Co)** are **relatively scarce** and production is **geographically concentrated,** leading to **high prices** and **high price volatility.** • Ni and Co **prices doubled from 2021 to mid-2023** in the wake of the Russia-Ukraine War and due to increased demand for EVs.	• **Battery chemistry advancements like cobalt-free batteries** (in which cobalt is replaced with nickel for higher performance and manganese for lower cost) and **recycling** will significantly mitigate long-term supply risk, but it could be hard to avoid a shortage in cobalt supply through at least 2028 or potentially through 2033 • **Supply chain diversification** will also be important. Australia, which has all four key elements for NCX battery production, could be an alternative source of raw materials.
	Sourcing of Ni and Co can be controversial: • The **Democratic Republic of Congo** produces >70% of the world's **cobalt** and possesses ~50% of the world's reserve, but mining utilizes **child labor** and Congo faces **political instability.** • **Nickel** mining involves **significant environmental damage,** including water pollution and energy-intensive smelting processes with high GHG emissions.	**More sustainable practices include:** • **Efforts led by international organizations (e.g., IMF) and industry leaders (e.g., BASF) to formalize the cobalt supply chain**, including introducing common standards and metrics, implementing a monitoring or assessment process, and promoting knowledge sharing. • **High-pressure acid leaching** can offer a less energy-intensive extraction technique for nickel. **Bioleaching** employs microorganisms to extract metals from ore or e-waste, offering an easier method to process ore, without relying on high temperatures.

Sources: Nature, Material demand for lithium-based batteries (2020); S&P Global, Lithium-ion battery capacity (2023); S&P Global, Lower lithium prices (2024); Argus, NMC to LFP transition (2023); Forbes, Lithium Iron Phosphate (2023); Journal of Energy Storage, Deploying lithium sulfur batteries (2023); IEF, Nickel (2024); Nature, Battery technology and recycling (2022); Journal of Energy Chemistry, Lithium-ion battery safety concerns (2021); WEF, Making Mining Safe and Fair (2020); Frontiers in Batteries and Electrochemistry (2024).

Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

LFP already popular in China, but wider adoption required to keep growing market share

Technological advancements required

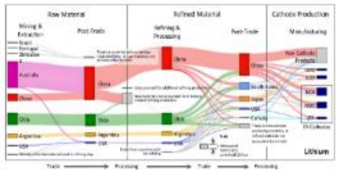
M

Bottlenecks

Energy density: As of 2023, **LFP battery cells** deliver an energy density of about **160 Wh/kg**, allowing a range of around **200 miles (320 km)**. This is inferior to **NCM battery cells**, which offer a higher energy density of about **250 Wh/kg**, enabling a range of roughly 300 miles (480 km).

Global flows of lithium

See appendix for full-size diagram.



Potential solutions and level of difficulty

Blend with other materials to achieve higher energy density at the cell level.

- Chinese battery manufacturers as well as European, American, and Korean players are developing LMFP or other variations of LFP (e.g., CATL's M3P), which are expected to achieve 15% to 20% higher energy density in comparison to conventional LFP.

Realize **higher energy density at the pack level:**

- At the battery-pack level, LFP energy density can effectively **match that of NCM**, thanks to its lower thermal runaway risk, which allows for **tighter cell packing.**
- **Cell-to-pack technology** builds a pack from battery cells without modules, reducing the need for inert materials and helping to increase energy density.

Supply chain, including raw material

H

Bottlenecks

The LFP supply chain is extremely concentrated in China, making it vulnerable to disruption.

- In the upstream, **a significant share of CAM materials**, including cobalt and nickel, currently **comes from operations with substantial ownership by China-headquartered companies**, making diversification extremely difficult.
- Mid- to downstream, **China produced 95% of LFP batteries in 2022**, while the U.S. produced just 3% of light-duty vehicles with LFP batteries.

Potential solutions and level of difficulty

Increase investment in battery metals extraction, refining, and battery production capabilities outside China.

- One option is to **build refining capacities in North America and FTA partners**, especially for minerals with limited local reserve availability, such as cobalt and nickel.
- **LFP production in South Korea-headquartered battery producers** could open up the commercialization of LFP batteries in North America.

Market adoption

L

Bottlenecks

The first-mover advantage of LFP in China has led to limited LFP uptake outside of China.

- LFP's market share in Europe is a mere 5.2% and less than 10% in the U.S. as of 2023.

Potential solutions and level of difficulty

Non-Chinese OEMs targeting the low/entry car segment are increasingly announcing plans to adopt LFP because of its low cost (e.g., the Stellantis-CATL partnership, Ford's BlueOval Battery Park).

Sources: Argus, NMC to LFP transition (2023); Forbes, Lithium Iron Phosphate (2023); Journal of Energy Storage, Deploying lithium sulfur batteries (2023); Nature, EV battery chemistry (2024); S&P Global, Lithium-ion battery capacity (2023); Stellantis (2023); Ford, BlueOval Battery Park Michigan (2024); IEA, Global EV Outlook (2024); Nature, EV battery chemistry (2024), S&P Global, China, South Korea battery-makers (2024).

Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Li-S/air batteries must overcome technical challenges before mass production and widespread market adoption

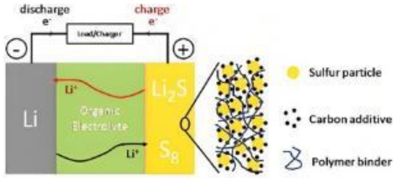
Technological advancements required

H

Bottlenecks

Li-sulfur battery (LiSB): Needs to overcome **multiple technical challenges to achieve theoretical energy density levels,** including **self-discharging and high internal resistance due to the shuttle effect (Fig. 1), rapid capacity failing,** and above all, **reaction stability.**

Polysulfide shuttle effect



See appendix for full-size diagram

The shuttle effect refers to the phenomenon where soluble polysulfide intermediates that formed during the battery's charge and discharge cycles dissolve into the electrolyte and travel between the anode and cathode. This results in **loss of active material**, **self-discharging**, **poor energy efficiency,** and **degradation of electrodes.**

Li-air battery (LAB): Faces challenges in **interfacial continuity/compatibility, air stability, significant overpotential during discharge/charge**, and the **working mechanism of solid-state electrolytes.**

Potential solutions and level of difficulty

LiSB: Active research is underway, including:

- **Securing a level of reaction stability** comparable to LiB without adding guardrails that may compensate for energy density, which will be key.
- **Constructing novel nanostructured sulfur electrodes** and developing **appropriate electrolytes/separators** to overcome the disadvantages.

LAB: Multiple areas still require further study to **achieve the theoretical level of performance**, including:

- Discharge-recharge mechanisms and kinetics
- Improvement in ionic conductivity and stability of electrolytes
- Trade-off strategies for balancing interfacial compactness and catalysts to enable high energy density

While LiSB is closer to commercialization, LAB is increasingly seen as a less viable option, mainly due to the openness of the thermodynamic system, which may lead to extremely high entropy.

Market adoption

H

Bottlenecks

LiSB/LAB: Commercialization remains in early stages for both, mainly due to their significantly shorter lifecycle.

- For example, to be marketable, LiSB cells must demonstrate trustworthy performance for at least 200 cycles without a capacity drop of more than 60%. If they maintain performance for 500 cycles, meanwhile, they can be adopted in a wider range of applications.

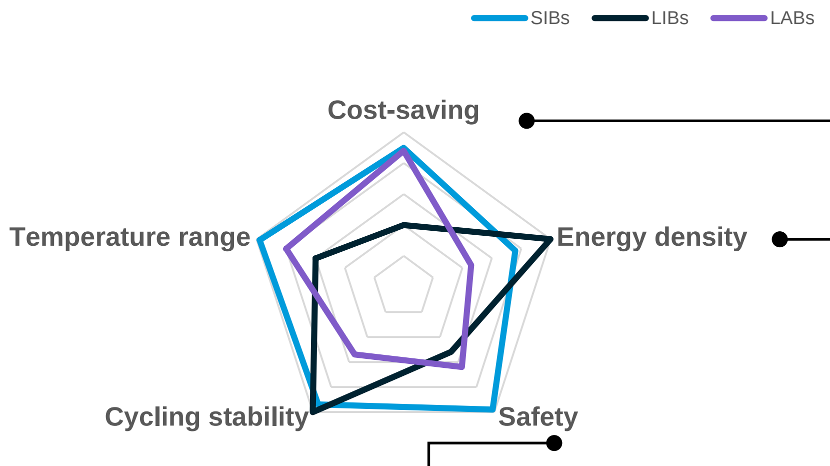
Potential solutions and level of difficulty

LiSB: OEMs (e.g., Stellantis) are investing in LiSB startups (e.g., Lyten) to accelerate commercialization.
LAB: A LAB design developed in 2023 operated in a stable manner over 1,000 cycles of test charging/discharging.

Sources: Journal of Energy Storage, Deploying lithium sulfur batteries (2023); Stellantis, Invests in Lyten (2023); Science, Room temperature rechargeable Li2O-based lithium-air battery (2023); BatteryBits, Introduction to Solid-State Batteries (2022); SmartMat, Solid-state Li–air batteries (2023).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

SiBs offer cost, temperature range, and safety advantages compared to LiBs; energy density still a challenge

How established rechargeable battery technologies stack up



Cost:

- Sodium is abundant and therefore inexpensive, especially relative to lithium (pure sodium cost USD $290/MT in 2023 vs. a lithium compound cost of USD $35,000/MT)
- SiBs are made using technology similar to that in LiBs, requiring minimal additional capital investments.

Energy density:

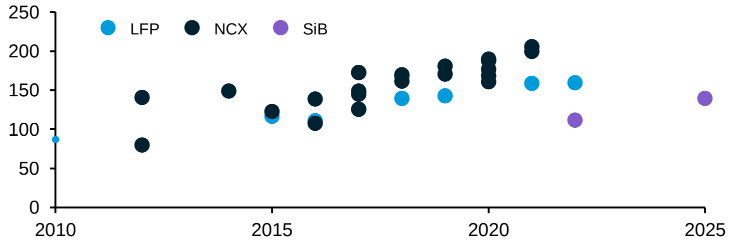
- SiBs could reach pack densities of nearly 150 Wh/kg by 2025, approaching the energy density of LiBs typically used in EVs (250-300 Wh/kg)
- **New electrode materials** could enable SiBs to improve their energy density even further, achieving a level close to that of LiBs.

Safety:

SiBs could possibly **avoid thermal runaway:**

- By avoiding highly flammable diethyl carbonate (DEC) and dimethyl carbonate (DMC) used in LIBs, SIBs can utilize electrolytes with higher propylene carbonate content, significantly enhancing safety.
- Unlike LIBs, which require transport at a specific state of charge to prevent copper foil dissolution, SIBs can be stored and transported in a fully discharged state (0V), providing an ultimate safety condition.

Battery pack energy density (Wh/kg)



Observations

- SiB technology is rising as an alternative to LiB, as it is **less susceptible to resource availability issues,** has a **low material cost, and is less dependent on the Chinese supply chain** than LiB.
- Sharing the **same cell structures and electro-chemical reaction processes as LiB** but utilizing Na+ as the charge carrier instead of Li+, SiB has some **advantages in terms of cost and safety.** However, **achieving an energy density** comparable to that of LiB remains a challenge.

Sources: MIT Technology Review, How sodium could change the game (2023); ING, Can sodium-ion batteries replace lithium-ion ones? (2023); Engineering, Sodium-Ion Batteries (2023); Shanghai Metals Market, Spot Metal Prices (2025).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

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The energy storage opportunity

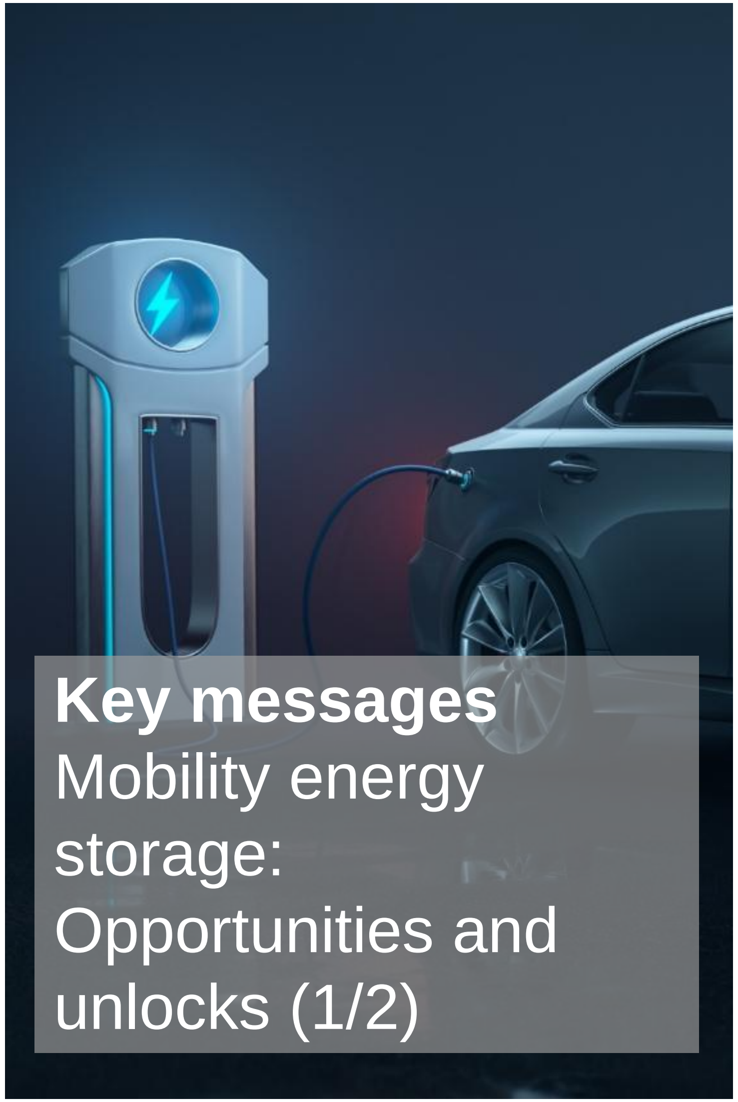
Mobility energy storage

Technology landscape

Opportunities and unlocks

Case study

Utility energy storage



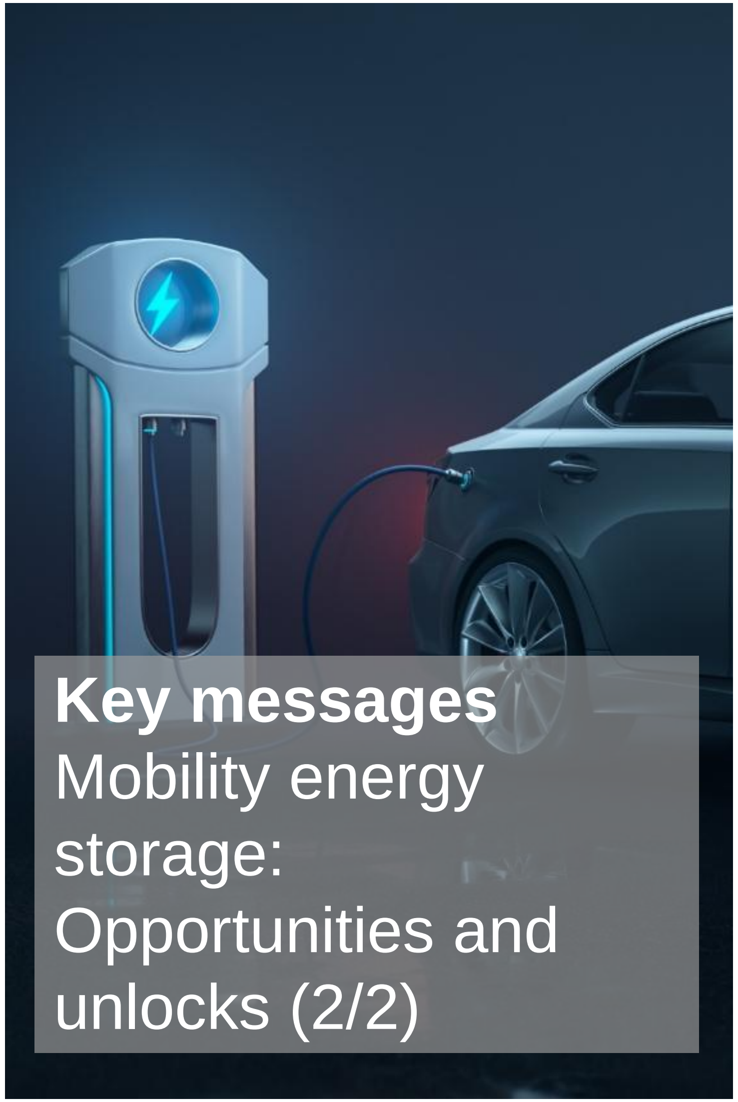
Key messages
Mobility energy storage: Opportunities and unlocks (1/2)

Batteries are critical components of the EV ecosystem. The full value chain includes **battery production** (from raw material extraction to battery recycling), **charging systems and infrastructure**, and related services such as **vehicle-to-grid (V2G) systems.**

Battery:

- **The battery (Li-ion) value chain** could become a **>$400 billion market by 2030**, with cell manufacturing and active materials being the largest segments. China dominates with around a 70% share of global production capacity, followed by Korea, which has an approximate 20% share.
- **The battery market will likely be oversupplied through 2030.** Government incentives are playing an essential role:
  - **In the United States, the IRA has boosted investments,** with over $140 billion in incentives. In the first year after the IRA was signed into law, planned gigafactory capacity increased by 67%.
  - **China's** battery industry has benefited from approximately **$29 billion in government incentives since 2009 and strategic international raw material acquisitions.** China now controls more than 80% of global refining capacity.
- **Technological advancement will continue to drive cost declines:**
  - EV battery cost **has dropped by 40%-50%** since 2010 and is expected to drop by as much as 90% by 2030.
  - The cost of materials will continue to drive overall battery costs. As such, **LFP** is anticipated to **remain the cheapest chemistry** in 2030 (<$50/kWh) because of its low material cost.

Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).



Key messages

Mobility energy storage: Opportunities and unlocks (2/2)

Battery (continued):

- **Critical minerals used in battery production may be in short supply in the next five to 10 years without additional development.** Recycling of these minerals could help fill the gap, but profitability remains a challenge:
  - Challenges in scaling up the recycling business include **limited supply and competition with mining/refining players.**
  - The market today is highly fragmented, and the players that can build **a closed-loop ecosystem from supplier to customer are the ones that will survive.**
  - **Policies around mandating OEM end-of-life collection and recycling are critical to boosting the recycling business** and ensuring long-term availability of raw materials.

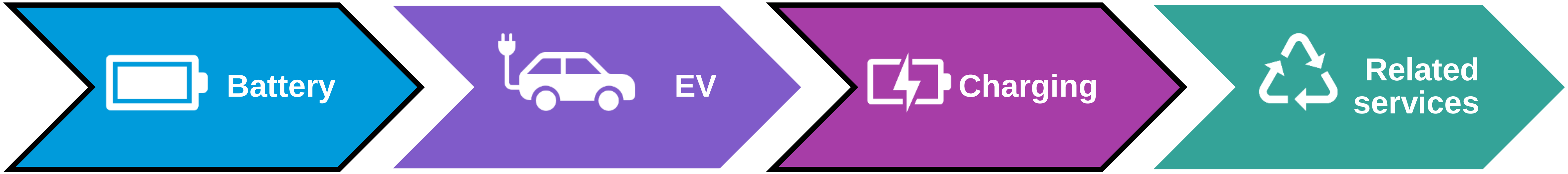
EV charging:

- **Extensive investments** are required**. LDV chargers** will need to grow by **5x** and **HDV chargers** will need to grow by **6x** through 2030.
- Incorporating **smart energy services will likely help distinguish business models in the charging ecosystem,** followed by the hardware and charging services.
- Norway and China are instructive as examples of how to boost charging infrastructure through incentive programs:
  - Norway: Public funding of charging infrastructure in rural and remote areas where independent business cases do not provide required returns, with grants to residential owners and developers covering up to 75% of charging port costs.
  - China: Large-scale public funding of charging infrastructure together with strict mandates for developers and building owners to provide EV charging infrastructure.

Batteries form an important part of the overall EV ecosystem

Focus of this section

EV value chain (non-exhaustive)



Battery
- Raw material mining
- Raw material processing and refining
- Cathode and anode material manufacturing
- Cell fabrication
- Battery packing
- Battery recycling

EV
- EV production
- EV sales

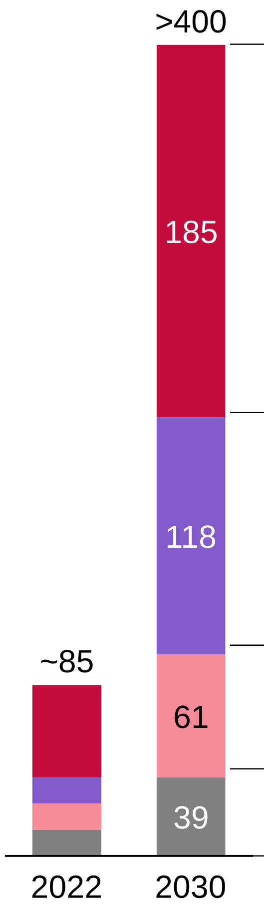
Charging
- Power generation
- Charging equipment manufacturing
- Charging operations

Related services
- Vehicle-to-grid (V2G)

V2G is discussed in the utility section

Li-ion battery value chain expected to >$400 billion market by 2030, mostly due to growth in cell manufacturing and active materials

Revenues in 2030, USD$B



	Mining	Refining	Active materials	Battery cells	Battery pack	Reuse and recycle
	Extraction of raw ore/ material required for battery	Processing and refining of raw material into precursors for battery	Manufacture of cathode and anode materials, electrolytes, separators, and casings	Fabrication of battery cells	Integrate cells into pack, including electronics, sensors, and battery management system	Recovery of critical materials, cathodes, and anodes and/or reuse of used batteries in storage applications
Total	34 (9%)	52 (13%)	110 (27%)	121 (30%)	74 (18%)	13 (3%)
China	15	22	54	53	34	6
Europe	10	15	31	37	22	3
U.S.	6	9	14	20	11	2
Rest of world	3	5	11	11	7	2

Observations

- As demand for Li-ion batteries surges across industries, **revenues for components across the value chain** are projected to increase **fivefold**, from **~$85 billion in 2022 to >$400 billion in 2030.**
- **Cell manufacturing and active materials** will likely be two of the largest markets.
  - When it comes to sourcing battery materials, **mining is one option while recycling is another**.
  - **Battery recycling** is expected to be **relatively limited in 2030**, but it is **projected to grow more than threefold in the following decade**, as more batteries reach end of life.
- While China is the biggest player today, the **EU and U.S. are expected to increase their share** over time given plans for new mining, refining, and cell production projects in those regions.

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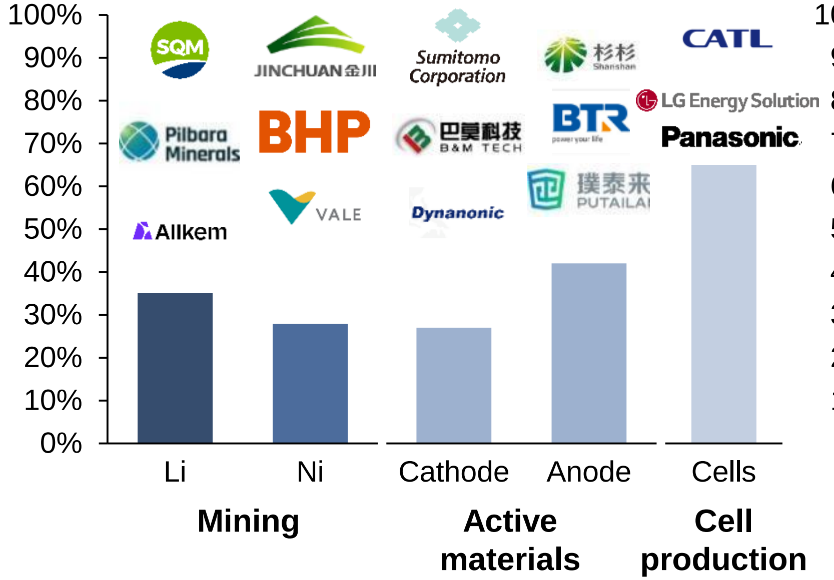
Source: McKinsey Battery Insights (2022).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

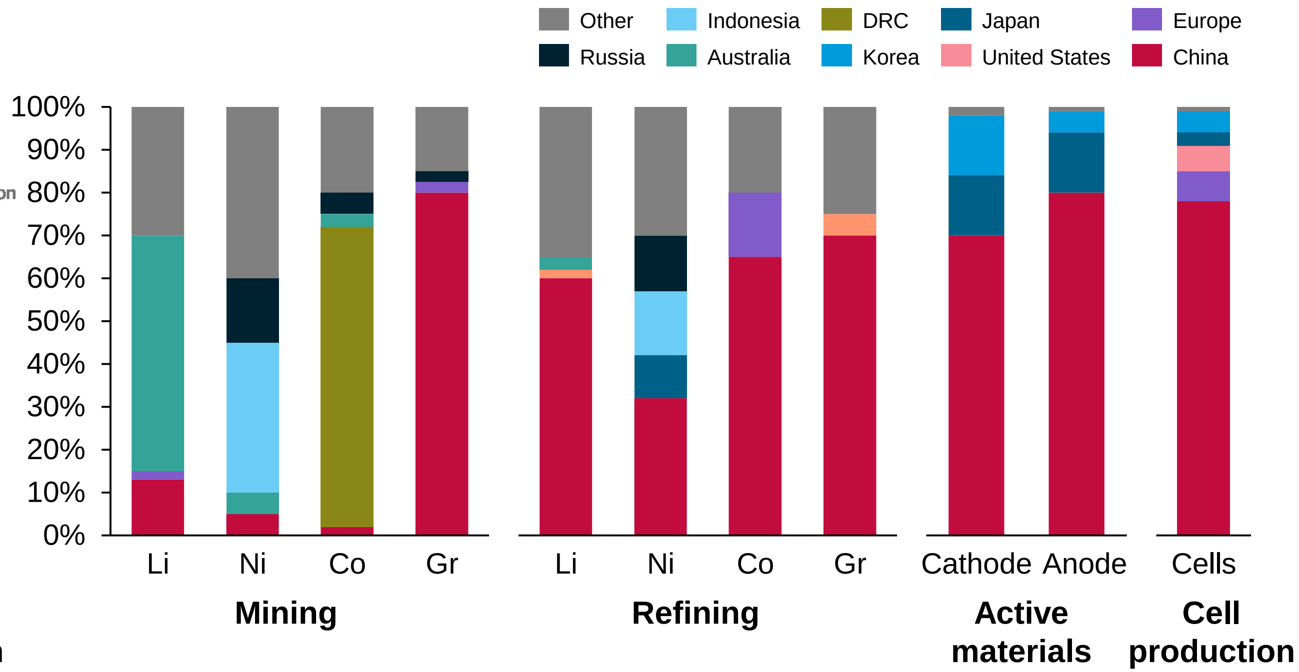
Many stages of EV battery supply chain dominated by a limited number of countries and companies

Share of total production of top three companies across supply chain,* 2021



* Mining by production capacity; cathode and anode by production capacity; cell production by MWh produced

Geographical distribution of the global EV battery supply chain,** 2022



**Geographical breakdown refers to the location of the production. Mining is based on production data. Material processing is based on refining production capacity data. Active material production is based on cathode and anode material production capacity data. Battery cell production is based on battery cell production capacity data.

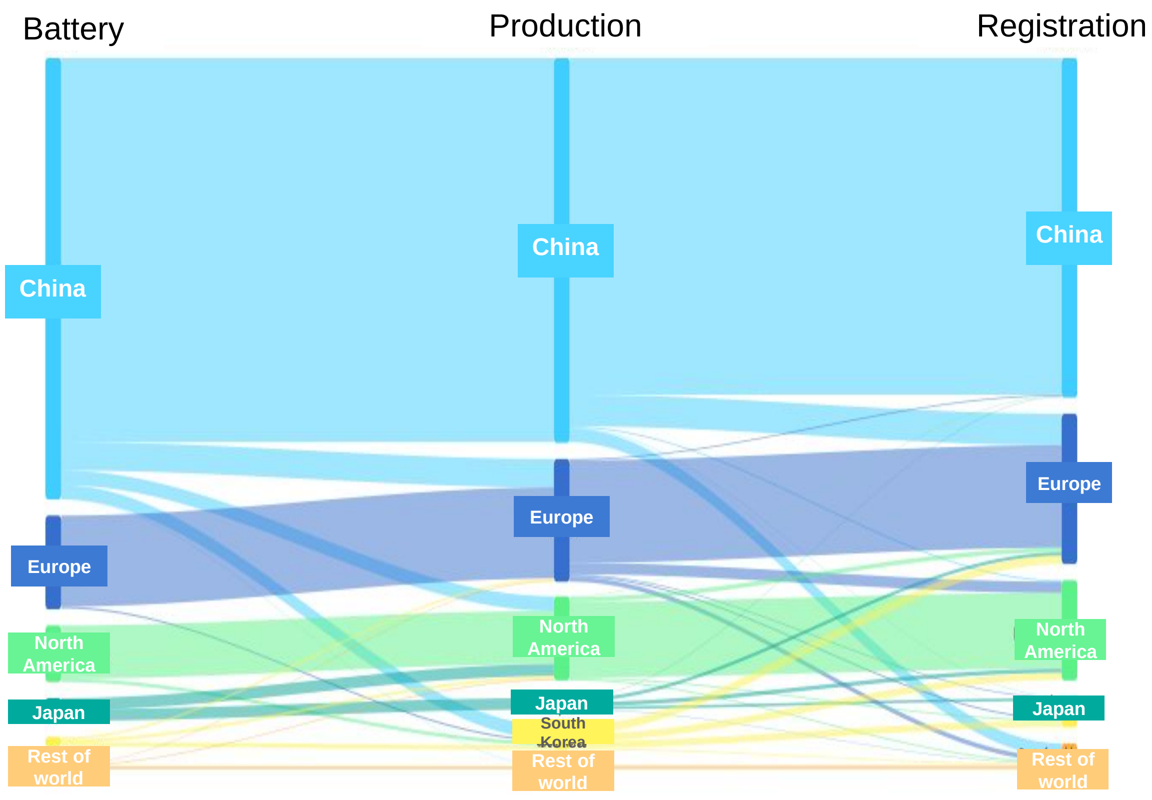
Observations

- Across **all stages of the EV battery supply chain,** production is concentrated among only a few companies due to their **economies of scale.**
- The same is true for countries, with **China** in particular dominating production at **every stage of the EV battery supply chain** downstream of mining.

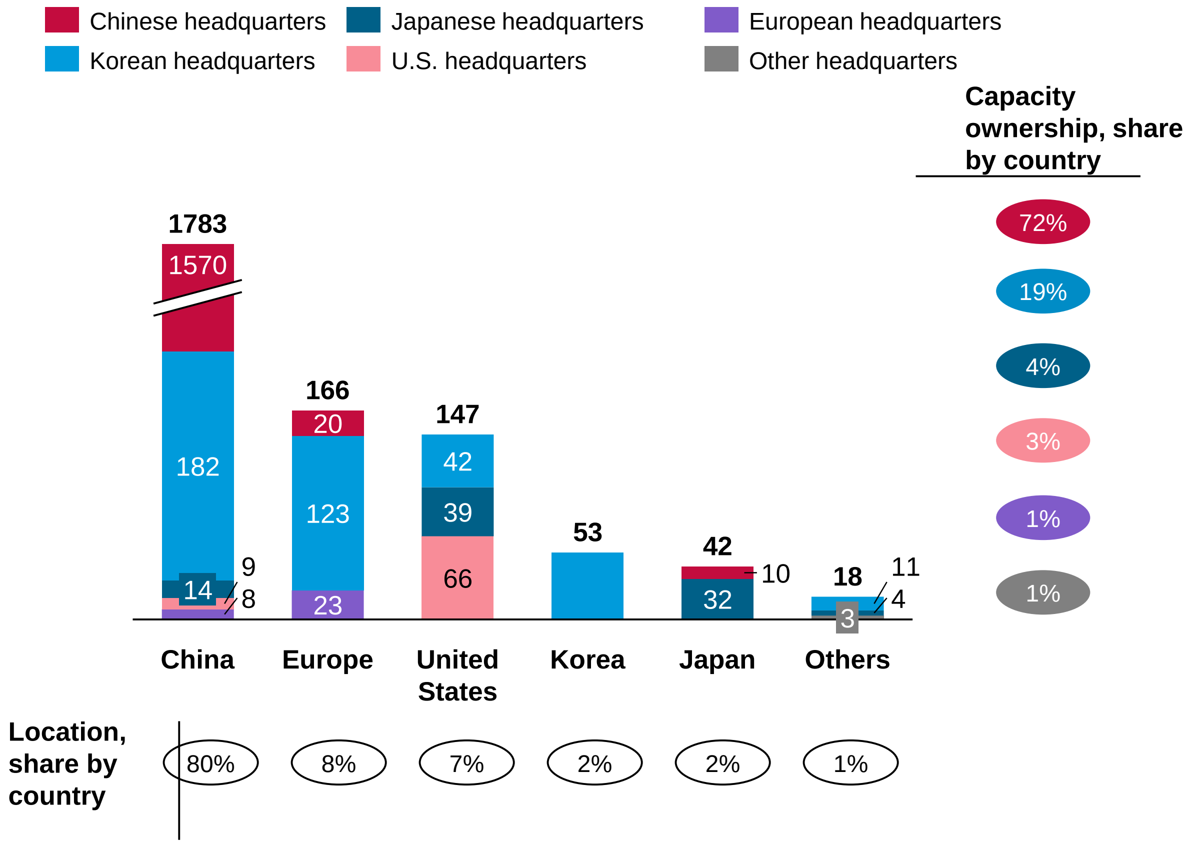
Sources: IEA, Global Supply Chains of EV Batteries (2022); U.S. Geological Survey (2022); Benchmark Mineral Intelligence; BloombergNEF; S&P Global.
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Battery production located close to demand centers, with 81% in China

Global trade flows for lithium-ion batteries and EVs in 2023



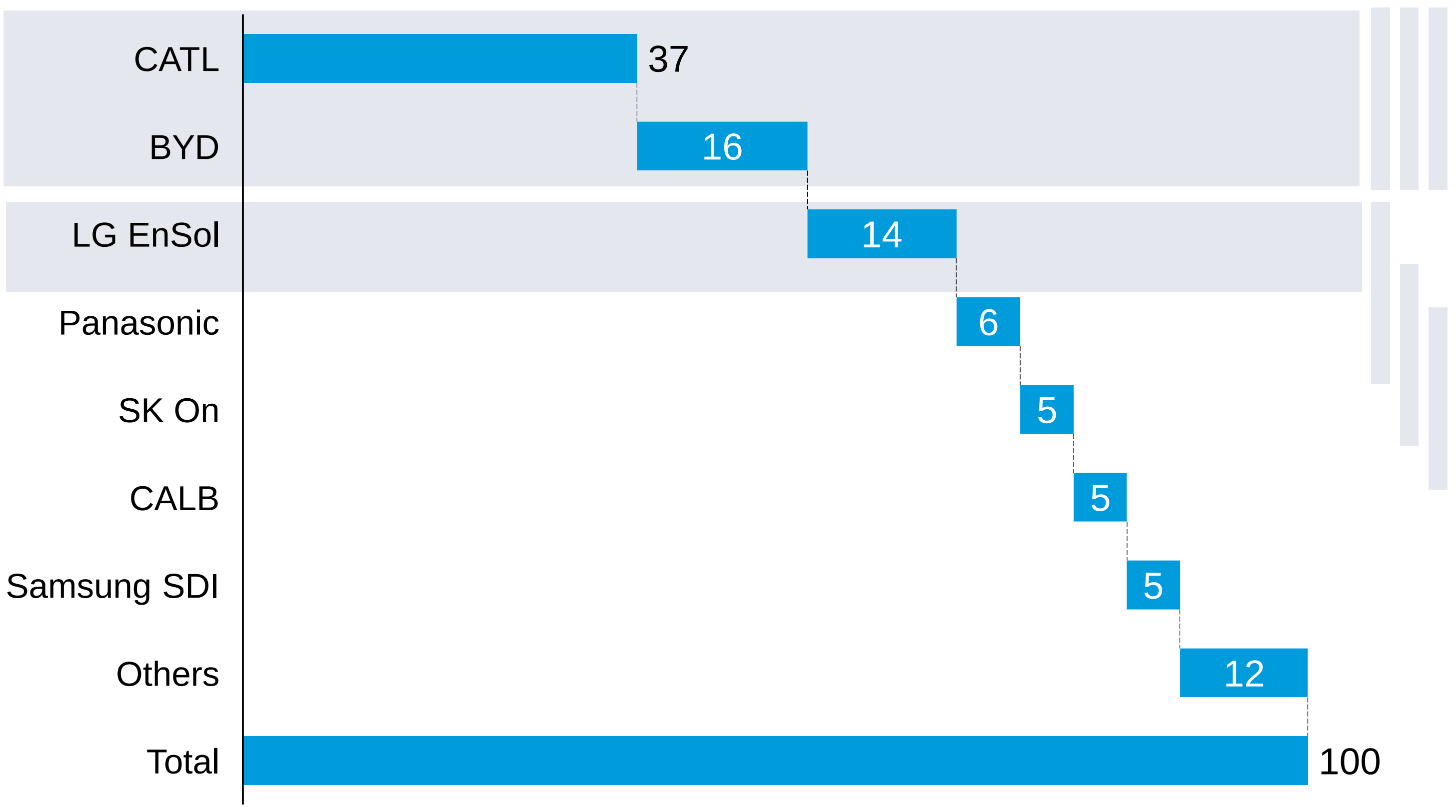
Installed regional Li-ion battery cell manufacturing capacity by location in 2023, GWh



Source: IEA, Global EV Outlook (2024).
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

With significant recent investments in batteries, top 10 companies currently dominate 94% of the market

Split of major battery makers globally in 2023, %



Recent news from the major players:

CATL vs. BYD

- China's Contemporary Amperex Technology Co., Limited (CATL), the world's leading EV battery manufacturer, has announced plans to reduce battery costs by up to 50% this year, engaging in a price war with FinDreams, a subsidiary of Build Your Dreams (BYD), China's second-largest EV battery producer.

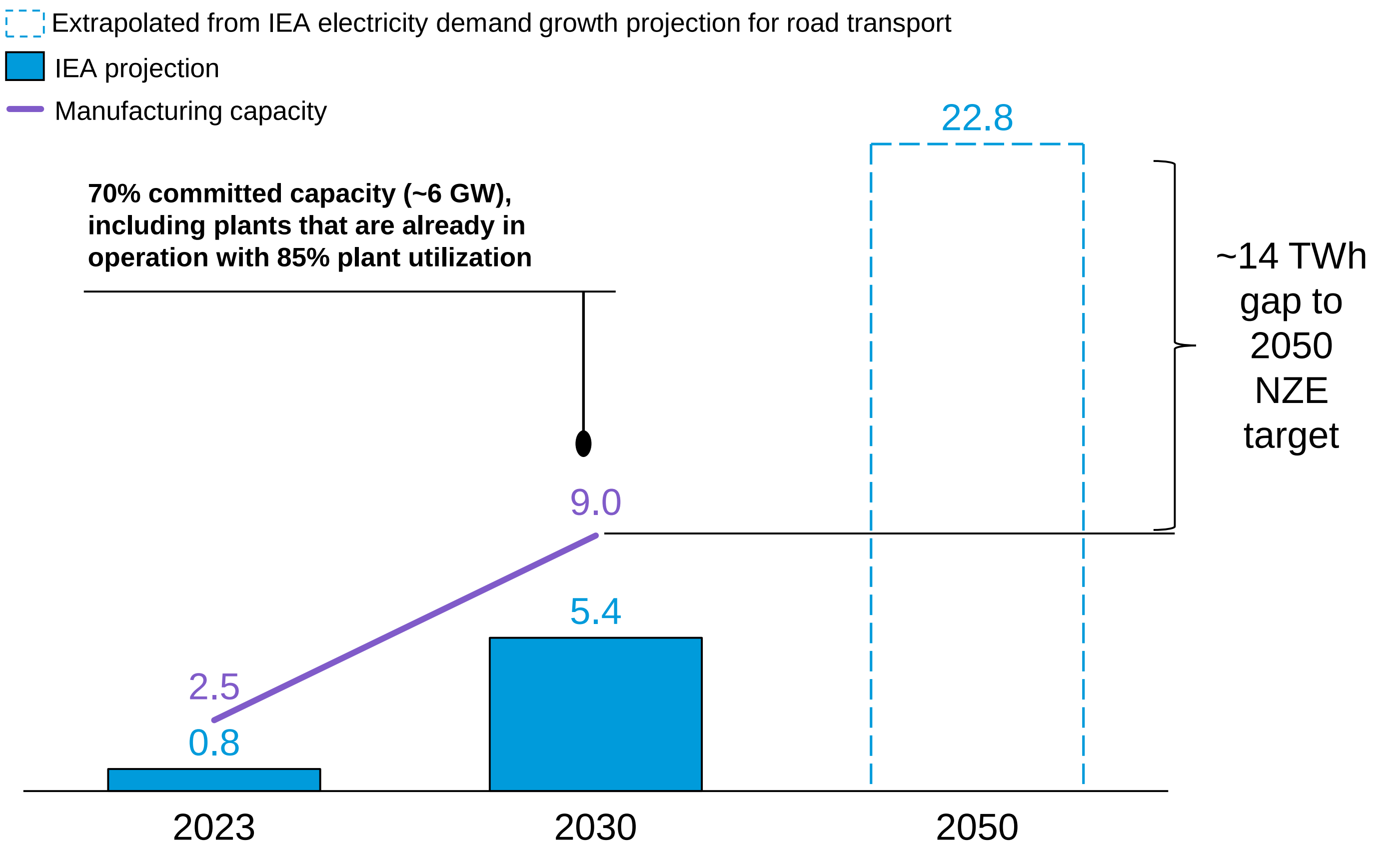
LG EnSol

- LG Energy Solution (LG EnSol) is expected to expand its market share in the United States through its collaboration on Ultium Cells, a joint venture with General Motors, alongside other CapEx investments in the United States.
- LG Chem will invest KRW 6 trillion in expanding battery material production capacity by 2025 to meet the rising demand for batteries. Additionally, it aims to establish anode material factories in Gumi, Korea, by 2026, with a target production capacity of 260,000 tons.

Sources: IEA, Global EV Outlook (2023); IEA, Electric Vehicles; LG Energy Solution, Beyond Carbon Neutrality; Battery Inside, Battery-Powered Future (2022); SNE research, SNE Research, January Global Monthly EV and Battery Monthly Tracker (2024); Energy Post, China's CATL.
Credit: Devashri Mehrotra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Battery oversupply challenge through 2030; additional investments needed to reach NZE by 2050

Energy storage demand vs. planned capacity, TWh



Observations

- In **China**, the total planned battery manufacturing capacity by 2030 is more than double **the domestic demand under the Announced Pledges Scenario (APS),** allowing the export of both batteries and battery-equipped EVs manufactured in the country.
- In the **U.S. and EU**, current and committed battery manufacturing capacity is nearly enough **to meet the projected demand** under the APS by 2030.
- Companies operating in the U.S. and EU will need to rapidly scale up production and prove **cost competitiveness to fully or largely satisfy** their **domestic demand.**
- Over **40% of China's planned manufacturing** capacity is based on the **expansion of existing facilities.**
- **In the U.S. and EU, meanwhile, 80% of planned manufacturing capacity** will come from **new plants**, with new companies expected to enter these markets in the coming years.

Source: IEA, Global EV Outlook (2024).
Credit: Devashri Mehrotra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

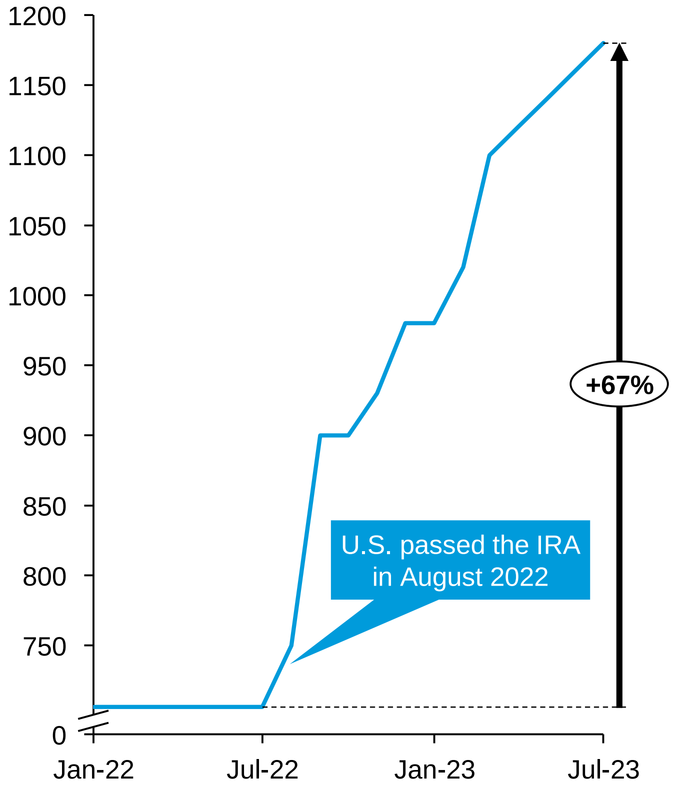
Inflation Reduction Act boosts U.S. gigafactory investments, with a nearly 70% increase in the first year alone

IRA provides subsidies on both the supply and demand side to support a supply chain expansion…

Focus areas	Policy details
Battery and EV manufacturing	• **Qualifying Advanced Energy Project Credit of up to 30%** on battery projects' capital costs, capped at $10 billion • **Advanced Manufacturing Production Credit (45X credit):** – **10% of production costs** for battery mineral manufacturing – **$35/kWh** for domestically produced battery cells, $10/kWh for domestically produced battery modules
EV sales	**New Clean Vehicle Credit (30D credit):** $7,500 for EVs that meet certain requirements with regards to the share of critical minerals that are mined, processed, or recycled within the U.S. or by a country with a free-trade agreement and share of components that are manufactured or assembled in the U.S.
Charging infrastructure	**Alternative Fuel Infrastructure Tax Credit (30C credit):** • Residential charging: Credit for up to 30% of the item's cost, capped at $1,000 • Fleet charging: Credit for 6% to 30% of the property cost, capped at $100,000
Battery recycling	**No specific incentives for battery recycling**; however, recycled battery materials are eligible for the Clean Vehicle Credit

…resulting in a 67% increase in gigafactory investment since 2022

U.S. gigafactory investment pipeline, GWh

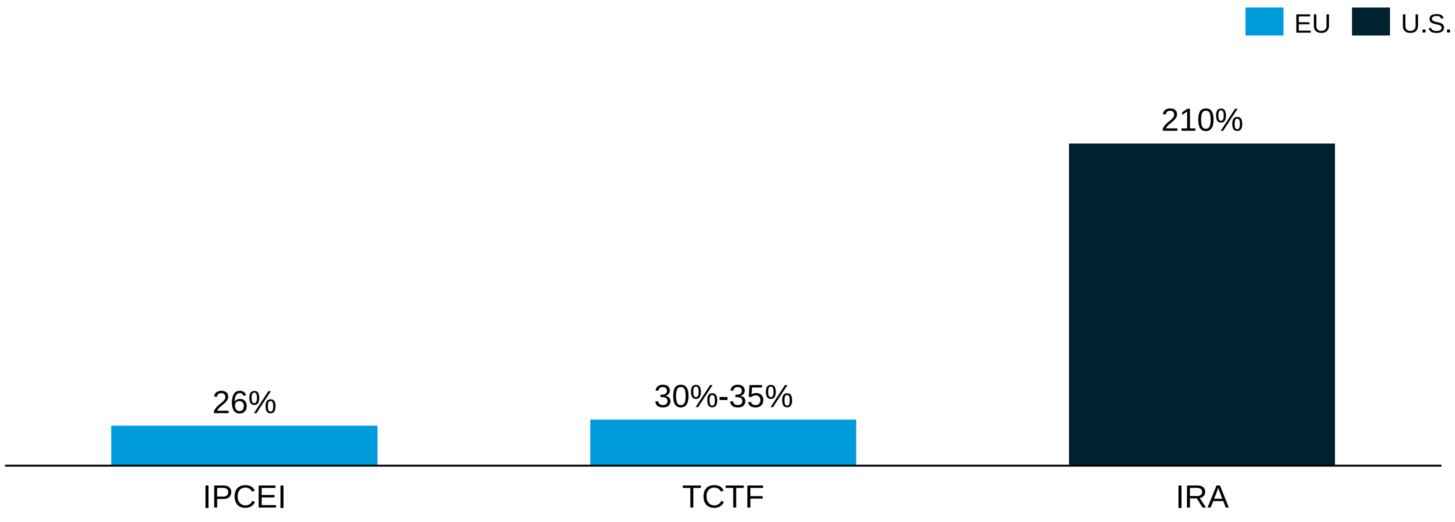


Observations

- **The CapEx cost of building gigafactories in the U.S. is about 30% higher than in China,** a gap the IRA has strategically addressed.
- Automakers and battery producers could get more than **$140 billion in benefits from battery production tax credits** over the next decade, with **Tesla and Panasonic** likely to be the main beneficiaries.
- However, **the U.S. still lacks battery recycling mandates**, which are critical to ensure that raw material supply is sufficient long term.
- The U.S. also has various grants under the Department of Energy to **support R&D in battery technology and EV infrastructure.**

Battery subsidies in the U.S. exceed EU's, but EU gigafactory capacity expected to grow due to market regionalization

Actual and estimated state aid for battery production facilities,
% of total investment in production facilities



Important Project of Common European Interest: Investment subsidy for mass production involving significant innovation; run and funded by participating countries in the EU

Temporary Crisis and Transition Framework: Aid for green tech production facilities capped at a certain percentage of investment costs

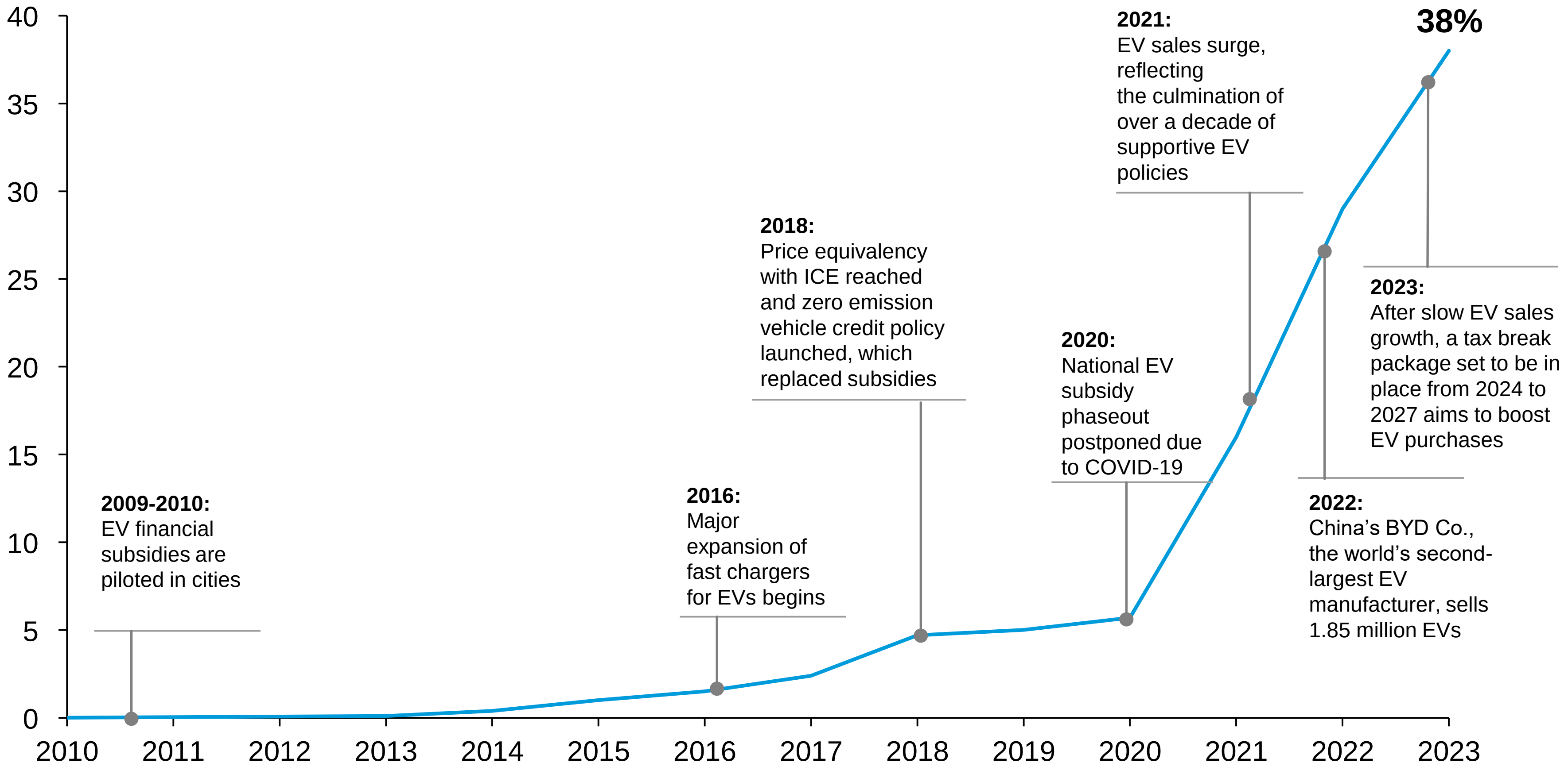
Observations

- U.S. producers have access to considerably larger subsidies than European manufacturers, leading to an estimated **1,000 GWh capacity** expected **by 2030** (from 70 GWh in 2023). Partners that committed to investments include:
  - Tesla, Our Next Energy, Ultium Cells (General Motors and LG Energy Solutions JV), SK On, and StarPlus Energy (Stellantis and Samsung JV)
- Although more public support is available in the U.S., **battery production in the EU will continue to grow, with 1,375 GWh capacity expected by 2030** (from 110 GWh in 2023), driven by:
  - Regionalization of battery and car markets, to avoid supply chain disruption.
  - The EU's plan to phase out new ICE sales by 2035, which will boost battery demand.
  - Potential for significant bottlenecks in U.S. production, including labor shortages, limited access to materials, and lengthy permitting processes.

Sources: Menon Economics, Battery subsidies in EU, Norway, and U.S. (2023); IEA, Global EV Outlook (2024).
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

China has spent the past 15 years focusing on EVs, enabling rapid growth and allowing EVs to capture ~40% of the car market

EV sales as a percent of all automobile sales in China, %



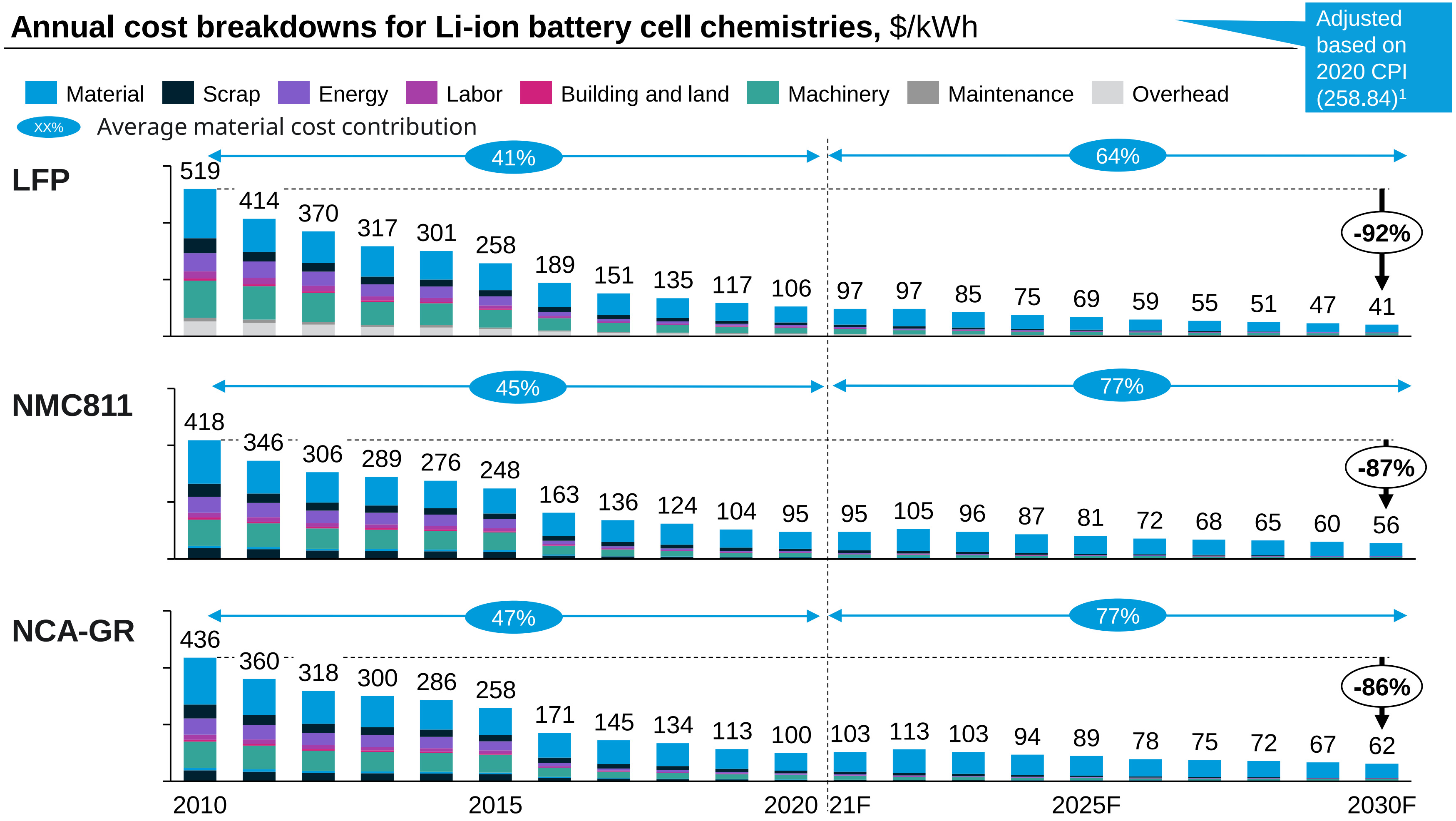
Observations

- Through a 15-year concerted policy effort, China has been able to rapidly dominate the EV market.
- China's supply-side policies include:
  - **$29 billion in subsidies for EV and battery manufacturing**
- China's demand-side policies include:
  - **Financial and tax breaks** for EV consumers since 2009
  - The **zero-emission vehicle credit system**, which has provided credits for manufacturers since 2018
- Other factors:
  - **760,000+ fast public chargers** and **1 million slow public chargers** installed
  - **2,000+ battery-swapping stations installed**
  - Control of over **80% of global raw material refining capacity**

Sources: IEA, Global EV Outlook - Policy Explorer (2024); WRI, Countries Adopting EVs (2023); MIT Technology Review, How did China come to dominate the world of electric cars? (2023); Berkeley Law, China Dual Credit Policy Brief (2022); IFC, Assessment of PLI scheme on EV manufacturing in India (2024).
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Technology advancements continue to drive cost declines, with material costs remaining the most important factor

Annual cost breakdowns for Li-ion battery cell chemistries, $/kWh



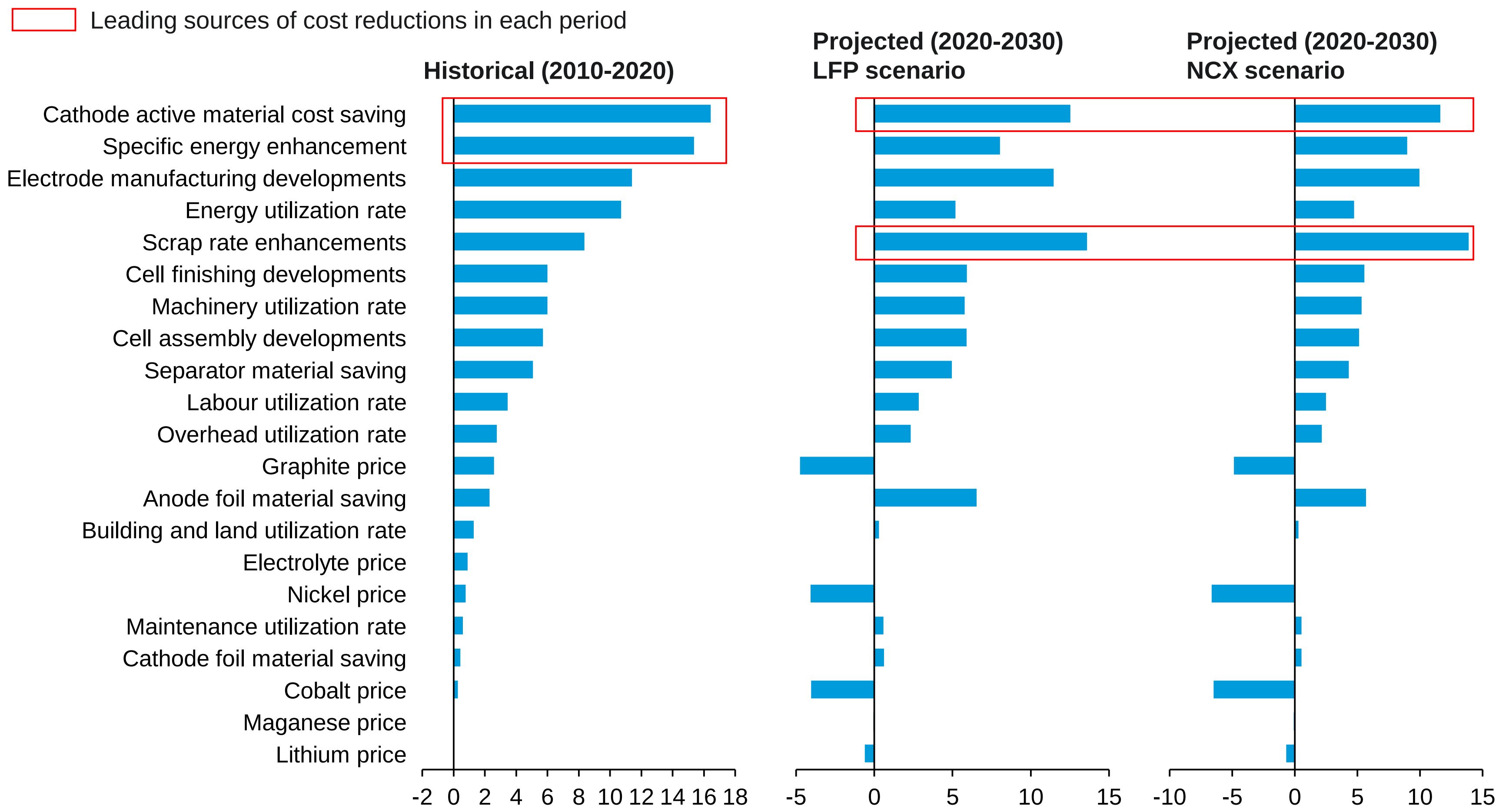
Observations

- By 2030, cell costs are anticipated to drop by more than **85% compared with 2010,** not including material costs.
  - This shift will likely be driven by **technological advancements in manufacturing, increased production volume**, and **improvements in cell performance.**
- As a result of this shift, **material costs will become a growing portion of overall cell costs** (both due to a decrease in total costs and an increase in material costs**).**
  - **LFP** is expected to **continue to be the cheapest battery chemistry (~$41/KWh)** through 2030. While the technology has relatively high machinery costs, it has **the lowest material costs (~$27/KWh).**

1) CPI assumes index 1982-1984 to be 100; Note: NMC811 and NCA-GR are two.
Sources: Journal of Energy Storage, Lithium-ion battery cost (2024); Federal Reserve Bank of St. Louis, Consumer Price Index.
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Material costs projected to grow; savings in other areas expected to contribute to an overall decline in battery costs

Factors influencing cost declines of Li-ion batteries and their contributions, %



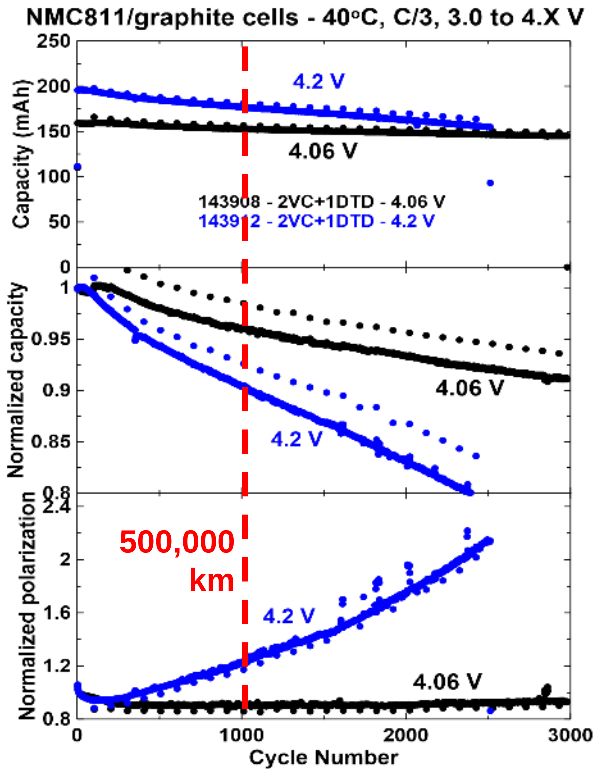
Observations

- From 2010 to 2020, efforts to thin separator, anode, and cathode foils led to **cathode active material (CAM) savings,** becoming the largest source of cost declines (16.4%), followed by **specific energy enhancement** (15.3%).
- But in the future, **scrap rate improvement** is expected to lead the downward cost trajectory from 2021 to 2030 (~14% cost reductions in both scenarios).
  - Technological enhancement will **outweigh the anticipated cost increase from price increase in some of the critical materials,** such as graphite, nickel, and cobalt, resulting in a **continued decline in cell cost.**

Source: Journal of Energy Storage, Lithium-ion battery cost (2024).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

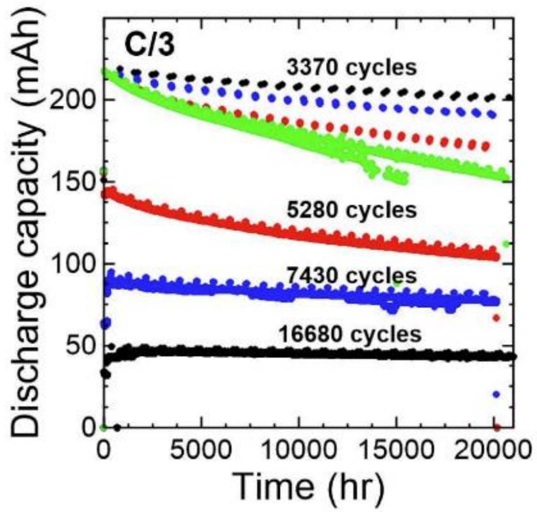
Battery lifetime can be extended by limiting full charging and deep discharging, unlocking second-life repurposing of EV batteries

Charge level impact on capacity



100% Charge level
80% Charge level

Depth of discharge impact on capacity



100% Depth of discharge
75% Depth of discharge
50% Depth of discharge
25% Depth of discharge

Observations

Battery life can be extended by:

- **Charging to 80% or less.** Limiting charge voltage to 4.06V (a charge of around 80%) allows batteries to retain 90% or more of their original capacity, even after 10 years of use or around 3,000 cycles (the equivalent of 500,000 km of typical EV use), as shown in the NMC811/graphite cell data (left).
- **Taking EVs out for short but frequent drives.** Smaller depth of discharge cycles (e.g., 25% or 50% DOD) significantly extend battery lifespan. Testing shows that at 50% DOD, batteries can last up to 7,430 cycles, and at 25% DOD, they can last even longer, up to 16,680 cycles. This suggests that frequent short drives followed by charging are better for battery longevity compared to infrequent, deep discharges.
- Careful usage practices may allow battery lives to be extended by as long as 80 or 100 years past the life of the EV, significantly reducing recycling need, as second-life repurposing in areas like grid integration would be unlocked.

Source: Jeff Dahn, Dalhousie University
Credit: Xiaodan Zhu, Jeff Dahn, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Longer battery lifetime outlives EVs, creates opportunity for second use, driving down battery lifetime costs

Proof of concept: BESS created from second-life EV batteries

Four different used EV battery cell packs linked with a custom battery management system (BMS) connected to the grid as a BESS:

Chevrolet Bolt

Hyundai Genesis GV60

Tesla Model 3 LFP (CATL)

Tesla Model 3 NCA 21-70 (Panasonic)

Conceptual proof that **used cell packs from different EVs and manufacturers can be linked to create an energy storage system** that can be connected to a building/the grid.

Observations

- Results from Renewable Energy Storage Lab at Dalhousie University (Lukas Swan)
- Four different used EV battery packs, each at varying states of health, have been successfully connected to the grid.
- **It is feasible to connect and use "random" used EV batteries in grid storage applications.**
- Practical considerations include testing battery capacity to ensure reliability:
  - Aim for batteries with at least 70% remaining capacity.
  - Group batteries with similar health states for optimal performance and management.
- Additional considerations before wide-scale implementation include development of a **purpose-built BMS and reliably addressing fire hazard concerns** stemming from repurposing and merging various EV cells into one system.

Source: Jeff Dahn, Dalhousie University
Credit: Xiaodan Zhu, Jeff Dahn, Petr Jenicek, Birru Lucha, Hyae Ryung Kim & Gernot Wagner. Share with attribution: Lucha *et al.,* “Storing Energy” (4 March 2025).

Although EV battery supply currently sufficient, critical mineral shortages expected to develop in the coming years

Expected supply*

Base case | High production case | Secondary

Primary supply requirements

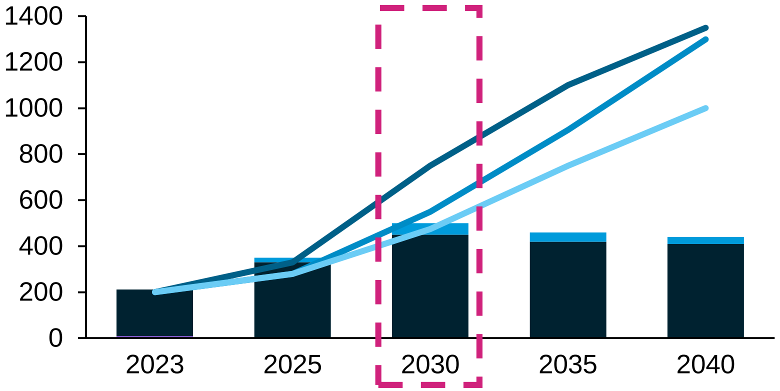
NZE | APS | STEPS

Beginning of shortage under NZE Scenario

Supply and demand balances for critical minerals based on existing and announced projects

Non-exhaustive

Lithium



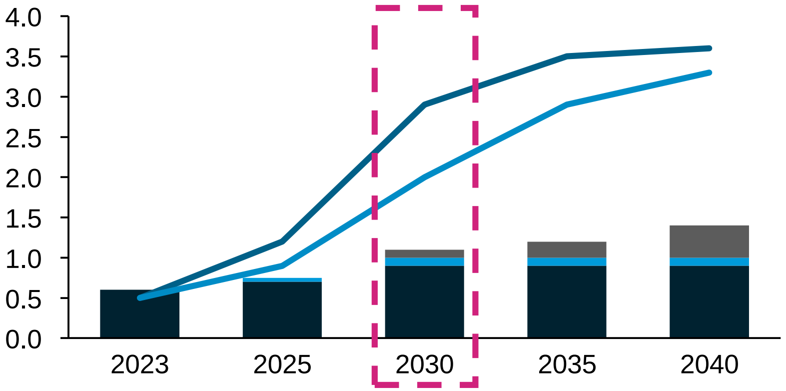
Short-term supply is expected to fulfill the demand, but **more projects are needed to meet the rapid growth** driven by EV expansion.

In the NZE Scenario, demand is expected to reach **1,700 kt by 2050, a tenfold increase** from today's levels.

Lithium is prone to **significant supply risks due to price volatility** and **low deployment of secondary supply and reuse.**

Only 3% of lithium is sourced from secondary supply today.

Nickel sulphate

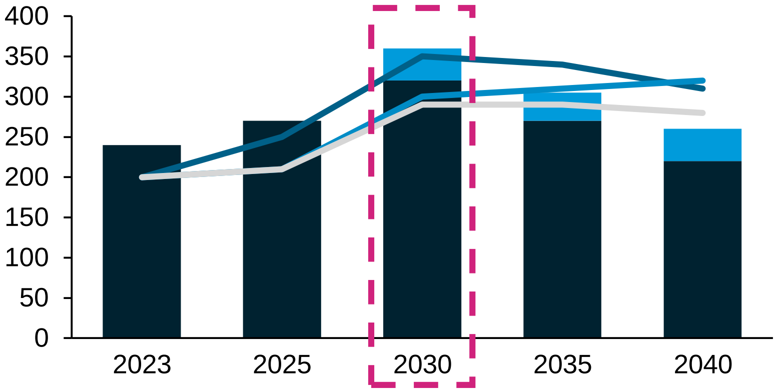


Battery-grade nickel, or **nickel sulphate, may face supply gaps to meet NZE targets**, even help from secondary supply.

New EV designs will likely lead to additional development. The timeline from EV design to production spans around four years, on average, and nickel sulphate capacity scaling takes 18 to 24 months.

One emerging risk worth monitoring is **recent low nickel prices,** which could lead to **further mine closures or the suspension of ongoing projects.**

Cobalt



Even with demand growth slowing due to a preference for low-cobalt batteries, **in the longer term, cobalt supply may fall short of meeting primary supply needs.**

Global mined supply may begin to decline starting in 2030 as **reserves in the DRC deplete**, which strong growth in Indonesia may partly offset.

Future cobalt supply could be threatened as **mining projects are delayed with weak cobalt prices persisting.**

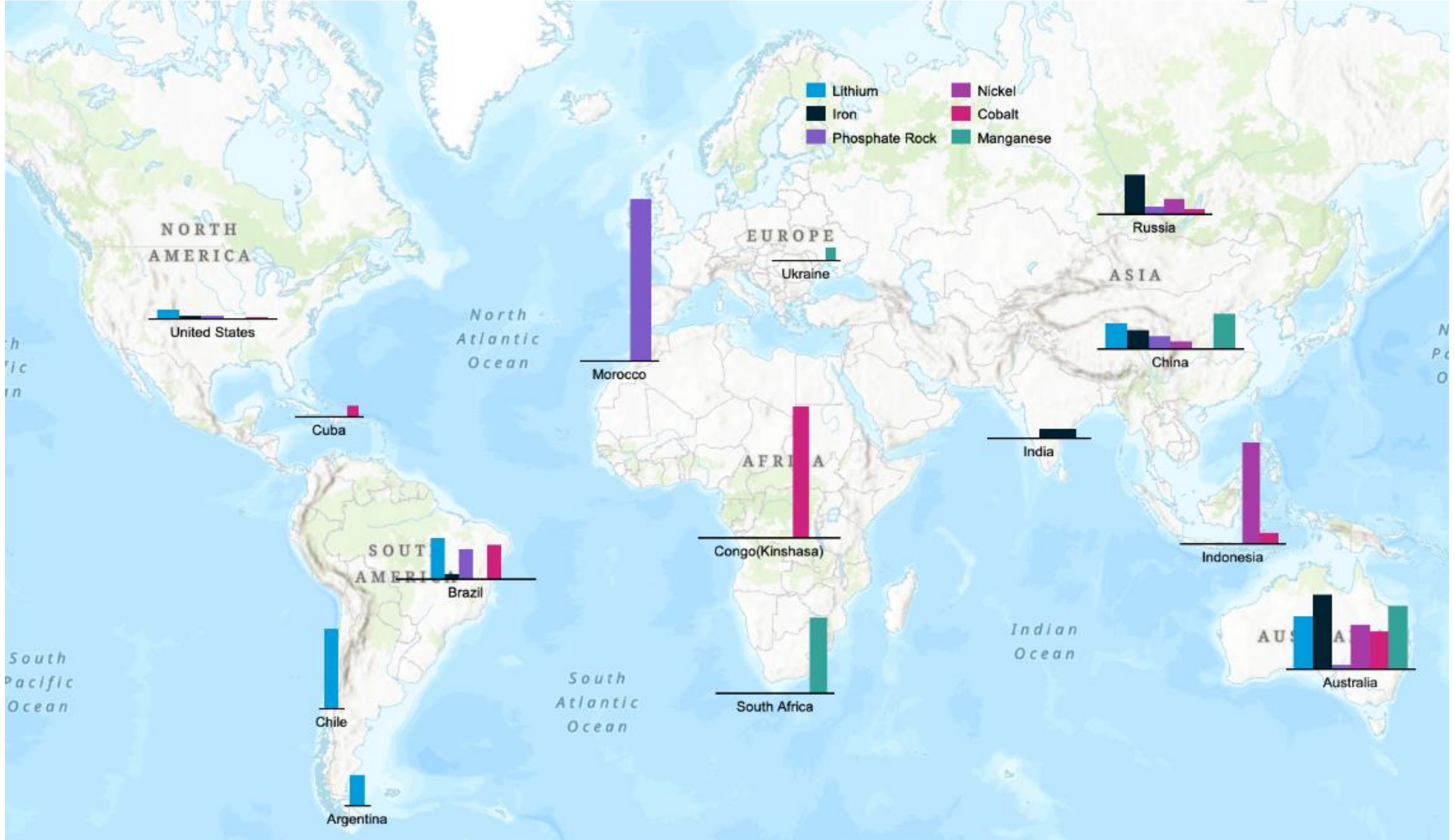
***Base case** includes production from existing assets and those under construction, along with projects that have a high chance of moving ahead, having secured all necessary permits and financing and/or established offtake contracts; **high production case** additionally considers projects at a reasonably advanced stage of development, seeking financing and/or permits.

Sources: IEA, Global Critical Minerals Outlook (2024); Nikkei Asia, Nickel shortage (2024).

Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Critical mineral for batteries widely distributed across continents, with China and Australia having a competitive advantage

Global reserves distribution of battery's critical minerals



Note: The length of the bar in each chart indicates the relative fraction of the total reserve of the respective minerals.

Observations

- **Major reserves of lithium, cobalt, nickel, and manganese,** which are crucial for the global supply, **are found in the U.S., China, Australia, Congo (Kinshasa), and Chile**..
- Vital for energy storage and EV markets, these reserves position the above countries as **key players in the renewable energy transition**.
- **China leads in LFP battery production with all three essential elements** — lithium, phosphate, and iron — available in large quantities. This integration significantly enhances its production capabilities and dominance in the market.
- **For NCM, Indonesia, South Africa, and Congo significantly influence the NCX battery market** due to their substantial shares in nickel, cobalt, and manganese production. Their resource availability is crucial and may impact global market prices.
- Additional sources of critical minerals are being investigated (e.g. lithium extraction from oil and gas brine, offshore cobalt, and nickel and manganese mining in the U.S., Australia, and Canada), as expected price increases enable higher cost extraction business cases.

Nevertheless, battery recycling is likely to play a major role in procurement of critical minerals.

Columbia Business School

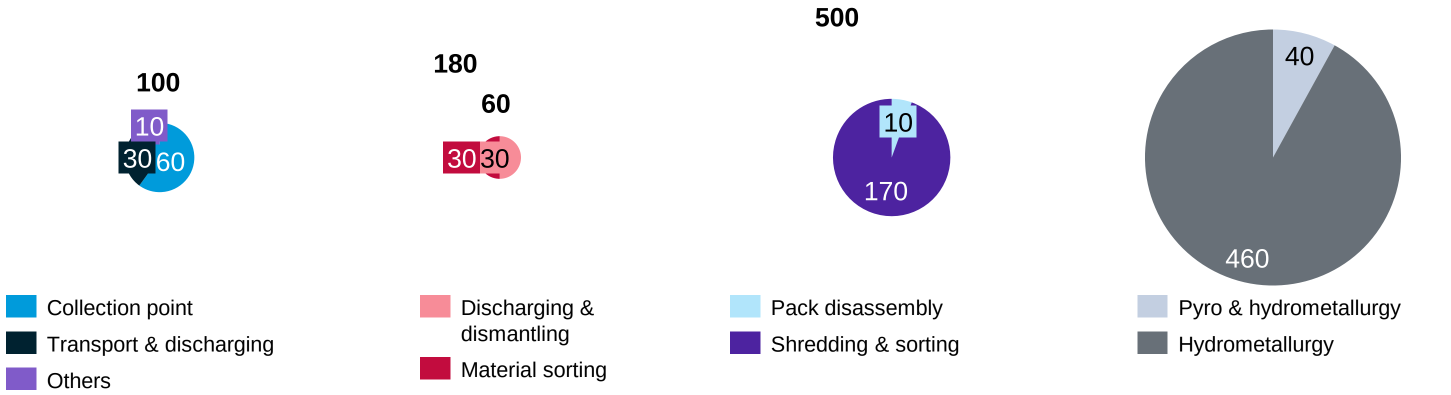
Sources: USGS, Mineral commodity summaries (2024); Statista, Reserves of lithium (2023).
Credit: Xiaodan Zhu, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Achieving profitability in battery recycling challenging due to feedstock shortage and cost advantage of mining

Potential value pool across the value chain

	Collection, logistics, and sorting	Discharge and dismantle	Pretreatment	Battery materials recovery
Business models	Collection point Transport and charging Sorting and warehousing	Discharging and dismantling Material sorting	Pack disassembly Shredding and sorting	Pyro and hydrometallurgy Hydrometallurgy Refining

EBITDA estimate by 2030 in Europe ($M)



	Collection, logistics, and sorting	Discharge and dismantle	Pretreatment	Battery materials recovery
Profit potential	Smaller margin potential but has lower commodity price risk and requires fewer skills.		Activities with low entry barriers, such as shredding, already face overcapacity in part due to a lack of scrap for recycling, resulting in lower margin.	Highest upside potential if given large enough scale and additional value such as new CAM technologies. Steepest entry barriers are due to CapEx and the expert knowledge required.

Observations

- The key EV battery recycling challenge is **feedstock shortages:**
  - Due to extended battery life, recyclers supplement their supply with waste material from battery cell manufacturing. However, **scrap rates are expected to fall** as battery manufacturers improve production efficiency.
  - Having battery manufacturers as both key suppliers and primary customers, recycling companies are facing **massive margin pressure from both sides of the market.**
- **Lack of scale** makes it **difficult for recyclers to compete with incumbent raw material producers**, given that the core recycling technologies are not fundamentally different from primary material processing.
- While battery recycling is essential for creating a circular supply chain, **making a profitable business case is challenging.**
- Traditional recycling players are advised to compete for the **overall materials recovery** profit pool, not just the front-end
  - Building **a cross-value-chain ecosystem through partnerships** can be an option
  - Investing in **technologies** that bring **better material recovery rates, product quality, and process efficiency** is essential to be chosen by OEMs

Sources: BCG, Striking Gold with EV Battery Recycling (2023); McKinsey, Battery recycling (2023); Catalyst podcast, World of battery recycling (2024).

Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Players with a closed-loop ecosystem from supplier to customer will survive among currently fragmented business archetypes

Business models across EV battery value chain

Value chain coverage: Collection, logistics, and sorting → Discharge and dismantle → Pretreatment → Battery materials recovery

Business model	Value chain coverage	Description	Success factors	Players
Pure collector	Collection, logistics, and sorting	Collection only (independent or OEM-related)	High-coverage infrastructure network Market/factory proximity	
Pure logistics provider	Discharge and dismantle	Collection and discharging Warehouse storage provider	Favorable regulations Decentralized network	
Forward-integrated logistics provider	Collection, logistics, and sorting; Discharge and dismantle	Add-on services beyond logistics, e.g., dismantling/sorting	Same as pure logistics provider and HV certification to discharge	
Black mass (BM) recycler	Discharge and dismantle; Pretreatment	Black mass production from delivered battery packs	Same as pure shredder and sufficient feedstock (>20k Mt)	
Pure shredder	Pretreatment	Black mass production from disassembly to shredding	Cheap energy supply Reliable supply with black mass	VEOLIA
Collection-integrated BM recycler	Collection, logistics, and sorting; Discharge and dismantle; Pretreatment	Collection of EoL batteries and processing to black mass	Decentralized network Shredding feedstock (>10K Mt)	
E2E recycler	Discharge and dismantle; Pretreatment; Battery materials recovery	Full battery recycling from discharging to metal recovery	Technological know-how Established customer network	
Recovery-integrated upstream player	Battery materials recovery	Metals/salts recovery done by (P)CAM/battery manufacturers	Sufficient feedstock for scale economies	
Pure metallurgists/ direct recyclers	Battery materials recovery	Recovery of metals/salts through hydro and pyro metallurgical process	Sufficient feedstock for scale economies and process know-how	SOLVAY
Collection-integrated E2E recycler	Collection, logistics, and sorting; Discharge and dismantle; Pretreatment; Battery materials recovery	Full recycling from collection, discharging to metal recovery	Technological know-how Specialized logistics network	umicore; BHMP

Some OEMs own battery recycling players to ensure a closed loop while maintaining material ownership and supply chain visibility.

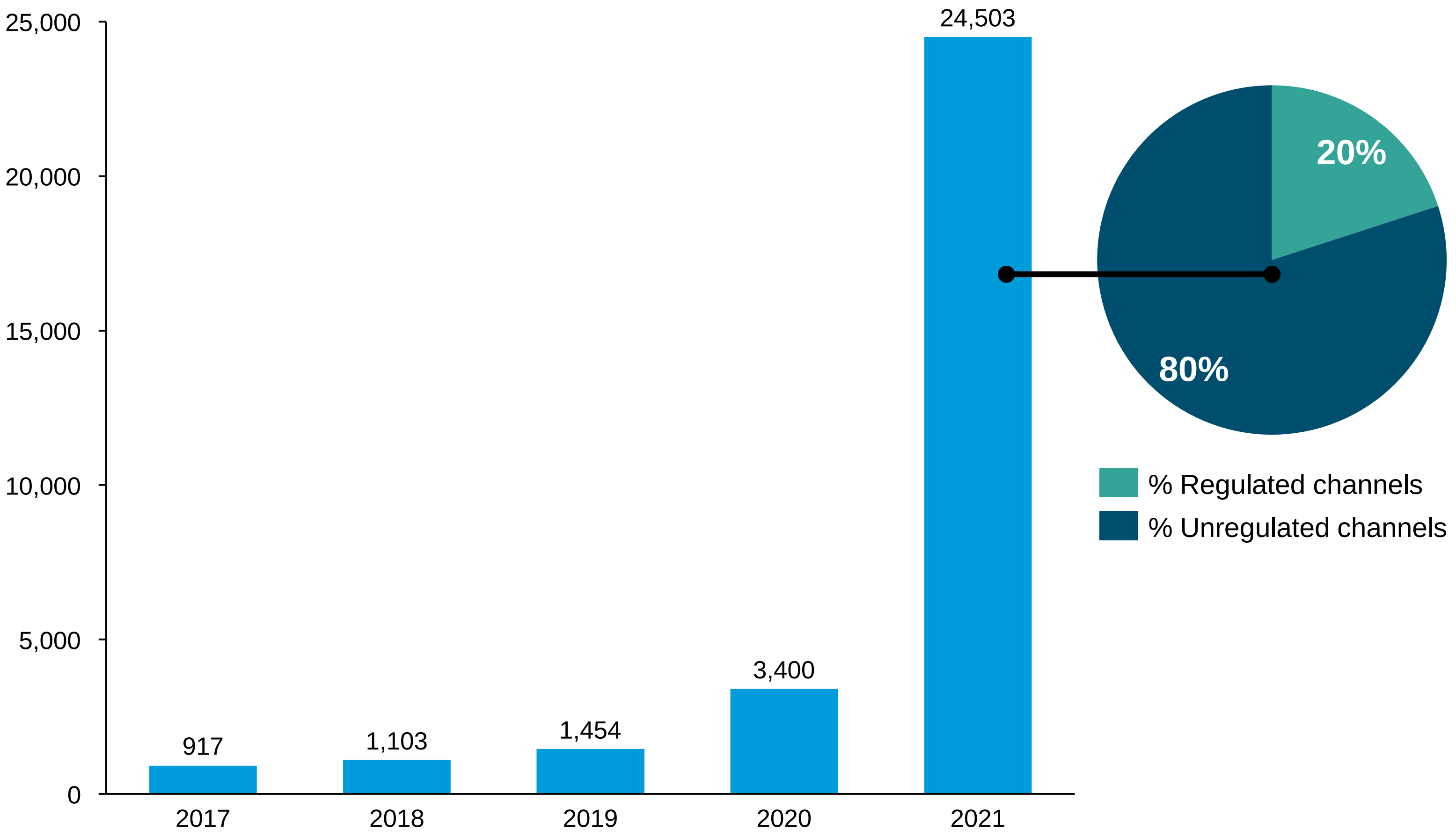
Observations

- Companies are trying to establish a foothold in niches of the market based on existing capabilities.
- Success will be determined by **the ability to forge closed-loop ecosystems.**
  - **Companies can't create competitive advantage with technology alone; supplier and customer relationships are key.**
  - It is critical for smaller players to integrate capabilities into **functioning ecosystems** often formed around **large OEMs and battery cell manufacturers.**

Sources: BCG, Striking Gold with EV Battery Recycling (2023); McKinsey, Battery recycling (2023).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Policies that enshrine recycling responsibilities to OEMs critical for creating robust supply

Yearly registrations of regulated and unregulated EV recyclers in China



Observations

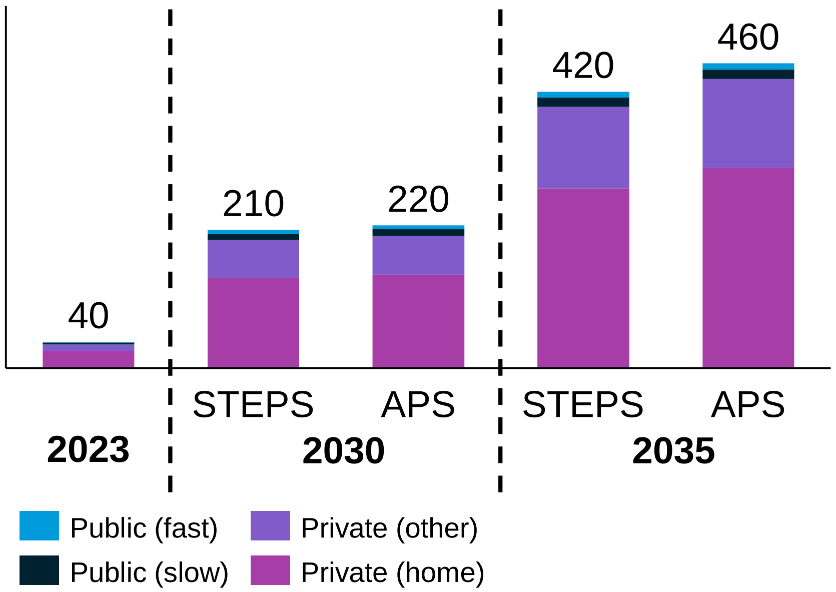
- Under the **2018 policy framework "Provisional Measures on the Recycling and Repurposing of EV Power Storage Batteries," China has enshrined end-of-life recycling responsibilities to OEM manufacturers.**
- This has led to a list of **88 white-listed recyclers** that meet recycling standards proposed by the policy framework. However, these regulated recyclers have been dwarfed by a **rise in noncompliant recyclers.**
- Policy actions to address this concern include:
  - **Subsidies for compliant recyclers** to increase recycled volumes, combined with **cracking down on unregulated recyclers**
  - **A battery leasing model** (e.g., NIO) where batteries are leased from OEMs by consumers, incentivizing OEMs to increase the recycling network
  - **Battery traceability standards** to serialize all produced batteries for government third-party agencies to track (e.g.: **EU Battery Passport policy** announced by the EU in 2023)

Sources: Dialogue Earth, China EV battery-recycling (2023); S&P Global, China new used EV power batteries rules (2024).
Credit: Hassan Riaz, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Extensive charging station investments, including dedicated HDV charging, required to meet growing needs of the ecosystem

Public charging for LDV could increase sixfold by 2035, accelerating EV adoption

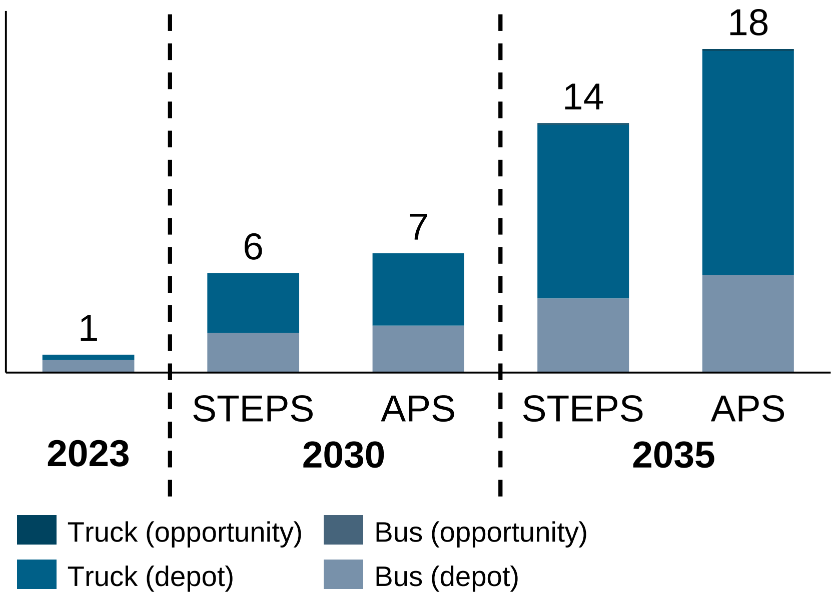
Light-duty vehicle charger stock, Mn chargers



Private (other) refers to charging points that are **neither publicly accessible nor charging points at private residences.**

Overnight depots will drive HDV charging, supplemented by opportunity charging

Heavy-duty vehicle charger stock, Mn chargers



Opportunity charging is the practice of charging a battery in short intervals throughout the day instead of charging it in full all at once.

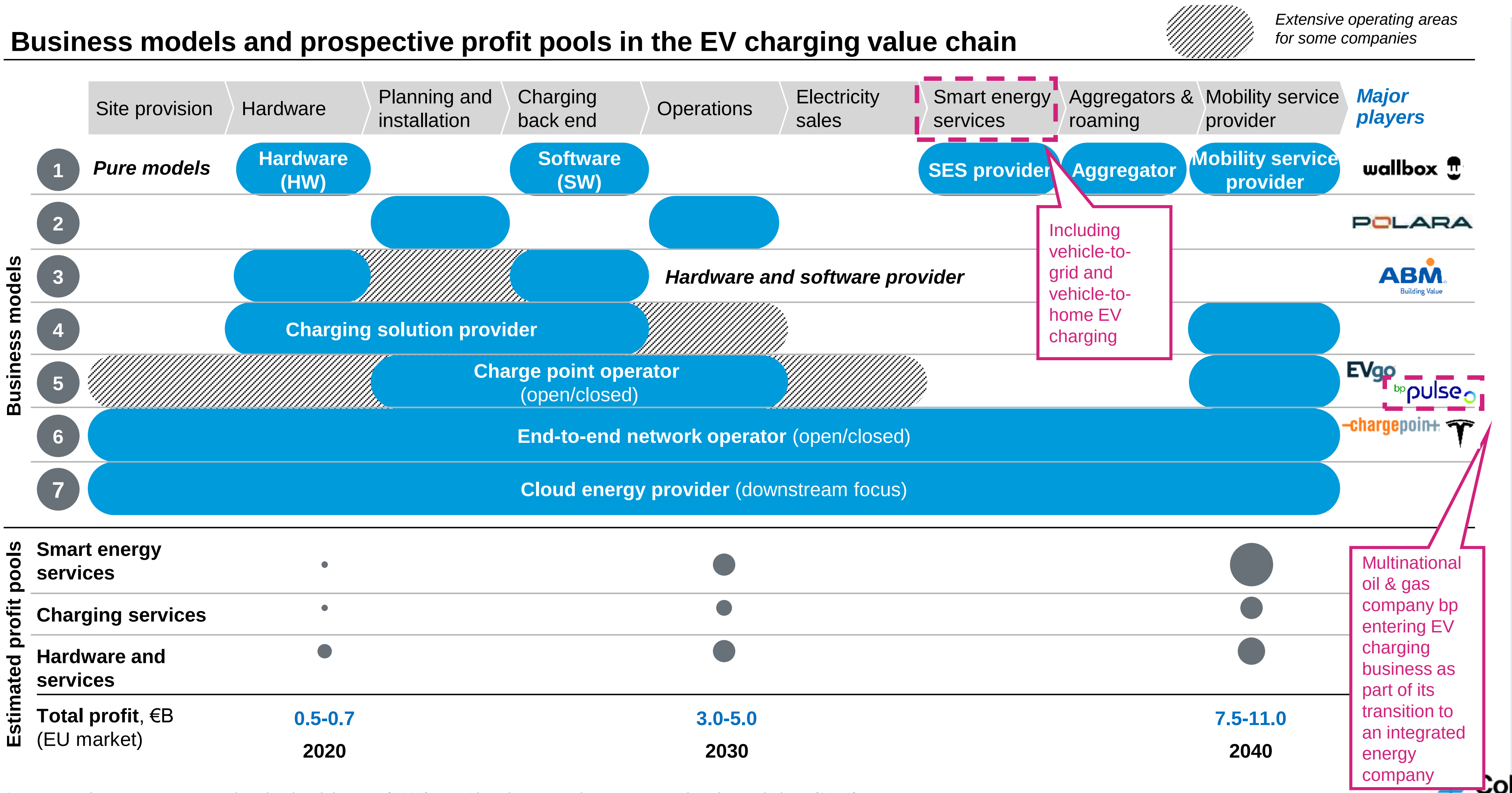
Observations

- **Private home charging (mostly L1[1])** is currently the most common method of charging.
  - Early EV adopters have typically resided in homes with easy and cost-effective access to home charging. Meanwhile, public chargers have predominantly been installed in urban locations.
- **Public charging infrastructure,** particularly fast charging (L2/L3), **must expand significantly** to support broader EV adoption and ensure equitable access.
  - To serve EVs required to achieve zero emissions by 2030, **1.2 million public chargers** need to be constructed and operated by the same year in the United States.
  - By 2035, the share of electricity coming from chargers outside homes is expected to reach almost 45%, compared to less than 35% in 2023.
- **Dedicated HDV charging facilities** are still in the early development and deployment stage.
  - **Mitigation plans for possible challenges** imposed on the electricity grid should be implemented at the same time (e.g., **stationary storage batteries** colocated with high-powered chargers).

1) L1 = slowest option, adding about 3 to 5 miles of range per hour; L2 = faster, adding 20 to 30 miles of range per hour; L3 = fastest option, adding 100+ miles of range in 20 to 30 minutes.
Source: IEA, Global EV Outlook (2024).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Business models that encompass smart energy services most likely to enjoy the largest profits

Business models and prospective profit pools in the EV charging value chain



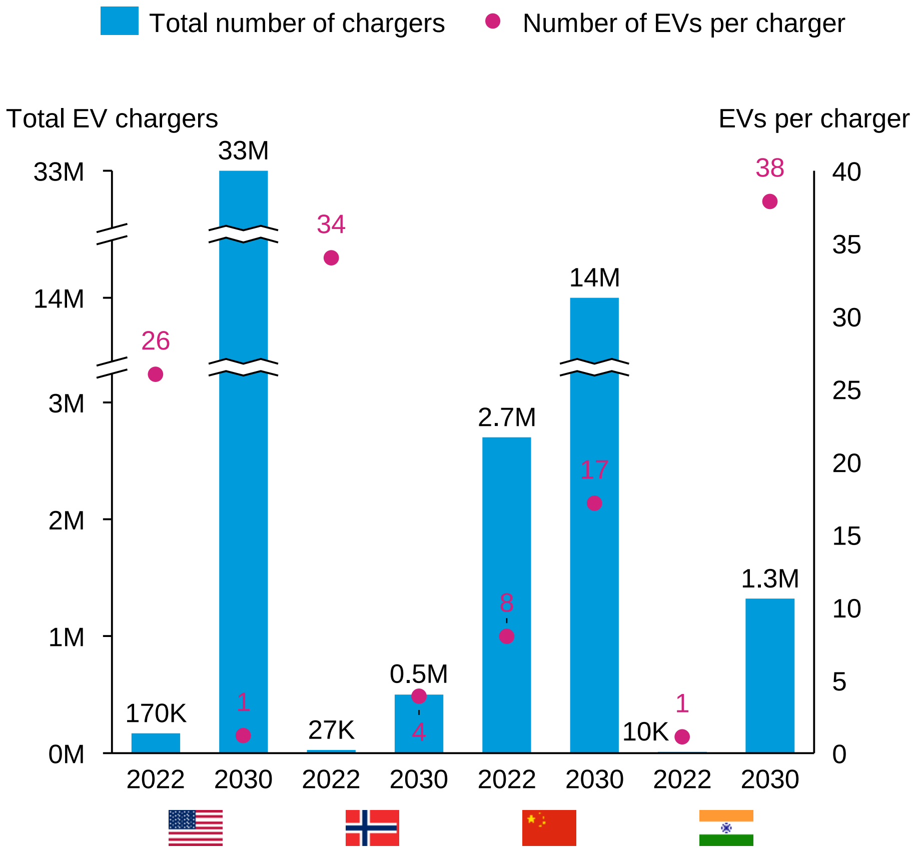
Observations

- **The current capital market prefers integrated models:**
  - Tesla's primary focus is on L3 and seamlessly integrating with the supercharger network (50,000 superchargers globally) and its apps.
  - Other players still mix between L2 and L3, with the main advantage being compatibility for all EVs.
- **The smart energy services** profit pool will grow faster due to a shift from HW to SW.

Sources: Bain & Company, EV Charging in High Gear (2022); EV Charging Summit, Top 20 EV Charging Solutions (2023).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Effective tax policies and incentives to fuel robust infrastructure development critical for ensuring sustainable EV market growth

Chargers and EV-charger ratio across geographies



Policy drivers

United States	Focuses on domestic EV manufacturing with tax credits (IRA). Incentives for charging infrastructure include bidirectional charging tax credits.
Norway	Provides tax incentives (e.g., VAT exemptions) and extensive EV charging infrastructure (34,000 by 2023).
China	Aggressively expands EV and battery production with tax breaks and subsidies. Aims for a 40% NEV sales share by 2030.
India	PLI scheme promotes domestic manufacturing. Goals include 15% passenger EVs by 2030 and significant investment in battery capacity.
EU	Prioritizes sustainable mobility, battery recycling, and raw material supply. Targets 30 million passenger ZEV stock by 2030.

Observations

- **EV-to-charger ratio reflects market maturity:**
  - A declining ratio in the United States and Norway indicates mature markets where policies and infrastructure align to support widespread EV adoption.
  - India and China show higher ratios, with EV sales outpacing infrastructure, reflecting markets in the promotion phase.
- **Impact of tax and policies:**
  - Norway leads with effective incentives like VAT exemptions, toll discounts, and free parking, which is driving infrastructure optimization and high EV adoption.
  - U.S. policies under the Inflation Reduction Act focus on incentivizing domestic manufacturing and private charging infrastructure, resulting in significant progress by 2030.
  - India and China focus on subsidies and production-linked incentives (PLI) to accelerate EV sales but need to prioritize infrastructure growth.
- **India's infrastructure challenges:**
  - India's high EV-to-charger ratio reflects the need for aggressive investment in charging infrastructure to match its growing EV market.

Sources: Statista, EV chargers (2023); Statista, EVs per charger (2023); Statista, EV charging infrastructure U.S. (2024); Statista, Norway EVs (2024); NREL, National Charging Network (2023); IEA, Global EV Outlook (2023).
Credit: Xiaodan Zhu, Petr Jenicek, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

The energy storage opportunity

Mobility energy storage

Technology landscape

Opportunities and unlocks

Case study

Utility energy storage

Contemporary Amperex Technology Co. Ltd. (CATL) is a global leader in battery production based in China

Overview

CATL is the world's largest EV battery producer, holding around **37%** of the global market in 2023. With 2023 production capacity exceeding **165 GWh,** future goals are to quadruple production to 600 GWh by 2025.

Technology and market

Specialization in lithium iron phosphate (LFP) batteries, which are safer and cost effective, and have longer life cycles

165 GWh — **Has been global leader for seven straight years, capturing 37% of 2023 market share (total 165 GWh)**

30% CAGR — **Capitalized on 30% CAGR in global battery EV market since 2013**

Financials

$2.8B raised — **In 2020, nine investors, including UBS AG and JPMorgan, invested $2.8 billion USD in equity financing (private share placement)**

6x revenue in 2 years — **Large increase in reported revenues from $7 billion to $46 billion from 2020 to 2022**

22.6% gross margin — **22.6% gross margin reported in FY2023 (compared to industry average of 15.76% in the same period)**

Operations

13 plants — **11 domestic and two European (German and Hungarian) production plants, including active material production, cell manufacturing, and assembly**

$1.5B expansion fund — **New fund managed by Lochpine Capital dedicated to capacity expansion in Europe**

$950 million acquisition of Yajiang Mining Development in 2021 to own 100% exploration rights at Dechenonba Mine

Sources: CATL; Financial Times, China's battery giant taps Europe's elite to expand supply chain (2024); S&P Global, CATL buys Chinese lithium mine (2023).
Credit: Hassan Riaz, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

CATL’s trajectory to success began 25 years ago…

- Technological Developments
- Financial Developments
- Operational Developments
- Business Developments

CATL 宁德时代

	First foray into batteries for early gen smartphones	Early R&D in e-mobility accelerated with generous policy support	Massive volume expansion as leading battery supplier for NEVs
Timeline	**1999** – Formation of ATL (ATL Amperex Technology Limited) **2005** – Acquisition by TDK	**2008** – Public demonstration of electric bus fleet at 2008 Beijing Olympics **2011** – CATL founded through spin-off of ATL **2013** – Partnership with BMW to develop all-electric Zinoro **2014** – First international subsidiary in Germany with CATG	**2018** – CATL goes public on Shenzhen Stock Exchange **2019** – JV established with Geely Auto Group (吉利汽车 GEELY AUTO) **2021** – 220 MWh energy storage project in Texas, largest in the world
Highlights	• **1999** – Amperex Technology Ltd. (ATL) acquires technology licenses from American and Japanese companies to produce batteries **2001** – Sales grow to 1 million+ devices • **2005** – Acquired by Japanese firm TDK with specialties in cassette and CDs • **2007** – Early research into batteries for e-mobility explored by ATL	• **2008** – Beijing begins concerted policy effort to grow and nurture nascent EV industry, evident through the first demonstration of a demo electric bus fleet supplied by ATL batteries • **2009** – State issues **“**Ten Cities, Thousand Vehicles**”** policy plan to introduce 1,000 EVs each in 10 cities with CATL’s first foray into batteries for consumer EVs • **2011** – Chinese investors, including Huang Shiling and Robin Zeng, spin off CATL from TDK, to acquire 85% ownership stake • **2013** – Through partnership with BMW, all-electric Zinoro is launched, building additional German engineering expertise • **2014** – CATL eyes international expansion, launches first international subsidiary, in Germany	• **2018** – In addition to official IPO on the Shenzhen Stock Exchange, the first overseas production facility in Erfurt, Germany, is launched • **2019** – Sales of Chinese EVs reach 1 million units per year, 10x from 2013, with CATL being a large beneficiary • **2021** – Milestone in energy storage project with construction of a 220 MWh facility in Texas • **2023** – With launch of new product platforms (e.g., Qilin) and accelerating year-over-year growth in NEVs, CATL is well positioned to lead in the future

Sources: CATL; Quartz, How CATL became the world's biggest electric car battery company (2019); TNI, The new Darwinian world of the energy transition (2024).
Credit: Hassan Riaz, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Through a combination of key differentiating factors, CATL has captured 37% of the market

CATL's keys to success helped it capture 37% of the total global battery market in 2023

Early-mover advantage

CATL's early research, bolstered by technology licenses and state support, was key to developing initial EV batteries.

Strong vertical integration

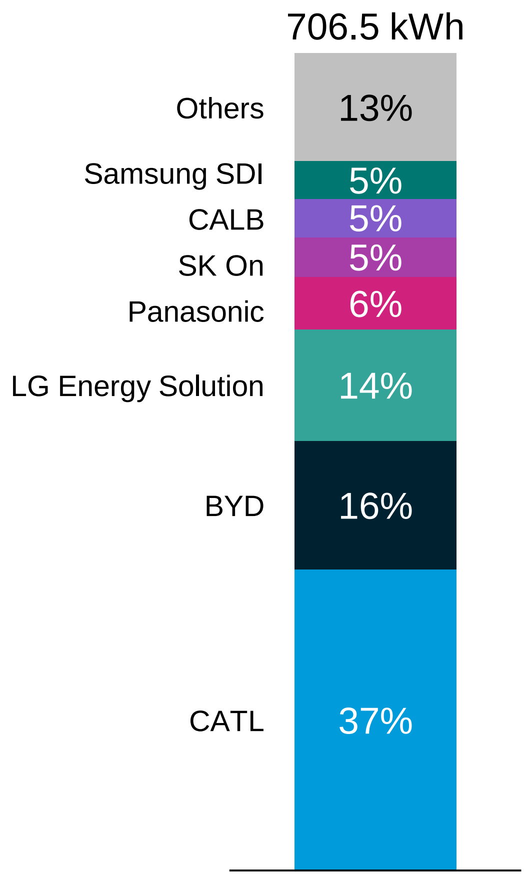
Mining subsidiaries, exploration partnerships, and large purchasing power drives down battery cost structure.

Capitalizing on rapid domestic EV growth

From market growth of 18,000 EVs to over 9 million over the past 10 years, CATL capitalized on exponential market growth.

Product innovation

With 20,000 R&D engineers and scientists, CATL filed 1,061 patents in 2022 vs. BYD's 662.



Observations

- In the early 2010s**, CATL was a small player (<5%)** of the global battery market.
- Specific factors that led to its current widespread success include:
  - Drove down cost of Li-ion batteries by **90% from 2010 to 2023**, leading to market expansion
  - Effective **long-term agreements** with both **domestic and international EV** manufacturers
  - Focus on **core strengths in producing batteries** (BYD, in comparison, also focused on manufacturing NEVs)

Sources: CATL; Insights by GreyB, CATL Patents (2024); SNE Research, Global electric vehicle battery usage (2024); Bloomberg, Dawning Age of the Battery (2020).
Credit: Hassan Riaz, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

The energy storage opportunity

Mobility energy storage

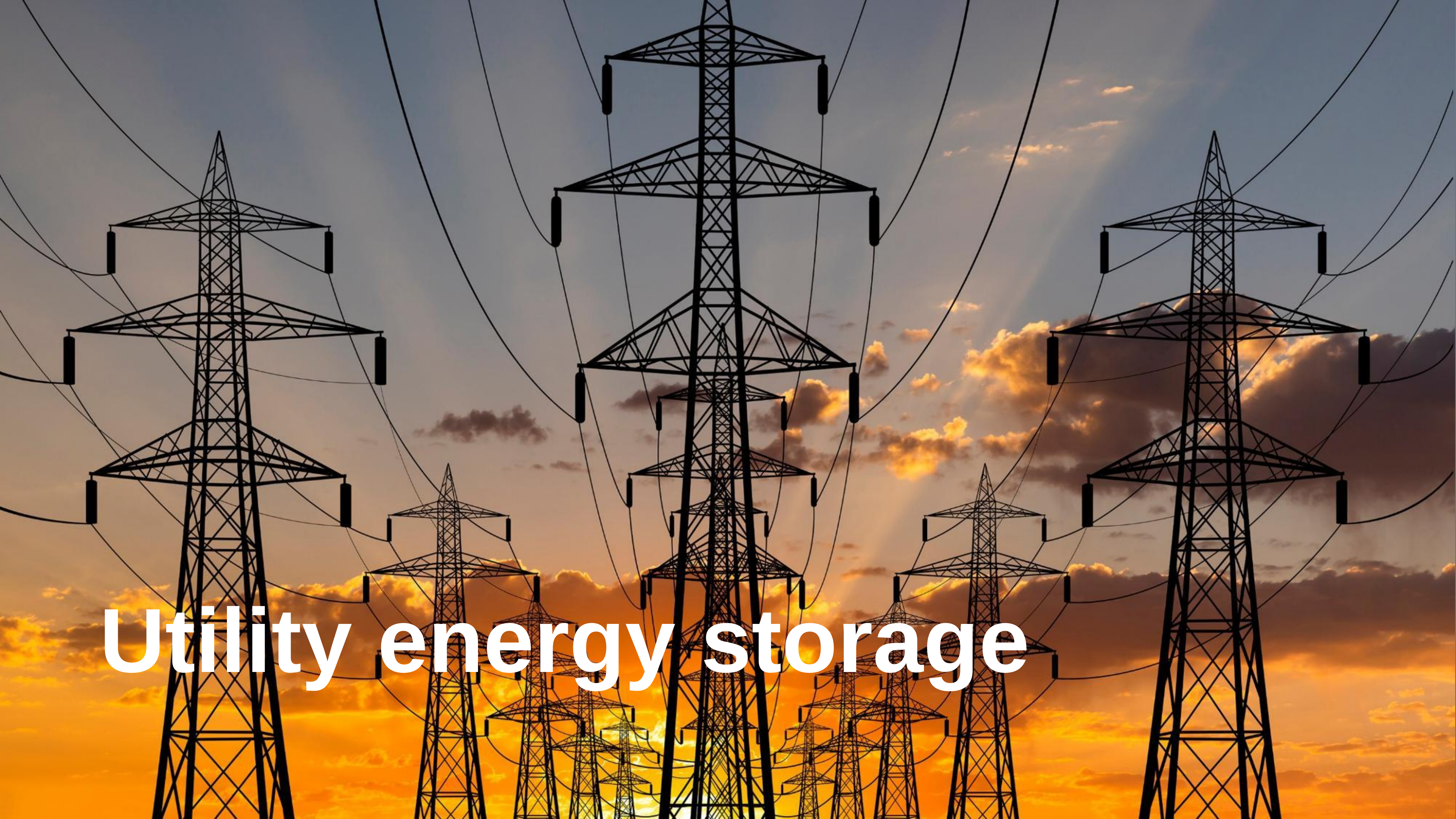
Utility energy storage

Technology

Opportunities and unlocks

Case study

Utility energy storage



The energy storage opportunity

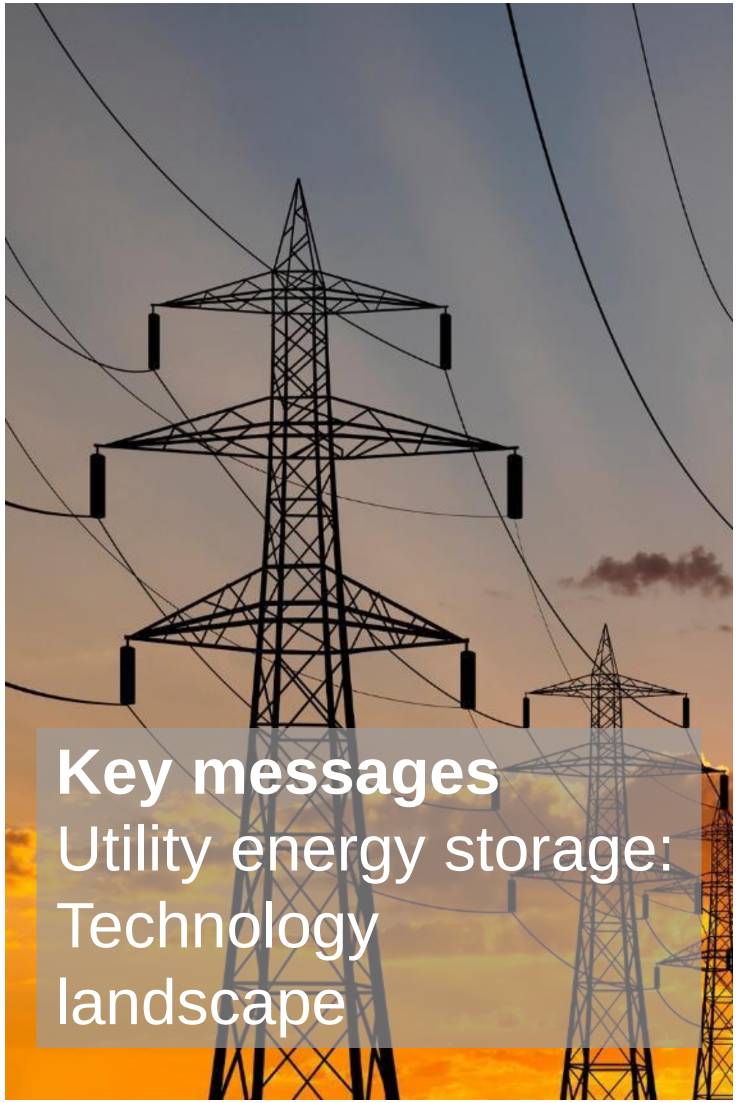
Mobility energy storage

Utility energy storage

Technology

Opportunities and unlocks

Case study



Key messages
Utility energy storage: Technology landscape

Several energy storage technologies are currently available for utility-scale deployment of long-duration energy storage (LDES), each with its own set of advantages: **mechanical** (e.g., pumped hydro (PSH), compressed air (CAES), gravitational storage), **electrochemical** (various battery technologies), **chemical** (hydrogen fuel cell) and **thermal.**

Pumped storage hydropower is currently the most prevalent, commercialized and widely deployed utility-scale storage technology, largely due to its high efficiency, wide range of discharge capabilities and its low green house gas emissions.

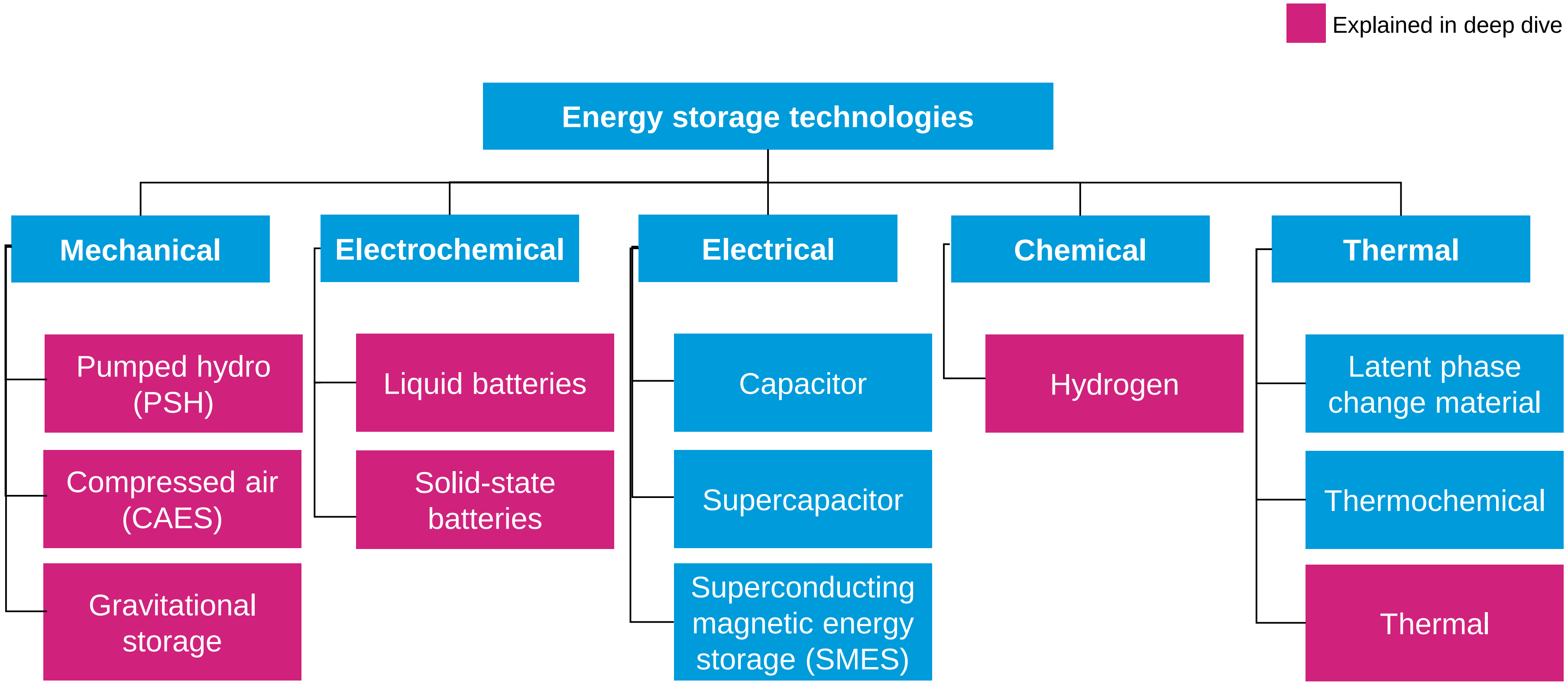
The main downsides of PSH are its **requirements for favorable geographical and geological conditions** as well as its **limited modularity.** Other novel storage technologies are primarily attempting to solve these downsides, with various degrees of success.

- **Discharge duration time:** Discharge duration range varies significantly across different energy storage technologies. However, only **hydrogen and CAES** reach a discharge duration range comparable to that of PSH (up to 24 hours).
- **Lifecycle environmental impact: Thermal storage** is the only technology that beats PSH in total lifecycle GHG emissions. Other technologies fall short of PSH mostly due to a significantly lower total lifetime.
- **Cost: CAES** leads in lowest installed cost ($100-$130 USD/MW) due to the use of preexisting geological formations, with **PSH** second ($250-$300 USD/MW) for the same reason and **Li-ion** battery ($310-$430 USD/MW) third. Further development is needed in the technology space to achieve an LCOS goal of $0.05 USD/kWh to facilitate commercial viability of large-scale LDES deployment.
- **Applicability and modularity:** The applicability of various technologies for LDES at the utility level varies significantly on the scale required and the deployment location. Several **battery technology** systems as well as other **novel storage technologies** offer high modularity and versatility for a wide range of applications. At the current stage, these benefits are not seen as valuable enough to balance out the drawbacks in performance metrics when comparing novel technologies to PSH.

Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Wide range of storage technologies available in the market, each with advantages and limitations

Various energy storage technologies



Observations

- **Mechanical:** Storing energy in physical forms, such as potential or kinetic energy, providing durability and scalability
- **Electrochemical:** Storing energy through chemical reactions, typically offering high energy density and efficiency
- **Electrical:** Storing energy in electric fields or magnetic fields, providing quick response times and high-power output:
  - Current electrical technologies such as capacitors are good for complementary purposes due to their lower energy storage capability (as a result, they will not be highlighted in the Deep Dive).
- **Chemical:** Storing energy in chemical bonds, offering high energy density and flexibility
- **Thermal:** Storing energy in the form of heat, which can be used for various applications including power generation and industrial processes

Sources: Renewable and Sustainable Energy Reviews, Stationary energy storage (2022); MDPI, Supercapacitors: An Efficient Way for Energy Storage Application (1998).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

PSH currently the cornerstone of LDES due to several advantages

Mechanical

1 **Pumped storage hydro and novel (PSH)**

2 **Compressed air energy Storage (CAES)**

3 **Gravitational storage**

	Pumped storage hydro and novel (PSH)	Compressed air energy Storage (CAES)	Gravitational storage
Description	Uses two water reservoirs at different elevations. Energy is stored by pumping water from the lower reservoir to the upper one, typically during off-peak hours, when demand for electricity is low.	Uses electricity to compress air; the compressed air is then stored and later re-expanded to generate electricity.	Excess electrical energy is used to lift heavy blocks onto a large tower. When electricity is required, the blocks are lowered, spinning a motor to generate electricity.
Advantages	Long lifetime, low-cost solution for bulk storage	Does not face fundamental technical challenges	Versatile technology that can be readily deployed at a variety of scales
Barriers	Difficult to finance (long duration times, large size, high and uncertain capital costs); geographical constraint	Availability of suitable, large-scale underground air storage	Supply chain, maintenance, efficiency, and lower lifetime.
Lifetime	50-100 years	30 years	20-35 years
Round-trip efficiency	70%-85%	40%-70%*	70%-90%
Discharge duration at max power	Several hours to days	Several hours to days	Several hours
Cost (LCOS)	Low	Low	Medium
Development stage for utility-scale grid applications	Widely commercialized	Initial commercialization	Initial commercialization

*As CAES can rely on both electricity to compress air and a fuel to expand the air (depending on technology used), its efficiency cannot be directly compared to other storage technologies.
Sources: Greening the Grid, Storage Technologies; MIT, The Future of Energy Storage (2022); ENTEC, Energy Storage Database and Use Case Matrix (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

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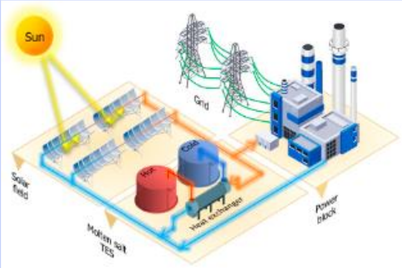
Battery systems the most advanced out of non-mechanical tech

	Electrochemical	Chemical	Thermal
	4 **Battery technologies**	5 **Hydrogen**	6 **Thermal**
			
Description	Interconverted chemical and electrical energy through reduction and oxidation (redox) reactions. These reactions occur on both the positive and negative electrodes connected by an external circuit and frequently separated by electrolyte.	Produced with electricity and stored until there is demand for the stored energy, at which point, the hydrogen is converted to generate electric power.	Systems use electricity to heat up a material, which is then insulated until the energy is needed. The heat is converted back to electricity through a power conversion device.
Advantages	Versatile technology that can be readily deployed at a variety of scales	Ability to scale power and storage capacities independently; use beyond energy storage	Heat can be stored in cheap materials
Barriers	Supply chain, thermal runaway, lower lifetime, support and safety technologies required (e.g. climate control, fireproofing)	High production costs, safety concerns, difficulty storing	Difficulty converting heat back into electricity efficiently and cost effectively
Lifetime	10-20 years	5-30 years	10-50 years
Round-trip efficiency	40%-90%*	20%-40%	55%-99%
Discharge duration at max power	Minutes to days (technology dependent)	Several hours to months	Several hours to months
Cost (LCOS)	Medium to high (technology dependent)	High	High
Development stage for utility-scale grid applications	Commercialized/prototyped (technology dependent)	Pilot stage	Initial commercialization

*Efficiency highly dependent on the battery technology selected.

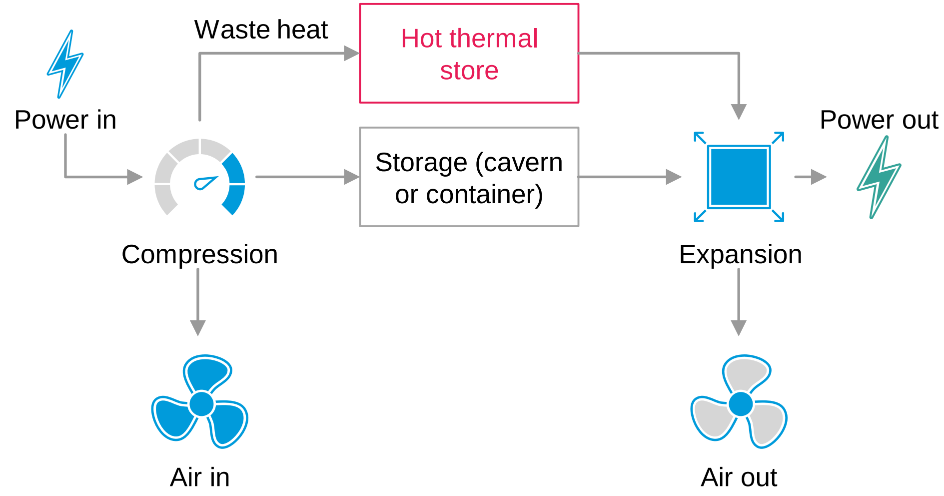
Sources: Greening the Grid, Storage Technologies; MIT, The Future of Energy Storage (2022); ENTEC, Energy Storage Database and Use Case Matrix (2022).

Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

CAES (compressed air) is a proven technology with significant geological requirements, similar to novel PSH

Definition

Excess electricity is used to compress and cool air, which is then stored under pressure either in specialized containers (CapEx intensive) or underground (e.g., In salt caverns). Air can be stored as pressurized gas (CAES) or liquified (LAES). Heat from the compression process can be stored in a separate thermal store for later use. To discharge, heat (from the thermal store or combustion of natural gas) is introduced back into the compressed/liquid air, which is released to spin a turbine and generate electricity.



Technical specifications

Maturity	Initial commercialization
Modularity	Dependent on project (container systems are modular, while systems using salt caverns are not)
Deployment size (MW)	200-500
Nominal duration (hours)	5-48+
Round-trip efficiency (%)	40-70

Use cases

Intraday	Intermittent daily RE generation; Grid stability services
Multiday	Weather-driven outages; Grid congestion
Seasonal	Seasonal imbalances; Long-term outages
Remote or off-grid	Grid stabilization; Backup power

Sample projects

Company	Project	Location	Rated power (MW)	Duration (hrs.)	Status
SIEMENS	McIntosh CAES Plant	Alabama, U.S.	110	26	Operational
HYDROSTOR	Goderich Energy Storage Facility	Ontario, Canada	2	5	Operational

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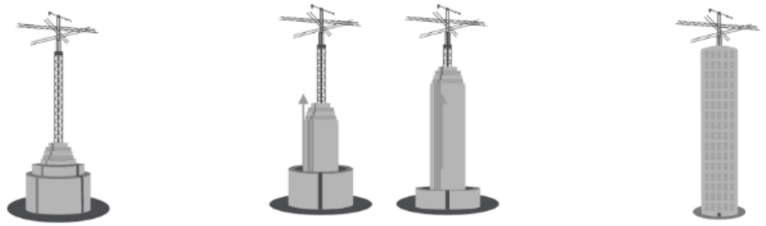
Source: Quidnet Energy
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Gravitational storage stores energy by way of a heavy mass kept at an elevated height, so space is a serious limitation

Definition

Gravitational storage utilizes excess electricity to raise heavy weights, creating gravitational potential energy. When masses are lowered during discharge, potential energy is converted to kinetic energy, turning a turbine and generating electricity. However, only so much energy can be stored per block, making extensive amounts of space a prerequisite for use of gravitational storage technologies.



Fully discharged

Charging/discharging state

Fully charged

Charging

Excess electricity produced by renewables is used to pull weights to the top of the shaft.

Discharging

When electricity is required, the weights are lowered, turning motors and generating electricity.

Technical specifications

Maturity	Pilot
Modularity	Modularity limited by space requirements
Deployment size (MW)	20-1,000
Nominal duration (hours)	0-20
Round-trip efficiency (%)	70-90

Use cases

- Intraday
  - Intermittent daily RE generation
  - Grid stability services
- Multiday
  - Weather-driven outages
  - Grid congestion
- Seasonal
  - Seasonal imbalances
  - Long-term outages
- Remote or off-grid
  - Grid stabilization
  - Backup power

Sample projects

Company	Project	Location	Rated power (MW)	Duration (hrs.)	Status
Energy Vault	EV 1 Tower	Castione, Switzerland	4-8	8-16	Demonstration prototype
Energy Vault	EVx GEE	Rudong, China	25	4-16	In construction

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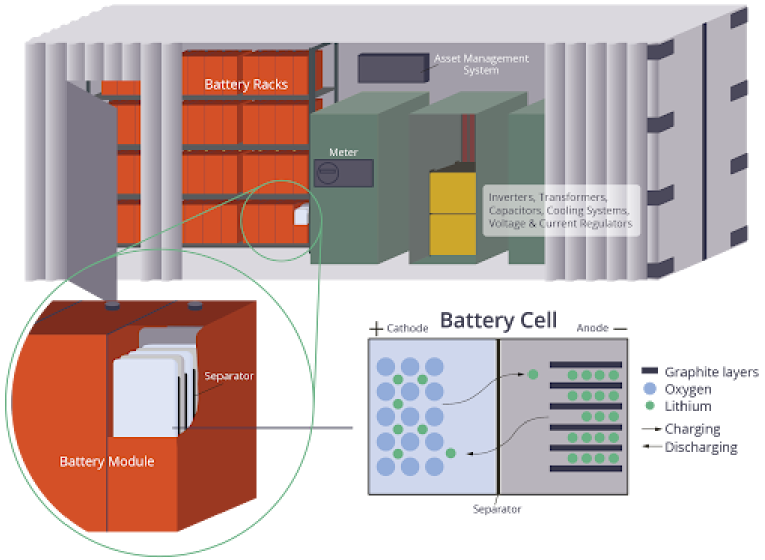
Sources: Energy Vault; Graviticity
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Lithium-ion batteries offer efficiency and energy density, at the cost of short duration and lifespan and high maintenance requirements

Definition

Lithium-ion batteries store electrical energy by moving lithium ions between two electrodes — typically a graphite anode and a lithium metal oxide cathode — through an electrolyte, a process that unfolds during both charging and discharging cycles. Lithium-ion batteries are currently the most widely used energy storage technology, largely due to their modularity, fast response times, and relatively high energy density. But major drawbacks, such as low duration, fast degradation, fire risks, and extensive O&M needs, may offer an opening for other technologies to dominate in LDES.



Technical specifications

• Maturity	• Commercialized
• Modularity	• Highly modular, limited only by safety requirements
• Deployment size (MW)	• 10-100+
• Nominal duration (hours)	• 0-8
• Round trip efficiency (%)	• 75-90

Use cases

Intraday	Intermittent daily RE generation
	Grid stability services
Multiday	Weather-driven outages
	Grid congestion
Seasonal	Seasonal imbalances
	Long-term outages
Remote or off-grid	Grid stabilization
	Backup power

Sample projects

Company	Project	Location	Rated Power (MW)	Duration (hrs.)	Status
VISTRA ENERGY	Moss Landing	California, U.S.	750 MW	4	Operational
NEOEN	Victorian Big Battery	Victoria, Australia	450 MW	1.5	Operational

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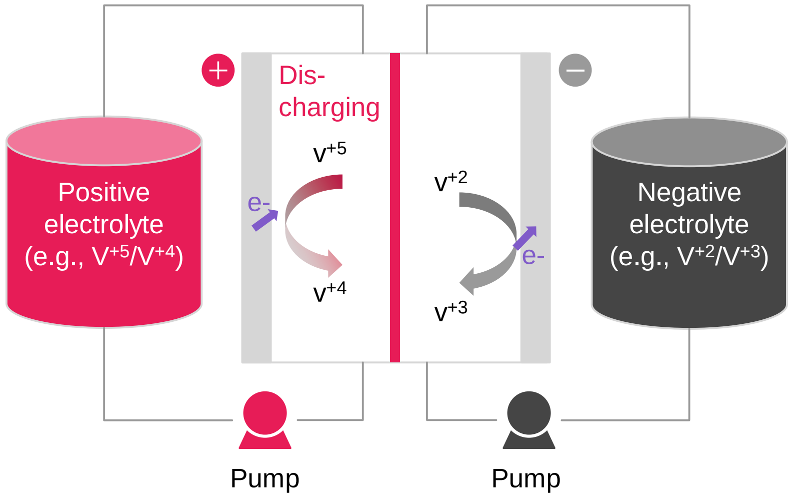
Sources: EIA, Battery Storage in the United States (2023); Enel X, Energy Storage; American Jobs Project.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Flow batteries have a longer lifespan than Li-ion and are safer but have a much lower energy density and carry higher CapEx costs

Definition

Aqueous electrolyte flow batteries, also referred to as simply flow batteries, store energy as a potential difference across two liquid electrolytes stored in separate tanks. During discharge, pumps bring the electrolytes together into a single container separated by a selective membrane. Half reactions at the two electrodes then generate an electric current. To recharge the battery, a current is run in the opposite direction through the battery, replenishing the electrolytes in the tanks. However, scaling energy capacity requires progressively larger tanks, and CapEx costs are high.



Technical specifications

Maturity	Wide range (R&D through commercial stages)
Modularity	Highly modular without safety concerns
Deployment size (MW)	10-100
Nominal duration (hours)	5-48+
Round trip efficiency (%)	50-80

Use cases

Intraday	Intermittent daily RE generation
	Grid stability services
Multiday	Weather-driven outages
	Grid congestion
Seasonal	Seasonal imbalances
	Long-term outages
Remote or off-grid	Grid stabilization
	Backup power

Sample projects

Company	Project	Location	Rated Power (MW)	Duration (hrs.)	Status
INVINITY ENERGY SYSTEMS	Energy Superhub Oxford	Oxford, UK	5 MWh	2-10	Active
LOCKHEED MARTIN	GridStar Flow battery	Alberta, Canada	6.5 MW	8	Announced

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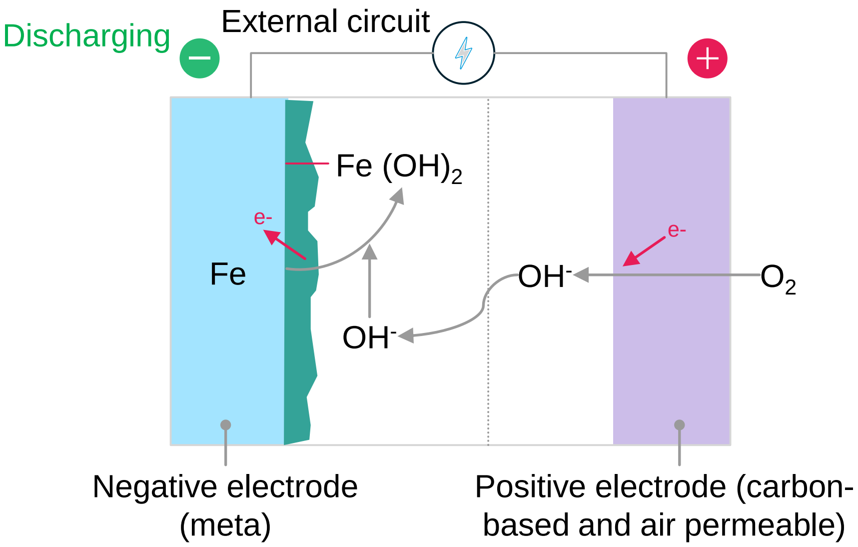
Sources: DOE, Energy Storage Reports and Data; Invinity; Lockheed Martin.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Metal air batteries offer safety, energy density, and lower costs, at the expense of a significantly shorter lifespan

Definition

Metal-air batteries are composed of a metal negative electrode and an air positive electrode. Oxygen from the air serves as the positive electrode and reacts with the metal electrode to drive a current. During discharge, the process is reversed and oxygen is released back into the atmosphere.



Technical specifications

Maturity	R&D/pilot
Modularity	Highly modular without safety concerns
Deployment size (MW)	10-100
Nominal duration (hours)	20-200
Round-trip efficiency (%)	40-70

Use cases

Intraday	Intermittent daily RE generation Grid stability services
Multiday	Weather-driven outages Grid congestion
Seasonal	Seasonal imbalances Long-term outages
Remote or off-grid	Grid stabilization Backup power

Sample projects

Company	Project	Location	Rated Power (MW)	Duration (hrs.)	Status
Form energy	Great River Energy	Minnesota, U.S.	1	150	Announced

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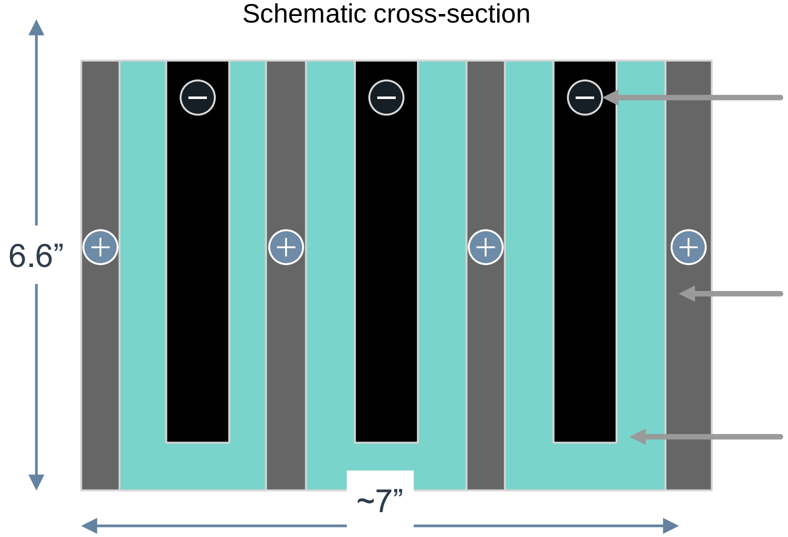
Sources: DOE, Energy Storage Reports and Data; Form Energy.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Solid-state and other new batteries are safer than Li-ion technologies, with significantly lower energy density

Definition

Solid-state batteries and other novel chemistry batteries use elements like metal alloys, solid metals, and salt electrolytes to hold a charge. These technologies are usually safer and easier to maintain than Li-ion batteries because they're more stable in extreme temperatures and don't pose a fire risk. They don't utilize lithium, which is in high demand — a factor that serves as a competitive advantage and allows solid-state batteries to avoid competing with mobility-designated battery technologies. However, these technologies have much lower energy densities and durations and are being used at a very limited scale.

Example of cell configuration
Schematic cross-section



Technical specifications

Maturity	Multiple projects in pilot phases, with technology set to be tested in utility-scale usage
Modularity	Highly modular without safety concerns
Deployment size (MW)	10-1,000
Nominal duration (hours)	4-24
Round trip efficiency (%)	80-90

Use cases

- Intraday
  - Intermittent daily RE generation
  - Grid stability services
- Multiday
  - Weather-driven outages
  - Grid congestion
- Seasonal
  - Seasonal imbalances
  - Long-term outages
- Remote or off-grid
  - Grid stabilization
  - Backup power

Sample projects

Project	Location	Storage capacity	Status
Microsoft	Massachusetts, U.S.	40 kWh	Implemented

Sources: DOE, Energy Storage Reports and Data; Microsoft.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

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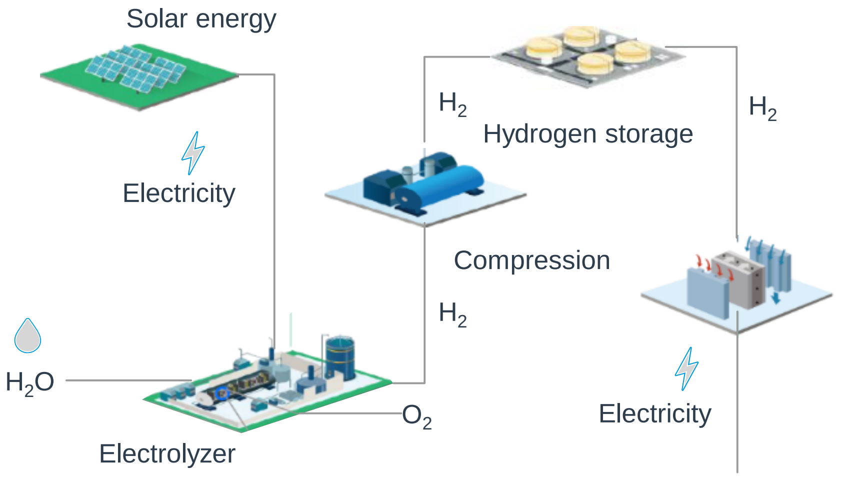
Hydrogen storage technologies are well suited for long-term storage, but high CapEx costs inflate their LCOS

Definition

Hydrogen storage involves energy stored in the form of chemical bonds (generally H_2 or synthesis gas). During charging, renewable electricity is used to power an electrolyzer that splits water into hydrogen and oxygen. The hydrogen is then compressed and stored in tanks or underground caverns, where it can then be used to produce electricity, either through combustion in a turbine or by running it through a fuel cell. Hydrogen storage provides very long duration, making it suitable for long-term storage. However, CapEx costs remain high, driving a high LCOS.



Technical specifications

Maturity	Pilot (with commercial project announced)
Modularity	Project dependent (container systems are modular, while systems using salt caverns are not)
Deployment size (MW)	10-100
Nominal duration (hours)	500-1,000
Round-trip efficiency (%)	40-55

Use cases

Intraday	Intermittent daily RE generation; Grid stability services
Multiday	Weather-driven outages; Grid congestion
Seasonal	Seasonal imbalances; Long-term outages
Remote or off-grid	Grid stabilization; Backup power

Sample projects

Company	Project	Location	Rated Power (MW)	Duration (hrs.)	Status
SIEMENS	Mohammed bin Rashid Al Maktoum Solar Park	Dubai, UAE	Size not announced (projected to generate 20.5 kg H_2/hour)		Operational
ingrid	Ingrid Hydrogen Demonstration Project	Troia, Italy	12	30+	Operational
ENGIE	Hyflexpower	Saillat-sur-Vienne, France	12	N/A	Announced

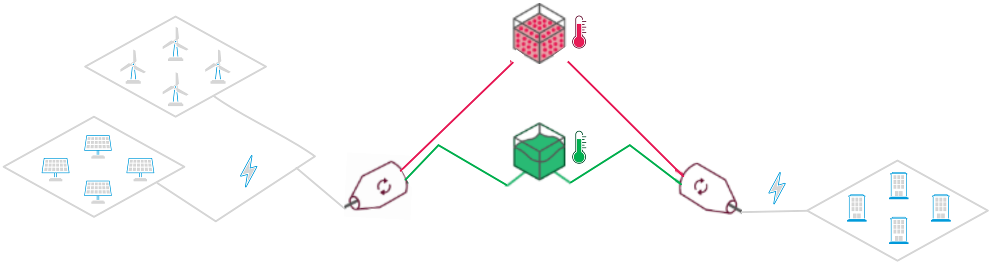
Sources: DOE, Energy Storage Reports and Data; Siemen; Engie

Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Thermal energy storage typically utilizes heat to store energy, though efficiency ranges widely with these technologies

Definition

A heat pump or electric resistance heater converts electrical energy into thermal energy by heating up a material (e.g., molten salt, volcanic rock) and/or chilling a liquid. Or, in an alternative approach, the heat needed for thermal energy storage can be provided by concentrated solar power. Then, when energy is needed, the heated or cooled substance can be converted back into electrical energy using a heat engine. For heated materials, for instance, the heat is used to power a steam turbine and thus generate electricity.



Energy gathered from wind, solar

Electricity drives a heat pump, heating/cooling liquid

Temperature difference turned back into electricity

Heat pump method shown here

Technical specifications

Maturity	Wide range (R&D through commercial phase)
Modularity	Modular but limited by infrastructure requirements
Deployment Size (MW)	10-500
Nominal Duration (hours)	25-200
Round trip efficiency (%)	20-90

Use cases

Intraday	Intermittent daily RE generation; Grid stability services
Multiday	Weather-driven outages; Grid congestion
Seasonal	Seasonal imbalances; Long-term outages
Remote or off-grid	Grid stabilization; Backup power

Sample projects

Company	Project	Location	Rated Power (MW)	Duration (hrs.)	Status
MALTA	NB Power Thermal Storage	New Brunswick, Canada	100 MWh	26	Canceled
AZELIO	TES, POD	Egypt	0.25 MW	13	Bankrupt

Sources: DOE, Energy Storage Reports and Data; Malta.

Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

PSH best positioned to support renewable energy grid integration, while batteries have wider application for short duration

Comparison of key characteristics for energy storage technologies (2022-2023 basis)

Most favorable for renewable energy integration | Least favorable for renewable energy integration

Parameter	Pumped storage hydro (PSH)	Compressed air (CAES)	Gravitational	Battery	Green hydrogen (Fuel cell)	Thermal energy storage (TES)
Discharge duration at max power (hours)	5-21	2-25	N/A	1-8	3-26	Several hours
Lifecycle GHG emission (gCO_2/kWh)	145-179	161-272	N/A	259-335	386-700	~26
Costs:						
Installed cost (USD/kWh)	250-300	100-130	455	310-430	260-340	~700
LCOS (USD/kWh)	~0.1	~0.1	~.0.2	0.1-0.3	0.3-0.4	~0.5
Applications:						
Renewable energy integration	Yes	Yes	Yes	Yes (Li-Ion)	Yes	Yes
Bulk energy storage	Yes	Possible	Yes	Possible (Li-Ion)	Yes	Yes
Ancillary services	Partial	Partial	Partial	Yes	Yes	Partial
Energy management	No	Partial	No	Yes	Yes	No

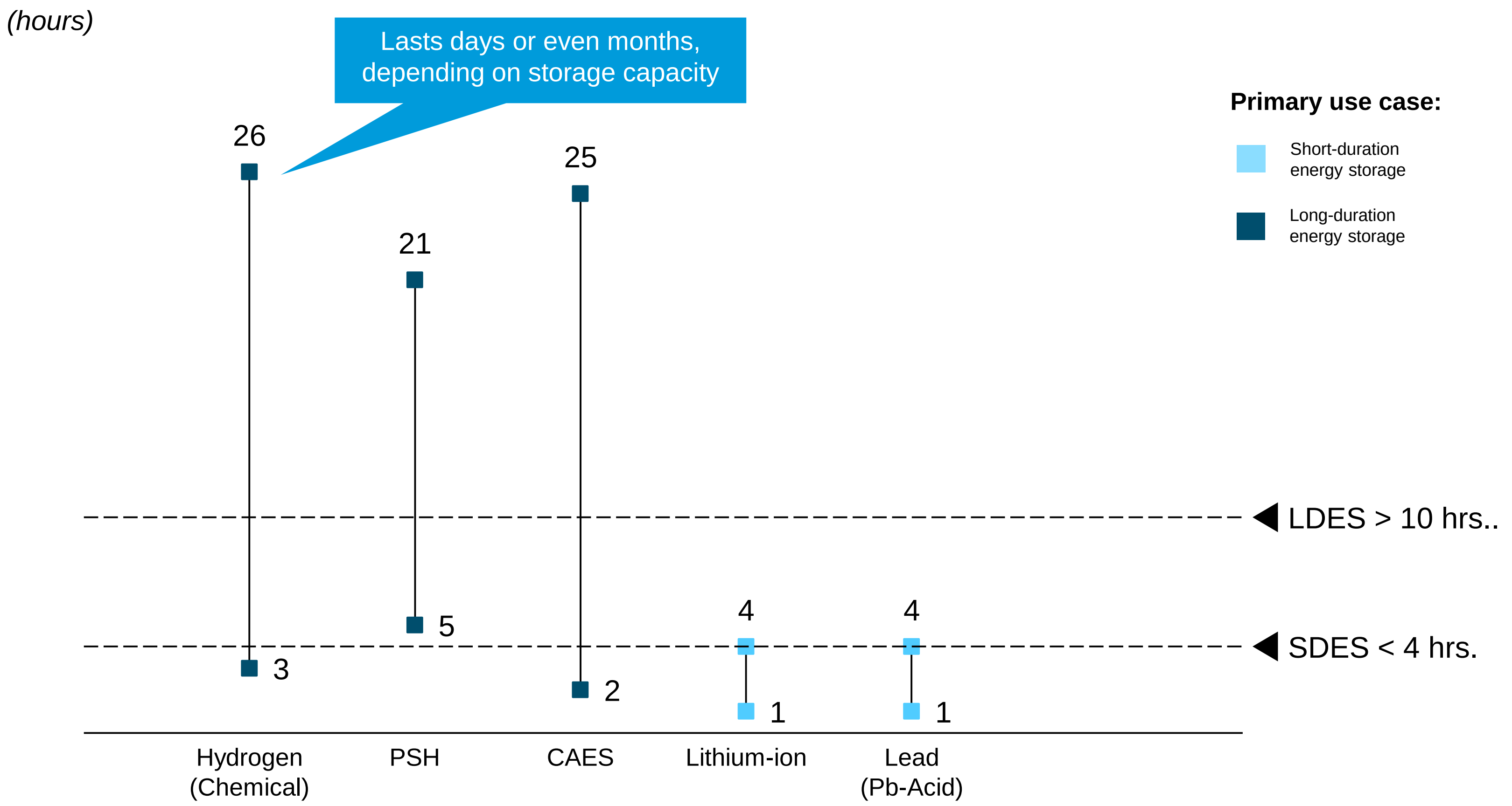
Observations

- **PSH dominates** due to its **wide discharge duration range**, making it suitable for **a wide range of applications.** PSH also **emits relatively low levels of GHGs.**
- **CAES,** meanwhile, has **limited applications** and is difficult to scale up due to **geographic constraints.**
- And while **hydrogen's long duration is promising,** the technology has significant **GHG emissions due to poor round-trip efficiency.**
- **Batteries can be used widely** for short-duration applications.

Sources: Applied Energy, Energy storage technologies (2016); Joule, Projecting LCOE Storage Technologies (2019); Oxford University Press, Monetizing Energy Storage (2023); PNNL, Energy Storage Cost and Performance; PNNL, LCOS Estimates; Applied Energy, Comparison of electricity storage options using LCOS (2016).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Hydrogen, PSH, and CAES deliver the longest discharge duration of current technologies, offering grid reliability

Discharge durations for stationary energy storage technologies operational in 2022



Observations

- **Long-duration energy storage (LDES)** technologies like hydrogen, PSH, and CAES deliver discharge durations of over 10 hours, offering significant value for grid reliability and renewable energy integration. They do this by:
  - Providing **a consistent and reliable energy supply.** This positions LDES as a replacement to traditional baseload power sources.
  - **Storing excess renewable energy** during periods of low demand and discharging during periods of high demand.
- **Short-duration energy storage (SDES)** is intended for short and high-power discharges**,** with key applications like**:**
  - **Stabilizing the frequency of power grids**, which is essential for maintaining the reliability and efficiency of electrical distribution systems.
  - Reducing strain on the grid during **peak periods.**

Sources: Oxford University Press, Monetizing Energy Storage (2023); DOE, Long-Duration Energy Storage; Alsym Energy, Understanding Short-, Medium- and Long-Duration Energy Storage (2024).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Most battery technologies are significantly more versatile in minimum size and maximum duration vs. competition

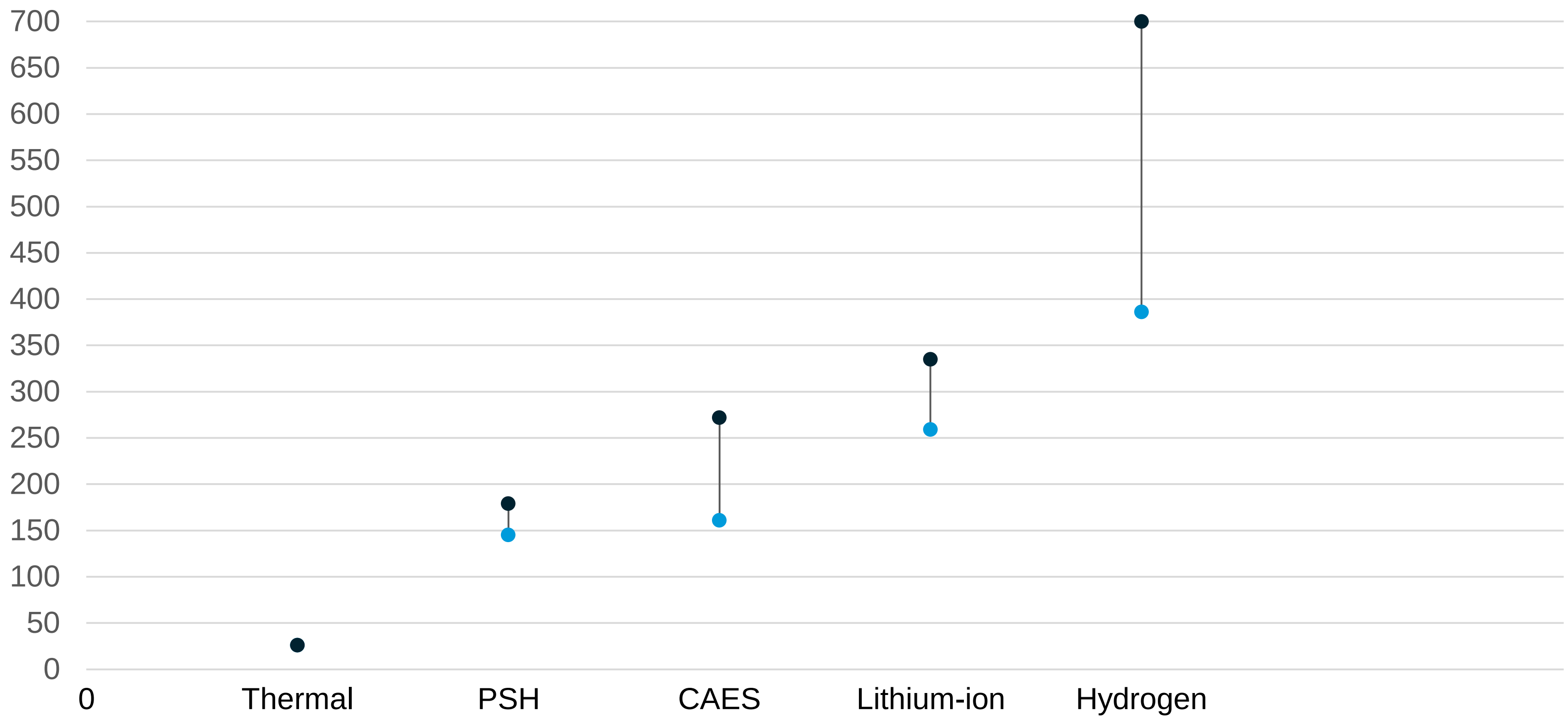
Capacity (MW)	1 MW							10 MW							100 MW							1,000 MW						
Duration (hours)	2	4	6	8	10	24	100	2	4	6	8	10	24	100	2	4	6	8	10	24	100	2	4	6	8	10	24	100
Lithium-ion LFP																												
Lithium-ion NCM																												
Lead acid																												
PSH[1]																												
CAES[1]																												
Hydrogen																												
Thermal																												
Gravitational																												

Feasible size and duration of the technology

1) Four hours for PSH and CAES represents a sweet point. Inefficiencies are seen at very short durations like two hours. PSH and CAES can match the continuous discharge capability that batteries and other technologies are at six and eight hours.
Source: DOE, Grid Energy Storage Technology Cost and Performance Assessment (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Of the technologies commercialized today, thermal and PSH offer the lowest total GHG emissions

GHG emissions across lifecycle,[1] gCO_2/kWh



Observations

- **Hydrogen** appears to be the largest producer of GHG emissions, due to **production methods** and **low system efficiency.**
- **Pumped storage hydropower**, meanwhile, produces limited GHG emissions because renewable energy is incorporated into the grid mix used for the pump's electricity. PSH facilities also have **long lifetimes**, and economies of scale could reduce GHG emissions even further.
    - PSH has lower impacts in all categories except **land-use requirements.**
- Hydrogen's GHG emissions could be greatly reduced and the technology could compete with PSH and CAES if electricity with a **low GHG-intensity is used in H2 production.**
- Thermal produces the lowest GHG emissions because **abundant, low-impact materials are** used in its storage**, it seamlessly integrates** with renewable energy sources, and it is **highly efficient, with minimal losses.**
- Results reflect a cradle-to-grave analysis. Lifecycle stages considered were production, use, and end-of-life.

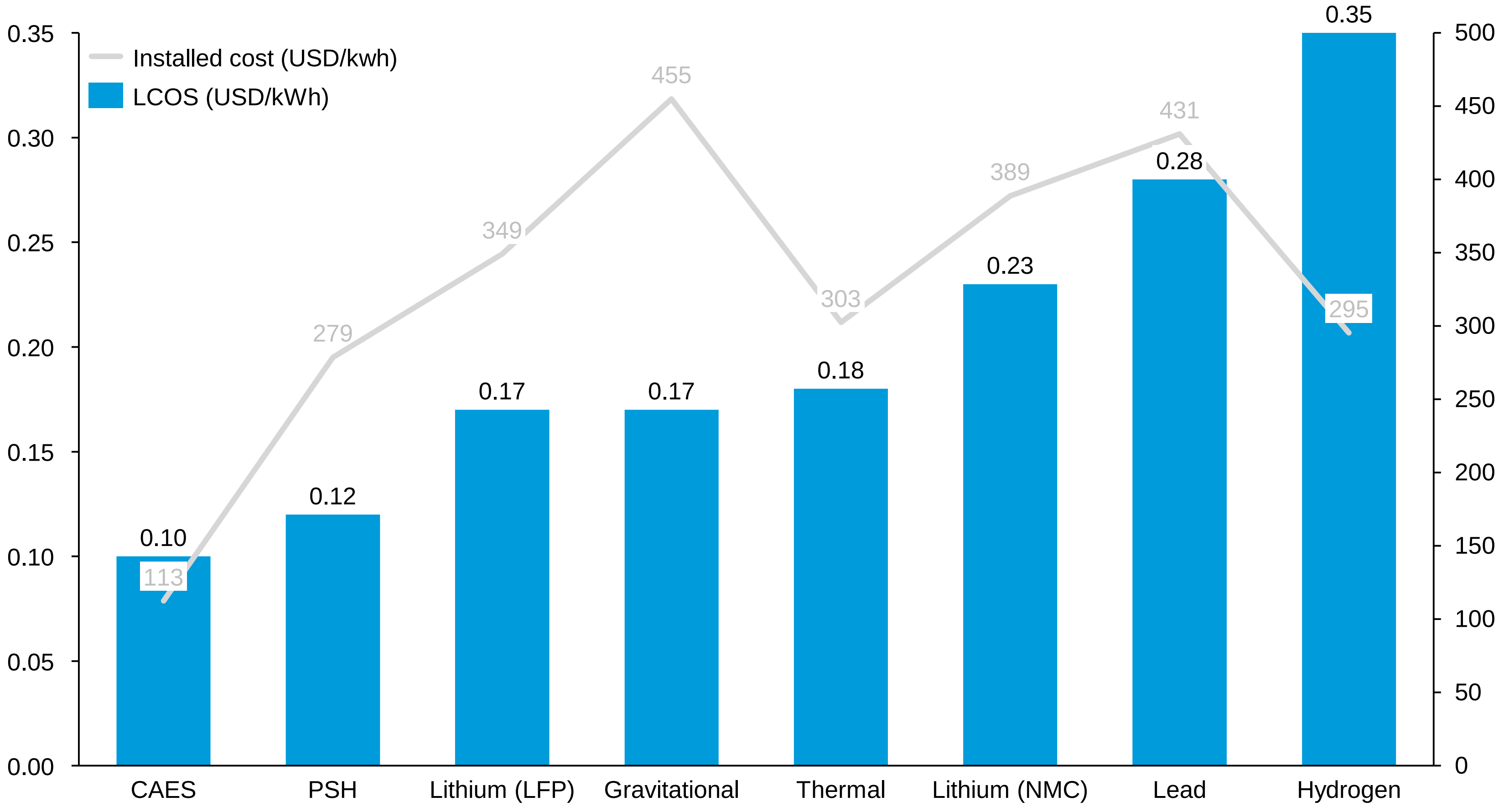
1) All emissions totals calculated in cradle-to-grave framework for ~100 MW system.

Sources: Energy Conversion and Management, Assessment of energy storage technologies (2020); Environmental Science & Technology, Life Cycle Assessment of PSH (2023); Energy, Assessment of stationary electricity storage (2017); International Journal of Energy and Environmental Engineering, Life-cycle of PHS (2017).

Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

CAES the most cost-effective technology when it comes to both the initial CapEx requirement and LCOS

LCOS vs. installed cost across storage technologies in 2023 for 100 MW/10 hours



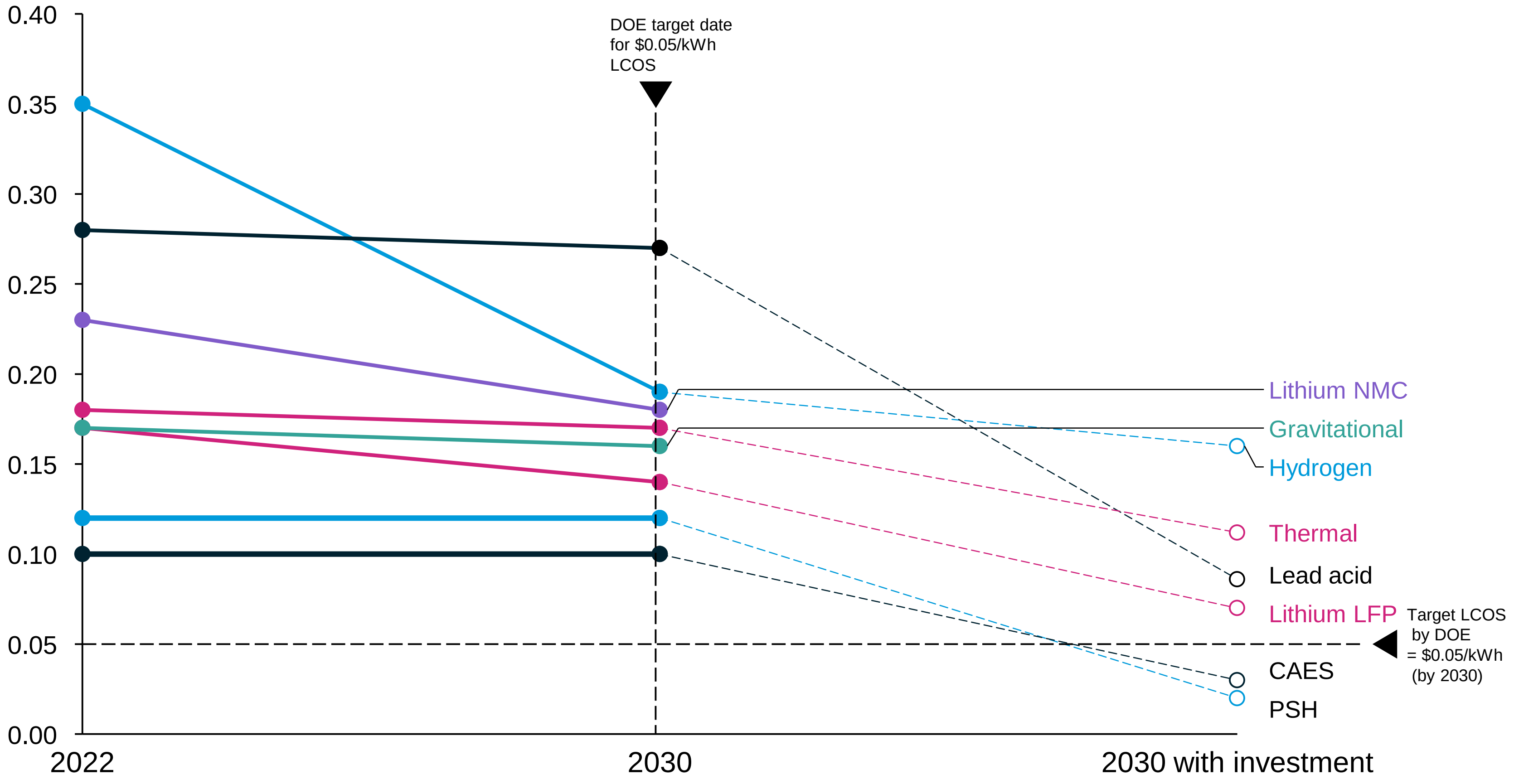
Observations

- Compressed air (CAES) boasts some of the lowest installed costs and LCOS due to its use of preexisting geological formations such as **caverns, aquifers, and other rock formations.**
    - Not having to construct new **storage facilities** provides significant cost savings.
- Of the different battery chemistries, **lithium (LFP)** stands out because of its **moderate costs and LCOS.** While not the cheapest, lithium compares favorably to **lead**, which has **higher costs and a higher LCOS,** reflecting lead's **lower efficiency, shorter life, and maintenance needs.**
- Hydrogen has competitive installed costs, but its LCOS is high due to **poor system round-trip efficiency,** attributable to **inefficiencies in the conversion process** involved in storing and retrieving energy.

*Hydrogen system capital costs reflect 2021 estimates, since hydrogen was not part of the 2024 research effort.
Sources: PNNL, Cost; PNNL (LCOS).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Further development needed for all technologies if they are to achieve a LCOS goal of $0.05/kWh

LCOS expectations for 100 MW/10 hours systems, $/kWh



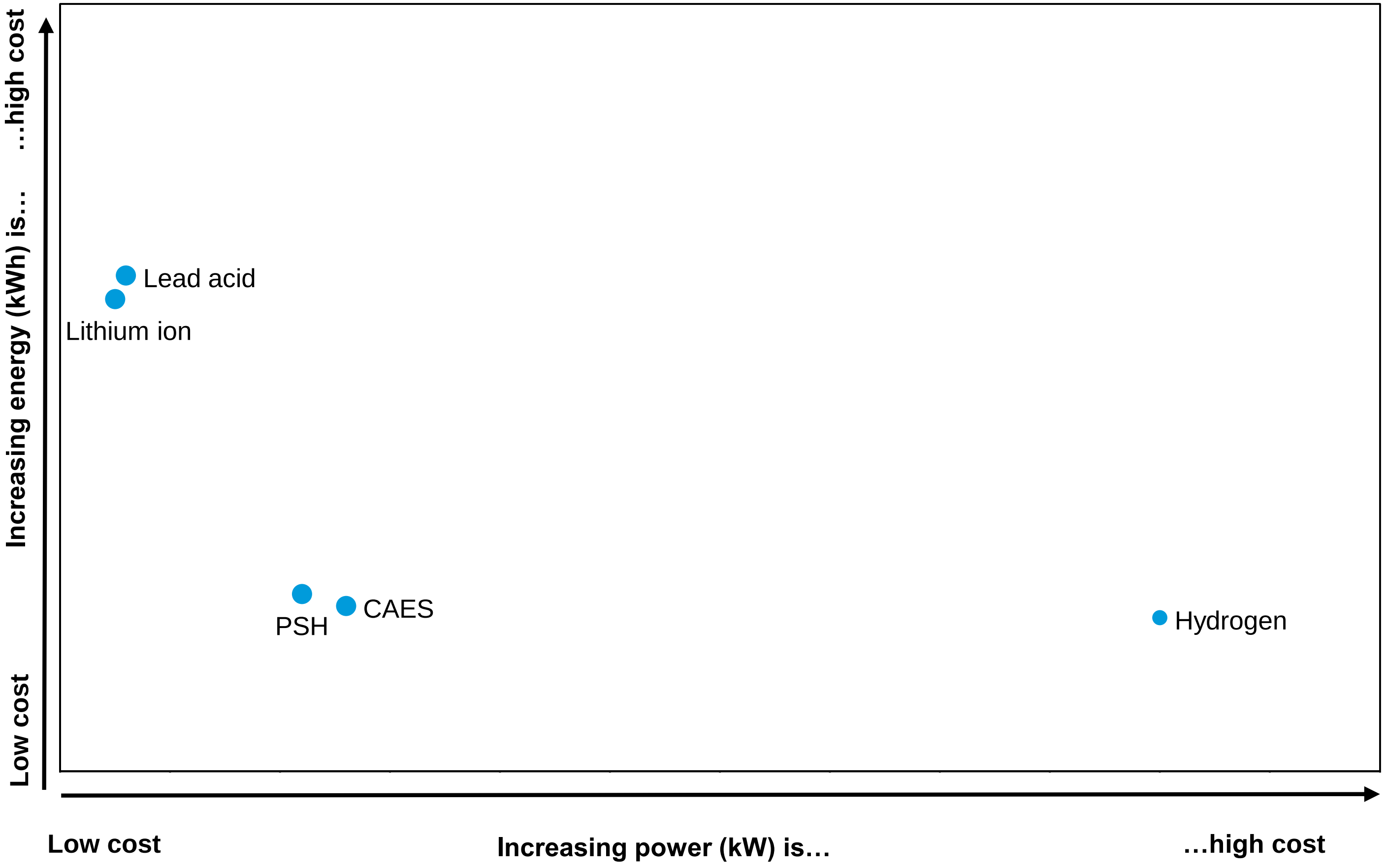
Observations

- **Hydrogen is the only technology** expected to see significant reductions in its LCOS by 2030, thanks to advancements in electrolysis, storage methods, and system integrations.
- That said, all technologies, including hydrogen, are projected to fall short of the U.S. Department of Energy's 2030 Energy Storage Grand Challenge Roadmap target of a LCOS of **$0.05/kWh** for long-duration stationary applications.
- Achieving the **$0.05/kWh LCOS target** is essential for energy storage to be **commercially viable** across a broad range of stationary tasks.
- **Continued innovation** in preexisting storage technologies such as batteries, hydrogen, and thermal storage will be critical to bridge the cost gap.
- With an **estimated $750 million** investment over **eight years**, CAES could reach a **LCOS as low as $0.03/kWh.**
- PSH, meanwhile, could reach an even lower LCOS, $0.02/kWh, with a **$560 million** investment over **the same period.**

Sources: PNNL, LCOS; DOE, Energy Storage Grand Challenge Roadmap (2020); DOE, Achieving the Promise of Low-Cost Long Duration Energy Storage (2024).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

PSH and CAES offer cost advantages, but batteries provide super-scalability for the future

Investment cost per power capacity and per energy capacity for stationary energy storage technologies, $/kW by $/kWh



Observations

- Power-specific cost reflects the cost related to power delivery and is most important when very high power must be delivered for very short periods.
- The energy-specific cost denotes the cost of storing energy and, therefore, is the most critical factor for applications that require a high amount of energy to be stored for a long period of time.
- Both PSH and CAES can boast of low costs for both power at $/kW and energy at $/kWh. This dual power-energy advantage makes it suitable for balancing grid demand over a longer duration.
- Lithium-ion batteries are positioned in the high-cost but high-performance option. In power delivery, in respect to short-duration storage, it is the best. This includes solutions that require quick energy discharge.
- Hydrogen is extremely effective in terms of capacity, but the high costs per kW prohibit the use of hydrogen when power output is important. It is still an option for long-term, large-scale energy storage.
- While PSH and CAES are cost effective for both, scalability is bound by geography and infrastructure.

Source: Oxford University Press, Monetizing Energy Storage (2023).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Energy storage technologies are used across various applications in the utility system

Definitions

Application areas	
Renewable energy integrations	Time shifting: Storing the excess generation of renewable energy and releasing it when demand is higher or intermittent generation is lower.
	Firming capacity: Keeping the grid stable in the face of potential wind and solar intermittency.
Bulk energy	Peak shaving: Reducing the energy consumed during peak demand on the electric grid by introducing energy stored to shave off the top of the power demand curve.
	Arbitrage of energy: Purchasing power at low price and selling it in high-price periods on wholesale or retail markets.
Ancillary services	Voltage support: Normally, designated power plants are used to generate reactive power (expressed in VAr) to offset reactance in the grid. These power plants could be displaced by strategically placed energy storage within the grid at central locations or by multiple VAr-support storage systems placed near large loads, following the distributed approach.
	Load balancing: Evenly distributing the amount of energy used across different applications to avoid power outages.
	Spinning reserve: The operation of an electric grid requires reserve capacity that can be called on when some portion of the normal electric supply resources unexpectedly becomes unavailable.
	Black start: Providing an active reserve of power and energy within the grid that can be used to energize transmission and distribution lines and provide station power to bring power plants online after a catastrophic failure of the grid.
	Frequency balancing: Balancing short-term mismatches in supply and demand, to maintain smooth and reliable power flow from the grid.
Energy management	Enhancing power quality: Protecting on-site load against short-duration power loss or variations in voltage or frequency.
	Power reliability: Covering temporal lack of variable supply and providing power during blackouts.

Source: ADB, Handbook on Battery Energy Storage Systems (2018).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

A technology’s application suitability varies depending on its power and duration properties

PSH, CAES, thermal, Li-ion, and VRFB are the most suitable energy storage technologies for renewable energy integrations

Application areas		Mechanical			Batteries		
		PSH	CAES	Gravitational	Li-ion	Pb-Acid	Thermal
Renewable energy integrations	Time shifting	Suitable	Suitable	Suitable	Suitable	Possible	Suitable
	Firming capacity	Suitable	Suitable	Suitable	Suitable	Possible	Suitable
Bulk energy	Peak shaving	Suitable	Possible	Suitable	Possible	Unsuitable	Suitable
	Arbitrage of energy	Suitable	Possible	Suitable	Possible	Unsuitable	Suitable
Ancillary services	Voltage support	Unsuitable	Unsuitable	Unsuitable	Suitable	Suitable	Possible
	Load balancing	Possible	Possible	Suitable	Possible	Suitable	Suitable
	Spinning reserve	Unsuitable	Suitable	Possible	Unsuitable	Suitable	Possible
	Black start	Possible	Possible	Possible	Suitable	Suitable	Possible
	Frequency balancing	Possible	Possible	Suitable	Suitable	Suitable	Unsuitable
Energy management	Enhancing power quality	Unsuitable	Unsuitable	Unsuitable	Suitable	Suitable	Unsuitable
	Power reliability	Unsuitable	Possible	Unsuitable	Suitable	Suitable	Unsuitable

Suitable application   Possible application   Unsuitable application

Sources: Applied Energy, Energy storage technologies (2016); HuntKey, Gravity Energy Storage; Journal of Energy Storage, Capability study of dry gravity energy storage (2019); Renewable and Sustainable Energy Reviews, review of stationary energy storage (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Columbia Business School

The energy storage opportunity

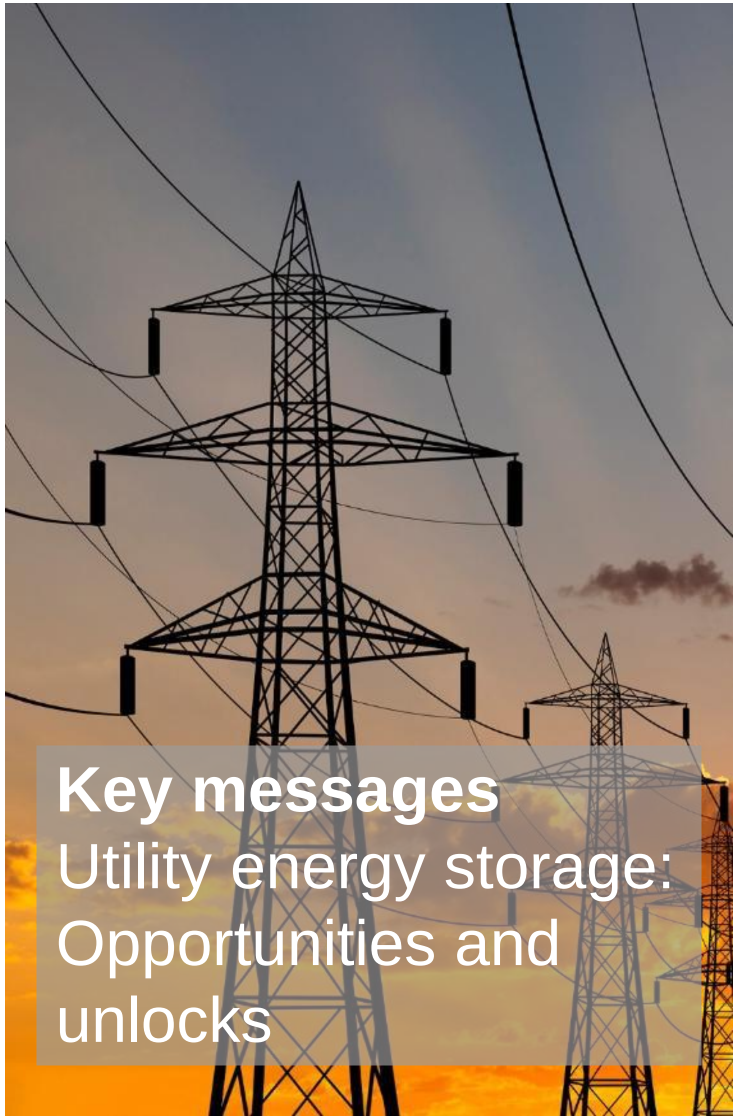
Mobility energy storage

Utility energy storage

Technology

Opportunities and unlocks

Case study



Pumped storage hydropower remains the dominant technology (74% share of global capacity) for long-duration energy storage due to its **maturity** and **capacity** edge.

Traditional PSH struggles with deployment given **geographical constraints, high upfront capital costs, and long construction timelines**. As a result, **novel developments in PSH** are emerging as the future, offering **more flexibility** and **cost efficiency**.

- Novel PSH offers **~33% cost savings** resulting from **efficiency in underground work** and **optimized civil works**. India expects an internal rate of return of 10% to 12% for this technology.
- **Quidnet Energy's innovative** geomechanical PSH approach reached a key milestone with its NYSERDA partnership and recently announced 300 MW commercial facility.

Battery will surpass PSH in utility energy storage due to **faster response**, **significant cost reductions** in battery technology, and **flexibility** in location.

- BESS **cost declines are driven by advancements in cell and pack technology**; further improvements are needed to reduce system costs.
- **In the United States, California and Texas lead in battery energy storage**, though other regions could see significant growth.

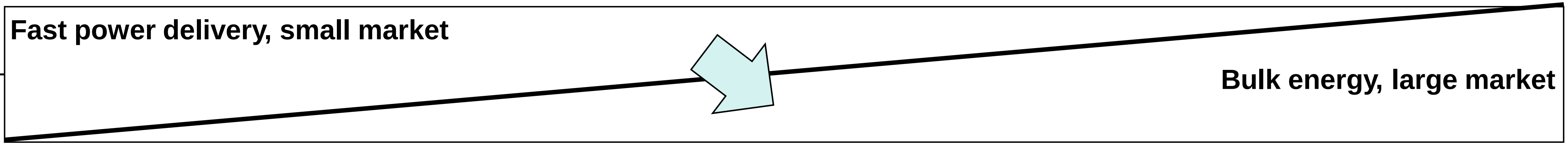
In the United States, **interconnection queues** present a bottleneck, with a **3.5x discrepancy** between projected builds and active projects. This challenge is delaying capacity deployment across the country.

Grid integration, smart grid, and vehicle-to-grid (V2G) could be a potential solutions:

- **Grid integration**: Interconnecting the grids would create a more expansive network, which would enable power flows among regions and reduce congestion.
- **Smart grid**: Data-based decision-making would enable better allocation of the location of new generation, and continuous monitoring of the grid would allow for more efficient interconnection requests.
- **V2G**: The addition of vehicles to the grid would increase the capacity of storage needed to reach decarbonization targets.

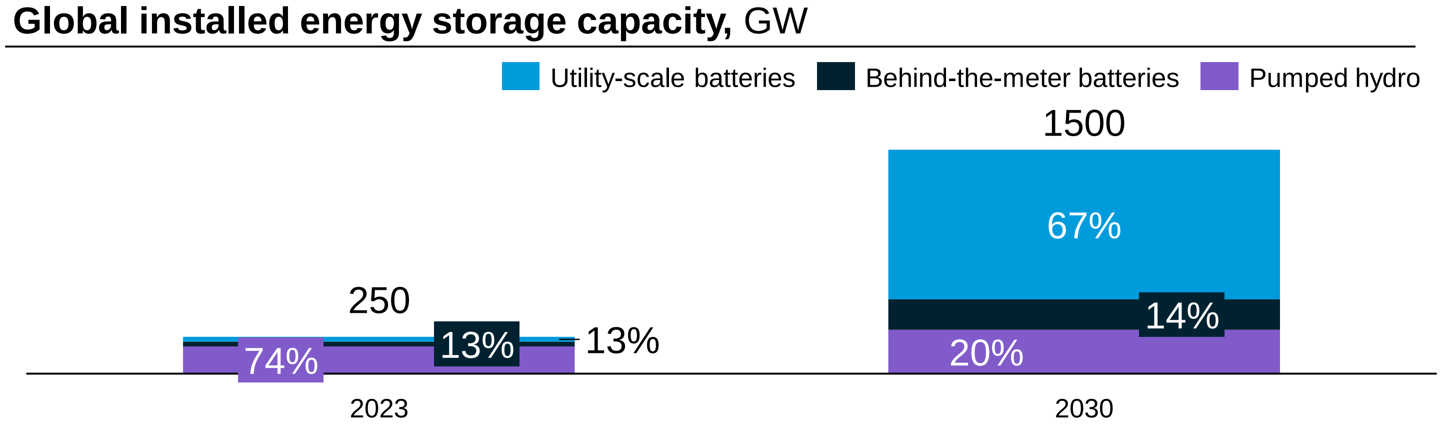
Amongst mechanical technologies, pumped storage hydro leads due to lifetime proposition; batteries stand to advance

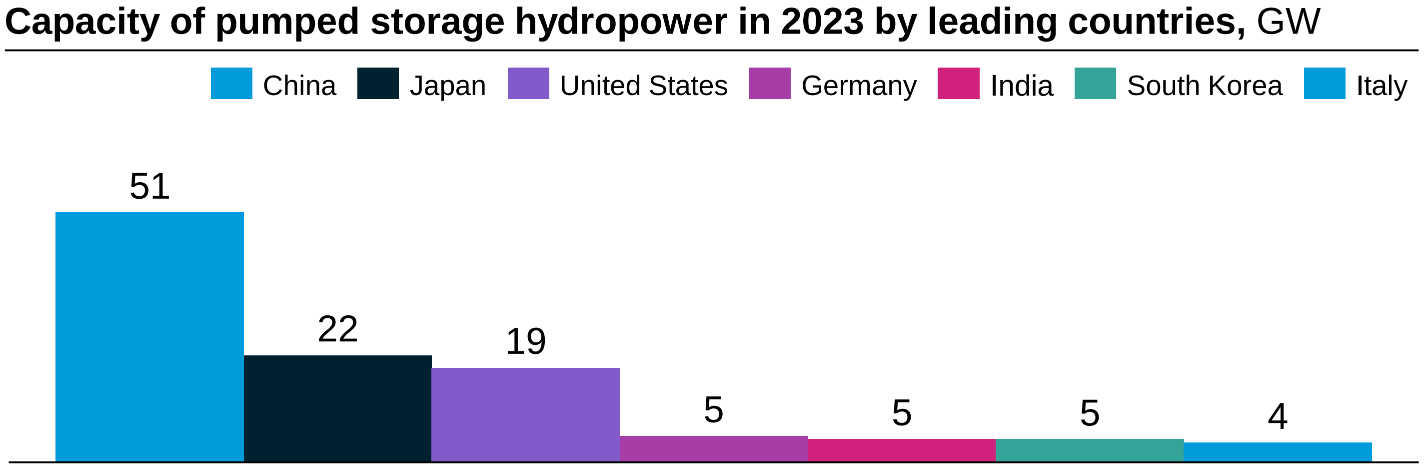
	1 Batteries	2 PSH
Description	Batteries convert chemical energy to electrical energy via reduction and oxidation (redox) reactions. These reactions occur along both the positive and negative electrodes, which are connected by an external circuit and frequently separated by electrolyte.	With PSH, two water reservoirs are built at different elevations. Energy is stored by pumping water from the lower reservoir to the upper one, typically during off-peak hours, when demand for electricity is low.
Rationales for future technology domination	**Scalability and flexibility**: Batteries can be scaled in various sizes in a way other technologies can not.	**Legacy storage**: PSH is a mature technology that offers large-scale energy storage and grid balancing.
	Quick response time: Batteries can provide immediate power at the peak of demand or during periods of instability, thus fitting as a combination for intermittent sources like solar and wind.	**High efficiency**: PSH is capable of storing and releasing energy at very high efficiencies (over 80%) for a long period.
	Technological advancements: Continuous cost reductions and technology improvements are lengthening batteries' duration and making them better equipped for bulk energy storage uses in larger electricity markets.	**Environmental considerations**: PSH requires large reservoirs, which often have significant environmental impact. Expansion could be possible via dam retrofit.



Sources: IEA, Global installed energy storage capacity (2024); DOE, Pumped Storage Hydropower; EIA, Pumped storage electricity generators in the U.S. (2019).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

PSH's dominance faces competition with batteries expected to grow





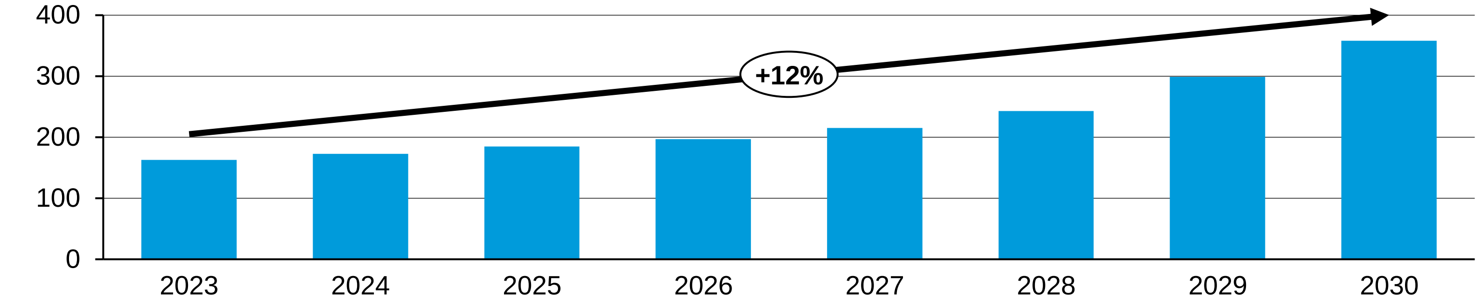
Observations

- There are two types of pumped storage plants: **open-loop** plants, which have an associated natural water source, **like a river,** for one or both of the reservoirs, and **closed-loop** (or **off-river**) plants, which do not have a connected **natural-water source**. Instead, **the same water is cycled** between the two reservoirs for pumping and generation.
- The PSH market should continue to grow as countries look to this **tried-and-true** energy storage mechanism for renewable energy integration with a relatively **limited environmental impact**.
- The **Chinese government** has placed importance on PSH, as seen in its **14th Five-Year Plan for Scientific and Technological Innovation in the Energy Sector**.
- In Japan, where the geography is characterized by **mountainous terrain and abundant water resources**, emphasis has been placed on PSH technologies in places like the **Kyushu** region.
- Pumped storage capacity in the U.S., meanwhile, is largely dated, having been built mostly between 1960 and 1990. Upgrading or building new PSH will require **significant capital investments** and the ability to navigate **geographic constraints** as well as **lengthy permitting processes**.
- Unlike PSH, battery storage systems **can be deployed virtually anywhere**. Their scalability, combined with short installation times, sets them up to be **commercially favored.**

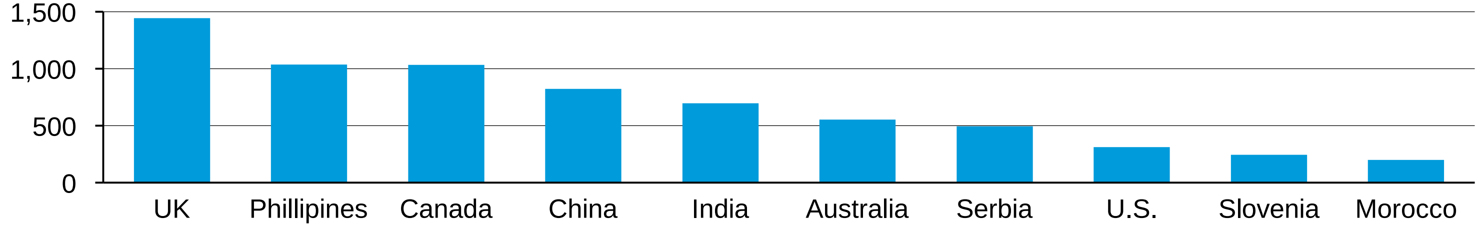
Sources: IEA, Global installed energy storage capacity (2024); DOE, Pumped Storage Hydropower; EIA, Pumped storage electricity generators in the U.S. (2019).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Global PSH remains a critical driver for storage through 2030

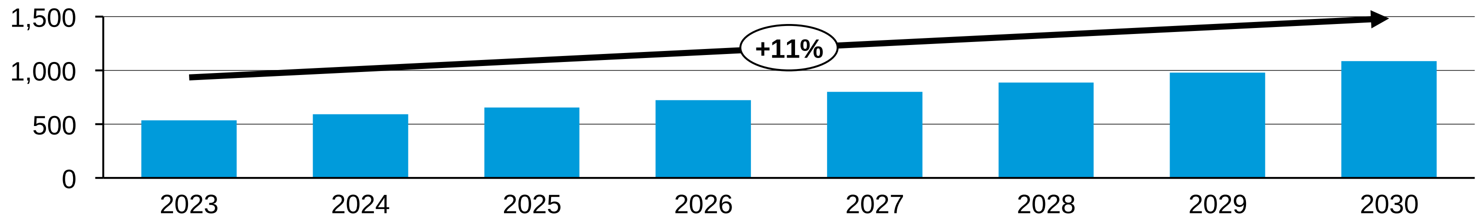
NZE global installed electric capacity of pumped hydro, GW



Top countries by prospective PSH capacity growth, prospective/operating (MW/MW)



PSH market size projections (USD$M)



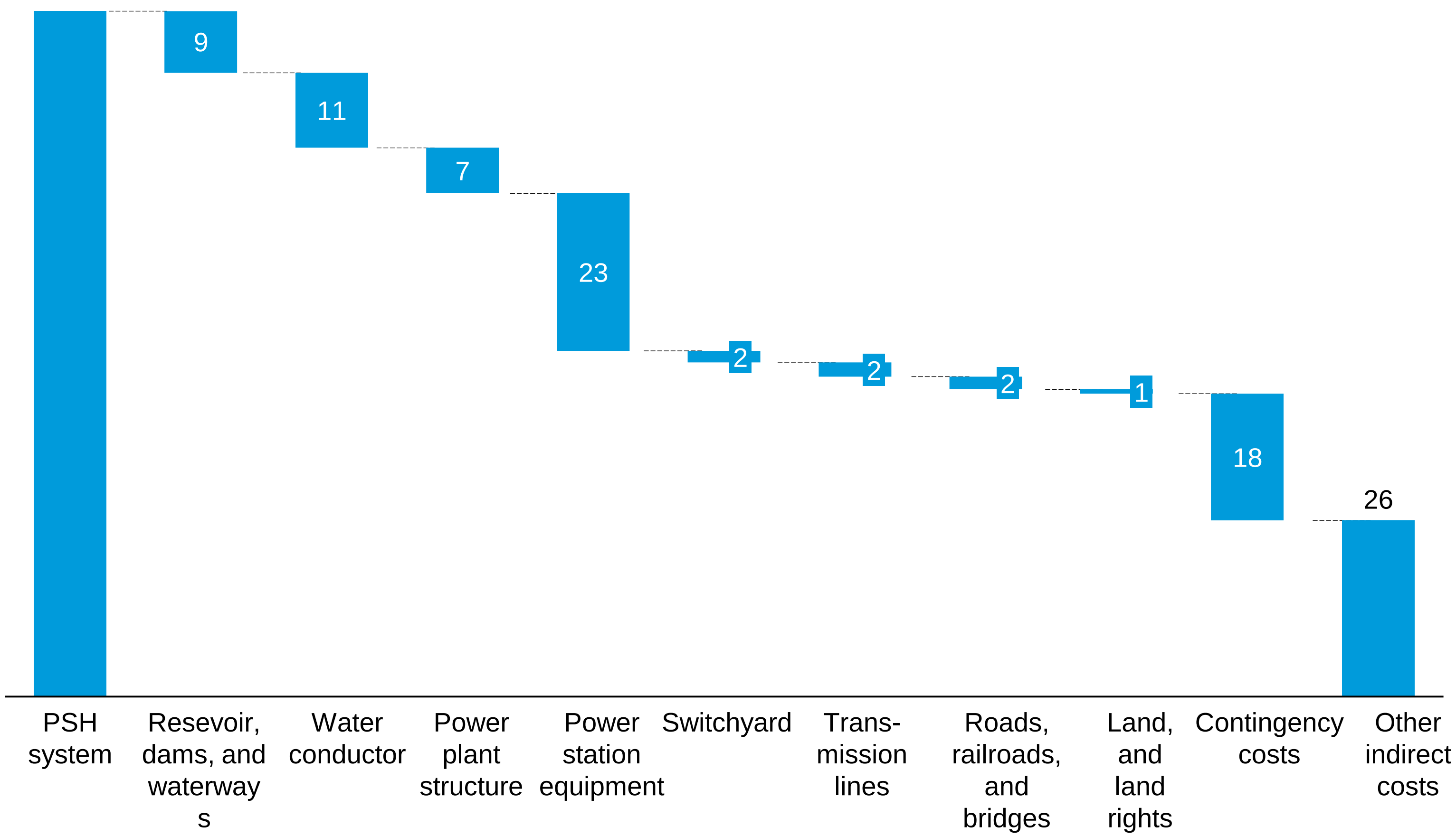
Observations

- The global pumped storage hydropower market is expected to grow steadily through 2030. Over this period, the PSH market is projected to expand **by 11%**, reflecting increased investments and demand for energy storage solutions.
- The **United Kingdom** is expected to grow its pumped storage capacity the most over the next decade, with a **staggering 1,443% in projected growth**, signaling a major strategic shift in energy storage.
- While China is expected to have a relatively smaller growth rate of 824%, **because it already has a vast operating capacity, China should see the largest absolute increase in megawatts worldwide**.
- **India's and Canada's** prospective growth reflects their commitment to bolstering energy storage as part of their renewable energy push.
- **Australia's 552% growth** highlights its efforts to stabilize its **renewable-heavy grid**. The planned expansion will be essential for the country's energy transition and decarbonization targets.
- **Philippines, Morocco, and Slovenia** are rapidly positioning themselves as key players in the global pumped storage market. These countries are demonstrating significant commitment to **integrating renewable energy and enhancing grid stability**.

Sources: Statista, Pumped hydro storage market; TERI, Pumped Storage Plants (2023); GEM, Global Hydropower Data
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

The bulk of conventional PSH costs come from indirect, contingency, and power station equipment costs

Component-specific cost breakdown for large pumped storage hydro system, %



Observations

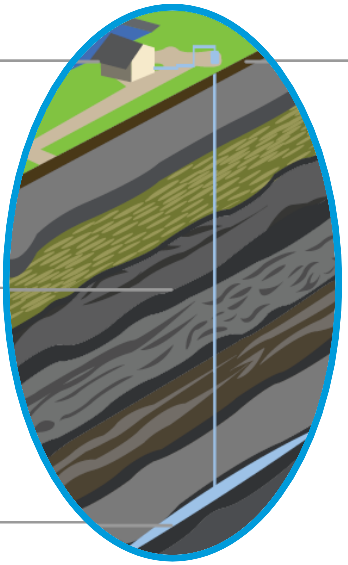
- **More than a quarter of total PSH project costs** are tied to **other indirect costs**, a category that includes **engineering, permitting, taxes**, and **interest during construction**. The size of these expenses underscores the importance of rigorous project management and early-stage financial planning to manage cash flows and optimize cost structures.
- **Another 18% of costs** come from **contingency** provisions, which account for unforeseen variables such as construction delays, technical challenges, or regulatory changes. This cost driver shows the **high levels of uncertainty** inherent in PSH projects and speaks to the need for risk mitigation strategies in these kinds of projects.
- At **23% of total costs**, **power station equipment** (including turbines, generators, and other essential machinery) constitutes the largest share of direct expenditures, indicating the critical role of advanced technology procurement and supply chain management in maintaining operational efficiency and reducing long-term costs.
- Categories such as **reservoirs, dams, and waterways (9%)** and **powerplant structures (7%)** also represent key infrastructure investments. Although not the largest cost drivers, these components require careful planning and robust contractor management to avoid budget overruns.

Source: NREL, A Component-Level Bottom-Up Cost Model for Pumped Storage Hydropower (2024).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Novel PSH provides an alternative: Relying on suitable geological conditions instead of two vertically separated lakes

Definition

Excess electricity is used to pump water from a reservoir down a well and into a body of rock where it is stored under pressure between rock layers. When electricity is needed, the well is opened, allowing pressurized water to flow through a turbine, generating electricity for the grid.



Technical specifications

Maturity	Commercial
Modularity	More modular than large-scale hydro but geographically constrained by need for underground rock bodies for storing water under pressure
Suitable deployment size (MW)	10-100
Suitable nominal duration (hours)	5-48+
Round-trip Efficiency (%)	70-85

Use cases

- Intraday
  - Intermittent daily RE generation
  - Grid stability services
- Multiday
  - Weather-Driven Outages
  - Grid congestion
- Seasonal
  - Seasonal Imbalances
  - Long Term Outages
- Remote or off-Grid
  - Grid Stabilization
  - Backup Power

Example projects

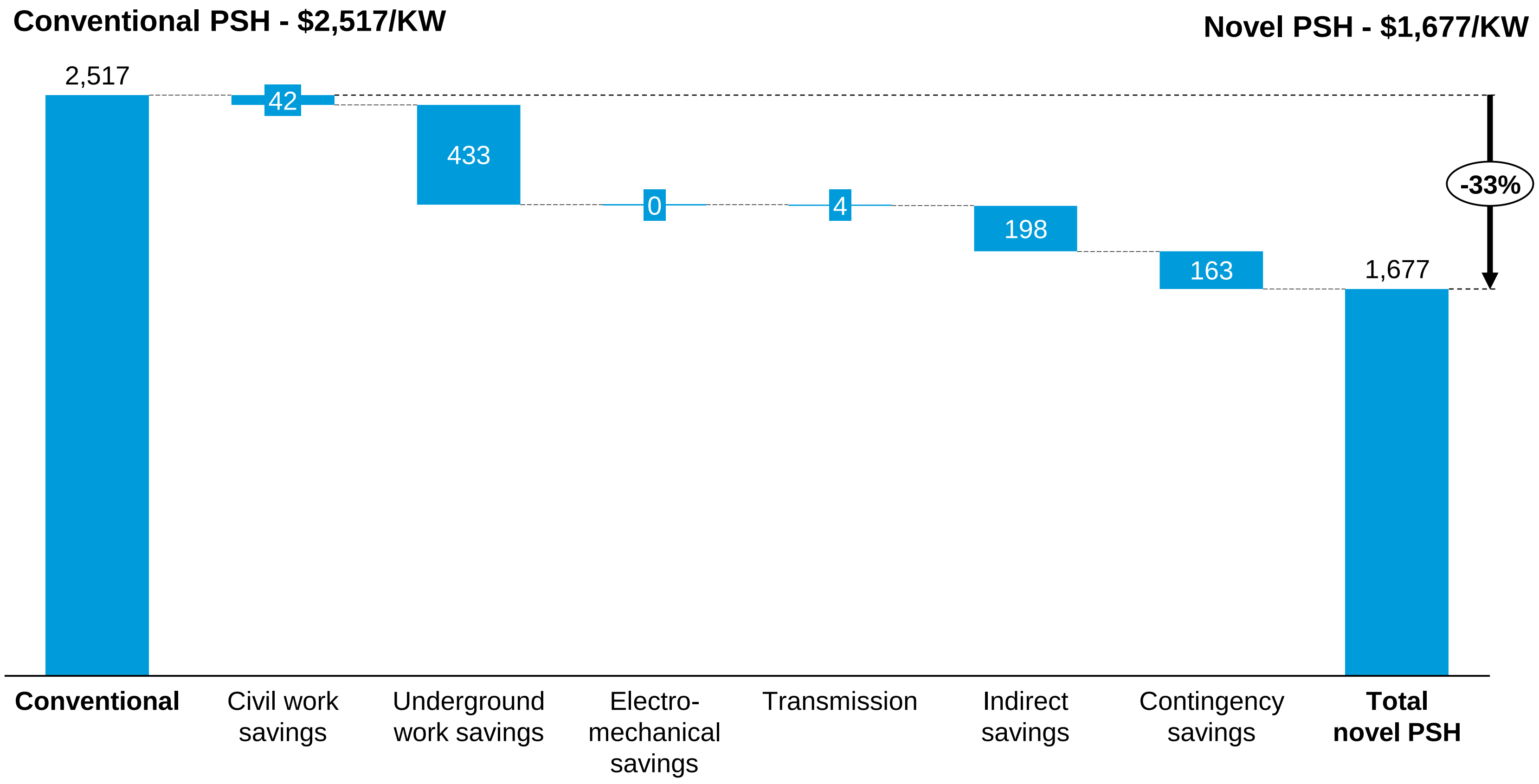
Company	Project	Location	Rated power (MW)	Duration (hrs.)	Status
Quidnet Energy	NYSERDA geomechanical pumped storage	New York, U.S.	2	10	Announced

Source: Quidnet Energy.

Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Novel PSH could drive down cost by ~30% by requiring less underground work and savings on indirect and contingency costs

Cost saving for conventional PSH vs. sample novel PSH, 2019 USD/KW



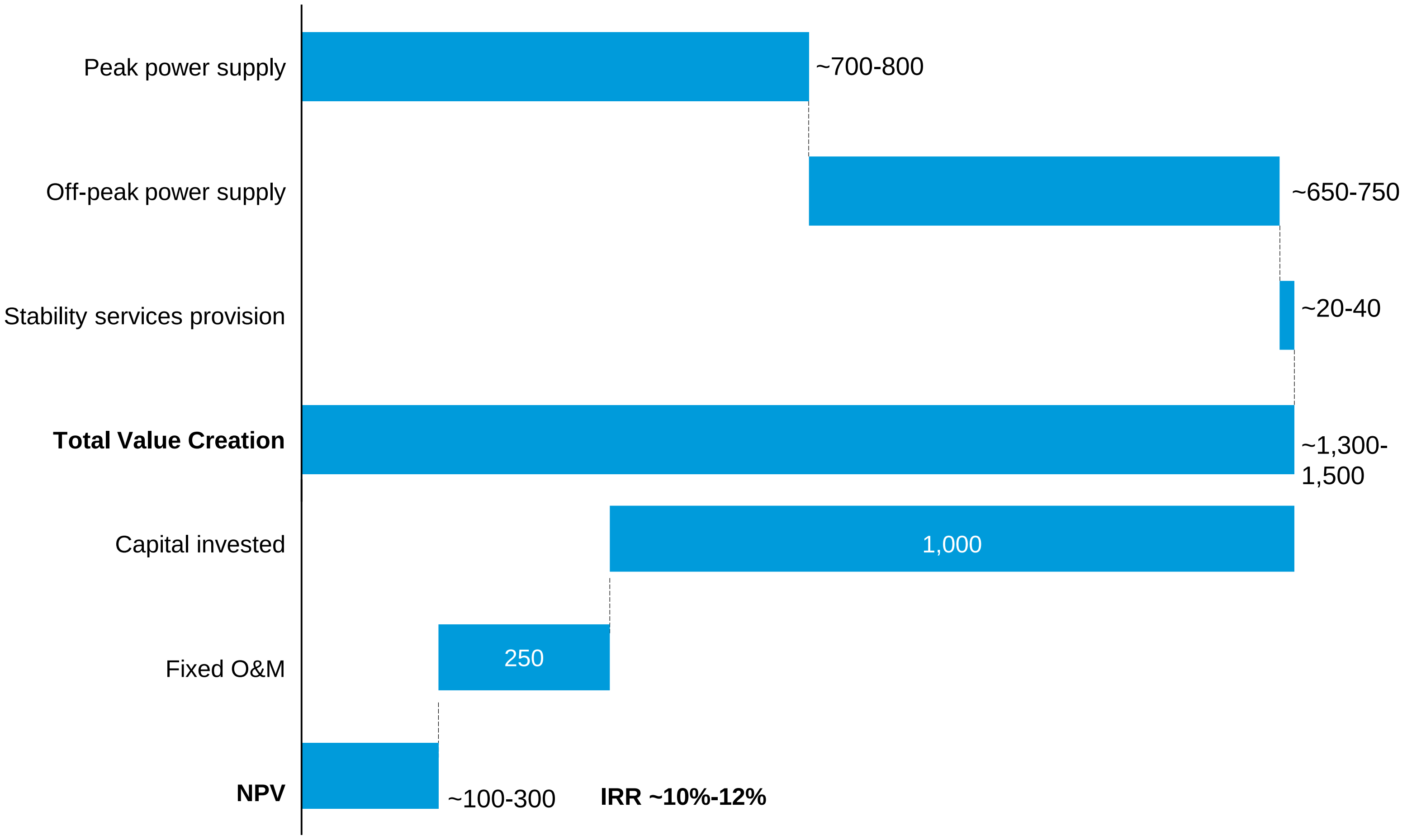
Observations

- Novel PSH technologies represent a transformative evolution in the field of energy storage. Unlike conventional PSH systems, which often require extensive aboveground infrastructure and are limited by geographical constraints, novel PSH designs utilize innovative underground and resource-efficient methods.
- Novel PSH designs offer significant cost savings, reducing costs from **$2,517/KW to $1,677/KW**, due to more **efficient underground work and optimized civil works**.
- Novel PSH technologies are expected to outcompete conventional, large-scale aboveground PSH, **leveraging innovative designs to minimize resource-intensive construction and thus accelerate project timelines**.
- The anticipated outperformance of novel PSH technologies over conventional large-scale projects could lead to **broader adoption and integration** by encouraging **private investment** in projects with more clear timelines and **shorter payback periods**.

Sources: DOE, Cost Effective Small Scale Pumped Storage Configuration (2019); DOE, Review of Technology Innovations for Pumped Storage Hydropower (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Novel PSH projects in India with the potential to achieve 10%-12% IRR

Net Present Value for a renewable developer, USD$M



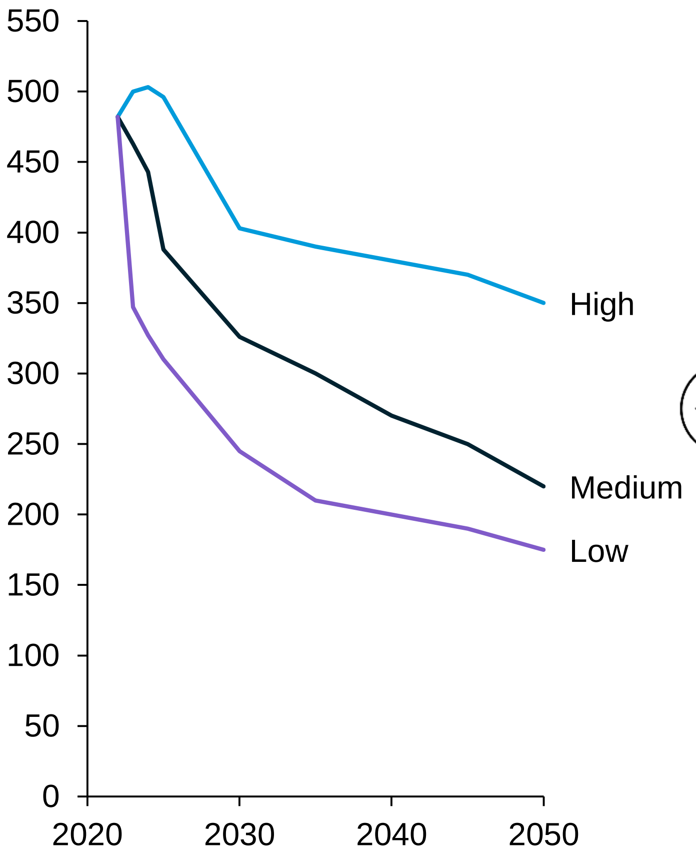
Observations

- A renewable developer in India is combining renewable energy with novel pumped storage hydro to achieve attractive **internal rates of return**.
- India's electricity demand is projected to rise sharply due to increased electrification of sectors like heating and transportation. Decarbonizing India's power supply will require the adoption of **flexible solutions like PSH** to manage demand and grid stability.
- The novel PSH system could experience **a faster cost reduction trajectory**, leading to higher returns.
- The case modeled was a six-hour PSH **300 MW/ 1800 MWh** system in combination with **600 MW** of contracted hybrid renewable energy (solar and/or wind).
- Assumptions: **2021 investment decision date**
- Commercial operation date: **2023**
- **WACC: 10%**
- RE cost outlook: **Midpoint scenario**
- PPA contract duration: **20 years**

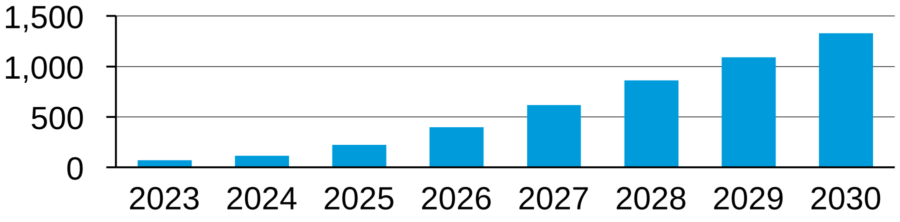
BESS set to dominate the energy storage market as capital costs continue to decrease

Projected trend of BESS

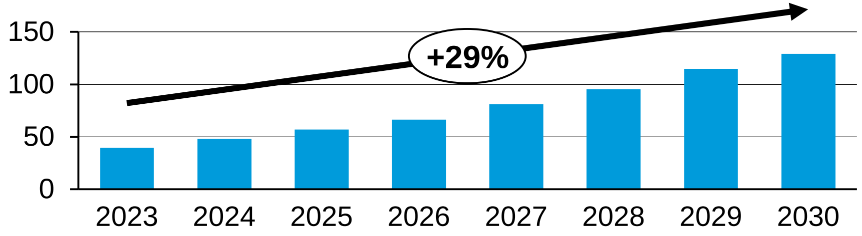
4-Hr BESS capital cost, 2022 $/kwh



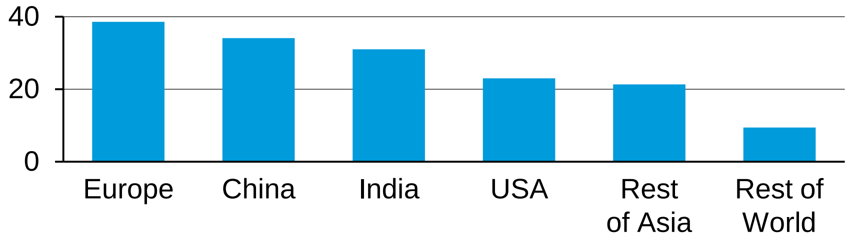
NZE global installed electric capacity of BESS, GW



BESS market size projections, USD billions



Prospective BESS capacity by country in 2026, GWh



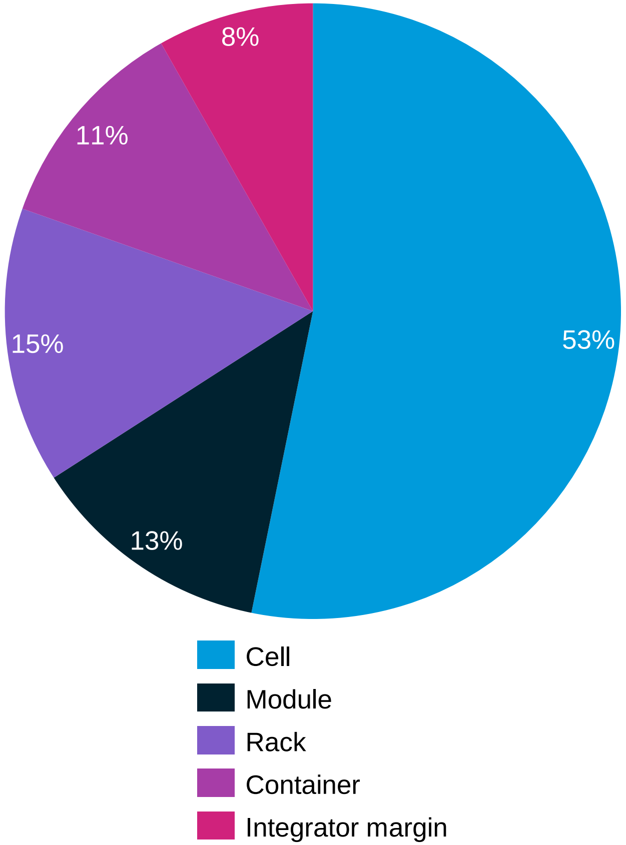
Observations

- **Battery energy storage systems** are set to dominate the global energy storage market with installed capacity expected to grow significantly through 2030.
- **Europe** leads the prospective BESS capacity for 2026, followed closely by **China, India, and the United States**.
- The BESS market size is projected to expand by **29% by 2030**, which reflects heightened demand fo**r energy storage solutions to accommodate flexible grid management**.
- Growth in the BESS market is expected to expand partly due to the **forecasted drop in capital costs**, potentially dropping below **$200/kWh by 2050**.
- China is expected to experience one of the largest increases in BESS capacity given its **access to necessary resources**.
- **India and** the **United States** are positioned to ramp up their BESS efforts.

Sources: BloombergNEF, New Energy Outlook (2024); McKinsey, Battery energy storage systems (2023); IEA, Battery storage capability (2021); NREL, Cost Projections Utility-Scale Battery Storage (2023)
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

BESS cost declines driven by advancements in cell and pack technology; further improvements needed to reduce system costs

U.S. manufactured DC container price breakdown, unsubsidized



Price direction ↓ ↔ ↑

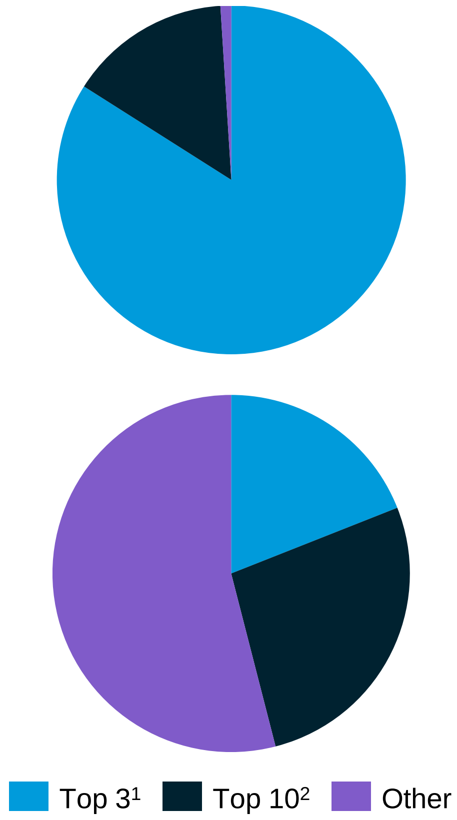
Category	Component	Key commodity	Price outlook
Cell	LIB cell COGS	Lithium carbonate	↓
Cell	LIB cell COGS	Synthetic graphite	↑
Cell	Profit margins	N/A	↓
Rack	DC racking, container and enclosure	Steel	↓ ↑
Rack	Switchgear and power conditioners	Power electronics	↔
Module	Busbars and cabling	Copper	↑
Module	Assembly/labor	Electronic manufacture	↓
BMS/EMS	Rack/container	Software	↑

Observations

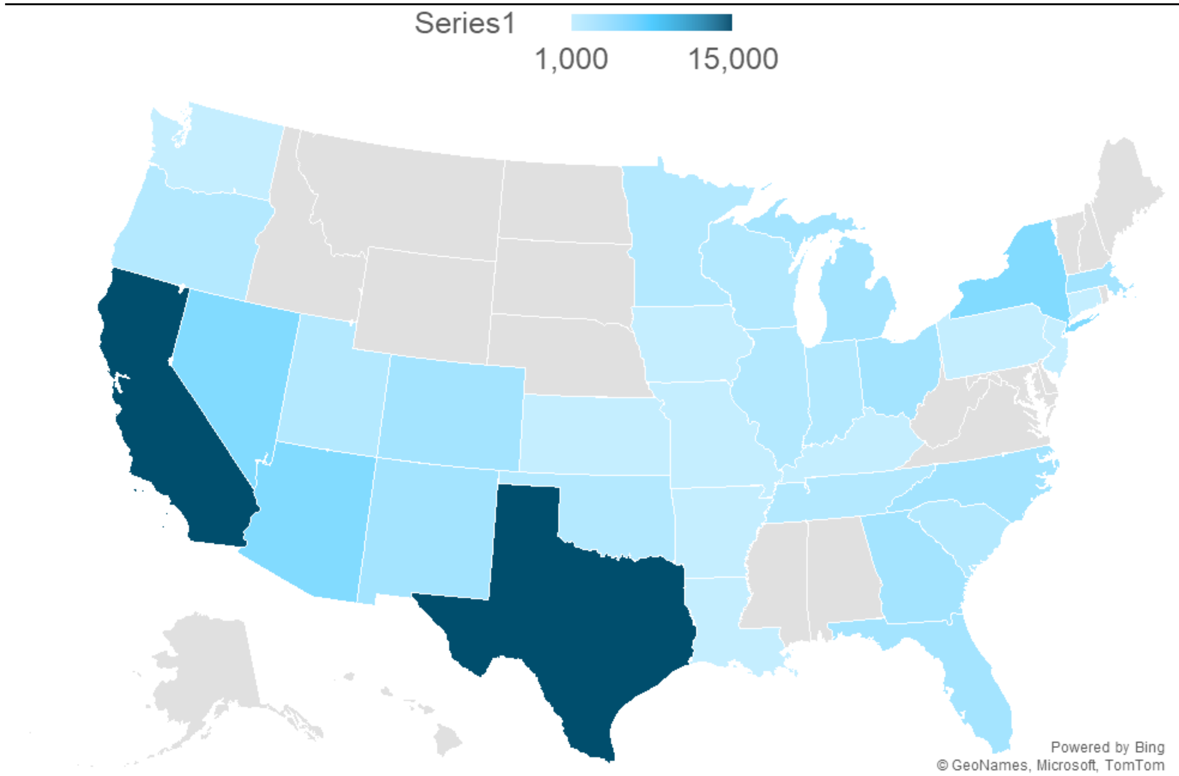
- BESS container prices are primarily driven by **cell COGS and vendor margins**.
- Declining lithium carbonate prices due to **greater supply and investment and weaker than expected near-term EV demand** should improve Li-ion pricing.
- Synthetic graphite, another key part of Li-ion costs, could see rising prices as trends like price weakness due to Chinese overcapacity **and diminished graphite electrode demand** for electric arc furnaces reverse.
- For **steel**, prices have **continued to drop** due to weak global demand, high export levels from China, and supply-side issues. **Future U.S. tariffs** on Chinese steel could lead to **price increases**.
- Competition in the **software** space looks to place upward pressures on personnel costs for industrial controls development.
- **Construction cost** is the area of most variability and holds the greatest potential for cost reduction potential, **e.g., through standardized modular designs**.

In the U.S., California and Texas lead in battery energy storage; other regions have potential for significant growth

U.S. energy storage market share in 2023 vs. 2033, MW



Cumulative grid-scale energy storage volume by state through 2033, MW



Observations

- The U.S. energy storage market is undergoing a shift: Three states held 84% of the market share in 2023, but that is **projected to drop to 54% by 2033**.
- This shows diversification and the entries by other states. States **like Nevada, Arizona, and New York** are looking to significantly increase their capacity.
- Federal incentives and state-level clean energy mandates have played a pivotal role in this growth. States that have battery energy storage system mandates or targets, including **California, Texas, and Arizona**, are expected to remain key players.
- States in the Midwest and Southeast that have historically had lower storage capacity **are expected to see rapid expansions** by 2033.

1) Top three states include California, Texas, and Arizona. 2) Top 10 include previous states plus Florida, Massachusetts, Nevada, Colorado, New Mexico, and New York.
Sources: Wood MacKenzie, US storage sector outlook (2024); EIA, U.S. battery storage capacity (2024).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

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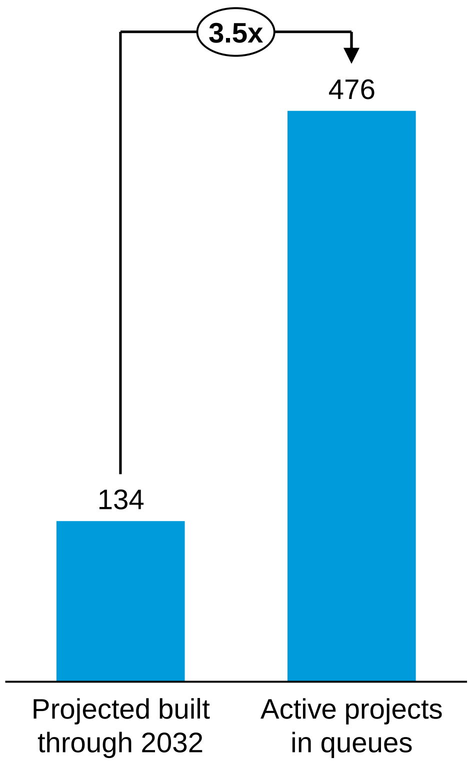
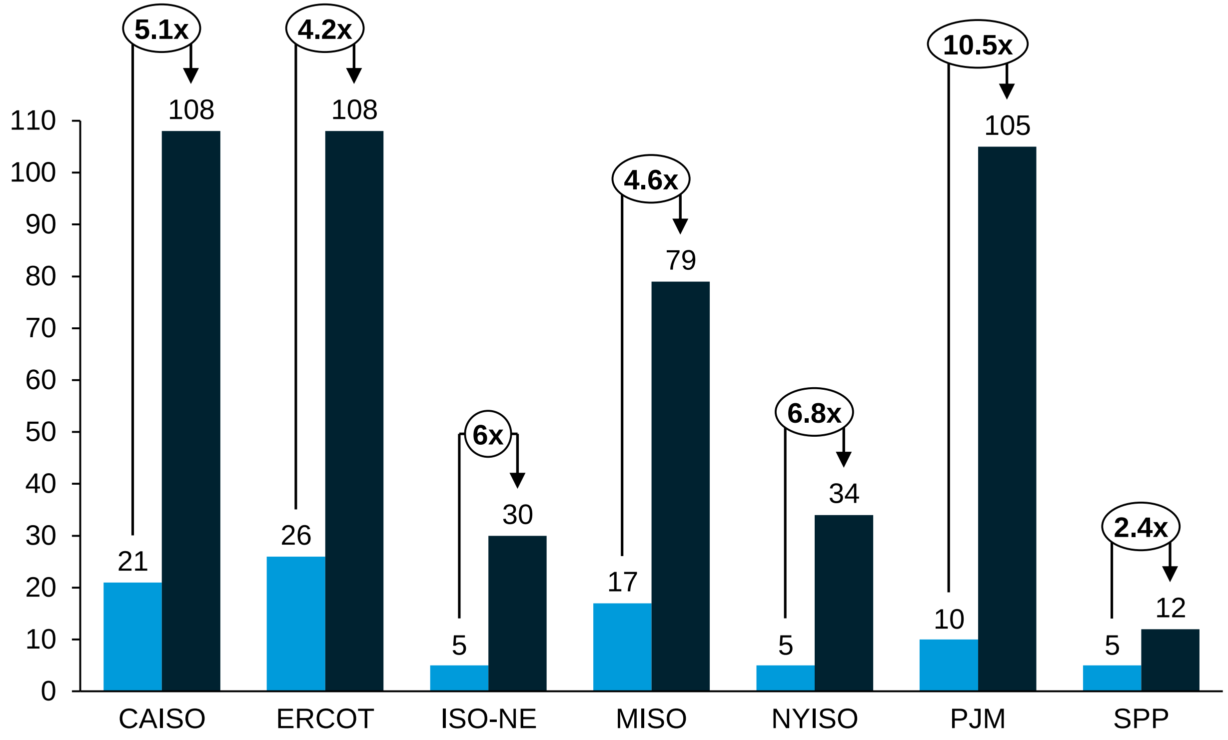
Interconnection queues hindering U.S. energy storage growth; streamlining critical

U.S. projected build through 2032 vs. active-queue capacity, GW



Regional projected storage build through 2032 vs. active-queue projects, GW



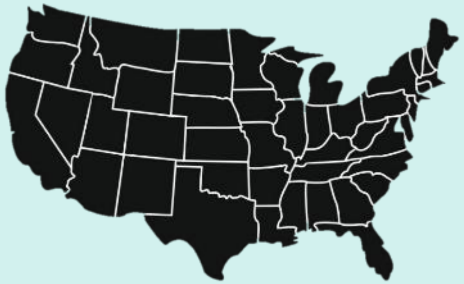
Observations

- The U.S. energy storage sector faces a **3.5x discrepancy** between 134 GW of projected builds and the 476 GW of projects sitting in interconnection queues. This indicates a major bottleneck that could delay or prevent necessary capacity from being deployed.
- **CAISO (California), PJM (Mid-Atlantic), and NYISO (New York**) are significantly overloaded with five to 10 more projects in queues than their projected builds through 2032.
- As a result, many projects in line **may never be fully deployed due to capacity limitations and process hurdles**. This poses a risk of underdelivery on the critical capacity needed for renewable integration and grid stability.
- **Streamlining the interconnection process** represents a major opportunity to **unlock tens of GWs** of storage capacity, ensuring the U.S. stays on track for its goals.

Source: Wood MacKenzie, US storage sector outlook (2024).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Three potential technological solutions to debottleneck grid interconnections currently being explored and developed

1 Grid integration



Horizontally integrating the grid would require **development of interconnections** between individual ISOs and **uniting grid control under a single operator**.

This would unlock the potential to **balance load across time zones and climates**, significantly smoothing out the load curve.

2 Smart grids

Smart grids utilize an array of sensors, smart meters, and control devices to **maximize optimization potential and prevent grid instabilities**.

A fully developed smart grid enables full demand response and **ensures maximum flexibility on both supply and load sides**.

3 Vehicle-to-grid (V2G)

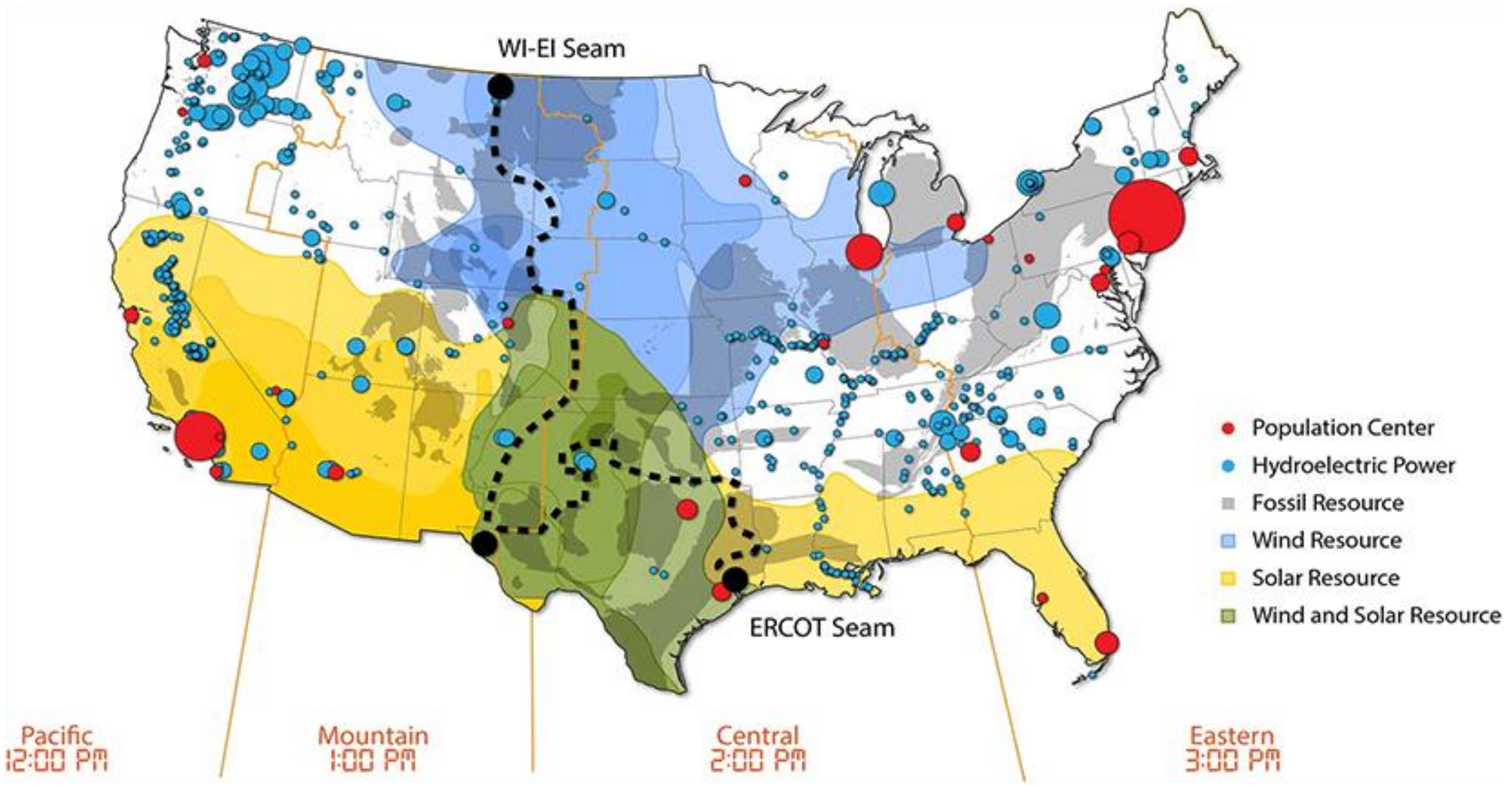
V2G technology allows EVs to act as a modular battery energy storage system, significantly expanding the total storage capacity of the grid.

Significant development is required in both the hardware and software infrastructure as well as in market design and compensation.

Sources: GridX; Prysmian.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Horizontal grid integration a potential option for optimizing cost and improving grid stability

Integration challenges and opportunities for a national power grid



Observations

- The U.S. operates three primary power grids: the Eastern Interconnection, Western Interconnection, and ERCOT. These grids function **independently, with little interconnection**.
- A horizontally integrated national grid would better handle extreme weather events by allowing power to flow to **areas in crisis, such as Texas during its 2021 storm**.
- Studies have found that an integrated nationalized grid could provide **consumer savings of up to $47.2 billion by optimizing grid efficiency and reducing congestion**.
- Creating a national grid would involve many challenges, including **resistance at the state level**, **pushback from the fossil fuel industry**, and the **technological complexity of grid integration**.
- Engaging in such a project could cost as much as $4 billion to $5 billion and would be paid for by taxpayer dollars.

Sources: American Security Project, Why the US Needs a National Power Grid (2021); Texas Scorecard, Is Nationalizing the Power Grid the Answer? (2024); NREL, Interconnections Seam Study; ACORE, Energy Assurance Depends on a Resilient Transmission Grid (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Smart grids address grid instability with real-time monitoring and automation

Components of a smart grid

Smart meters

Smart meters measure consumers' real-time energy consumption, providing detailed information on consumption patterns to both the consumer and the energy provider.

Sensors and automation devices

These are installed throughout the grid to monitor voltage, current, and load capacity. They can automatically adjust parameters to prevent overloads and prolonged, large-scale blackouts.

Communication networks

The backbone of any smart grid, communication networks facilitate the transmission of data between various components, including sensors, automated devices, and control centers.

Software and analytics

Smart grids generate massive amounts of data. To manage, analyze, and interpret this data, utilities rely on advanced software and analytics tools.

Differences between a conventional grid and a smart grid

Category	Conventional grid	Smart grid
Consumer desire	Does not allow customers to choose how they acquire electricity.	Provides customers with access to a range of power sources.
Distribution system	Requires unidirectional power transmission. Power from primary plants is distributed using traditional infrastructure.	Enables electricity supply in both directions. A supplementary power source provides electricity to customers.
Power plant monitoring	Utilizes manual monitoring for energy distribution.	Employs cutting-edge technology and can self-monitor to reduce power outages.
Method of energy control	Energy suppliers have limited control over the energy they supply.	Offers better control over electricity distribution through smart grid technologies and sensors.
Power restoration and maintenance	Personnel travel to the physical location of a distribution system breakdown for maintenance and repair.	Uses sensors to detect and repair anomalies without requiring a physical presence.
Technological aspects	Uses electromechanical power, resulting in limited internal regulation and communication.	Employs digital technologies to give devices autonomy and enable communication.
Addition of sensors	Limited control over infrastructure restricts the use of sensors, making flaw detection harder.	Enables the installation of multiple sensors along the line, aiding in fault detection.

Sources: IBM, Optimizing energy production (2023); Heliyon, Recent developments in smart grid (2024).

Investments in smart grids are underway across the world, aiming to bolster resilience and enable renewables implementation

International plans to invest in smart grids

Countries	Highlight
EU	Presented an EU action plan, “Digitalisation of the energy system,” at the end of 2022. Plans to spend about **$184 billion** on **grid digitization** by 2030.
China	Plans to spend an equivalent of **$442 billion** on **modernizing and expanding power grids** between 2021 and 2025.
Japan	Announced plan in 2022 to invest an equivalent of **$155 billion** to promote smart power grid investments.
India	Launched a **$38 billion** program in 2022 mandating **installation of smart meters** across the country.
U.S.	Announced the Grid Resilience and Innovation Partnerships (GRIP) program in 2022, with up to **$10.5 billion** available to support the **upgrade and expansion of U.S. electric grids**.
Canada	Is investing **$100 million** through its Green Infrastructure Smart Grid Program to support the **development of smart grid technologies** and smart integrated systems.

Legislative and regulatory actions on grid modernization in Q1 2024

Observations

- Several major countries have invested in smart grids as part of broader grid modernization efforts to enhance **grid resilience, efficiency, and digitization**.
- **Forty-nine U.S. states and Puerto Rico** engaged in actions related to grid modernization during the first quarter of 2024.
  - **A total of 567 grid modernization actions** were taken, with New York, Massachusetts, Michigan, California, Connecticut, and New Jersey taking the greatest number of actions during the quarter.
- Several states, including **Maryland and Colorado,** also passed legislation on **virtual power plants,** which utilize the capabilities of smart grids as a backbone.

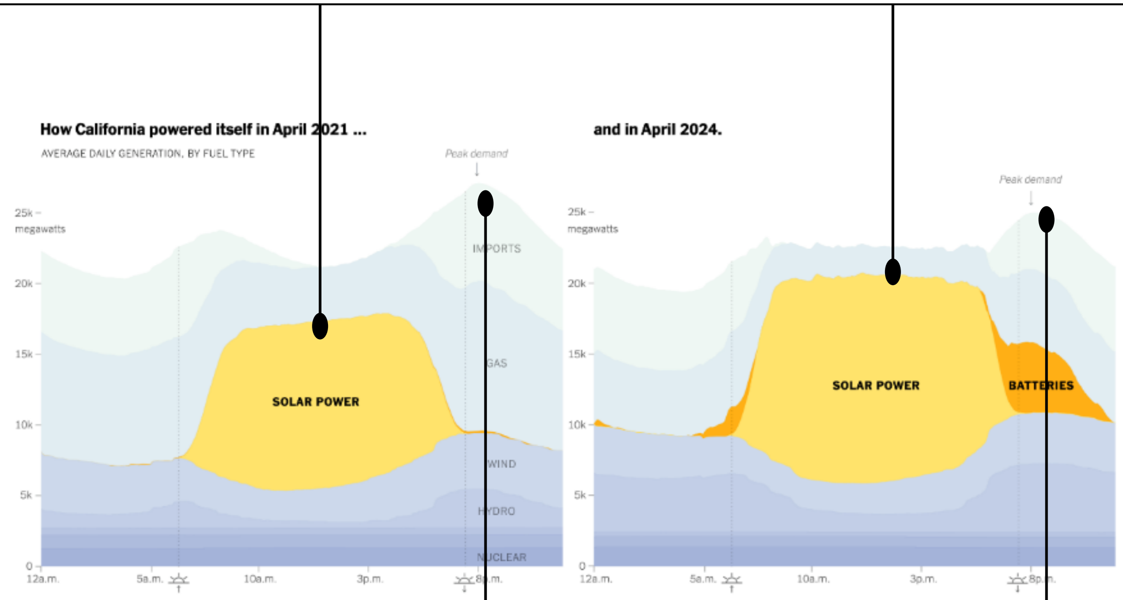
Sources: NC Clean Energy, 50 States of Grid Modernization (2024); IEA, Smart Grids.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Renewable energy and EV growth cause volatility in the electricity system; batteries have significantly improved grid stability

California grid net load in April 2021 vs. 2024 impacted by battery installation, MW

Midday solar abundance

With significant battery integration, the midday solar power excess is absorbed and stored, smoothing out the excess energy spike that used to create the "duck's belly." This results in a more stable and flattened curve.



Evening peak

Batteries discharge stored energy during the evening peak, reducing the steep rise in demand for conventional power sources. This leads to a less abrupt increase in grid load, stabilizing the grid and minimizing the 'neck' effect seen in the traditional 'duck curve.'

Observations

- The **growth of solar power and electric vehicles has caused instability in the grid**:
  - During midday, the abundance of solar energy significantly reduces the grid's net load, while peak demand at night requires conventional energy sources to ramp up quickly to meet the demand.
  - The increasing adoption of electric vehicles also results in a substantial rise in electricity demand in the evening.
- **Integrating batteries into the grid has reduced the frequency and severity of grid instability events**, such as blackouts and brownouts:
  - Economic benefits include reduced costs associated with grid instability and less frequent need for expensive emergency interventions.
  - Public safety improves, as critical services are less likely to be disrupted.

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Source: NYT, Giant Batteries Are Transforming the Way the U.S. Uses Electricity (2024).
Credit: Xiaodan Zhu, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

EVs could serve as an additional measure against grid instability, providing energy storage capacity through V2G technology

Deep dive next

Solutions to reduce grid instability	Description	Effectiveness
Energy storage incentives	• **Battery storage**: Deploy batteries to store excess energy during low demand and supply it during peak demand. • **Pumped hydro storage**: Develop large-scale hydro storage systems to balance supply and demand.	• Battery storage: 1,000 MW in California, reducing ramp by 20%. • Pumped hydro storage: Large-scale solutions.
Demand response programs	• **Time-of-use pricing**: Encourage consumers to shift usage to off-peak times with variable pricing. • **Incentives for load shifting**: Offer incentives for industrial and commercial users to reduce or shift energy use during peak periods.	• Time-of-use pricing: Shifts 15% residential use. • Demand response: Reduces peak by 30%.
Grid modernization	• **Smart grid technologies**: Invest in smart meters, grid automation, and real-time monitoring to enhance grid management. • **Infrastructure upgrades**: Strengthen transmission and distribution networks to handle variable energy sources efficiently.	• Smart grid tech: Reduces peak by 30%. • Flexible infrastructure: Enhances balancing.
Vehicle-to-grid (V2G)	• **Bidirectional charging**: Enable EVs to discharge electricity back into the grid during peak demand times, acting as distributed energy storage. • **Incentives for V2G**: Provide financial incentives for EV owners to participate in V2G programs.	• **Nuvve Corporation Pilot Programs**: In several pilot programs, Nuvve has demonstrated that V2G **can reduce peak demand by up to 15% to 20% in participating regions**. For instance, a pilot in Denmark showed significant peak shaving during high demand periods. • **UK Power Networks:** A study by UK Power Networks found that V2G could help **reduce peak load by 10%,** thus delaying the need for grid infrastructure upgrades.

Sources: Nuvve Corporation, Pilot programs; UK Power Networks, TransPower Vehicle to Grid; Governor of California, 10,000 Megawatts of Battery Storage (2024); Brattle Group, Time-of-use rate (2019); DOE, Smart Grid; PNUCC, Northwest Regional Forecast.
Credit: Xiaodan Zhu, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Vehicle-to-grid (V2G) could act as a mobile BESS and play a key role in stabilizing the grid without the need for a grid upgrade

Grid Compliance	G2V/H[1]	V2B/H[2]	V2G

Level 0 | Level 1 and Level 2 | Level 3 | Level 4

Use Cases

Level 0
- Simple charging

Level 1 and Level 2
- Time-of-use and self consumption
  - Load shifting
  - Peak shaving
  - Priority charging
- Demand response participation
  - Implicit demand response (price signals)
  - Explicit demand response (control signals)

Level 3
- Backup power, discharge, and self-sufficiency

Level 4

Full-level grid services

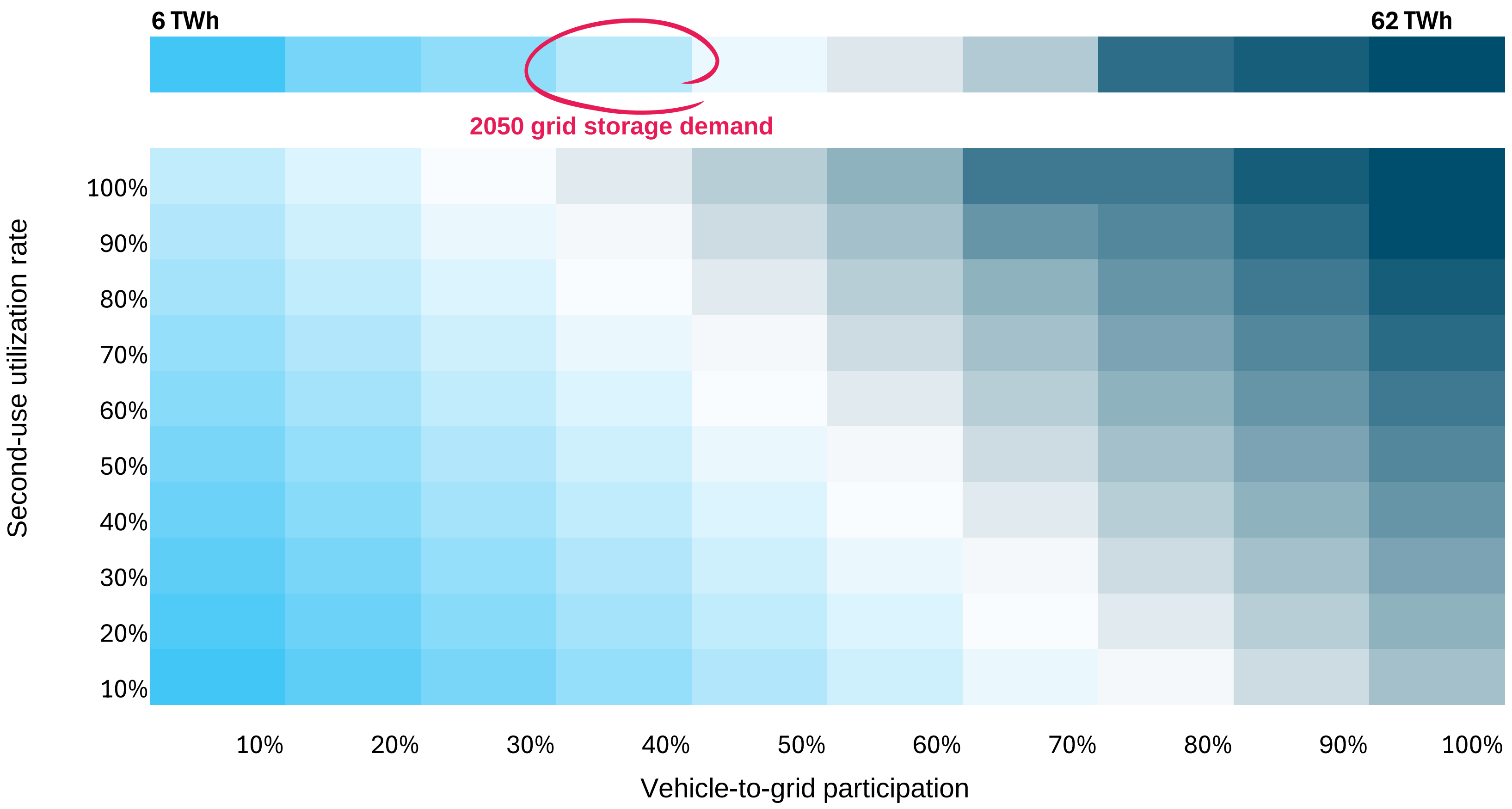
Feed energy back into the grid for:

- Power quality and voltage control
- Congestion management and curtailment
- Reserve and frequency services, etc.

1) Grid-to-vehicle/house smart demand response; 2) Vehicle to battery/house.
Source: CRA, Introduction to V2G (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

V2G could single-handedly satisfy grid storage demand; up to 62 TWh to be unlocked in combination with second-use

Total actual available capacity under various conditions in STEP-NCX scenario in 2050



Observations

- V2G participations plays a role in determining the **real-world capacity for short-term grid storage** using EV batteries together with second-use utilization rates.
- When both V2G participation rates and second-use rates are **at 50%,** the projected real-world capacity reaches **between 25 and 48 TWh by 2050** (STEP-NCX scenario).
- For participation rates between **23% and 96%,** the impact on capacity ranges from **-24% to +21%,** respectively. This indicates the impact V2G adoption could have.
- Meeting grid storage demands by 2050 (3.4 to 19.2 TWh) can be done with different combinations of V2G and second-use. **Without any second-use batteries** in stationary storage, grids would require V2G participation rates of an **achievable 12% to 43**%.
- **Assuming half of second-use batteries** are used for grid storage, the required participation rate of V2G **drops to below 10%.**

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Source: Nature, Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030 (2023).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Large barriers to widespread adoption and scaling of V2G exist at different stages in the value chain

Electric vehicles

- Only a few EV models on the market fully **V2G-compatible**
- Messaging from OEM dealerships often unclear.

EV chargers

- V2G chargers have 5x to 10x **price premium**
- **Limited compatibility** with latest ISO standards
- **Little availability** of V2G-ready AC chargers

Consumers' home

- Lack of **consumer awareness** about V2G
- **Strict requirements for consumers** to participate in V2G, such as the EV needing to remain plugged in at specific times of day

Power grids

- While larger hubs can adopt procedures similar to those for BESS, **fewer established processes exist** for on-street chargers
- Little low-voltage grid visibility and smart meter adoption

Regulators

- **Underdeveloped regulations for** flexible procurement limit revenue streams available to V2G systems
- **Regulatory enforcement** of V2G standards and protocols is early stage and remains rare

Source: CRA, Introduction to V2G (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

The most promising V2G applications are frequency control and load leveling; charging power and efficiency can enhance benefits

Factors influencing the net revenue of V2G business

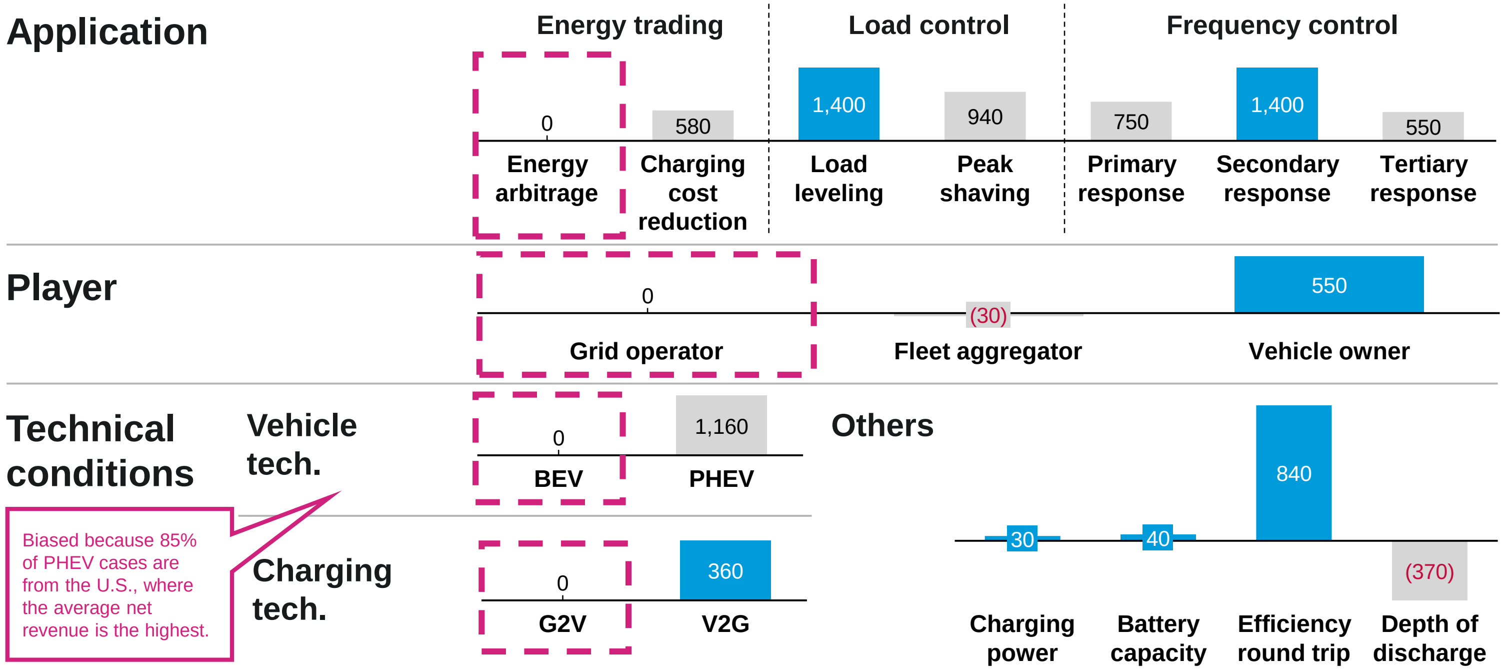
Base case (intercept) | Key profitability factors

Relative effects of key factors on net revenue, €

Numbers on the right are **regression coefficients** from a multivariate model with:

- Dependent variable: **net revenue (revenue - battery degradation cost)**
- Independent variables: **applications, players, technical conditions, market conditions, control variables**

The larger the positive coefficient the independent variable has, **the higher the net revenue** observed



Other factors

- The effect of the following variables needs to be further investigated as more data accumulates:
  - **The number of PEVs** in relation to the balancing market size could be a critical factor, as the revenue from both frequency and load control markets decrease with an increasing number of participants in the market.
  - **Charging locations** (e.g., home, work, public charging stations) influence charging timing and thus the suitability for time-sensitive applications.
  - More data points are needed for meaningful analysis on the impact of **market conditions** such as **RES share, electricity price, energy archetype, and countries**.

Observations

- **Secondary frequency response and load leveling** are expected to be V2G's most beneficial use cases.
- **Individual vehicle owners** seem to generate higher revenues than aggregated fleet operators or grid operators.
  - However, **grid operators may enjoy additional advantages** by counteracting negative impacts from RES generation.
- **Technical variables** will play a crucial role in shaping the vehicle and charging technology:
  - **A higher charging power** enhances the flexibility.
  - **A higher round-trip efficiency** significantly boosts benefits by minimizing the system losses.
  - **A greater battery capacity** has a notable positive effect, as it increases revenue potential and reduces battery degradation by lowering the number of charge cycles required.

Source: Renewable and Sustainable Energy Reviews, Factors influencing the economic success of grid-to-vehicle and vehicle-to-grid applications (2021).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Key regions implementing policies to advance V2G adoption

Policies in select regions

	V2G pilot project with EV batteries in North Carolina	Electric school bus effort in Beverly, Massachusetts	Electric school bus powers V2G in Durango, Colorado	New York City government moves to all-electric fleet
Vehicle	**Passenger light-duty EVs**	**Electric school buses (MHD EVs)**	**Electric school buses (MHD EVs**)	**Passenger light-duty EVs**
Description	Roanoke Cooperative partnered with Fermata Energy to carry out a V2G pilot project in North Carolina. The project looked at the financial value provided by V2G using the batteries in an EV when the vehicle was parked at home and assessed how the EV could contribute power to the grid during periods of high demand and grid strain.	In a V2G pilot carried out by New England utility National Grid during the summer of 2021, an electric school bus was used to provide power to the grid to **reduce grid strain** during peak demand. The project was an early instance of an electric school bus being used for V2G.	Colorado got its first V2G-compatible electric school bus in 2021 as part of a collaboration between the V2G tech company Nuvve, bus manufacturer Blue Bird, and electricity distribution co-op La Plata Energy Association (LPEA). Durango School District 9-R was also provided with infrastructure to support the bus's use in V2G, like a bidirectional charging station. The district can **use the electric bus to pick up students — incurring cheaper fuel costs in the process — as well as to supply energy to the grid.**	In 2023, it was announced that all city government vehicles will have to be fully electric by 2038 and its ridesharing vehicles to be zero emission or wheelchair accessible to 2030. To accompany this, NineDot partnered with Revel and Fermata Energy to **launch New York City's first V2G pilot** at Revel's Red Hook warehouse in Brooklyn to assist peak demand for Con Edison.
Key Takeaways	Using V2G in this way allowed **Roanoke Cooperative to cut down its electricity consumption** during peak usage **by an average of around 14 kW.** It also produced **more than $2,600 a year** in savings for the utility. V2G capabilities became a source of **back-up power** for Roanoke's microgrid, **improving resilience** during periods when it was operating independently.	The electric school bus was utilized **30 different times** that summer, working for more than 50 hours and delivering nearly 3 MWh of electricity to the grid — roughly **the amount of electricity used by 100 homes in a day**. School buses are an especially good fit for efforts like these because they are often underutilized, especially in the summer, when electricity demand is high.	The Colorado effort was largely **funded by a state alternative fuels grant, with additional funding provided by LPEA**. In a given afternoon, the bus might charge for a period — powered by extra solar energy — then transport students home from school, before an evening of supplying the grid with energy, helping balance out high electricity demand.	*TBD*

Sources: Electrification Coalition, Advancing V2G Technology Adoption (2022), Nine Energy, NYC EV charging solutions, NYC Government Vehicles, NYC Ride Share
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

The energy storage opportunity

Mobility energy storage

Utility energy storage

Technology

Opportunities and unlocks

Case study

Quidnet Energy's journey from innovation to commercial

- Technological Developments
- Financial Developments
- Operational Developments
- Business Developments

Quidnet Energy

First foray into novel pumped storage

Timeline

- Formation of Quidnet – 2013
- Initial pilot project in Texas – 2016
- Series A funding – 2017
- ARPA-E award – 2018

Highlights

- **2013 –** Quidnet is founded with the goal of exploring energy storage using subsurface rock formations. In its initial years, the company refines the concept of **geomechanical pumped storage**. This novel pumped storage hydropower technique looks to leverage subsurface reservoirs to store energy by pressurizing water underground.
- **2016** – Quidnet gains momentum after securing seed funding, allowing the company to initiate pilot projects in Texas.
- **2017 – Breakthrough Energy Ventures** leads Quidnet's Series A funding.
- **2018 – ARPA-E** awards Quidnet $3.3 million grant to continue expanding research and development of geomechanical pumped storage.

Department of Energy support of supercharged scaling

Timeline

- New York State contract – 2020
- SCALEUP – 2021
- Commercial agreement with CPS Energy – 2022
- 300 MW partnership with Hunt Energy Network – 2022

Highlights

- **2020 –** Quidnet closes a Series B round of $10 million backed by **Breakthrough Energy Ventures and Evok Innovations**. The funding helps scale operations and secure a contract **with the New York State Energy Research and Development Authority (NYSERDA**) for a 2MW/2MWh project.
- **2021–** Quidnet receives **ARPA-E SCALEUP** funding to retire technical risks associated with the deployment of geomechanical pumped storage.
- **2022** – Quidnet enters into a 15-year commercial agreement with **CPS Energy in San Antonio, Texas**. The partnership involves deploying a 10Mh system, which becomes its first commercial-scale implementation of geomechanical pumped storage.
- **2024:** Quidnet announces a 300MW partnership with a $10 million investment from **Hunt Energy Network**.

Sources: Quidnet, ARPA-E, Quidnet Energy.

Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Natron Energy pioneers the commercialization of SIBs

Technological Developments
Financial Developments
Operational Developments
Business Developments

Natron Energy

	Early battery innovation and market entry		Accelerated research and strategic partnerships				Commercial-scale expansion and industry leadership		
Timeline	Formation of Alveo Energy	ARPA-E GRIDS	Rebrands to Natron Energy	Strategic investment from Chevron Technology Ventures	H5 adds Natron Energy technology to campus	Natron raises Series D to expand	Natron announces first-ever UL-listed sodium-ion battery	World's first production of battery-grade Prussian blue	First-ever commercial-scale production
	2012	2012	2017	2019	2020	2020	2020	2022	2023

Highlights

Early battery innovation and market entry

- **2012 –** Colin Wessells and other researchers from Stanford University found **Alveo Energy** with the goal of developing **sodium-ion battery (SIB) technology** using **Prussian blue analogs**.
- **2012** – ARPA-E grants Alveo Energy funding through its Grid-Scale Rampable Intermittent Dispatchable Storage **(GRIDS)** program.

Accelerated research and strategic partnerships

- **2017** – The company rebrands from Alveo Energy to **Natron Energy** to reflect its focus on commercialization of its sodium-ion technology.
- **2019 –** Natron closes strategic investment from Chevron Technology ventures to support the development of stationary energy storage systems for demand-charge management at EV charging stations.
- **2020** – Colocation provider H5 adds Natron Energy technology for test installation of cooling at its data center campus in Phoenix, Arizona.
- **2020** – Natron raises **$35 million in Series D** financing to expand sodium-Ion battery commercialization led by **ABB Technology Ventures, NanoDimension Capital, and Volta Energy Technologies**.

Commercial-scale expansion and industry leadership

- **2020** – Natron achieves **an industry first** Underwriters Laboratories (UL) listing of sodium-ion for data center usage.
- **2022 –** Natron and Arxada announce **world's first large-scale production of battery-grade Prussian blue materials**. This enables 600 MW of annual production of Natron's sodium-ion battery products for data center, uninterruptible power supply, and energy storage.
- **2023 –** Natron Energy **achieves first-ever commercial-scale production** of sodium-ion batteries in the U.S., in Holland, Michigan.

Sources: Natron Energy, ARPA-E, Natron Energy.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

World’s largest battery located at Tesla’s Hornsdale Power Reserve

- Technological Developments
- Financial Developments
- Operational Developments
- Business Developments

TESLA

Timeline

The problem and initial engagement		Government response and project planning			Construction, deployment, and impact		
Storms start conversation	Musk and Cannon-Brooks discuss plan	SA government announces plan	SA government opens procurement	Hornsdale Power Reserve forms	ElectraNet connection signed; timeline starts	Battery constructed in under 100 days	Battery responds to downed coal generator
Sept. 2016	March 2017	March 2017	March 2017	July 2017	Sept. 2017	Dec. 2017	Dec. 2017

Highlights

The problem and initial engagement

- **September 2016 –** Storms cause significant and sustained statewide **blackouts in South Australia**.
- **March 2017** – Tesla CEO **Elon Musk** and Atlassian entrepreneur **Mike Cannon-Brookes** begin discussing interest in **a battery solution** to the problem. Musk makes a promise of completion: “**100 days from contract signature or its free.”**

Government response and project planning

- **March 2017** – The South Australian government announces an **AUD$550 million energy plan to increase grid reliability** that, among other objectives, **includes building a 100 MW battery** before the 2017/2018 Australian summer.
- **March 2017 –** The South Australian government opens a two-stage competitive procurement process for national and international companies **interested in constructing the 100 MW battery**.
- **July 2017 –** The **Hornsdale Power Reserve** consortium, **led by Neoen and using Tesla’s battery equipment**, is awarded the contract to build the battery and the project agreement is signed.

Construction, deployment, and impact

- **September 2017** – The grid connection agreement is signed with **ElectraNet**, the electricity transmission network operator, and approved by the Australian Energy Market Operator. **Musk’s 100-day deadline begins**.
- **December 2017 –** The battery is constructed and connected to the NEM, **ahead of the 100-day promise**.
- **December 2017 –** The first opportunity for the battery to respond to a grid stabilization issue arises **when a coal generator in New South Wales shuts down**. The battery **responds to the sudden loss of 689 MW** of generation within a fraction of a second, **faster than any other existing generation technology**.

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Sources: Global Infrastructure Hub, Hornsdale Power Reserve Project, Australia (2019).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

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Attribution: Lucha *et al*., "Storing Energy," Columbia Business School Climate Knowledge Initiative (4 March 2025).

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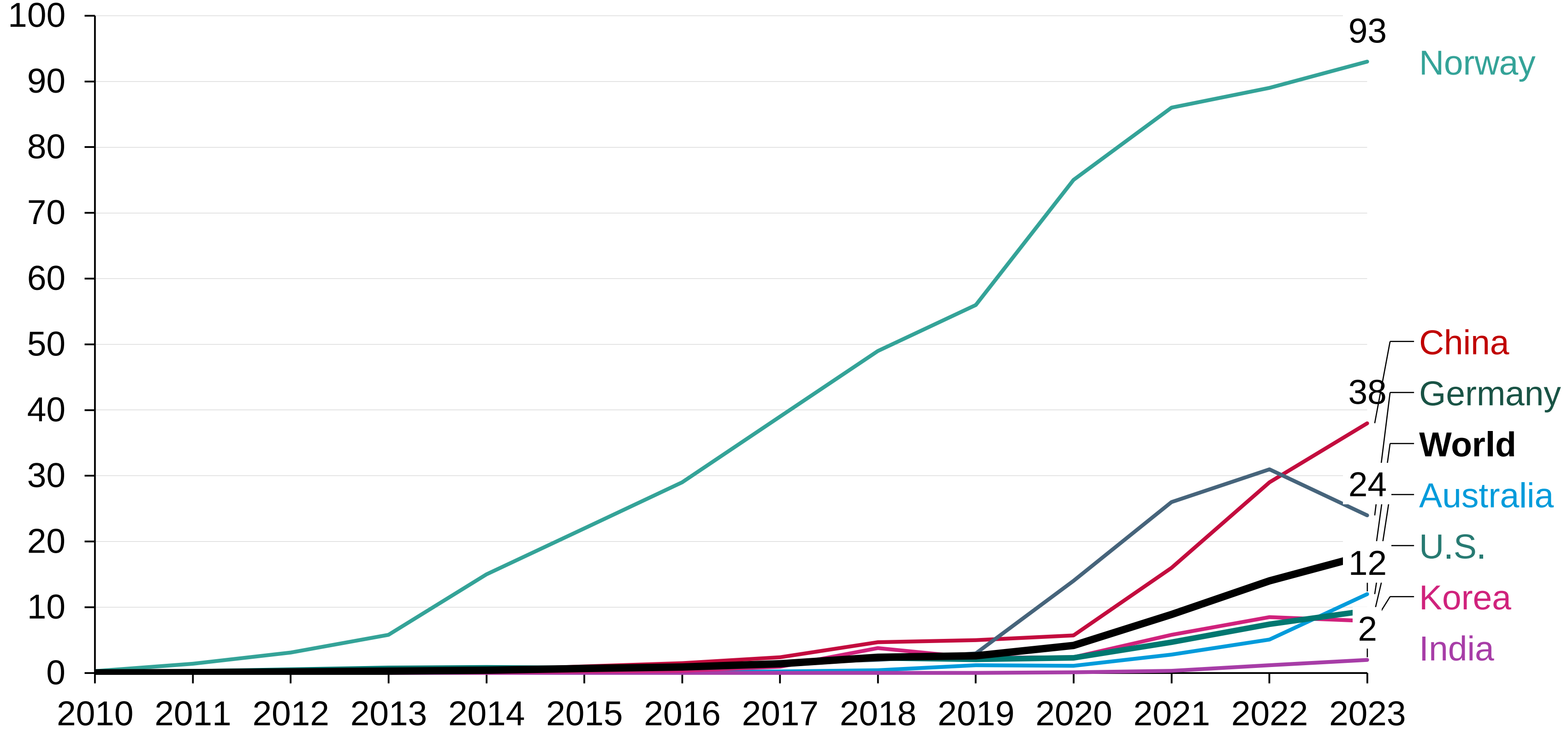
AT THE VERY CENTER OF BUSINESS

Appendix

EV sales are accelerating with uptake rates ranging across countries; Norway leads with 93% share of EV sales in 2023…

Share of EV sales across countries, %



Observations

- **EV sales are accelerating** at different years for different countries; following a similar S-curve, **exponential growth was observed when EV share reached 1%.**
- Most EV leaders are from **high-income countries**, where EV growth is supported by **government policy and financial incentives,** enabling the cost of EV to fall.
- **Norway is currently leading** with >90% share of EV sales, while **China is the biggest EV player**.
- **Norway's key success factors are:**
  - **EV incentives:** Tax breaks for EV users include purchase tax and VAT exemption as well as local incentives (e.g., tolls and parking discount)
  - **EV charging incentives** results in a total of 34,000 charging points as of 2023

Sources: IES, Global EV Outlook - Policy Explorer (2024); ERI, Countries Adopting EVs (2023); IEA, Global EV Data Explorer (2024).
Credit: Devashri Mehrotra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

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…supported by government incentives across the EV ecosystem

Policy overview across select countries/region

	1 U.S.	2 EU	3 China	4 India
Main policy focus	Incentivize industry to **boost domestic growth** in EV ecosystem	Enable **faster permitting, financial support, enhanced skills, and open trade** for net zero projects	A plan to reach carbon peaking before 2030 sets a target for the sales share of **NEVs to reach around 40% by 2030**	Incentivize industry to **boost local manufacturing of EVs and related infrastructure**
Main policies	**Inflation Reduction Act (IRA)**	**Green Deal Industrial Plan** **Fit for 55 package**	**2030 Carbon Peak Action Plan**	**Production-linked incentive (PLI)**
• Raw material extraction	*No specific policies*	**Critical Raw Material Act** (proposal) to ensure security of supply, extraction, and environmental standards	*No specific policies*	*No specific policies*
• Battery and EV manufacturing	**Tax credits** on capital and production cost	**Net Zero Industry Act** (proposal) to scale up manufacturing of clean technologies, including batteries	**Subsidies and tax break**	**Advanced chemistry cell PLIs** to reach a cumulative 50 GWh in domestic manufacturing capacity by 2030
• EV sales	**Clean vehicle tax credit** for EV purchases that meet certain requirements (e.g., % of locally processed material)	**Sustainable and Smart Mobility Strategy** to achieve 30 million passenger ZEV stock by 2030 and nearly all passenger LDV and HDV stock by 2050	**Subsidies and tax break** for EV producers and consumers; **market-based zero-emission vehicle credit system** to replace direct subsidies	**Automobile and auto component PLIs** to incentivize sales of BEV and FCEV and respective components
• Charging infrastructure	**Alternative fuel infrastructure tax credit for EV charging**, including bidirection charging	**Alternative Fuels Infrastructure Regulation** to ensure minimum coverage of publicly accessible recharging points for LDVs and HDVs	**14th Five-Year Plan** targets to achieve high-quality charging infrastructure system by 2030	**FAME Scheme Phase II** targets an additional 7,432 public fast-charging stations by 2024
• Battery recycle	*No specific policies*	**EU Batteries Regulation** mandates that new batteries meet minimum recycled content requirement	**Circular Economy Promotion Law** mandates **extended producer responsibility (EPR),** including battery manufacturers to recycle the products	**Battery Waste Management Rules** (2022) based on **EPR concept**

Observations

- Despite shared goals, each country has distinct approaches; the **U.S., China, and India are heavy on incentivizing** EV growth and battery manufacturing.
- **The U.S. IRA is a strategic catalyst to boost giga factory developments**, due to its significant gap vs. the EU's incentive program.
- **The EU** is the only region with **explicit policies addressing the security of the raw material supply for EV batteries.** This reflects Europe's desire to reduce dependence on foreign sources and ensure sustainable procurement.
- **China and India have an ambitious target for developing charging infrastructures,** a key to increased EV adoption rates.

Sources: IEA, Global EV Outlook – Policy Developments (2023); IEA, Global EV Outlook - Policy Explorer (2024); EU Commission, Compass to boost EU competitiveness; CGEP, IRA and the US Battery Supply Chain (2023); DOE, Tax Credits.
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

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EU policies have addressed entire EV ecosystem, but incentives vary across member states

Detailed EU policies across EV ecosystem

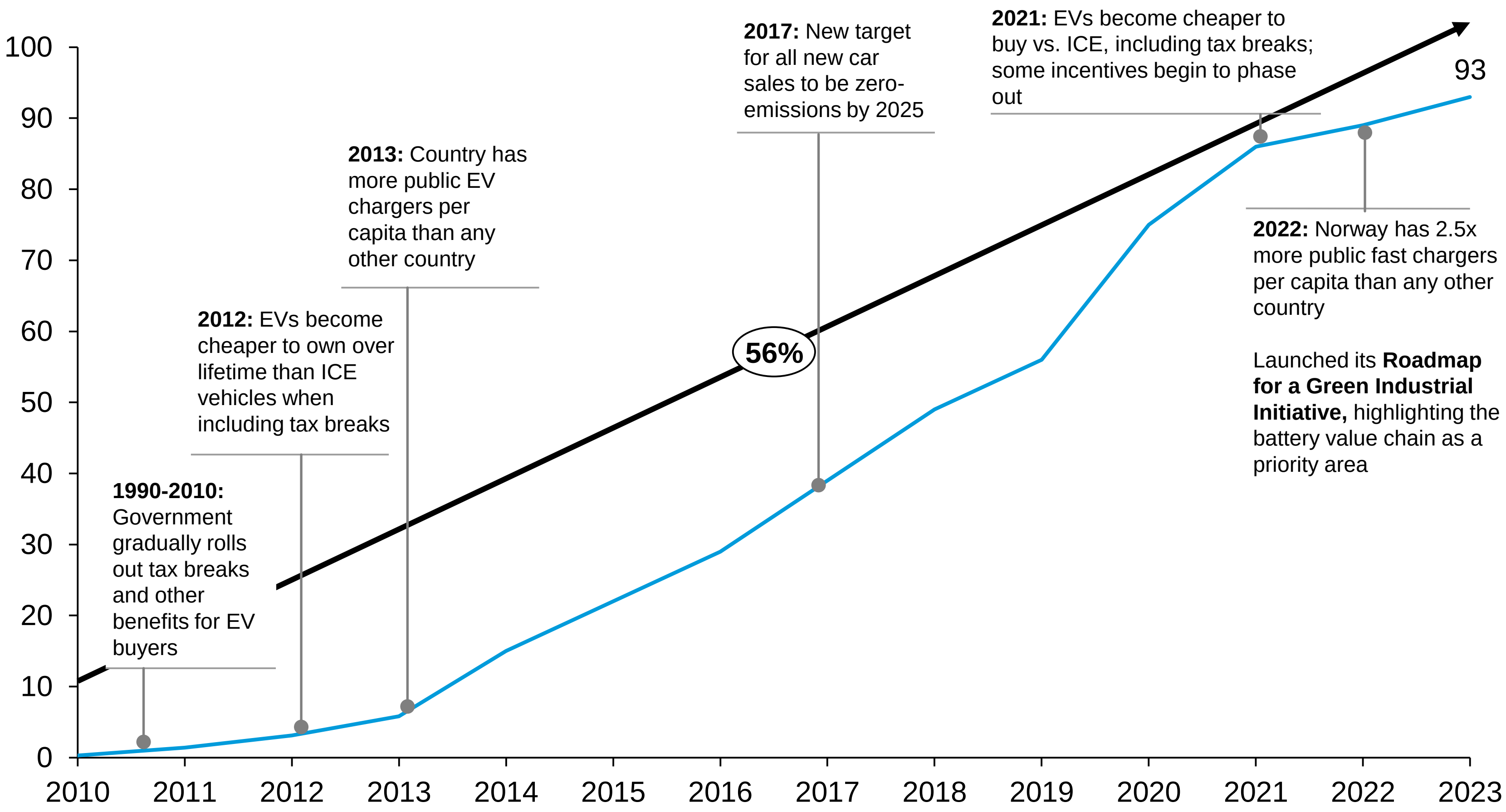
Focus areas	Policy details	Examples by countries
Raw material extraction	**Critical Raw Materials Act (2023 proposal)** focuses on: • **Strategic critical raw mineral** application • **A network of European agencies** to anticipate supply risks • **A resilient supply chain**, e.g., 30% of the EU's demand for refined lithium should originate from the EU by 2030, or to recover at least 20% of the rare earth elements by 2030	**Spain:** Government awards €18.8 million for the construction of Extremadura New Energies' lithium hydroxide plant, located next to the mining site. It reinforced the country's ambition to maintain a leading position in the EU for the development of EV supply chain from locally available critical raw materials.
Battery and EV manufacturing	**Net Zero Industry Act (2023 proposal):** EU battery manufacturers to **meet 90% of EU demand**, with a combined capacity of at least **550 GWh by 2030**, in line with European Battery Alliance objectives	**Germany and France:** Subsidies from Important Projects of Common European Interest (IPCEI) for select projects, such as Automotive Cells Company (ACC), Verkor, and Northvolt factories
EV sales	**Sustainable and Smart Mobility Strategy** to achieve 30 million passenger ZEV stock by 2030 and nearly all passenger LDV and HDV stock by 2050	**Netherlands:** Tax exemption for zero-emission cars **Sweden:** Low annual road tax for zero-emission vehicles **Belgium**: €5,000 premium for a new zero-emission car purchased by retail customers
Charging infrastructure	**Alternative Fuels Infrastructure Regulation,** under which member states must ensure: • **Publicly accessible recharging stations** are set up in proportion to the number of registered vehicles • Adequate deployment of **recharging stations along the trans-European transport network** road network • Sufficient coverage of **recharging points for HDVs**	**Norway:** Grant up to 20% of charging point purchases and installation cost **Sweden:** Grant up to 50% cost of residential charging points installation **Belgium:** • 100% deductible for charging installation accessible to public • 15% tax reduction for private owners for mono- and bidirectional charging installation
Battery recycling	**EU Batteries Regulation** mandates that new batteries meet the minimum recycled content requirement by 2030: • Recycling target of **80% for lead-acid and 70% for Li-ion** • **Material recovery target of 95%** for cobalt, copper, lead, and nickel and **70%** for lithium	**Germany: Waste Management Act,** which turns a waste management culture into a resource management culture, minimizing waste generation and maximizing reuse and recycling

Sources: IEA, Global EV Outlook – Policy Developments (2023); IEA, Global EV Outlook - Policy Explorer (2024); EU Commission, Compass to boost EU competitiveness; CGEP, IRA and the US Battery Supply Chain (2023); DOE, Tax Credits.

Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Norway, an early EV adopter, has prioritized EV and charging incentives, though its battery value chain is still emerging

Norway EV sales share, %



Observations

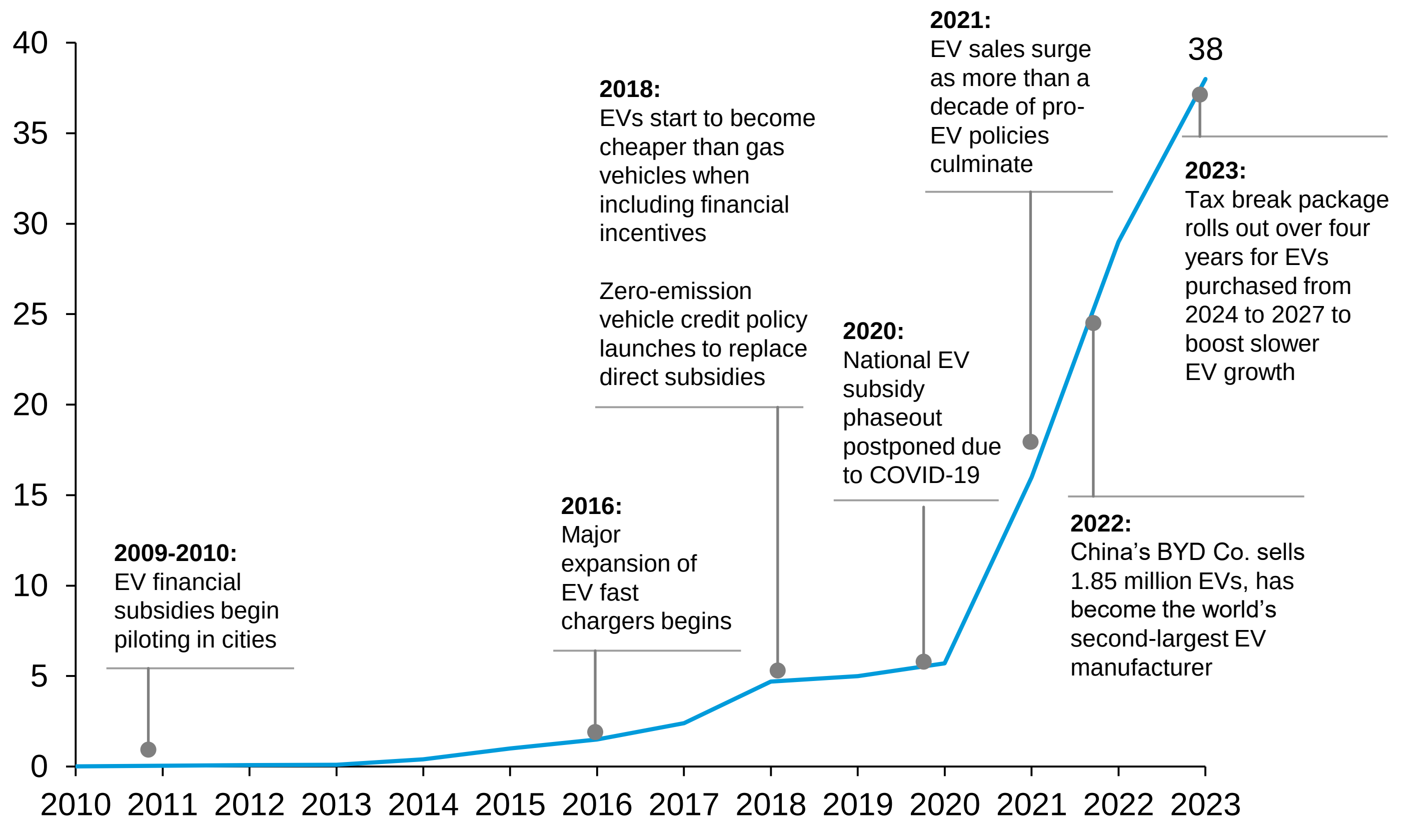
- Norway has shown that **replacing ICE vehicles with EVs is achievable,** with the total cost of ownership for EVs now lower, supported by tax breaks and high taxes on ICE vehicles to internalize carbon costs.
- **Key success factors** for Norway to lead global EV adoption rates:
  - **EV incentives** offer considerable tax breaks for EV users:
    - **National tax benefits** include exemption from purchase tax and VAT, no road traffic insurance tax, and company car tax discount.
    - **Local incentives** include half-price tolls, half-price parking, and the flexibility to use bus and taxi lanes.
  - **EV charging incentives have** resulted in a total of 34,000 charging points as of 2023.
- Norwegian industry has recently begun **consolidating its battery value chain initiatives** through various joint projects, including the **construction of a giga factory**.

Sources: IEA, Global EV Outlook - Policy Explorer (2024); WRI, Countries Adopting EVs (2023); IEA, Global EV Data Explorer (2024); Wallbox, Norway's Unique EV And EV Chargers Perks; Norwegian Ministry of Trade, Industry and Fisheries, Norway's battery strategy (2022).
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

China's EV growth mainly supported by direct subsidies and massive expansion of fast-charging networks

China's EV ecosystem has grown rapidly as the country aims to reach NEV sales share of around 40% by 2030…

China EV sales share, %



…supported by incentives, tax breaks, and a strategic push to dominate EV, battery production

China's key success factors:

- **EV and battery manufacturing:** Financial and tax breaks with a **total of $29 billion in subsidies from the government**
- **EV sales:**
  - **Financial and tax breaks** for both EV producers and consumers since 2009
  - Since 2018, direct subsidies have been gradually replaced with market-based **zero-emission vehicle credit system** for Corporate Average Fuel Consumption (CAFC) and new energy vehicle (NEV) in light-duty vehicles
- **Charging infrastructure:**
  - Massive expansion on fast charging drives EV growth; China has installed **760,000 public fast-charging points** and **1 million public slow-charging points,** more than ROW combined
  - **Promote 10,000 battery swapping-enabled EVs** with 1,000 swapping stations before 2025

In addition, China has been proactively **acquiring raw material extraction from local and international resources**, controlling more than **80% of global raw material refining capacity** for battery production and **75% of the battery cell market**.

In **battery recycling,** China has established a **closed-loop system in which battery manufacturers bear the primary responsibility** for recycling old batteries, and established a network of recycling service centers, supported by a government platform for battery tracing.

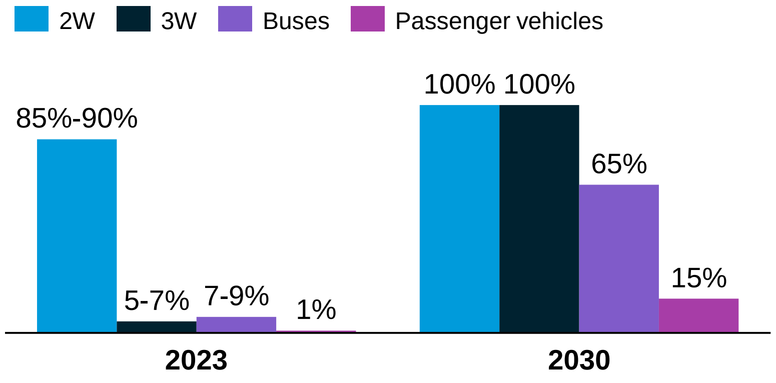
Sources: IEA, Global EV Outlook - Policy Explorer (2024); WRI, Countries Adopting EVs (2023); IEA, Global EV Data Explorer (2024); MIT Technology Review, How did China come to dominate the world of electric cars? (2023); Berkeley Law, China dual credit policy brief (2022); IFC, PLI Scheme on EV Manufacturing in India (2024).
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

India heavily incentivizing EV ecosystem to boost growth in EV supply chain through Production Linked Incentive scheme

India has an aggressive target to grow its EV ecosystem…

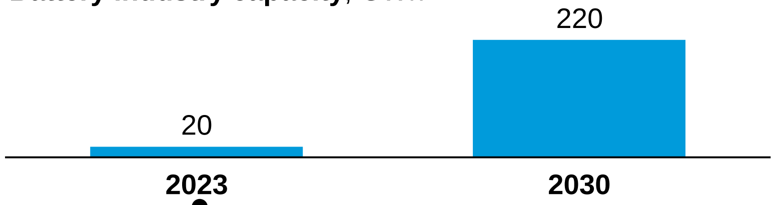
EV market growth target

Composition of the EV market, % share



Battery industry growth target

Battery industry capacity, GWh



India still in early stage in battery value chain, mainly involved in battery packing and still reliant on imports from China, Taiwan, and EU

…with a total of ~$ 7 billion in incentives allocated to support the industry

India's previous policy and incentives (a **total of ~$ 1.7 billion**) have played a crucial role in **fostering the EV industry in India**. They include:

- **FAME (Faster Adoption and Manufacturing of Hybrid and Electric Vehicles)**, which focuses on lowering car costs, promoting R&D, and constructing charging infrastructure
- **GUTS (Green Urban Transport Scheme)**, which aims to reduce air pollution by switching to eco-friendly public transport

However, those policies emphasize primarily consumer incentives and market growth, with **inadequate focus on addressing supply chain challenges.** Hence, the country launched its **Production Linked Incentive (PLI) in 2022 to bridge the supply chain gaps:**

- **First scheme (auto initiative)** to promote advanced automotive technology products:
  - Allocated a **~$ 3 billion budget spanning five fiscal years** (since 2022)
  - Successfully **raised a total investment of ~$ 9 billion** in 2022
- **Second scheme** to set up manufacturing facilities for **advanced chemistry cells**:
  - Allocated **~$ 2 billion budget** over a two-year span (since 2023) before introducing the next scheme, which will span a five-year period (until 2029)

In addition, India has the **disadvantage of mineral import dependence** for battery production, due to a lack of national reserves. As such, the country is turning inward to **capitalize on the untapped potential of battery recycling and mineral conservation to achieve self-sufficiency**.

Sources: IEA, Global EV Outlook - Policy Explorer (2024); IFC, PLI Scheme on EV Manufacturing in India (2024).
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Mobility energy storage – policy scan

Utility energy storage – policy scan

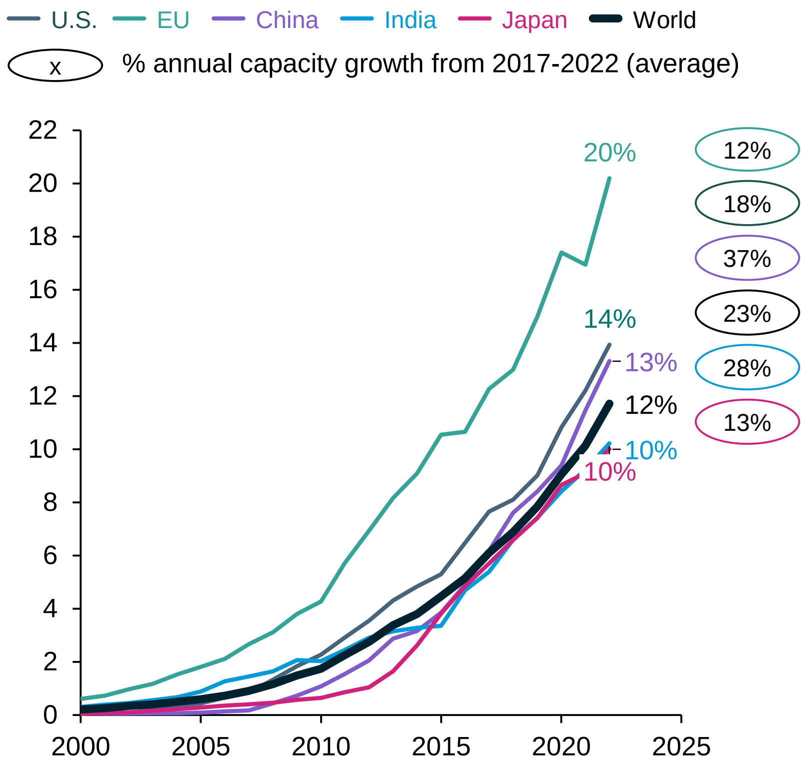
Other supporting pages

Glossary

EU, U.S., and China at the forefront of solar and wind, but gaps remain in stationary energy storage capacity…

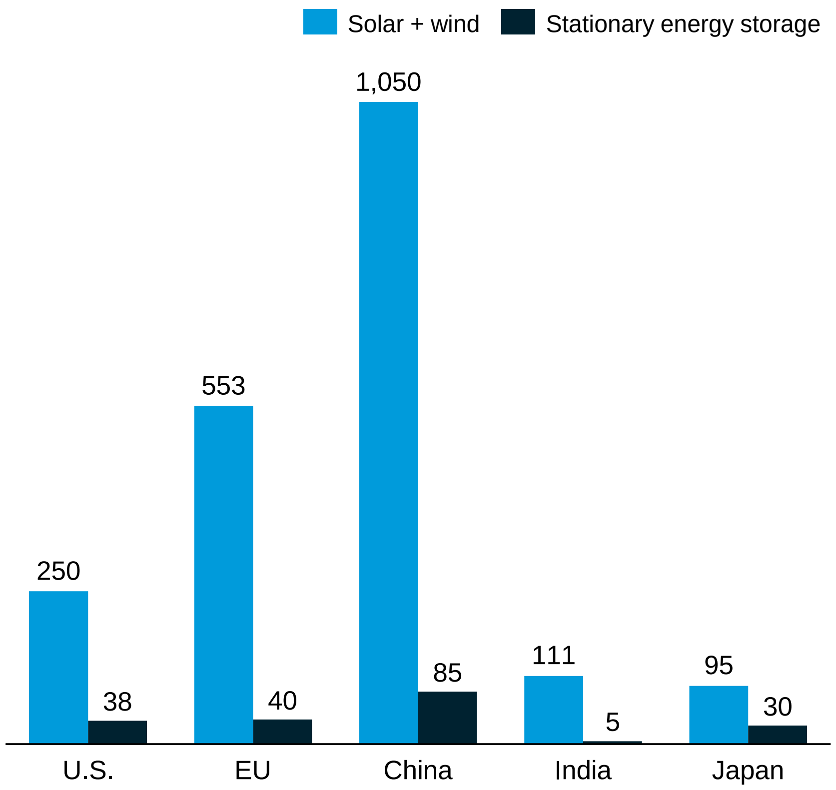
EU, U.S., and China are leading in growing solar and wind power generation

Share of solar and wind in total electricity mix for select countries, %



Energy storage is growing, but significant capacity gaps remain

Installed capacity of solar and wind vs. stationary energy storage in 2023, GW



Observations

Growth projection:

- The EU, U.S., and China have a **60% share of global solar and wind capacity.**
- **China has been scaling up rapidly**, with 37% p.a. capacity growth for solar and wind, the fastest rate among the other leading countries.

Current gaps:

- The EU, U.S., and China have significant capacity gaps between solar and wind vs. energy storage, highlighting the need for more storage solutions.
- China leads in solar and wind with 1,050 GW, but its energy storage capacity remains at only 85 GW.
- The U.S. and EU show a more balanced growth in solar, wind, and storage capacity, yet gaps persist.
- India and Japan trail with smaller storage capacities, underscoring a need for further development.

Sources: IEA electricity mix China; IEA electricity mix EU; IEA electricity mix U.S.; IEA electricity mix India; IEA electricity mix Japan; Ember Climate (2021); Wind Exchange (2024); EIA (2024); Energy EC EU; S&P Global (2024); GlobalData (2023); Renewables Now (2024); PV Magazine (2023); China Daily (2024); IEEFA (2023); TERI (2023); Wikipedia; Mercom India (2024).
Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

…requiring strong government supports through policy and incentives to drive investments

Policy overview across select countries/regions

	U.S.	EU	China	India	Japan
Main policy focus	• Renewable energy expansion • Grid reliability and innovation in energy storage	• Renewable energy expansion • Circular energy system	• Renewable energy expansion • Large-scale deployment and technological advancement	• Renewable energy expansion • Grid stability and renewable integration	• Renewable energy expansion • Grid stability
Key policies (related to energy storage)	• **Renewables Portfolio Standards (RPS, 2021)** • **FERC Order 841 (2018)**: Integrates storage into wholesale markets • **American Energy Innovation Act (2020)**: Framework for energy innovation, including storage • **Investment Tax Credit**	• **Net-Zero Industry Act (2023)**: Simplifies the regulatory framework for net-zero technologies • **Renewable Energy Directive (2021, 2023)**: Sets binding targets for renewable energy and storage integration • **EU Green Deal (2019)**: Comprehensive plan for decarbonization	• **14th Five-Year Plan** (2021-2025): Targets 30 GW of non-hydro energy storage by 2025 • **New Energy Storage Implementation Plan**: Aims for 100 GW by 2030 • **National Development and Reform Commission (NDRC) Energy Regulation** (2021)	• **National Framework for Promoting Energy Storage Systems** (2023) • Viability Gap Funding **(VGF) scheme** for BESS (2024) • **Energy Storage Obligation (ESO)** and **Renewable Purchase Obligation (RPO)** framework (2022)	• **Renewable Energy Act** • **Act on Special Measures Concerning Procurement of Electricity from Renewable Energy Sources by Electricity Utilities (2022),** for standalone BESS business
Key incentive programs (non-exhaustive)	• **ITC:** 30% credit for standalone ES projects • **Federal loan guarantees**: Up to 80% of project costs for ES projects • **Self-Generation Incentive Program (SGIP)** in California for residential • **DOE Energy Storage Grand Challenge** for energy storage R&D	• **Horizon Europe funding for R&D** ($105 billion) • **European Regional Development Fund (ERDF)** ($220 billion) • **Feed-in tariffs (FiTs)** • **capacity market payments** • EU Innovation Fund: **$11 billion**	• **Cost reduction target**: 30% cost reduction in storage by 2025 • Additional **provincial subsidies and incentive**s for storage projects • $93.9 billion investment in new-type energy storage by 2032	• **Production Link Incentive (PLI) scheme**: ~**$2.18 billion over** five years, by FY28-29 • **VGF**: Up to 40% of capital cost for BESS projects • **Transmission charge waivers**: 25 years for hydro PSP or 12 years for BESS	• **Green Innovation Fund**: ~**$14 billion** • **Tax incentive** of ~**$12 billion** in 10 years • **Transition finance**: $1.05 trillion in public-private investments by 2030, supporting battery production and storage technologies

Observations

- **U.S.**: Leading in market integration (FERC Order 841), with significant federal incentives for storage (ITC, SGIP)
- **EU**: Strong regulatory framework for net-zero technologies
- **China**: Focused on large-scale deployment and cost reduction strategies
- **India**: Leading in financing mechanisms for storage through its PLI scheme and VGF for BESS
- **Japan**: Strong incentives for innovation through the Green Innovation Fund and support for large-scale energy storage transition projects

Sources: IEA (2024); U.S. RPS (2021); FERC Order (2018); Net-Zero Industry Act (2023); RE Directive (2023); EU Green Deal (2019); MoP (2023); MoP (2024); MoP (2022); Apko Worldwide (2024); IHA (2024); BNEF (2024).

Credit: Shailesh Mishra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

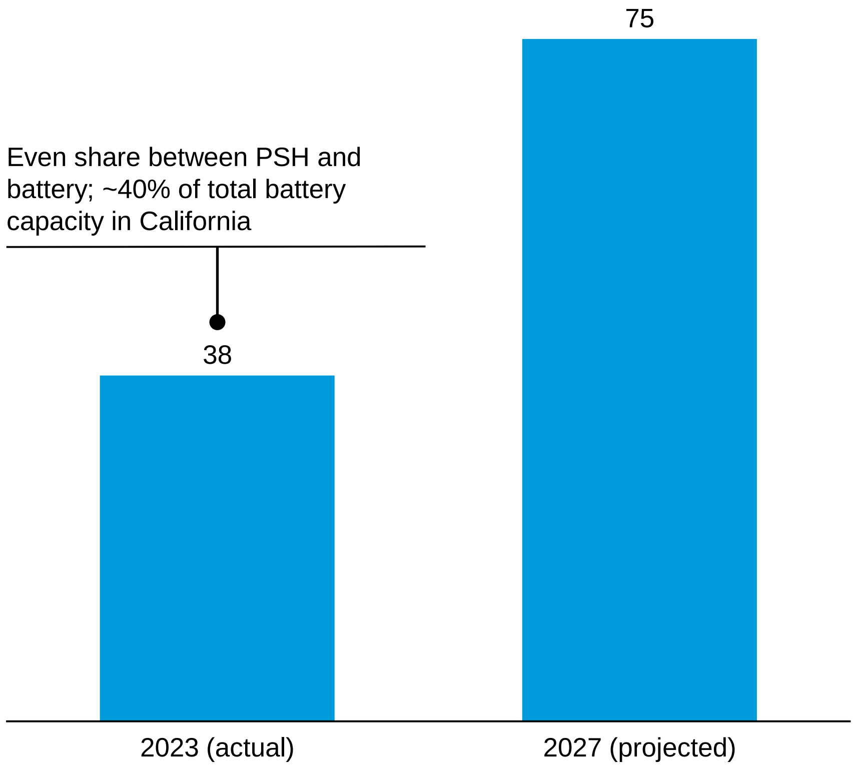
California, New York, and Massachusetts are leading states in advancing storage and reintegration

States have put in place significant policies and incentives to boost renewables and achieve their renewables mandates

State	Renewables mandate	Storage target	Financial incentives
California	60% by 2030, 100% clean energy by 2045	1,325 MW by 2020	• **~$450 million consumer rebate** in 2019 • **$830 million rebate for behind-the-meter** technologies by 2026
New York	50% by 2030	1.5 GW by 2025 6 GW by 2030 (3 GW bulk storage)	• $35 million in incentive and $200 million fund to provide loans • $15.5 million funding from NYSERDA
Massachusetts	35% by 2030	1 GWh by 2025	• ~ **$20 million in grants** for 26 energy storage projects
Maryland	50% by 2030	5 MW by 2022	• Tax credits for energy storage systems: $5,000 for residential and up to $75,000 for commercial applicants
Nevada	50% by 2030	590 MW by 2023	• Low-Income Solar Program: $1 million per year until 2023 • EV and other ESS: $15 million in total
Oregon	25% by 2025	Established storage mandates	• $2 million earmarked for rebates • Capped at $2,500 for residential ESS and $15,000 for low-income service providers
Hawaii	100% by 2045	Included in RE goals ~2.3 GWh by 2045	• Through state and federal programs, exact numbers not specified

U.S. is projected to increase energy storage capacity by 7x (2027 vs. 2023)

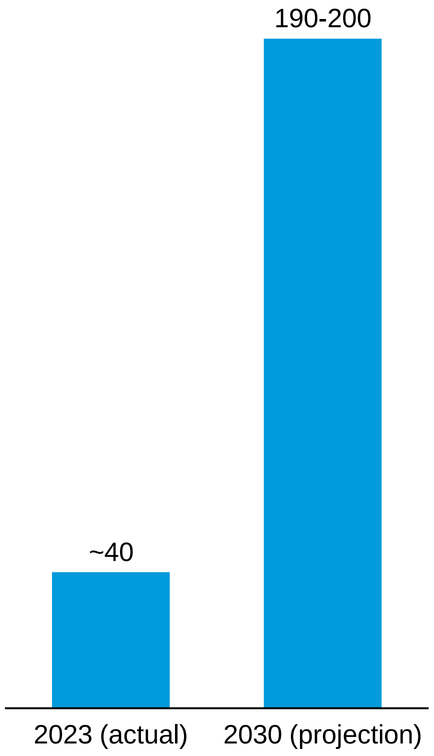
U.S. energy storage capacity (battery and PSH), GW



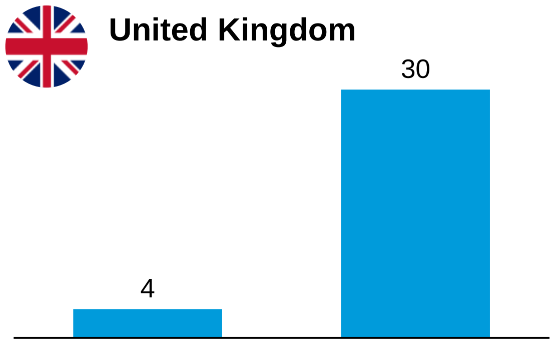
EU aims to increase utility-scale energy storage by 5x from 2023 to 2030; UK and Italy lead investments

EU targets significant growth by 2030

EU utility-scale energy storage capacity, GW

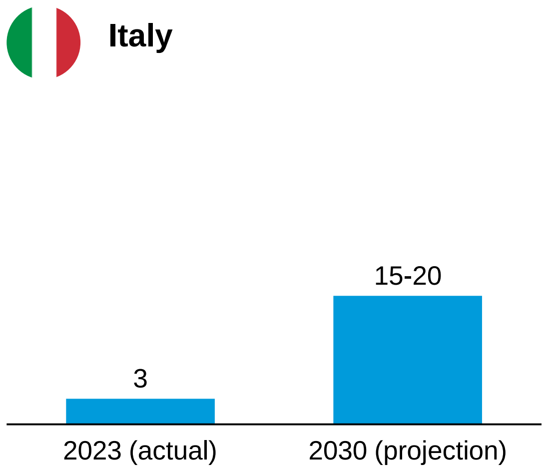


UK and Italy lead the investment pipeline, backed by strong government support



The UK has launched multipronged policy support to boost investment for LDES:

- As of 2023, the UK has 80 GW planned capacity in project pipelines; it is the largest deployer in the EU.
- Sophisticated energy market design includes a well-established and diverse revenue stack for BESS. Upgrades to the National Grid ESO's Open Balancing Platform supports the bulk dispatch of battery storage in real time.
- A new energy bill classes BESS as a generation asset, easing rules around construction and offering specific tariff structures.
- The government is committing £20 billion to establishing a world-leading battery industry by 2030.
- A new Cap & Floor scheme is being introduced to attract private investment, ensuring achievable minimum returns for various types of technology (PSH, batteries, CAES, etc).



Residential installations face slower growth, while utility-scale projects show promise:

- Residential:
  - In 2023, residential energy storage dominates the country's energy storage landscape.
  - Italy introduced Superbonus in 2020, a tax credit program for residential PV and battery storage system installation, along with net metering policy.
  - However, a recent reduction in the tax credit has impacted the growth in this space.

- Utility scale:
  - The utility-scale sector is still in its infancy and suffers from regulatory uncertainties, supply difficulties, and increasing costs.
  - To boost the scale, Italy will aid the investment in the BESS facility for over £17 billion in the next 10 years.
  - The new storage capacity will be acquired through tenders published by Terna, with a target of a 12 to 15 GW capacity addition by 2030. The aim is to create a centralized electricity storage system to support the integration of renewable energy into the Italian power grid.

Sources: REN (2024); EASE (2022); Eco Affect (2024); ITA (2024); EnergyTrend (2024); EY Renewable Energy Country Attractiveness Index (2024); Energy Storage news (2024).

Credit: Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

China's 14th Five-Year Plan for stationary energy storage targets broad development in a variety of technologies

China's policy focuses on the transition to clean energy sources, emphasizing new-type energy storage systems…

	Strategy	Overview	Targets	Examples
Hydro energy storage	Accelerate capacity growth	With a large existing base of over 480 GW, hydro energy storage synergizes well with existing hydro capacity.	120 GW by 2030 (current capacity: 32 GW)	World's largest pumped storage system at **3.6 GW**, Fengning Pumped Storage system commences operations in 2024.
Battery energy storage	Accelerate capacity growth	China has long dominated the lithium battery supply chain and is setting its sights on applications in utility energy storage.	100 GW by 2030 (current capacity: 10 GW)	"World's first" large-scale semi-solid BESS connects to grid in China with **100 MW** in capacity in 2024.
Compressed air storage	Promote innovation	As this is a more nascent technology, China has supported partnerships with Tsinghua University to promote R&D in the field.	No specific targets found at this time	China's first salt cavern compressed air energy storage starts operation in 2022.
Thermal energy storage	Promote further development with solar/wind projects	With existing solar utility projects developing, there is policy incentive to combine utility-scale solar projects with thermal energy storage.	No specific targets found at this time	30+ CSP, with thermal energy projects under construction in Qinghai and Gansu provinces, totaling over 2.5 GW.

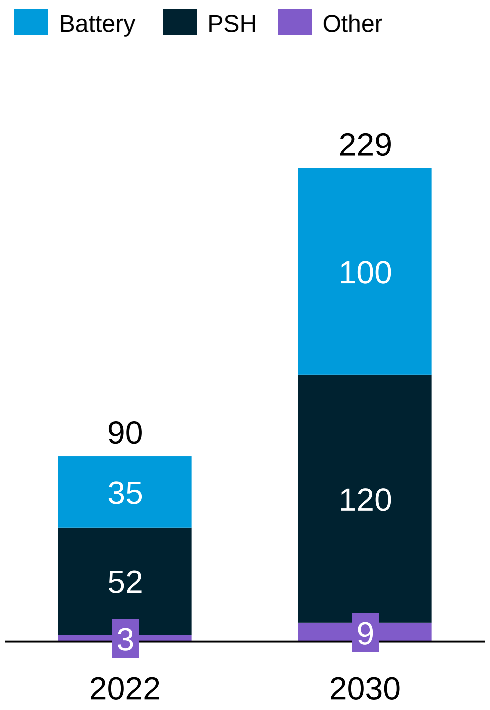
…with a massive investment to achieve its target of ~230 MW capacity by 2030

$93.9 billion **Current market size in 2023**

$13.9 billion **Investment recorded from 2021-2023**

18.9% CAGR **Forecasted growth from 2023 to 2030**

Forecasted growth of utility-scale energy storage in China to 2030, GW



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Sources: ChinaDaily (2024); PAMIR (2024); Apco Worldwide (2023); CarbonBrief (2024).
Credit: Hassan Riaz, Shailesh Mishra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

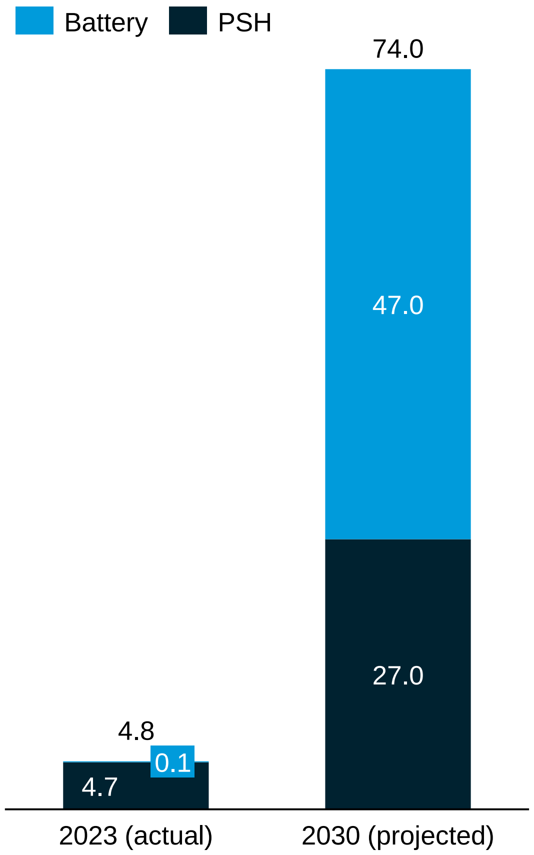
India poised to achieve its 2030 renewable energy targets, with energy storage playing a critical role

India has established various incentives to promote BESS and PSH development to support the transmission of renewable energy in the country

	Policy name	Target	Policy details	Financial incentives
Overall energy storage	National Framework for Promoting Energy Storage Systems, MoP (2023) Waiver of Inter-State Transmission Charges, MoP (2021)	50 GW by 2030 Supports transmission of RE paired with storage systems	Integration of energy storage across the energy value chain, including both grid-scale and distributed energy storage systems Waiver of interstate transmission charges for solar, wind, hydro PSP, and BESS projects commissioned by June 2025	Fiscal incentives, subsidies, and support for R&D **~40% VGF to initial BESS projects**; must be completed within 18 to 24 months Waiver applicable for 25 years for hydro PSP or 12 years from commissioning for BESS
Battery development	Production Linked Incentive (PLI) scheme on battery storage, MoHI (2021)	Not specified	Focus on scaling up local production capacities for various battery technologies to reduce dependency on imports	~**$2.18 billion** in five years, by FY 2028-29 Firms setting up **>5 GWh** of advanced chemistry cell manufacturing
	VGF for BESS, MoP (2024)	4,000 MWh of BESS by 2025-26	VGF up to 40% of the capital cost for BESS projects, targeting grid stability and renewable energy integration	Total outlay of **$1.13 billion**, including **$451.51 million** in budgetary support, with disbursements in five tranches
PSH development	Guidelines to Promote Development of Pumped Storage Projects (PSP), MoP (2023a)	Not specified, PSH to support 500 GW RE by 2030	Encourages the development of pumped storage projects as critical for grid balancing and RE integration	Subsidies, low-interest loans, and waivers to reduce development costs
Others	RPO and ESO, MoP (2022)	RPO ~43.33% and ESO ~4% by FY 2029-30	Obligates DISCOMs to procure power from renewable sources, including energy storage	Trading in RECs to meet RPO/ESO obligations

Note: VGF = viability gap funding, RPO = renewable purchase obligation, ESO = energy storage obligation, DISCOM = distribution companies

Targeting over 70 GW utility energy storage capacity by 2030



Sources: MoP (2023); MoHI (2021); MoP (2023a); MoEFCC (2022); MoP (2024); MoP (2022); MoP (2021); Rose et al. (2020); PIB.gov (2022).
Credit: Shailesh Mishra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

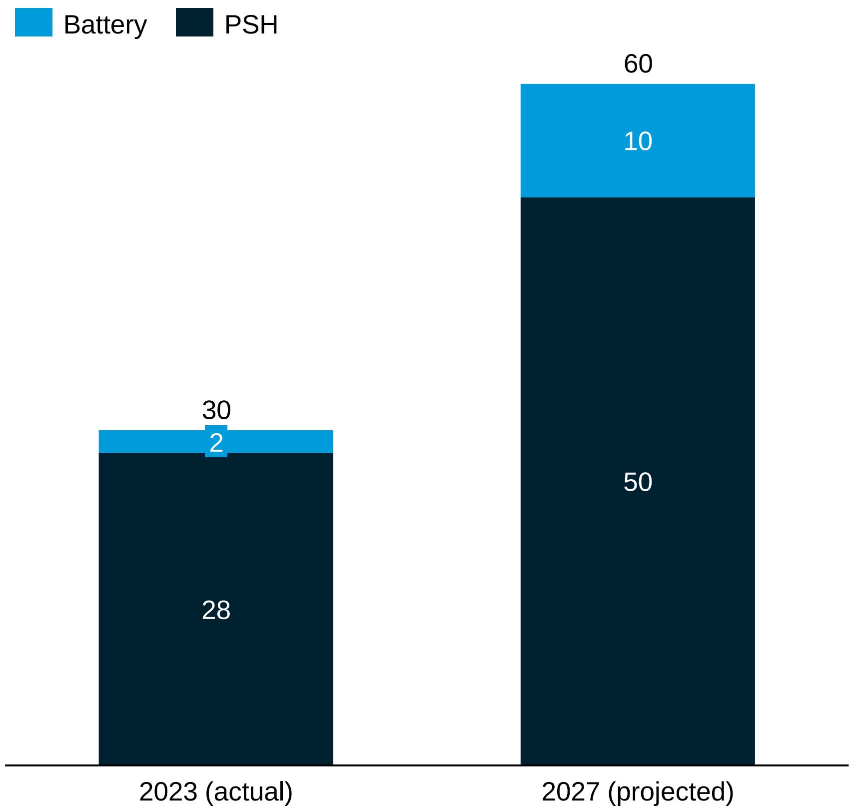
Japan energy storage development is lagging; recent government incentives aim to achieve 60 GW capacity by 2030

Most recent incentive schemes are set to boost renewables and battery storage growth

	Policy name	Target	Policy details	Financial incentives
Overall energy storage	Green Growth Strategy (2021)	Achieve carbon neutrality by 2050 Integrate 100 GW of renewable energy by 2030	Promotes RE integration and battery storage, supports smart grids and emphasizes hydrogen, ammonia, and next-gen nuclear	**Green Innovation Fund**: **$13.66 billion** over 10 years to leverage **$102 billion** of private R&D and investment. **Tax incentive** of **$11.64 billion** over 10 years
Energy storage development	Battery Industry Strategy (2022)	750 GWh battery manufacturing capacity by 2030, 100% domestic battery recycling by 2030	Focus on domestic manufacturing and recycling: • EV and stationary batteries • Advance all-solid-state battery technologies	Government funding for large-scale manufacturing infrastructure, tax incentives for R&D, and capital investments; numerical value not specified
	6th Strategic Energy Plan (METI, 2021a)	36%-38% renewable energy share by 2030 10 GW of BESS and 50 GW of PSH capacity by 2030	Supports the integration of energy storage for grid stability Enables advanced battery technologies for distributed systems	**FIT and FIP** incentives for renewable energy and storage projects Significant investments in grid reinforcement
Others	Japan's Green Transformation (GX) Plan (2023)	10 GW of offshore wind 104-118 GW solar capacity by 2030	Promotes decarbonization strategies with energy storage for renewable energy and industrial applications	**Transition finance**: $1.05 trillion in public-private investments by 2030, including support for battery production and storage technologies

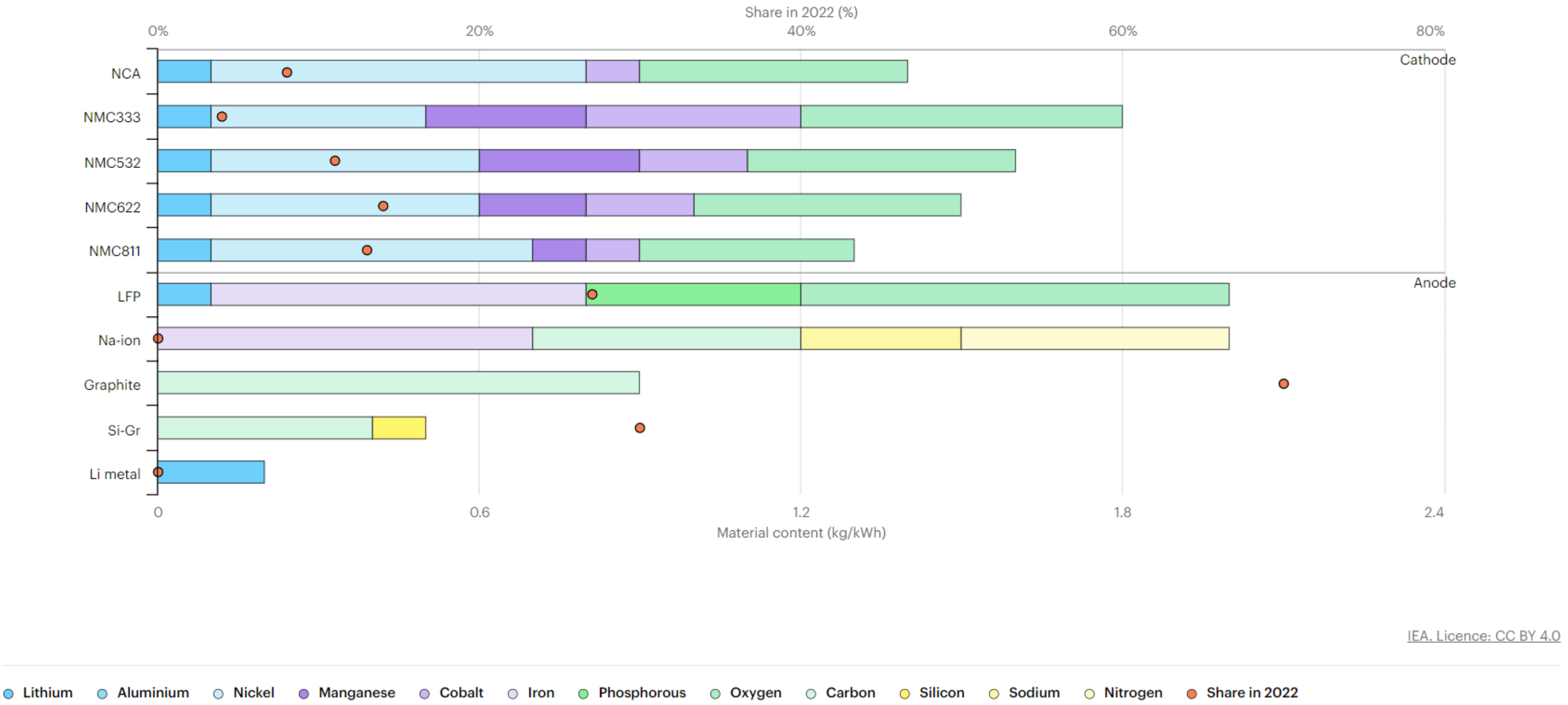
Aims to grow its storage capacity to 60 GW by 2030; ~$50 billion in investments are underway

Japan's energy storage capacity (battery and PSH), GW



Sources: METI (2022); MoFA (2021); METI (2021a); Green Transformation (2023); EIA (2024); IEA (2021); BNEF (2024); IEA Mid-Year (2024); Rhodium Group (2024); Power Technology (2023); World Hydropower Outlook (2024); BNEF (2024).
Credit: Shailesh Mishra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Material content in different anodes and cathodes



Source: IEA, Global EV Outlook (2023).

Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

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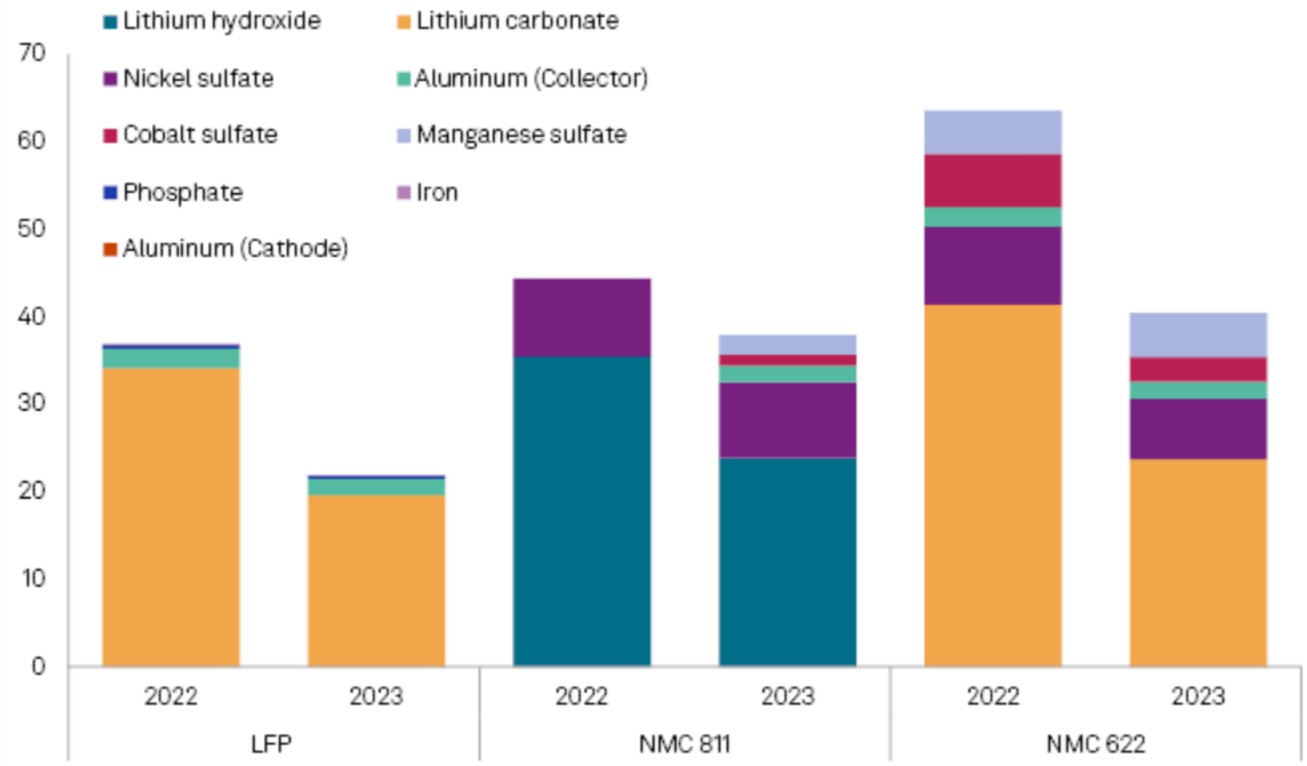
Costs of cathode active materials by technology, 2022-2023 ($/kWh)



Data compiled March 4, 2024.

LFP = cathode that contains lithium iron phosphate; NMC 811 = cathode that contains eight parts nickel to one part each manganese and cobalt; NMC 622 = cathode that contains six parts nickel to two parts each manganese and cobalt.

Aluminum is used to make the collector that gathers the electrical current generated at the electrodes to send to external circuits.

Sources: S&P Global Commodity Insights; ScienceDirect.

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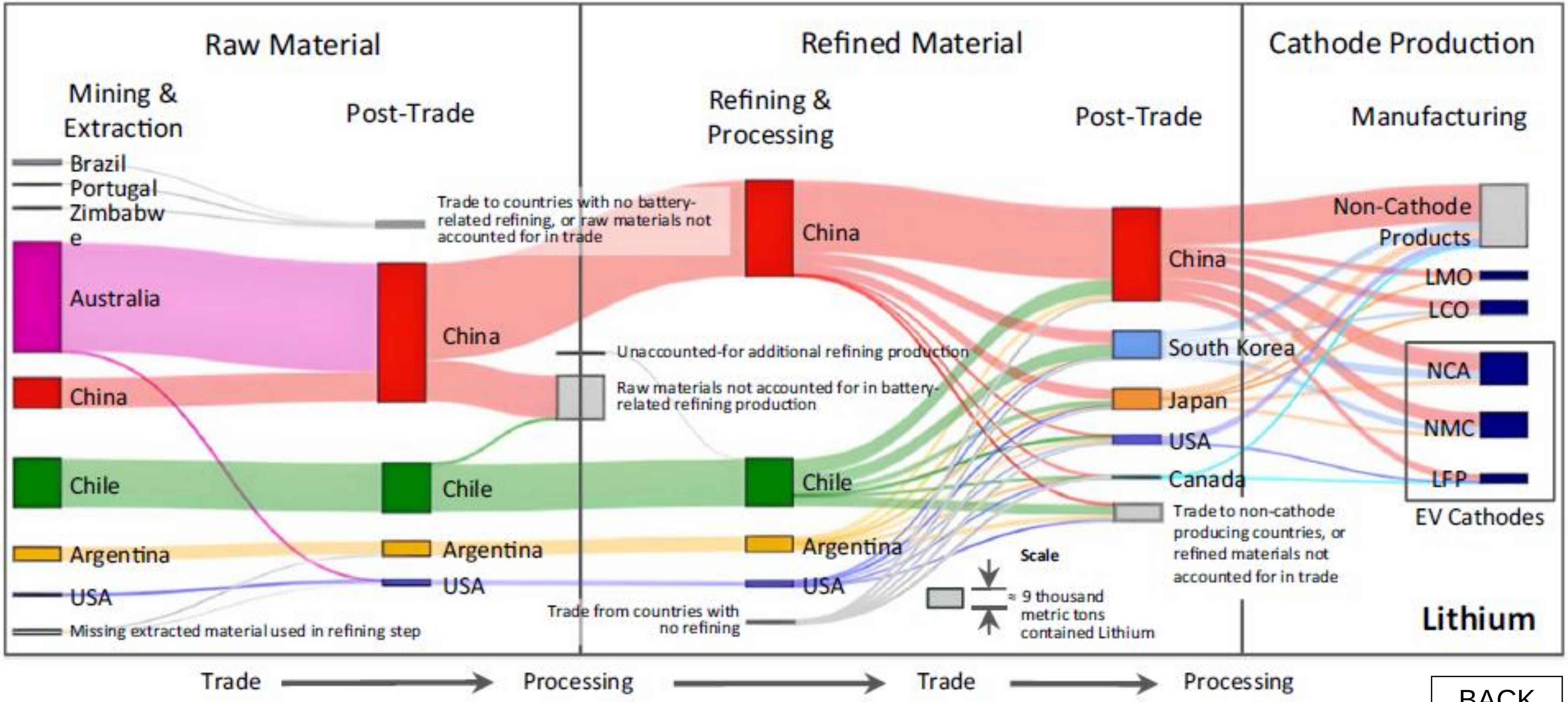
Source: S&P Global, Lower lithium prices support adoption of lithium-rich EV batteries (2024).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Sankey diagram for global flows of lithium



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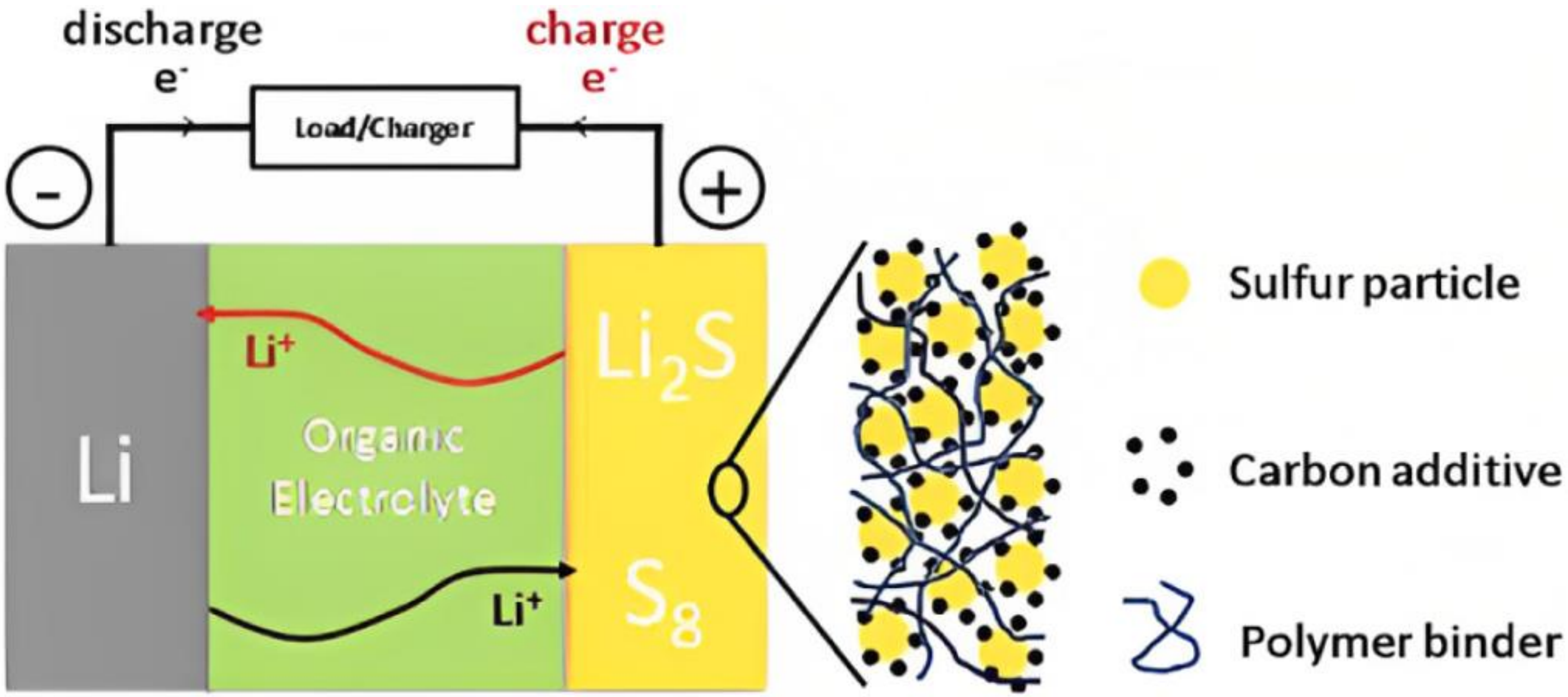
Source: Nature, Electric vehicle battery chemistry affects supply chain disruption vulnerabilities (2024).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

LiSB polysulfide shuffle effect



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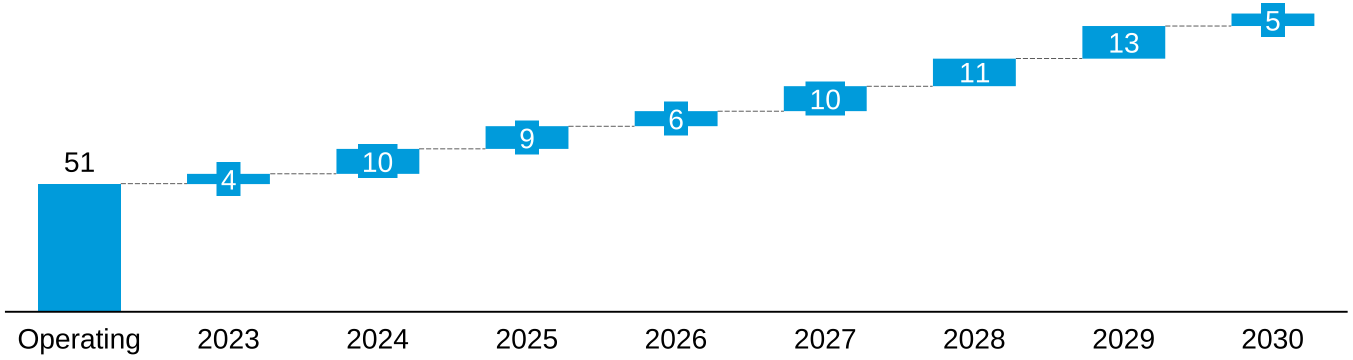
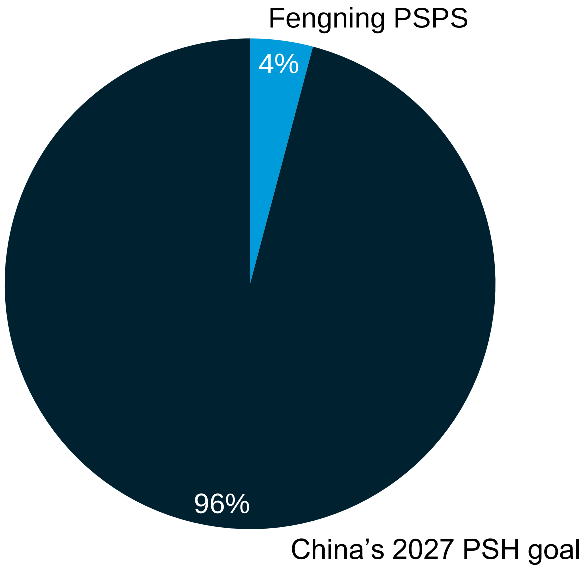
Source: Nature, Recent advancements and challenges in deploying lithium sulfur batteries as economical energy storage devices (2023).
Credit: Ashley Kim, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

In China, state support is driving force behind completion of Fengning pumped storage power station

China's PSH capacity increases by year, GW





Observations

- **China** has set a new global benchmark with the completion of its Fengning Pumped Storage Power Station, **the largest of its kind in the world**.
- Located in Hebei province, this facility has a total installed capacity of 3.6 GW and is operated by the **State Grid Corporation of China.**
- State support enables China to overcome infrastructural, financial, regulatory, and environmental barriers, driving projects like the Fengning station to successful completion
- The project reached completion on **August 11, 2024,** with the operation of the 12th and final reversible turbine unit.
- Construction on the station began in **June 2013**, with Gezhouba Group securing the main construction contract in April 2014.
- The project was built **in two phases**, each involving six 300 MW reversible pump turbine units.
- The Fengning plant now surpasses the **Bath County project in the U.S.** as the **largest pumped hydro station worldwide in terms of capacity**.
- With the Fenining station now online, China is on track to expand its pumped storage capacity **to 80 GW by 2027**.

Source: IHA, China's Fengning Station (2024); GEM, Led by China, Eastern Asia can meet key target for pumped storage (2023).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Wider deployment of pumped storage hydropower (PSH) faces technical and socioeconomic barriers

Technical and environmental barriers to deployment		Socioeconomic barriers to deployment	
Lacking infrastructure	• The foremost barrier in reviewed studies. Absence of roads and transmission lines prevents access to cheap surplus power, creating a technical barrier that delays development.	**Project investment**	• The foremost socioeconomic barrier. Complex financial hurdles include capital costs, operation and maintenance costs, payback period, and other economic parameters. Additionally, the payback period is considered another hurdle, as it requires at least 2.5 to 5.5 years to repay loans.
Landscape topology	• Decides the type, height (head or elevation), slope, and shape of a dam, the head-to-length ratios, and the amount of earthwork required to built it.	**Public opposition**	• Public acceptance, lack of awareness, “not in my backyard” syndrome, business impact, forced displacement, construction time complaints, and scattered settlement issues, among other issues.
Land acquisition challenges	• Land use, vegetation clearing, and land ownership among environmental complications that affect pumped hydro development.	**Institutional challenges**	• Absence of legal frameworks, lack of decision-making, and lack of coordination among participating institutions.
Water Issues	• Water availability, water quality, water loss, conflict of interest with the local water supply (for open loop), loss of oxygen, and other hydrological effects.	**Political government interference**	• Government lobbying, bureaucratic drag, and corruption.
Biodiversity loss	• Environmental impacts on birds and fisheries as well as temperature changes and soil erosion.	**Market failures**	• State-controlled energy sector, market rule uncertainties, and a lack of skilled labor.
Geological faults	• Geological constraints such as active faults, large-scale faults and fracture zones and the presence of permeable bedrock should be considered as they may increase overall construction time	**Sponsorship**	• Very rarely do organizations or private investors agree to finance such long-term projects due to licensing timeframe uncertainties or long backpack periods. A study found most PSH systems in operation are financed under public sector ownership

Source: Cleaner Engineering and Technology, Drivers and barriers to the deployment of pumped hydro energy storage applications (2021).
Credit: Shailesh Mishra, Petr Jenicek, Birru Lucha, Hyae Ryung Kim & Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Strategic financial structuring and operational insights: Kurukutti PSH Project

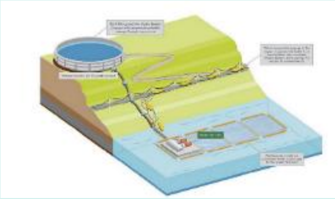
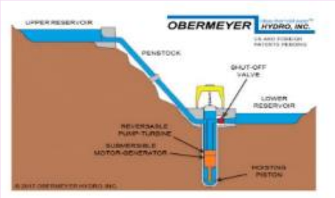
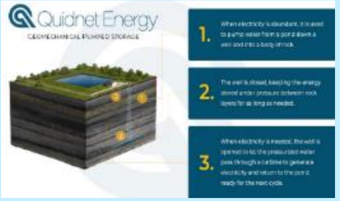
Parameter	Planned value
Basic project cost (including FC)	4377.00 Rs. in crores
Indirect cost (IDC)	531.00 Rs. in crores
Power component (total cost including IDC and FC)	4908.00 Rs. in crores
Debt	3435.60 Rs. in crores
Equity	1472.40 Rs. in crores
Debt: Equity ratio	30%
Rate of O&M charges	3.50%
Annual increment in O&M charges	4.77%
Spares (15% of O&M charges)	15.00%
Interest on working capital	10.00%
Rate return on equity	21.71%
Rate of depreciation	5.28%
Discounting rate	10.00%
Input energy	3338 Mu
Annual energy generation	2527 Mu
Aux. consumption	1.20%
Weighted average rate of interest	10%
Plant useful life	40 years

Observations

- **Kurukutti PSH** is a project developed by **Adani Green Energy** for the Andhra Pradesh region.
- Per the feasibility report, the proposed **Kurukutti PSH plant** envisions **recycling stored water between upper and lower** reservoirs and having to fill the reservoirs **only once in their lifetime**.
- Kurukutti PSH envisions a scheme to generate **1200 MW of peak power on weekdays**.
- Project is expected to be completed by **2028.**

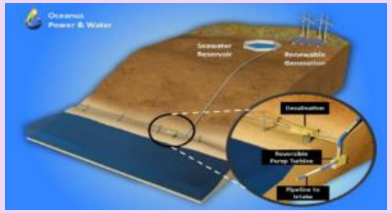
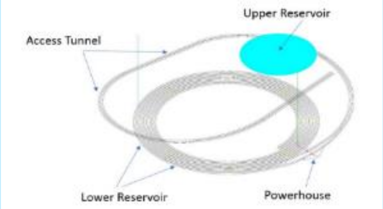
Sources: TATA, Techno-Commercial Feasibility Report (2020); TERI.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Novel PSH technologies currently in development (1/4)

	Small PSH with reservoirs of corrugated steel and floating membranes	PSH using submersible pump turbines and motor generators	Geomechanical PSH
			
Description	Creation of a closed-loop system using corrugated steel for the upper reservoir and a floating membrane reservoir in a larger body of water	Use of submersible pump turbines and motor generators, both in a vertical shaft, to eliminate the need to construct a powerhouse	Water pumped down into the ground between rock layers, where water is kept under pressure
Advantages	• **Modularity**: Lower cost and higher accessibility due to use of off-the-shelf equipment and materials • **Scalability**: More potential locations due to relatively small plant size. • **Quick installation**: Use of prefabricated materials such as corrugated steel and floating membranes, allowing for quicker setup	• **Cost effective**: With no need to construct an underground powerhouse, lower cost and less construction time • **Scalable**: Highly adaptable, which supports a wide range of project sizes • **Versatility**: Applicable for development of pumped storage capabilities at existing hydropower plants and for applications at non-power dams	• **Fast construction**: Underground deployment leads to an accelerated timeline • **Scalable**: Flexible for various project sizes; modular design allows phased growth • **Low project cost**: Reduced capital expenditures compared with CapEx for PSH or battery storage
Estimated unit plant size (MW)	1-10	10-200	16-320
Plant lifetime (years)	30	60	30
LCOS range ($/MWh)	246 338	156 174	127 158

Source: DOE, Technology Innovations for Pumped Storage Hydropower (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Novel PSH technologies currently in development (2/4)

	Hybrid PSH and wind plant	Integrated PSH and desalination plant	Underground PSH using TBM for storage excavation
			
Description	A small concrete reservoir is constructed around the foundations of wind turbines located on a hill.	Combines a seawater PSH plant with a reverse-osmosis desalination plant to provide an integrated energy storage and fresh-water supply system.	Uses tunnel boring machines (TBM) to excavate a lower reservoir in solid rock. Excavated rock is used to construct an upper reservoir on the surface for a closed-loop system.
Advantages	• **Cost reduction**: Lower expenses through standardized construction and prefabricated components. • **Dual functionality**: Possibility of hybrid operations with other renewable resources in addition to wind. • **Environmental impact:** By utilizing the space directly around the wind turbine base, the design minimizes land usage and reduces footprint.	• **Synergies**: Future demand for both energy storage and freshwater production is expected. • **Additional revenue**: Addition of freshwater production adds another revenue stream for project developers. • **Location**: Addresses energy storage and freshwater needs, making it an efficient, dual-purpose infrastructure solution for coastal communities facing water scarcity and energy demand.	• **Flat geography solution**: Enables large amounts of energy storage in areas that do not have the topography to support conventional PSH plants. • **Large capacity and duration**: Supports large plant sizes at around 500 MW, which makes it economically viable. • **Community benefits**: Underground development limits disruptions to daily life.
Estimated unit plant size (MW)	8-32	100-500	500-1000
Plant lifetime (years)	50	60	60
LCOS range ($/MWh)	151 – 208	174 – 230	210 – 230

Source: DOE, Technology Innovations for Pumped Storage Hydropower (2022).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

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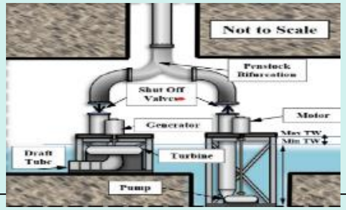
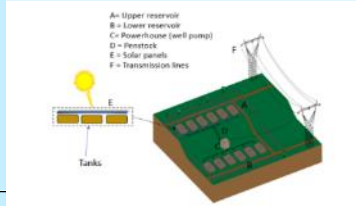
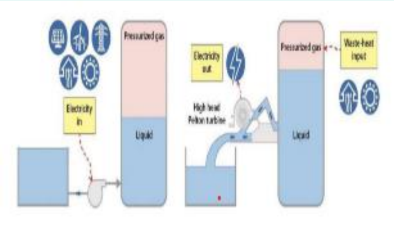
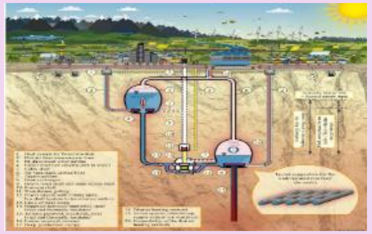
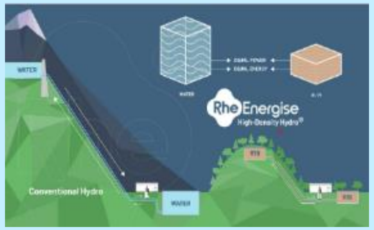
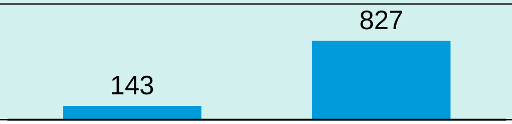
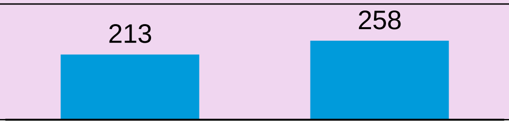
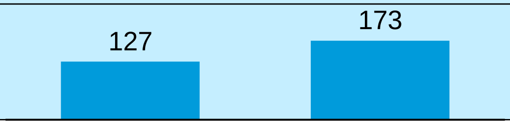
Novel PSH technologies currently in development (3/4)

	Underground mine PSH	Open-pit mine PSH	Hybrid modular closed-loop scalable PSH
			
Description	Uses the tunnels and galleries of an existing abandoned mine as a lower reservoir and constructs an existing surface reservoir to serve as an upper reservoir for the PSH plant.	Uses the infrastructure of decommissioned open-pit mines for the development of PSH projects.	Converts electrical energy into chemical energy for storage and reverses the process to release it, stabilizing the grid during demand shifts.
Advantages	• **Reduced project costs**: Using mine structures can lower overall project costs in comparison to building new reservoirs. • **Economic and environmental benefits**: Repurposing mines reduces the need for extensive civil works. • **Market potential**: Many abandoned mines in the U.S. could be converted into PSH plants.	• **Improved water conveyance**: Provides better water conveyance hydraulics compared to underground alternative. • **Scalability**: Supports a range of plant sizes, from 100 to over 2,000 MW. • **Market potential**: Many open-pit mines in the U.S. could be converted into PSH plants.	• **Geographic flexibility**: Batteries can be installed almost everywhere, meaning they can be located closer to demand centers, reducing transmission losses and infrastructure costs. • **Scalability**: Allows utilities to add capacity incrementally as demand grows. • **Faster response time**: Response to changes in load and generation needs happens within milliseconds.
Estimated unit plant size (MW)	20-100	100-2000	1-10
Plant lifetime (years)	60	60	20
LCOS range ($/MWh)	162 – 201	193 – 193	221 – 369

Sources: Department of Energy; Engie.
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Novel PSH technologies currently in development (4/4)

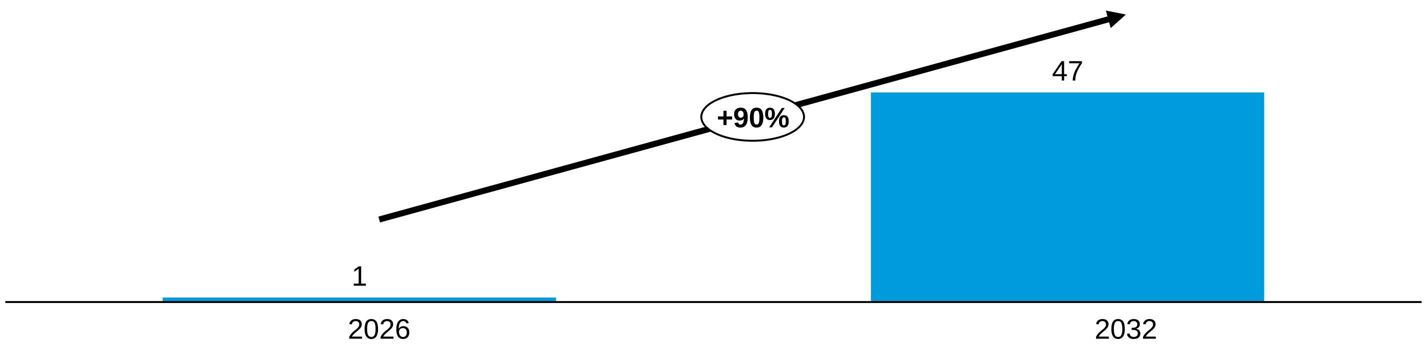
	Pressurized vessel PSH	Thermal underground PSH	High-density fluid PSH
			
Description	Uses water to pressurize air in a high-pressure vessel. Water is used as a liquid piston to compress air. Storage occurs when water is pumped into the vessel, increasing air pressure.	Both the upper and lower reservoirs of the PSH plant are built underground, allowing geothermal energy to heat water.	Uses a high-density fluid instead of water to reduce the size of reservoirs and infrastructure.
Advantages	• **Modularity**: Can be implemented in both small systems and large-scale installations. • **No geographic restrictions**: Suitable for regions without elevation differences. • **Cost effective**: Use of high-pressure pipe segments and underground reservoirs can reduce cost.	• **Multipurpose**: Can provide electricity, heating, and cooling to enhance efficiency and flexibility. • **Urban use**: Suitable for urban and industrial areas with significant heat demand. • **Minimal environmental impact**: System prevents any impact on natural water sources.	• **Reduced plant size**: Small reservoirs and infrastructure due to high-density fluid. • **Cost savings**: Significant decrease in project costs when compared to traditional PSH plants. • **Geographically diverse:** Can be implemented in geographically diverse locations with lower elevation differentials due to lower hydraulic head requirement.
Estimated unit plant size (MW)	1-300	300-1,000	5-50
Plant lifetime (years)	30-60	60	60
LCOS range ($/MWh)			

Sources: Department of Energy; Rhe Energise
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

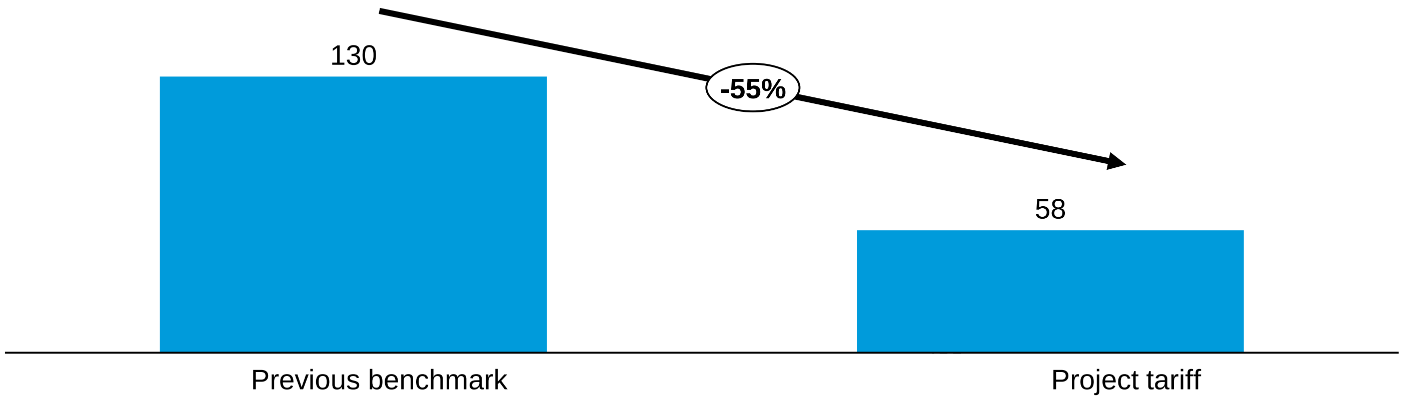
Columbia Business School

India's first utility-scale battery energy storage system completed in record time with tariff boost

India's projected growth in utility-scale battery energy storage by 2030, GW



Tariffs for India's first utility-scale battery energy storage project, INR/kWh



Observations

- India achieved a significant milestone with the regulatory approval of **its first commercial utility-scale battery** energy system project, paving the way for further BESS integration throughout the country.
- The initiative is supported by **the Global Energy Alliance for People and Planet's (GEAPP)** concessional loan, which amounts to **70%** of the total project cost.
- The project is **a 20 MW/40 MWh BESS**, strategically installed at BSES Rajdhani Power's 33/11 kV **Kilokari substation**.
- India set the BESS tariff **55% lower** than the previous benchmark, **which sets a new standard for BESS affordability in India** and makes this the fastest BESS to be commissioned, with a **record time of 18 to 20 months**.
- The project boasts a comprehensive **Monitoring, Evaluation, and Learning plan** aimed at sharing key insights and learnings with other Indian distribution companies and other **GEAPP BESS Consortium members in Asia, Africa, Latin America, and the Caribbean.**
- India's urgent need for BESS integration in distribution is underscored by the country's **substantial variable renewable energy penetration**, which exceeds **12%** in certain regions.

Source: GEAPP, India's First Commercial Utility-Scale Battery Energy Storage System (2024).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, "Storing Energy" (4 March 2025).

Italy's energy policies facilitate rapid growth in battery storage market

Italy’s regional congestion levels for stand-alone BESS deployment

High congestion

Low congestion

Observations

- Italy aims to integrate **40% renewables** into its energy mix by 2030.
- The country’s BESS market currently stands at **around 2.3 GW**, mainly in small-scale residential systems integrated with solar.
- **Utility-scale BESS** is still in early stages but set for rapid growth with an ambitious **Integrated National Energy and Climate Plan targeting 11 GW of new capacity by 2030**.
- Italy has introduced the **Electricity Storage Capacity Procurement Mechanism** as a long-term contract system to encourage **battery energy storage investments**.
- Government-backed tenders **worth €17 billion** will push this expansion with a focus on lithium-ion batteries.
- The areas showing the most promise for stand-alone BESS look to be **in south Italy**, in regions like **Sicily and Calabria**.

Sources: EY, Renewable Energy Country Attractiveness Index (2024); ITA, Italy Energy Storage; Timera, Italy rolls out new model for BESS investment (2024).
Credit: David Foye, Petr Jenicek, Birru Lucha, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Lucha *et al.*, “Storing Energy” (4 March 2025).

Modeling V2G, Australian Renewable Energy Agency (2022)

Objective

Optimize the energy supply cost for a customer while ensuring that **EVs are adequately charged to meet upcoming trip demands**, all within the given constraints

An example optimization formulation for a customer with a single EV and solar considering import and export tariffs that vary as a function of the day

Target function	$Min \sum It\, pimp,t + Etpexp,t$	• t: a time period • It: the costs of importing energy from the grid, Et: the payment for exporting energy to the grid • $Pimp,t$: the amount of power imported, $Pexp,t$: the amount of power exported to the grid • The costs and amount paid will vary depending on the specific tariffs used
Constraint 1	$Pimp,t + Pexp,t + Psol,t + Pch,t + Pdis,t = 0$	$Psol,t$: the solar generation, Pch,t: the EV charging energy, $Pdis,t$: energy discharged from the EV
Constraint 2	$-Matb1,t \le Pdis,t \le 0$, $0 \ge Pch,t \ge (1-b1,t)Mat$ $-Mb2,t \le Pexp,t \le 0$, $0 \ge Pimp,t \ge (1-b2,t)M$	• The constraints on the left are applied to reflect that the EV cannot be charged and discharged at the same time, as well as to ensure that power cannot be imported from and exported to the grid at the same time: – $b1,t$ and $b2,t$: binary decision variables, M: a large value, at: a binary value representing whether the EV is plugged in and available to charge

Input data

Vehicle data	**ACT government fleet data**	Assumes the vehicle is plugged in and could be used for V2G when it is at its home location
	Electric nation charge data	The charger energy data assumes that vehicles participating in the Electric Nation trial could engage in V2G functionality only when plugged in, which typically occurs only every few days
Energy and generation data	**ACT government consumption data**	The dataset includes metering data from ACT government sites involved in the REVS program. It contains 30-minute time-series energy transfer data at connection points but does not include solar PV data
	NetGen energy data	The data set consists of de-identified behind-the-meter consumption data for homes involved in the NextGen trial, including information on consumption, generation, and battery power

Scenarios

Pricing	**Current pricing**	• Customers are optimized against an existing retail price, assigned based on the customer class: – Houses are assigned the “ActewAGL Home Time of Use” tariff – Offices are assigned the “ActewAGL LV TOU demand” tariff
	Dynamic pricing	• Dynamic pricing builds a price signal that reveals the underlying nature of price drivers. It is split into two components: – A network price, based on the EVO energy “smart battery” tariff – A market price which is directly passed through for consumption, scaled to 90% for feed-in
Conservatism	**None**	The optimizer charges vehicles for planned trips or when necessary to achieve the optimization target. Unless otherwise specified with a conservation level, all results assume free battery use.
	50%	50% of the battery’s capacity reserved for driving, which is equivalent to approximately 135 km range in a 40 kWh Nissan Leaf
	90%	90% of the battery’s capacity reserved for driving, which is equivalent to approximately 243 km range in a 40 kWh Nissan Leaf

Source: Australian Renewable Energy Agency (2022)

Glossary

ACC	Advanced chemistry cell
AEI	American Energy Innovations
APS	Announced Pledges Scenario
BASF	Badische Anilin- und Sodafabrik
BESS	Battery energy storage system
BEV	Battery electric vehicles
BM	Black mass
BNEF	Bloomberg New Energy Finance
BoS	Balance of system
BTM	Behind the meter
CAES	Compressed air energy storage
CAFC	Corporate average fuel consumption
CAGR	Compound annual growth rate
CAISO	California's Independent System Operator
CAM	Cathode active material
CapEx	Capital expenditure
CATL	Contemporary Amperex Technology Co. Ltd.
CCS	Carbon capture and storage
CPI	Consumer price index
DAM	Day-ahead market
DER	Distributed energy resources
DISCOM	Distribution companies
DOE	Department of Energy
DRC	Democratic Republic of the Congo
E2E	End to end
EPR	Extended producer responsibility
ESO	Energy storage obligation
ESS	Energy storage system
ETS	Economic Transition Scenario
EU	European Union
EV	Electric vehicles
FAME	Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles
FCEV	Fuel cell electric vehicles
FCH	Fuel cell hydrogen
FERC	Federal Energy Regulation Commission
FIT	Feed-in tariff
FTM	In front of the meter
G2V	Grid-to-vehicle
GEAPP	Global Energy Alliance for People and Planet
GHG	Greenhouse gas emissions

Glossary

NZE	Net Zero Emissions
O&M	Operations and maintenance
OEM	Original equipment manufacturer
p.a.	Per annum
PEV	Plug-in electric vehicles
PHEV	Plug-In hybrid electric vehicles
PLI	Production Linked Incentive
PNIEC	Integrated National Energy and Climate Plan
PSH	Pumped storage hydropower
PSP	Pumped storage projects
R&D	Research and development
REC	Renewable energy certificate.
RPO	Renewable purchase obligation
RT	Real time
SDES	Short duration energy storage
SGCC	State Grid Corporation of China
SGIP	Self-Generation Incentive Program
SiB	Sodium-ion battery
SOH	State of health
STEPS	Stated Policies Scenario
SW	Software
T&D	Transmission and distribution
TCO	Total cost of ownership
TCTF	Temporary Crisis and Transition Framework
TEN-T	Trans-European Transport Network
TES	Thermal energy storage
TL fee	Transmission loss/levy fee
TOU pricing	Time-of-use pricing
TWh	Terawatt hour
V2G	Vehicle-to-grid
VALCOE	Value-adjusted levelized cost of energy
VAr	Volt-ampere reactive
VAT	Value-added tax
VGF	Viability gap funding
VRFB	Vanadium redox flow battery