2025 | BATTERY REPORT

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"The battery is the technology of our time." - The Economist

The Battery Report summarizes what we consider to be the most significant developments in the battery industry in 2025. A massively collaborative project by 120+ battery professionals from 90+ institutions, this annual report seeks to provide a comprehensive and accessible overview of the current state of battery industry, research, talent, and policy. We hope to catalyze in-depth conversations on the state of batteries and its trajectory into the future.

We Consider The Following Key Dimensions In Our Report:

INDUSTRY	Commercial milestones in battery development, manufacturing, & end-use verticals
CHINA	History, state-of-art, and state-of-play of the world's most integrated battery supply chain
ACADEMIA	Academic breakthroughs in fundamental battery science & applications
TALENT	Supply, demand, and insights on talent working in the field
POLICY	Government targets, incentives, regulations, patent trends, and their implications
COMMUNITY	Global and virtual conferences and networking events
PREDICTIONS	Trends we believe are likely to happen in the next 12 months

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2025 | BATTERY REPORT

INDUSTRY

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Volta Foundation is the world's largest network of battery professionals. As a global not-for-profit association, Volta Foundation produces publications, networking opportunities, and industry resources to foster collaboration, innovation and advocacy within the battery industry.

Industry Executive Summary

2025 marked a year of resilience and recalibration in the global battery industry. Global xEV sales surged 22% to 21.6M units, with BEV demand up 28% while PHEV demand climbed 12%. For the first time, xEVs account for >50% of new car sales in China. This milestone comes as China continues to lead the world in EV market penetration, while Europe returned to growth and the US EV market remained comparatively stagnant. Automakers are adapting their market-entry strategies: Chinese OEMs accelerated their push into Europe by transitioning from exports to local manufacturing and by increasing emphasis on hybrids and PHEVs to navigate anti-subsidy tariffs and market access constraints. In parallel, the "BESS decade" continued apace: deployments surpassed 100 GW added in 2025, driven by dramatically falling costs (31% year-on-year decline), storage-friendly policies, and new markets, while BESS product performance (energy density, efficiency, warranties) continued to improve. New BESS installations reached 104 GW / 257 GWh in 2025, taking cumulative global capacity to 267 GW / 610 GWh; in other words, roughly 40% of today's cumulative BESS capacity was installed in 2025 alone, underscoring BESS's significance as one of the most promising and fast-growing sectors in the battery industry landscape.

Global battery prices at the pack level decreased 9% to a record low of $108/kWh, with China LFP pack costs around $84/kWh (down 13% year-on-year), while pack costs remained materially higher in the US (+44%) and Europe (+56%) due to localization costs, manufacturing inefficiencies, and tariffs. The industry grappled with overcapacity, particularly in China where operating capacity reached 4x current market demand, eroding margins and catalyzing a wave of "involutionary" consolidation, forcing manufacturers to prioritize cost-down execution, vertical integration, and overseas market expansion into Southeast Asia and Europe to bypass trade barriers and to improve margins.

The investment landscape in 2025 shifted decisively from venture capital to infrastructure. Climate-related investment funds raised $101 billion, up 40% year-on-year, driven largely by infrastructure funds focused on scaling mature assets like BESS and data centers. Conversely, early-stage and growth equity VC funding tightened to $14 billion in 2025 (-50% vs 2023), contributing to high-profile insolvencies, most notably Northvolt's wind-down and Powin's Chapter 11 filing (both June 2025) sent shockwaves through the ex-China battery ecosystem and reinforced investor risk sensitivity. Public markets reflected this bifurcation, with established Asian battery giants gaining market value (eg. CATL reported net profit of $6.8 billion Q1-Q3) while many Western startups and SPAC-era companies struggled to maintain valuations.

Emerging technology trends in 2025 include an aggressive pivot toward LFP, which now accounts for nearly 50% of global EV battery sales and dominates the stationary storage market. Innovation accelerated in high-compaction-density LFP and ultra-fast charging cells. Sodium-ion had a breakout year in stationary storage with grid-scale deployments, while solid-state development transitioned from lab breakthroughs to industrial pilot lines, with OEMs targeting 2027–2030 for integration. Artificial Intelligence (AI) solidified its role as a critical enabler, embedding itself into manufacturing quality control, materials discovery, and the management of booming power demands from AI data centers.

Novel use cases such as robotics, drones, satellites, specialized industrial and heavy equipment, and virtual power plants (VPPs) are achieving higher levels of technical readiness and commercialization. Opportunities tied to AI datacenters including BESS, UPS, BBUs, and other layers of the power stack to enable speed-to-power and operational resilience are emerging as a new focus for commercial R&D and entrepreneurial energy in the space.

INDUSTRY

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Notable Events: January

Week 1

U.S. DEPARTMENT of ENERGY

SAMSUNG STELLANTIS

LPO announced $7.54B loan to StarPlus Energy (SDI/Stellantis JV) to construct EV battery factories in Indiana

China proposed export restrictions on LFP, LMFP, DLE, spodumene processing technologies

Week 2

Tesla's 40 GWh Shanghai Megafactory started trial production with full scale mass production expected in Q1 2025

HONDA

Honda started test production on its solid-state battery demonstration line

gm Vianode

GM signed supply deal with Vianode for synthetic graphite, deal to run from 2027 to 2033

Week 3

VISTRA ENERGY

Fire broke out at the Vistra Power Plant, one of the world's largest battery storage facilities in Moss Landing, California and destroyed approximately 75% of the facility

BYD

BYD launched its first EV in Korea starting at $21,500

Week 4

CATL

CATL was selected as the preferred supplier for Masdar's solar-plus-storage project in Abu Dhabi featuring 19 GWh of storage using TENER technology

SK on NISSAN

Nissan Motor announced plans to procure batteries for EVs sold in the U.S. from South Korea's SK On in 2028

Notable Events: February

Week 1

Elevated Materials spun out of Applied Materials, manufacturing roll-to-roll lithium thin films for pre-lithiation and Li-metal anodes.

KORE Power abandoned plans for $1B Arizona cell factory with initial capacity aimed for 6GWh

Critical Metals announced a $22.5M PIPE to fund the development of two of its mining assets

*PIPE: Private Investment in Public Equity.

Week 2

CATL filed for $5B Hong Kong Stock Exchange listing to fund international expansion

Honda and Nissan ended their merger talks (first announced in Dec.'24) that aimed to create a $60B combined automaker

BYD announced plans to begin 'demonstration use' of all-solid-state batteries by 2027

Week 3

Toyota shifted $1.5B order to LG's Lansing battery plant from another Michigan plant after GM exits.

Electric-truck maker Nikola filed for Chapter 11 bankruptcy protection.

Week 4

Democratic Republic of the Congo banned cobalt exports for 4 months to curb oversupply.

Mercedes-Benz and Factorial engineers launched the solid-state battery test program, putting the first car powered by a lithium-metal solid-state battery on the road.go

Notable Events: March

Week 1

Rio Tinto completed acquisition of Arcadium Lithium for $6B.

Ørsted broke ground for its first large-scale UK battery energy storage system, planned for 600MWh capacity

LG Chem unveiled precursor-free LPF cathode material for batteries, with plans to start production in first half of 2025.

Week 2

Northvolt filed for bankruptcy in Sweden after mounting financial pressures, production ramp-up challenges, and an unsuccessful restructuring attempt, despite investor interest.

Samsung SDI secured an ESS battery supply deal with NextEra Energy valued at over 400B Won ($275M).

Week 3

SK On and Nissan signed a supply agreement for 100GWh U.S. manufactured, high-nickel batteries from 2028 to 2033 to power Nissan's next-generation EVs produced at its Canton, Mississippi plant.

Week 4

BYD reported a record 2024 revenue of $107B driven by 40% sales growth in Battery EVs and Hybrid vehicles.

ION Storage Systems (ION) produced its first multi-layer ceramic solid-state battery cell on its semi-automated production line.

TotalEnergies announced investment decisions for 221MW battery storage projects totaling €160 million outlay.

Notable Events: April

Week 1



US announced major reciprocal tariffs, with exemptions for critical minerals including Gr, Mn, Co, Li.

LG Energy Solution

LGES agreed to acquire GM's stake in their Lansing, Michigan JV plant for $2.05B.

LUCID

Lucid priced $1.0 billion of 5.00% convertible senior notes due 2030 with an initial conversion price of $3.00 per share (25% premium).

Week 2

BYD

BYD launched first EVs on new Super e-platform with ultrafast charging, starting MSRP $30k in China.

SAMSUNG

Samsung SDI cut share sale price 14% as US tariffs hit. Samsung SDI started producing larger 46-series cylindrical cells, over 1 year ahead of schedule.

LG Energy Solution

LGES reported a 138% year-over-year increase in Q1 operating profit to 374.7 billion KRW (~$255 million).

Week 3



China issued world's strictest EV battery safety standard (no fire, no explosion) to take effect July 2026.

ARCHER

Archer Aviation unveiled eVTOL air taxi network with United Airlines at all major NYC airports.

CATL

CATL launched 587 Ah, 430 Wh/L cell for BESS.

Week 4

CATL

CATL unveiled world's first mass- produced Na-ion EV battery Naxtra, Freevoy dual-chemistry pack and 2nd- gen Shenxing Superfast Charging LFP battery at Super Tech Day.



US installed BESS capacity reached nearly 30GW.

STELLANTIS Factorial

Stellantis and Factorial validated EV-sized SSBs with 375 Wh/kg, 18 min charging.

SK on

SK On to supply 20GWh high-Ni NCM cells to Slate from 2026-2031 in $1.1B deal

Notable Events: May

Week 1

Amprius unveiled 450 Wh/kg, 950 Wh/L cell SiCore for aerospace and e-mobility

CustomCells filed for insolvency following the collapse of its largest customer, Lilium.

BYD April sales surged 45% to 195k BEV units to outsell PHEVs, overseas sales set new record for 5th consecutive month

ABTC received letter of interest for $900M in financing to support the construction of Li mine and refinery near Tonopah, Nevada

Week 2

CATL launched 9MWh stacked BESS designed to meet transport weight restrictions

Ascend Elements to receive up to $320M in Polish government grants to build Li-ion recycling and materials facility in Poland.

KoBold Metals to acquire stake in Manono lithium project, investing $1B to expand footprint into Democratic Republic of the Congo.

Lyten announced U.S. focused drone propulsion initiative using lithium-sulfur batteries

Week 3

CATL raised $5b in Hong Kong in 2025's 2nd largest IPO.

Li-Cycle filed for bankruptcy protection in Canada and US, receives financing and bid from Glencore as court-supervised sale begins

GM and LG pioneer LMR batteries, production to begin in 2028 for first prismatic LMR EV batteries to reduce cost and extend range to 400 miles per charge

TDK accelerated timeline of next-gen Si anode batteries, launching 2026 Fall to meet the next consumer device release cycle

Week 4

BYD surpassed Tesla EV sales in Europe for first time

GM pivoted to LFP in US factories with LGES and Samsung SDI

Fluence invested $700M to open Arizona factory as part of its US onshoring strategy

Gotion completed it's first 0.2GWh pilot line for all-SSBs with 90% yield rate.

Notable Events: June

Week 1

Toshiba started sample shipments of "SCiB™Nb", its Innovative Rechargeable Lithium-ion Battery with Niobium Titanium Oxide Anode.

GM requested LG Energy Solution and Samsung SDI to install LFP production lines to their U.S. plants.

CATL unveiled its new "Choco-SEB" battery packs, capable of being swapped in less than 2 minutes.

Week 2

Trump issued two executive orders that allow drones to be flown beyond visual line of sight, promote eVTOL aircraft and streamline advanced air mobility rules. These changes will help promote the US drone and eVTOL industry.

BYD launched Seal 06 EV - affordable midsize sedan with 545 km range, starting at $15,270

EVE Energy's board endorsed a fundraising plan aimed at bolstering its international expansion & prepared to raise funds on the HK Stock Exchange for an IPO.

Week 3

AESC 10GWh Gigafactory in France started production to power Renault EVs

Hithium began mass production of world's first 1,175 Ah cell, targeting LDES applications.

Chevron secured lithium-rich acreage from TerraVolta Resources and East Texas Natural Resources, thus joining oil majors in the US lithium production push.

Week 4

Ganfeng Lithium shipped first batch of lithium concentrate from Mali's Goulamina project to China.

COBCO started EV battery material production in Morocco.

Ronbay Technology and Rock Tech Lithium signed a strategic MoU to build an integrated local battery materials chain in Europe (LiOH offtake and support for Ronbay's Polish CAM plant).

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Notable Events: July

Week 1

Idemitsu Kosan announced a $142M investment in a new Li-sulfide plant to supply Toyota with solid-state battery materials.

Week 2

Panasonic Energy officially began mass production at its second U.S.cell factory in Kansas, targeting annual capacity of 32 GWh.

Redwood Materials and General Motors confirmed they would pursue the use of GM's U.S.-built EV batteries for Redwood Energy's grid-scale power storage systems.

Week 3

Farasis Energy commenced pilot production of sulfide-based solid-state batteries on July 21, aiming for energy densities over 400 Wh/kg.

Lyten acquired Northvolt's Polish BESS plant

Week 4

LG Energy Solution (LGES) reported Q2 financial results and announced a strategic pivot towards the Energy Storage System (ESS) market. On July 30, LGES signed a major new battery supply contract worth $4.3 billion with Tesla.

Notable Events: August

Week 1



US EV sales surged 20% in July from year ago, with 11 brands posting record sales ahead of 30D elimination.

ProLogium announced fourth-generation solid-state battery tech introducing a super fluidized inorganic electrolyte delivering 57 mS/cm conductivity.

BASF and CATL signed an agreement, making BASF a key cathode materials partner supporting CATL's global production expansion.

Week 2

Korea's big 3 cell makers operated at ~50% capacity globally amid mounting Chinese competition.

A 2026 Chevrolet Silverado EV Max Range Work Truck set a world record, driving 1,059.2 miles on a single charge and surpassing Lucid's 749 mile mark.

Week 3

CATL suspended lithium production in Yichun, accounting for ~3% of global capacity, due to mining license expiration.

POSCO Future M signed an MOU with CNGR to build a plant for LFP CAM for ESS & expand beyond its NCMA and NCA focused cathode portfolio.

Week 4

Group14 raised $463M Series D led by SK, acquires full ownership of manufacturing operations for its JV with SK in South Korea.

LG Energy Solutions became the first major global battery producer to initiate large-scale rollout of ESS-bound LFP batteries in the US, catering to rising data center demand.

WoCheng New Energy debut its ultra-low cost BESS product at $53(USD)/kWh-AC, provokes price war discussion at Shanghai trade show.

Notable Events: September

Week 1

U.S. Immigration and Customs Enforcement (ICE) took nearly 300 Korean skilled workers into custody, at the Hyundai-LG battery plant construction site in Georgia

US based Natron Energy has ceased operations,, halting plans for a giant $1.4 billion factory in Rocky Mount, North Carolina.

LGES secured a 107GWh battery deal with Mercedes for LG's next-generation "46 series" batteries.

EVE Energy lanched new solid-state battery factory in Chengdu China to reach a capacity of 500 000 cells produced annually. A significant step towards industrialization of solid state batteries.

Week 2

CATL unveiled Shenxing Pro LFP, long life & long range battery for Europe. The first LFP battery to deliver 758 kms WLTP and 12 years / 1000 000 lifespan.

Canada delayed the introduction of its 20% EV sales mandate by one year.

Toyota Tsusho acquired 25% of LG Chem CAM plant in Gumi Korea, lowering Huayou Cobalt's ownership from 49% to 24% to qualify for US tax credits as a non-PFE.

Week 3

InoBat received 54M€ funding, from Spanish ministry of industry, for battery cell plant in Spain.

SK On opened a pilot plant to fast-track solid state batteries.

Ford cut 1000 jobs at its Cologne factory due to weak EV demand.

AMG lithium opened Europe first refinery to produce 20 000 Tons of LiOH.

Week 4

LG Chem announced a supply agreement for cathode active materials to Prime Planet Energy & Solutions (PPES) in Japan targeting to start production in 2026.

Hyundai, Kia worked on new LFP cathode process with Ecopro to eliminate the precursor production step, reducing import reliance from China and lowering cost.

SAIC-GM and CATL presented 6C ultra fast-charging LFP battery to be used on the upgraded Ultium platform.

Notable Events: October

Week 1

US BEV tax credit ended (7500$ for new BEV & 4000$ for used BEV).

China announced new export controls limiting export of graphite material & equipment, precursor for ternary cathode materials, LFP Gen 4 and battery & CAM equipments.

Nissan cancelled EV production in the US due to falls in demand. Instead, they will switch to producing hybrid vehicles.

Week 2

Xiaomi delivered 40,000 EVs in a single month as waitlist grows to 48 weeks

China files a WTO complaint over India's EV and battery subsidies

Archer acquired Lilium's patent portfolio for €18 million

JPMorganChase Launches $1.5 Trillion Security and Resiliency Initiative

Week 3

US Department Of Energy cancelled $718M of funding to five companies: Ascend Elements, American Battery Technology, Anovion, ICL & LuxWall.

Lyten finalized acquisition of Northvolt Dwa in Gdańsk, Poland, the largest Battery Energy Storage System (BESS) manufacturing facility in Europe.

GM & Posco paused expansion at their Canadian CAM plant due to weak EV demand.

Sunwoda unveiled a solid state battery (400 Wh/kg) and announced a pilot line (200MW).

Week 4

Redwood has closed a 350M$ series E funding round, let by Eclipse, and including strategics (NVentures).

Nissan partnered with Lithion for battery recycling.

Gotion cancelled plans to build battery cell factory in Michigan due to environmental risks alleged by local residents and Chinese ownership.

Notable Events: November

Week 1

Tesla announced it would purchase $2B of ESS batteries from Samsung SDI over 3 years.

LG Chem signed an agreement with China oil major Sinopec to develop Na-ion batteries.

Samsung SDI, BMW signed an agreement to jointly validate all-solid-state batteries using SolidPower's electrolyte technology.

U.S.-Japan meeting resulted in $350M of investment commitments from Japan/Japanese companies for LFP production from Mitra Chem.

Week 2

Toyota announced it would launch its 2nd U.S. battery plant with up to $14 billion investment (including hybrids).

Tesla officially launched a 510-mile Model Y Long Range RWD model in China.

CATL started mass production of 5th-gen LFP batteries with higher energy density.

China officially suspended the implementation of the rare earth export controls announced in October for a one-year period per latest US-China trade deal.

Week 3

Peak Energy signed a 4.75 GWh contract with Jupiter Power for Na-ion BESS.

Trump administration allowing detained South Koreans to return to bring-up GA gigafactory

Standard Lithium received $225M funding from Washington in the race to be the first company to produce lithium from the Smackover in Arkansas.

Week 4

Gotion commenced mass production to supply 46xx format LFP & LMFP cells to VW starting in 2026.

Ronbay became CATL's top supplier of sodium-ion battery cathode materials by providing more than 60% of its annual volume.

Notable Events: December

Week 1

CATL STELLANTIS

CATL and Stellantis broke ground on €4.1B LFP gigafactory in Spain, training 4000 local workers.

Panasonic ENERGY ZOOX

Panasonic Energy announced agreement to supply battery packs for Amazon-backed Zoox robotaxi.

Vianode

Vianode to invest $3.2 billion to build North America's largest synthetic graphite production facility in Ontario

Week 2

Ford SK on

Ford and SK On unwound $11.4B BlueOval SK JV: Ford takes full ownership of Kentucky plants.



China pledged to accelerate the implementation of targeted policies and measures to curb "irrational competition" in the power and battery energy storage industry.

FARASIS GAC

Farasis Energy announced it would supply 10 GWh of batteries for GAC Aion European models.

Week 3

Ford LG Energy Solution

Ford canceled $6.5B battery supply contract with LG Energy Solution.

AESC

AESC restarted clock on construction of $1.6B Florence plant after six-month hiatus.

Factorial

Factorial announced plans to go public via SPAC merger at a $1.1 billion valuation.

Week 4

LG Energy Solution

LGES acknowledged $9.6B in US deals lost in December (Ford cancelled $6.5B, Freudenberg $2.7B).



Japan rolled out its national Li-ion battery safety and EOL handling package.

SAMSUNG

Samsung SDI signed a JV with KGM for next-gen EV battery packs using SDI's 46xx cylindrical cells.

Energy Tech Solution

Seoul | Chungju | Detroit

Your scale-up partner

FACTORY BUILDOUT

Equipment | Cell Design | Technical Advisory

- Coaters
- Stackers
- Mixers
- Winders
- Formation
- and more!

CONTRACT MANUFACTURING

Pouch | Prismatic | Cylindrical

- LFP
- NMC
- LMB
- LTO
- Na+
- Si-anodes

START YOUR SCALE-UP TODAY.

Contact: Bruno Vanzieleghem
brunov@energytechsolution.com

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2025 | BATTERY REPORT

INDUSTRY

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Notable Events

Industry Value Chain

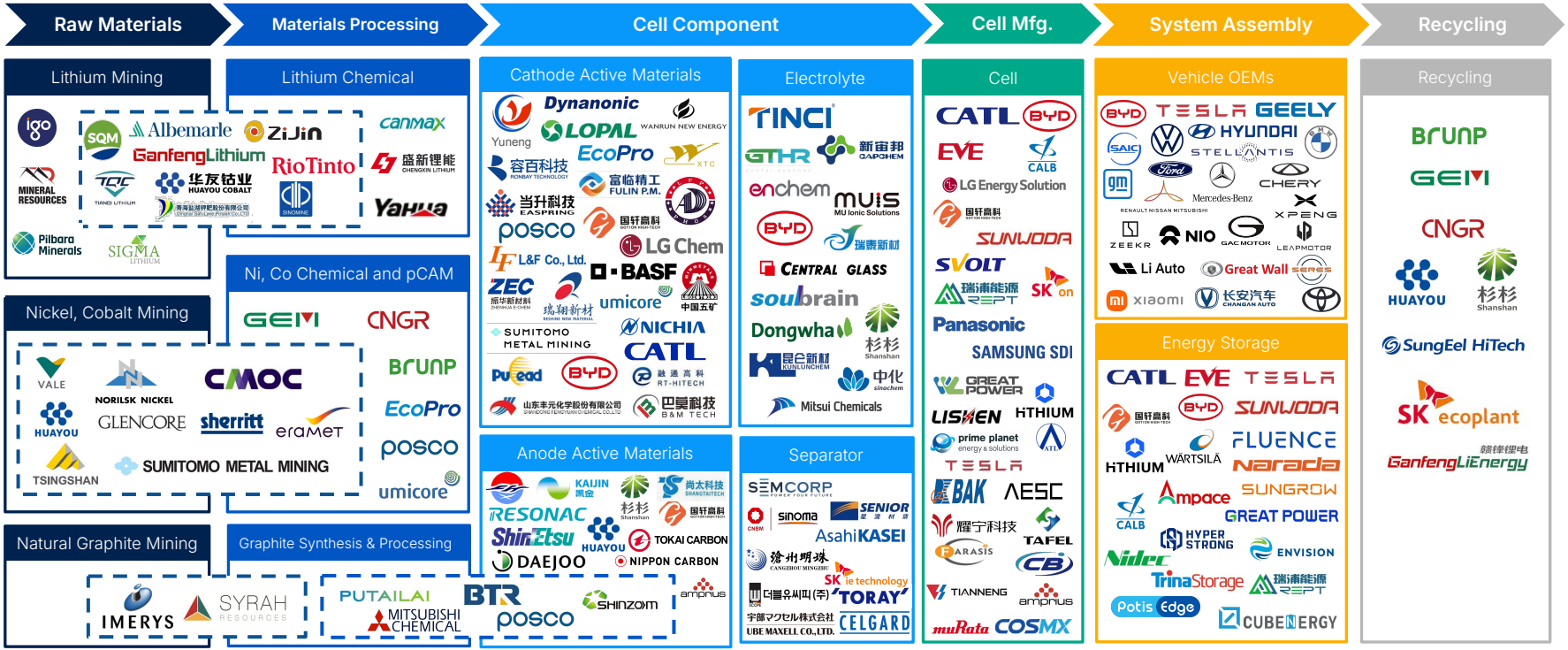
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

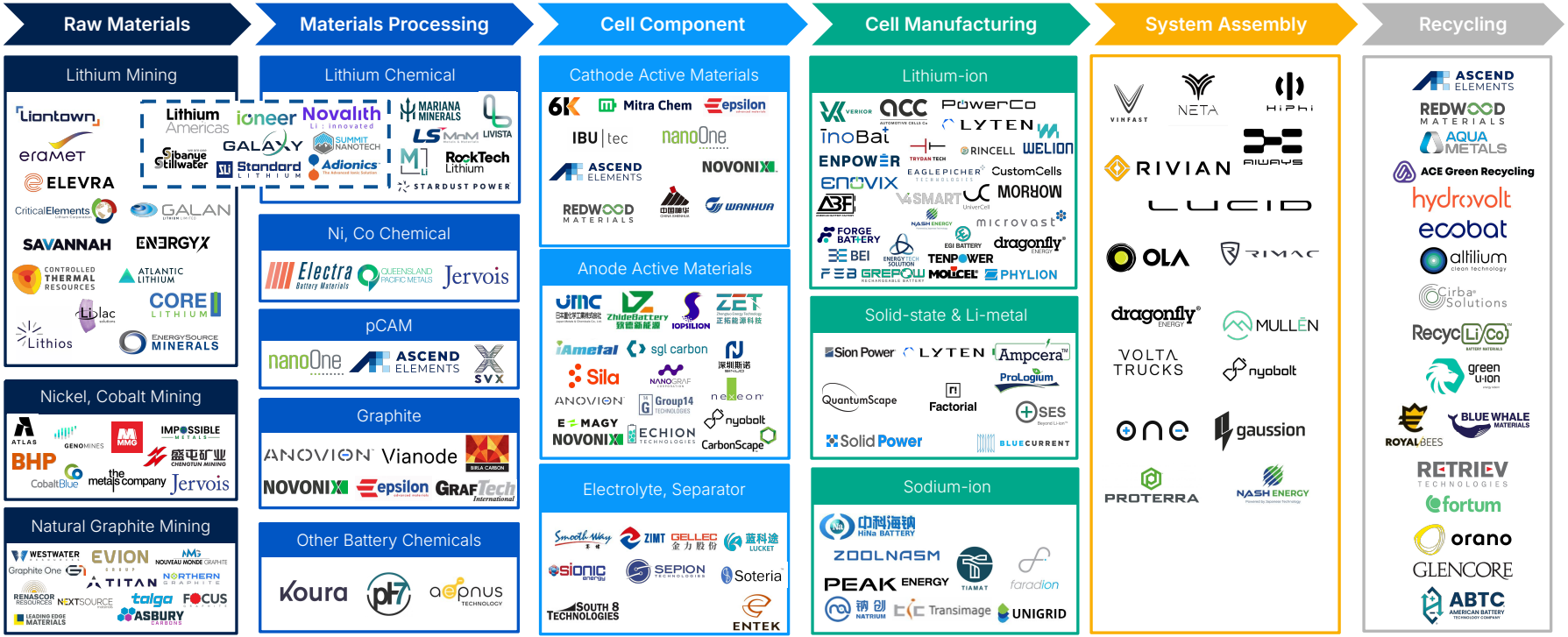
Software / AI

Incumbents and/or Public Companies (>$1B Market Cap/Valuation)*



*Estimated as of December 2025

Emerging Players and/or Small Companies (>$30M Valuation)*



*Estimated as of December 2025

Startups and/or University Spin Offs*

Materials Processing

Lithium Chemical
LIVISTA
AUSTVOLT

pCAM
CHEMX MATERIALS

Graphite
CONOVATE
granode

(Solid) electrolytes
NATRION
Ampcera™

Cell Component

Cathode Active Materials
altilium clean technology
INTEGRALS POWER

Anode Active Materials
E-MAGY
SILI ENERGY
IN ALL SOLID STATE BATTERY
NEBA Lithium Solution
Nanode
ADVANO

Other components
Soteria™
FEON

Cell Manufacturing

Li-ion
TYFAST
Molyon
ABF
ATEIOS SYSTEMS

Solid-state
Solidion
GQenergy
RECHARGE OUR PLANET
BTRY
TAISAN
CYMBET CORPORATION
zakuro
Piersica

Other battery concepts
Battolyser Systems
broadbit BATTERIES
GEYSER BATTERIES
P+L

Process Technology
8inks
Dynami
SAKUU

System

endurance MOVE ON
VIVITRON
欣视界Inx
CLEAN ELECTRIC
Rolled-Ribbon BATTERY COMPANY
东渐
DAOPULSE
INTECELLS
INDIGRID TECHNOLOGY

Recycling

ecomet recycling
Primobius
Battery recycling without limits
tozero
altilium clean technology
librec Closed-loop Battery Recycling
PRINCETON NUENERGY
BATX ENERGIES Beyond Limitations
ABTC AMERICAN BATTERY TECHNOLOGY COMPANY
CYLIB
EverGreen Lithium

*Estimated as of December 2025

Battery Development Value Chain

Materials Identification & Characterization

eurofins | EAG Laboratories
CLARK TESTING
TÜV SÜD
intertek
worley
HATCH
element
Exponent
CITRINE INFORMATICS
AIONICS
LUCIDEON
chemix
BATTELLE
DNV
SGS

Modeling & Simulation

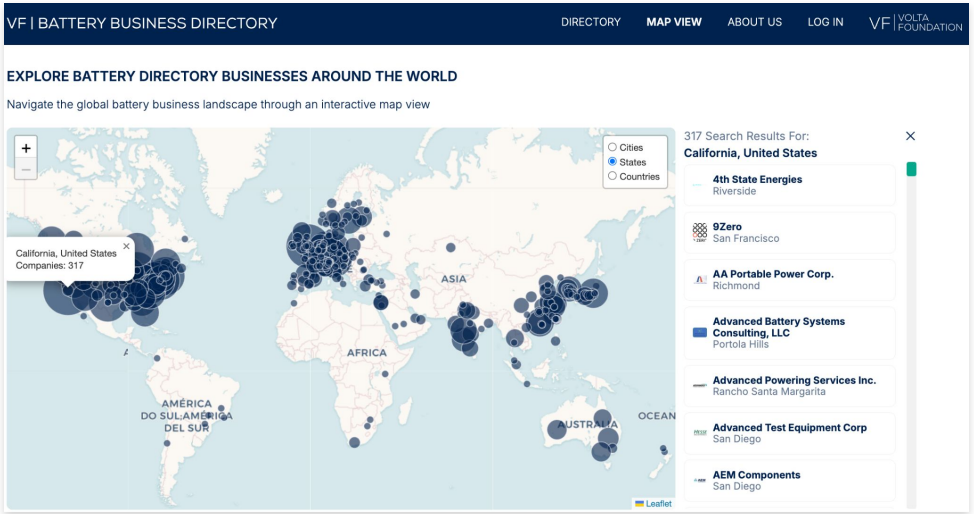
BATEMO UNDERSTANDING BATTERIES
ionworks
ABOUT:ENERGY
ReJoule
ALTAIR
UL Solutions
VOLTAIQ
eatron TECHNOLOGIES
SIEMENS
COMSOL MULTIPHYSICS
HEXAGON
BREATHE
DASSAULT SYSTEMES
ELECTRA
ELECTRODER
Schrödinger
SES
MICANTIS
BattGenie.
PyBaMM

Battery Testing

VOLTAIQ
element
MICANTIS
ReJoule
electricgoddess
ENERGY ASSURANCE.
VoltR
UL Solutions
S9
DEKRA
intertek Total Quality. Assured.
ENERGSOFT
BLUE WHALE ENERGY & INNOVATION
TÜV SÜD
DNV
eurofins | EAG Laboratories
kiwa
Daniel Consulting Group, LLC
MIRA
BattGenie.
Bib batteries
BUREAU VERITAS

A Comprehensive Database of Battery Companies: The Battery Business Directory

3,000+ COMPANIES MAPPED TO 15 SUPPLY CHAIN SEGMENTS



Key Industry Pain Points:

- **Fragmented Market**: Difficulty identifying and evaluating potential partners, suppliers, or customers due to a fragmented and siloed global battery supply chain.
- **Inefficient Sourcing**: Significant time wasted manually sourcing and vetting battery companies via trade shows, personal networks, or unreliable sources.
- **Inconsistent Data Quality**: Limited access to accurate, comprehensive, and regularly updated information on companies across the battery industry globally.
- **Limited Visibility**: Companies - especially startups or specialized vendors - face challenges gaining visibility and connecting with larger industry players and investors.

The Battery Business Directory

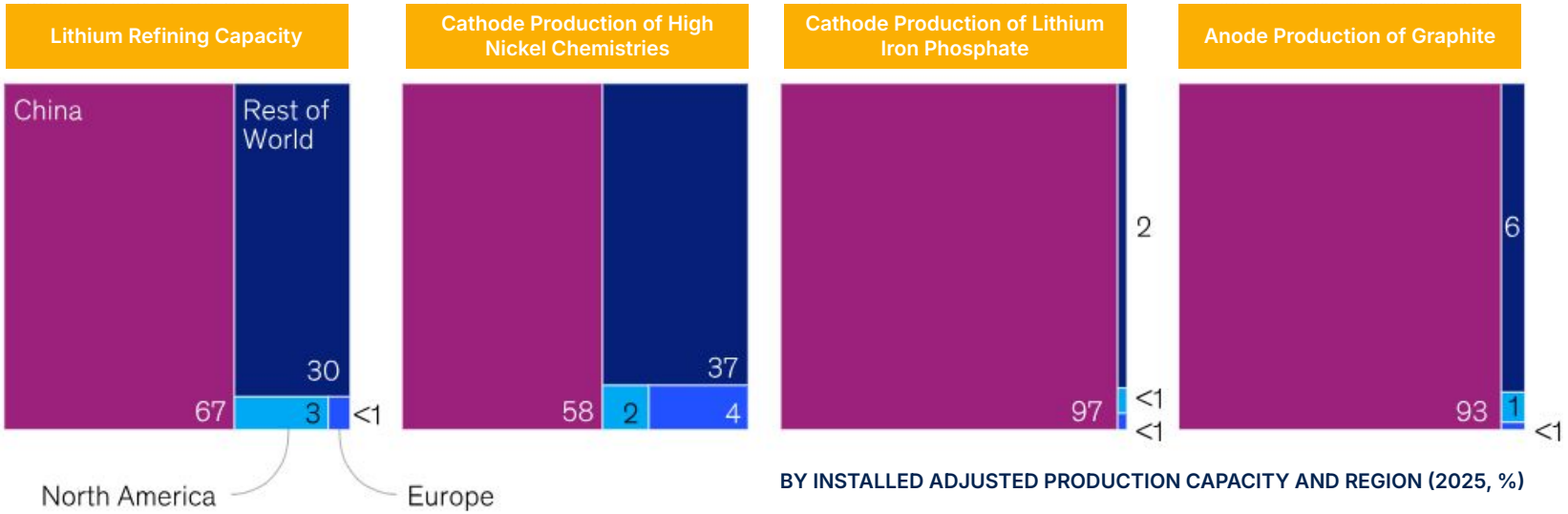
The Battery Business Directory is the largest open-access database for companies operating across the global battery industry. The directory maps over 3,000 organizations spanning 15 key supply-chain segments, providing comprehensive, reliable data that helps battery professionals discover potential partners, suppliers, and customers.

Source: Battery Business Directory

Chinese Companies Have the Largest Market Share for Critical Battery Materials

LFP cathode and graphite anode are the most critical materials in the supply chain

GLOBAL MARKET SHARE FOR KEY BATTERY MATERIALS

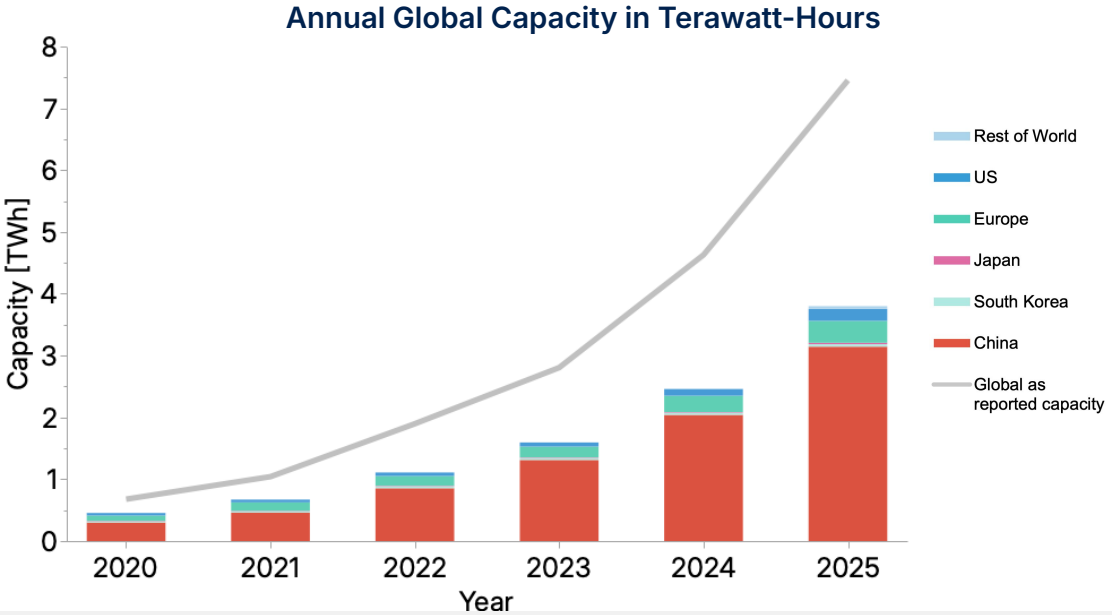


BY INSTALLED ADJUSTED PRODUCTION CAPACITY AND REGION (2025, %)

Source: McKinsey

Overcapacity at 4x Demand Continues to Erode Margins Across the Value Chain

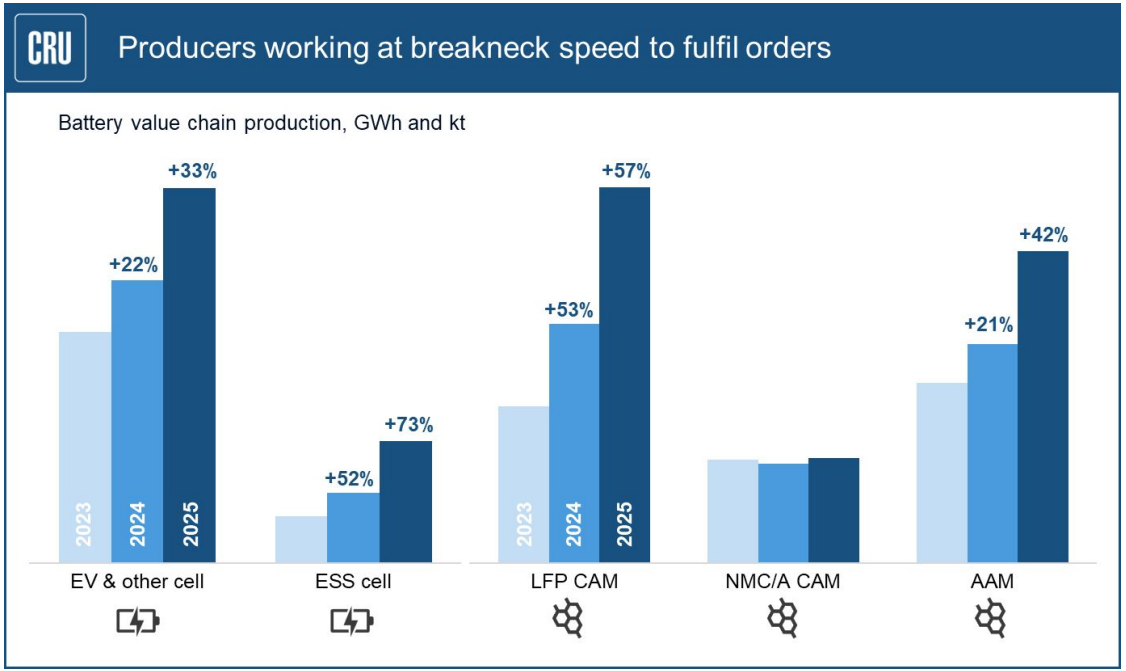
- Average global battery pack costs may have fallen to $108/kWh, but there are regional disparities
- Chinese battery firms have operating capacity at 4x market current demand and pack costs were roughly $84/kWh (a 13% drop YoY)
- Chinese firms are also largely vertically integrated across the battery supply chain and control the majority of global high-purity battery raw material production
- This dominance is being exacerbated by fierce competition in China pushing prices downward that will continue into 2026
- Pack prices are roughly 44% higher in the U.S. and 56% more in Europe compared to China, causing many cancelled plans and re-evaluations of OEM electrification strategies



Graph represents risk-adjusted cumulative lithium battery cell manufacturing capacity by region, compared with as-reported global capacity

BloombergNEF Source: Data from BloombergNEF (Distinguished Partner).

Policy Shifts are Driving Demand Front-Loading and a Manufacturing Race to Deliver



Policy changes or pending policy implementations in China, US, and other regions have driven a front-loading of demand at various points throughout 2025.

China: changes to its renewable power pricing mechanisms, co-located storage mandate, technology export controls, phase-out of export VAT rebate → rush of installations and procurement before implementation

US: sourcing rules now applying to production tax credit and BESS investment tax credit, abolishment of EV tax credit, successive tariff hikes → front-loading of orders and stockpiling before implementation

Rest of World: having observed trade tensions rising and China's anti-involution campaign intensifying, other regions are also accelerating procurement from China, especially BESS while costs remain extremely low.

This has all fuelled a manufacturing race to deliver. China's battery factories are operating at high utilisation while also upgrading lines for new cell technologies, which in turn prompts customers to secure more long-term supply. This behavior amplifies underlying demand growth and has led to elevated order volumes, especially for ESS battery cells and LFP CAM.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

BESS Value Chain Experiencing the 'Bullwhip Effect': A Growing Disconnect Between Demand and Production

ESS demand has exhibited remarkable growth, but that is being magnified up the supply chain as manufacturers overreact to perceived demand.

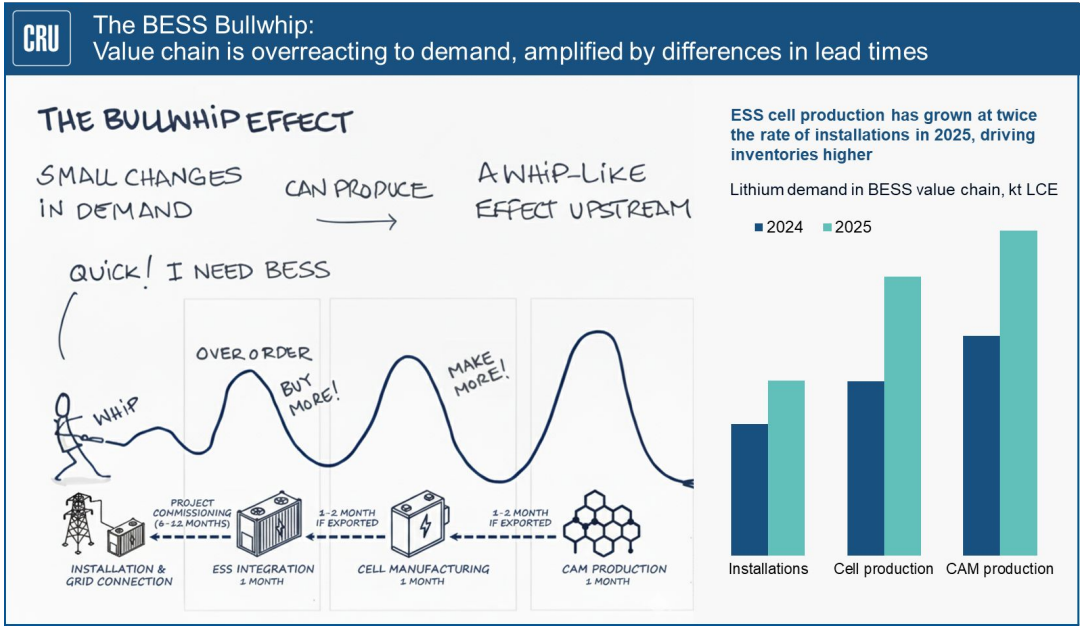
ESS battery cell production this year is around 600 GWh – almost twice that of installations – and even higher for ESS-destined CAM production, even when accounting for time lags in the supply chain.

This is the '**Bullwhip Effect'.** In the case of ESS, it is amplified by long lead times becoming the new normal, especially for ex.China customers. At the same time, installers are struggling to secure equipment due to full order books at cell manufacturers, and previous policy-driven front-loaded demand has contributed to this.

Cell and CAM producers say they are confident in demand being sustained, because of:

- A huge order backlog and long-term sales contracts
- High utilisation ratio of ESS cell plants
- High profitability of ESS cell and integrators
- Further room for cost reductions by upgrading products: larger cell capacities etc.
- Very strong pipeline of ESS projects

However, LFP cell and cathode inventories have reached alarming highs, and the longer it goes on, the more pronounced the drawdown will be.



Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
*Showing only cells and CAM destined for BESS applications. Image adapted from Sketchplanations.

Chinese & European Players are Partnering to Ensure Ramp-Up and De-Risking for Overseas Projects

Chinese battery manufacturers have created a strong foothold in the European market. One third of gigafactory capacity planned in Europe will have Chinese involvement.

Many Chinese operations involve a local European partner (industrial or financial) to **share costs and risks.**

This also applies to p/CAM/AAM projects.

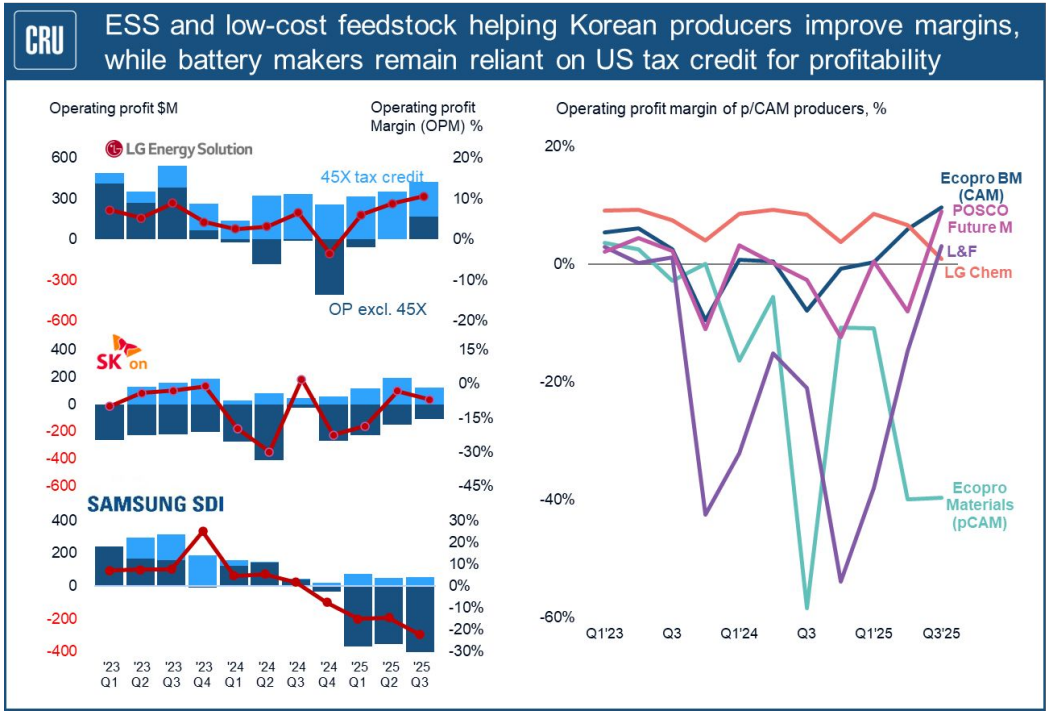
Almost all major joint venture battery plants are for the EV sector, whereas there is less of an imperative to localise ESS battery plants in Europe due to higher costs and minimal trade barriers.

The concern from the European side is that these partnerships currently lack meaningful **knowledge sharing**. The EU is hinting at a regulatory framework for this under proposals for the Clean Industrial Deal.

	VW / GOTION	InoBat / GOTION	STELLANTIS / CATL	NISSAN / AESC	RENAULT / AESC	Multiple / AESC
GWh (status)			50 (2026-27)	15.8 (2025)	10 (2025)	30 (2026)
Ownership structure	VW holds 26.5% in Gotion	Gotion: 80% | InoBat: 20%	Stellantis: 50% | CATL: 50%	AESC: 80% | Nissan: 20%	AESC: 100%	AESC: 100%
IP or technology transfer provisions	"Limited"	Some	✗	Some	✗	✗
Local supply chain	✗	✗	✗	✗	✗	✗
Local workforce	Local R&D centre	Some, incl local schools	No known provisions	No known provisions	No known provisions	No known provisions
Equal battery side decision-making	✗	✗	✗	✗	✗	✗

Source: Transport & Environment

Korean Producers Implementing Strategies to Turn Around Squeezed Profits



Survival Hinges on Diversification and Cost Reduction

Korean battery value chain companies, having relied on the US as a captive market largely protected from Chinese competition, have been been facing growing financial pressure from:

- Rising costs driven by US tariffs
- Repeal of the US EV tax credit (30D) and tighter restrictions on the battery production tax credit (45X)
- Slower EV demand and battery orders in US

Their main survival strategies have involved:

- Diversifying into LFP and BESS, capturing the booming demand for both, while capitalising on the US-China divide that is prompting demand for China-free supply.
- Upstream integration for lower raw material costs to improve margins and reduce reliance on third-party suppliers.

Efforts are already paying off, with improved profitability seen in 2025 Q3 filings, and a couple of companies growing a large order backlog for ESS products. Remaining firms struggling with profitability have yet to fully carry out their plans.

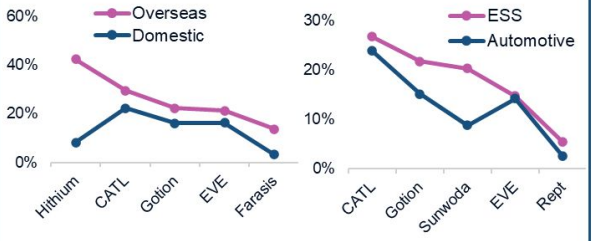
However, pressures on US EV demand remain a reality, and both Korean companies and their automaker customers claim they still have more to do in terms of recalibrating their investments in the NMC value chain. Battery joint ventures are unravelling, and major NMC battery orders are being cancelled.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
Data from company financial reports.

Korean-origin Companies are Diversifying into LFP & BESS

They have seen how Chinese peers get higher margins overseas and for BESS

Gross profit margin of selected companies in 2025 Q1, %

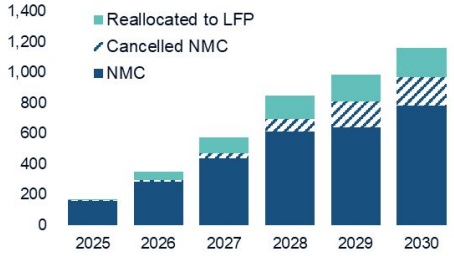


They have secured LFP ESS cell contracts in a captive US market

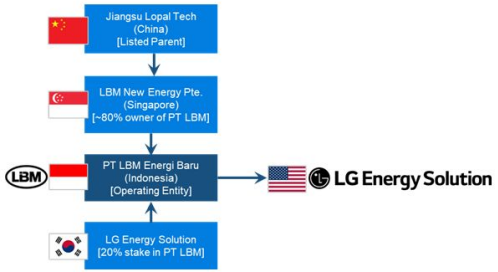


They are establishing LFP supply chains

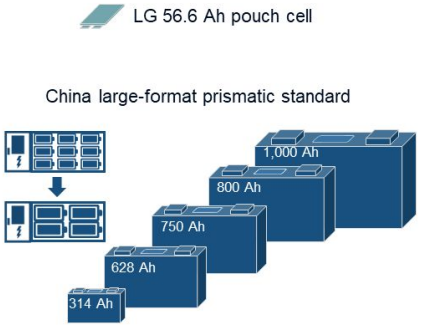
US Tier 1 gigafactory pipeline, GWh



Indonesia CAM plant supplying US & other markets



But they are way behind on the Chinese on LFP tech



And they start at a relatively high cost

Producers are Finding Pragmatic and Cost-Effective Ways to Adapt to US Policy Pressures

CRU

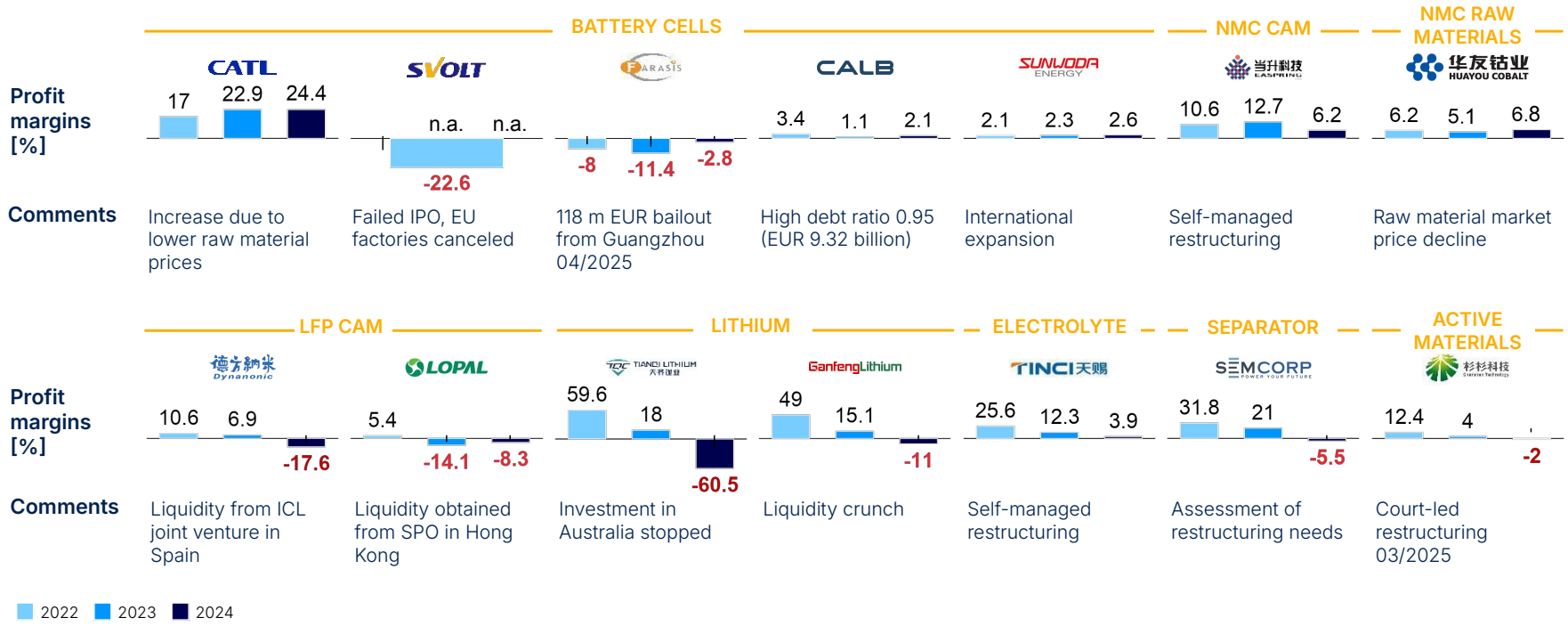
Three common themes:

1. Recalibration of excess investments
2. Restructuring of supply chains to retain tax credits
3. Acceleration of shift to LFP

Automakers	BESS project developers	US (Korean) battery makers	Chinese battery makers	CAM producers
▪ Accelerate LFP adoption ▪ Produce domestic LFP cells (JV or LRS) ▪ Diversify into ESS business ▪ Import LFP cells as stop-gap ▪ Pull back NMC JV investments, transfer capacity to other OEMs	▪ Front-load orders from China ▪ Source domestic (nascent) batteries ▪ Without tax credits: Power pricing changes	▪ Retooling for LFP ▪ Pull back NMC investments ▪ Secure LFP CAM from ex. China ▪ Secure ESS orders	▪ Front-load production ▪ Explore SEA as a production base ▪ Explore ownership restructuring in US ▪ Licensing (LRS) for US gigafactories	▪ Dilute Chinese ownership for PFE compliance ▪ Overseas expansion, especially Indonesia ▪ Ongoing technical innovation and diversification (LFP, MNHV) ▪ Refined metals (non-battery)

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

Profit Margin Development in the EV Battery Value Chain for Selected Producers



Source: Content & analysis provided by Roland Berger (Distinguished Partner). For more information, visit https://www.rolandberger.com/en/Insights/Global-Topics/Battery. List is non-exhaustive, and updated June 2025.

2025 Saw Many New Supply Agreements & Partnerships, but Also Cancellations

Common themes: securing supply outside China, and scramble for LFP

Ongoing Asian-led Li/Ni/Co partnerships

Chengxin Lithium	Ford	Spodumene concentrate
Chengxin Lithium	Huayou (Youshan)	Lithium carbonate + hydroxide
Mineral Resources	POSCO	Spodumene concentrate
GEM	XTC	Lithium carbonate, phosphate, nickel/cobalt sulphate
CNGR	XTC	Lithium carbonate, phosphate
~~Alliance Nickel~~	~~Stellantis~~	~~Nickel sulphate~~

Search for Ex.China lithium chemical supply for local CAM production

EcoPro	SK On	Lithium hydroxide
Rock Tech Lithium	Ronbay	Lithium hydroxide
Mandrake Lithium	Stardust Power	Lithium chloride
Stardust Power	Sumitomo	Lithium carbonate

Trading houses securing feedstock from new producers

Ascend Elements	Trafigura	Recycled lithium carbonate
Vulcan Energy	Glencore	Lithium hydroxide
Premier African Metals	Glencore	Spodumene concentrate
EVelution Energy	Mitsui	Cobalt sulphate + metal

Securing Chinese domestic LFP CAM to fuel growing ESS demand

Yuneng	Hithium	LFP CAM
Wanrun	Hithium	LFP CAM
Wanrun	CATL	LFP CAM
Lopal	CATL	LFP CAM
Lopal	Cornex	LFP CAM
Fangyuan	BYD	LFP CAM
CNGR	BYD	FP
CNGR	EVE Energy	FP
CNGR	Gotion	FP
CNGR	CALB	FP

Extensions of agreements: manufacturers invested in NMC

LG Chem	Panasonic, Tesla	NMC CAM
Umicore	SK On	NMC CAM
MCC RAMU	Minmetals, EVE Energy	NMC CAM
Easpring	LG ES	NMC CAM
POSCO	LG ES, Hyundai	NMC CAM
Eco & Dream	Umicore	NMC pCAM
CNGR	Umicore	NMC pCAM
CNGR	XTC	NMC pCAM
GEM	XTC	NMC pCAM
~~Huayou~~	~~POSCO (joint venture)~~	~~NMC pCAM~~

Securing ex.China LFP CAM for new ex.China cell production

PT LBM (Lopal)	Ford	LFP CAM
PT LBM (Lopal)	EVE Energy, Tesla	LFP CAM
PT LBM (Lopal)	Sunwoda	LFP CAM
PT LBM (Lopal)	CATL	LFP CAM
L&F	Unannounced	LFP CAM
IBU-Tec	PowerCo	LFP CAM
~~Dynanonic~~	~~CATL, Stellantis~~	~~LFP CAM~~

Chinese NMC CAM producers in Europe securing more contracts

Easpring	SK On	NMC CAM
Huayou	EVE Energy, BMW	NMC CAM
Huayou	LG ES	NMC p/CAM
CNGR (COBCO)	Umicore	NMC pCAM

OEMs remain searching for ex.China AAM supply

Vianode	GM	AAM
POSCO	GM	AAM
Syrah	Lucid	AAM
Syrah	Tesla	AAM
~~Novonix~~	~~Stellantis~~	~~AAM~~
~~Westwater~~	~~Stellantis~~	~~AAM~~

Establishing supply chain for ex.China LFP for EVs and strong US ESS demand

LG ES	GM	LFP
LG ES	Mercedes-Benz	LFP
Samsung SDI	GM	LFP
LG ES	Tesla Energy	LFP
SK On	Flatiron Energy	LFP
LG ES	SK Eternix	LFP

OEMs partnering with Chinese cell makers

CALB	Hyundai	NMC
BYD	Hyundai	LFP
CATL	Scania	NMC

NMC-based partnerships

SK On	Nissan	NMC
LG ES	GM (JV)	LMR
~~SK On~~	~~Ford (JV)~~	~~NMC~~

Note: Stellantis terminated partnerships with Alliance Nickel (missed milestones); Novonix (unable to agree on specifications); and Westwater (change in direction). SK On and Ford have ended their JV with each company taking over the plants in Tennessee (SK On) and Kentucky (Ford). Other strikethroughs indicate canceled or terminated partnerships.

Source: CRU Group (Distinguished Partner) supply chain database, company announcements.
Strikethroughs indicate cancelled deals. Non-exhaustive list.

Acquisitions & Consolidation

2025 saw significant industry consolidation and acquisition, driven by the acquisition of bankrupt companies either as a whole or in parts to enter new sectors, expanding supply chains for critical materials, or boosting production capacities.

Scania VW subsidiary acquires Northvolt's heavy industry battery packs unit

Bought Northvolt assets in Sweden, Germany, and Poland + IP + Cuberg

Volvo takes full control of NOVO Energy after Northvolt Bankruptcy

Takes over insolvent German parts supplier Manz (equipment + employees)

Completes purchase of Nikola's battery assets for US battery production

Acquired Maxwell Technology to expand energy storage portfolio

Acquires parts (technology + U.S. production) of Superior Graphite

Acquired bankrupt Li-Cycle assets and subsidiaries

- 40% in the Goulamina lithium mine in Mali
- 45% in Avalonia lithium project in Ireland

- Acquired Arcadium Lithium for $6.7 billion
- Acquired controlling stake in Chile's Salares Altoandinos

- 5% in Lithium Americas
- 5% in Thacker Pass JV
- 15% in MP Materials

Acquired 125k acres of lithium-rich Smackover Formation (TX, AK)

Acquired 24.8% of Zangge Mining for their lithium assets for $1.87 billion

Source: Company announcements

New Plant Openings & Agreements Outside of China

Panasonic

Began mass production at a plant with 32 GWh (EV) of capacity in Kansas
Auto partner: Multiple

NEXTSTAR ENERGY

Began mass production at its 49.5 GWh (ESS + EV) plant in Ontario
Auto partner: Stellantis

Envision AESC

New plant 12GWh plant in Sunderland, UK, commenced operations
Auto partner: Nissan

PowerCo

Opened first phase of a plant in Germany with an initial capacity of 20 GWh
Auto partner: VW



Signs a $2 billion supply agreement with LGES Lansing plant for NMCA

LG Energy Solution

Expanded Michigan plant to include production of LFP battery packs for ESS

CUSTOMCELLS®

Restructuring with existing and new investors keeping 80% of workforce

HASCO®

Acquired a 49% stake solid-state battery joint venture with SAIC

Neuron™

Launched a battery plant in India with an Initial capacity of 1.5 GWh

VERKOR

Launched battery plant in France with an Initial capacity of 16 GWh

Source: Panasonic; Nextstar; Envision AESC; PowerCo; Toyota; LG Energy Solution; CustomCells; Hasco; Neuron; Verkor

Difficult Year for Many Companies as Industry Restructures

In 2025, the battery industry faced significant financial challenges, leading to several notable bankruptcies and restructurings. Several factors, such as financial challenges lowering system prices and performance from China, including a growing difficulty to scale in the West and a challenging investment environment.

"Big Players" Insolvencies

Ambri

northvolt

POWIN

Natron Energy

Li-Cycle

Company Restructuring

SK → SK on + SK enmove

CELLFORCE → Focus on R&D for Porsche

FREYR Clean battery solutions → Energy

Further Notable Insolvencies:

CANOO	BOLLINGER MOTORS	LILIUM	iM3NY	VOLTA	NIKOLA	ample, BMZ, ENERPOLY, VOLTSTORAGE
Ceased operations and is in bankruptcy proceedings	Shut down e-Truck commercial manufacturer	The eVTOL aircraft carrier ceased operations	Assets sold in April and case moved toward dismissal	Filed for bankruptcy for a second time in 2025 & ceased ops	Filed for bankruptcy and is under court-supervised liquidation	

Source: Company announcements

Cancelled Gigafactory Plans

With partner Posco Future M paused Canadian CAM plant expansion leading to Vale withdrawing from planned nickel sulfate plant

Subsidiary in Quebec: Although the bankruptcy of the Swedish parent company in 2024 put this project in a precarious position, it was still a go until September 2025 when the Quebec government pulled funding

Plans for a $1.4 billion gigafactory in North Carolina has been canceled due to closure

Cancelled plans for a $1.25 billion gigafactory in Buckeye, Arizona, citing construction costs and market uncertainties

The Stellantis-backed ACC joint venture is close to "definitely giving up" plans for a gigafactory plant in eastern Italy

Paused plans for a $1.6 billion gigafactory in Florence, South Carolina citing market uncertainty

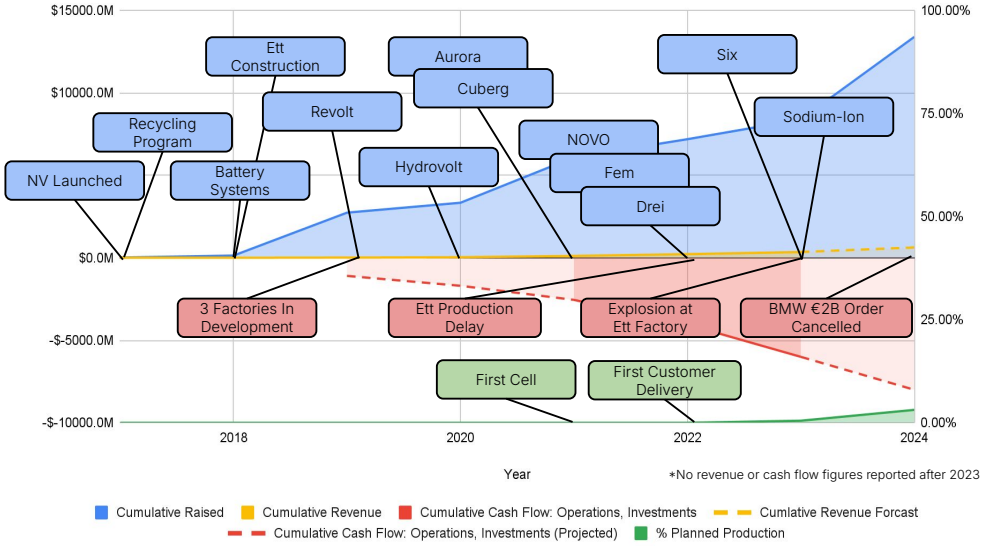
Abandoned plans for a $2.4 billion gigafactory in Big Rapids, Michigan, due to intense community opposition and lawsuits

Cancelled plans for a $2.6 billion gigafactory in Georgia citing interest rates and falling battery prices

Source: Company announcements

Unable to Secure Financing at the 'Eleventh Hour'

Northvolt officially filed for bankruptcy in March 2025, which had wide reaching implications for the European and North American battery industries. Before the complete shutdown, production capacity at Northvolt's primary Skellefteå plant was only 30k battery cells per week and hampered by inconsistent cell quality. This production rate was not enough to service debt.



After failing to secure a buyer as the risk profile was too high, Northvolt was ordered to wind down in June 2025:

- A $5.8 billion debt burden with only $30 million in cash on hand → Assets were only valued at $250 million compared to a $12 billion valuation in 2022
- Lyten acquired core assets in Europe and IP; Volvo took full ownership of NOVO Energy; Norsk Hydro took full ownership of Hydrovolt (recycling)
- Plans to build a 60GWh plant in Canada ceased in September when the Quebec government pulled future funding after their new plan was rejected
- Lyten is planning to restart production lines at Northvolt Ett and Västerås in Sweden as operations achieved over 90% efficiency before closure

Source: Volta Battery Report 2024; Company announcements

Cellforce Group: The Rise, Ambition, & Strategic Retreat

Ideation (Pre-2021)

Concept initiated by P3 Group (Stuttgart consultancy)

P3 + Customcells applied for EU IPCEI EuBatIn funding

Porsche AG joined as automotive lead

Founded Cellforce Group (CFG) as a JV between Porsche and Customcells

Technology: High-performance silicon-anode pouch cells (high energy density + fast charging)

Received public funding of ~€60M total (incl. €17M from Baden-Württemberg)

Ramping Up (2022)

Site: 28,151 m² facility in Reutlingen/Kirchentellinsfurt

Oct 2022: High-tech Dürr coating line commissioned (double-sided electrode coating)

Construction: Foundation stone laid Oct 2022

Pilot Capacity: ≥100 MWh/year

Scaling up to ≥1 GWh

Meltdown (2023-2025)

2023: Porsche takes full ownership of Cellforce

Expansion Vision: Plans floated for up to 20 GWh capacity

Business model deemed not economically viable due to slow EV market growth, insufficient volumes, and intense price pressure from Asian suppliers

Battery-related special expenses rise

April 2025: Porsche halts independent scale-up

Restructuring (2025)

Aug 25, 2025: Porsche formally ends production expansion plans

New Role: CFG becomes an independent R&D unit (cell + system development only)

VW Integration: Expertise to support PowerCo via development contracts

Financial Impact: €295M depreciation on production assets (FY 2025)

Workforce: ~200 of 286–290 jobs cut (~70% reduction), effective Nov 30, 2025

Source: next slide, company announcements

Cellforce Group: Learnings & Takeaways

Scale Rules Everything

Scale is the primary cost-driver. While CFG succeeded in R&D and pilot production of high-performance cells, the necessary step to commercial success - achieving competitive cost-per-kilowatt-hour - requires global volumes.

Small scale manufacturers cannot compete with the harsh economies of global battery manufacturing dominated by Asian Tier 1 suppliers

R&D vs. Reality

Battery mass production and high-volume manufacturing are not only technology-driven businesses but also commodity businesses.

As a result, a scalable, professional, and reliable value chain is of the utmost importance.

Trend Awareness

The restructuring was catalyzed by the slower-than-expected ramp-up of electromobility and disappointing regional sales.

This underscores the inherent volatility in new technology adoption and the risk of building fixed industrial capacity based on overly optimistic growth and sales forecasts.

Talent Impact

The decision to cut approximately 70% of staff risks causing a critical mass of battery specialists to scatter to other competitors, to change their field and subsequently disrepute the industry, potentially hindering the development of the national battery cluster

Source: Germany's Porsche is closing battery subsidiary Cellforce, reports say; Porsche focuses battery activities on cell and system development; Porsche halts Cellforce battery production plans;

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AMBRI: The Liquid Metal Battery Story

Growing Pains

Founded (2010): MIT spinoff by Sadoway, Bradwell & Ortiz.

Goal: Safe, affordable electrical storage solution for grids

Backers: Seed money from Bill Gates & Total S.A. and ARPA-E

Tech[1, 2]: Liquid Metal Battery (molten metals + salt; calcium anode for low cost)

Challenges[2, 3, 4]: Needed to invent its own manufacturing; 2015 seal failure caused delays & layoffs

Revamp

Gates-backed leadership pivot → retire technology risk & commercialization push[2]

Achieved UL 1973[5], secured antimony supply[2], proved safe + 20-yr life

Major deals: Microsoft[6,7], Reliance[8], Xcel Energy[9], Earth & Wire[10]

Scaling up[11]: 140,000 sq ft Milford facility ($18M retrofit)

Financial Hurdles

$300M Series F collapsed when the lead investor backed out[11]

$50M bridge loan failed[11] (Reliance declined its $8M share)

Despite $1.7B[11] in MOUs, funding gap killed scale-up

Nov 2023[11]: Laid off ~⅔ of staff

May 6, 2024[11]: Filed Chapter 11 to exit plant lease (after raising $150M equity + $42M debt)

Restructuring (2025)

July 31, 2024[12, 13]: Assets sold via Section 363 to lender consortium (Gates Frontier, Paulson & Co., Fortistar)

Ambri recapitalized[12] with a stronger balance sheet

Co-founder David Bradwell becomes CEO[13]

Company shifts[13] to a lean, capital-efficient model

Renewed focus[13]: scaled, low-cost, long-duration storage to meet strong demand

Source: [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] | [10] | [11] | [12] | [13]

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AMBRI: Learnings & Takeaways

Invention vs. Innovation

Due to the uniqueness of the technology, Ambri was forced to design and build much of its own machinery, which introduced a high risk of limited scalability.

While a unique value proposition (UVP) creates a high barrier to entry, it simultaneously increases the time-to-market and capital intensity, as the firm must build a bespoke industrial ecosystem from the ground up rather than plugging into existing global supply chains.

Investors Diversification

Ambri experienced sudden investment withdrawals on two occasions, leaving the company without viable alternatives and forcing it to absorb significant consequences.

For industrial-scale "hard-tech," the failure of a single anchor investor can create a catastrophic domino effect. There has to be a "Plan B" funding sources and avoid over-leveraging the commitment of any single investor.

Scaling Risks

There is a critical disconnect between market demand and capital readiness. Having $1.7 billion in potential sales does not solve a liquidity crisis when the cost of "building a battery plant from scratch" is prohibitively high.

Startups should consider licensing or joint ventures (JVs) early on to offload manufacturing capital expenditures (CapEx) until their technology reaches full commercial maturity

Industry Reality

Intellectual property and technical success cannot save a company if it fails to bridge the "valley of death" between prototype and delivery at scale.

Restructuring can clear debt, but it cannot fix a fundamental lack of capital required for heavy industrialization.

Source: previous slide, company announcements

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Li-Cycle: Ups & Down of a Dream

Start & Early Growth

2016: Founded in Ontario, Canada, by engineers Ajay Kochhar and Tim Johnston[1,2].

Hydrometallurgical processing method with IP-protected Spoke & Hub Technologies™ [1].

2021: A $100 million investment from Spring Creek Capital[3].

2021: Public on the New York Stock Exchange via a SPAC merger[2].

Expansion

2022: Rochester Hub Construction in New York[2,4].

2022: strategic partnership with LG Energy Solution and LG Chem, involving a $50 million investment and a long-term offtake agreement[3].

2022: investment by Glencore of $200 million via an unsecured convertible note[3].

2022- 2023: Operational commence of some Spokes[3,4].

2023: conditional $375 million loan commitment from DOE to support the Rochester Hub[5].

Hindrances

Escalating costs paused construction at the Rochester Hub[3].

Cash Preservation Plan[3].

A $75 million emergency investment by Glencore[6].

DOE loan increase to $475 million[7].

delisted from the NYSE and transitioned to the OTCQX Best Market[4,8].

Restructuring (2025)

Formation of an independent directors' committee to assess financial and strategic options, including potential sale to a longtime investor[7].

Filed for creditor protection under the Companies' Creditors Arrangement Act (CCAA) in Canada and Chapter 15 bankruptcy in the United States[9].

Glencore entered a "stalking horse" credit bid of $40 million for a significant portion of the company's assets[9].

Li-Cycle, now Glencore Battery Recycling ("GBR"), has been acquired by Glencore Plc[10].

Source: [1] | [2] | [3] | [4] | [5] | [6] | [7] | [8] | [9] | [10]

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Li-Cycle: Learnings & Takeaways

Liquidity Trap

Relying on complex debt structures and restrictive government lifelines during a period of rapid expansion is dangerous.

It went public via a SPAC, raising millions but faced pressure to scale before the technology was fully proven at a commercial level.

It failed to access a DOE loan because it could not meet equity and cash requirements amid a collapsing stock price and investor caution.

Reliance on convertible notes left the lender in control.

Operational Scaling

"Spoke-and-Hub" model illustrates the risk of operational mismatch - where one part of the value chain outpaces another.

Rochester Hub was halted after construction costs nearly doubled. It became a sinkhole for capital that the company could not sustain.

When a hub fails despite functioning spokes, the value chain becomes imbalanced and incomplete.

Market Dynamics

It must be recognized that price swings and changing chemistry can undermine even top technologies.

As revenue is tied to the market price of the metals it recovers, when the prices of lithium, nickel, and cobalt crash, profits sink.

Any shift to chemistries with fewer precious metals is potentially dangerous, as it makes recycling less profitable.

When industry or technology attractiveness declines, or other markets perform better, investor interest shifts, making fundraising difficult or likely to fail.

Strategic Alliances

For Glencore, Li-Cycle represented a way to secure sustainable battery materials without the initial startup risk; when Li-Cycle failed, Glencore was positioned to acquire it.

Aggressive fundraising by major industry incumbents can risk the entire enterprise, as seen with Li-Cycle, where the co-founder and CEO stepped down and later served as a senior advisor to support the company's sales process.

Source: previous slide, company announcements

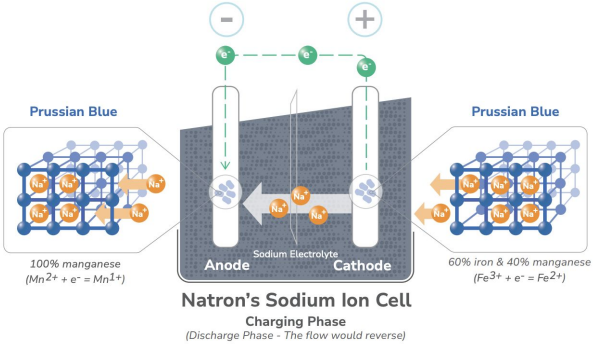
Natron Energy

Founded in 2012, Natron Energy commercialized a sodium-ion battery, based on Prussian Blue analogue chemistry, for data center uninterruptible power supply (UPS) applications.

Citing insufficient funding, Natron permanently shuttered its operations in September 2025, including its R&D facility in California, pilot plant in Michigan, and Gigafactory plans in North Carolina. Natron's assets have since been liquidated via ABC.

Observations on Natron's Approach:

- Natron pursued full vertical integration, from controlling design and process from anode/cathode synthesis up to BlueRack system engineering which proved technically and financially challenging.
- Key Product Features:
  - 185 W/L 2-minute power density at system-level
  - Cell-level safety (UL9540A testing verified no thermal runaway)
  - 1C cycle life of >50,000 cycles and a high-power service life of >5 years
- Funding: Natron received ~$370M in total funding from investors including DOE ARPA-E, Chevron Energy Ventures, Intel Capital, Khosla Ventures, Mercuria, ND Capital, and United Airlines.

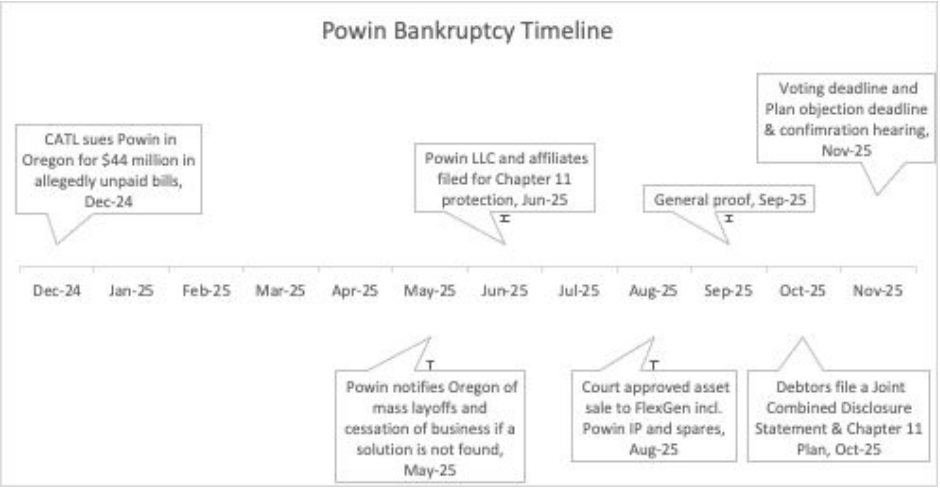




Source: Natron Energy, BlueRack 250, Tracxn, BatteryTechOnline

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Powin's Chapter 11: A Post-Mortem



Powin, LLC, and multiple affiliates, filed Chapter 11, U.S. Bankruptcy Court in June citing "suffering from liquidity constraints, an over dependence on trade credit, increasing assertions of liquidated damages, and a credibility problem."

Top unsecured creditors include Ace Engineering (enclosures) and CATL (cells), among others. During the bankruptcy proceedings, the debtors completed three major asset sales totaling $54 million. FlexGen was the largest sale at $36M, and they purchased IP and spare-parts inventory FlexGen is dedicated to service operating Powin systems.

Key takeaways:

- Counterparty risk is real - even for market leaders
- Thin-margin integrators squeezed by vertically integrated OEMs
- Trade policy/tariff volatility can tip a shaky balance sheet
- Supplier disputes can cascade into liquidity crises
- LDs + schedule slips + damaged credibility = a doom loop
- Warranties are only as good as the warrantor's solvency
- Incident history matters and can cause a reputation drag

Source: Stretto, Canary Media, Energy Storage News, Energy Storage News, Verita Global, Togut, Segal & Segal LLP, Oregon Rapid Response Activity Tracking System

INDUSTRY

Notable Events
Industry Value Chain

Finance

Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Finance Summary

Fundraising for Climate-related funds increased overall driven by **Infrastructure funds** focused on stationary storage for grid and data centers, while Venture/Growth funds raised declined slightly. There is rising thematic interest to fund the "**missing middle**" for the survivors of the last several years of battery private investments so they can scale up.

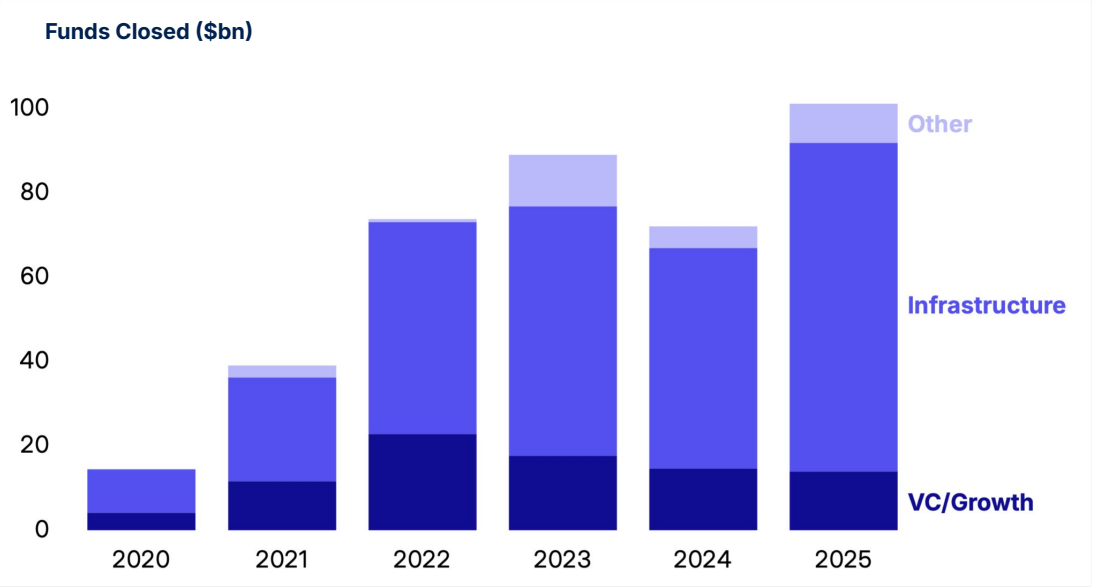
Overall Private investment in battery companies declined due to **slowing EV markets** and overcapacity, but investment increased in niche high margin applications such as **robotics**, **defense/aerospace**, and **stationary storage** for **data centers/AI**.

Public battery-related equities **outperformed benchmarks** over one year in 2025, but still lag market benchmarks over the **past three years**.

Asian-listed battery companies gained market share and market valuation. In North America, select survivors of the wave of SPACS from several years ago had strong share performance driven by grid, AI and defense, but their market values remain far behind Asia.

Private Market Fundraising Overview

Climate-related investors closed on 40% more funding in 2025 than 2024, driven by a boom in infrastructure funds



CLIMATE-RELATED INVESTMENT FUNDS BY CLOSED DATE, 2020-2025

- **Climate-related investment funds raised $101bn in 2025,** up 40% YoY.
- **78% of funding was raised by infrastructure investors** in their strongest year yet while the capital VC/growth funds closed on fell by 5% YoY to 14bn.
- **Infrastructure funds have cash to finance the deployment of mature climate technologies** like lithium-ion batteries for stationary energy storage and charging infrastructure. But, emerging technologies face a tighter fundraising landscape as VC/growth investors struggle to raise funds.

sightline climate

Source: Content provided courtesy of Sightline Climate. Note: Includes climate-related funds with announced size and confirmed close. Funding tallied by date of most recent close.

Private Capital Market Investors

>$100bn of total private climate assets under management (AUM) across 100+ Early-stage VCs, Corporate VCs, Growth Equity, Infrastructure, and Private Equity funds in 2025.

	Early Stage VC	Corporate VC	Late Stage VC / Growth Equity	Private Equity	Infrastructure	Sovereign Wealth Fund / Pension
Investment Characteristic	Early-Stage venture investments into pre-revenue / pre-product fit companies Seed – Series A	Early-Stage investments. Likely synergies with VC's corporate parent. Corporate VC helps in validating new technologies	Revenue generating companies pre-earnings with revenue backlog Series B – Series D	Control investments into mature companies with defined cash flow profile and clear customer relationships	Asset heavy project based financing supported by long term offtake contract	Patient long term investors with a national mandate to progress climate sustainability
Investor Base	Arctern Ventures, foothill ventures, Anzu Partners, VoLo Earth Ventures, aiim, Collaborative, Chevron Technology Ventures, Xora, Breakthrough Energy, Gigascale Capital, Earthshot Ventures, EIP, Ecosystem Integrity, e, Eclipse, Transition, Fifth Wall, material impact, Prelude Ventures, Voyager, emerald, +Volta, Climentum Capital, Vireo Ventures	ABB Technology Ventures, bp ventures, NVIDIA, BMW i Ventures, Engie New Ventures, gm Ventures, Chevron, Hitachi Inspire the Next, Hyundai, idemitsu, Porsche Ventures, Hyundai Cradle, Bosch, Microsoft, LG Technology Ventures, Shell Ventures, Svensqo, Samsung Venture Investment, woven capital, Toyota Ventures, TDK Ventures, The Climate Pledge, Vale, amazon	Breakthrough Energy, Baillie Gifford, TigerGlobal, Decarbonization Partners, catalus, Marunouchi Innovation Partners, e, Energy Impact Partners, Fifth Wall, Investcorp, Koch, MKB, s2g ventures, Cathay Innovation, Blackstone, SoftBank Vision Fund, Keyframe, TPG Rise Climate, +Volta, T.RowePrice	Apollo Clean Energy Transition, Ara Partners, Arcline Investment Management, Cleanhill Partners, ECP	CIP Copenhagen Infrastructure Partners, EQT, Generate, KKR, Brookfield, MNES, J.P.Morgan, Zouk	CPP Investments, GIC, KI, ADIA, Temasek, QIA Qatar Investment Authority

Source: Press Releases, Sightline Climate (Distinguished Partner)

Select VC & PE/Growth Equity Funds Raised in 2025

More than **$7.6bn of capital was announced by early-stage VC and CVC funds** towards climate and energy transition in 2025, with 50+ new funds raised, increasing marginally from the previous year. Number of PE/Growth Equity funds increased more significantly, with more than $10bn of capital announced as well, but 25 funds raised, greater than 21 and 17 funds from 2024 and 2023, respectively. This indicates the desire to fund the "missing middle" to turn the "valley of death" into the 'valley of opportunity". Here are a select few that have previously announced or indicated interest towards battery investments, with examples in the description.

Blackstone **$5.6B** February Aypa Power, Ample	ENERGY IMPACT PARTNERS **$1.36BN** October Dragonfly Energy, 6K, Form Energy	CATHAY INNOVATION **$1BN** May SVOLT	Marunouchi Innovation Partners **$744MM** January *Targeting batteries in new fund*	CHERRY **$500M** February TWAICE	JUST CLIMATE **$375MM** November Ascend Elements
BOSCH **$270MM** May cylib, Electroder	BNP PARIBAS ASSET MANAGEMENT **$176MM** June Vulcan Energy	Breakthrough Energy **$150MM** September QuantumScape, Stratus Materials	TDK TDK VENTURES **$150MM** April Glimpse, AM Batteries, Peak Energy, Ascend	VoLo Earth VENTURES **$135MM** September ION Storage Systems	HYUNDAI **$88MM** May 3DC, POEN
TRANSITION **$80MM** December Emo Energy	Climentum Capital **€60MM** December Scale Energy	emerald **$69MM** October Nanograf	CLEAN GROWTH FUND **£49MM** August Indra, Sunswap	Vireo VENTURES **€50MM** September Scale Energy	

Source: Sightline Climate (Distinguished Partner).

Select Infrastructure Funds Raised in 2025

There was a large increase in the number of infrastructure funds that raised capital in 2025, growing to 26 funds compared to only 17 and 19 in 2024 and 2023, respectively. Infrastructure funds constitute ~70% of total AUM closed in 2025. Most of these closed funds were the largest infrastructure funds ever closed by the firm. Funds with a battery related investment leaned towards large-scale energy storage battery development and critical mineral technologies.

	EQT	Brookfield Emerging Markets Transition	CIP Copenhagen Infrastructure Partners	MNES	actis	J.P.Morgan	Ridgewood Infrastructure
Fund	**Infrastructure VI**	**Transition II**	**Infrastructure V**	**Capenergie V**	**Infrastructure II**	**Forest & Climate II**	**Infrastructure II**
2025 Fund Size	€21.5bn	$20bn	€12bn	€2bn	$1.7bn	$1.5bn	$1.2bn
Close Date	March	October	March	January	May	April	January
Description	Largest fund yet funding infrastructure companies with energy as a focus	Largest fund yet; flagship energy transition fund	Greenfield investments within large-scale renewable energy infra	Largest fund yet for renewable energy infrastructure	Brownfield infrastructure in growth markets and regions	Through Campbell Global, invests in nature-based solutions	Invests in energy, utilities, transportation infrastructure
Current and Previous Investments	OX2, Statera, Madison Energy Infrastructure, Instavolt, Cirba Solutions	Neoen, geronimo power	Infrastructure projects include offshore wind, energy storage, and solar in low-risk OECD countries in North America, Western Europe, and Asia Pacific	enray power, Faria, NRG 2all	Rezolv Energy, Levanta Renewables	chestnut	Environmental Infrastructure Partners

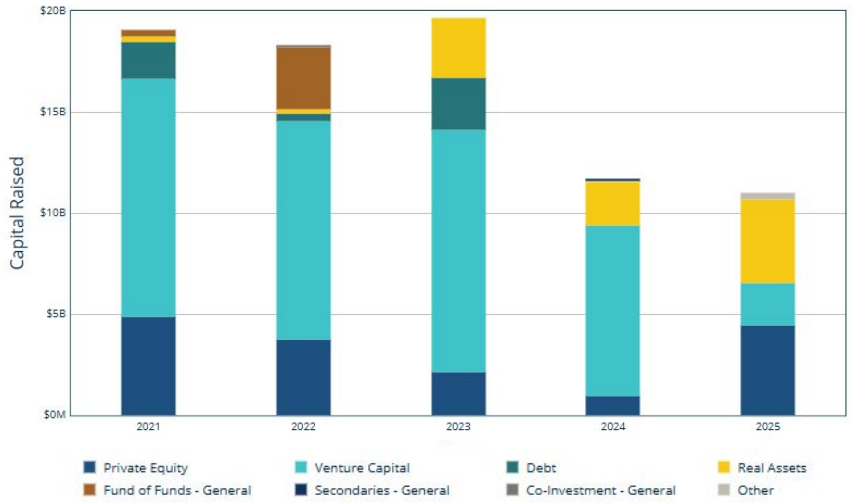
sightline climate

Source: Press Releases, Sightline Climate (Distinguished Partner). For more information, visit https://www.sightlineclimate.com. (1) Some fund sizes adjusted from the previously announced amount

Private Market Battery Investments

The capital market continues to pull back focus from batteries due to high interest rates, tough IPO/M&A exit markets, and an overall shift away from climate investing in the volatile equity market. Although there were a few sizeable returns in the space, the slowdown in EV adoption has kept many on the sidelines.

BATTERY INVESTMENT BY TYPE OF INVESTMENT



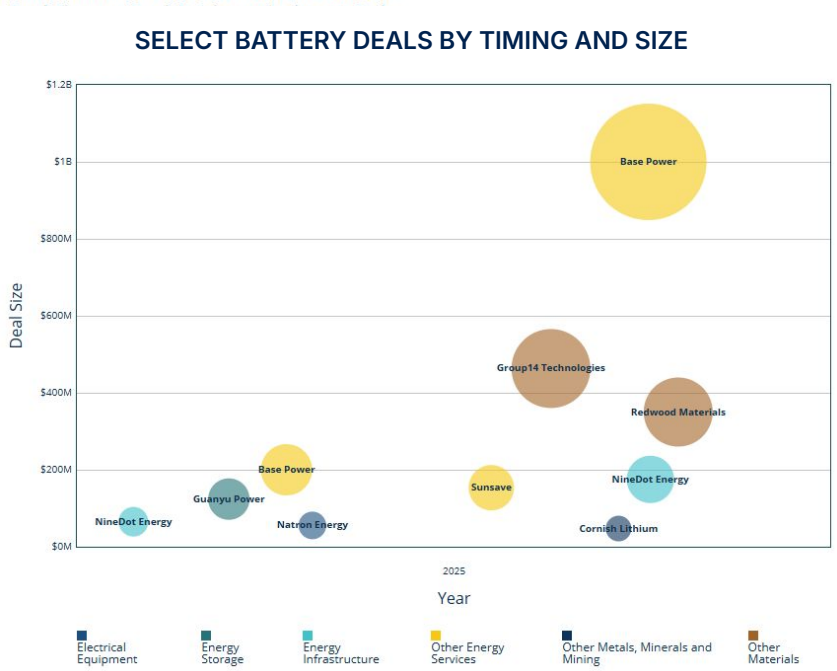
Battery related **investing peaked in 2023,** but **dropped sharply in 2024 and has not seen a recovery in 2025:**

- VC investment has declined as less new dry powder is available for early-stage battery startups to test their designs
- Capital *still flows* into real assets and infrastructure development to support later stage build out
- Although investments in EV-applications have slowed significantly, **there's an uptick in battery investments towards high-margin applications** such as robotics, defense, aerospace, heavy duty, as well as ESS, especially supporting AI data center infrastructure (UPS, peak shaving)

Source: Pitchbook

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Private Market Battery Investment Themes



- **2025 VC activity is dominated by Base Power's $1B round,** underscoring strong investor conviction in ESS deployment.
- **Materials (Si anode + second-life BESS) occupy the #2 and #3 spots,** signaling sustained support for upstream critical supply chain capacity and more ESS deployment.
- **US companies captured the majority of top-10 VC checks,** reinforcing the U.S. as the global center of battery investment momentum.
- **Capital alignment with U.S. national strategy:** ESS + critical materials prioritized → grid reliability + supply chain security.
- **Midstream manufacturing missing from top-10** suggests it is increasingly financed via **infrastructure + real-asset capital, not VC.**
- **UK + China emerge as secondary hubs,** with meaningful activity in minerals + services.
- **Investment into high performance markets emerging,** including robotics, military, and aerospace applications.

Source: Pitchbook

Select Equity Finance Transactions in 2025

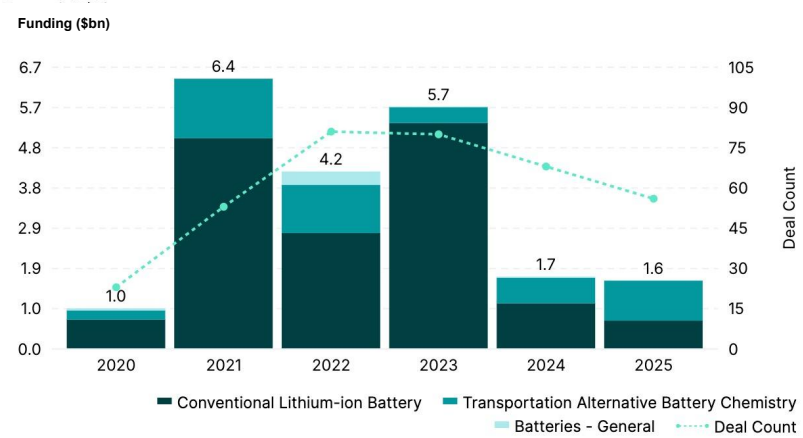
Equity finance transactions, including venture funding, typically went to companies mainly focusing on utility-scale or large-scale energy storage batteries and accelerating critical minerals. In 2025, there were also new trade agreements with Asian players and government investments, such as US & Japan government's investment in Mitra Chem and South Korea government's investment in Peregrine Energy.

VULCAN ENERGY **$2.6BN** Financing Package German lithium project with geothermal	BASE **$1.3BN** Series B & C Deploying home battery systems	eos **$1BN** Financing Package American-made Zinc-based LDES	KoBold Metals **$700MM** Series C & D Critical minerals exploration	GROUP14 **$463MM** Series D Advanced silicon battery materials	PEREGRINE ENERGY **$447MM** Financing Package + South Korea Deal U.S. utility-scale battery storage
REDWOOD MATERIALS **$350MM** Series E Clean energy storage and critical minerals	Mitra Chem **$350MM** US / Japan Deal US-based LFP production	LYTEN **$200MM** Equity For Northvolt asset acquisitions & expansion	TeraWatt TECHNOLOGY **(Undisclosed)** Series C Manufacturing lithium ion batteries at scale	Electra Battery Materials **$82MM** Equity + Debt North America's first cobalt sulfate refinery	Nanoramic LABORATORIES **$54MM** Series 1 Equity Advanced battery material
amber **$45MM** Series D Battery automation product	FORGE NANO **$40MM** Equity US-made batteries and ALD platform	SPARKCHARGE **$30.5MM** Series A-1 North American EV infrastructure	ZincFive **$30MM** Series F Nickel-zinc batteries for data centers	moment energy **$20MM** Series A & Debt Remanufacturing second life batteries	XL Batteries™ **$7.5MM** Seed II Organic, LDES flow batteries

Source: Sightline Climate (Distinguished Parter), CapIQ, Pitchbook

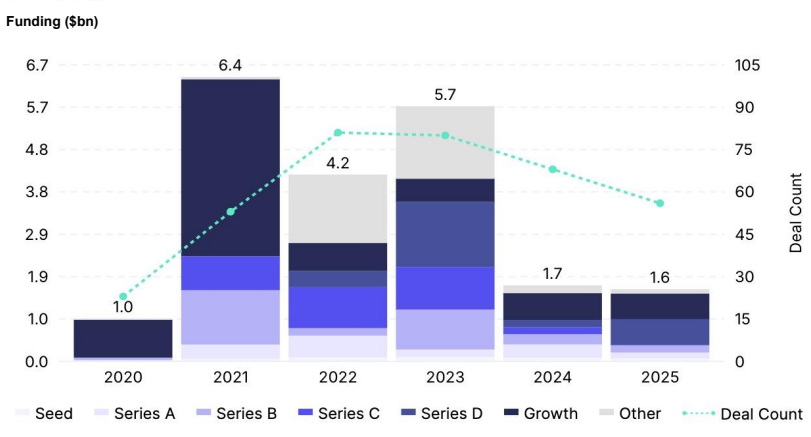
Transportation Battery VC/Growth Investment Low & Shifting Away from Conventional Lithium-Ion

TRANSPORTATION BATTERY INVESTMENTS BY SECTOR



VC/Growth investment in transportation batteries including EV chemistries and recycling, ($1.5bn) was down 73% from the 2021-2023 period ($5.4bn/year). **Investment is shifting to solid-state and silicon anode** technology as VC investors shy away from conventional lithium-ion battery manufacturing after the collapse of Northvolt.

TRANSPORTATION BATTERY INVESTMENTS BY STAGE

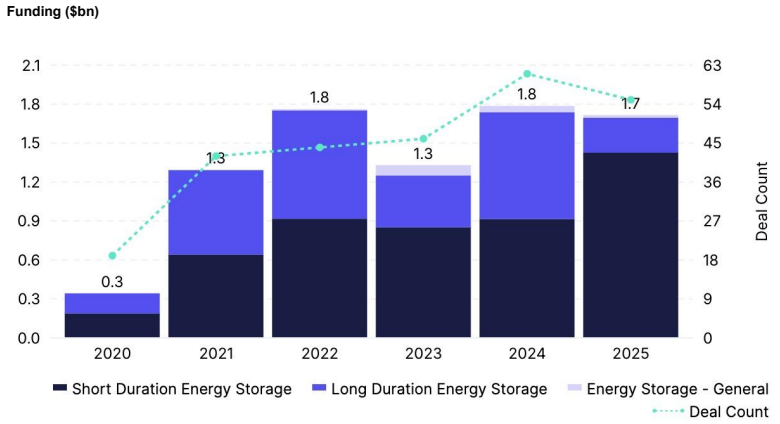


Both early-stage and late-stage funding have dropped ~70% since 2021-2023, with the largest dollar-amount decrease in late-stage. Chinese battery dominance could be reducing VC investors' appetite for both large late-stage rounds for battery manufacturing and early-stage rounds for battery innovation.

sightline climate Source: Sightline Climate (Distinguished Parter)

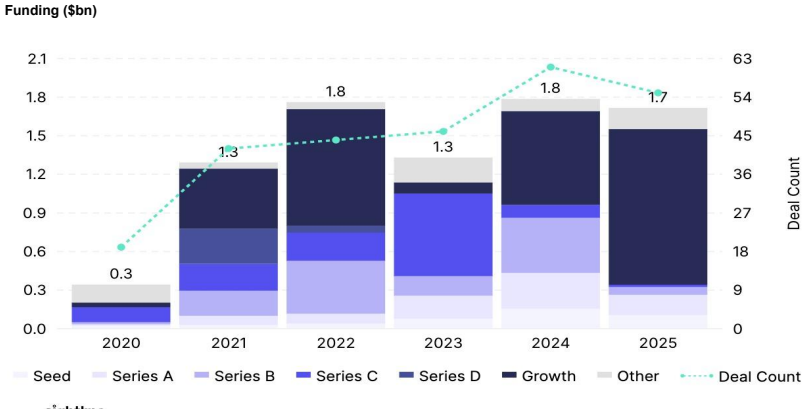
Stationary Energy Storage VC/Growth Investment Stable as Short Duration Storage Makes Up for LDES Drop

STATIONARY ENERGY STORAGE INVESTMENTS BY SECTOR



Short duration energy storage investment increased 56% as stationary storage deployment outperformed EVs and renewables in many markets. Of short duration storage funding, lithium-ion technologies received 87%.

STATIONARY ENERGY STORAGE INVESTMENTS BY STAGE

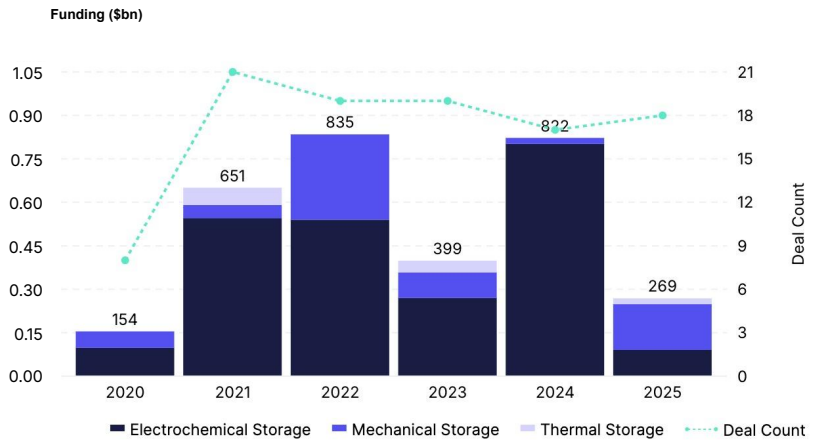


Late-stage funding nearly doubled (+70%) as investment shifted from technology development to deployment. But, early-stage investment decreased 66% from 2024 as investors instead doubled down on existing lithium-ion technology.

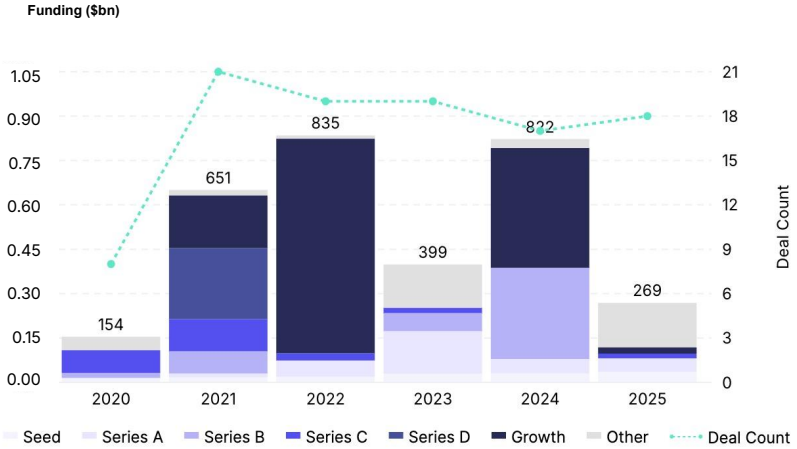
Source: Sightline Climate (Distinguished Partner). Note: data excludes residential batteries.

Long Duration Energy Storage VC/Growth Investment Down 67% as Industry Reset After 2024 Megarounds

LONG DURATION ENERGY STORAGE INVESTMENTS BY SECTOR



LONG DURATION ENERGY STORAGE INVESTMENTS BY STAGE



LDES funding was down 67% in 2025 after megarounds in 2024 like $552m to Form Energy (iron-air battery) and $308m to Enervenue (nickel-hydrogen). **Mechanical storage had its strongest year since 2022** with 95% of known funding going to Canadian compressed air technology integrator Hydrostor and an investment of unknown size by Google in liquid CO2 technology licenser Energy Dome.

Early-stage funding was down 80% to $81m. Some investors had placed LDES bets in 2023 and 2024 and others are wary of competition from inexpensive lithium-ion batteries.

Only two LDES deals were >$20m at any stage ($150m to Hydrostor and $21m to vanadium flow battery manufacturer VFlowTech).

Source: Sightline Climate (Distinguished Partner). Sightline defines LDES as companies targeting applications at 8+ hour duration.

Public Battery Equities Perform Well in 2025, but Lag the Market Over Past 3 Years

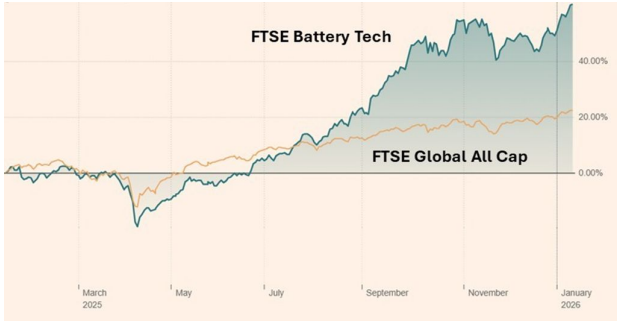
Global battery and clean-energy equity indices significantly outperformed broad market benchmarks over 1-year (FTSE Global Battery Tech at 52% vs. FTSE Global All Cap at 16%), reflecting a recovery in investor sentiment toward electrification and energy transition themes. However, over a 3-year horizon, battery-focused indices lag global equity markets.

BATTERY AND CLEAN ENERGY EQUITY INDICES: 1 & 3-YEAR RETURNS

Public Market Battery Indices	1-year return	3-year return
FTSE Global Battery Tech	52%	16%
FTSE Global All Cap	23%	75%
S&P Global Core Battery Metals	137%	50%
S&P Global Clean Energy Transition	55%	-18%
S&P Kensho EV & Battery	28%	-6%
S&P Global Broad Market	25%	59%
NASDAQ Clean Edge Green Energy	41%	-5%
NASDAQ 100	20%	122%

% change over time frame as of Jan 13, 2026

FTSE GLOBAL BATTERY TECH VS FTSE GLOBAL ALL CAP 1 YEAR RETURN



FTSE GLOBAL BATTERY TECH VS FTSE GLOBAL ALL CAP 3 YEAR RETURN



Source: FTSE, S&P, NASDAQ as of Jan 13, 2026

Asian Listed Battery Companies Gaining Market Value & Market Share

Over the past year, Chinese-listed battery manufacturers and materials companies outperformed their domestic equity markets as they continued to consolidate global market share in EVs, energy storage, and data-center batteries. Strong global demand, supported by AI-driven power build-out and accelerating electrification, has allowed leading Chinese players to expand capacity, secure customers, and raise new capital, including through Hong Kong IPOs such as CATL's $5bn listing in 2025.

In contrast, non-Chinese Asian battery manufacturers have faced pricing pressure and slower growth, while Korean battery materials suppliers have outperformed by supplying both Chinese and global OEMs.

CHINA	Value USDb	1-year return	3-year return
Battery			
CATL	233	42%	43%
BYD	128	5%	7%
EVE	20	55%	-19%
Gotion	11	95%	32%
CALB	7	140%	44%
REPT Battero	4	35%	N/A
Great Power	3	95%	-28%
Sunwoda	7	18%	11%
Sungrow	48	122%	91%
Hyperstrong (IPO 1/2025)	7	303%	N/A
MSCI China		38%	32%

CHINA	Value USDb	1-year return	3-year return
Materials			
Ronbay	4	76%	-27%
Easpring	5	64%	-1%
Guangzhou Tinci	13	142%	-4%
Yunnan Energy New Materi	8	76%	-64%
Hunan Yuneng	7	38%	N/A
Jiangsu Lopal	2	98%	-20%
Dynanonic	2	40%	-70%
Wanrun New Energy	1	33%	-42%
BTR	5	85%	N/A
Ningbo Shanshan	4	84%	-28%
Putailai	9	88%	-21%
Ganfeng Lithium	22	208%	1%
Tianqi Lithium	14	135%	-9%
Huayou Cobalt	22	169%	24%
GEM	7	38%	18%
MSCI China		38%	32%

REST OF ASIA	Value USDb	1-year return	3-year return
Battery			
LGES	61	10%	-19%
Samsung SDI	15	21%	-54%
SK Innovation	12	-16%	-31%
Panasonic	33	44%	95%
GS Yuasa	3	57%	81%
Materials			
EcoPro	9	51%	330%
LG Chem	18	36%	-46%
MSCI Asia		28%	48%

Source: Yahoo Finance and MSCI as of Jan 13, 2026

North America Battery Market Values Improving, but Remain Below Asia and Still Recovering Over Medium Term

- Many of the SPAC companies have either shut down (Nikola, Fisker, Canoo, Lion Electric, Proterra), been acquired as distressed assets (LiCycle) or pivoted (Freyr).
- The SPAC survivors had strong 1-year stock performance in 2025 based on sharpened sales focus (AI, military) and technical progress, although they are still 40-80% below their highs in 2022.
- BESS companies generally performed well on surging demand. Critical minerals also improved, partially on the expectations of rising BESS demand.
- EVs had a mixed year as the established players (BYD, Tesla) faced slowing EV sales and intensifying competition in some markets, but achieved global expansion into new markets.
- SPAC-listed EVs and charging share prices continued to struggle.
- Indian EVs (2-wheelers) showed a large divergence in performance reflecting different IPO pricing strategies and business execution.

North America	Value USDb	1-year return	3-year return
Battery			
Amprius (SPAC)	1.4	210%	69%
SES AI (SPAC)	0.8	139%	-36%
Solid Power (SPAC)	1.1	241%	114%
EOS Energy (SPAC)	5.6	179%	936%
Microvast (SPAC)	1.0	47%	94%
Quantumscape (SPAC)	6.5	105%	42%
Electrovaya	0.4	248%	107%
Enovix (SPAC)	1.8	-23%	0%
NanoOne	0.1	11%	-56%
Dragonfly (SPAC)	0.0	-84%	-99%
BESS			
Enersys	6.1	73%	102%
Fluence	4.1	57%	3%
ESS (SPAC)	0.0	-68%	-95%
Critical minerals			
Albermarle	21	89%	-27%
Standard Lithium	1	215%	51%
SQM	24	108%	-1%
NASDAQ 100		20%	122%

EV	Value USDb	1-year return	3-year return
China			
BYD	128	5%	7%
Nio	12	11%	-58%
Li Auto	16	-26%	-24%
Xpeng	20	49%	104%
Leap Motor	8	38%	72%
Rest of World			
Tesla	1,461	6%	246%
Rivian	22	23%	6%
Vinfast (SPAC Aug 2023)	8	-17%	-66%
Lucid (SPAC)	4	-65%	-86%
Polestar (SPAC)	2	-34%	-88%
Ather (India IPO May 2025)	3	116%	NA
Ola (India IPO Aug 2024)	2	-48%	NA
EV Infrastructure			
EVGo (SPAC)	1	-12%	-45%
Chargepoint (SPAC)	0.2	-68%	-97%
blink	0.1	-39%	-93%
NASDAQ 100		20%	122%

Source: Yahoo Finance as of Jan 13, 2026

Notable Exits, Mergers, & Acquisitions of 2025

January

HyperStrong, a Chinese energy storage system integrator, filed for IPO in Shanghai

May

Evyon and Elywhere merge to use second life batteries for EV charging

CATL completed its $5b secondary listing IPO on the Hong Kong Stock Exchange as one of the year's biggest global IPO

June

Endless acquires Ecobat's European battery distribution business, a leading battery supplier for a range of applications

August

U.K. BESS maker, Palmer Energy, acquires Brill Power, a BMS provlder

September

Following CATL's strong HK IPO and positive IPO sentiment in HK, multiple battery companies in HK IPO pipeline

September

Exxon Mobil acquires Super Graphite battery material facilities, supporting Exxon's energy storage capabilities

I Squred Capital acquires majority stake in ENTEK, funding a separator gigafactory in the US

October

CoreWeave acquires Monolith AI, developing data-driven AI models for battery performance

Clarios acquires Maxwell Technologies extending commitment to new low voltage energy storage

December

StoreDot SPAC announced with Andretti Acquisition Corp.

Factorial Energy merges with SPAC Cartesian Growth Corporation

Source: Company announcements

Tax Equity & Transferability Powers the Next Wave of Standalone Storage in US

Prior to the Inflation Reduction Act (IRA), Section 48 investment tax credit (ITC) did not apply to standalone storage projects. The **IRA added Section 48(a)(3)(A)(ix) to create ITC for standalone energy storage technology**, enabling tax equity financing for standalone projects.

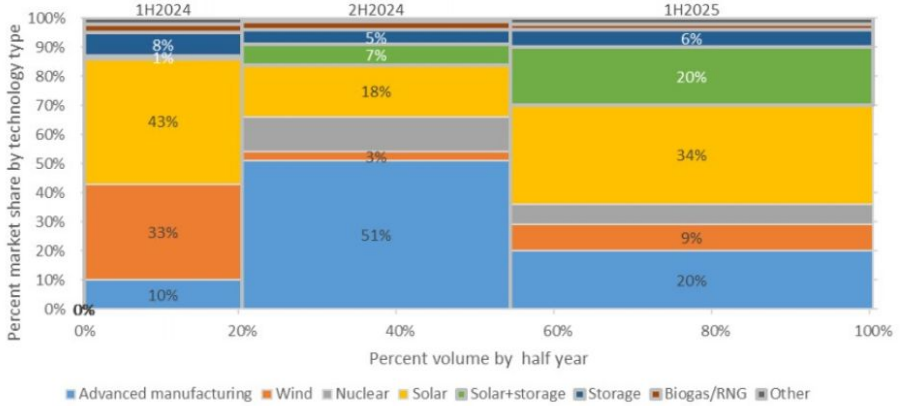
Leading bank investors - **U.S. banks - JP. Morgan, Bank of America, Wells Fargo, US Bank, and Credit Suisse** - have traditionally dominated the tax equity market and remain the most active players.

The IRA also introduced the **tax credit transferability mechanism,** which has been a game-changer for standalone storage, allowing project developers to sell their tax credits to third parties, without requiring investors to take long term ownership in the project.

Standalone storage deal structures in the first half of 2025 were **split nearly evenly between tax equity (49.5%) and direct transfer deals (46.5%)**

Standalone storage deals **made up 20% of the volume in** first half of 2025

YEAR ON YEAR MARKET COMPOSITION BY TECHNOLOGY TYPE



Source: Crux State of Clean Energy Finance: 2025 Mid-Year Market Intelligence Report

Select Tax Equity & Debt Project Finance Transactions in 2025 in US

Transgrid	RECURRENT ENERGY A subsidiary of Canadian Solar	Ørsted	RECURRENT ENERGY A subsidiary of Canadian Solar	eolian	BRIGHTNIGHT Power when you need it
$1.4BN Atlas VII and Atlas IX Arizona, USA	**$825MM** Desert Bloom Storage & Papago Solar Arizona, USA	**$680MM** Eleven Mile Solar Center and Sparta Solar Arizona & Texas, USA	**$513MM** Papago Storage Arizona, USA	**$463MM** Padua 2 and Padua 3 Texas, USA	**$400MM** Greenwater Energy Storage Washington, USA
Clearway	AREVON.	spearmint energy.	SWIFT CURRENT	akaysha	aypa
$200MM Daggett Storage Texas, USA	**$258MM** Peregrine Storage California, USA	**$252MM** Tierra Seca and Seven Flags; Texas, USA	**$242MM** Prospect Power Virginia, USA	**AU $300MM** Global BESS portfolio	**$190MM** Bypass BESS Texas, USA

Source: Company announcements

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance

Costs

Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

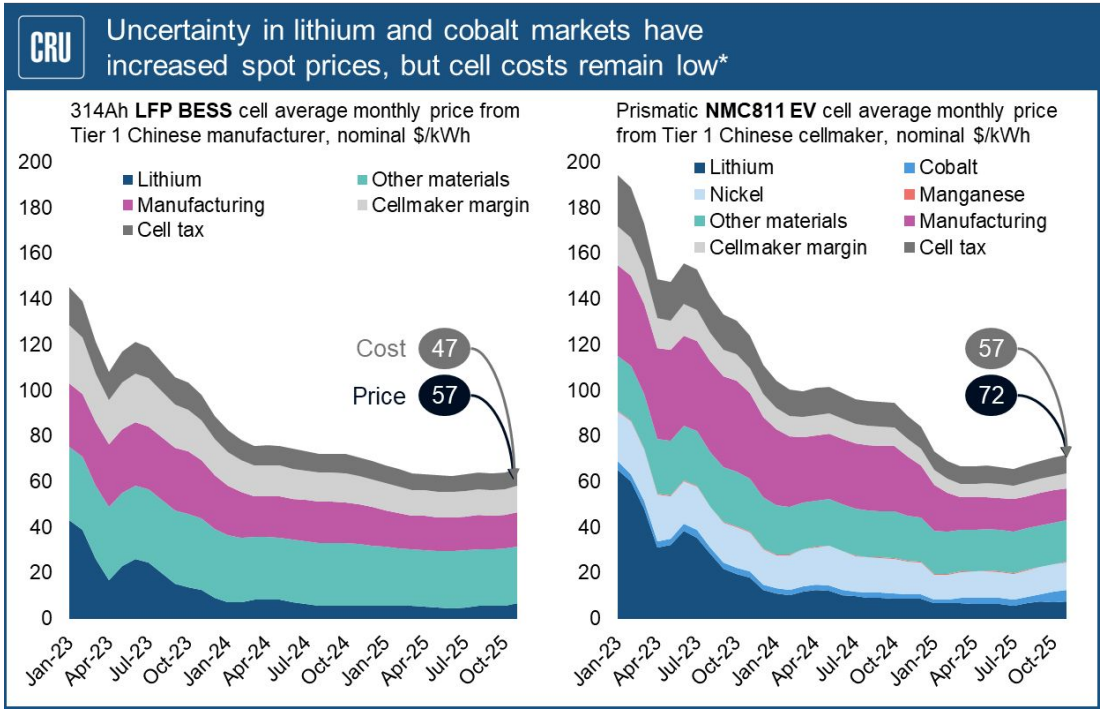
Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

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China Cell Production Costs Have Rebounded in 2025 with Raw Material Disruption, but Remain Relatively Low



Li-ion cell manufacturing costs have crashed since 2023 thanks to:

- Raw material prices have plummeted
- Reduced use of passive materials
- Increasing manufacturing efficiency

Speculation over the short-term future of lithium and cobalt supply has raised raw material spot prices and impacted cell manufacturing costs, but they remain low relative to previous years.

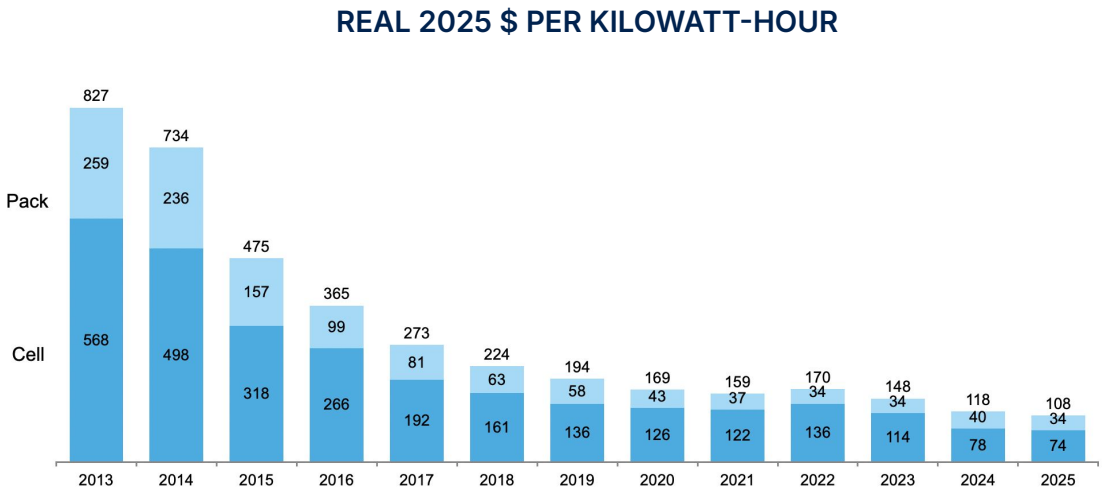
Some producers are more insulated from material prices than others, having long-term contracts, vertically integrated supply, or strong bargaining power.

Margins also vary by manufacturer, and China provides a sales tax rebate for exports, although this is to be phased out.

However, there is no benchmark price for cells as batteries are highly bespoke to the customer. ESS and EV battery buyers mainly purchase through long-term contracts as altering cell supplier or chemistry requires lengthy qualification times.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
Cell costs based on raw material spot prices are not representative of most actual production costs.

Cell & Pack Global Average Selling Prices Fell in 2025, Despite Rising Raw Material Prices



- Cell and pack sales prices fell to all time lows in 2025 due to continued improvement in cell chemistry and manufacturing processes overcoming slight raw material price increases.
- ESS pack prices remained the lowest on the market at $70/kWh, with average BEV packs just below the $100/kWh mark.
- LFP packs, $81/kWh, were significantly cheaper than their NMC counterparts at $128/kWh.
- Chinese pack prices are world leading at $84/kWh, highlighting the high proportion of LFP packs used in China.
- In contrast, packs in Europe were the most expensive, being sold at just over $131/kWh, with North America coming in at $120/kWh.

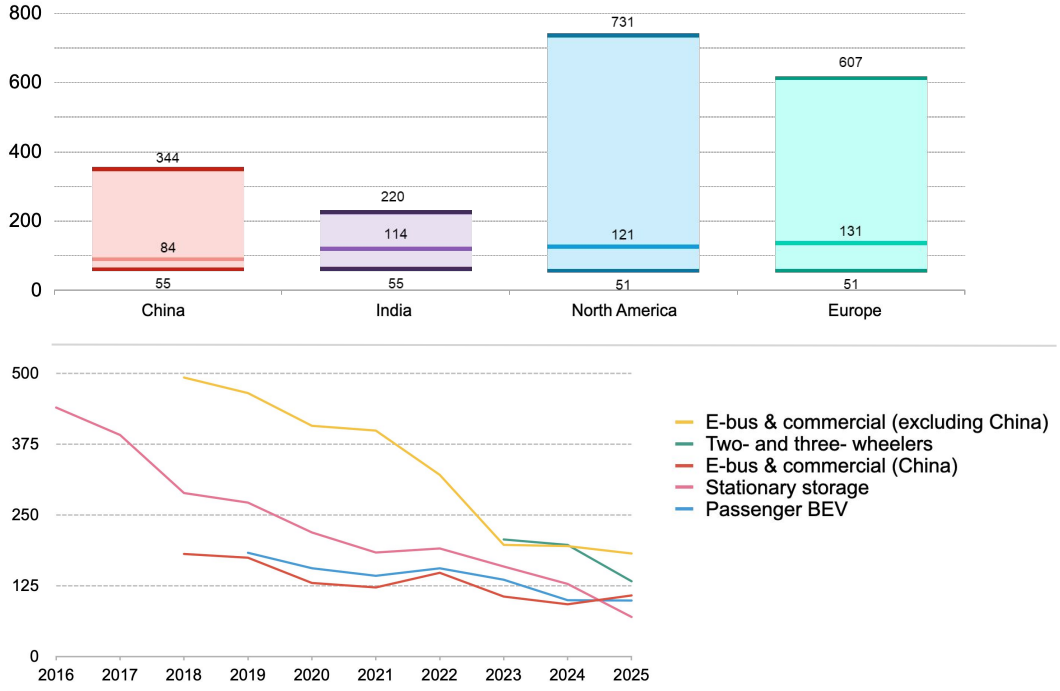
BloombergNEF

Source: Data from BloombergNEF (Distinguished Partner). For more information, visit https://about.bnef.com/contact-us.
Note: Historical prices have been adjusted using June 2024 to June 2025 inflation rates based on US Consumer Price Index (CPI) index.

VF | VOLTA FOUNDATION

Volume-Weighted Average Battery Pack Price & Range by Region and Sector

Real 2025 $ per kilowatt-hour



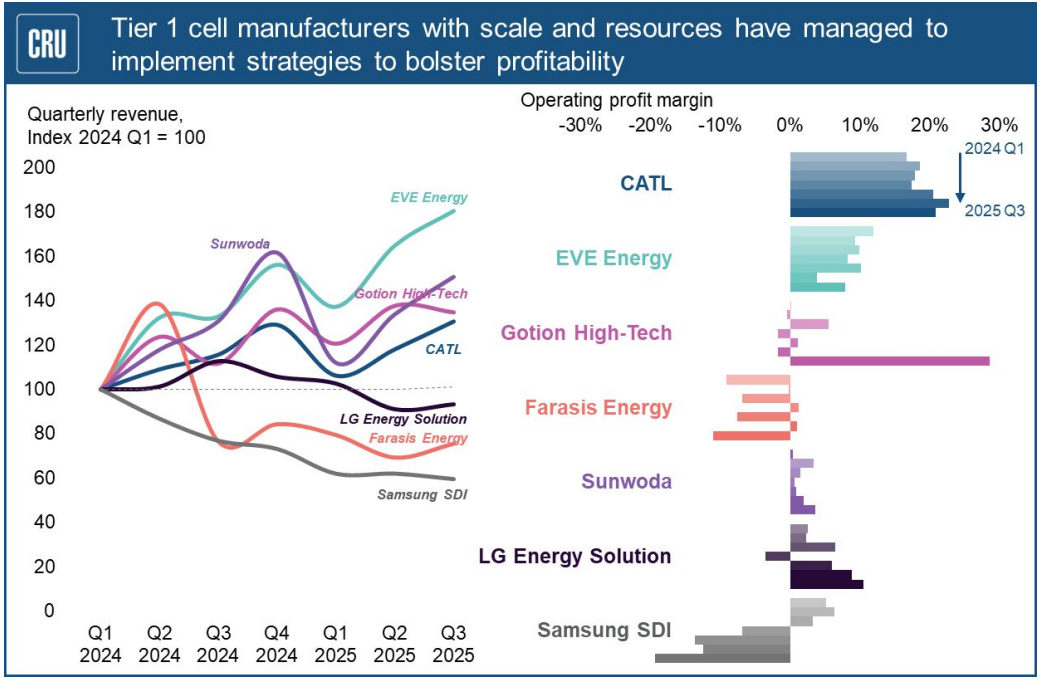
Source: BloombergNEF

- Chinese manufacturers continue to lower their underlying costs and selling prices, but also remain in a state of intense price competition, depending on the sector.
- China is making heavy use of low-cost LFP, as is the global BESS industry.
- Prices in North America are affected by tariffs. A growing focus on domestic supply chains gives North American and European battery manufacturers greater negotiating leverage, allowing them to command higher prices from domestic customers.
- The price gap between sectors/applications continues to narrow.

BloombergNEF Source: Data from BloombergNEF (Distinguished Partner).

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Tier 1 Cell Manufacturers Have Bolstered Their Profitability



Offering integrated energy storage systems has helped grow revenues for Chinese cell manufacturers as the storage market continues to boom.

They have also benefited from commanding higher prices/margins in growing overseas markets, and continue to limit investment in new capacity expansions in China.

Exposure to the US market and its weakened EV sales, combined with growing competition in Europe, has harmed revenues for Korean cellmakers, but they have already managed to turn profit margins around with the expansion into BESS, among other strategies.

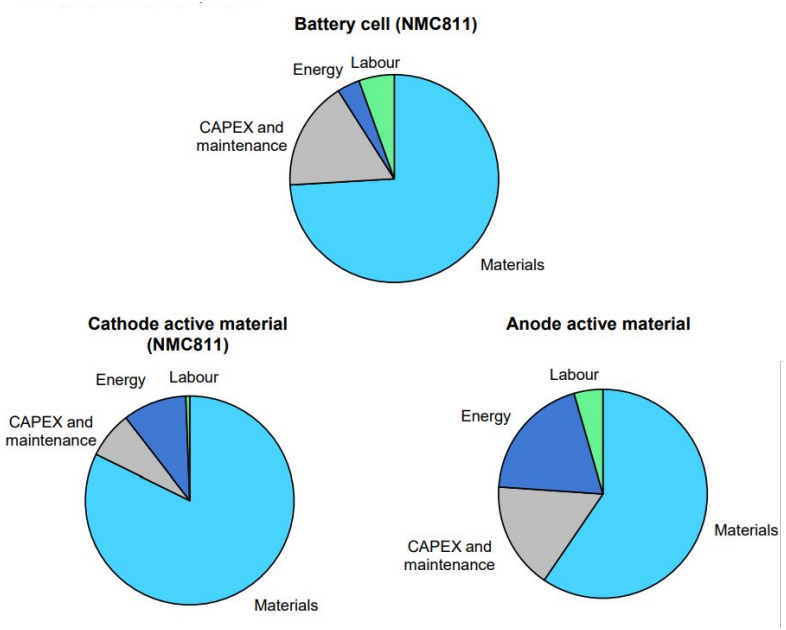
There remains a significant disparity between Tier 1 versus smaller manufacturers – the former have had the resources and strategies to bolster profitability:

- Vertical integration (both ways)
- Strong bargaining power with suppliers, and aggressively securing long-term contracts
- Expansion into BESS
- Increasing yields / manufacturing efficiency
- Overseas investment
- R&D investment

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
Financial data from company filings.

Materials Remain the Single Largest Cost Component of Producing Cells & Electrode Materials

SHARE OF LEVELISED COST OF PRODUCTION FOR BATTERY CELLS, ANODES AND CATHODES IN CHINA, 2024



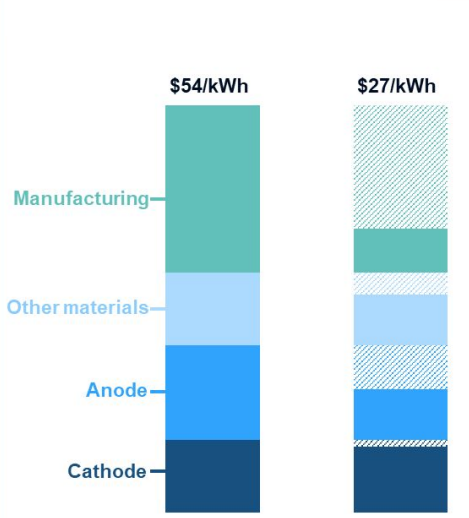
- The basic cost structure for battery cells and components is made up of input materials, capex and maintenance (spread across lifetime of depreciation of equipment), energy, and labour.
- Alongside these is the concept of yield (efficiency or quality rate), which if low can drive up all costs.
- These all vary by region and manufacturer and throughout the ramp-up timeline of a production facility.
- The price of input materials is the single largest contributor to overall costs, especially so for cathode materials such as LFP. This is why tariffs on input materials from overseas are a significant issue for localisation in regions such as the US.
- However, the price of materials is mainly a function of market conditions, and those without the means to secure cheaper feedstock have opted to focus on other cost factors such as reducing labour through automation or improving yields through technical process innovation.

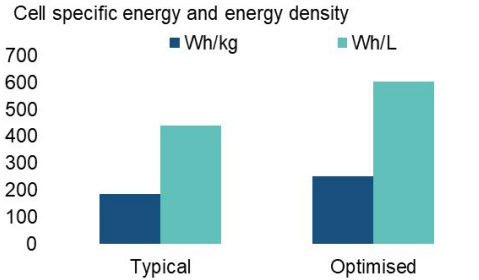
Source: IEA. See source link for full footnote.

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Chinese LFP Cost Floor Under Optimized Conditions: A Scenario Analysis

Scenario to optimize LFP costs below $30/kWh





	Typical	Optimised
Gigafactory capacity, GWh	X	X
Workers per GWh	X	X
CAPEX, $M per GWh	X	X
Yield	X	X
CAM capacity, mAh/g	X	X
CAM loading, mAh/cm^2	X	X
Cathode foil thickness, µm	X	X
AAM capacity, mAh/g	X	X
Anode foil thickness, µm	X	X
Cell format	X	X
Cell capacity, Ah	X	X

**Assumes lithium carbonate price is a mixture of manufacturer vertically-integrated supply costs and the China 2025 average spot price of 75,600 RMB/t LCE*

Although LFP at a basic cathode material level is nearing its theoretical limit, further cost reductions can be made:

- Manufacturing: e.g. greater mass loading on cathode, further automation (highest impact)
- Electrode materials: e.g. high compaction density on cathode, silicon loading on anode
- Passive materials, moving to thin foils, separator, and large cell formats (lowest impact)

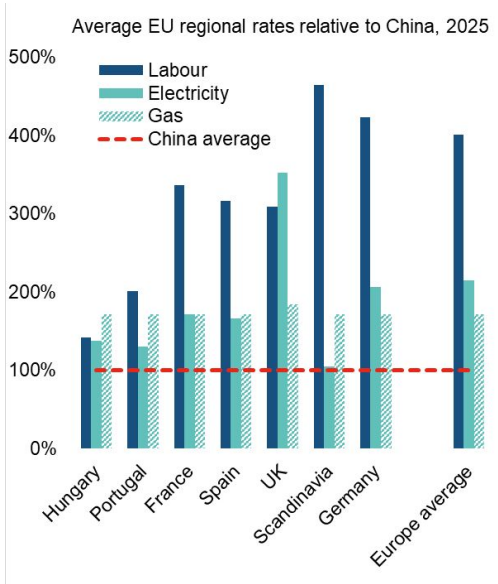
However, **optimised costs may only be achievable after several years from commissioning** due to the scale and learning rate associated with such a large gigafactory and extreme cell metrics.

Source: Content & analysis provided by CRU Group (Distinguished Partner).

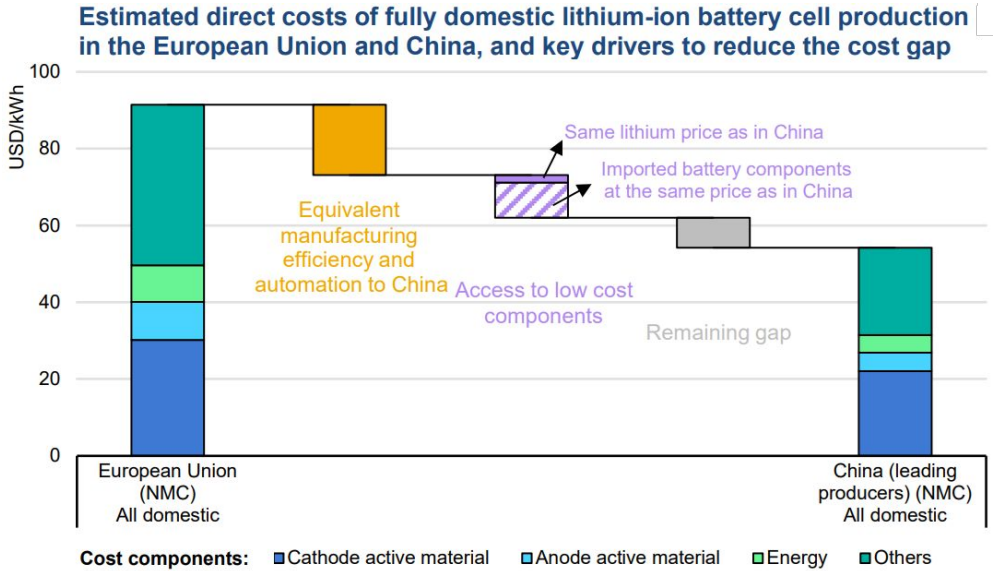
Ex.China Factories Face an Inherent Cost Disadvantage, but There Are Routes to Cost-Competitiveness

Energy and labour costs are inherently higher than China, depending on the region [1]

Example: Europe

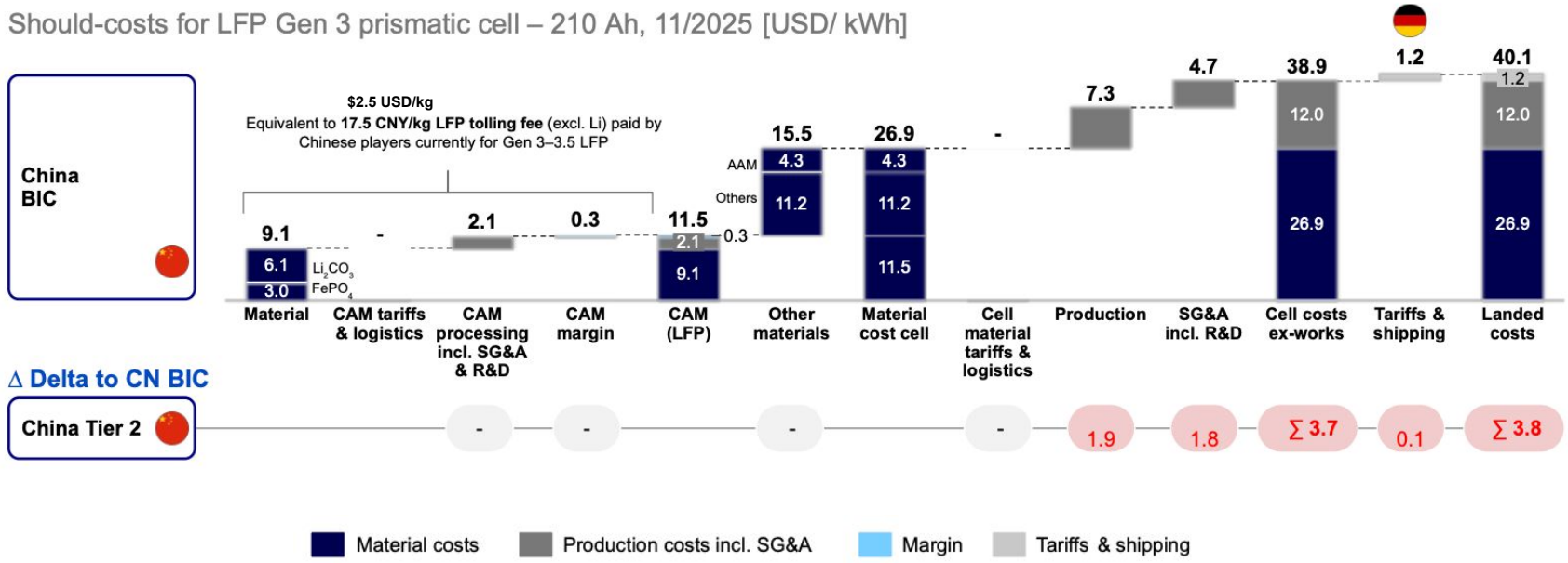


...but there are realistic pathways to cost reduction, through location choice, factory automation, higher yields, and cheaper materials [2]



Source: [1] CRU Group (Distinguished Partner), [2] IEA (see link for full footnote explanation)

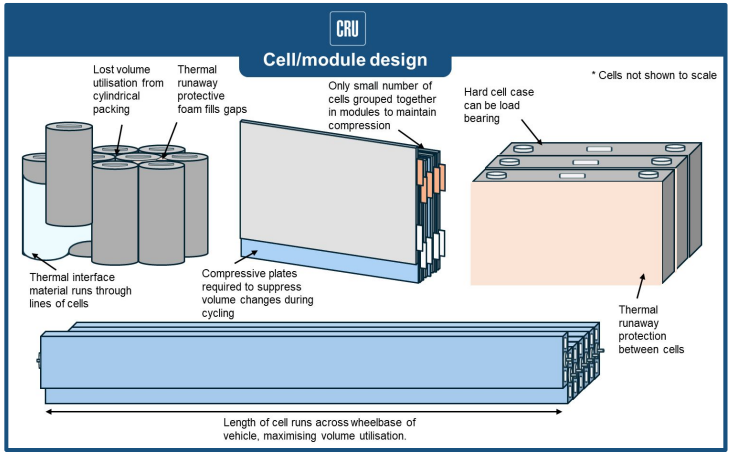
LFP Cell Production in EU Has Cost Disadvantages of $15-25 /kWh Compared to Chinese BIC



Exchange rates: 8.19 CNY = 1.00 EUR = 1.15 USD

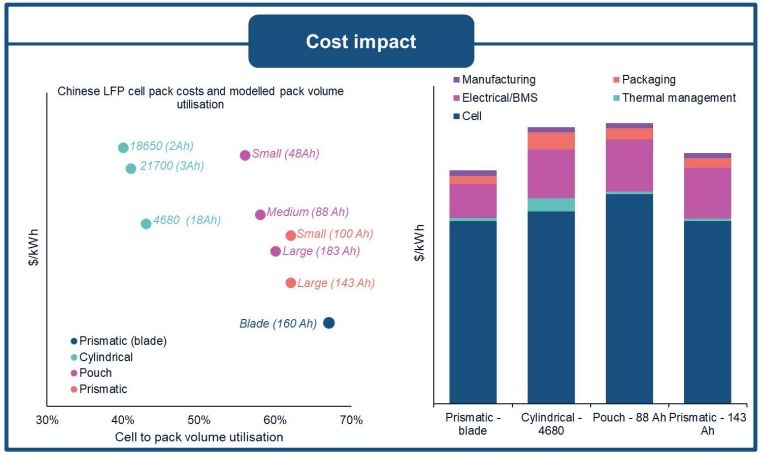
Source: Content & analysis provided by Roland Berger (Distinguished Partner), ICCSino, interviews with market participants.

Cell Size & Format Selection Heavily Impacts Battery Pack Costs



Bigger cells result in lower pack cost on a $/kWh basis

Scaling cell size increases the volume of active materials in the pack while reducing passive components (e.g. casings, housings, thermal interface materials), resulting in higher pack-level energy density and lower $/kWh.

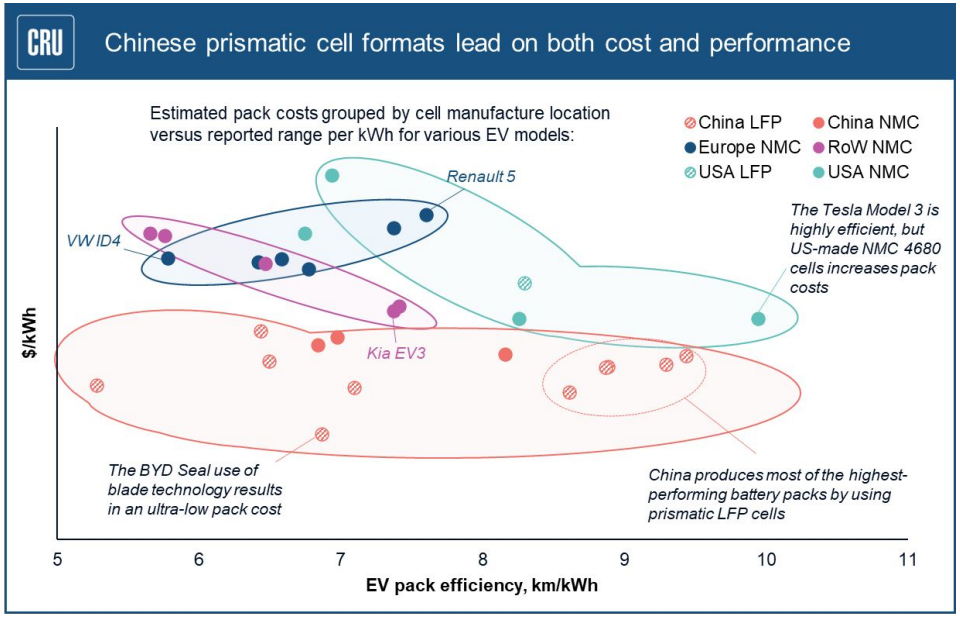


However, cells account for >70% of overall pack cost, and cell format selection still matters:

- Prismatic (especially large 'Blade' cells) give the best volumetric utilisation and can be load-bearing, reducing structural components.
- Pouch: typically need multiple smaller modules and additional housing to maintain compression.
- Cylindrical: geometry limits volume utilisation compared to prismatic.

Therefore, **large prismatic cells deliver the lowest overall pack costs.**

Chinese EVs Benefit from Low Pack Production Costs Alongside High Pack Efficiencies

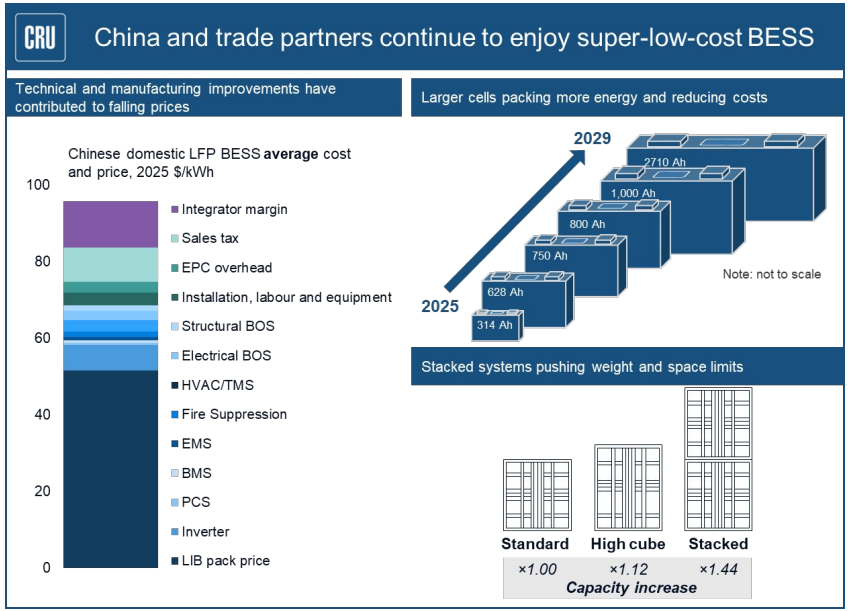


Chinese EV manufacturers enjoy a cost and performance advantage driven by:

- **Cell pricing:** Low cell costs and vertically integrated pack (and vehicle) production results in the lowest pack costs globally.
- **Pack architecture:** Many Western EVs still use pouch-based packs containing many modules, while Chinese packs centre on prismatic formats and increasingly cell-to-pack architectures, enabling high volume utilisation.
- **Chemistry choices:** Western manufacturers remain centred on NMC/A up to recently, while Chinese producers have largely shifted to LFP, benefiting from lower material costs.
- **Efficiency:** Many Chinese EVs demonstrate competitive range efficiency, delivering similar or higher range per kWh compared to their peers.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

Energy Storage Systems: More Battery for the Same Money



∗Residential and C&I storage also continue to get cheaper, although they remain more expensive than utility storage due to smaller scale and more specialised products.

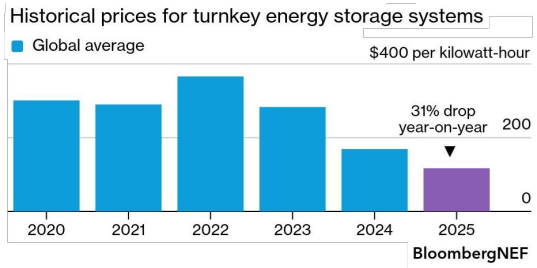
Costs and prices for Chinese-manufactured utility-scale* BESS continued to fall.

China's domestic market is showing increasing concentration with Tier 1 manufacturers that can produce at scale and innovate in systems far quicker than lower tier providers – helped along by China's efforts to phase out low-quality capacity.

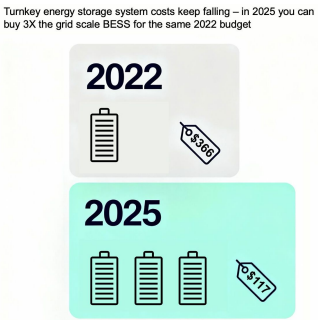
Further incremental cost reductions have been achieved through:

- Innovations that push container-level system energy, such as larger cells and stacked systems
- Manufacturing improvements such as factory automation and higher yields
- Vertical integration and strong bargaining power for input materials

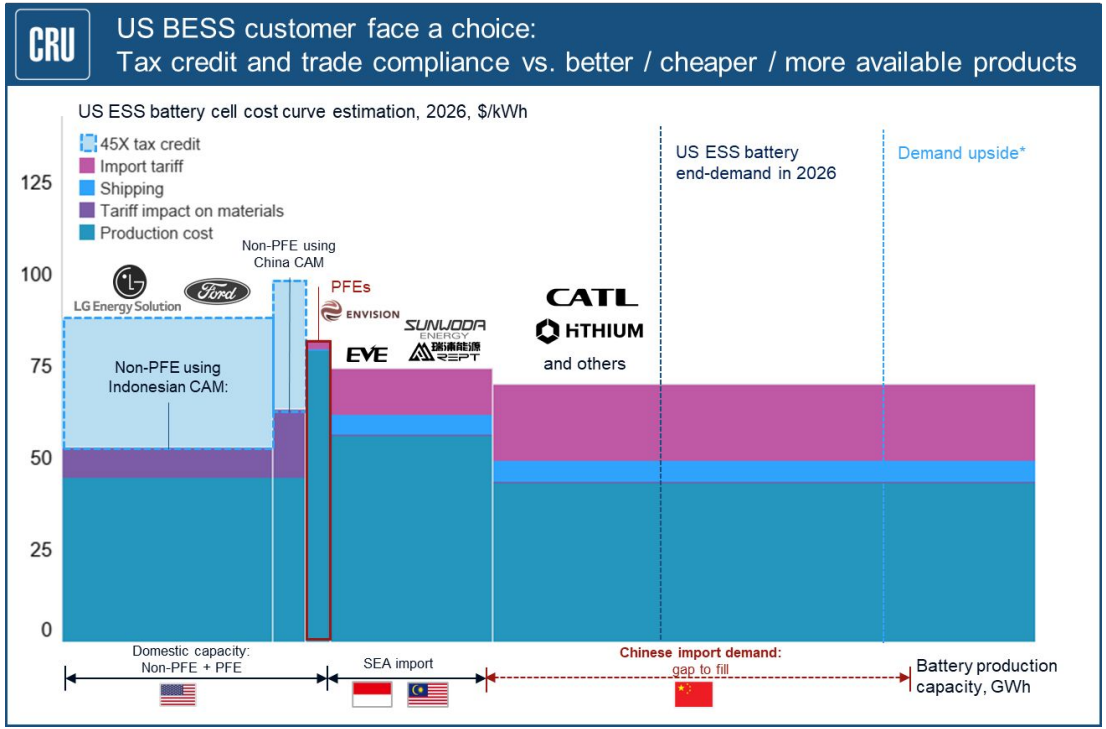
Price competition has also been intense, sometimes going below production costs.



Turnkey defined as the DC battery (rack and balance of system), PCS, EMS, transformer, expenses, system integrator margin, & warranty.



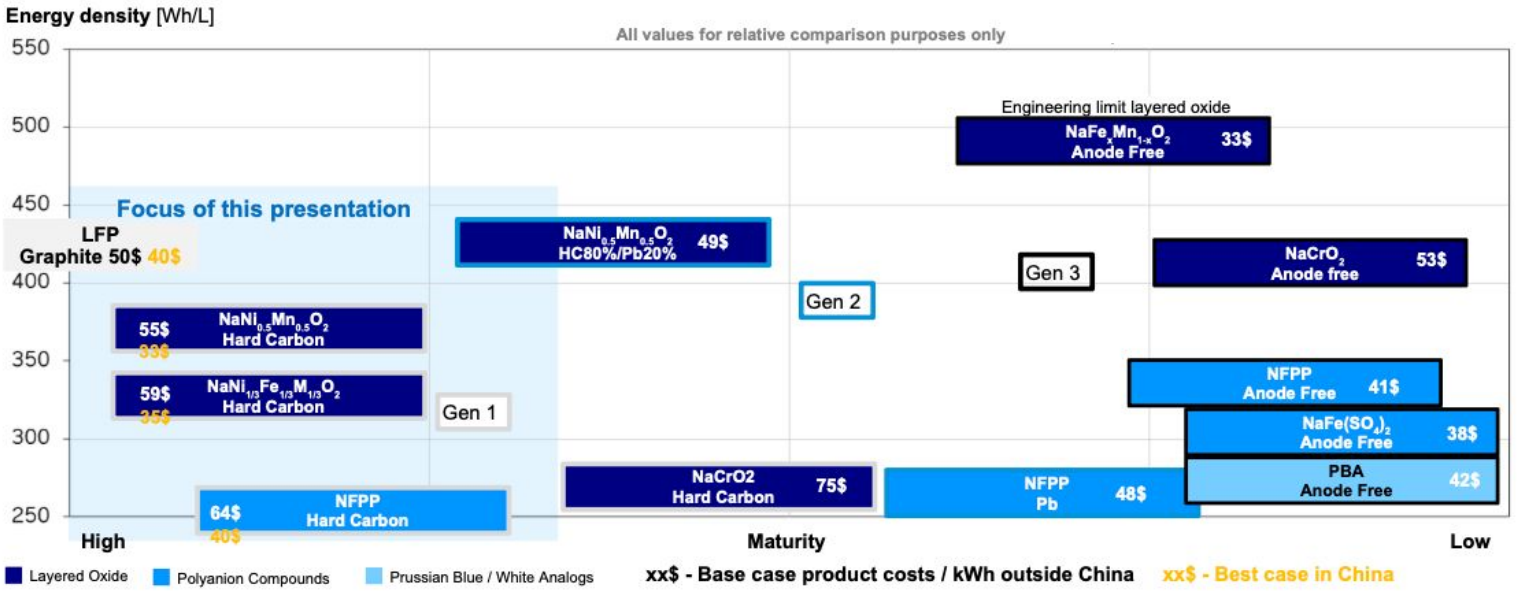
US Lacks Cost-Effective Options to Fulfill Domestic ESS Demand



- **US domestic (Korean)**: nascent but accelerating quickly. Eligible for ITC, low cost for the batterymaker due to tax credit, but they are generally charging a premium for China-free supply, and cells are currently small-capacity pouch.
- **US domestic (Chinese):** not eligible for production tax credit and customers not eligible for ITC.
- **Southeast Asia import:** Relatively cheap, but future risk of countervailing duty cases, and some capacity is spoken for by other customers.
- **China import:** large amount of capacity available to US customers, start-of-the-art cells and systems, (depending on the manufacturer), most cost-effective option even when factoring in tariffs (notwithstanding future rises).

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
*Demand upside considers the overproduction due to Bullwhip Effect.

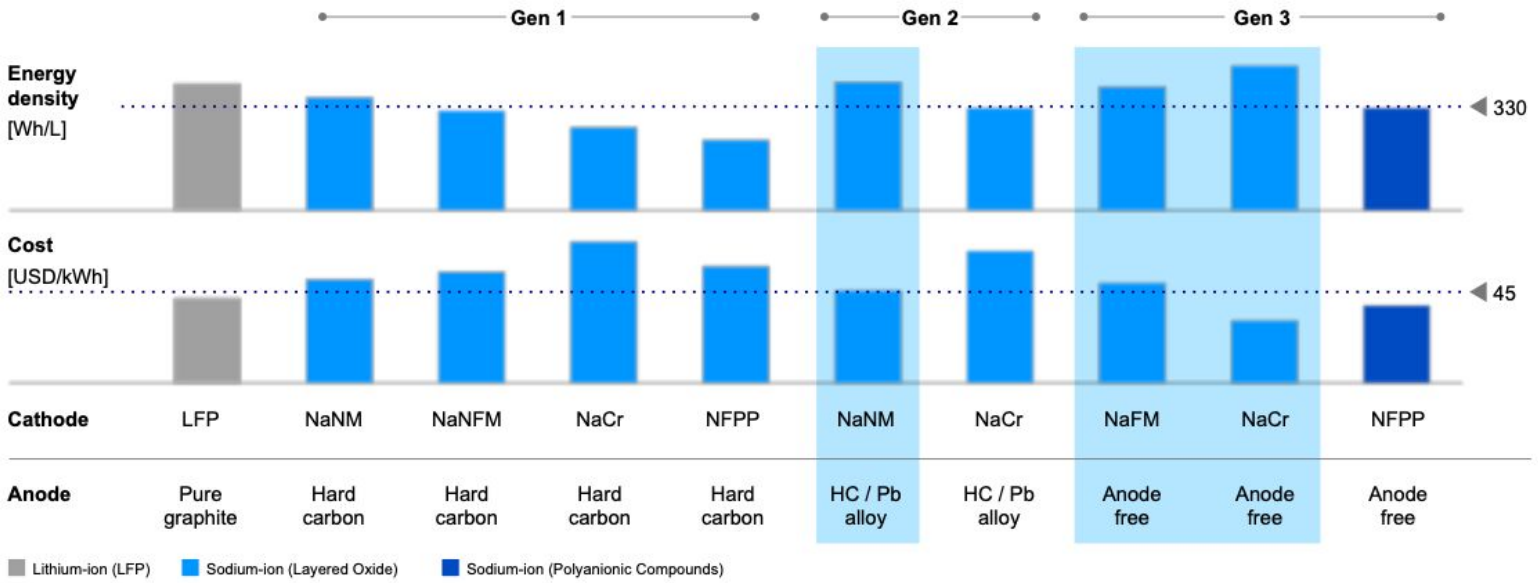
Analysis of Three Possible Technologically Variations of Sodium-ion Batteries



Focus on current technology generation already in production in China - Only 3rd generation solution potentially achieve LFP cost parity outside of China.

Source: Content & analysis provided by Roland Berger (Distinguished Partner), Shanghai Metal Market, ICCSino, interviews with market participants.

Analysis of Sodium-ion Batteries Using Western Production Assumptions Compared to LFP



Layered oxides can reach desired energy density levels, however, cannot achieve LFP cost parity without significant tech and supply chain development.

Source: Content & analysis provided by Roland Berger (Distinguished Partner), interviews with market participants.

INDUSTRY

Notable Events
Industry Value Chain
Finance
Costs

Cell & Pack Manufacturing

Applications
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- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

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Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Cell & Pack Manufacturing Overview

Global Market Dynamics

- **Battery production surpassed 2.3 TWh**, but **overcapacity surged**, especially in LFP and ESS cells.
- Despite global diversification efforts, **China remained the core of supply**, producing **86% of all cells** and expanding to **6.4 TWh** (current and future) capacity.

North America & Europe Retrench

- **EV demand softness** and the end of U.S. 30D tax credit triggered cancellations, retooling, and JV restructuring.
- *Ex. "BlueOval SK ends all Kentucky positions, transitioning to [ESS]"*
- NA saw the **first net reduction in gigafactory capacity**: 464 GWh cancelled or delayed; 195 GWh NMC cancelled, 190 GWh reallocated to LFP.
- Europe contracted by **363 GWh** due to weak demand, high energy costs, and stalled projects.

Quality, Automation & AI

- Strong momentum behind **AI/ML-driven QC**: in-line sensing, X-ray/CT, ultrasound, tool-to-tool matching, and formation-data analytics.
- OEMs and cell makers push toward **data integration & analytics** to stabilize yield and reduce variability.

Technology & Product Shifts

- Industry pivoted from NMC → **LFP**, driven by cost & safety benefits, AI data center demand, ESS growth, and lower EV-related procurement.
- **Tier-2 Chinese manufacturers gained share in ESS**, while **CATL & BYD** maintained dominant global positions.
- Manufacturers broadened **chemistries** (LFP, LMFP, NRM) and **formats** (pouch, prismatic, cylindrical).

APAC Diverges

- **China expanded strongly**, adding capacity and deepening overseas partnerships.
- Indian projects progressed slowly; Japan/Korea scaled back; Chinese firms shifted investment to ASEAN to bypass trade barriers.

Operational & Process Issues

- Persistent bottlenecks remain: led by **electrode production** (slurry dispersion, coating throughput, electrode alignment, etc.).
- Companies continue to push **dry electrode** technology (AMB, LiCAP, Sakuu, Dürr, OLA, Tesla) but **face challenges.**

Key Trends & Notable Events

Strategic Shifts & Geopolitics



Domestic Push & Tariffs: The Sign-off of U.S. Government's Big Beautiful Bill to encourage domestic production. US tariffs on Chinese manufacturers threatened supply chain disruption.



Manufacturing Localization: Europe focused on local battery supply chains and materials partnerships reinforcing manufacturing localization with opening of new battery factories.



Export Control & Expansion: Material and technology export controls and focus on more sustainable Chinese capacity expansion domestic and overseas

Technology and Manufacturing Trends



Portfolio Diversification: Diversification of suppliers and manufacturing portfolios.



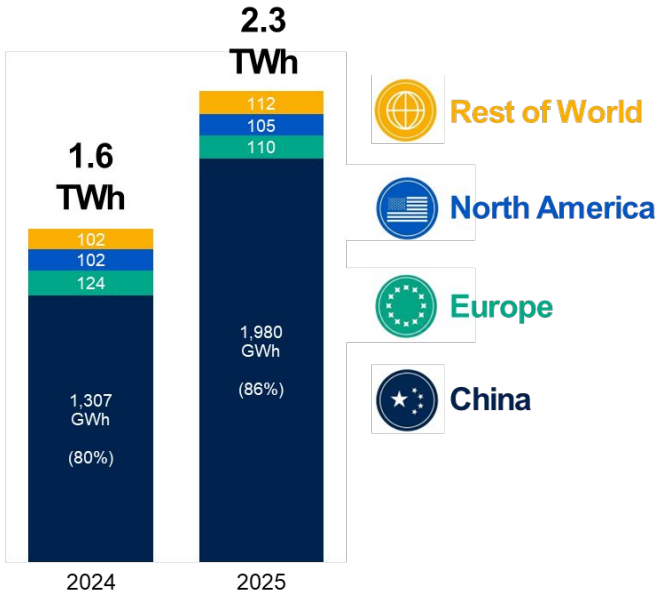
Security Awareness: Security awareness in the battery industry as LGES battery facility attacked by ransomware.



LFP/BESS Pivot: Pivot to LFP and BESS battery manufacturing for AI Data Centers.

2025 Battery Production Summary

Battery production surpasses 2 TWh



In 2025, global lithium-ion battery cell production surpassed

2.3 TWh

65% were LFP batteries

1/5 were ESS batteries

86% were made in China

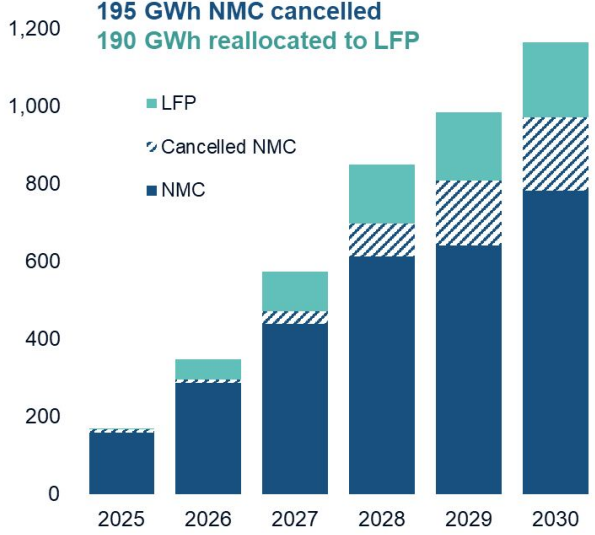
- There is still considerable overproduction compared to demand, especially in LFP/ESS cells.
- This is the reason for LFP's share being higher than in end-use demand.
- EV battery gigafactories outside China are ramping up, but almost all ESS cells are imported from China.
- The industry remains an oligopoly with the top 2 manufacturers making up half of output, but more Tier 2 manufactures have been taking market share in ESS.

Source: Data provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
*Battery production data from CRU's primary data collection, national industry associations, and manufacturer reports. December 2025 data is estimated.

North America Battery Industry Consolidating and Re-Tooling for LFP

Battery manufacturers reallocating excess NMC investments into LFP

North America Tier 1 gigafactory pipeline, GWh



Manufacturer	Location
LG ES	Lansing, Michigan
LG ES	Queen Creek, Arizona
LG ES	Holland, Michigan
LG ES	Windsor, Ontario
LG ES	Lordstown, Ohio
LG ES	Spring Hill, Tennessee
SK On	Commerce, Georgia
Samsung SDI	New Carlisle, Indiana
AESC	Smyrna, Tennessee
Ford	Marshall, Michigan
Ford	Glendale, Kentucky

Over the last couple of years, US EV demand has underwhelmed compared to the automotive and battery industries' expectations.

Now, combined with US policy changes, this is exacerbating an overcapacity situation for NMC/A batteries in the country.

US Tier 1 battery producers reported declined revenue and profitability remains low even with the 45X production tax credits.

OEMs remain cautious about battery procurement and keep cutting their order plans due to the end of the 30D EV tax credit.

Manufacturers have responded by recalibrating their investments. Out of Tier 1 capacity:

- 195 GWh of NMC capacity has been cancelled or suspended
- 109 GWh of joint venture capacity has been transferred to other OEMs or acquired by the battery manufacturer or automaker
- 190 GWh has been reallocated to LFP production

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
Capacity pipeline is from company announcements as of December 2025.

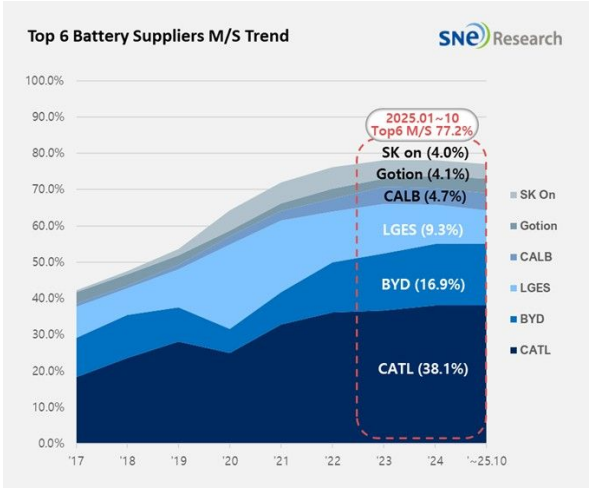
Market Share of Leading Cell Manufacturers in 2025

The top six cell manufacturers dominate the market, accounting for **77.2%** of total EV market share. CATL remains the leading company and slightly increased its share compared to 2024, reaching **38.2%**. BYD and LGES continue to trail CATL; BYD maintained its market share, while LGES lost ~2% year over year.

Overall, the global market grew by **32.6%**. In terms of capacity (GWh), Gotion, EVE, and SVolt showed outstanding performance, each achieving growth of around **80%** compared with 2024.

*** Annual Cumulative Global EV Battery Usage** (Unit : GWh)

Rank	Group	2024. 01~11	2025. 01~11	Growth Rate	2024 M/S	2025 M/S
1	CATL	297.4	400.0	34.5%	37.7%	38.2%
2	BYD	133.4	175.2	31.3%	16.9%	16.7%
3	LG Energy Solution	87.3	96.9	11.1%	11.1%	9.3%
4	CALB	35.8	50.9	42.0%	4.5%	4.9%
5	Gotion	25.3	44.9	77.8%	3.2%	4.3%
6	SK on	35.6	40.6	14.1%	4.5%	3.9%
7	Panasonic	31.3	38.5	23.1%	4.0%	3.7%
8	EVE	16.0	28.4	77.0%	2.0%	2.7%
9	SVOLT	14.8	27.5	85.6%	1.9%	2.6%
10	Samsung SDI	28.5	27.1	-5.1%	3.6%	2.6%
	Others	**83.4**	**116.1**	**39.1%**	**10.6%**	**11.1%**
	Total	**788.9**	**1,046.0**	**32.6%**	**100.0%**	**100.0%**



Source: [1] SNE Research, [2] SNE Research - January

Profiles of C&P Industry Players

CATL

Summary: CATL remained the world's dominant battery cell supplier in 2025, reinforced by continued technology leadership and global expansion despite limited direct exposure to the US market. The company pushed aggressively into next-generation chemistries and form factors, including fast-charging LFP, sodium-ion, and high-energy-density Qilin packs. While geopolitical constraints limited CATL's ability to build US manufacturing capacity, it expanded licensing, technology partnerships, and overseas production in Europe and emerging markets. CATL's ESS business continued to grow rapidly, benefiting from grid-scale demand and vertical integration advantages.

Notable events:

- VW announces strategic cooperation with CATL to develop batteries in China jointly (Feb 2025)
- CATL unveils 3 new battery technologies at "Tech Day" (Apr 2025)
- CATL begins construction of additional European manufacturing capacity to support BMW, Stellantis, and VW platforms (Jun 2025)
- CATL launches new grid-scale ESS products targeting long-duration (Oct 2025)

Top level numbers: CATL's global installed and planned capacity exceeded 600 GWh in 2025, maintaining its position as the world's largest battery manufacturer by a wide margin. While direct US production remains minimal, CATL continues to supply a significant share of global EV and ESS demand through China, Europe, and licensing-based market access.

BYD

Summary: BYD further strengthened its position in 2025 as the world's most vertically integrated EV and battery manufacturer. The company's Blade Battery platform continued to gain adoption across BYD's own vehicle lineup and select third-party OEMs, while BYD accelerated global expansion in both EV and stationary storage markets. Unlike other Chinese suppliers, BYD made meaningful inroads into overseas manufacturing, positioning itself as both a battery supplier and a full-stack energy solutions provider. Its ESS business grew alongside large-scale solar-plus-storage deployments worldwide.

Notable events:

- BYD Energy Storage secures multi-GWh utility-scale ESS contracts outside China (Feb 2025)
- BYD expands Blade Battery production capacity to support new global EV platform launches (Mar 2025)
- Introduction of next-gen C&I BESS, the Chess Plus (Apr 2025)
- BYD continues international EV market share gains, driving internal battery demand growth (Nov 2025)

Top level numbers: BYD's total battery manufacturing capacity exceeded 400 GWh globally in 2025, split between internal EV consumption and third-party EV and ESS customers. The company remains one of the largest global producers of LFP batteries, with expansion plans focused on vertically integrated growth rather than merchant cell sales alone.

Companies are generally shifting their focus from EVs to a broader portfolio that includes energy storage.

Source: Company announcements

Profiles of C&P Industry Players

LG Energy Solution

Summary: 2025 was a year of ups and downs. While Ultium, the LGES and GM JV, scaled back in 2025, LGES was able to sign new deals with Toyota and Tesla. LGES is also expanding its product portfolio, from being dominated by NMC pouch cells for EVs to a much broader portfolio of chemistries (NMC, LFP, NRM) and formats (pouch, cylindrical, and prismatic) for both EV and ESS applications. LGES also in the news as the JV site with Hyundai was the target of a high-profile ICE raid in September.

Notable events:

- GM sells stake in Lansing battery cell plant to LG Energy Solution (Dec 1 2024)
- Toyota agrees to shift a $1.5B order with LGES to Lansing plant (Feb 2025)
- GM and LGES announce the commercialization of LMR prismatic battery cells (May 2025)
- LGES shifts to LFP BESS production in Holland, MI (June 2025)
- LGES signs a deal with Tesla for LFP cell production (July 2025)
- IS immigration agents arrest hundreds at Hyundai plant (September 2025)
- Ultium Cells furloughs employees in Tennessee and Ohio, combined with layoffs (Oct 2025)
- LGES and Stellantis JV to produce LFP cells for BESS (November 2025)
- Ford cancels LGES EV battery deal worth $6.5B for the supply of EU EV models (Dec 2025)
- LGES sells US factory assets of its Ohio battery JV plant to Honda (Dec 2025)

Top level numbers: LGES is on track to add ~150GWh worth of battery production capacity between 2025 and 2030, maintaining their position as the largest cell producer in North America. While the customer and product portfolio has shifted, the overall volumes remain mostly intact.

SAMSUNG SDI

Summary: 2025 was a year of diversification for Samsung SDI as well, expanding into new cell formats and energy storage markets. While the partnership with GM is slowing down, Samsung SDI signed a major ESS battery supply deal with Tesla. Samsung also initiated an approach into solid state batteries in partnership with Solid Power and BMW. Unfortunately, Samsung SDI was in the news in November due to a Stellantis recall of Samsung SDI powered plug-in hybrid vehicles due to fire risk.

Notable events:

- Samsung SDI begins production of 46-series cylindrical batteries in the US (Mar 2025)
- Samsung SDI unveils new ESS products (Sep 2025)
- Samsung SDI signs an agreement with Solid Power and BMW to collaborate on solid-state batteries (Oct 2025)
- Tesla set to buy $2B in BESS batteries from Samsung SDI (Nov 2025)
- Samsung SDI announces conversion of EV lines in Indiana to ESS due to Stellantis battery demand drop(Nov 2025)
- GM, Samsung SDI battery plant construction slows down (Nov 2025)
- Stellantis recalls PHEV Jeeps (Nov 2025)

Top level numbers: Samsung SDI is on track to be producing ~50GWh worth of battery production capacity between 2025 and 2030, maintaining their position as a mid-level producer in North America. While the customer and product portfolio has shifted, the overall volumes remain mostly intact.

Companies are generally shifting their focus from EVs to a broader portfolio that includes energy storage.

Source: Company announcements

Profiles of C&P Industry Players

Panasonic

Summary: Panasonic's Kansas plant reaching production was a major milestone. It materially expanded Panasonic's US cell capacity and shifted more production onshore for customers like Tesla and others. Panasonic's energy unit showed improved profitability in early 2025, but the company also implemented aggressive cost and organizational reforms to boost returns. Public signaling of ambitions for higher energy density, anode-free cells indicates a rapid timeline to commercialize advanced chemistries.

Notable events:

- Lucid begins production using Panasonic's 2170 cells (Jan 2025)
- Panasonic raises earnings outlook for its energy unit and signals group management reforms (Feb 2025)
- Major corporate restructuring. Panasonic announced global job reductions (May 2025)
- Mass production begins at Panasonic's new automotive battery factory in De Soto, KS (July 2025)
- Panasonic confirms R&D push, targeting anode-free, high energy density EV batteries in ~2 years (Sep 2025)

Top level numbers:
Combined with the Panasonic/Tesla gigafactory in Nevada (~41 GWh) capacity, the Kansas plant adds another 32 GWh of US cell production capacity to Panasonic's portfolio. The company plans to build at least two new factories for 4680 battery production in North America, with the goal of boosting its capacity to 200 GWh by March 2031.

SK on

Summary: SK On is expanding in the US market with large loans, multi-GWh supply deals with Nissan & Slate, and ESS contracts. At the same time, it is under pressure from weak demand as a result of the EV slowdown and financial losses. The dissolution of the Ford JV has forced SK to pursue other customers and segments.

Notable events:

- DOE finalized $9.63bn loan to BlueOval SK to support construction of 3 battery plants in TN and KY, intended to produce >120 GWh of batteries (Dec 2024)
- SK On announces supply agreement with Nissan for ~100 Gwh of batteries from 2028-2033 (Mar 2025)
- Slate Auto selects SK On as supplier of approximately 20 GWh of batteries from 2026-2031 (Apr 2025)
- SK On rose to the #3 global EV battery supplier, excluding Chinese firms (May 2025)
- Announcement of ESS deal with Flatiron Energy Development to supply ~7.2 GWh of batteries from 2026-2030 (Sep 2025)
- SK On and Ford Motor Company to end US battery joint venture with a Ford subsidiary taking ownership of the KY plant and SK On assuming ownership of the TN plant (December 2025)

Top level numbers:
In addition to the two plants SK On currently runs in the US, they plan to build additional factories with partners and independently. Once fully operational, SK On's US production capacity is slated to exceed 180 GWh.

Companies are generally shifting their focus from EVs to a broader portfolio that includes energy storage.

Source: Company announcements

VF | VOLTA FOUNDATION

North American Gigafactory Plants - 908* GWh of Capacity

USA

1 ABF, Tucson, AZ, (+15 GWh)**
2 Amprius Tech, Brighton, CO, (+5 GWh)**
3 Electrovaya, Jamestown, NY, (+0.3 GWh)
4 AESC, Smyrna, TN, 3 GWh
5 AESC/BMW, Bowling Green, KY, (+30 GWh)
6 AESC/Mercedes, Florence County, SC, (+30 GWh)**
7 Ford/CATL, Marshall, MI, (+20 GWh)
8 Nanotech Energy, Storey County, NV, (+6 GWh)**
9 LGES, Queen Creek, AZ, (+53 GWh)
10 LGES, Holland, MI, 16.5 GWh
11 LGES, Lansing, MI, (+50 GWh)
12 Ultium Cells, LGES/GM, Spring Hill, TN, 50 GWh**
13 Honda, Jeffersonville, OH, (+50 GWh)**
14 Panasonic, DeSoto, KS, (+32 GWh)
15 Panasonic/Tesla, Storey County, NV, 41 GWh
16 Samsung SDI/GM, New Carlisle, IN, (+36 GWh)
17 *(2 plants)* StarPlus Energy (Samsung SDI/Stellantis), Kokomo, IN, (+33 GWh & +34 GWh)
18 SK, Commerce, GA, 22 GWh
19 SK On, Stanton, TN, (+43 GWh)
20 SK/Hyundai, Bartow County, GA, (+35 GWh)
21 Tesla, Fremont, CA, ~4 GWh
22 Toyota, Greensboro, NC, 30 GWh
23 LGES/Hyundai, Bryan County, GA, (+30 GWh)
24 Ultium Cells, LGES/GM, Warren, OH, 45 GWh
25 Forge Battery, Raleigh, NC, (1-3 GWh)*
26 SAFT, Jacksonville, FL, (+5 GWh)
27 Tesla, Austin, TX, ~6 GWh (+94 GWh)
28 Gotion, Manteno, IL, (+35 GWh)
29 *BlueOval (Ford), Glendale, KY,* (+43 GWh, +43 GWh)**
30 Pomega, Waterboro, SC, (+3 GWh)
31 Amplify Cell Tech, Marshall County, MS, (+21 GWh)*

CANADA

32 NexStar Energy LGES/Stellantis, Windsor, ON, (+49.5 GWh)
33 PowerCo, St. Thomas, ON, (+90 GWh)
34 Blue Solutions, Montreal, QC, 0.2 GWh
35 Electrovaya, Mississauga, ON (+0.5 GWh)

2025 was the first year with a **reduction in North American Gigafactory sites**, with several projects having been cancelled or facing significant delays.

Calculated **464 GWh reduction in total capacity**.



No new gigafactory announcements in 2025. Significant project delays and cancellations.

BASIC FORMAT = *Current Capacity* GWh, (+*Additional Future Capacity* GWh)
CONSTRUCTION AT RISK = (+*Additional Future Capacity* GWh)*
CONSTRUCTION HALTED/BANKRUPTCY = (+*Additional Future Capacity* GWh)**

**total includes future & current capacities; excludes plants with halted construction; takes the highest of future capacity ranges (if range exists)*

European Gigafactory - 1,141* GWh of Capacity

FRANCE
1 ACC, 13 GWh, (+27 GWh)
2 AESC, 10 GWh, (+20 GWh)
3 Verkor/Renault, 16 GWh, (+34 GWh)
4 Prologium, (+48 GWh)
5 Tiamat, (+5 GWh)

GERMANY
6 ACC, (+40 GWh)**
7 CATL, 14 GWh, (+10 GWh)
8 Leclanche, 2 GWh
9 (Lyten) Northvolt Drei, (+15 GWh)
10 SVOLT, (+24 GWh)**
11 SVOLT, (+16 GWh)**
12 Tesla, (+8 GWh)
13 PowerCo, 20 GWh, (+20 GWh)
14 Customcells, (+unknown GWh)**
15 EAS, 0.5 GWh

ITALY
16 FAAM, 0.35 GWh, (+8 GWh)

PORTUGAL
17 CALB, (+15 GWh)

SWEDEN
18 NOVO (Volvo), (+50 GWh)**
19 (Lyten) Northvolt Ett, 16 GWh

HUNGARY
20 CATL, 40 GWh (+60GWh)
21 EVE Energy, (+28 GWh)
22 Samsung SDI, 40 GWh, (+10GWh)
23 SK On, 47.5 GWh
24 Sunwoda, (+unknown GWh)

NORWAY
25 FREYR, (+29 GWh)**
26 Morrow, 1 GWh (+42 GWh)

SPAIN
27AESC, (+50 GWh)
28 PowerCo, (+60 GWh)
29 Basquevolt, unknown GWh (+10 GWh)
30 CATL/Stellantis, (+50 GWh)

U.K.
31 AESC, 17.6 GWh, (+17.4 GWh)
32 Agratas/Tata, (+40 GWh)
33 Nanotech Energy, (+unknown GWh)
34 EVE Energy, (+60 GWh)

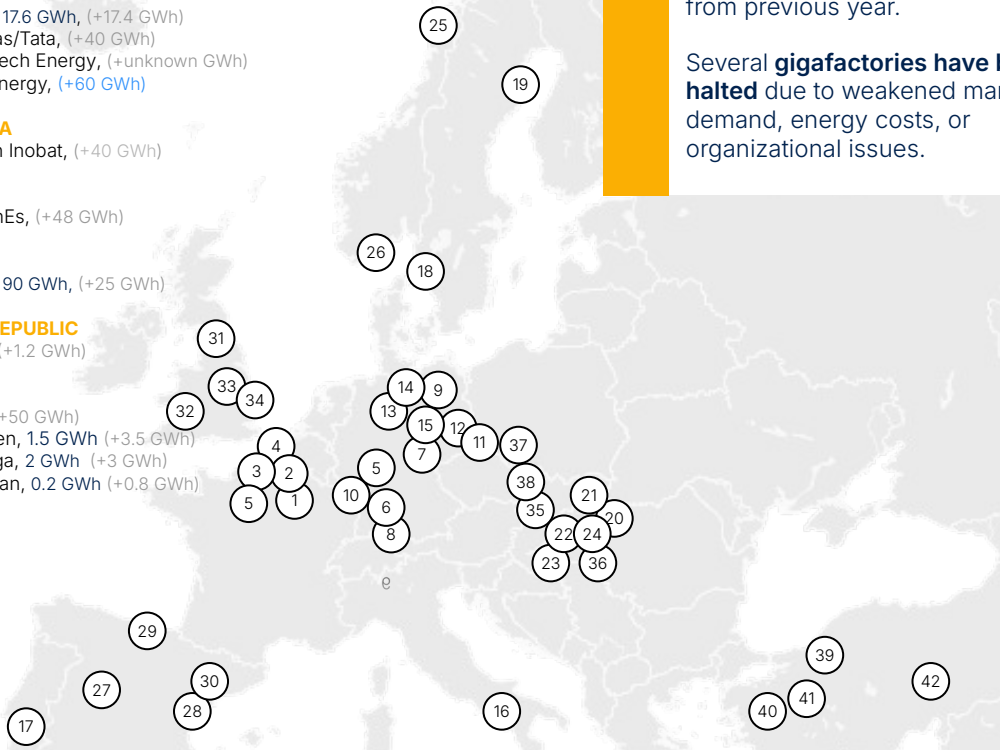
SLOVAKIA
35 Gotion Inobat, (+40 GWh)

SERBIA
36 ElevenEs, (+48 GWh)

POLAND
37 LGES, 90 GWh, (+25 GWh)

CZECH REPUBLIC
38 MES, (+1.2 GWh)

TURKEY
39 Siro, (+50 GWh)
40 Maxxen, 1.5 GWh (+3.5 GWh)
41 Pomega, 2 GWh (+3 GWh)
42 Aspilsan, 0.2 GWh (+0.8 GWh)



Total capacity **shrunk by 363 GWh** from previous year.

Several **gigafactories have been halted** due to weakened market demand, energy costs, or organizational issues.

BASIC FORMAT = *Current Capacity* GWh, (+*Additional Future Capacity* GWh)
CONSTRUCTION AT RISK = (+*Additional Future Capacity* GWh)*
CONSTRUCTION HALTED/BANKRUPTCY = (+*Additional Future Capacity* GWh)**

**total includes future & current capacities; excludes plants with halted construction; takes the highest of future capacity ranges (if range exists)*
***note:** sodium-ion excluded*

Source: All uncited factories are from Batteriezellproduktion: Europa gerät ins Hintertreffen

VF | VOLTA FOUNDATION

APAC Gigafactory - 495* GWh (+6,401 from China) of Capacity

APAC gigafactory development is diverging:

- **Indian gigafactories** are progressing slowly
- **Chinese companies** are shifting capacity to ASEAN to circumvent trade barriers and respond to intensifying domestic competition
- **South Korea and Japan** are slowing down capacity expansion amid weaker global EV demand

INDIA
1 Ola, Tamil Nadu, (+100 GWh)
2 Reliance, Gujarat, (+50 GWh)
3 Agratas / TATA, Gujarat, (+20 GWh)
4 Amara Raja, Telangana, (+16 GWh)
5 Exide, Karnataka, (+12 GWh)
6 Godi, Hyderabad, (+12 GWh)
7 24M / Lucas TVS, Thervoy Kandigai, (+10 GWh)
8 LGES / JSW, India, (+10 GWh)
9 Nash Energy, India, 0.6 GWh (+10 GWh)
10 Mahanagar / IBC Inc., Bengaluru, (+unknown GWh)

VIETNAM
10 Gotion / VinES, Vung Ang, 5 GWh
11 Tianneng, Nghe An, 2 GWh
12 Exquisite (Highpower), Hai Phong, (+unknown GWh)

THAILAND
13 Sunwoda, Chon Buri, (+17.4 GWh)
14 GPSC, Map Ta Phut, (+10 GWh)
15 EA Amita Technology, Bang Pakong, (+4 GWh)
16 24M / Nuovo+, Rayong, 0.1 GWh

MALAYSIA
17 Samsung SDI, Seremban, unknown GWh, (+16 GWh)
18 EVE Energy, Kedah, (+~11 GWh)
19 Tenpower, Selangor, ~5 GWh
20 Highstar, Johor, 2.5 GWh
21 CosMX, Seremban, (+unknown GWh)
22 Enovix, Seremban, (+unknown GWh)

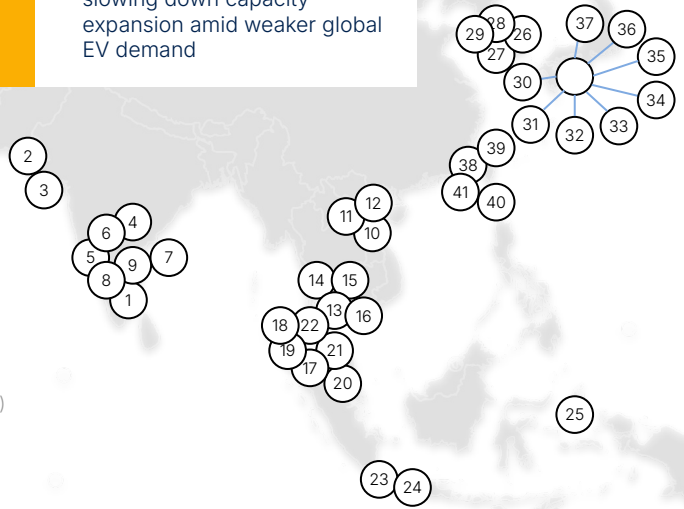
INDONESIA
23 LGES / Hyundai, Karawang, 10 GWh (+20 GWh)
24 CATL, Karawang, (+15 GWh)
25 REPT Battero, Weda Bay, (+8 GWh)

SOUTH KOREA
26 LGES, Ochang, 21 GWh (+12 GWh)
27 Samsung SDI, Cheonan, unknown GWh, (+12 GWh)
28 SK On, Seosan, 5 GWh
29 Kumyang, Gijang, (+unknown GWh)

JAPAN
30 PPES, Himeji, Japan, unknown GWh, (+30 GWh)
31 AESC, Kanagawa, 2.6 GWh
32 AESC, Ibaraki, 6 GWh, (+12 GWh)
33 Panasonic, Osaka, 4 GWh
34 Panasonic, Uchida, 10 GWh
35 Panasonic, Asonaka, (+unknown GWh)
36 Panasonic, Gunma, (+16 GWh)
37 Nissan, Japan, (+5 GWh)**

TAIWAN
38 Formosa Smart Energy, Changhua, 2.1 GWh, (+2.9 GWh)
39 ProLogium, Taoyuan, 2 GWh
40 Molicel, Kaohsiung, ~~1.8 GWh~~
41 Molicel, Tainan, 1.5 GWh

CHINA
See "Chinese Gigafactory" on the following pages.



BASIC FORMAT = *Current Capacity* GWh, (+*Additional Future Capacity* GWh)
CONSTRUCTION HALTED/BANKRUPTCY = (+*Additional Future Capacity* GWh)**
DECOMMISSIONED = ~~Previous Capacity GWh~~

Source: All uncited factories are from Battery Production, India 1, India 2, Thailand, New Energy Terminal

**total includes future & current capacities; excludes plants with halted construction*
***note:** sodium-ion excluded*

VF | VOLTA FOUNDATION

Chinese Gigafactory - 6,401* GWh of Capacity | Part 1 of 3

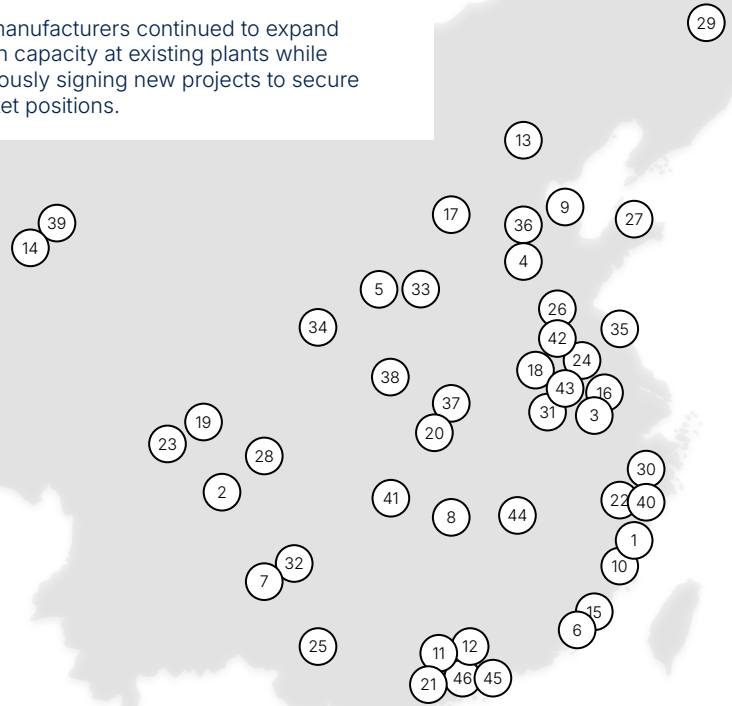
CATL
1 Ningde, 278 GWh, (+12 GWh)
2 Yibin, 210 GWh, (+115 GWh)
3 Changzhou, 158 GWh, (+60 GWh)
4 Jining, 60GWh, (+120 GWh)
5 Luoyang, 60 GWh, (+60 GWh)
6 Xiamen, 60 GWh, (+30 GWh)
7 Guiyang, 30 GWh, (+30 GWh)
8 Yichun, 50 GWh
9 Dongying, (+40 GWh)
10 Fuzhou, (+40 GWh)
11 Zhaoqing, 25 GWh
12 Guangzhou, 12 GWh, (+6 GWh)
13 Beijing, (+15 GWh)
14 Xining, 11 GWh

CALB
15 Xiamen, 30 GWh, (+30 GWh)
16 Changzhou, 32 GWh, (+25 GWh)
17 Handan, (+51 GWh)
18 Hefei, 20 GWh, (+30 GWh)
19 Chengdu, 20 GWh, (+30 GWh)
20 Wuhan, 40 GWh
21 Jiangmen, 35 GWh, (+15 GWh)
22 Jinhua, (+33.6 GWh)
23 Meishan, 20 GWh

LGES
24 Nanjing, 139 GWh, (+6 GWh)

BYD / FINDREAMS
25 Nanning, 55 GWh, (+15 GWh)
26 Xuzhou, 15 GWh, (+15 GWh)
27 Yantai 20GWh, (+30 GWh)
28 Chongqing, 35 GWh, (+10 GWh)
29 Changchun, 15 GWh, (+30 GWh)
30 Shaoxing, 45 GWh
31 Wuhu, 40 GWh
32 Guiyang, 25 GWh, (+15 GWh)
33 Zhengzhou, 14 GWh, (+26 GWh)
34 Xi'an, 32 GWh
35 Yancheng, 30 GWh
36 Jinan, 30 GWh
37 Wuhan, 12 GWh, (+18 GWh)
38 Xiangyang, 10 GWh, (+20 GWh)
39 Xining, 24 GWh
40 Taizhou, 22 GWh
41 Changsha, 10 GWh, (+10 GWh)
42 Bengbu, 10 GWh, (+10 GWh)
43 Chuzhou, 5 GWh, (+15 GWh)
44 Fuzhou, 15 GWh
45 Shenzhen, 14 GWh
46 Huizhou, 2 GWh

Leading manufacturers continued to expand production capacity at existing plants while simultaneously signing new projects to secure their market positions.



BASIC FORMAT = *Current Capacity* GWh, (+*Additional Future Capacity* GWh)

Source: New Energy Terminal

*total includes future & current capacities; excludes plants with halted construction
**note: sodium-ion excluded

VF | VOLTA FOUNDATION

Chinese Gigafactory - 6,401* GWh of Capacity | Part 2 of 3

EVE Energy and **SK On** restructured their joint-ventures, swapping shares so SK On took full control of its Yancheng plant, while EVE gained full ownership of the Huizhou plant.

GOTION HIGH TECH
47 Hefei, 14 GWh, (+52 GWh)
48 Nanjing, 28 GWh, (+20 GWh)
49 Anqing, 30 GWh, (+10 GWh)
50 Liuzhou, 15 GWh, (+15 GWh)
51 Yichun, 30 GWh
52 Tangshan, 20 GWh, (+10 GWh)
53 Lu'an, 15 GWh, (+10 GWh)
54 Chuzhou, 10 GWh, (+10 GWh)
55 Wuhu, (+20 GWh)
56 Qingdao, 3 GWh

SVOLT
57 Changzhou, 18 GWh, (+47 GWh)
58 Chengdu, 31.5 GWh, (+28.5 GWh)
59 Huzhou, 15 GWh, (+15 GWh)
60 Dazhou, (+30 GWh)
61 Suining, 20 GWh, (+9 GWh)
62 Ma'anshan, 28 GWh
63 Shangrao, 24 GWh
64 Yancheng, 22 GWh
65 Nanjing, 15 GWh
66 Wuxi, 2.3 GWh

SUNWODA
67 Jinhua, 30 GWh, (+20 GWh)
68 Nanchang, 36 GWh, (+14 GWh)
69 Zaozhuang, 24 GWh, (+26 GWh)
70 Yichang, 20 GWh, (+10 GWh)
71 Nanjing, 18 GWh, (+12 GWh)
72 Deyang, 20 GWh

EVE ENERGY,
73 Jingmen, 146 GWh, (+43 GWh)
74 Chengdu, 20 GWh, (+50 GWh)
75 Shenyang, 10GWh, (+30 GWh)
76 Huizhou, 24 GWh
77 Qujing, 11.5 GWh, (+14.5 GWh)
78 Nantong, 10 GWh
79 Yuxi, (+10 GWh)

SK ON
80 Yancheng, 57 GWh
81 Changzhou, 7.5 GWh

REPT
82 Jiaxing, 32 GWh, (+45 GWh)
83 Wenzhou, 26 GWh, (+24 GWh)
84 Foshan, 15 GWh, (+17 GWh)
85 Chongqing, (+30 GWh)
86 Liuzhou, 10 GWh, (+10 GWh)

HITHIUM
87 Chongqing, 28 GWh, (+33 GWh)
88 Xiamen, 45 GWh
89 Heze, (+30 GWh)

AESC
90 Shiyan, 20 GWh, (+20 GWh)
91 Ordos, 10.5 GWh, (+20 GWh)
92 Cangzhou, 10 GWh, (+20 GWh)
93 Wuxi, 20 GWh

CORNEX
94 Xiaogan, 35 GWh, (+115 GWh)
95 Yichang, 65 GWh, (+80 GWh)
96 Xiangyang, (+70 GWh)
97 Wuhan, 10 GWh, (+40 GWh)

GREAT POWER
98 Quzhou, 11 GWh, (+36 GWh)
99 Qingdao, 12 GWh, (+24 GWh)
100 Ulanqab, (+11 GWh)
101 Liuzhou, 10.5 GWh
102 Xuancheng, (+10 GWh)
103 Changzhou, 3 GWh, (+4 GWh)
104 Zhuhai, unknown GWh
105 Zhumadian, unknown GWh

GANFENG
106 Chongqing, 10 GWh, (+34 GWh)
107 Hohhot, (+20 GWh)
108 Xiangyang, (+20 GWh)
109 Xinyu, 13 GWh, (+6 GWh)
110 Dongguan, (+10 GWh)
111 Nanchang, (+10 GWh)

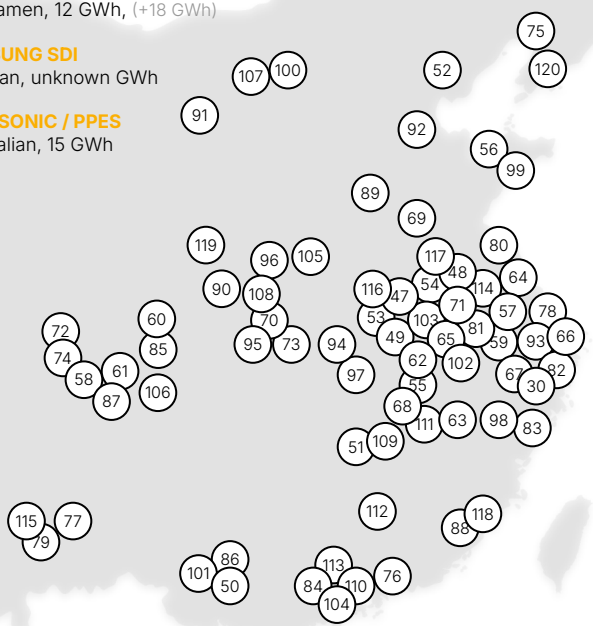
FARASIS
112 Ganzhou, 37 GWh, (+12 GWh)
113 Guangzhou, 15 GWh, (+15 GWh)
114 Zhenjiang, 24 GWh
115 Kunming, (+24 GWh)

PYLON
116 Hefei, 5 GWh, (+5 GWh)
117 Yangzhou, 8 GWh

AMPACE
118 Xiamen, 12 GWh, (+18 GWh)

SAMSUNG SDI
119 Xi'an, unknown GWh

PANASONIC / PPES
120 Dalian, 15 GWh



*total includes future & current capacities; excludes plants with halted construction
**note: sodium-ion excluded

Source: New Energy Terminal

BASIC FORMAT = *Current Capacity* GWh, (+*Additional Future Capacity* GWh)

Chinese Gigafactory - 6,401* GWh of Capacity | Part 3 of 3

DFD
121 Nanning, 20 GWh
122 Jiaozuo, 11.5 GWh

GEELY, JIYAO, YAONING
123 Ganzhou, 12 GWh, (+30 GWh)
124 Quzhou, 24 GWh
125 Tangshan, (+24 GWh)
126 Yingtan, 5 GWh, (+15 GWh)
127 Xuancheng, 15 GWh
128 Yancheng, 6 GWh, (+6 GWh)
129 Yueyang, (+12 GWh)
130 Hangzhou, 12 GWh
131 Chongqing, (+18 GWh)
132 Zhenjiang, 3 GWh, (+6 GWh)
133 Shangrao, 6 GWh

CHERY
134 Wuhu, 6.25 GWh, (+20.75 GWh)
135 Tongling, 5 GWh, (+20 GWh)
136 Suzhou (+20 GWh)

GAC / YINPAI
137 Guangzhou, 12 GWh, (+24 GWh)

CHINA AUTO NEW ENERGY
138 Chuzhou, 22 GWh, (+20 GWh)
139 Tianjin, 4 GWh, (+26 GWh)
140 Wuxi, 8 GWh, (+16 GWh)
141 Qingdao, 4 GWh, (+10 GWh)

LISHEN
142 Suzhou, 11.3 GWh

DESAY
143 Changsha, 6 GWh, (+14 GWh)

TIANNENG
144 Huzhou, 9 GWh, (+17 GWh)
145 Ma'anshan, 3 GWh, (+17 GWh)

SHUANGDENG
146 Xiangyang, 2.8 GWh, (+7.2 GWh)
147 Taizhou, 2 GWh, (+4 GWh)

ETC BATTERY
148 Wuhu, 4 GWh, (+11 GWh)

COSPOWERS
149 Chuzhou, 10 GWh, (+10 GWh)
150 Nantong, (+12 GWh)
151 Changde, 4 GWh, (+4 GWh)
152 Dongying, 2 GWh, (+4 GWh)
153 Taizhou, (+5 GWh)
154 Dali, 3 GWh, (+3 GWh)

HIGHSTAR
155 Changsha, (+30 GWh)**
156 Nantong, 11.7 GWh, (+6 GWh)
157 Zhuhai, 7.5 GWh

GENLEAD
158 Yancheng, 5 GWh, (+10 GWh)

SACRED SUN
159 Taian, 2 GWh, (+2 GWh)

EVPS
160 Chuzhou, 7 GWh, (+3 GWh)

PHYLION
161 Chuzhou, 8 GWh, (+4 GWh)
162 Suzhou, 2.2 GWh

CBAK
163 Nanjing, 2 GWh, (+18 GWh)
164 Dalian, 4 GWh
165 Shangqiu, 0.5 GWh

BAK
166 Zhengzhou, 4.5 GWh, (+30 GWh)
167 Fuzhou, 2 GWh, (+11.5 GWh)
168 Shenzhen, 3.5 GWh

COSMX
169 Deyang, (+25 GWh)
170 Chongqing, (+15 GWh)**
171 Jiaxing, 8.5 GWh, (+4 GWh)

ZENERGY
172 Changshu, 25.5 GWh, (+25 GWh)

EXENCELL
173 Mianyang, 3 GWh, (+15 GWh)
174 Yancheng, (+18 GWh)
175 Zhuhai, (+18 GWh)
176 Dali, (+18 GWh)

RISESUN MGL
177 Nanjing, (+30 GWh)
178 Tianjin, 6.3 GWh, (+9.2 GWh)
179 Beijing, 0.5 GWh

WELION
180 Huzhou, 2 GWh, (+20 GWh)
181 Zibo, 6 GWh, (+14 GWh)
182 Beijing, (+8 GWh)
183 Shenzhen, (+0.6 GWh)
184 Changzhou, 0.2 GWh

QINGTAO
185 Chengdu, (+15 GWh)
186 Suzhou, 4.2 GWh, (+6.5 GWh)
187 Yichun, 1 GWh
188 Taizhou, (+10 GWh)
189 Shanghai, (+0.5 GWh)

TALENT NEW ENERGY
190 Huainan, (+10 GWh)
191 Chongqing, 0.2 GWh, (+2

ENPOWER
192 Chuzhou, (+10 GWh)
193 Beijing, 0.2 GWh, (+2.8 GWh)

Source: New Energy Terminal

*total includes future & current capacities; excludes plants with halted construction
**note: sodium-ion excluded

Manufacturers upgraded battery designs and deepened collaboration with automakers. Meanwhile, some firms rebranded or restructured their battery businesses:

- **Geely** rebranded its battery subdivision as **Jiyao Tongxing**
- **Qingdao Lishen** was acquired by state-owned enterprises and named **China Automotive New Energy**



BASIC FORMAT = *Current Capacity* GWh, (+*Additional Future Capacity* GWh)
CONSTRUCTION HALTED = (+*Additional Future Capacity* GWh)**

List of Private Pilot Lines and R&D Services in US [1 of 2]

	Location / Size	Battery Focus	Fabrication & Build	Testing & Safety	Teardown & Analytics
OBIC	Newberry, IN (HQ) Founded 2013 ~11–50 emp (Non-profit)	Battery testing, evaluation, certification, and pilot-scale cell fabrication support	Electrodes: in-house pilot coating line incl. slurry mixing & coating Cells: pilot-scale cell fabrication workflow incl. calendaring, slitting, assembly Dry room: expanded cell build capacity	Testing: cell → module → large-format battery systems Safety: abuse testing explicitly described (thermal / abusive testing)	Teardown: not advertised as a standard service Analytics: not published as a detailed instrument list; positioned as testing/evaluation/certification
Coulometrics	Chattanooga, TN Founded ~2008 ~50–150 emp (est.)	End-to-end cell development and contract manufacturing services through production scale	Materials: pilot material synthesis, half-cell & full-cell work Electrodes: toll coating on 4 coating lines, slot-die / roll-to-roll Cells: cylindrical (14500, 18650, 21700, 26650) and pouch assembly	Cycling: customer cell validation & performance testing Safety: nail, hot-box, crush reported in partner testing contexts	Teardown: cell characterization & failure analysis implied via materials/cell services Analytics: materials analysis, separator evaluation
NANOTECH	California (multiple) Founded 2015 ~50–150 emp (est.)	Battery materials & product company focused on safer electrolytes and advanced materials	Materials: graphene-based battery materials, conductive inks & pastes Cell Build: internal product development incl. cylindrical formats (e.g., 21700)	Cycling: internal product-level testing implied Safety: safety-focused / non-flammable chemistry development	Teardown: not listed Analytics: internal materials characterization
NOVONIX	Chattanooga, TN (US) + global Founded 2013 200+ emp	Battery test equipment maker with R&D services and materials development	Electrodes/Materials: advanced synthetic graphite & precursor processing; (**pilot line in Canada)	Cycling: extensive automated cell cycling via NOVONIX test systems Safety: supported via test systems & customer programs	Teardown: case-dependent materials diagnostics Analytics: in-house materials tools + UHPC systems

List of Private Pilot Lines and R&D Services in US [2 of 2]

	Location / Size	Battery Focus	Fabrication & Build	Testing & Safety	Teardown & Analytics
Polaris Battery Labs	Beaverton, OR Founded ~2012 ~2–10 emp	R&D-focused cell building, process engineering, and performance testing for materials-to-cell path	Electrodes: R&D mixing/coating incl. moisture-controlled lab coater & double-side pilot coater Cells: coin cells (2032); custom pouch builds	Cycling: cell build + performance testing services Safety: offered via consulting / partner engagements	Teardown: custom cell characterization (implied) Analytics: battery diagnostics + partner lab tools
SpectraPower	Livermore, CA Founded 2002 ~1–10 emp	End-to-end contract R&D: electrode fabrication → cell build → testing → teardown/analytics	Electrodes: lab-scale slurry mixing + roll-to-roll coating up to 200 mm width × 50 m length Cells: coin cells; pouch cells (single & multi-layer)	Cycling: 730+ channels, 10 mAh–1000 Ah, 5 V & up to 1000 A, –40 °C to +170 °C chambers Safety: Yes (environmental / abuse per services page)	Teardown: cell & pack analysis offered Analytics: SEM/EDS, FIB-SEM, ICP-AES, LC/MS, GC/MS, DSC, TGA (*inhouse or with partners)
Wildcat Discovery Technologies	San Diego, CA Founded 2006 ~135+ staff (per press)	Materials discovery + cathode production pathway with integrated cell validation	Electrodes/Materials: high-throughput cathode materials (LFP, LMFP, DRX variants) Cell Building: pouch cell validation up to ~20 Ah	Cycling: extensive materials & pouch-cell performance testing Safety: not explicitly listed	Teardown: not marketed (focus on materials/cell performance) Analytics: high-throughput analytical platforms for material data

List of Open-Access / Quasi-Foundry Pilot Lines in US

Organization	Location / Size	Battery Focus	Fabrication & Build	Testing & Safety	Teardown & Analytics
RIT – Battery Development Center (BDC)	Rochester, NY Established ~2014–2015 ~15–30 staff	Open-access pilot cell manufacturing, testing, and safety validation	Electrodes: slurry mixing + roll-to-roll coating Cells: pouch (34×50 mm → 250×250 mm), cylindrical	Cycling: 650+ channels, 0–1000 V, up to 240 kW Safety: abuse & thermal testing up to ~500 Ah	Teardown: diagnostic analysis via testing center Analytics: partial in-house
University of Michigan – Battery Lab	Ann Arbor, MI Established 2015 ~20–30 staff	Industry-accessible academic pilot line bridging lab → commercial formats	Electrodes: reel-to-reel pilot coating Cells: 18650, 21700, pouch up to 15 Ah	Cycling: 500+ channels, 5 V, 30 µA–50 A Safety: abuse + ARC testing	Teardown: not marketed Analytics: XRD, DSC/TGA-MS, rheology, EIS
Binghamton University – NECCES Dry Room	Binghamton, NY Established ~2015 ~15–30 staff	Open-access academic dry-room cell build & test capability	Electrodes: slurry mixing, coating & calendaring Cells: pouch assembly line	Cycling: 400+ channels Safety: not specified	Teardown: not specified Analytics: campus-shared facilities
BEACONS (UT Dallas)	Richardson / Dallas, TX (UT Dallas) ~15,000 sq ft facility	Rapid prototyping & scale-up for commercialization	Cells: pouch (~80×100 mm, ~10–20 Ah) & 18650 cylindrical Dry rooms: 3,500 sf ≤1% RH + 400 sf ≤0.25% RH (same source)	Cycling: formation & aging available (same source)Safety: abuse testing via partners (same source)	Teardown: not specified Analytics: materials characterization via UT Dallas facilities

List of National Labs with R&D Battery Capabilities in US

Institutions	Location	Battery Focus	Fabrication / Prototype Capability	Testing / Safety Capability	Notes / Facilities / Scope
SLAC National Accelerator Laboratory	Menlo Park, CA	Materials → device translation; advanced characterization	Lab-scale prototype cell fabrication supporting materials and device research; no open foundry or manufacturing pilot line	Extensive cell cycling, informatics-driven testing, environmental testing; abuse testing in research context	Joint SLAC–Stanford Battery Center; unique access to synchrotron and operando techniques tightly coupled to battery research
Lawrence Berkeley National Laboratory (LBNL)	Berkeley, CA	Fundamental materials, interfaces, scale bridging	Cell prototyping to support materials, interfaces, and electrolyte research; not positioned as an open pilot line	Cell testing, diagnostics, degradation analysis, safety research (program-specific)	Strong focus on electrochemistry, interfaces, and advanced diagnostics; closely integrated with UC Berkeley
Lawrence Livermore National Laboratory (LLNL)	Livermore, CA	Battery safety science and diagnostics	Prototype cells and modules built for R&D programs; not a service pilot line	Battery safety, abuse testing, thermal runaway research, failure diagnostics, modeling + experimental validation	Known for multi-physics modeling, thermal/abuse testing, and advanced diagnostics rather than manufacturing scale-up
Idaho National Laboratory (INL)	Idaho Falls, ID	System- and grid-scale validation	Limited cell/module fabrication tied to research programs; not an electrode or cell pilot line	Large-scale battery, module, and system testing; grid integration; safety and validation	Strength is in infrastructure-scale testing, grid integration, and operational validation
Argonne National Laboratory (ANL)	Lemont, IL	Lab-to-pilot battery development	Pilot-scale electrode processing and cell prototyping (coin, pouch, cylindrical) within structured programs	Extensive cell and module testing, abuse/safety testing, modeling	Home of JCESR; most complete end-to-end battery ecosystem among US national labs
Pacific Northwest National Laboratory (PNNL)	Richland, WA	Long-duration storage & system validation	Prototype cell and materials scale-bridging for research; not an open foundry	Cell and system testing, degradation studies, abuse/safety modeling, grid integration	Major contributor to Battery500 and long-duration energy storage programs
Oak Ridge National Laboratory (ORNL)	Oak Ridge, TN	Manufacturing science & scale-up physics	No dedicated battery cell pilot line; strengths are in manufacturing science and materials processing	Materials testing, manufacturing process validation, mechanical/thermal characterization	Battery work centers on manufacturing readiness, materials scale-up, and diagnostics rather than cell builds
National Renewable Energy Laboratory (NREL)	Golden, CO	Independent testing & grid integration	No battery cell pilot manufacturing line; prototype work limited to research support	Extensive battery testing, performance validation, degradation studies, safety research, module/system testing	Frequently used for third-party validation, modeling, and grid-connected storage evaluation

List of Pilot Lines and R&D Services in Europe

Germany

- Chem4Batteries
- RWTH AACHEN UNIVERSITY
- Fraunhofer
- CustomCells
- ZSW
- EAS
- UniverCell

United Kingdom

- WARWICK THE UNIVERSITY OF WARWICK
- danecca
- UK BATTERY INDUSTRIALISATION CENTRE

Sweden

- intertek Total Quality. Assured.
- SEEL Swedish Electric Transport Laboratory
- RI.SE

Belgium

- ABEE AKESTA BATTERY & ENERGY ENGINEERING
- Energy Ville

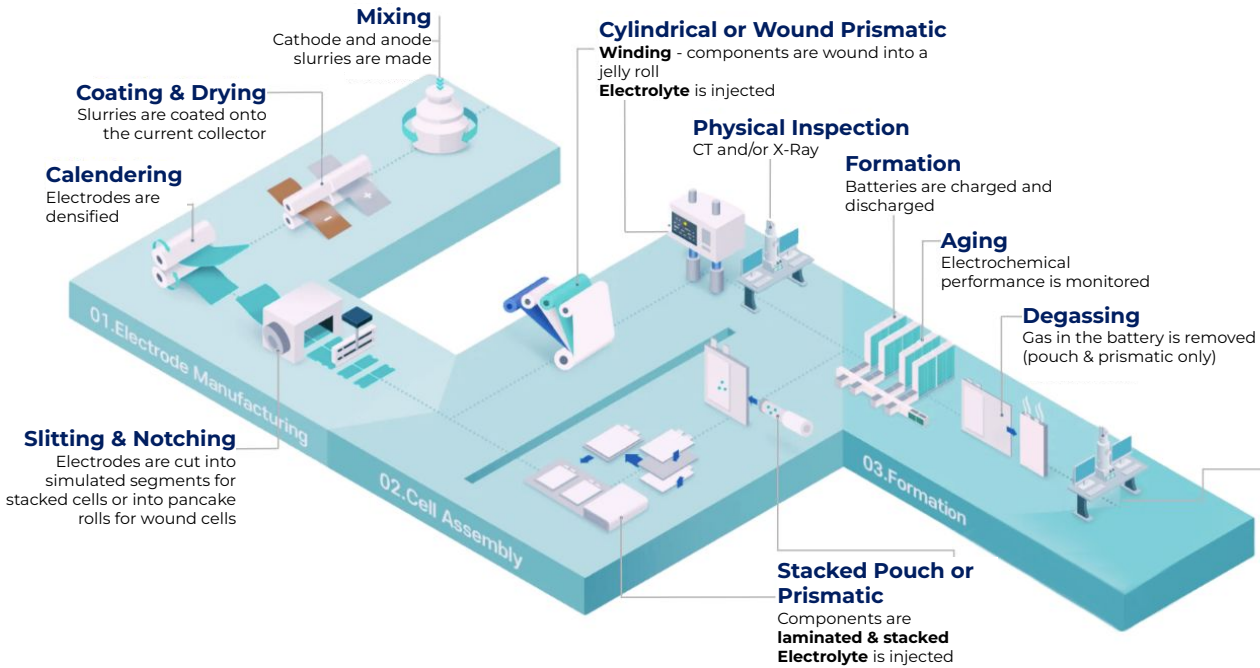
Spain

- cidetec energy storage
- CIC energiGUNE MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

France

- EMITECH
- SERMA GROUP
- cea liten

Manufacturing Process Map - Overview



Cell Capacity
Prismatic: 1-200+ Ah
Pouch: 1-100+ Ah
2170: 3-6 Ah
4680: 15-25 Ah

CAPEX*
$55-150 million/GWh

SCRAP (RAMP UP)

Scrap remains high in ramp-up, mainly due to **electrode quality**.

See **QC**/**analytics** slides for example detection points & solutions.

**CAPEX reflects tooling only. The higher end of the range is driven by the fact that most equipment is sourced from Asia and is subject to significant import tariffs.*

Note: Graphics courtesy of LG Energy Solution. Reproduced with permission.

Manufacturing Process Map - 1. Electrode Production

MIXING

Challenges
dispersion uniformity; viscosity consistency; reaction time of mixing team to batch variation

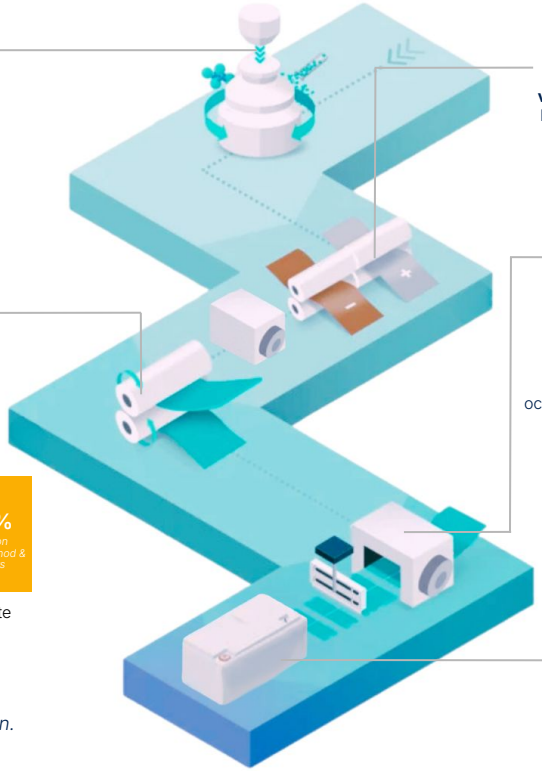
Slurries are formed from active material, binder, solvent, and additives that improve dispersion and viscosity control.
Mixing order, speed, tooling, and material variability all affect the final slurry and may require recipe adjustments to hit viscosity specs.

CALENDARING

Challenges
wrinkling/elongation of substrate & cracks/tears of electrode from thickness variation; managing target density; electrode waste

Electrodes are **densified to a target value**

Thickness is verified here, but primary quality screening occurs during slitting.



COATING & DRYING

Slurry is coated onto the current collector (~54% of electrode cost). Operators must **continuously adjust** pump speed, die gap, and die-lip settings as slurry **viscosity varies** with temperature and batch changes. In-line gauges enable tight control, but **poor reactions** lead to foil breaks and long oven/die-head downtime.

Challenges
electrode uniformity; processing time; utilization loss (lengthy oven cool down & heat up cycles due to broken foil pieces); Finally, **operator training and reaction time t**o all these issues

SLITTING & NOTCHING

Electrodes are cut into singulated segments or pancake rolls.
Uncoated areas are **cut out** leaving the parts where tabs will be grounded.
Detection & marking of electrode defects occurs here. For **contamination**: must contain proper brush clearance & vacuum systems.

Challenges
edge quality due to blade edge wear (burrs are dangerous), difficult to inspect at speed; tool wear; **lowest OEE of any process due to lengthy marking process; contamination**

VACUUM DRYING

Removes **residual water** that would react with electrolyte and cause HF / swelling.
Not needed when electrodes are made in dry rooms.

Challenges
processing time; large footprint; mostly batch;

usually Karl Fischer titration is used for water-content checks

30-50%	60-100 m/min	20-60 m/min *depending on patch design*	2-10% *depending on calculation method & other factors*
of total manufacturing cost	pouch film speed	cylindrical (pattern coating) film speed	scrap rate

**Graphics courtesy of LG Energy Solution. Reproduced with permission.*

Source: LG Energy, BCG, internal expertise

Manufacturing Process Map - 2. Cell Assembly - Pouch

Challenges
electrode alignment; balancing speed and accuracy

LAMINATION & STACKING
Stacking notched anode & cathode sheets with separator between.
(Some lines heat-press layers after stacking.)

Minor Challenges
sealing around tabs; overheating can cause pouch leaks

INSERT STACK INTO POUCH + INITIAL SEALING
Stack is placed inside the formed pouch.
Three edges are heat-sealed, leaving one open for electrolyte injection.

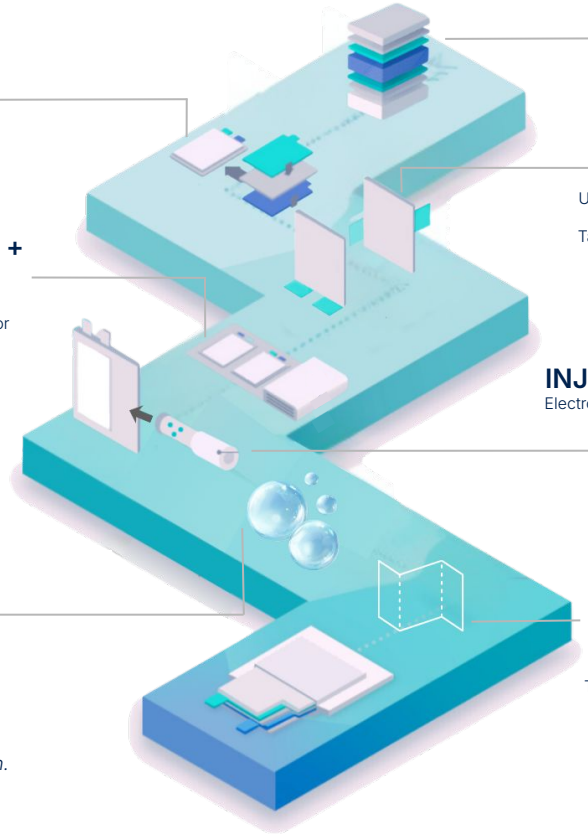
15-35% of total manufacturing cost

2-20 parts/min speed

3-5% scrap rate

Challenges
maintaining a clean edge for sealing cell after degassing

FORMATION → VACUUM DEGASSING → FINAL SEAL
During formation, gas collects in the gas pocket. After formation, the pocket is cut open, the cell is vacuum-degassed, and sealed.



POUCH FORMING
Forming the pouch cavity from laminate using a draw-form press.

Challenges
corner cracking

TAB WELDING
Ultrasonic welding of electrode tabs and attaching tab extensions.
Tabs are wrapped with insulating tape to stay isolated from aluminum pouch.

Challenges
foil damage; coating adhesion/cohesion

ELECTROLYTE INJECTION + TEMP. SEAL
Electrolyte is metered into the pouch through the open edge, then sealed.

Challenges
dosing & distribution accuracy; no electrolyte residue in sealing area; temp. seal integrity

FINAL EDGE FOLDING
Pouch edges are folded to create a compact cell.
These folds help slow moisture ingress.

Challenges
damaging cell corners

**Graphics courtesy of LG Energy Solution. Reproduced with permission.*

Source: LG Energy, BCG, RWTH PEM, internal expertise

Manufacturing Process Map - 2. Cell Assembly - Cylindrical

1. WINDING & TAB WELDING
Winding the cathode, anode, and two separator rolls. Ultrasonic welding the aluminum and copper tabs onto the cathode and anode respectively.
SPEED: 30 parts/min

Challenges
anode, cathode, separator alignment; tabing, taping, cutting accuracy; tab welding quality (can introduce safety issues)

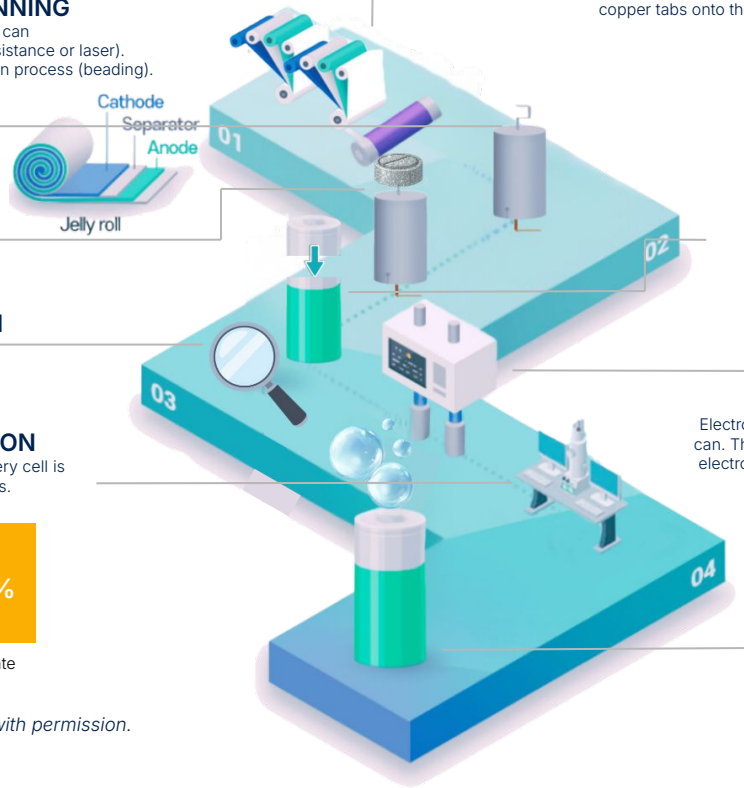
Note on tabless cells
There is no tab welding step. Instead, there are folded (notched) aluminum or copper ends.
SPEED: 30-60 parts/min *(depending on jelly roll size)*

2. TAB SHAPING & CANNING
The jelly roll is put in the cylindrical can and then fixed through welding (resistance or laser). High-speed mechanical deformation process (beading).
SPEED: 300-600 parts/min

Challenges
metal contamination; jelly roll fit

3. INSULATOR PLACEMENT
Insulator is punched and placed onto cell opening.

Minor Challenge
missing or multiple insulators



4. TOP CAP WELDING
Top cap is laser welded onto cathode tab.

Challenges
weld spatter; weld quality

5. HI-POT INSPECTION
Internal short check

Challenge
false positives

6. ELECTROLYTE INJECTION + SEALED
Electrolyte is injected into the vacuumed can. The can is pressurized to accelerate electrolyte absorption and then crimped, final height sizing.

Challenges
electrolyte absorption due to density; pooling of electrolyte; scratching and contamination (during crimping)

7. PHYSICAL INSPECTION
Through CT and/or X-Ray, the battery cell is analyzed to detect potential defects.

Challenge
speed of analysis doesn't allow real-time analysis

8. DEGASSING/ PRE-CHARGE
Optional process to remove gas

Challenges
exhaust gas treatment (for open pre-charge); avoiding residual gas during sealing and folding steps

10-20% of total manufacturing cost

1-5% scrap rate

**Graphics courtesy of LG Energy Solution. Reproduced with permission.*

Source: LG Energy; BCG; RWTH PEM; internal expertise

Manufacturing Process Map - 2. Cell Assembly - Prismatic

Challenges
anode, cathode, separator alignment

Z-STACKING

Stacking the cathode, anode, and two separator rolls. Welding the aluminum and copper tabs onto the cathode and anode respectively.
SPEED: 5-15 parts/min

Challenges
throughput

HOT PRESS

The hot press machine works on the principle of heat and pressure application to achieve a strong and reliable bond between battery components.
SPEED (DWELL TIME): >10 seconds/unit

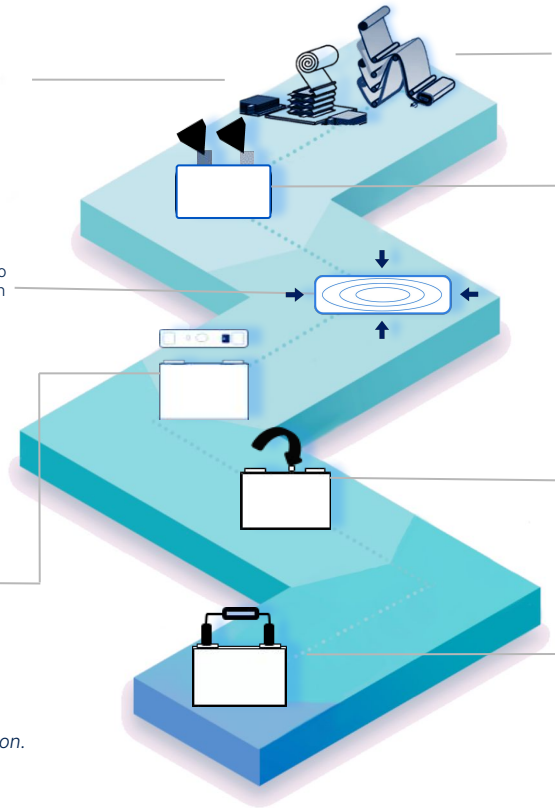
10-20%
of total manufacturing cost

4-6%
scrap rate

Challenges
cap to can alignment, missed laser welding spot; pinholes (leak)

CAP TO CAN WELDING

The can to cap spot welding by laser source and followed by complete laser welding of the cap to can



WOUND PRISMATIC

Wind the slitted cathode, anode, and separator together by controlling speed, tension, etc. to create one or more jelly rolls.
SPEED: (consumer electronics) 30 parts/min; (EV) 10 parts/min

Challenges
uneven stress, burr issues, and powder loss; coating cracking

PRE WELDING & TRIMMING

The cathode and anode tab are aligned and U/S welded
SPEED: 18-20 parts/min

Challenges
anode, and cathode tab alignment

ELECTROLYTE INJECTION

Electrolyte is injected into the vacuumed can. The can is pressurized to accelerate electrolyte absorption and then sealed

Challenges
electrolyte absorption due to density; pooling of electrolyte

PRE CHARGE & FORMATION

After the filling pre charge is performed and cell is kept for RT aging and followed by formation & grading process.
Note Large cells require open formation and second fill step

Challenges
throughput

**Graphics courtesy of LG Energy Solution. Reproduced with permission.*

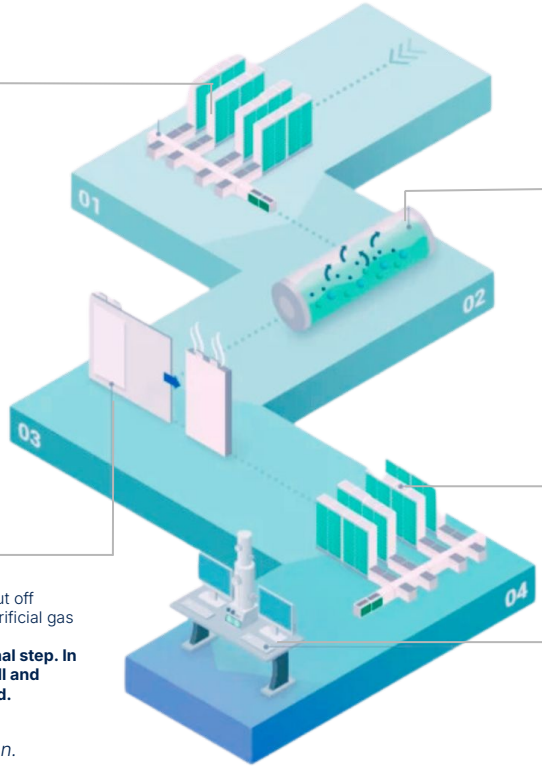
Source: CATL, RWTH PEM, internal expertise

VF | VOLTA FOUNDATION

Manufacturing Process Map - 3. Formation

Challenges
slow throughput due to long time required; fire (most factory fires occur here)

FORMATION
Electrochemical activation.
SEI is formed on the anode



AGING
Battery is stored at a consistent temperature and humidity to allow for corrosion mechanisms from potential contamination

Challenges
process time/throughput; factory footprint; quality escapes

30-50%
of total manufacturing cost

5-25 days
time

2-10%
scrap rate

CHARGING, DISCHARGING/ CAPACITY CHECK

Challenges
throughput; footprint

DEGASSING
Pouch & prismatic only.
Gases formed during aging are cut off inside of a vacuum chamber (sacrificial gas bag).
Typically in pouch, this is the final step. In some large cells, a secondary fill and subsequent charge is performed.

Challenges
residual gas inside the cell; seal quality; throughput (a lot of additional CAPEX due to dry room requirement)

QUALITY CONTROL
End of line check - capacity, resistance, voltage, etc., + cosmetic

Challenges
cosmetic & variation in capacity; yield

∗Graphics courtesy of LG Energy Solution. Reproduced with permission.

Source: LG Energy, BCG, RWTH PEM, internal expertise

Manufacturing Process Map - 4. Pack Assembly

Challenges
surface cleaning; cell-to-current collector bond quality; cell matching

CONNECTING BATTERY CELLS

Battery cells are placed into the module arrangement and connected to current collectors after surface cleaning

Challenges
damage due to placement (primarily pouch); large machinery required due to module mass & dimensions; avoiding cell damage during assembly; safety at high voltages

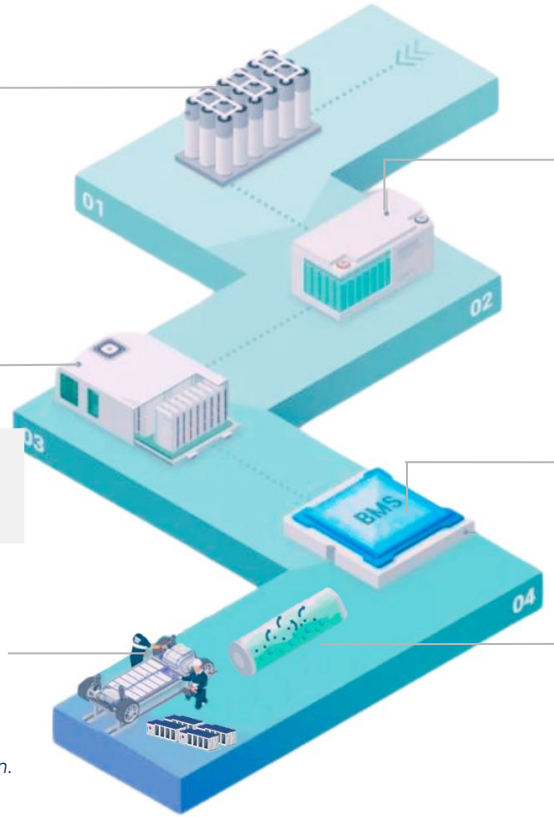
PACK ASSEMBLY

The modules are put in the battery pack and connected, including voltage sense and thermal connections

Design Challenges
i. Ensuring low resistance connections between modules and other connections to prevent fire
ii. Maintaining creepage and clearance distances for high voltage elements
iii. Preventing arcing due to contact with metallic objects during assembly

FINAL INTEGRATION

The battery packs are then used in Electrical Vehicle (EV) and Battery Energy Storage System (BESS)



MODULARIZATION

The cells are attached to the module case, before or after connection to current collectors

Challenges
ensuring cable flexibility; avoiding cell damage during handling

APPLYING BMS

A Battery Management System is applied to battery pack; modules typically interface with the pack BMS

CHALLENGES
difficult & time consuming to test in a high-throughput environment

FINAL TEST

A series of electrical tests are performed to ensure the highest quality, including verification of cell connections, isolation, and BMS function

∗Graphics courtesy of LG Energy Solution. Reproduced with permission.

Source: LG Energy, RWTH PEM, Mondragon, internal expertise

AI/ML Enhanced Production & Quality Control

AI and machine learning are becoming central to battery manufacturing quality control. Global leaders like LG, SK On, Samsung SDI, and Panasonic Energy are developing in-house models to manage production variability, improve yield, and reduce costs, with similar initiatives growing across Europe and North America. Established quality control providers are adding AI capabilities, while AI-native companies are emerging to harnessing factory data to turn it into actionable insights.

Incoming quality control and in-line characterization with chemical analysis tools, microscopes, imaging tools, etc.

ThermoFisher SCIENTIFIC, PerkinElmer, PDF/SOLUTIONS, TESCAN, KEYENCE, TA Instruments, ZEISS, SirenOpt, METTLER TOLEDO, Hitachi High-Tech, SCANTECH®, in-core systèmes

AI-native analytics that bridge data silos across the factory to drive consistency and advanced QC

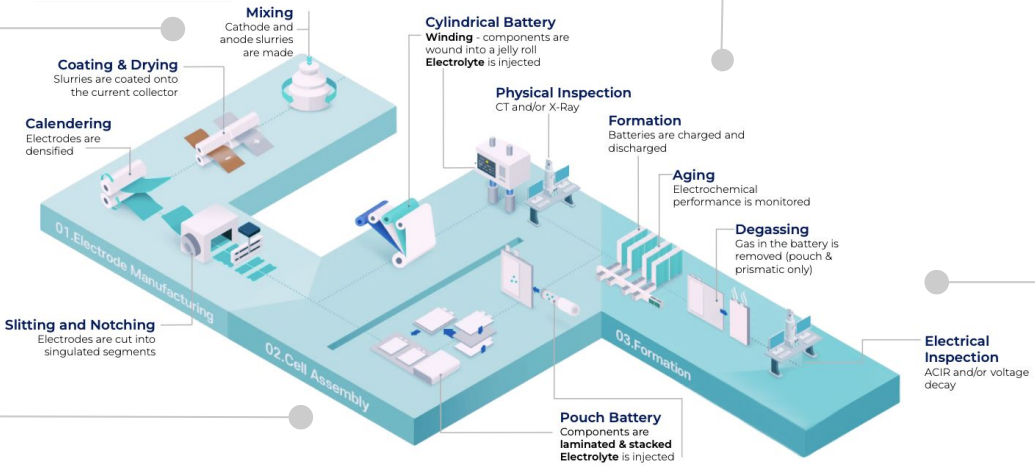
Aris Machina, PDF/SOLUTIONS, SMART BATTERY ANALYTICS, AccelionTech

Data driven quality control from formation data to analyse defects from charge and discharge signals

VOLTAIQ, ACCURE, Capgemini, MICANTIS

End-of-line testing and grading equipment to analyze performance and quality based on test data.

KEYSIGHT TECHNOLOGIES, NEWARE, NOVONIX, HIOKI, Arbin INSTRUMENTS, SAFION



In-line manufacturing quality control tools that monitor and regulate equipment while tracking machine parameters to ensure consistent production standards.

SIEMENS, Honeywell, Rockwell Automation, Schneider Electric, PDF/SOLUTIONS, Ignition, SICK Sensor Intelligence., Palantir

End-of-line cell build inspection using techniques such as CT scanning, ultrasound, X-ray, and optical scanning to ensure structural integrity and quality compliance.

GLIMPSE, excillum, EXACOM, Nikon, Waygate Technologies, ISRA VISION, liminal, evbattery, lumafield, TITAN, VOLUME GRAPHICS, UNITX, SENTION

Source: Panasonic Energy, Samsung SDI [1] [2], SK On, LG ES [1] [2], and providers listed above

CT Scanning - From R&D Tool to Production Quality Control

Scope: Industry-wide view of industrial X-ray CT for battery inspection. Capabilities vary by cell format and system design.

What CT does
Computed tomography (CT) uses **X-rays and reconstruction to create a 3D volume of a battery cell's internal structure**. Practical performance depends on the full imaging chain (X-ray source, detector, geometry, and reconstruction).

Strengths (typical)

- Internal 3D visibility (geometry, alignment, placement)
- Can detect hidden internal issues not visible from the outside
- Enables quantitative 3D measurement and localization
- Beyond pass/fail process feedback (geometry trends, defect KPIs and CpK into change control)
- Useful for failure analysis and targeted production sampling, especially during ramps and change control

Constraints (in production)

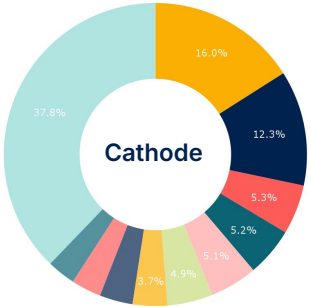
- Typically higher cost and shielding footprint than 2D methods
- Integration complexity (handling, safety, uptime in production)
- Throughput and achievable resolution vary widely and depend on system design and X-ray output
- Not always the best fit for very large assemblies where other methods suffice



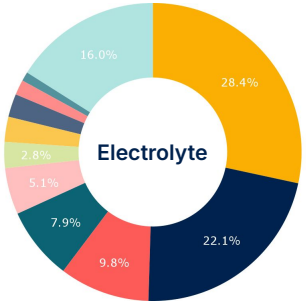
From R&D to production
CT is increasingly evaluated for use beyond R&D, including production sampling and selected inline quality control applications.

- **Recent advances:** Higher-throughput industrial CT systems for battery cells combine faster full-cell scans, automated handling, and automated accept/reject (or severity scoring), making CT more practical for sampling plans and selected high-risk steps in production.
- **Evidence from larger datasets** Published studies and teardowns with larger sample sizes report internal defect modes and build variations that may not be detectable with external-only inspection, supporting CT as a complement in targeted quality control.

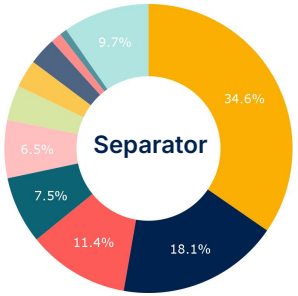
Material Suppliers - Market Share Breakdown - 2025 Data



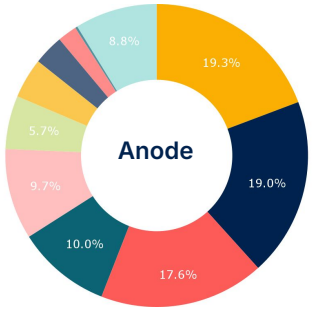
- Hunan Yuneng (LFP)
- Dynanonic (NCM)
- LOPAL
- Hubei Wanrun
- BYD
- Ronbay
- ECOPRO
- Xiamen Tungsten
- Pulead Tech
- Anda
- Other



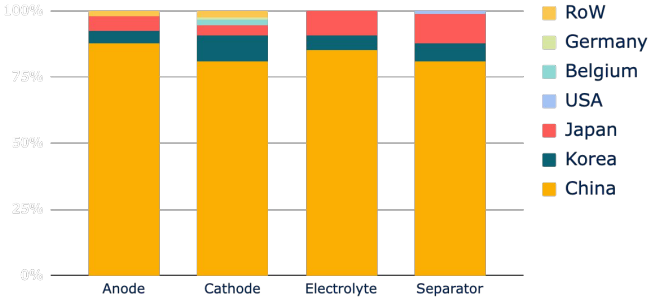
- Tinci
- Shenzhen Capchem
- Guotai-Huarong
- BYD Cell
- MU Ionic Solutions
- Enchem
- Central Glass
- Dongguan Shanshan
- Soulbrain
- Dongwha Etec
- Other



- SEMCorp/JGP
- Shenzhen Senior
- Chinaly New Material
- Mingzhu
- SKIET
- Asahi
- W-Scope
- Toray
- Celgard
- Ube Maxell
- Other



- Zichen
- BTR New Energy
- Kaijin
- XFH
- Shinzoom
- Shanshan Group
- Posco
- Resonac
- Mitsubishi Chemical
- Nippon Carbon
- Other



ACTIVE MATERIALS MARKET SHARE

China continues to dominate in the active materials market. The cathode industry is **more populated** than others, with many small players.

LFP CAM production skews even **higher than 65%** cell market share due to loading considerations.

Source: Tim Wicke, Fraunhofer ISI

List of Equipment Manufacturers - USA

**US Subsidiary - Manufacturing Within USA*

Process Area	Nol-Tec	Ross	CPEG	Delta ModTech	DURR	BW	Wirtz	Koops	GROB	Convergix	Mühlbauer	Coesia	Comau	Digatron	PEC
Mixing	✔	✔	✔				✔								
Coating				✔	✔	✔	✔								
Calendaring				✔	✔	✔	✔								
Slitting				✔	✔	✔	✔								
Stack				✔		✔	✔		✔	✔	✔	✔	✔	✔	
Wind						✔			✔			✔		✔	
Packaging				✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	
Filling					✔	✔	✔			✔	✔	✔		✔	✔
Formation												✔	✔	✔	✔
Degassing													✔	✔	✔
Aging												✔	✔	✔	✔
Test / Grade									✔	✔			✔	✔	✔

Source: Nol-Tec Systems, Ross, CPEG, Delta ModTech, DURR, barryWehmiller, Wirtz Manufacturing, Koops, GROB, Convergix, Coesia, Comau, Digatron Systems, PEC Corp - Non exhaustive list

List of Equipment Manufacturers - Europe

Process Area	Eirich	NETZSCH	Mathews Intl.	Jagenberg	Dürr	Körber	IMA	GROB	Mpac	Mühlbauer	Coesia	Comau	Andritz Group	Digatron
Mixing	✔	✔												
Coating			✔	✔	✔									
Calendaring			✔	✔	✔									
Slitting			✔	✔	✔									
Stack						✔	✔	✔	✔	✔	✔	✔	✔	✔
Wind								✔	✔		✔		✔	✔
Packaging					✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
Filling					✔				✔	✔	✔		✔	✔
Formation											✔	✔	✔	✔
Degassing												✔	✔	✔
Aging											✔	✔	✔	✔
Test / Grade												✔	✔	✔

Source: Eirich, NETZSCH, Mathews International, Jagenberg, Dürr, Körber, Körber, IMA, GROB, Mpac, Mühlbauer, Coesia, Comau, Andritz Group, Digatron - Non exhaustive list

List of Equipment Manufacturers - China

Process Area	AutoRich	ONGOAL	MESNAC	GMK	Shangshui	Yinghe	NAKNOR	Lyric	LEAD	KATOP	Hymson	Bozhon	Hangke	HYNN
Mixing	✔	✔	✔	✔	✔	✔		✔	✔					
Coating			✔	✔	✔	✔		✔	✔	✔	✔			
Calendaring			✔	✔	✔	✔	✔	✔	✔	✔	✔			
Slitting			✔	✔	✔	✔	✔	✔	✔	✔	✔			
Stack						✔		✔	✔	✔		✔		
Wind						✔		✔	✔	✔	✔			
Packaging						✔		✔	✔	✔	✔	✔		
Filling						✔		✔	✔	✔	✔	✔		
Formation								✔	✔	✔			✔	✔
Degassing								✔	✔				✔	✔
Aging								✔	✔				✔	✔
Test / Grade								✔	✔	✔			✔	✔

Source: AutoRich, Ongoal Technology, Mesnac, GMK, Shangshui, Yinghe Technology, Lyric, LEAD, KATOP, Hymson, Bozhon, Hangke Tech, HYNN - Non exhaustive list

List of Equipment Manufacturers - South Korea

Process Area	TSI	CIS	KGA	PNT	mPlus	ETS	KOEM	Hanwha	Hana	Wonik	DA Tech	MOT	SNF
Mixing	✔					✔							
Coating		✔	✔	✔	✔	✔		✔					
Calendaring		✔	✔	✔	✔	✔		✔					
Slitting		✔	✔	✔	✔	✔		✔					
Stack					✔	✔		✔	✔	✔	✔	✔	✔
Wind				✔	✔	✔	✔	✔	✔	✔	✔	✔	
Packaging					✔	✔		✔	✔	✔	✔	✔	✔
Filling					✔	✔		✔	✔	✔	✔	✔	✔
Formation								✔	✔	✔	✔		
Degassing					✔	✔		✔	✔	✔	✔	✔	
Aging								✔	✔	✔			
Test / Grade								✔	✔	✔	✔		

Source: TSI, CIS, KGA, PNT, mPlus, ETS, KOEM, Hanwha Momentum, Hana Technology, WonikPNE, DA Technology, MOT, SNF - Non exhaustive list

List of Equipment Manufacturers - Japan

Process Area	Toray	Hohsen*	Hitachi	Nagano	Primix	Kurimoto	Toyo Hitec	Hirano	Techno Smart	Hakusan	Nishimura	Hi-Mecha	Kaido	SECI	Factem	Kyoto
Mixing		✔			✔	✔	✔									
Coating	✔	✔						✔	✔							
Calendaring		✔	✔													
Slitting	✔	✔								✔	✔					
Stack		✔	✔	✔								✔				✔
Wind													✔			
Packaging		✔	✔	✔								✔				✔
Filling		✔	✔	✔												
Formation														✔	✔	
Degassing			✔													
Aging														✔	✔	
Test / Grade																

*Lab scale only

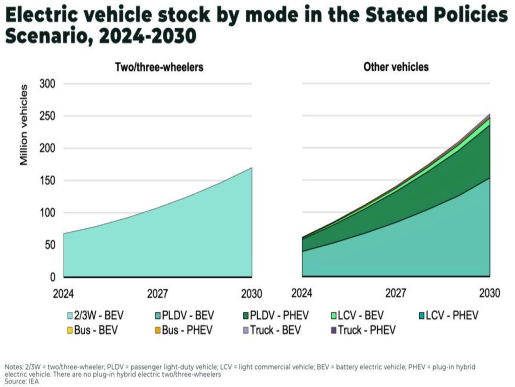
Source: Logos linked - Non exhaustive list

Rising EV Adoption Makes Battery Manufacturing Emissions a Critical Challenge

As battery production scales alongside EV adoption, emissions from cell manufacturing are an increasingly important consideration. Transport accounts for **~28% of global GHG emissions,** driving rapid electrification of vehicles

1

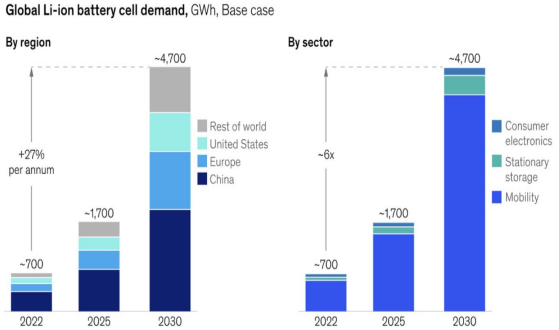
Global EV stock is projected to reach **145–230 million vehicles by 2030,** increasing demand for battery cells.



Notes: 2/3W = two/three-wheeler; PLDV = passenger light-duty vehicle; LCV = light commercial vehicle; BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle. There are no plug-in hybrid electric two/three-wheelers
Source: IEA

2

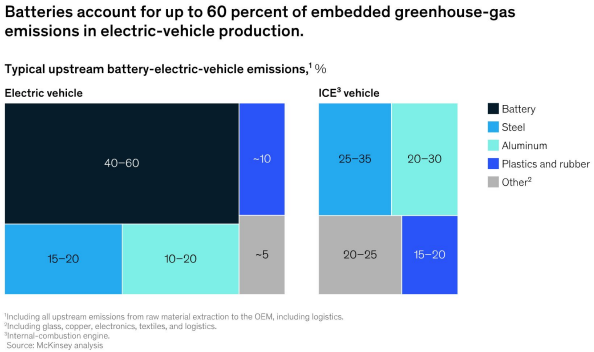
Battery demand for EVs alone is estimated at **~4300 GWh/year by 2030.**



[1]Including passenger cars, commercial vehicles, two-to-three wheelers, off-highway vehicles, and aviation.
Source: McKinsey Battery Insights Demand Model

3

Batteries account for up to **60% of GHG emissions in EV production**



[1]Including all upstream emissions from raw material extraction to the OEM, including logistics.
[2]Including glass, copper, electronics, textiles, and logistics.
[3]Internal-combustion engine.
Source: McKinsey analysis

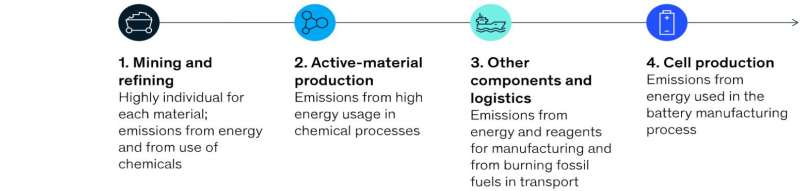
Source: Oregan Group, UNDP, McKinsey 1, McKinsey 2, MDPI

Key Drivers of Battery Manufacturing Emissions

Battery production emissions arise from multiple stages of the value chain, with contributions varying significantly by materials, processes, energy sources, and geography.

Value-Chain Driver	What Contributes to Emissions
Raw-Material Extraction and Refining	Mining and refining of lithium, nickel, cobalt, manganese, and graphite are energy-intensive and generate significant GHG emissions. Emissions vary widely by ore type, location, and processing technology.
Energy-Intensive Material Manufacturing	Cathode and anode active-material production involves prolonged high-temperature processing, making these steps among the most energy-intensive in the battery value chain.
Cell Manufacturing Processes	Cell manufacturing adds emissions through thermal and drying processes, particularly electrode drying and other heat-based operations.
Carbon Intensity of Electricity	The emissions footprint depends strongly on whether production is powered by renewable electricity or fossil-fuel-based grids. Electricity source is a primary driver of variability in emissions per kWh.
Geography and Value-Chain Configuration	Battery production is concentrated in regions with differing grid carbon intensities, leading to large regional differences. Battery chemistry, supplier choices, and transportation routes further influence embedded emissions.

Emissions in the battery value chain are primarily driven by production location and sources of raw materials and energy.



[1]Bottom-up modeling of cell-level emission intensities in individual "gigafactories." Emission intensities were estimated based on existing supply agreements with providers of raw materials, active materials, and energy. Market average has been taken where no information on the source of raw materials or energy was available.
[2]Based on a nickel-free battery; all other examples are based on nickel-rich batteries.
Source: Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET); MineSpans by McKinsey; McKinsey Battery Insights

McKinsey & Company

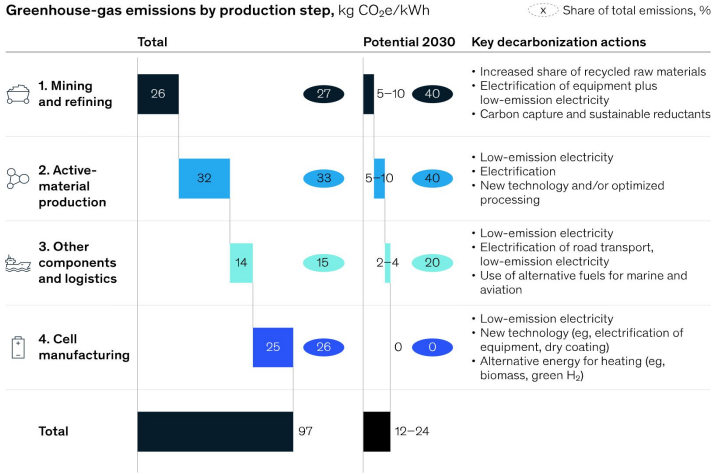
Source: McKinsey 1

Decarbonization Levers in Battery Manufacturing

Significant emissions reductions are achievable by 2030 through a combination of clean electricity, low-carbon materials, and manufacturing process improvements.

Value-Chain Stage	Primary Emissions Source	Key Decarbonization Levers
Electricity Supply (Cross-Cutting)	High electricity demand across mining, materials processing, and manufacturing, often supplied by fossil-fuel-based grids	Switch to renewable electricity; deploy high-quality, 24/7 matched green power purchase agreements (PPAs) across the value chain
Raw-Material Extraction & Refining	Energy-intensive mining and refining of lithium, nickel, cobalt, and other materials; emissions vary widely by location and processing technology	Source materials from producers using electrified mining equipment, renewable electricity, and lower-emission refining technologies
Active-Material Manufacturing (Cathode & Anode)	Prolonged high-temperature processing during precipitation, drying, and thermal treatment; heavy reliance on electricity and boilers	Power production with low-carbon electricity; ensure stable, continuous clean power supply to support energy-intensive thermal processes
Cell Manufacturing	Medium-temperature electrode drying (≈50–160 °C), typically using natural gas; additional thermal steps	Adopt dry-coating processes; replace PVDF binders with water-based alternatives (***both are tough to implement as not scaled in industry***). Electrify electrode drying; supply fully electrified lines with continuous low-carbon electricity
Policy & Market Frameworks	Cost and competitiveness barriers to low-carbon production	Regulatory mechanisms and incentives (e.g., EU CBAM, EU Battery Regulation, U.S. IRA) that encourage low-carbon production, local supply chains, and recycling

Today, battery makers' focus should be on reducing emissions in four key areas.



Note: Figures may not sum to 100%, because of rounding.
Source: Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET); MineSpans by McKinsey; McKinsey Battery Insights

Source: McKinsey 1

Cell Manufacturing LCA - Pathway to Lowering the Impact

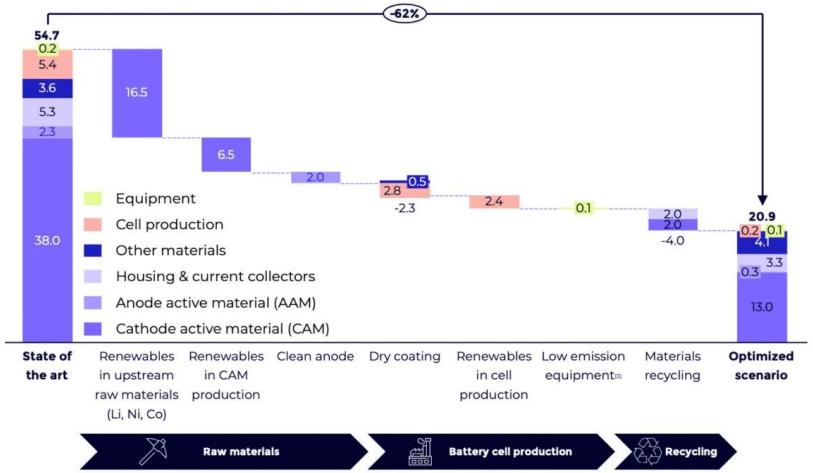


Figure 1: Emission reduction potentials along the battery value chain from raw materials to cell production and materials recycling.

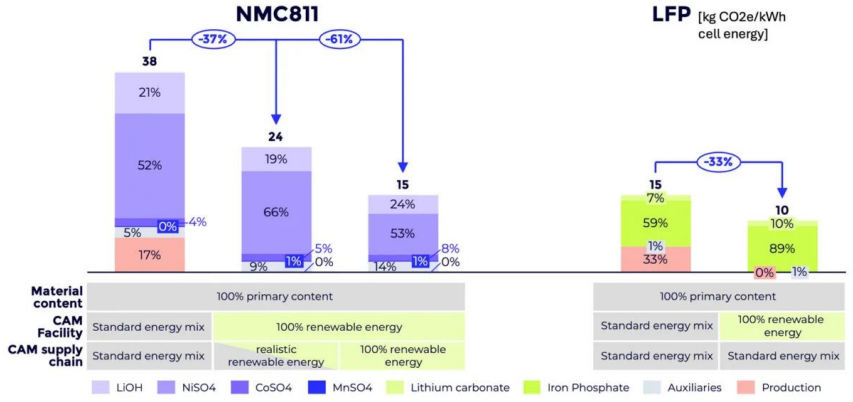


Figure 6: Product carbon footprint of NMC811 and LFP in kgCO2e/kWh cell energy

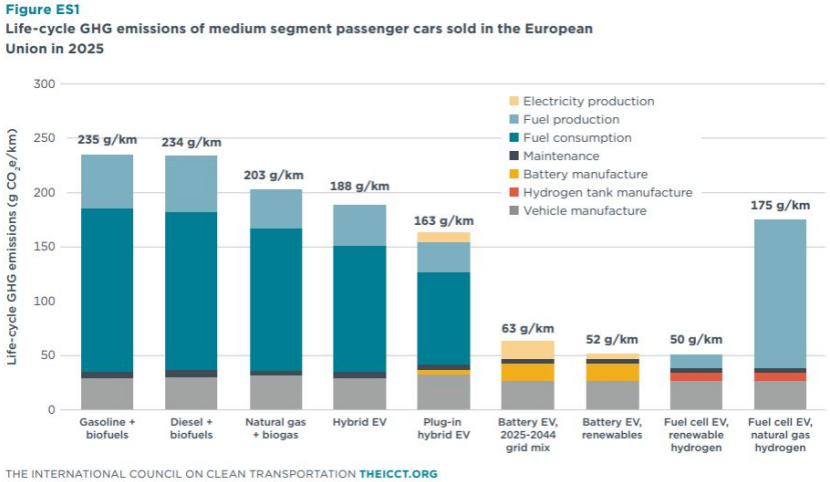
The study from P3[1] shows that a state of the art battery manufacturing emits approximately **54.7 kgCO2e/kWh** in regards of product **carbon footprint** (PCF). P3[1] shows that this PCF can be lowered massively to 20.9 kgCO2e/kWh or -62% by using **renewable energy** in the upstream of raw material, CAM production as well as in cell manufacturing. Second driver is dry coating technology and material recycling.

In regards of the used CAM chemistry there is a **huge benefit for LFP** with 15 kgCO2e/kWh versus NCM811 with 38 kgCO2e/kWh (+2,5x). But there are possible savings in PCF by using **renewables in CAM supply and manufacturing** which lower the impact for NCM811.

Source: [1] P3 consulting

Lifecycle GHG Emission Studies of Different Propulsion Systems

ICCT



P3 Group

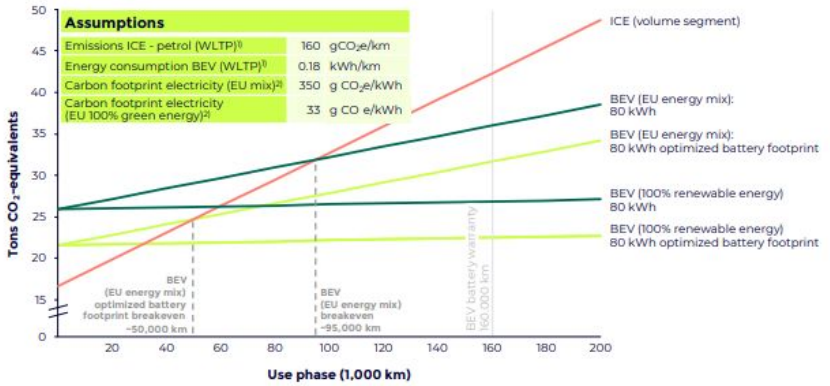


Figure 2: Total cumulated amount of greenhouse gas (GHG) emissions, depending on total kilometers driven, for ICE and BEV incl. materials production and refining, Li-ion battery pack, manufacturing. End-of-life included in in initial emissions.[1]

ICCT[1] compares the Lifecycle Emissions of several propulsion types while P3[2] shows how CO2 emissions increase over the vehicle use phase.
Electric cars have a bit more "CO_2 debt" when they leave the factory, due to the battery. In Europe they repay this debt very quickly - P3[2] claims within the first 30,000 - 50,000 km regarding the used energy mix. After that, every additional km is much kinder to the climate than with a gasoline, diesel, or even hybrid car. All serious recent studies agree:

For the **European market** in 2025+, **battery electric cars are by far the best choice** when it comes to lifetime greenhouse gas emissions and the advantage keeps growing as electricity gets cleaner. **Hybrids and plug-in hybrids are only a small improvement** over conventional cars, not a real solution for deep CO_2 reductions.

Source: [1] ICCT, [2] P3 Group

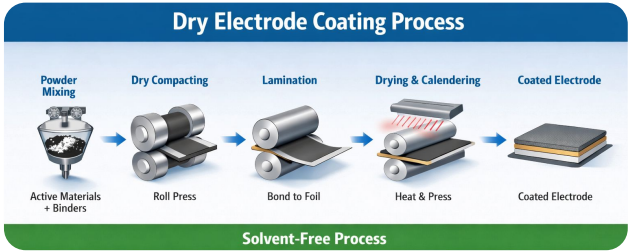
Dry Electrode Technology - Advancing, Yet Not Production-Ready at Scale

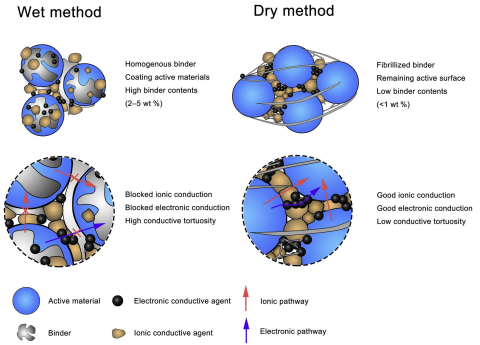
Dry-electrode technology forms battery electrodes by coating and calendering a powder–binder mixture-typically PTFE-based-directly onto the current collector without the use of solvents, eliminating the need for energy-intensive oven-drying steps. The primary advantages are the potential for **lower manufacturing costs and energy consumption, a smaller factory footprint**, and **higher throughput** by avoiding solvent handling, recovery, and drying processes.

Historically, the approach proved significantly more **challenging to scale** than conventional wet-coating methods. Achieving consistent powder dispersion, uniform film thickness, strong adhesion and cohesion, and effective defect control required new equipment architectures and process controls that did not yet exist at industrial scale. Early development programs - including Tesla's initial 4680 battery ramp with dry coated anodes- encountered substantial manufacturing challenges, with Elon Musk noting that dry-electrode processing (particularly for cathodes) was "way harder" than anticipated. However, the industry has since made meaningful progress. By the 2024, improvements in mixing, powder handling, calendering, and inline quality control began enabling more stable, high-throughput manufacturing. Dry coated cathodes have yet to be produced at high volume.

Dry Electrode Technology Advantages:

- Eliminates **NMP**, solvent recovery systems, and long drying ovens → reduces CapEx & OpEx.
- Reduced **factory footprint** due to shorter process flow.
- Enables **thicker electrodes** (higher areal loading) with maintained mechanical integrity.





Dry Electrode Technology Challenges:

- Achieving **consistent binder fibrillation** across different materials.
- Controlling **porosity, adhesion, and compression** without slurry-based homogenization.
- Equipment availability: limited commercial-scale dry-coating lines proven at >GWh scale.
- Sensitivity to **powder morphology, particle size distribution**, and **surface chemistry**.
- Electrochemical performance variability vs. optimized wet-process electrodes.

Binder fibrillation is the key enabler of dry electrode processing, forming a nanofiber network that mechanically binds particles without solvent and enables strong, flexible, high-loading electrodes.

Source: Dry Electrode Technology 1 Dry Electrode Technology 2 Tesla Nov 2025 Annual Shareholder Meeting

Key Events: Dry Electrode Technology

Q1

Tesla recently marked a major 4680 milestone "100-millionth cell" and noted it is continuing to advance dry-cathode manufacturing lines.

Durr Systems AG and **LiCAP Technologies** announced plans for an innovative pilot line for dry coating electrode foils at Cellforce in Germany.

Sakuu has announced that its platform supports dry-processed electrodes for both LFP and NMC, enabling solvent-free printing/coating of cathodes

Q2

Dragonfly Energy was named "Battery Technology Company of the Year" by the CleanTech Breakthrough Awards

LiCAP Technologies announced a Letter of Intent with SK On to explore collaboration on advancing dry-electrode manufacturing.

AM Batteries revealed DBE-2.0 process enables roll to roll dry electrode processing

Addionics Ltd is combining their 3D current collectors with dry coating.

Q3

International Battery Company partners with Sakuu to deploy Kavian, Sakuu's next-generation dry-process battery manufacturing technology.

LiCAP Technologies producing its first roll of free-standing cathode film (>500 m) using its ADE process.

LEAD (LEAD Intelligent) launched/announced an industrial "dry mixing + dry coating" system (solvent-free, no drying ovens), positioning it for mass production.

Matthews Engineering (parent co. of Saueressig) signed an agreement with Heynck to secure sole access to critical tech for the Company's dry battery electrode, multi-roll calendering equipment.

Q4

Anaphite raised a total of £1.4m in combined equity & grant funding to develop LFP and graphite dry coating technology.

AM Batteries showcased their DBE-2.0 process proprietary dry electrode manufacturing process at a "Demo Day"

OLA Electric has begun mass production of NMC-based 4680 lithium-ion cells manufactured using dry cathode and dry anode electrode processes in their gigafactory, followed by successful integration into electric scooters and their commercial sale.

Durr Systems AG and GROB Werkzeugbau GmbH revealed a "concept factory" for battery cell production.

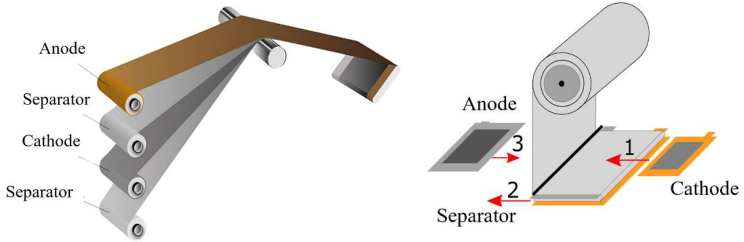
Despite meaningful progress, cathode dry coating has yet to be commercialized at meaningful volumes. Significant challenges in scalability, consistency, and equipment readiness mean it is not 'solved' or production-ready at GWh levels.

Source: Company announcements

Architecture, Process, & Performance. A Comparative Framework - Prismatic Wound, Z-Stacked [1 OF 2]

Wound cells are constructed by feeding a continuous web of anode, cathode & 2 separator layers into a rotating mandrel under tension and singulated at the end of each cell jelly roll production. Winding is typically a cheaper manufacturing approach with faster equipment, fewer operators, less cutting tool maintenance, etc.

Stacked cells are assembled using singulated anode and cathode sheets woven into a Z shaped oscillating separator web, followed by a heat pressing operation to maintain the layer alignment.



Applications like **Consumer Electronics & Premium EVs** with high power & high energy requirements would benefit from Stacking architectures and are typically paired with high Ni / Co chemistries. Applications like **Stationary storage & low cost EVs** with would benefit from the cost and scalability advantages of winding, especially with large ESS's multiple paddle-wound jelly rolls connected in parallel. This can allow winding to maintain market share even as stacking catches up.

CELL DESIGN ARCHITECTURE	
Sizing & Aspect Ratio	Stacked cells offer high flexibility in X-Y dimensions compared to Wound, but are limited in Z thickness (/JR) due to alignment risks as layer count increases
Component Selection	Electrode Foil Thickness: Since wound cells are assembled under web tension to maintain AC overhang, foils need to be thicker compared to stacked cells to prevent web breaking. Separator: Stacked cells require laminatable separators to maintain electrode alignment during assembly and early cell life. Laminated separator increases complexity in electrolyte migration within the cell.
Performance	Wound cells do not completely fill the available volume in prismatic cells and result in lower energy density. Wound cells have a lower tabs to layers ratio due to tab alignment challenges in winding resulting in higher impedance and increased DCFC time.
Safety & Durability	Wound structure of the electrode causes compressive and tensile loading on the electrode during cycling expansion. This can result in accelerated aging of the cell from wrinkle formation and make these cells prone to core collapse during impact loading around the corners if they lack adequate design considerations. Anode silicon content can affect the swelling rate and stresses.

Source: sciencedirect, medium, xiaoweitop, tobmachine

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Architecture, Process, and Performance. A Comparative Framework - Prismatic Wound, Z-Stacked Cont. [2 OF 2]

CELL PROCESS & COMMERCIAL IMPLICATIONS

CapEx	Winding process is twice as fast as stacking. This decreases both the equipment purchase cost and the factory floor space & conveyance. This combined with the complexity & size of the stacking equipment, net CapEx could be 3-4x more for stacking compared to winding.
Component Cost	Lamination separators have a PVDF coating to help with layer adhesion and increases the cost of the separator by 2x. This is often overlooked when cell architecture decisions.
Op Ex	Complexity of the stacking process increases failure modes and results in lower yields, higher downtime. Increased equipment count also results in need for higher number of skilled operators. This can be challenging in countries with limited talent pool.
Future Proofing	Solid state cells with oxide/ceramic based brittle electrolytes can be incompatible with winding. Investing in stacking technology would future proof companies as they transition to solid state architectures.

INDUSTRY

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing

Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

VF | VOLTA FOUNDATION

Applications Overview

Electric Vehicles

Electric mobility remains the largest global battery market, with EV sales growing despite economic, trade, and policy headwinds.

Cathode chemistry and cell form factor vary by region, driven more by differences in policy incentives, supply-chain localization, and manufacturing scale rather than technology limitations.

Public charging networks expanded globally in 2025, led by China and Europe, while North America grew more slowly and unevenly.

BESS

Battery energy storage system (BESS) deployments continue to soar with over 100 GW added in 2025, led by China with over 50% of this capacity, driven by falling costs (31% YoY decline), new markets and storage-friendly policy.

BESS products have improved on energy density, cycle life, and efficiency, backed by 25-year warranties. LFP continues to dominate the market, but many new contenders are vying to take its place as the leading chemistry.

New stationary storage applications include virtual power plants, data centers, and long-duration energy storage (LDES).

Aviation

Electric aircraft and drones are now driving significant demand for high specific energy cells and systems. Cells >450 Wh/kg of specific energy see adoption in early drone platforms.

Several major test flights of EVTOL and other forms of electric aviation recorded in 2025 by Joby, Beta, Electra, Vertical, and other OEMs signalling technical feasibility of the platforms.

The United States sees major first-of-a-kind Presidential directives and executive department initiatives (U.S. DoT) towards 'Advanced Air Mobility' and 'Drone Dominance'.

Other Emerging Markets

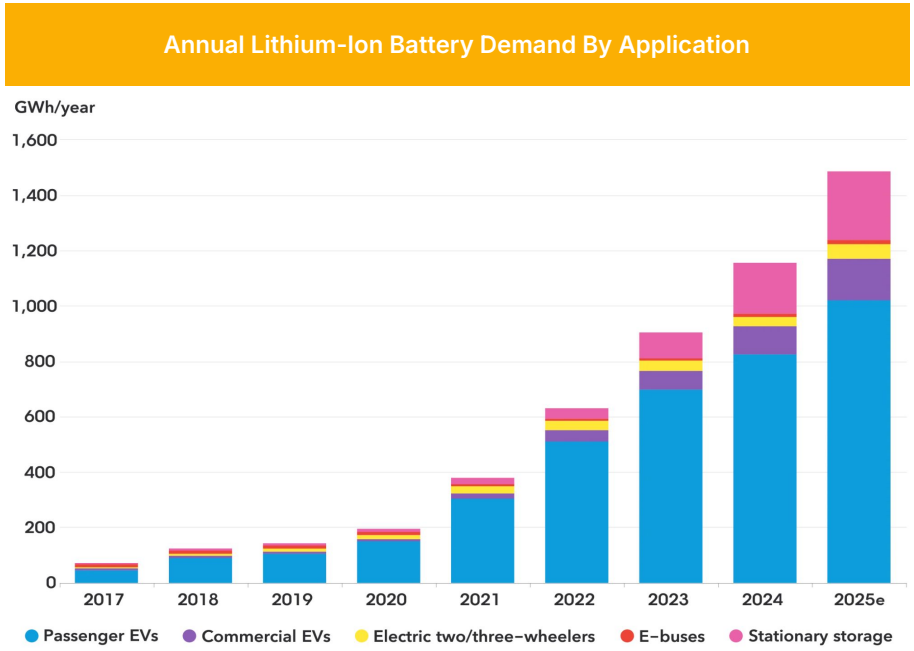
Heavy duty trucking companies face challenges due to technology limitations, regulatory hurdles, and high costs.

High growth markets including robotics (bipedal humanoids) present opportunity for high performance and higher margin battery manufacturers.

LFP dominates the E-bike market and technology trends include increased capacity, standardization and integration.

Battery Deployment Overview

Mobility remains the largest deployment of energy storage in 2025, while Stationary Storage deployment accelerated with a 79% CAGR



BloombergNEF Source: Data from BloombergNEF (Distinguished Partner) - [1]. For more information, visit https://about.bnef.com/contact-us.

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing

Applications
- **EV**
- Stationary Energy Storage
- Data Centers
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- Solid-state
- Sodium-ion
- Alternative Chemistries

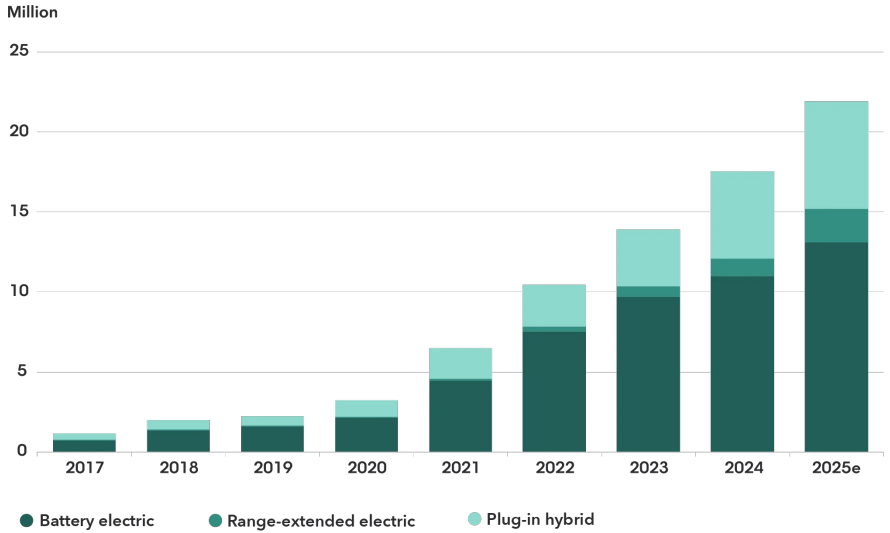
Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

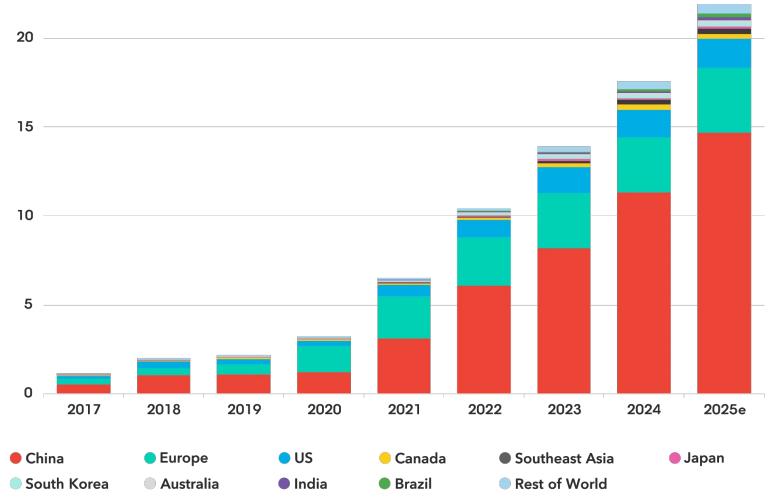
Global Sales of Electrified Vehicles by Region & Year

Passenger vehicle segment continues steady electrification trend, with hybrid and range-extender vehicles growing at faster pace in 2024/25

Global Passenger EV Sales By Drivetrain



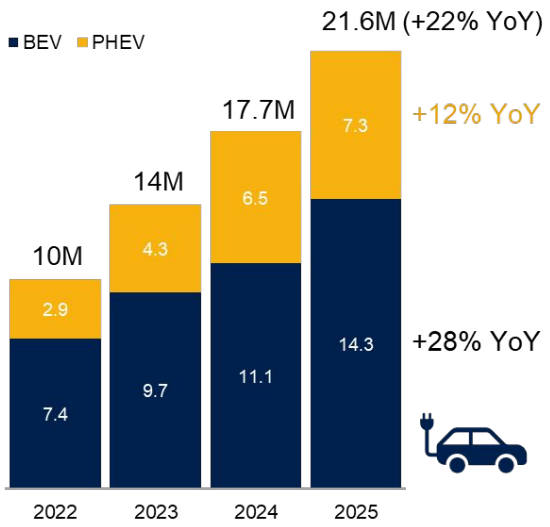
Global Passenger EV Sales By Market



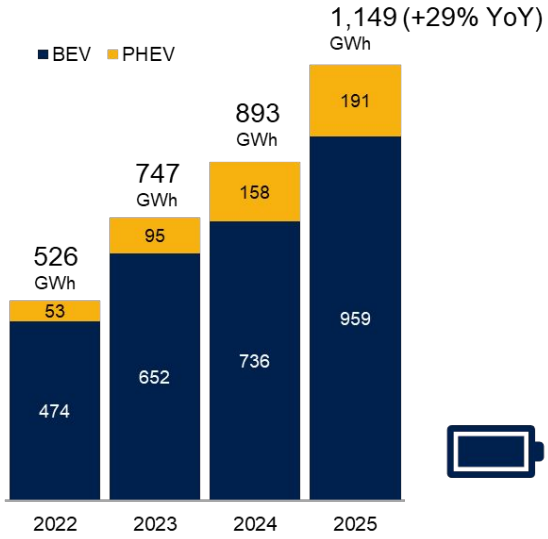
BloombergNEF Source: Data from BloombergNEF (Distinguished Partner). For more information, visit https://about.bnef.com/contact-us.

Global EV Demand & Battery Deployment Return to Growth, Led by China

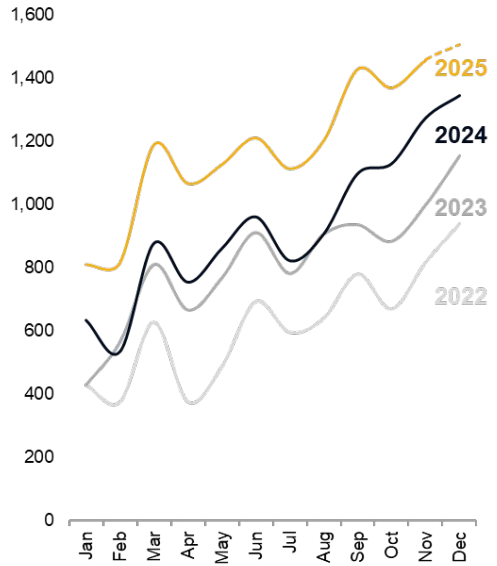
GLOBAL LIGHT DUTY EV* SALES, MILLION VEHICLES



GLOBAL LIGHT DUTY EV* BATTERY DEPLOYMENT, GWh



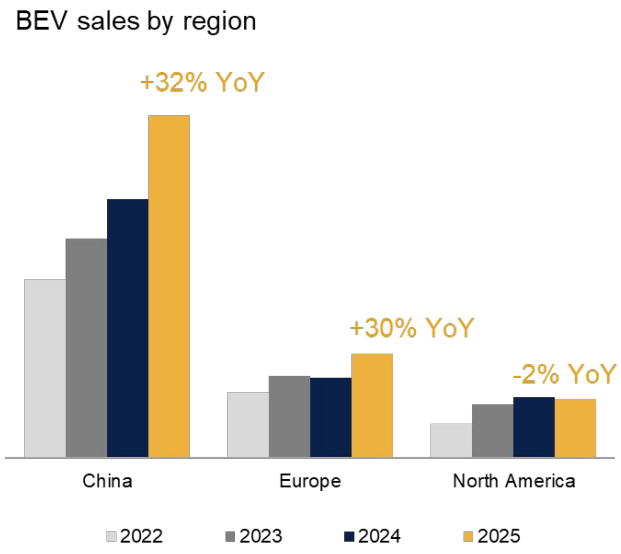
GLOBAL BEV SALES, THOUSAND VEHICLES



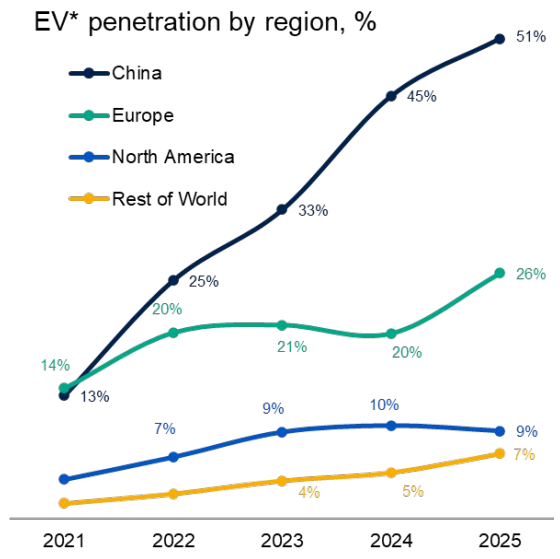
Source: Data from CRU Group (Distinguished Partner), GlobalData, national industry associations. *EV includes BEV, PHEV, EREV. Showing passenger cars and light commercial vehicles. Dec-2025 volumes are partially estimated.

Global EV Demand & Battery Deployment Return to Growth, Led by China

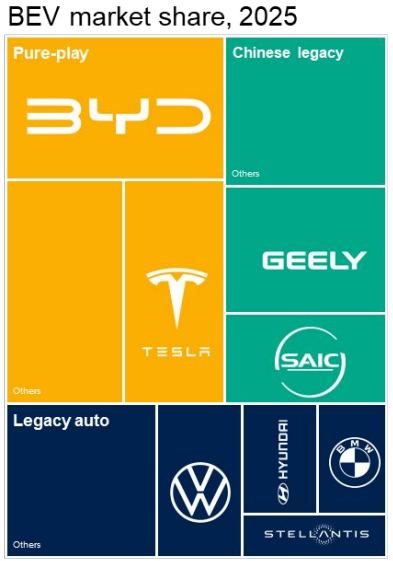
CHINA CONTINUES TO PROP UP GLOBAL DEMAND



½ OF NEW CARS IN CHINA ARE EVS; EUROPE RETURNS TO GROWTH; US STAGNATES

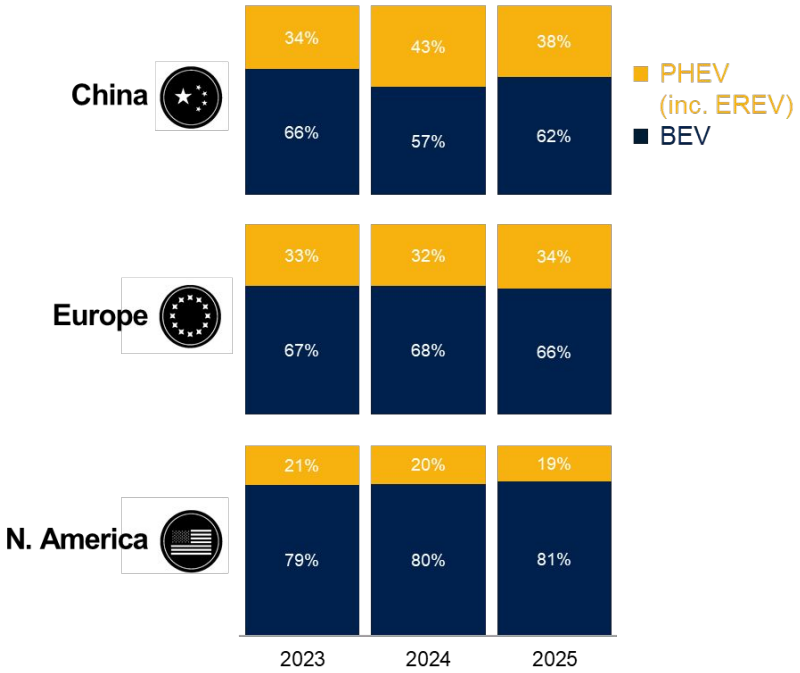


PURE-PLAY MANUFACTURERS CONSOLIDATING THEIR LEAD



Source: Data from CRU Group (Distinguished Partner), GlobalData, national industry associations. *EV includes BEV, PHEV, EREV.
Showing passenger cars and light commercial vehicles. Dec-2025 volumes are partially estimated.

BEV vs. PHEV: Pure BEVs Remain the Main EV Type but PHEVs Serving as a Transition Technology for Longer



China: Despite their popularity, PHEV growth has cooled this year:

- Falling battery costs encourage OEMs to launch more BEV models
- Improvements in fast-charging tech for BEVs have eased anxiety
- Charging infrastructure has expanded and can support growing demand for fast-charging
- BEVs benefit disproportionately from trade-in subsidy – small vehicle segments get same subsidy as larger models but do not use PHEV powertrains
- In some cities, incentives slightly more favourable for BEVs
- Intensifying competition in the BEV space: more entrants, more model launches, and technology improvements

Ex.China: PHEVs serving as a transition technology for longer:

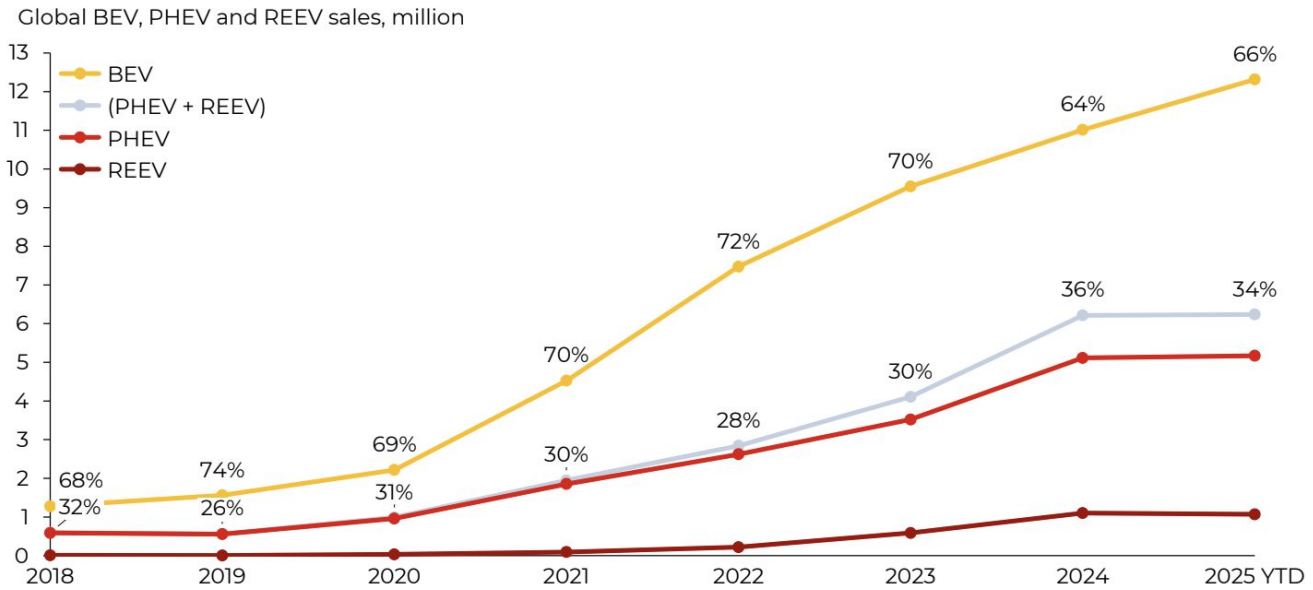
- Broader model availability, including competitive Chinese models
- Larger battery packs encouraged by regulations
- OEMs in Europe and US are falling back on full hybrid and plug-in hybrid offerings, as regulations are allowing them greater flexibility
- Pullback of BEV targets by several OEMs and countries

Source: Data from CRU Group (Distinguished Partner), GlobalData, national industry associations.
Showing passenger cars and light commercial vehicles. Dec-2025 volumes are partially estimated. | EREV = extended range electric vehicle; REEV = range-extended electric vehicle

Globally Pure BEV Sales Are Growing Whereas PHEV and EREV/REEV Sales Are Stagnating

Rapid rise in EREVs/REEVs* in 2024 flattened in 2025. EREVs are most meaningful in large, heavy vehicles. With the broader market moving towards affordability and smaller battery packs, EREVs serve a niche market.

BEV: Battery Electric Vehicle
PHEV: Plug-In Hybrid Electric Vehicle
EREV: Extended Range Electric Vehicle
REEV: Range Extended Electric Vehicle

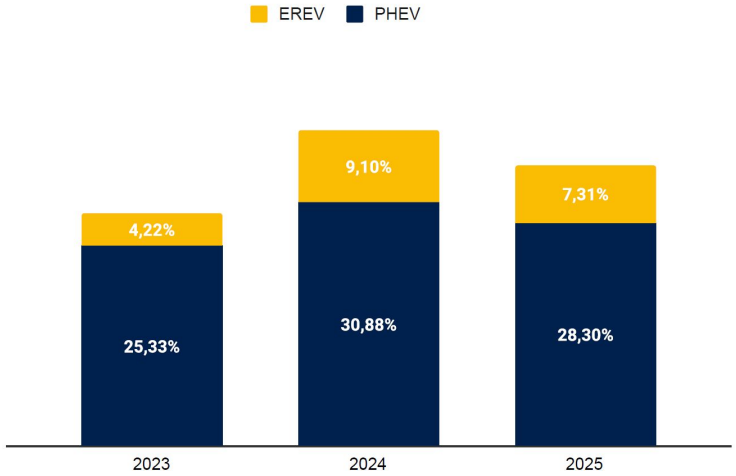


BENCHMARK Source: Benchmark Mineral Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com.
2025 YTD is updated as of November 2025. | *EREV = extended range electric vehicle; REEV = range-extended electric vehicle

PHEV & EREV Market Share Erodes in China

The predominant market for EREVs is China, although US (and to lesser extent European) OEMs plan to launch EREV models.
While PHEV and especially EREV have seen massive growth between 2023 and 2024, in 2025 the market share slightly decreased, being replaced by growing pure BEV sales.

Share of PHEV+EREV share of total NEV sales in China



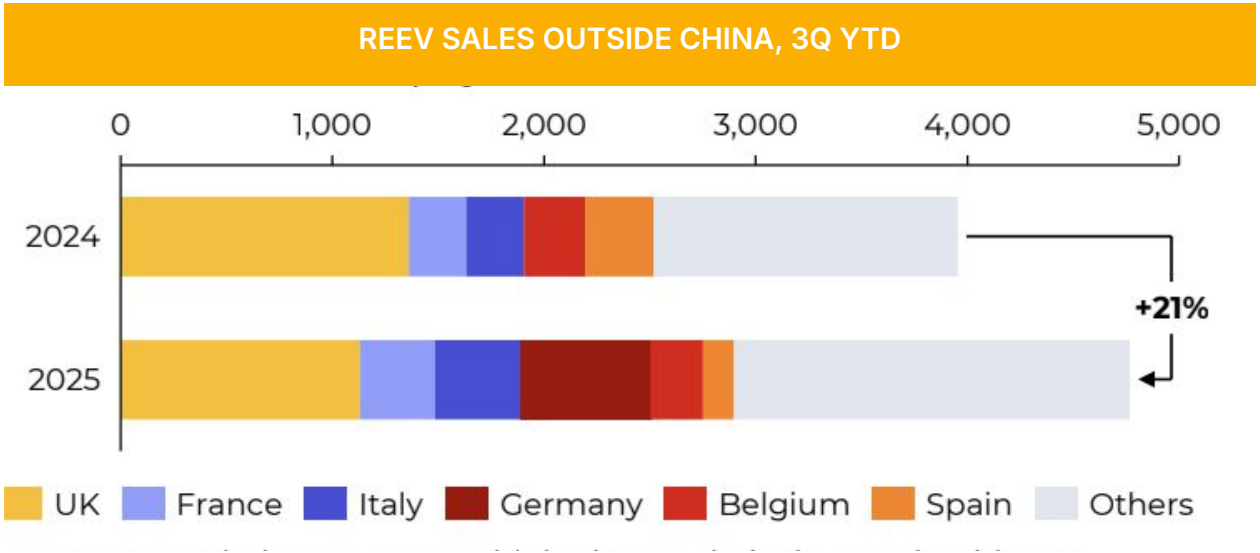
BEV: Battery Electric Vehicle
PHEV: Plug-In Hybrid Electric Vehicle
EREV: Extended Range Electric Vehicle

Year	2023	2024	2025*
EV total	9.5 million	12.9 million	14.8 million *
PHEV (w/o EREV)	2.3 - 2.5 million	3.98 million	4.18 million *
EREV	0.3 - 0.5 million	1.17 million	1.08 million *

BloombergNEF Source: [1] BloombergNEF (DIstinguished Partner), [2] IEA Global EV Outlook 2025, [3] Oxford Energy, [4] CEIC, [5] Autovista24, *data up to November 2025

Beyond China, EREVs Have Limited but Growing Sales

Leapmotor's new C10 has become the best selling EREV/REEV with 1,933 sales in the first 9 months of 2025. Extended Range EVs remain key in the European market as many lobby for special status in emissions standards.



BENCHMARK Source: Data from Benchmark Mineral Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com.
2025 YTD is updated as of November 2025.

China's Foray into the EU Market - Transitioning from Exporters to Local Manufacturers

BYD

- An EV plant in Szeged, Hungary, is expected to start production in H1 2026
- A $1 billion plant in Manisa, Turkey, is expected to start production by the end of 2026
- Doubling retail footprint to 2,000 points of sale across Europe by 2027
- Tripling e-bus capacity at plant in Komarom, Hungary, to 1,250 vehicles per year
- Additional 17% anti-subsidy tariff levied

CHERY

- Acquired a former Nissan plant in Barcelona, Spain, and is ramping up capacity to 200k vehicles
- Chery, Omodo, Jaecoo and, Lepas, brands expanding rapidly across 19 countries in Europe
- Actively seeking an additional plant in Germany or Italy
- Additional 20.7% anti-subsidy tariff levied

GEELY

- Already established presence in Europe through acquisition of Volvo and Lotus
- Co-owns Polestar with Volvo
- Introduced the EX5 e-SUV in the UK using existing plant
- Partnered with Jameel Motors to access distribution networks in Italy
- Additional 18.7% anti-subsidy tariff levied

MG

- Increased focus on hybrids and PHEV models not subject to additional tariffs
- Additional 35.3% anti-subsidy tariff levied

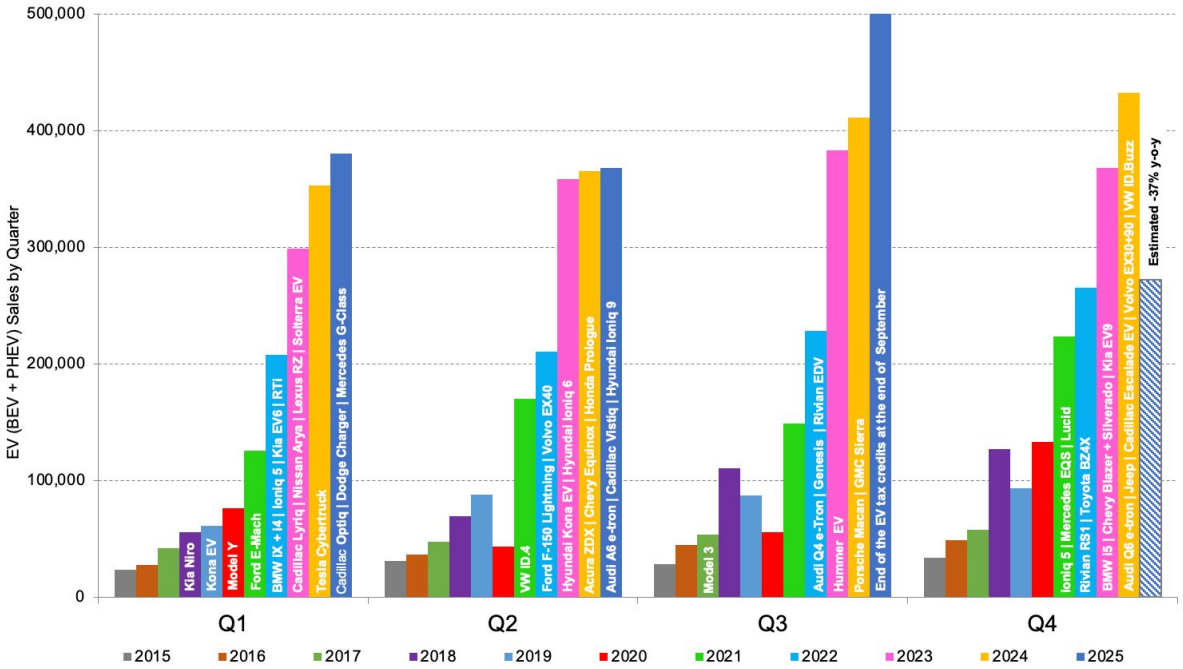
LEAPMOTOR

- Partnered with Stellantis to use its dealer network
- Additional 20.7% anti-subsidy tariff levied

Mitigate additional auto specific tariffs on top of the 10% blanket amount placed on China made BEVs imported into the country that will also be renegotiated in 2026

Source: company announcements

US EV Market Only Started to Grow When More Models Better Suited to Consumer Needs Were Introduced



EV sales flourished after 2021 as e-SUVs and higher range vehicles were introduced, but the end of the tax credit has slowed market momentum:

- Uncertainty surrounding state incentives and OEM product planning will continue to hurt EV sales well into 2026
- Q3 BEV sales grew ∽30% YoY as consumers took advantage of the tax credit → 69% of BEV sales were eligible vehicles
- Q4 EV sales were down -37% YoY, but will rebound like other markets that removed incentives (e.g., Germany) starting in 2027
- OEMs are retooling their EV strategies with an eye on local battery production, supply chain security, and reducing assembly costs
- Low cost mainstream EV options are needed in this market for the industry grow past niche status in many states

1) EV adoption only started to gain traction when EV variety and availability increased - Especially new offerings from GM (e.g. Equinox)
2) Chinese auto brands will not be entering the U.S. market given the 100% baseline tariffs placed on EVs produced in China
3) Estimated EV sales for the U.S. are only released on a quarterly basis and subject to revisions

Source: Pivot Research, Kelly Blue Book

EV Demand: List of Factors Behind Slower EV Growth

While several global factors continue to influence EV adoption, the recent slowdown in sales growth reflects a combination of **cost pressures, policy shifts, consumer confidence, and region-specific market dynamics**, not a reversal of electrification.

North America
Primary constraint: affordability + infrastructure friction

- Reduction and uncertainty in federal incentives (e.g., IRA eligibility, leasing rules, end of the EV tax credits) and lack of availability/vehicle variety
- Higher upfront prices compared to ICE vehicles and higher electricity prices compared to gas prices in some states
- Charging infrastructure gaps continue, but will narrow as non-Tesla OEMs adopts the North American Charging System (NACS) for access to Tesla's vast and easy supercharging network
- Home charging barriers for renters and multi-family housing along with inadequate electrical panels in older homes built before 1980.
- Elevated interest rates in states/provinces without local rebates disproportionately affect EV affordability due to their more rapid depreciation and higher insurance costs
- Weak used-EV resale values affecting lease pricing (higher monthly lease payments) and consumer confidence (increased total cost of ownership and market stability)

Europe
Primary constraint: cost pressure + policy fragmentation

- Norway remains the global leader with EVs representing 90%+ of new car registrations and Germany's EV sales have bounced back by 35%+ after incentives were cut in December 2023
- Phase-out of EV purchase incentives across major markets this year such as France, Denmark, Finland and Italy has impacted sales.
- Slower EV uptake in Southern Europe due to a lack of charging infrastructure and government incentives compared to Northern Europe.
- Limited affordable EV models from European OEMS are facing increased competition from the Chinese automakers (BYD, XPENG, NIO, etc.)
- High inflation, elevated interest rates, and higher electricity prices have reduced consumer willingness to finance new EV purchases
- Tighter CO_2 emissions targets coming into effect in 2025 alongside regulatory uncertainties, particularly the ICE vehicle phase-out, are shaping OEM strategies towards Hybrids and PHEVs as a transitional option.

Source: Pivot Research, company announcements

EV Demand: Asia-specific Commentary

EV sales increase in parts of Asia despite market constraints, with Chinese OEMs expanding into the fast-growing South/Southeast Asian markets

China
Primary constraint: market saturation + policy normalization

- New NEV sales exceeded 50% in 2025 with a new group of automakers (Leapmoter, Hongmeng, and Xiaomi) challenging the market
- Entering "survival test" phase of EV adoption as NEV demand normalizing reflecting market correction, not technology rejection
- End of national EV purchase subsidies and the full purchase tax exemption starting in 2026 - the tax rate for EVs is now 5% compared to 10% for ICE vehicles
- Tax exemption cap for 2026-2027 has been halved to 15,000 yuan and will be eliminated by 2028
- Early-adopter market saturation as NEV sales surpass 50% of all new vehicles sold making affordability more important following rapid early growth
- OEM overcapacity driving intense price competition and margin pressure causing many to export vehicles to overseas markets (i.e. BYD)
- Charging infrastructure challenges in lower-tier cities and rural regions continues but is expected to improve with a three year action plan to establish a nationwide network of 28 million charging facilities by 2027

East, South, and Southeast Asia (ex-China)
Primary constraint: consumer caution + brand repositioning

- Represents the fastest growing EV markets globally as a mix of incentives such as tax breaks and purchase subsidies across ASEAN countries
- Shifts in brand perception and pricing strategies influencing purchase decisions with India, Vietnam, and Thailand, accelerating rapidly
- Slower sales growth in mature urban markets as South Korea and Japan experiencing a 'demand chasm'
- Revision of EV incentives to favour local manufacturing and Indonesia will remove import duty exemptions starting in 2026.
- Hybrids and PHEVs are gaining market share as an alternative to address range anxiety and charging infrastructure gaps.
- Continued consumer hurdles include higher upfront costs, limited affordable offerings, limited financing options, unreliable electricity, long-term battery durability and repair costs
- Regulatory uncertainties affecting product planning as local brands look to reduce reliance on China

Source: Pivot Research, company announcements

New Alliances, Partnerships, Investments by OEMs into Battery Suppliers

OEM / Partner / Buyer	Agreement type	Deal / Partnership / Consolidation Type	What It Means / Why It's Relevant
NISSAN SK on	Supply agreement	SK On agreed to supply Nissan with ~100GWh of batteries from US battery plants starting in 2028 through 2033 to support EV production in Mississippi.	Deduce tariff risk, reduce dependency on Chinese made batteries and meet policies that support domestic manufacturing.
STELLANTIS SAMSUNG SAMSUNG SDI	Joint venture	$2.5 billion joint venture to build a battery cell and module factory in Indiana	Strategic domestic battery sourcing for next-gen passenger EVs
TOYOTA LG Energy Solution	Supply agreement	Long-term battery supply agreement (US/global EV programs) including recycling	Traditional OEMs favor strategic suppliers over spot sourcing, reinforcing supplier consolidation around Tier-1 battery leaders.
gm LG Energy Solution	Technology partnership	GM and LGES announced plans to jointly develop EV batteries using new lithium manganese rich (LMR) cathodes.	OEMs are diversifying cathode chemistry, especially with China-free supply chains, and developing next-gen battery tech that use cheaper materials.
TOYOTA SUMITOMO METAL MINING	Battery-tech development agreement	Collaboration on cathode materials for new battery technology (all solid state batteries)	Upstream integration into materials for next-gen technologies

Note: Ford and SK ON ended battery partnership in December 2025.

Source: [1] Nissan + SK On [2] Stellantis + Samsung [3]Toyota + LG [4] GM + LGES [5] Toyota + Sumitomo

Changes in Full Electrification Target Timelines by Each OEM

In 2025, the main shift in EV commitments was from date-certain, BEV-only endpoints toward hybrids/plug-in hybrids as stepping stone, implementing more flexible phase-outs, and reduced near-term BEV ramp rates. There were also delayed launches, driven by demand softness, profitability pressure, and policy/incentive uncertainty.

OEM	Earlier Commitment	2025 Status / Adjustment
Audi	No new ICE launches ~2026; full ICE exit by 2033	Fixed 2033 phase-out removed; ICE & PHEV continue based on market
Mercedes-Benz	EV-only where possible by 2030; electric platforms from 2025	EV-only sales ambition reset; some 2025 electric platforms retained
Volvo	100% BEV sales by 2030	BEV-only 2030 target dropped; hybrids retained
Stellantis	100% BEV passenger cars in Europe by 2030	100% BEV-by-2030 no longer pursued
Ford	Aggressive BEV scale-up	Major EV reset; cancelled models, hybrids prioritized, EREVs
General Motors	End ICE light-duty sales by 2035	Long-term goal intact; near-term EV ramp slowed
Honda	~30% BEV sales by 2030	2030 EV share reduced to ~20%
Toyota	~3.5M BEVs by 2030	EV volumes reduced/delayed; to continue strong hybrid focus
Jaguar Land Rover	Jaguar all-electric brand	Direction impact; BEV launches delayed
Hyundai Motor Group	Strong BEV growth toward 2030	Target reframed as “electrified” (incl. hybrids)

Source: Company announcements

Western Automakers Restructure EV Strategies Towards Vertical Integration & Powertrain Flexibility

Re-aligning EV strategy to include new cathode

Paused production of EVs at Factory Zero and stopped production of e-vans at the CAMI plant

Retrofitting production lines at Samsung SDI plant in Indiana to include LFP

Suspending phase 2 of a its NMCA battery materials plant expansion with POSCO in Becancour, Quebec

Investing in LMR cathode production with long-time partner LGES to start in 2027

Focusing on hybrids and in-house production

Dissolving JV with SK ON "BlueOval SK" and halting Ford F-150 Lightning

Diversifying EV powertrain mix to also include hybrids and EREVs - 50% by 2030

Adopting the 'Universal EV Platform' for more affordable BEV lines starting in 2027

Partnered with Renault for vehicles on the European market

Launched BESS business that will have 20GWh of annual capacity by 2027

Adopting a more flexible 'multi-energy' approach

Removed pledge to sell 100% BEVs in Europe by 2030

Adopting EREVs for larger e-SUVs and pickup trucks

Halted development a Chrysler mid-size EV and the RAM 1500 REV truck

Started production of B10 to e-SUV through partnership with Leapmoter in Europe

The NextStar Energy plant in partnership with LGES will include lines for LFP for BESS applications

Focus on cost-cutting and leveraging MEB platform

Launching affordable EVs in the €25k mark starting in 2026

Use LFP in lower range models and standardize battery packs

Expected to introduce 15 new EV models by 2027

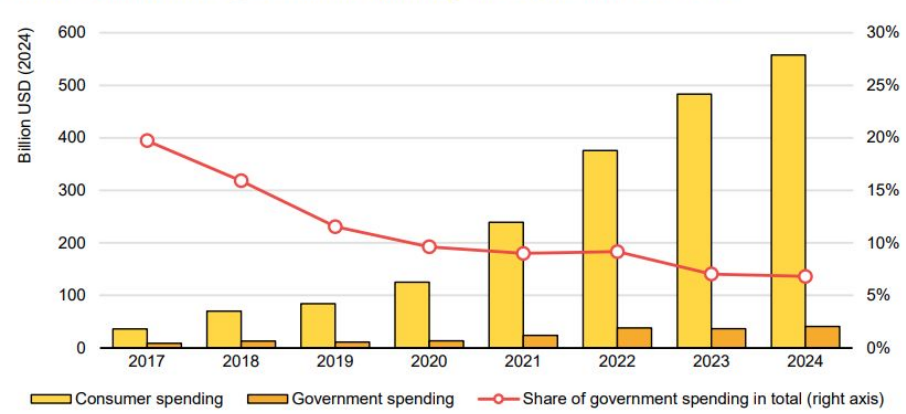
Plans in place to expand EV production in the U.S. (NC + KY), Thailand and Argentina

Source: Pivot Research, company announcements

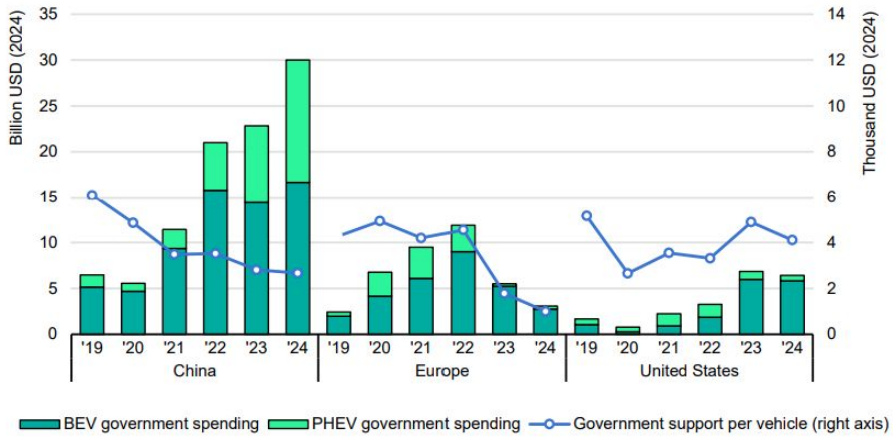
Retail & Government Spending on EVs

Share of government spending has plateaued since 2023 in all regions as subsidies are reduced. In China, the fraction of support offered to PHEVs has increased. The full impact of IRA ending in the US will be seen in 2026.

GLOBAL CONSUMER AND GOVERNMENT SPENDING ON ELECTRIC CARS, 2017-2024



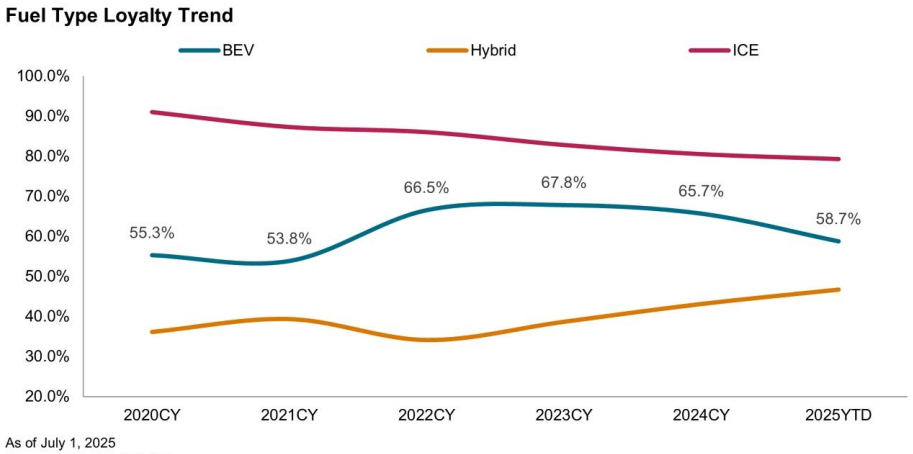
GOVERNMENT SPENDING ON ELECTRIC CARS BY REGION AND POWERTRAIN, 2019-2024

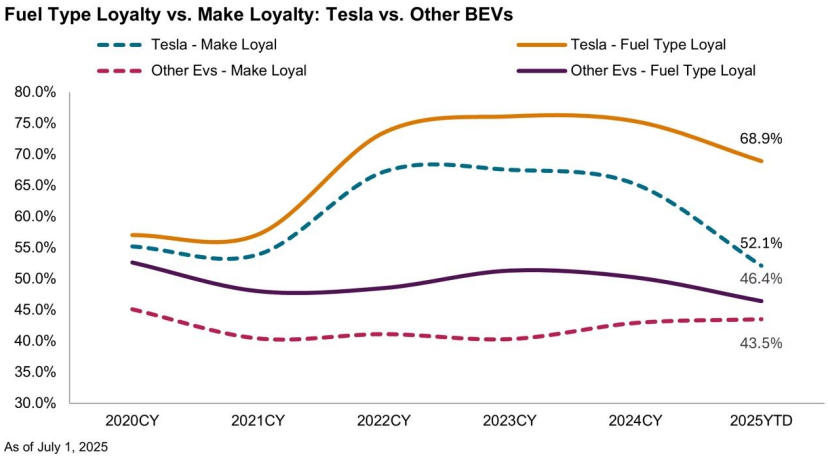


Source: IEA

Electrified Vehicle Ownership & Loyalty

Availability of new BEV models means customers are exploring newer options and expanding segments.





- BEV loyalty overall has declined in 2025
- As of year-to-date, only 58.7% of BEV households remained loyal to BEVs when they returned to market, down from nearly 68% two years ago.
- Internal combustion engine (ICE) vehicles still lead in loyalty at approximately 84%, though they too are slowly eroding.
- Hybrid loyalty is improving but remains behind both ICE and BEVs.

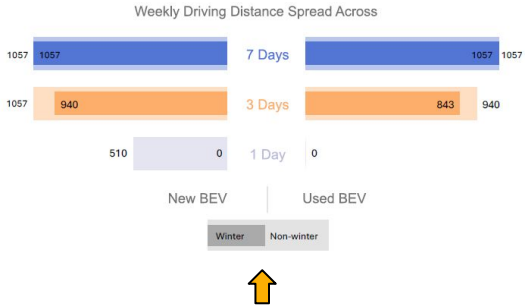
- Tesla owners remain committed to BEVs but are increasingly open to switching brands.
- This marks a shift toward a more mature EV customer base that prioritizes features, utility, and value over Tesla brand loyalty or brand familiarity.

Source: S&P Global

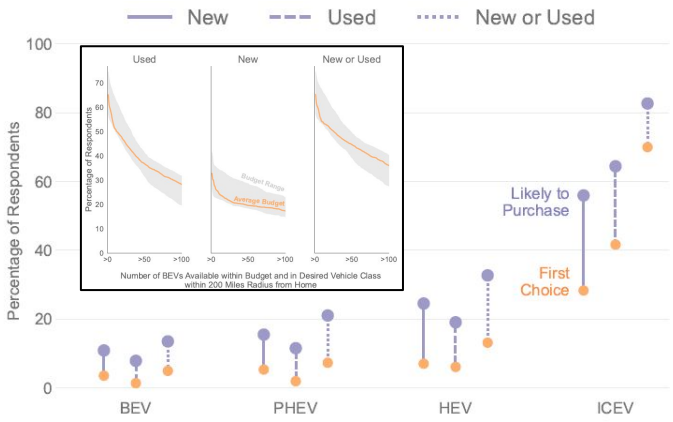
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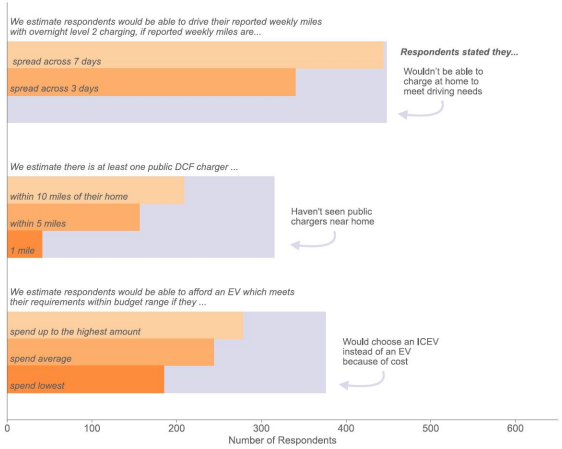
Real and Perceived Barriers to EV Adoption in Rural US Regions

The responses of 1,063 rural Michigan residents, in a survey that reached 43,000, reveals consumer constraints and attitudes around EV adoption: Only 5% of respondents would choose a BEV as their next vehicle. 70% of the respondents do not have a public DC fast charger within 5 miles of their home, and **42% underestimate their ability to cover their driving needs with overnight Level 2 charging at home.** Used ICEVs are preferred over new, whereas new PHEVs, EVs and HEVs are preferred over used. **65%of drivers could purchase at least one used BEV** within their stated budget and desired vehicle class.



Over 50% of the respondents could meet their weekly driving needs spread over 3 days, even with a used (aged) EV in freezing temperatures.





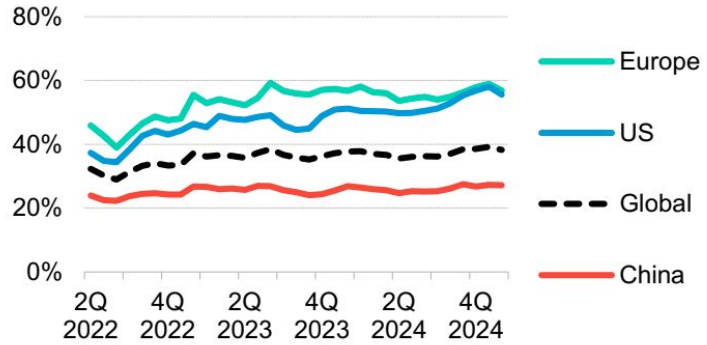
Low-cost information interventions about Level 2 home charging and used/winter BEV range could ameliorate the effect of pessimistic attitudes around range, charging at home, and affordability, while policy initiatives should focus on improving access to fast public chargers.

Source: S. Tomkins et al., Scientific Reports (2025)

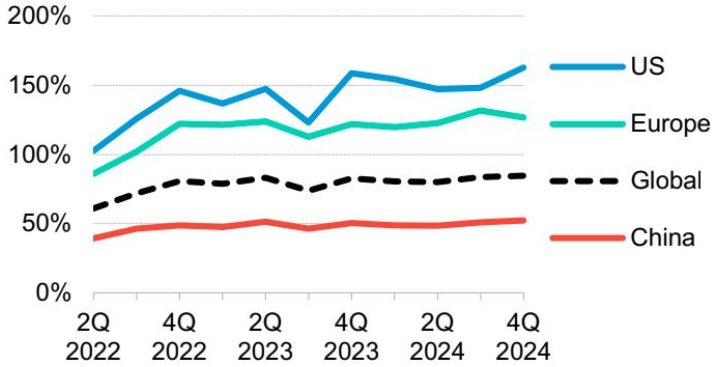
Cost of Charging Varies by Location & Has an Impact on EV Adoption

Residential charging is cheaper than public charging in all markets. Public charging is more expensive than gasoline in US and Europe.

Relative Cost Of Residential Electricity Compared To Gasoline



Relative Cost Of Fast Public Charging Compared To Gasoline

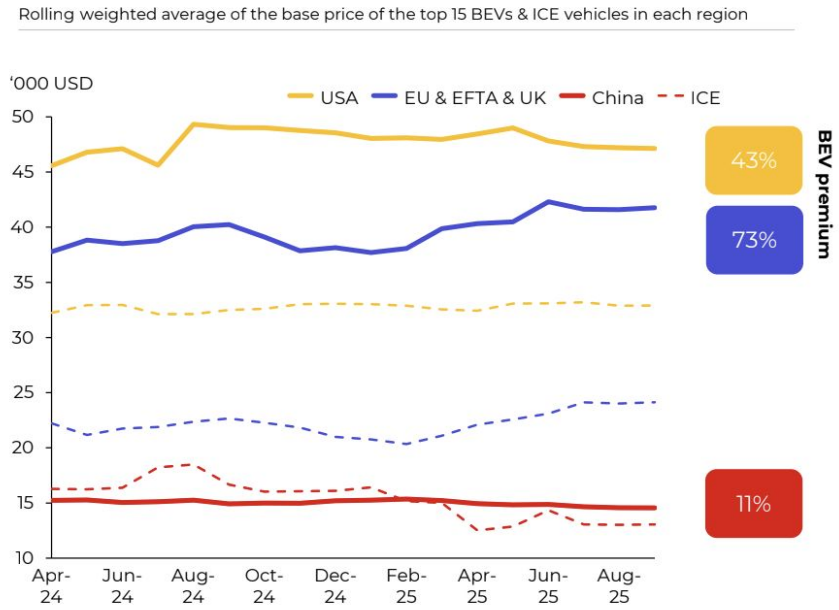


- Most EV drivers today rely heavily on home charging, which is typically 20-60% cheaper than gasoline on a per-kilometer-driven basis and use of dedicated EV home charging tariffs can extend savings.
- But public fast-charging prices have risen sharply since 2022 in many markets in Europe and the US, pushing costs per kilometer above gasoline and likely discouraging some consumers from switching to EVs. Relative refueling costs are likely to have a growing impact on EV adoption over time.

BloombergNEF Source: Content & analysis provided by BloombergNEF (Distinguished Partner). For more information, visit https://about.bnef.com/contact-us.

Regional BEV and ICE Vehicle Prices

Chinese EVs join the global trend of EVs carrying a price premium over ICE vehicles.



China

- In recent months, cheaper ICE vehicles entered the top 15 best-selling vehicles, pushing down the average price. **BEVs hold a 11% price premium**

USA

- BEVs hold a **43% price premium** over ICE vehicles especially as the federal EV tax credit has ceased

Europe

- ICE prices increased, but BEVs still retain a **73% price premium** depending on the local market incentive

Note: Data takes a sales weighted average of the base price of the top 15 models in each major region on a 12-month rolling basis. Result are before VAT for accurate cross-region comparison and converted to USD.

BENCHMARK Source: Data from Benchmark Mineral Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com.

Regional Differences in Cathode Chemistry

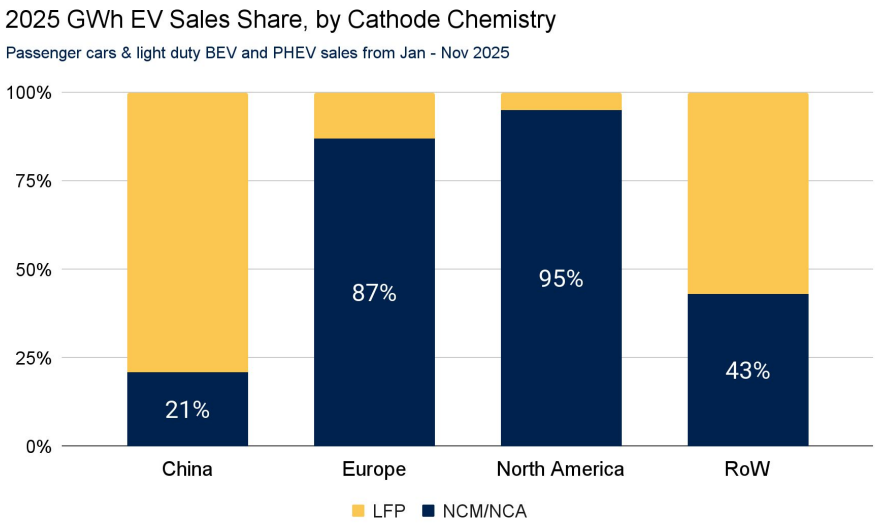
Regional divergence in cathode chemistry reflects differences in policy incentives, supply-chain localization, and manufacturing scale rather than fundamental technology limitations.

Nickel-Based (NMC, NMCA, LMR)

- Dominant choice in North America and Europe due to legacy production capacity and energy density/range needs in those markets
- Supply constraints for geographically concentrated cobalt continues as market is impacted by DRC's export restrictions
- Production of battery-grade nickel intermediates & precursors, although in oversupply, remains concentrated in Indonesia and is also heavily influenced by Chinese entities
- New cathode development is focused on shifting toward lower-nickel, cheaper manganese-rich variants such as high-voltage mid-nickel NMC and LMR

Lithium Iron Phosphate (LFP)

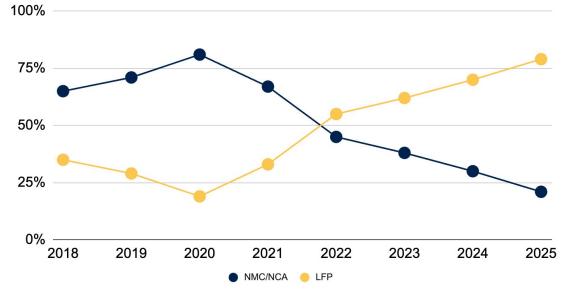
- Favored for cost, stability, thermal safety, long cycle life, and less critical minerals
- Iron and phosphate may abundant materials, but high purity production is complex and limited outside of China
- China dominates production of LFP cells and cathode material, and IP surrounding chemistry improvements and cell-to-pack architectures (CATL, BYD)
- Increasing adoption in entry-level and mass-market EVs with major automakers licensing the technology from Chinese firms



Industry is Moving Towards Diversification of EV Cell Chemistries by Vehicle Segment and Region

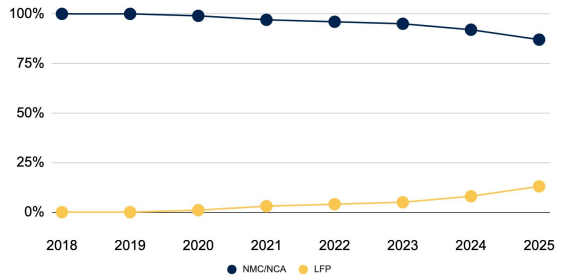
China

- Scale, vertical integration, and super-low costs has enabled LFP-centered EV production growth
- Strong OEM and policy alignment around prismatic LFP platforms
- Sodium-ion emerging in 2-wheelers, but not yet as EV traction batteries in 2025



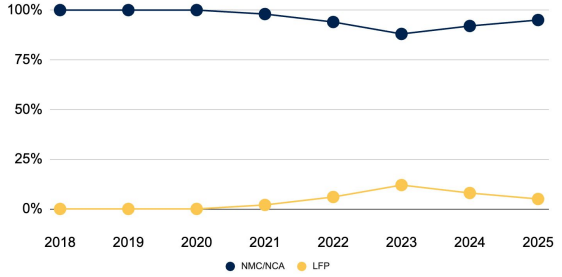
Europe

- Mixed chemistry strategies across OEMs with Chinese battery firms building local production capacity
- Continued reliance on NMC for premium vehicle segments with a gradual LFP adoption for cost-sensitive platforms



North America

- Slower LFP penetration due to established NMC production capacity and limited access to advanced manufacturing methods
- IRA sourcing rules and geopolitical tensions between the US and China has influenced chemistry and localization strategies
- Nascent domestic LFP industry, but initially focused on ESS



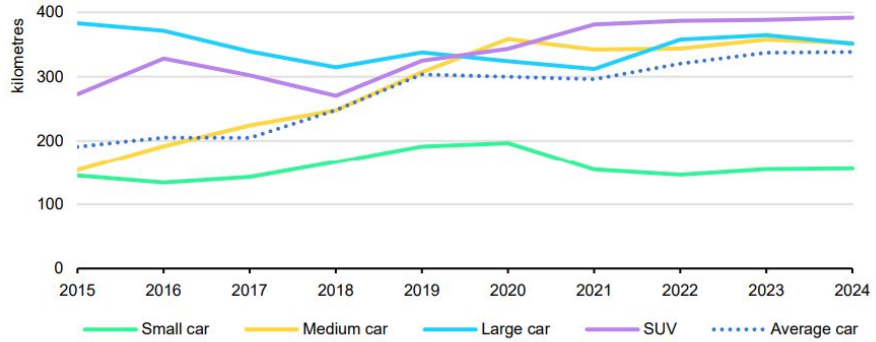
BENCHMARK BloombergNEF Source: Data from Benchmark Mineral Intelligence (Distinguished Partner), BloombergNEF (Distinguished Partner), IEA, OEM announcements

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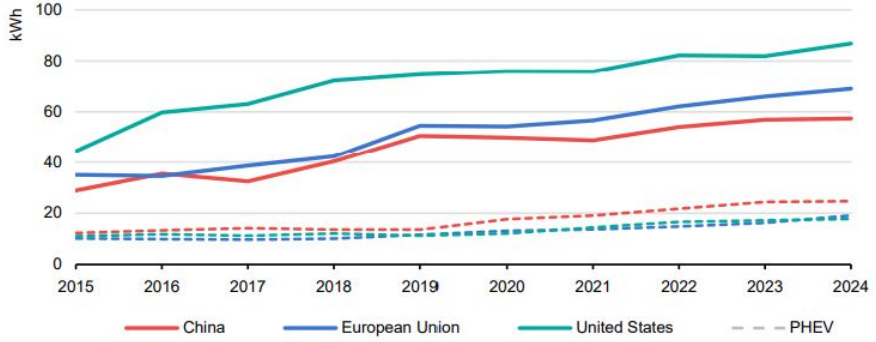
EV Range and Battery Capacities

Range of EVs have plateaued for most segments. Yet battery energy capacity continues to increase as the market moves towards larger SUVs.

Sales-weighted average range of battery electric cars by segment, 2015-2024

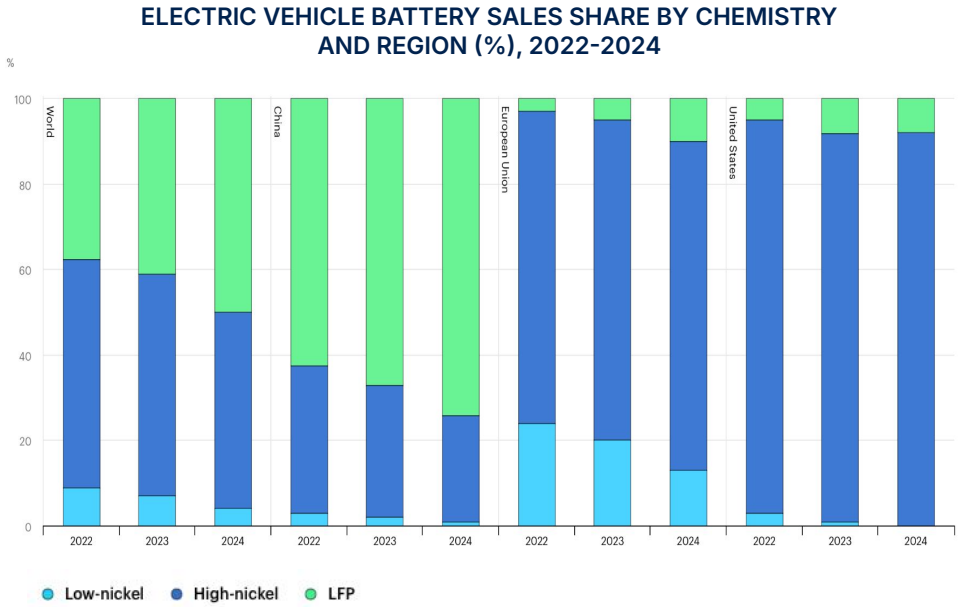


Average electric car battery pack size by region and powertrain, 2015-2024



Source: IEA

LFP is Positioning Itself as the Default Battery Chemistry for Affordable EV Segments Globally



LFP chemistry is growing on the EV market

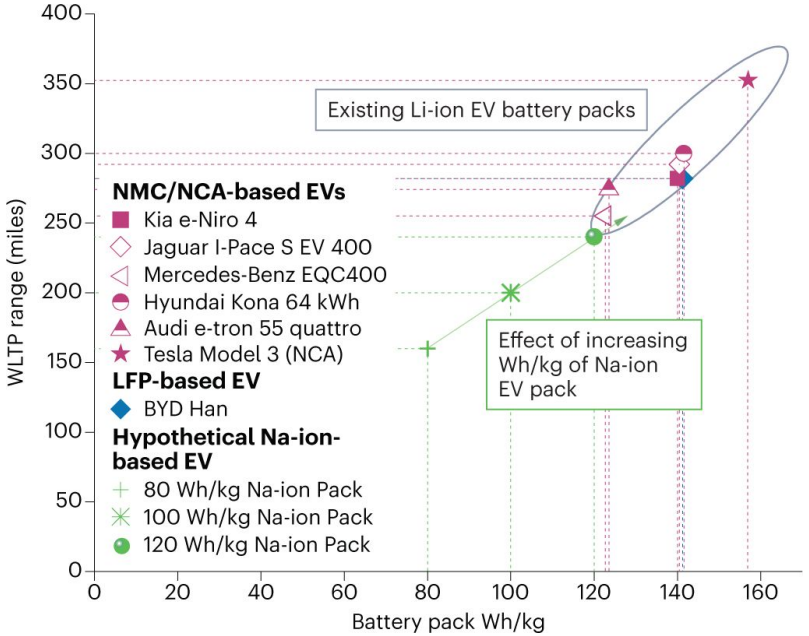
- The share of Lithium-iron phosphate (LFP) batteries in global EV battery sales rose from about 38 % in 2022 to over 41 % in 2023, and reached nearly 50 % in 2024.
- China continues to lead LFP adoption, reaching a 75% market share domestically in 2024. Meanwhile, Europe is showing rapid growth, doubling its share to 10%.

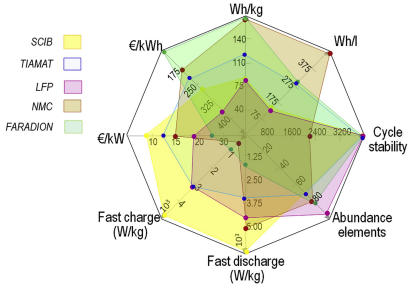
Why LFP is winning?

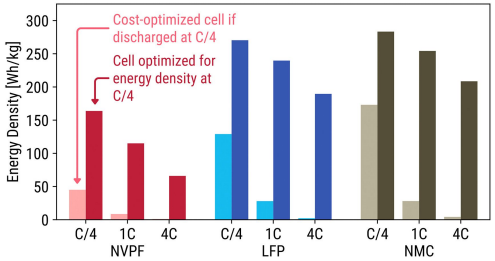
- **Cost Advantage:** LFP packs average $81/kWh, nearly 40% cheaper than NMC ($128/kWh) in 2025,with a more resilient cobalt and nickel-free supply chain.
- **Safety & Durability:** Superior thermal stability and higher cycle life, ideal for high-utilization vehicles.
- **Breaking Density Barriers**: New products (e.g., CATL Shenxing PLUS) now reaches 200 Wh/kg, closing the range gap with NMC.
- **Global OEMs Ecosystem using LFP batteries**:
  - Pioneers: BYD (full lineup) & Tesla (Model 3 SR).
  - Western scaling: Ford (Mach-E), Rivian (R1 Standard), and Stellantis (ë-C3 / Grande Panda), Mercedes-Benz, VW, and Toyota.

Source: IEA

EV Cell Chemistry Performance Comparison: LFP, NMC & Na-ion







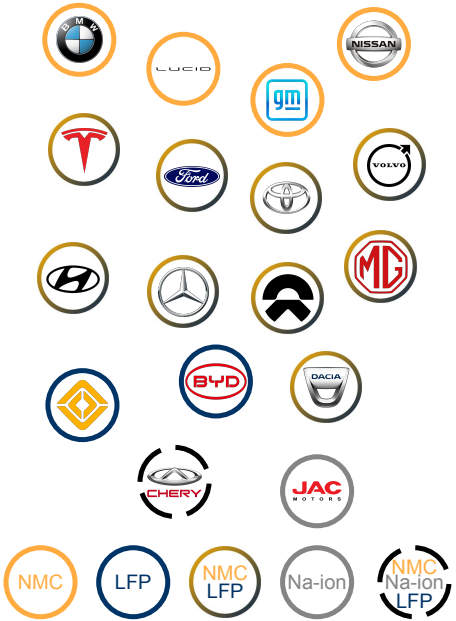
- NMC still provides the **highest energy density** and longest range[1,2]
- Sodium-ion shows best cold-temperature performance and does not rely on active thermal management unlike LFP and NMC
- Today's longest-range EVs use NMC, mainstream mass-market models increasingly use LFP, and sodium-ion is targeting short- to mid-range city cars and entry EVs.
- Sodium-ion is expected to complement, not replace, LFP and NMC - filling the lowest-cost, shorter-range segment.

Source: Academic articles

EV Cell Chemistry Performance Comparison: LFP, NMC & Na-ion

	LFP Batteries	NMC Batteries	Na-ion Batteries
Status (Maturity)	LFP powers ~40% of EVs on 2024; Tesla and BYD lead with ~68% of global deployments (2022).	Supply ~50% of global EV battery demand; Dominant for long-range and premium EVs (VW, GM and BMW).	CATL, BYD, JAC, and JMEV launched sodium-ion EVs in 2023–2024; Stellantis investing for future models.
Energy Density (Wh/kg)	CATL's LFP cells reach ~205 Wh/kg; BYD's Blade improved from ~140 Wh/kg (2020) to ~150–190 Wh/kg (2024–2025).	High-Ni NMC cells in volume production reach ~240–280 Wh/kg; NMC EV packs typically ~250–300 Wh/kg	CATL's Na-ion energy density rose from ~160 Wh/kg (2021) to ~175 Wh/kg (2025 Naxtra), nearing LFP levels.
Fast-Charging Capability	LFP EVs charge 10–80% in ~25–40 min; next-gen BYD Blade enables ~3C charging, reaching ~20 min.	800 V NMC platforms like Hyundai Ioniq 5/6: 10–80% in ~18–30 min; NMC packs in VW ID.4: 10–80% in ~28–40 min.	CATL's Na-ion charges to 80% in ~15 min; 3C–4C prototypes fully charge in ~15–20 min, even cold.
Cycle Life (Durability)	LFP batteries deliver 2,500–9,000 cycles, often exceeding 200,000 miles, ensuring exceptional durability for taxis and buses.	Cells ~1,000–2,000 full-equivalent cycles to ~80% SOH (~250k–500k km), with OEM warranties ≥70% capacity for 8 years or 100k–150k miles.	CATL's Naxtra Na-ion battery exceeds 10,000 cycles (~3.6 million miles), surpassing LFP durability in recent lab tests.
Thermal & Cold Performance	LFP batteries are fire-resistant and stable up to ~300 °C but lose performance in cold, needing heating below 0 °C.	BMS keeps cells near 15–45 °C using pre-heating & active thermal management to reduce cold-weather losses.	Sodium-ion cells retain >90% capacity at –20 °C and operate –40 °C to +60 °C, offering superior cold-weather safety.
Cost & Materials	2024: LFP packs cost ~$115/kWh, some cells near $50/kWh.	NMC cells ≈$140/kWh; With estimated NMC-graphite EV packs of ≈$103/kWh; costs sensitive to Ni/Co price.	Sodium-ion cells cost ~$50/kWh vs ~$70 Li-ion; scalable production may reach ~$40/kWh using lithium-free materials.
Typical EV Range	Tesla Model 3 (60 kWh LFP) reaches ~500 km WLTP; BYD Seal (~82 kWh) achieves ~570 km WLTP.	Long-range NMC crossovers/SUVs (Ioniq 5/6, EV6, ID.4 Pro, Lyriq) give ~280–330 miles real-world EPA/WLTP.	JMEV EV3's 21.4 kWh Na-ion pack offers ~251 km CLTC range; CATL's 160 Wh/kg pack targets ~500 km.

COMPANY LANDSCAPE†



†May not reflect all companies

Source: Company announcements

Target Na-ion Cell Specifications for EV Mass Market

Na-ion batteries need to provide sufficient energy while delivering same cost, weight, package & charging time as LFP

Requirements (indicative)

- **Minimum of ~250 mile range**
- **10 min quick charge capability**
- **Same pack size**
- **Same pack weight**
- **Similar cost to LFP**





	LFP benchmark		SiB target
Energy [kwh]	~80 kWh[1)]	>	**~60 kWh[1)]**
VED (cell) [wh/kg]	410 Wh/L	>	**330-340 Wh/L**
GED (cell) [wh/L]	220 Wh/kg	>	**160-170 Wh/kg**
C-rate [60/min]	6 C	=	**6 C**
Cost [USD/kwh]	~USD 45/kWh	=	**~USD 45/kWh**

1) Assuming 4 miles per kwh

Source: Content & analysis provided by Roland Berger (Distinguished Partner). For more information, visit https://www.rolandberger.com/en/Insights/Global-Topics/Battery.

OEMs Target ASSB (All Solid State Battery) Implementation in Production Vehicles as Early as 2027-2028

Vehicles On the Road

BMW is testing a **Solid Power** ASSB in an i7 test vehicle on the road.

Partnership and Development Announcements

BMW, Samsung SDI, and Solid Power have signed a trilateral agreement to collaborate on ASSB development.

BYD develops a sulfide-based ASSB, with expected driving range >1000 km. Small batches will be installed by 2027. Mass production is scheduled to start by 2030.

Chery announces the RhinoS ASSB module at the 2025 Global Innovation conferences, with a target vehicle range of 1200+ km. [1, 2]

Hyundai launched an ASSB pilot line in their Uiwang R&D Center and aims for mass production by

Nissan and **LiCAP** partner to produce ASSBs. Pilot line production started in January 2025, with planned release of ASSB in production vehicles by 2028

Panasonic will launch an anode-free ASSB by 2027.

Quantumscape entered a JD agreement with an unnamed Top-10 global OEM to develop ASSB.

Toyota and **Sumitomo Metal Mining** entered a JD to mass produce cathode materials for ASSB; Toyota aims for a market launch in 2027-2028.

Source: Company announcements

Prismatic Cell Formats Retain the Leading Global Market Share

Cell format choice increasingly driven by manufacturability and integration costs, rather than just energy density.

Prismatic

- Dominant in China, produced at massive scale
- Well-suited for LFP and cell-to-pack architectures

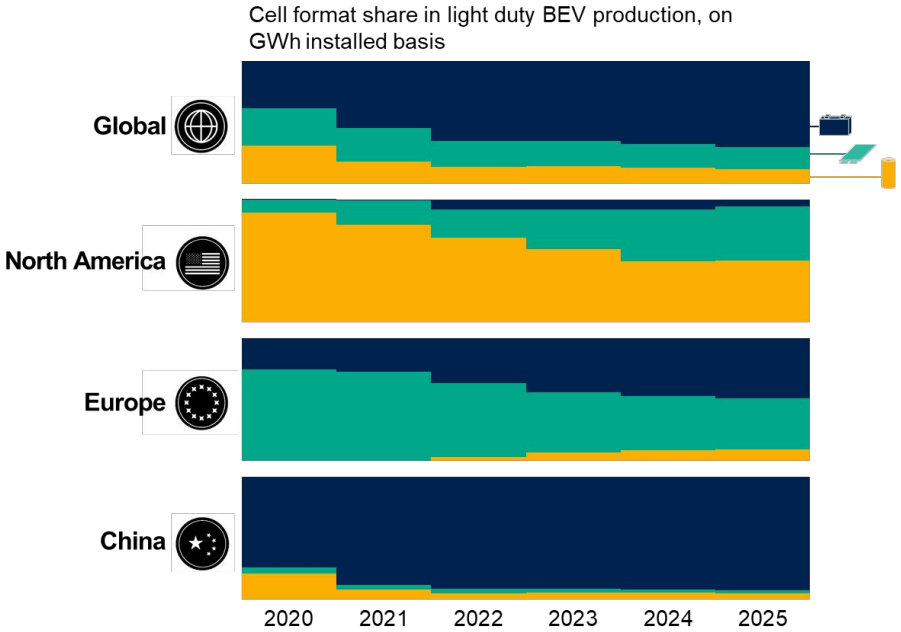
Cylindrical

- Incumbent format in North America
- Benefits from automation, yield learning, and cost-down potential

Pouch

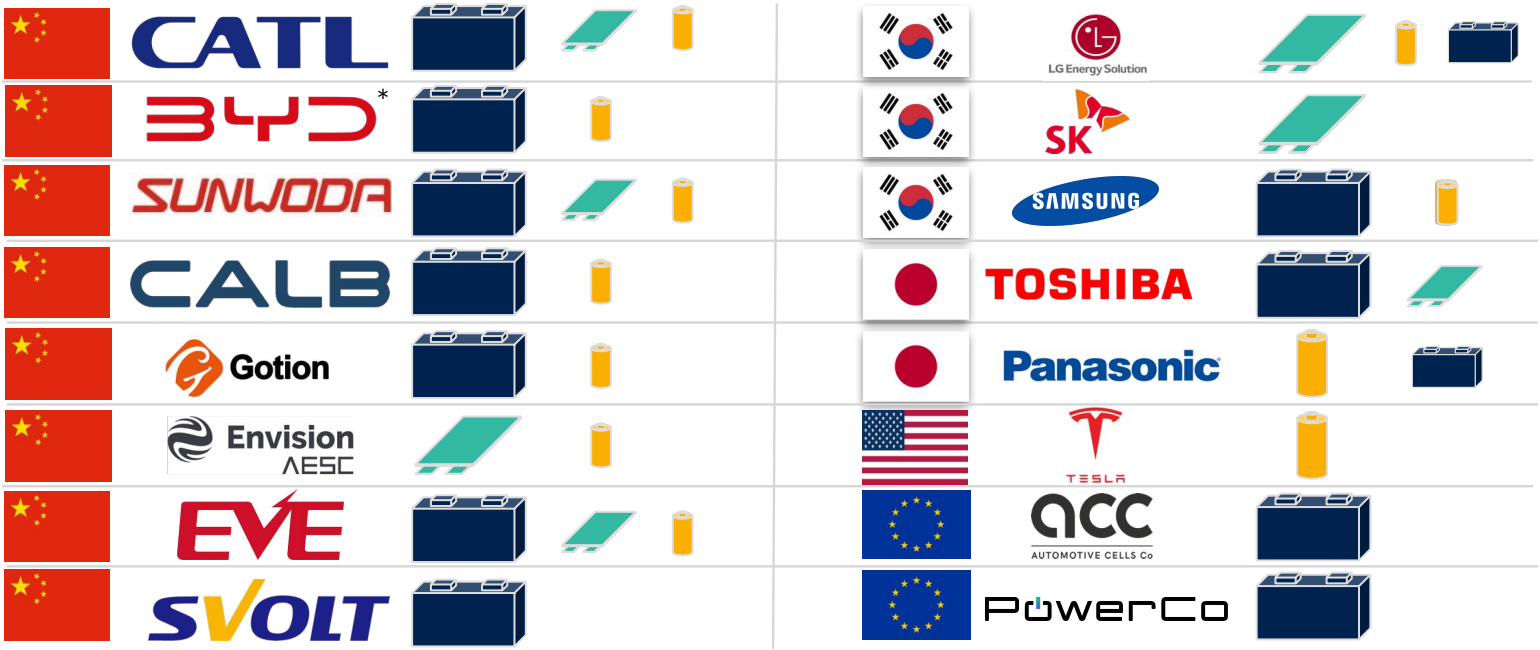
- Mainstay of Korean manufacturers but declining relative share
- Challenges in mechanical robustness and manufacturing yield

See **Cell Design & Materials** section for more information.



Source: Data provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

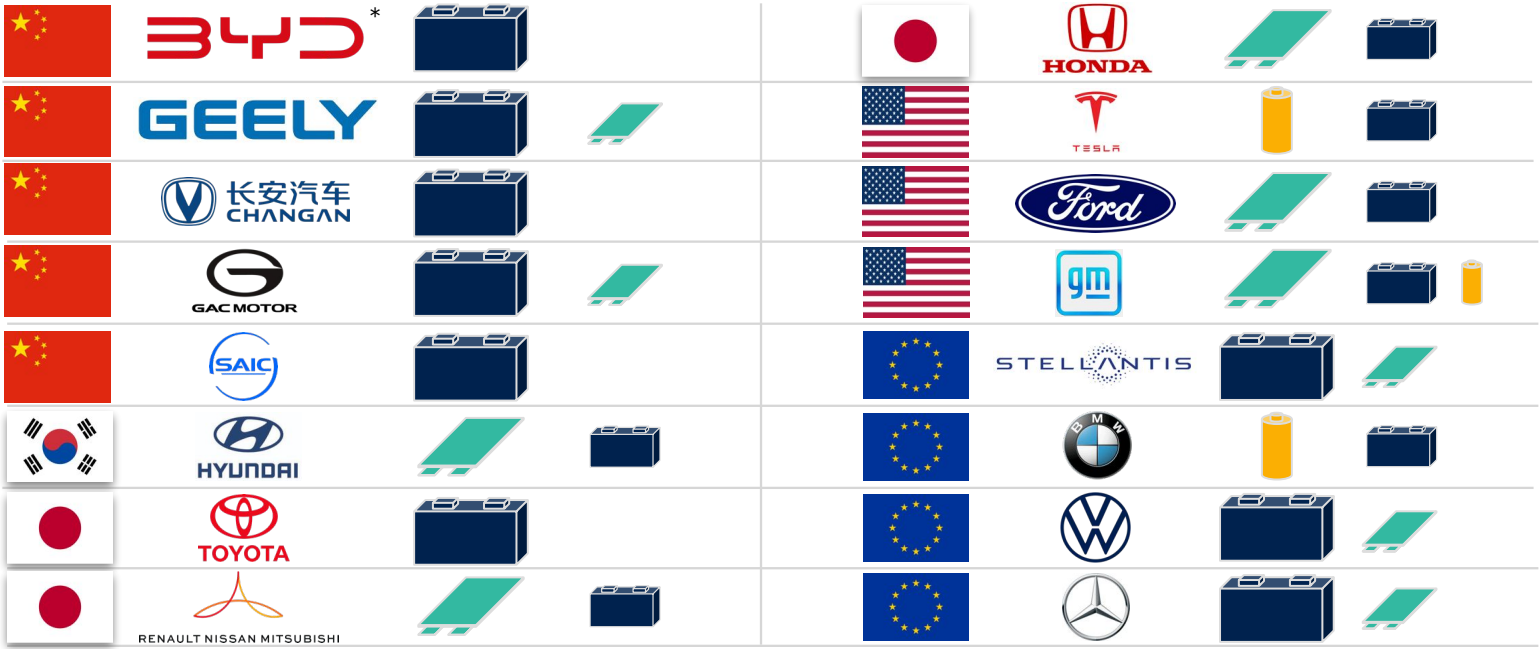
EV Battery Manufacturers Trending Towards Large Format, Prismatic Cells



Large and small icons denote primary and secondary cell preference respectively.
**Prismatic cell icon used as best fit for blade battery representation*

Source: For primary form factors: Added to company icons, CATL, BYD, CALB, Sunwoda, LGES, Toshiba, Gotion High Tech, Envision, Farasis, EVE, See Cell Design & Materials section for more information.

Primary Form Factor Varies Regionally; Prismatic Dominating Asia and Non-Prismatic in EU and N.America



Large and small icons denote primary and secondary cell preference respectively.
**Prismatic cell icon used as best fit for blade battery representation*

Source: For primary form factors: Added to company icons, Geely, GAC, Hyundai, Renault Nissan Mitsubishi, Honda, Tesla, Ford, GM, Stellantis, BMW, VW, Mercedes-Benz
See Cell Design & Materials section for more information.

New Product Launch Highlights in 2025

There is a trend towards higher voltage battery platforms, which has also reduced charging times.

800V

Several legacy OEMs now have at least one product in the 800V segment, marking a broader trend in this direction.

Chinese OEMs introduced their 800V variants in the European market after success in their home markets.



iX3 (Neue Klasse)
17.8 kWh/100km
10-80% 21 min**



GLC 400 4Matic
18.8 kWh/100km
10-80% 22 min**



ES90
18.1 kWh/100km
10-80% 22 min**



Escalade IQ
29.7 kWh/100km
10-80% 25 min



Polestar 5
18.3 kWh/100km
10-80% 22 min**



B10
12.3 kWh/100km
30-80% 18 min**



G9
19.8 kWh/100km
10-80% 12 min**

G6
18.8 kWh/100km
10-80% 12 min**



IM5
18.2 kWh/100km
10-80% 17 min**

IM6
19.3 kWh/100km
10-80% 17 min**



YU 7 4WD Max
14.8 kWh/100km
30-80% 12 min**



Ioniq 9
21.4 kWh/100km
10-80% 24 min**

1000V

1000V battery systems enabling 1MW DC-Fast Charging at 10 C were introduced by BYD



Han L
13.7 kWh/100km*
30-70% 6min**

Tang L
17.1 kWh/100km*
30-80% 6min**

400V

Suzuki launched its first-ever EV - e-Vitara
Tesla launched a 3-rowed Model Y L in response to growing competition from domestic Chinese OEMs in the SUV segment.



e-Vitara
18.1 kWh/100km
10-80% 44min**



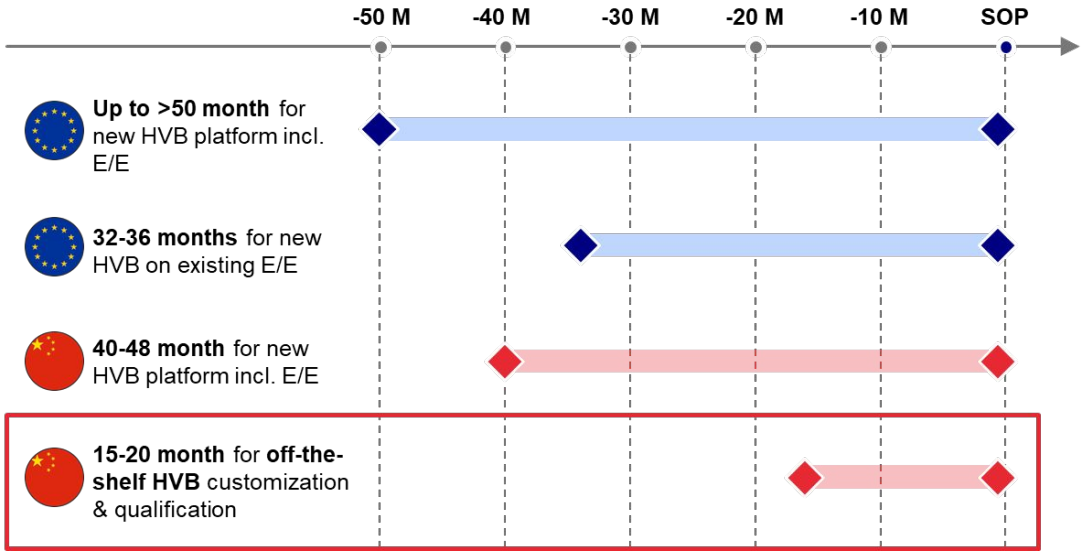
Model Y L
12.8 kWh/100km*
10-80% 27 min**

Source: Link to exhaustive list of launches in 2025; * Efficiency figures for CLTC Driving Cycle; ** Charging time when charged at DC-Charging stations supporting greater than 150 kW power output.

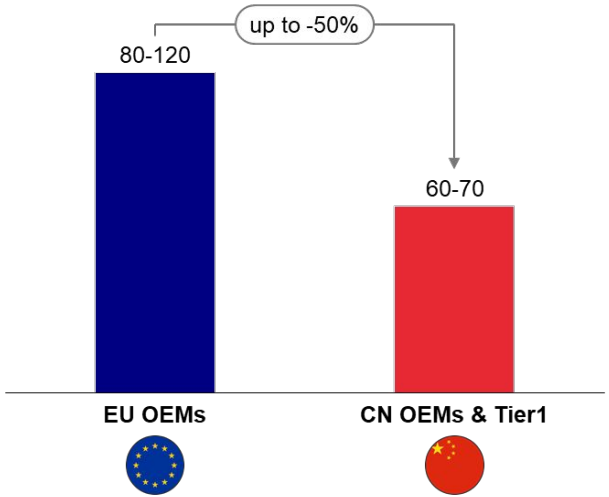
High Voltage Battery (HVB) Development Timelines

New HVB and Electrical architectures require 3-4 years of development, while integrating of OTS* systems is possible in ~1.5 years. Chinese OEMs and Tier 1 HVB suppliers can offer nearly a ~50% reduction in development cost.

Development time for battery pack [months until SOP]



R&D cost for battery pack excl. cell [EUR m]



Source: Content & analysis provided by Roland Berger (Distinguished Partner). For more information, visit https://www.rolandberger.com/en/Insights/Global-Topics/Battery.
** OTS = off-the-shelf.

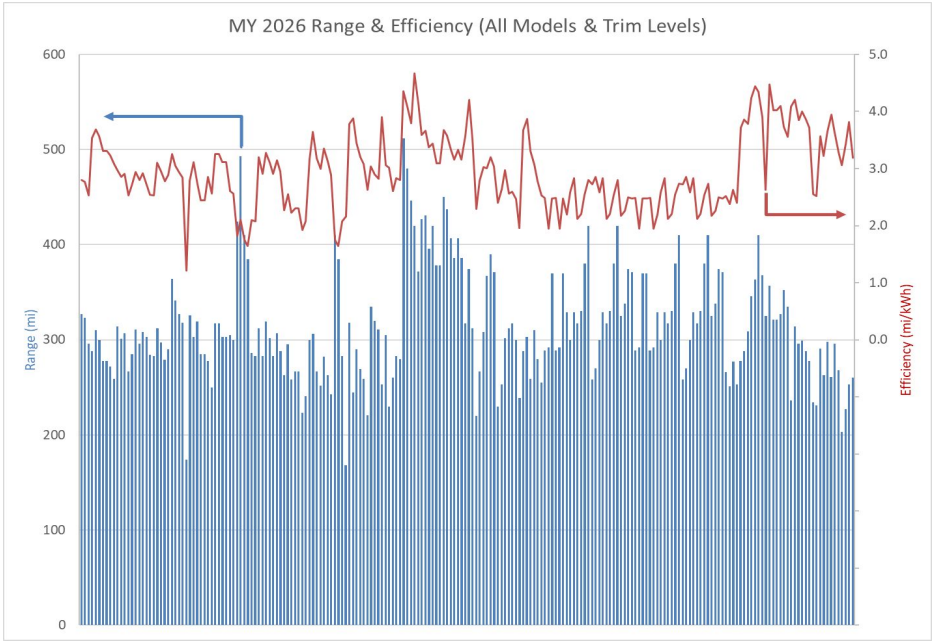
Electric Vehicle Range & Efficiency (United States)

Range:

- Highest range vehicle is the Lucid Grand Touring AWD with 19″ wheels with a combined range of 512 mi.
- The average range of all models and trim levels certified for MY2026 was 314 mi.
- Lucid had the highest average range for all models & trim levels at 419 mi.

Efficiency:

- Highest efficiency vehicle is the Lucid Air Pure RWD with 19″ wheels with a calculated efficiency of 4.7 mi/kWh
- The average efficiency of all models and trim levels certified for MY2026 was 2.9 mi/kWh
- Toyota had the highest average range for all models & trim levels at 4.0 mi/kWh



Blue bars represent individual vehicle model/trim ranges and red corresponds to their efficiency (mi/kWh)

Source: US Department of Energy Fuel Economy Database for new vehicles, based on US EPA combined range rating and documented energy capacity (kWh). Data for plot located here.

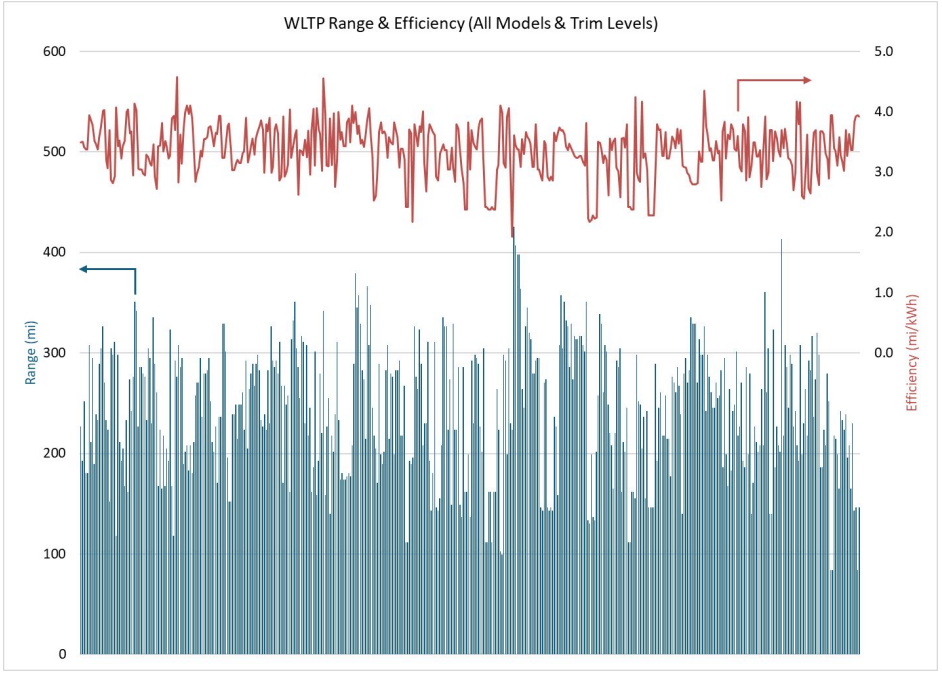
Electric Vehicle Range & Efficiency (Europe)

Range:

- Highest range vehicle is the Mercedes-Benz EQS 450+with a WLTP range of 685 km (426 mi)
- The Lucid Air Grand Touring has the second highest WLTP range at 665 km (413 mi)
- The average WLTP range of all models is 390 km (243 mi)

Efficiency:

- Highest WLTP rated efficiency vehicle is the Tesla Model 3 RWD and Tesla Model 3 Long Range RWD at 4.6 mi/kWh
- The average WLTP rated efficiency of all models is 3.4 mi/kWh



Blue bars represent individual vehicle model/trim ranges and red corresponds to their efficiency (mi/kWh)

Source: European Alternative Fuels Observatory database of currently available EV models. Range reported as based on WLTP and efficiency is calculated based on documented energy capacity (kWh). Data for plot located here.

Electric Vehicle Range & Efficiency (China)

Range:

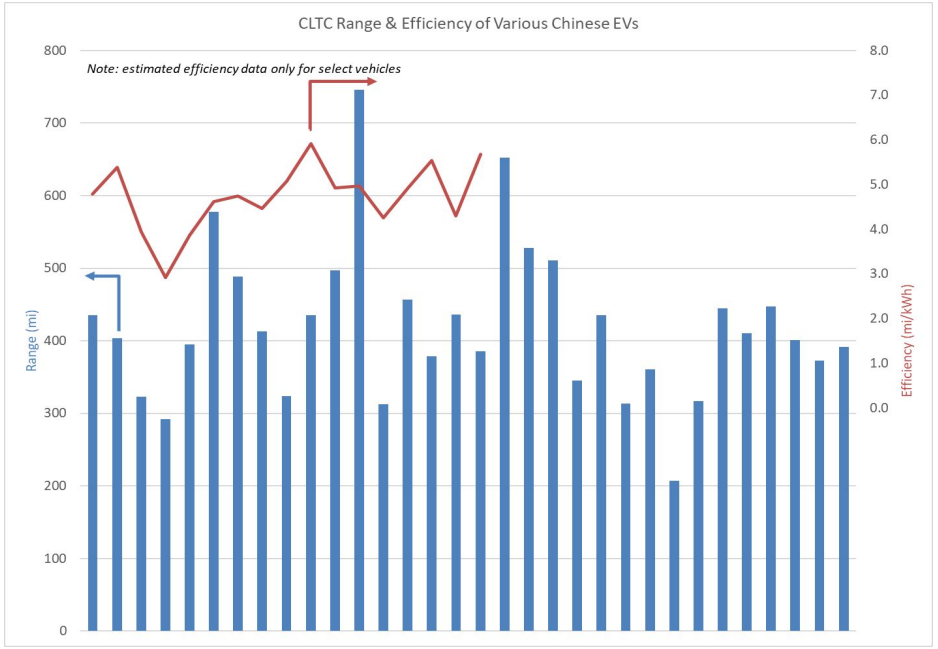
- Highest range vehicle is the Xaiomi SU7 Ultra with a range of 746 miles on the CLTC
- The average CLTC range of all models analyzed is 420 miles

Efficiency:

- Highest CLTC rated efficiency vehicle is the Xaiomi SU7 (standard) with an efficiency of 5.9 mi/kWh
- The average CLTC rated efficiency of all models is 4.7 mi/kWh

Note:

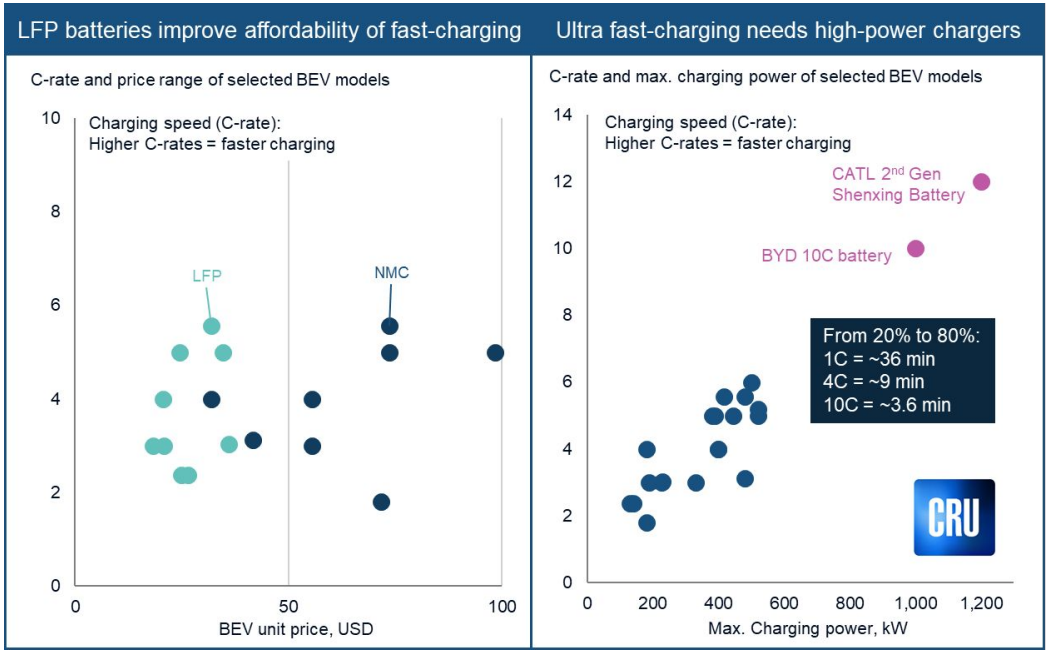
- Data presented is from the press or public information releases from various chinese OEMs and is not inclusive of all vehicles that are available in China [1]. Range in the figure to the right is reported based on the CLTC test procedure and efficiency is calculated based on the documented energy capacity (kWh).
- Given the light loading and lower speed of the CLTC drive cycle, EPA and WLTP range is estimated to be roughly 70% and 80% lower than what is shown here, respectively.[1,2,3]



Blue bars represent individual vehicle model/trim ranges and red corresponds to their efficiency (mi/kWh)

Source: 2026 China EV Range & Efficiency, EV Range Converter, How To Convert Conflicting EV Range Test Cycles: EPA, WLTP, CLTC

Chinese Producers Are Rapidly Commercializing Super-Fast-Charging LFP Batteries



Challenges:

- Fast-charging at 4C or above requires higher system voltages (800V+) and power levels, needing significant innovation in battery design.
- This shift also faces several infrastructural hurdles. Only 8% of China's public charging piles currently offer power exceeding 240kW, and grid capacity often cannot support megawatt-level loads without large upgrades.
- At the same time, megawatt-level charging places intense demands on thermal management systems. China's MIIT recently strengthened national EV battery safety standards, requiring batteries to prevent fire or explosion even during thermal runaway - not only issue early warnings.

Enablers:

- Advanced thermal solutions, including dual liquid-cooling plates, improve heat dissipation.
- Silicon carbide inverters manage heat during driving, preserving thermal headroom for ultra-fast charging.
- Advanced graphite anode materials enhance conductivity under high current loads.
- High compaction density LFP cathode material plays a large role in fast charging.

In a recent announcement, CATL will bring its latest Shenxing battery to the European EV market, indicating that fast-charging tech may not be constrained to China.

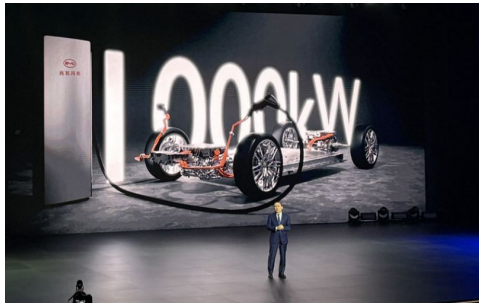
Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

Entering the Megawatt Charging Era: BYD (10C) & CATL (5-Minute LFP)

BYD

Megawatt charging is in development for heavy duty vehicles, but this has seen development for consumer vehicles as well. In March 2025, BYD unveiled its "Super e-Platform," which uses redesigned "Blade" batteries that support ultra-fast charging, high-performance electric motors, and a new generation of SiC power chips.

The Super e- Platform supports 10C charging and up to (1MW) charging power with a charging current of 1000A. BYD said is the first time the industry has used MW as a unit of measurement for charging power, signifying that charging power has entered the MW era. This enables 5 minutes of charging for 400 kilometers of range.



CATL

In April 2025, CATL publicly teased its next-gen Shenxing Pro LFP battery using its proprietary Non Propagation 3.0 technology that sets new benchmark for safety, lifespan, range and super fast charging designed for meeting Europe's expanding e-mobility market.

The Shenxing Pro is claimed to charge at 12C, adding 520 km (CLTC) rated range in 5 minutes - equivalent to 1.7 km per second. The battery is also claimed to deliver 830 kW at even 20% state of charge, accelerating from 0-100 km/h in 2.5 seconds.



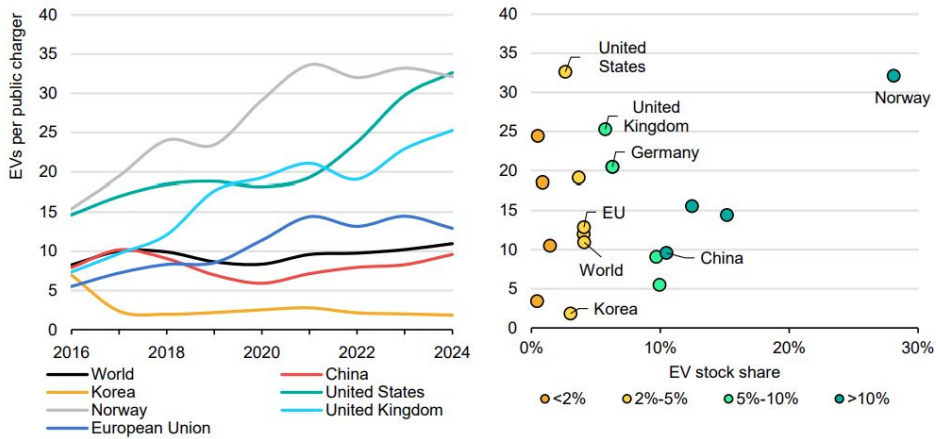


Source: (CATL), 2025, InsideEVs, 2025, BYD, 2025

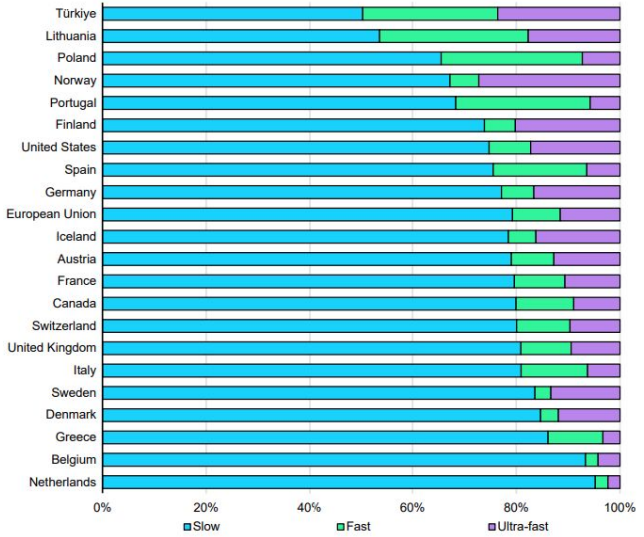
Public Charging Status

EVs per charger is rising in several markets as EV adoption grows, but public chargers are slower to deploy. Markets with higher EV share are seeing a plateau in charger availability. Slow chargers dominate deployment, with increasing interest in ultra-fast chargers (>150 kW).

Electric light-duty vehicles per public charging point in selected regions, 2016-2024 (left) and ratio compared to electric vehicle stock share in selected regions, 2024 (right)

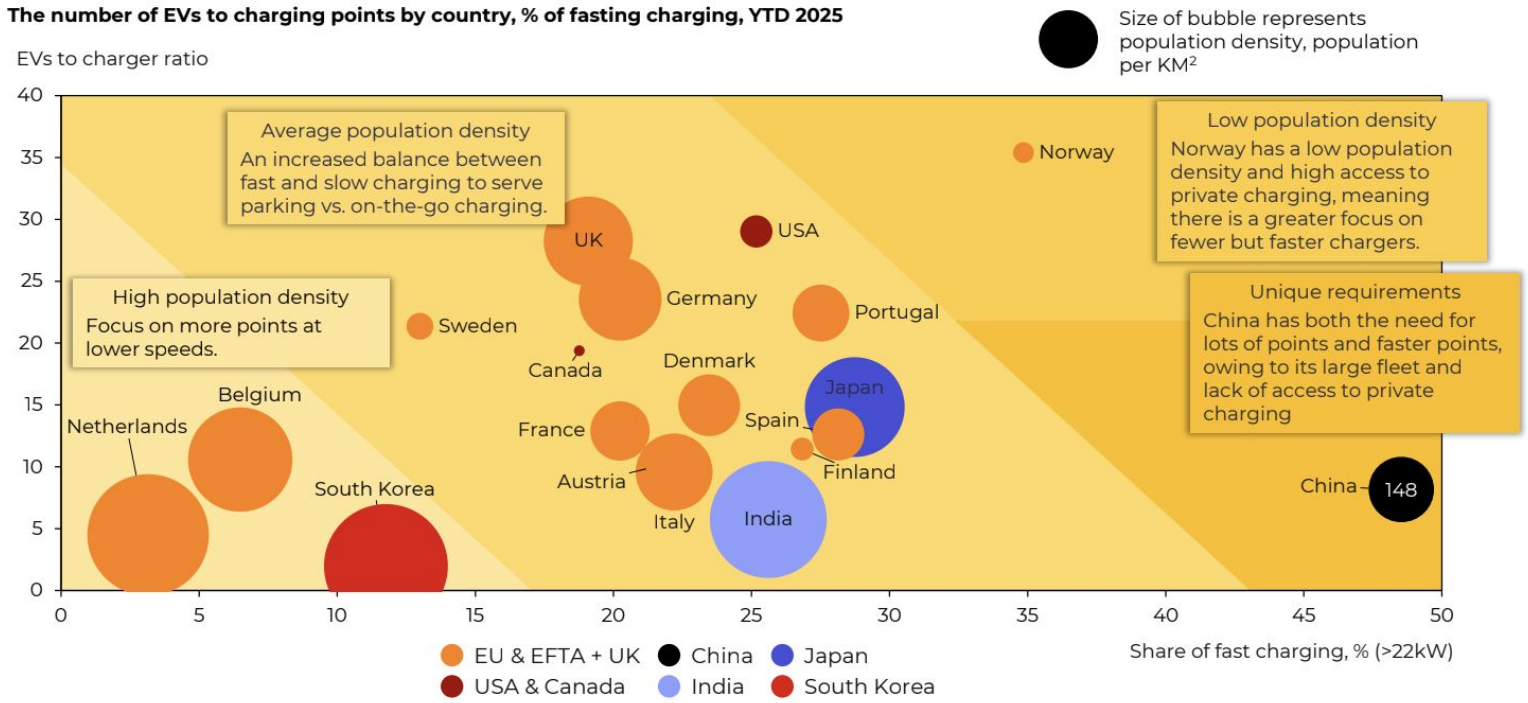


Proportion of slow, fast and ultra-fast public chargers in selected countries, 2024



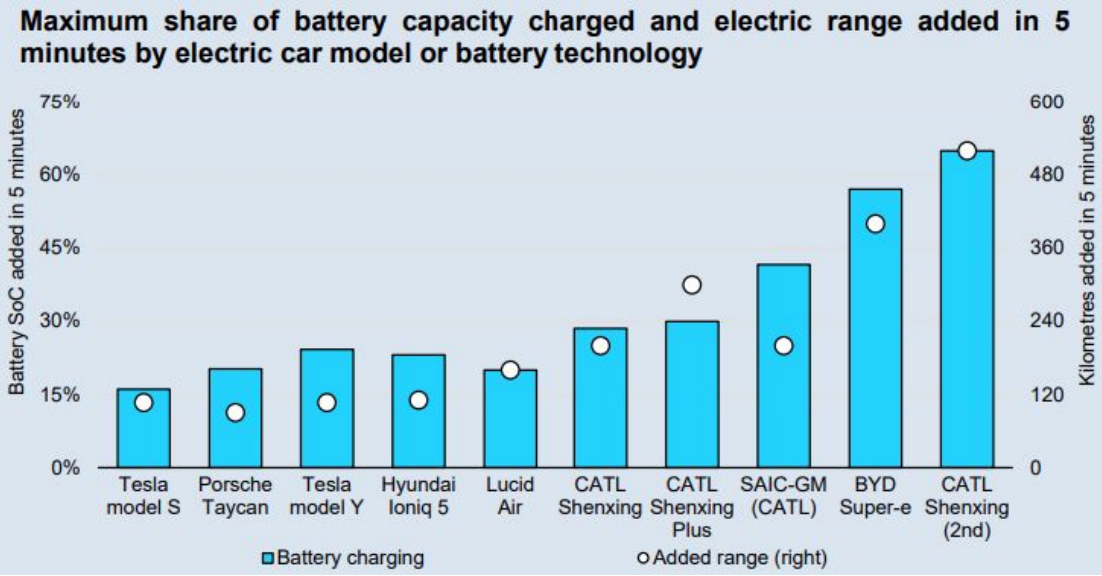
Source: IEA

Population Density Dictates Prioritization of Widespread Charger Quantity Versus Faster Charging Speeds



Fast Charging Performance

Chinese vehicles and batteries show the highest charging C-rates, although large-scale production vehicles are yet to be seen with this technology. Outside of China, while the Hyundai Ioniq 5 and Tesla Model Y have a higher C-rate, the Lucid Air shows the highest range added in 5 min owing to its higher driving efficiency.



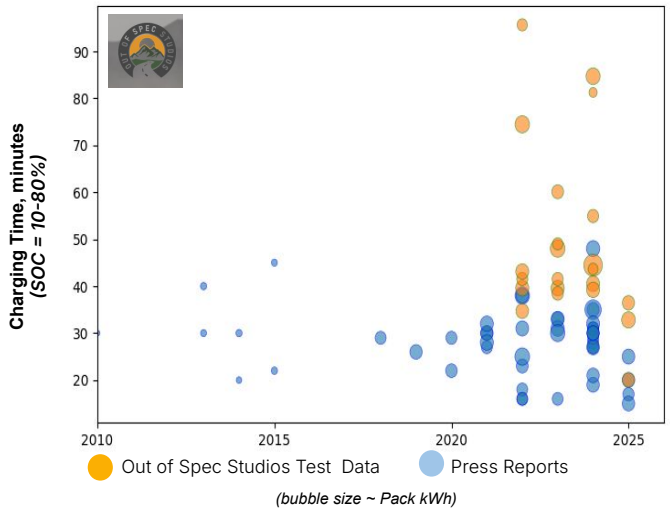
Source: IEA

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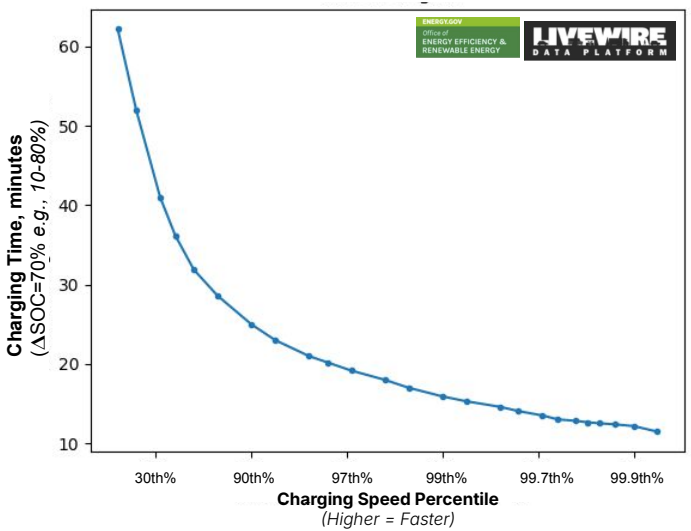
Fast Charging Trend Over Time - Fastest 10-80% vs Year

Charging times of EVs have steadily dropped while battery energy has increased. Real-world charging performance, however, often lags behind claimed numbers. Several factors influence real-world charging behavior, including weather conditions, HVAC use, battery age, battery temperature, charger limitations, etc.

Charge Times Improve, Packs Are Larger



Typical Performance Often Lags Optimal

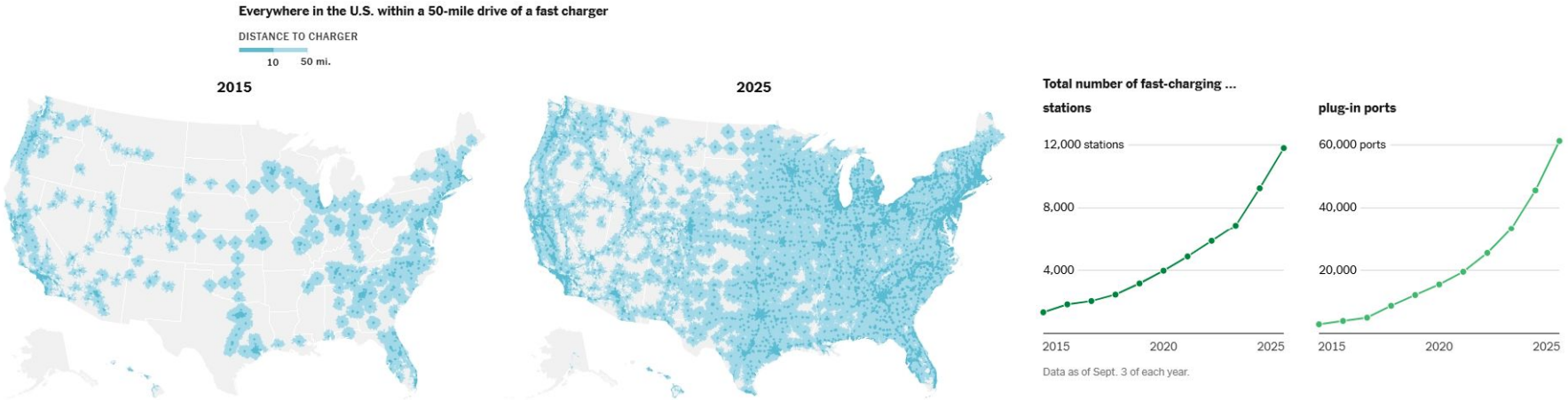


Source: Out of Spec Studios (Post-processed), EERE LiveWire EVWatts Data (Post-Processed), Press Reports from various OEMs

Fast Charging Infrastructure Growth in the US

Highway chargers in the US have vastly improved in density, with total charge port count increasing beyond 60,000

- High power DC fast chargers are a major feature of the interstate highway system in 2025
- Under the NEVI program, the goal is to have “a fast charger within 1 mi of the highway, every 50 mi of the interstate”
- The 60,000 chargers are about a third of the >180,000 chargers that are estimated to be necessary for public charging in the US (NREL)



Source: NY Times, Alternative Fuels Data Center, NREL: The 2030 National Charging Network

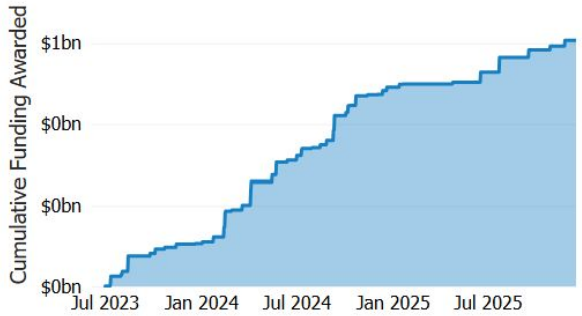
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Status of NEVI Awards for Charging Infra in the US

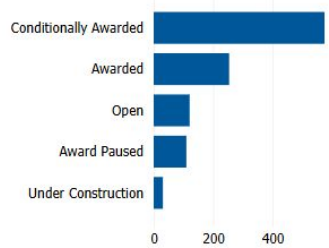
Cumulative funding for National Electric Vehicle Infrastructure (NEVI) projects reached **more than $3B** since FY22

- Between July 2023 and July 2025, disbursement totaled more than $1 billion.
- The rate of funding disbursement slowed from 2024 to 2025.
- Most chargers still deployed CCS connectors, followed by J3400/NACS connectors.
- Funding per port was roughly $136k and varies depending on the award recipient, with Tesla receiving and deploying a charger under $60k.

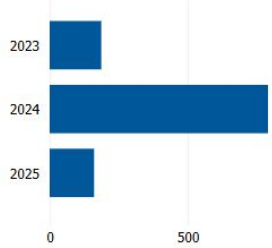
Funding Awarded Over Time



Site Status



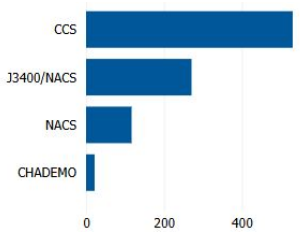
Year Awarded



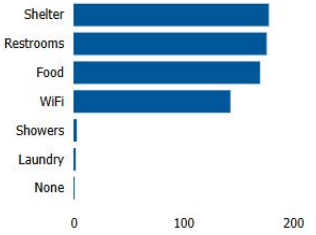
Top 5 Award Recipients

Award Recipient	Funding Awarded	Number of Ports
Francis Energy Charging	$107,757,066	494
Love's Travel Stops & Country Stores	$57,098,546	384
Tesla	$37,437,137	654
Universal EV Chargers	$34,747,976	183
Pilot Travel Centers	$29,061,080	211

Connector Types



Site Amenities



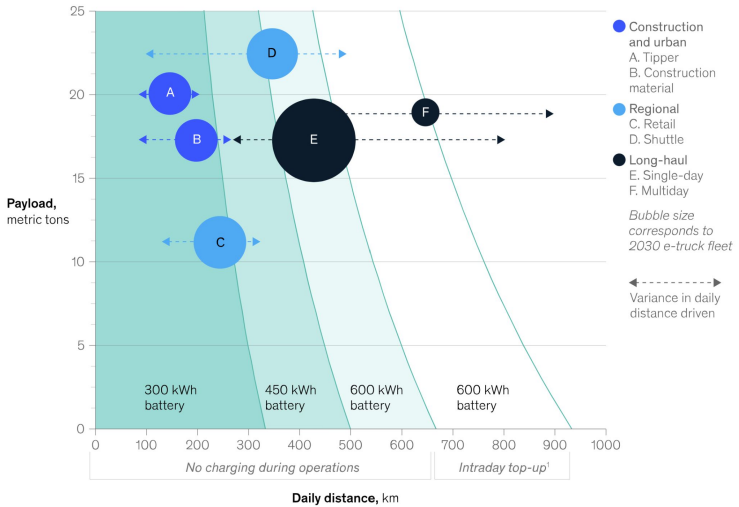
Source: EV States Clearinghouse

Charging Infrastructure for On-Highway Heavy Mobility (EU)

Charging is a major fraction of the TCO and ubiquity is necessary to reduce operational cost and flexibility. Long-haul operations need intra-day charging events.

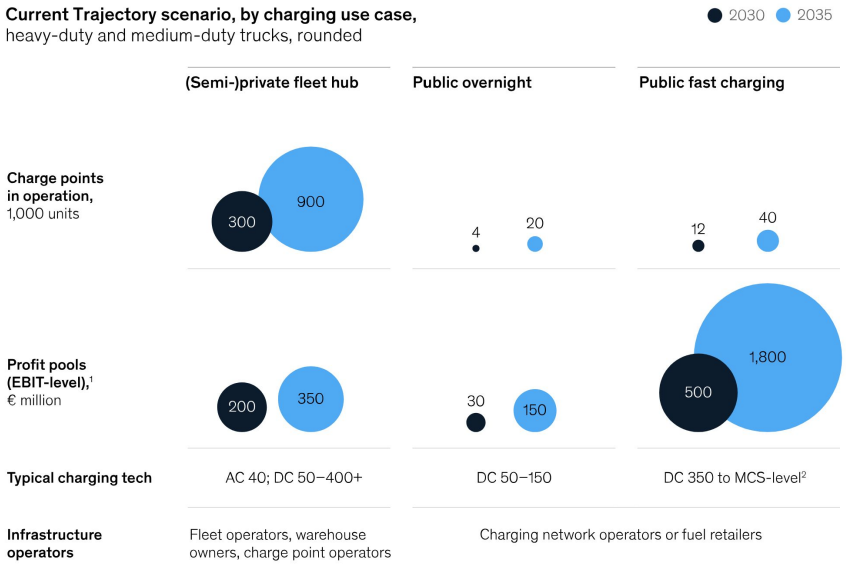
Public charging is the largest area for improvement since this has the lowest availability currently, but with the largest profit pool. Fleet operations also have the opportunity to ensure more predictable charging costs.

2030 view, use cases



¹Assumes charging during mandatory break of 45 minutes at 400 kW DC charger.

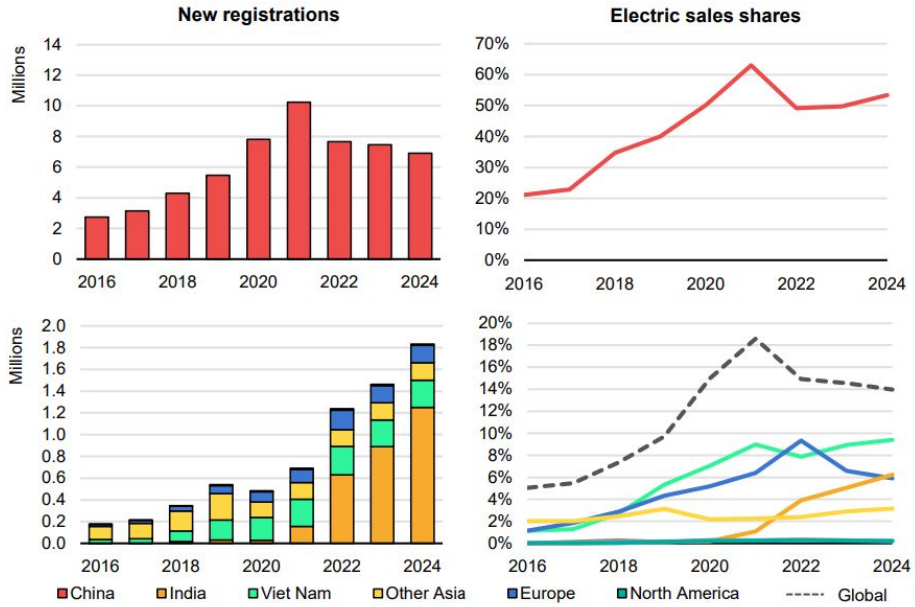
Current Trajectory scenario, by charging use case, heavy-duty and medium-duty trucks, rounded



Source: McKinsey Building Europe's electric-truck charging infrastructure

2-Wheeler EV Sales by Market

China leads the market, followed by India and Vietnam. Sales in China and Vietnam have **plateaued**, but India and other regions continue to **grow**.

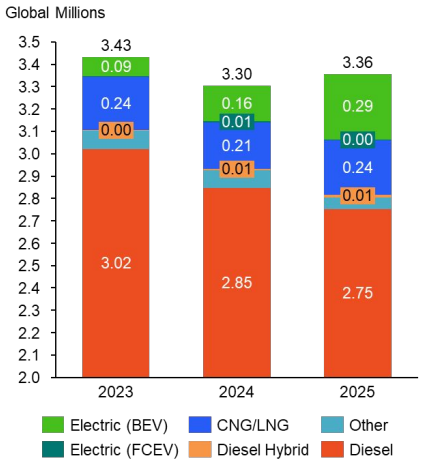


Source: IEA

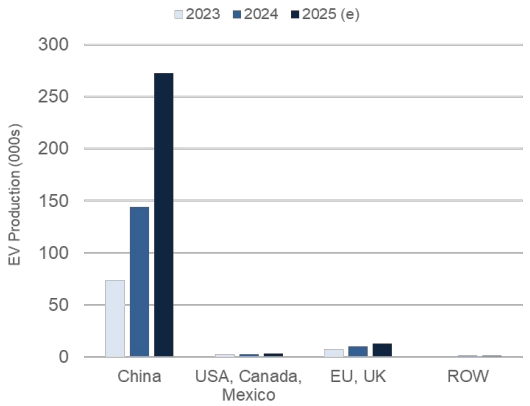
Heavy Mobility Market Developments - Market Size & Demand Growth

- Global electric truck and bus production (>6t GVW) is estimated to have increased 130,000 units in 2025 to nearly 300,000 vehicles, up from from 163,000 units in 2024 and just 90,000 in 2023. Total production increased to 3.6m units, giving BEV a 8.8% of the total, up from 4.7% in 2024.
- China accounted for the majority of volume and growth, increasing by 128,000 units, 89% in 2025.
- Stringent CO_2 and GHG legislation in Europe, US and China, alongside falling TCO for heavy EVs, will see over 717,000 BEV units produced in 2030.
- Total battery demand in 2024 is estimated at 96 GWh, up from 24 GWh in 2023, excluding spares for swappable batteries swapping in China.

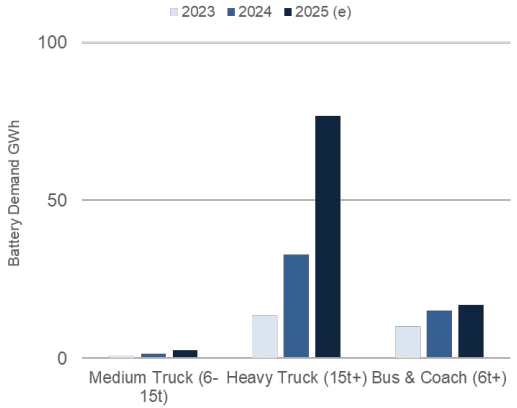
Commercial Vehicle Production >6t GVW - Fuel Type 2023-2025



Heavy Vehicle EV Production 2023-2025



Heavy Vehicle GWh Battery Usage 2023-2025

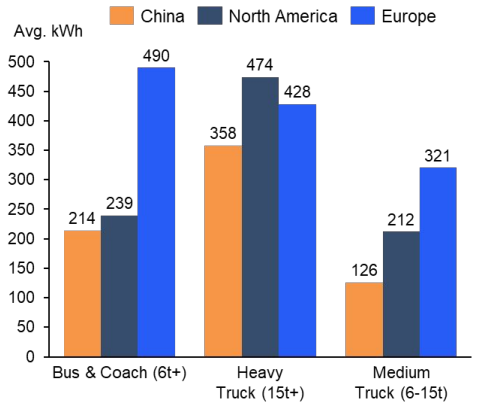


Source: KGP-GlobalData Global Commercial Vehicle Powertrain Q3 2025. EV Includes Battery Electric and Fuel Cell vehicles >6t GVW.

Heavy Mobility Key Players - Battery Solutions & Partnerships

- In 2025, Heavy Truck EV batteries averaged 358 kWh, Medium Trucks averaged 146 kWh, and Heavy Bus averaged 252 kWh.
- LFP is the dominant chemistry as OEMs prioritise cycle life and cost. Technology development will see battery life extending to over 1.6M miles, comparable with diesel engine vehicles.
- CATL dominates the global market, and announced its new TECTRANS LFP battery in 2024, estimated its share at 71% in 2025 at its capital raising.
- Other significant suppliers including Samsung SDI, Gotion and EVE. A slow down in the US e-truck market has seen the planned 2027 SOP for the JV between Daimler Truck, Paccar, Accelera and EVE, Amplify Cell Technologies delayed until 2028/2029.
- Battery swapping share in China share reached above 30% in early 2025, and expected to be stable in the near future

AVERAGE BATTERY SIZES BY SEGMENT 2025



CATL Dominates Global Supply

- In its 2025 Global Offering prospectus CATL reported it had a 71% share of the e-Truck and 80% of the e-Bus battery market.
- It expects the share of NEV (BEV mainly) CV trucks in China to increase from 13.6% in 2024 to 59.6%in 2030.
- Total battery demand for heavy CVs would reach 380 GWh in 2030 at these levels.
- CATL has 4 dedicated battery types for CVs:
  a. Tianxing L-Fast Charge/L-Long Range: Lifespan of up to 8 years, 0.8 Mkm.
  b. Tianxing Bus: Lifespan of up to 15 years, 1.5 Mkm.
  c. E-Truck: Lifespan of up to 15 years, 3 Mkm
  d. Tianxing battery for heavy CVs including construction and mining machinery.

AMPLIFY CELL TECHNOLOGIES

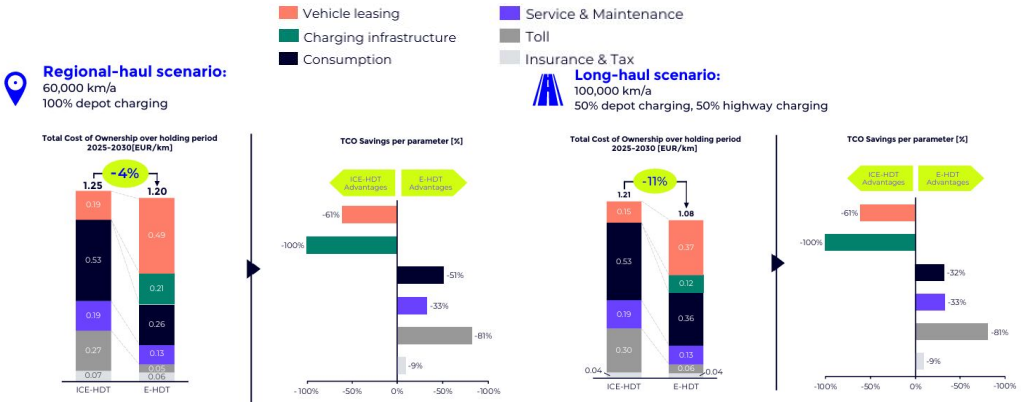
Amplify Cell Technologies

- Joint-venture between Daimler Truck (30%), PACCAR (30%), Accelera (30%) and EVE (10%).
- 21GWh capacity plant to start production in 2027, but delayed to 2028, due to market uncertainty.

Source: KGP xEV Model Database November 2025, CATL Prospectus

TCO & ROI Analysis for HD Regional vs Long-Haul Trucking

Regionally focused economic policies, fuel/energy cost, duty cycle, charging infrastructure, etc. are important factors that influence Total Cost of Ownership (TCO). To achieve cost parity with diesel, OEMs and operators must focus on hitting the right KPIs. Data released by Cummins illustrates the cost saving benefits of BEV compared to other fuels (when energy is <0.15 $/kWh). The projections assume a ~3.0-3.7x increase in upfront vehicle and charging infrastructure costs. By reducing the cost of the battery through a lower $$$/kWh or applying smaller but fast charging battery packs, ROI can be decreased. Many fleet level CFO's performing the risk analysis are seeking a break-even ROI of 3 years using a 8-12% discount rate in order to justify the switch from ICE.



Regional logistics applications typically travel <150 km per day. This reduces the dependance on large batteries if infrastructure can be put in place for short duration opportunistic charging 1-2 times per day. Smaller, high-cycle, and fast charge batteries have shown to produce a strong TCO and short ROI in these scenarios.

Long-haul logistics needs increased on-board stored energy to account for the sustained high tractive effort requirements. Improvements in $$$/kWh, Wh/kg, and Wh/L are all critical barriers in this space to achieve the ROI and TCO that will lead to mass adoption. Early e-HDT trials have also shown clear performance benefits.

Powertrain Type	BEV	FCEV	H2 ICE
Grid to Wheel Efficiency %	~75%	~25%	~15%

	Price Scenario	Price	Units (US$)	Fuel Consumption	Units	100,000 km H_2 Price p.a. (US$ Thousand)	5-year H_2 Fuel Price (US$ Thousand)
FCEV	Low	5	$/kg H_2	6.7	kgH2/100km	$33.3	$167
	Medium	7.5	$/kg H_2	8.1	kgH2/100km	$60.4	$302
	High	10	$/kg H_2	9.4	kgH2/100km	$94.3	$471
H_2-ICE	Low	5	$/kg H_2	7.0	kgH2/100km	$35.0	$175
	Medium	7.5	$/kg H_2	8.5	kgH2/100km	$63.4	$317
	High	10	$/kg H_2	9.9	kgH2/100km	$99.0	$495
BEV	Low	0.1	$/kWh	1.0	kWh/km	$10.0	$50
	Medium	0.15	$/kWh	1.5	kWh/km	$22.5	$113
	High	0.27	$/kWh	2.0	kWh/km	$54.0	$270
DIESEL	Low	0.9	$/L Diesel	7.3	mpg	$29.9	$150
	Medium	1.2	$/L Diesel	7.3	mpg	$38.8	$194
	High	1.5	$/L Diesel	7.3	mpg	$48.5	$243

Source: Electric Vehicles: Land, Sea, and Air 2025-2045: IDTechEx; P3 Total Cost of Ownership of E-HDT VS. ICE-HDT

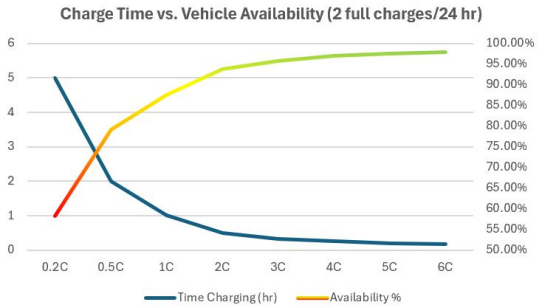
Heavy Duty Mobility: Drivers for Battery Technology Adoption in Heavy Off-Road Applications

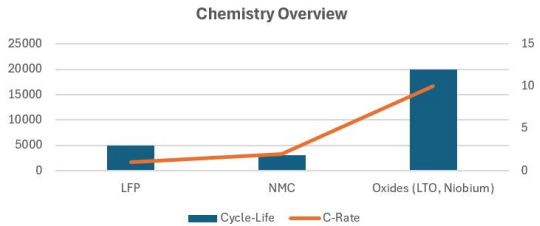
The HD commercial sectors are navigating pathways towards electrification with a critical lens for Total Cost of Ownership (TCO) and operability across a broad range of environments. Average Power and asset availability accounting for charging are good early indicators for an optimal battery technology strategy. While mini and light duty commercial sectors have begun to find a path utilizing NMC and LFP battery chemistries, OEMs and operators continue to search for the optimal strategy and technology that will enable larger vehicles to adopt full or hybrid electrification without diminished productivity.

HD Vehicle Battery Paradox

High utilization vehicles benefit from a significant reduction in fuel/energy cost as well as maintenance. However, if down time due to charging creates high out of cycle times, operators may need to increase their fleet size to compensate. This increase can counteract the initial fuel savings and harm TCO metrics. Selecting batteries focused on high-energy density, fast-charging, long-life, and/or a high-power hybrid solution will be important to finding the best operational fit.

ASSET AVAILABILITY TCO DRIVERS





STANDARD TCO DRIVERS

CAPEX		
Vehicle-related	Vehicle leasing considering residual value	☑
	Battery replacement within holding period	☒
Charging infrastructure related	Depot charging infrastructure installation	☑
OPEX		
Distance-related	Fuel, ad-blue and electricity cost	☑
	Highway toll	☑
	Lubricants and oil	☑
	Tires	☑
	Repair and service	☑
	Charging losses	☑
	Vehicle insurance	☑
Time-related	Depot charging infrastructure operation	☑
	Vehicle tax	☑
	Driver cost	☒
Revenue streams		
Vehicle-related	Vehicle subsidies	☒
Charging infrastructure related	Depot charging infrastructure subsidies	☒
Time-related	Greenhouse gas quota	☑

Source: P3 Total Cost of Ownership of E-HDT VS. ICE-HDT

Micromobility: Notable Events & Key Partnerships

APAC (excl. China)

Yuma Energy partnered with HPCL to boost battery swapping in India for ⅔ wheelers, utilizing HPCL's extensive network of retail outlets.

Battery Smart scaled India's battery-swap ecosystem to over 100,000 swaps per day through a partner-led model.

Banpu NEXT announced a strategic investment in Oyika, a Singapore- based technology company providing Batteries-as-a-Service (BaaS) for electric two-wheelers, to expand in Southeast Asia.

China

Chinese firms including ZhiZu, Beijing Pure Lithium New Energy Technology, and Yadea launched solid-state battery-swapping pilots for electric bicycles in Beijing.

National e-bike trade-in programs are driving greater battery standardization, safety, and recycling partnerships.

Middle East & Africa

EV LAB partnered with Pure Electric to introduce e-scooters and micromobility technologies into Middle Eastern markets.

Spiro raised $100M to expand electric motorbike production and battery-swapping infrastructure across Africa.

Source: Company announcements

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vaisala.com/battery

Micromobility: Notable Events & Key Partnerships

North America

- **Lime named Redwood Materials** as its exclusive recycler for end-of-life e-scooter and e-bike batteries across the U.S., Germany, and the Netherlands.
- **Lime partnered with Cyclic Materials** to recover rare-earth materials from retired micromobility vehicles.
- **Swobbee is participating in a New York City** pilot to deploy battery-swapping and charging infrastructure for e-bike delivery workers.
- **Rad Power Bikes** filed for Chapter 11 bankruptcy protection, signaling continued market consolidation.

Europe

- **Swobbee partnered with Yamaha-founded ENYRING** to deploy battery-swapping platforms in Berlin and Amsterdam.
- Charging and parking solutions provider, **Standab**, partnered with shared micromobility operators such as Dott and Tier to integrate standardized charging infrastructure across multiple European cities.

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing

Applications
- EV
- **Stationary Energy Storage**
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

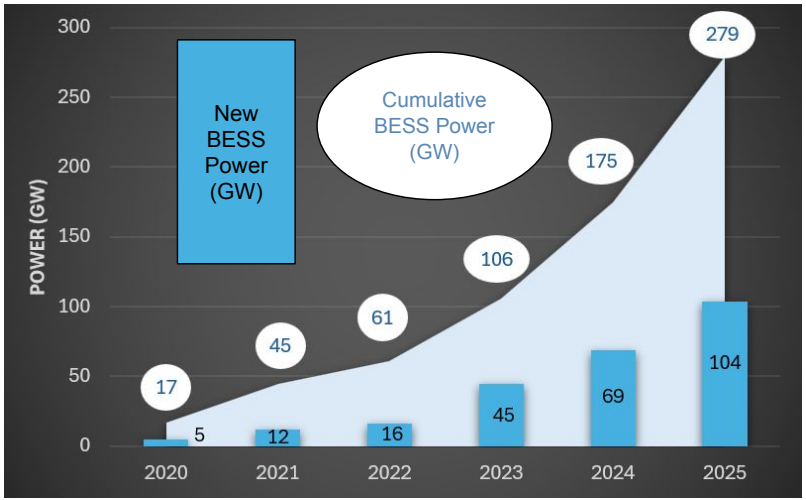
Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

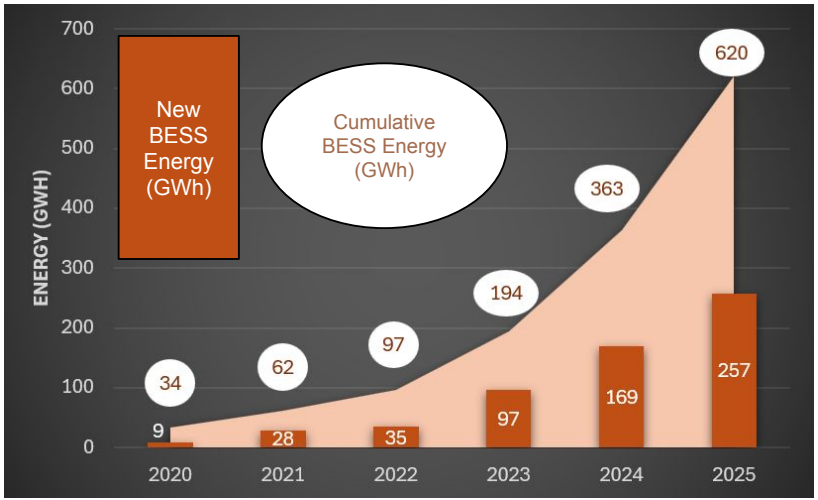
Software / AI

Battery Energy Storage Systems (BESS) New & Cumulative Deployment History

Midway into what BNEF called the "Decade of Energy Storage," BESS deployments continue to soar, with a CAGR of 79% by power. In 2025, new BESS installations totalled **104 GW / 257 GWh**, crossing the 100 GW mark for the first time, and bringing global cumulative BESS capacity to 267 GW / 610 GWh

- New BESS capacity added was approximately 10% of all global new power generation capacity brought online in 2025
- Average duration of new BESS projects has continued to rise, moving to approximately 2.5 hours, up 37% since 2020
- Costs have continued to plummet, hitting new lows even more quickly than anticipated
- Energy storage attractive policies continue to be the biggest driver for where and how fast BESS projects are deployed

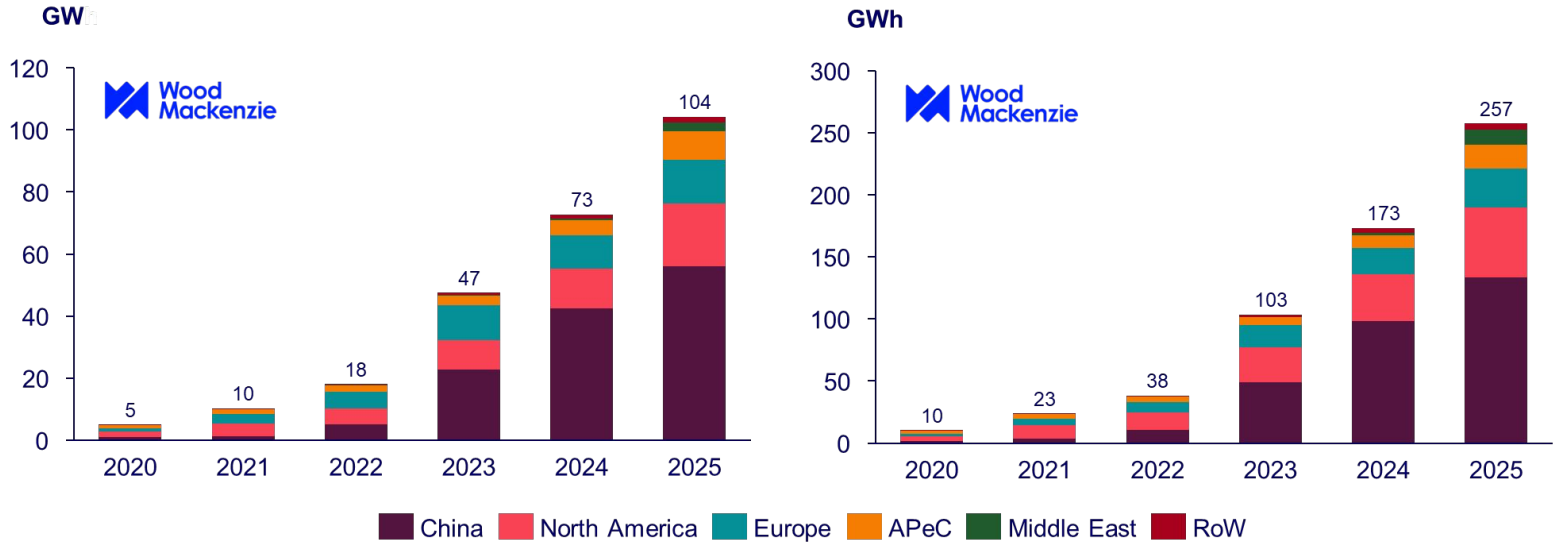




Source: Partner content data from Wood Mackenzie, BNEF, and IEA, Graphics by PowerSwitch. Note that 2020-2024 data varies from Regional deployment as this represents averages from a variety of reporters.

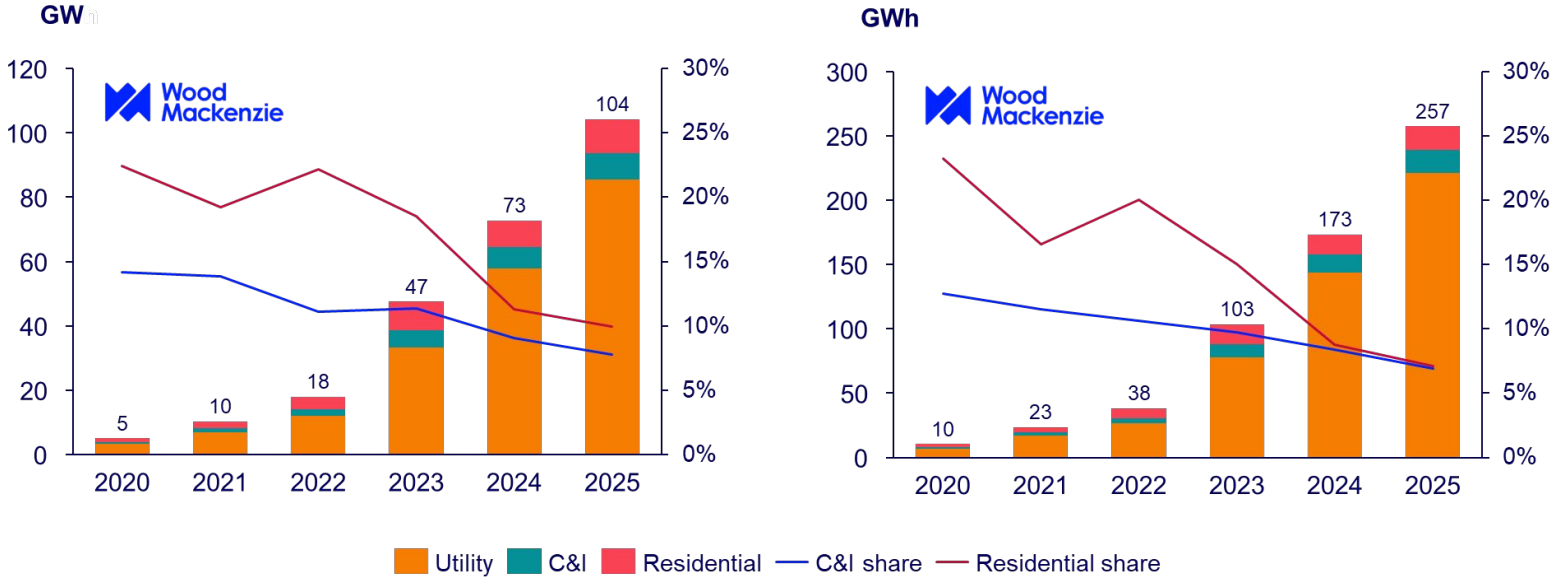
BESS Deployment by Geography (GW / GWh by Region)

The charts show annual new BESS capacity additions by region. **China dominated** with over half of global capacity deployments . **North America maintained a stable second position** in energy capacity (MWh), though the gap with Europe is much smaller in MW terms, indicating that US deployments favor longer-duration batteries on average. The **Middle East, led by Saudi Arabia, showed a remarkable boom** concentrated in just the last two years, rapidly closing the gap with APeC installations.



Global Overview of C&I & Residential Yearly Installation Trends

While **C&I and residential new installations are growing rapidly in absolute terms**, their relative share has plummeted over the past five years. **Both shares dropped to single digits** in GW and GWh terms in 2025. **More mature technologies and investor confidence have driven utility-scale projects to dominate** with over 80% of global new installed capacity in 2025.

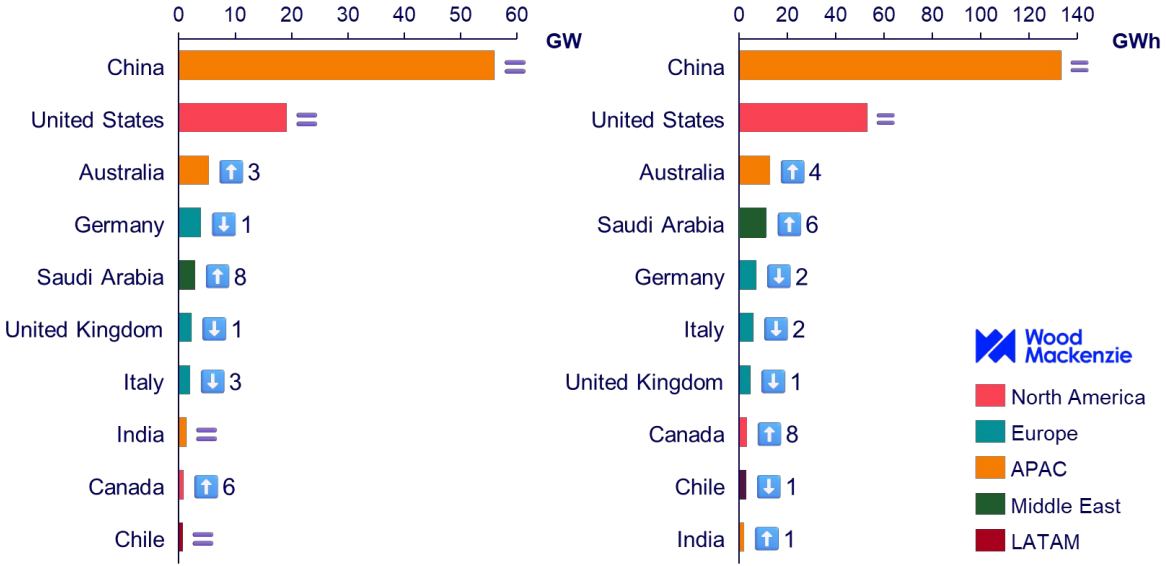


Top 10 Countries by BESS Deployed Capacity in 2025 (GW/GWh)

The charts show total deployed BESS capacity in 2025 across all applications and change in position with respect to 2024 deployment.

China dominates, representing over 50% of global capacity installed, while the **United States** maintains second place, demonstrating **sustained growth despite adverse policy headwinds.**

Saudi Arabia and Australia emerge as new leaders, both driven by massive utility-scale projects. In Europe, Germany, UK, and Italy confirm their positions as leading regional markets.



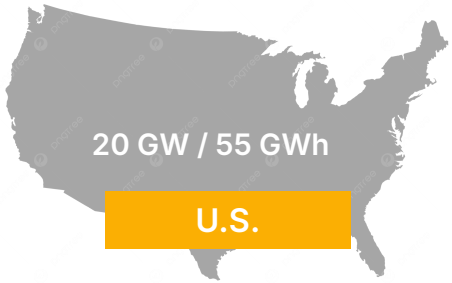
Source: Content & analysis provided by Wood Mackenzie (Distinguished Partner). For more information, visit https://www.woodmac.com.

Notable Regional BESS Developments



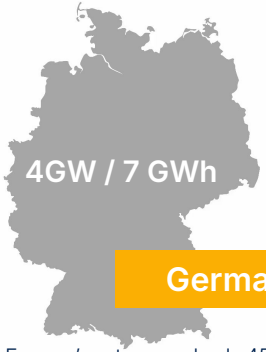
China

- Leading the charge in installations of energy storage projects
- With nearly 3x the installations, China is speeding away from the US, its next closest competitor
- Projects are driven by drastically lower costs than other markets based on local manufacturing capacity



U.S.

- Despite policy headwinds, the U.S. continued strong growth
- U.S. continued to dominate the largest projects in the world
- Foreign Entity of Concern (FEOC) provisions of the OBBB threaten to limit future grown
- Uncertain tariffs presented a large bias



Germany

- Europe's storage had 45% YoY growth, led by Germany
- Notably, the residential share is higher than in other leading markets



Australia

- Supported by aggressive government renewable energy target
- Energy-only market and strong frequency regulation value creates strong incentive for BESS deployment
- Coupled with high PV and wind penetration, BESS has come to be an indispensable tool to address fossil retirements and transmission congestion



Saudi Arabia

- Although smaller in absolute terms, KSA leads in average project size (GW) and duration, as well as annual growth
- Driven by Saudi Vision 2030 renewable goals and mega-projects backed by Saudi government
- KSA's installations have dwarfed those of other Middle Eastern nations

Source: CNESA, Wood Mackenzie (Distinguished Partner), PV Magazine

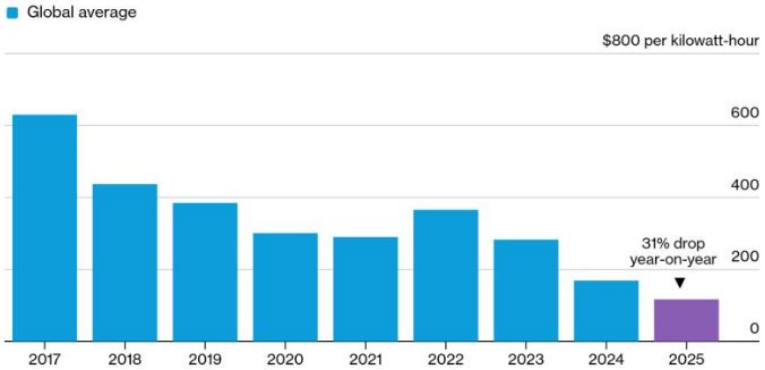
BESS Project Cost Trends - Massive Decline Continues with 31% YoY Drop

Prices for key components (DC-Block + PCS + MVT +EMS) vary greatly regionally and based on system size. As shown on the right, depending on the built location prices for the AC Block range from **$63/kWh** for large products in China, to **$120/kWh** for smaller projects in the EU.

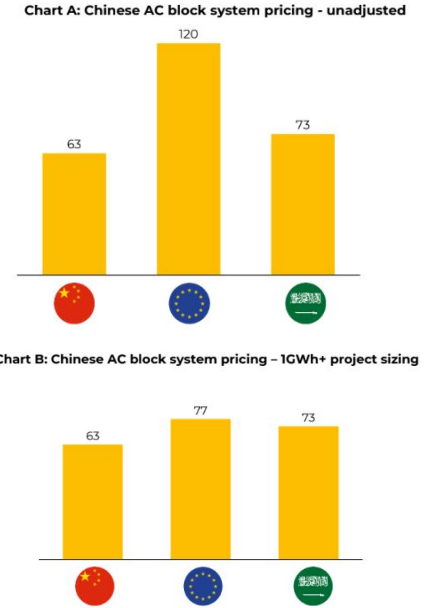
Turnkey BESS costs continue to plummet, **dropping another 31%** from 2024 → 2025, landing at $117/kWh (global weighted average across all markets and durations) - almost 70% down since 2022

In 2025 the same CapEx will build **over 3x** the system size (by MWh) than in 2022

TURNKEY BESS COST TREND 2017-2025 ($ / kWh) [2]

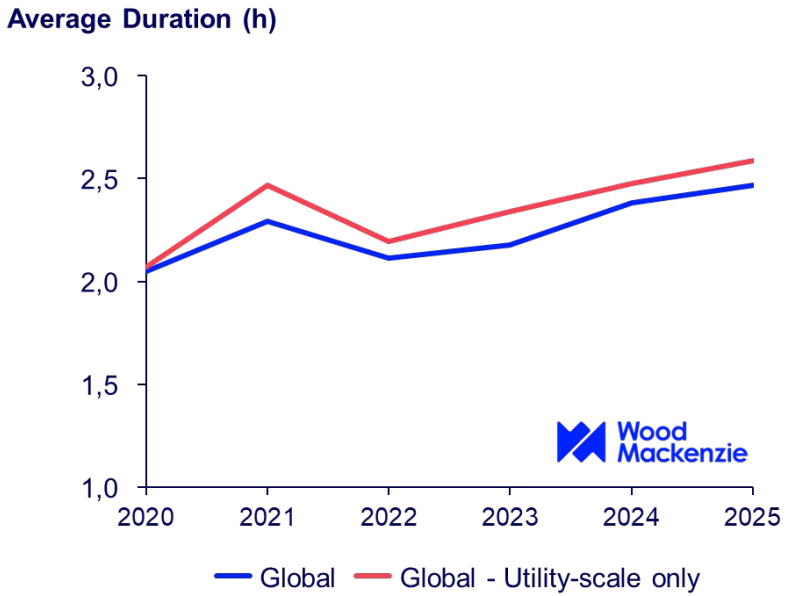


2025 KEY COMPONENT COSTS($/kWh) (DC-BLOCK + PCS + MVT + EMS) [1]



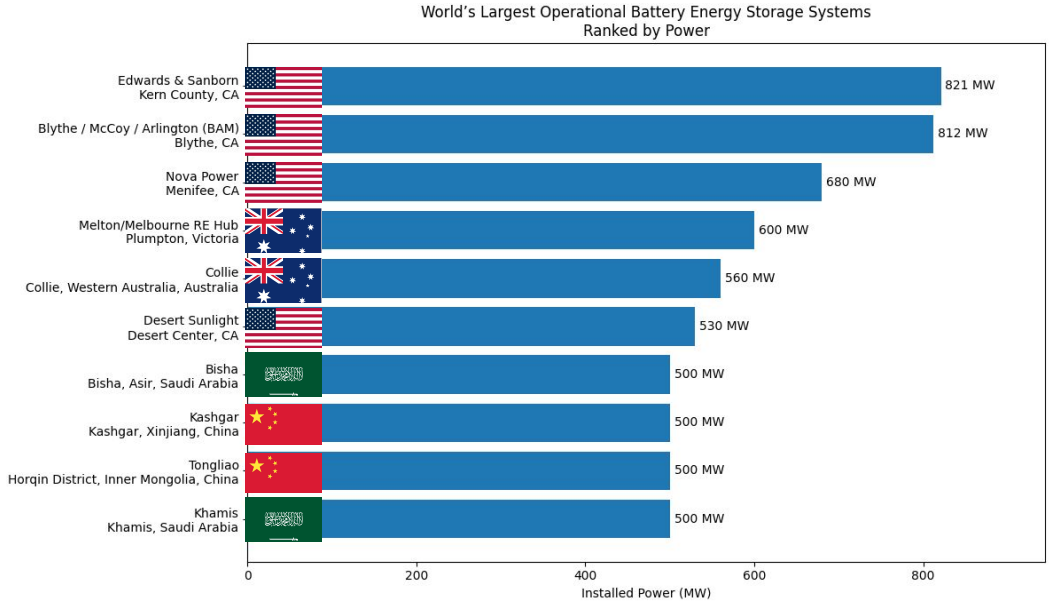
Duration Trends

- **Duration** of an ESS is defined as the ratio between energy (MWh) to maximum charge/discharge power (MW).
  - Duration typically ranges from 1-8 hours for most utility-scale applications, with most new LFP installations at 2 or 4 hours
  - Duration is the inverse of C-Rate (2-hour BESS equates to a C-Rate of 0.5, while 4-hour BESS equates to C-Rate of 0.25, etc.)
- Global duration of ESS has steadily increased, driven by falling energy costs, from **1.8 hours** in 2020 to **2.5 hours** in 2025.
- **Regional differences reflect market design**: Markets typically define the earnings of BESS; energy-only markets like Texas and Australia favor 2-hour batteries, where 4-hour requirements in China and California favor those durations.
- **Longer-duration configurations are becoming economically viable** due to falling costs, technological breakthroughs, and economies of scale, but have had limited deployments to date (<0.1% by power)
- **Longer-duration unlocks business cases**, enabling energy arbitrage, capacity and renewable firming, while still stacking ancillary services. The LDES case is also becoming a competitive alternative.



Leaderboard / Map of Largest BESS Deployments Across the Globe

This is a list of confirmed **operational** BESS global deployments ranked by the overall discharge **power of the deployment**



- While the US has fallen to China in overall GW and GWh, they still lead the mega-projects with **5 of the top 10**.
- **Saudi Arabia** was the breakout star of 2025, bringing online 4 giga-projects in the 2025 Top 10
- While there are several 1,000 MW BESS projects under construction, as of 2025 **no single project has broken the 1 GW barrier** - this is sure to happen in 2026.
- **Moss Landing** - The **750 MW / 3,000 MWh** BESS saw a **Jan 2025 fire destroy a major battery building**, taking a large portion (~300MW) of capacity offline and triggering an extended remediation and investigation.
- **Waratah Super Battery** - The NSW **850 MW / 1,680 MWh** project suffered a **catastrophic high-voltage transformer failure in Nov 2025**, halting final commissioning and pushing full operation into 2026.

Source: BESS100.org

Leading Energy Storage Project Developers

BESS developers are the firms acquiring land, signing offtake agreements, procuring components, and managing the EPC of the BESS project. The sector includes a mix of large and small firms, ranging from multinational IPPs with broad generation profiles down to small companies with only a handful of projects. This slide shows leading BESS project developers, classified per region where their largest project is located - please note that some developers also operate in regions other than the one mentioned.

Developers In North America



In North America, Arevia Power, GridStor, and OnStone were acquired, while Hecate Energy entered bankruptcy restructuring. In the US market, Key Capture Energy, SB Energy, and Vesper Energy have paused or slowed their BESS development pipelines

Developers In Europe And Latin America (*)



In Europe and Latin America, BW ESS merged into BW Renewables, Grenergy cut a third of its storage pipeline, Giga Storage suspended projects due to grid constraints, and Zenobē entered administration.
(*) projects in Latin America.

Developers In Asia And Africa



In Asia and Africa, JSW Energy shifted focus toward pumped hydro, Scatec exited several African storage markets, and Terra Solar was acquired by Reliance New Energy.

Developers In Australia



In Australia, Akaysha Energy reduced new project activity under BlackRock, Amp Energy exited parts of the APAC storage market, and Equis shifted its focus toward green hydrogen, slowing its BESS pipeline.

Source: BESS100.org

Notable 2025 BESS Mergers, Acquisitions & Bankruptcies

- **Powin Energy**, a DC-block integrator that was one of the pioneers in the U.S. market, filed for Chapter 11 bankruptcy in June. stranding over 11 GWh of deployed projects. Their assets were purchased by Flexgen in August. Hitachi acquired Powin's 20% stake in PCS manufacturer Eks Energy.
- Following the Northvolt bankruptcy, **Lyten** acquired Northvolt's BESS manufacturing infrastructure (Europe's largest), product portfolio, and IP.
- **AESI Terastor**, a US-based BESS integrator, declared bankruptcy in May.
- **Li-cycle**, a leading US battery recycler declared bankruptcy, also in May.
- **Hithium** had filed for IPO in Hong Kong (HKEX) in March 2025, but the application lapsed in September related to a $21m intellectual property lawsuit filed by CATL. HiTHIUM is still private as of the end of 2025.

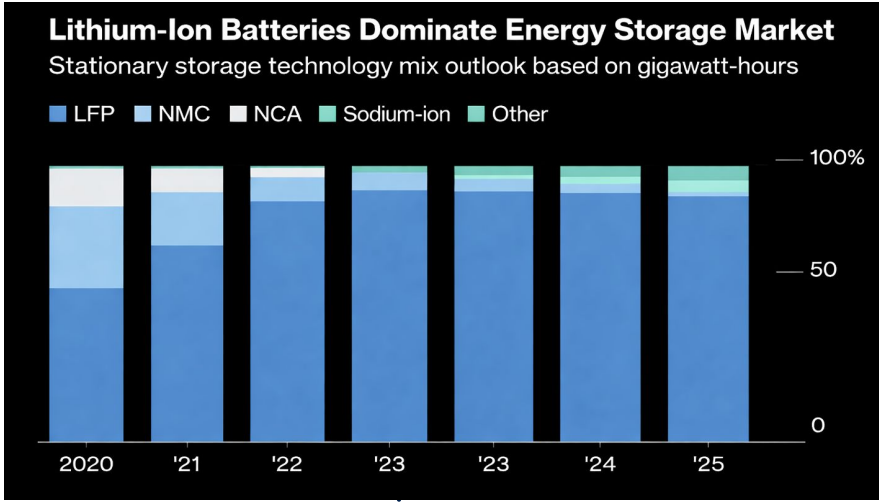
Leading Cell Chemistries & Market Share in BESS

Lithium versus alternative chemistries global market share

- **Lithium-ion batteries (>90%)** batteries remain the dominant technology
- **Lead-acid batteries (<5%)** persist in legacy & cost-sensitive applications
- **Flow batteries (<2%)** continue to be of interest for long-duration energy storage applications, with a pipeline of projects entering development phase
- **Sodium-ion batteries (<1%)** are garnering increased industry attention, with early commercial milestones achieved, including the first grid- and C&I-scale deployments

BESS market share within lithium chemistries

- LFP is the leading chemistry for stationary storage applications:
- **LFP** held the majority **market share of ~85%** held the majority due to its superior safety profile, longer cycle life, and cost-effectiveness compared to other lithium-ion chemistries
- LFP accounts for **over 80% of new deployments** across utility-scale and C&I sectors
- **NMC** persists in **legacy installations**, with its market share dropping to 33%



2020 - 2025: Increasing LFP capacity additions, at the expense of NMC market share

BloombergNEF Source: Future Market Insights; BloombergNEF (Distinguished Partner); company announcements

Li-Ion Continues to Dominate the BESS Market but Alternative Chemistries Are Making Strides

Sodium

Types:
- Sodium Ion
- Sodium Sulfur
- Sodium Metal Chloride

Example Companies:

BYD, CATL, PEAK ENERGY, ENERGY STORAGE NAS Sodium Sulfur Battery, HiTHIUM, LiNa Energy, INLYTE ENERGY

Flow

Types:
- Vanadium
- Iron Chromium
- Organics (Quinones, Solid organic)
- Zinc

Example Companies:

INVINITY ENERGY SYSTEMS, SUMITOMO ELECTRIC, ESS INC, QUINO ENERGY

Lead-Acid

Types:
- Vented/Flooded
- Sealed/VRLA (AGM, Gel)
- Bipolar
- Tubular

Example Companies:

STRYTEN ENERGY, Advanced Battery Concepts (Better Batteries, Better World®), EnerSys, EXIDE

Zinc

Types:
- Nickel Zinc
- Zinc Manganese Dioxide
- Zinc Bromine
- Zinc Ferrocyanide

Example Companies:

eos, ZincFive, URBANELECTRIC POWER

Metal Air

Types:
- Iron Air
- Zinc Air

Example Companies:

Form energy, ENERGY, ABOUND an energy solutions company

Source: Battery Energy Storage Surges as Global Leader Emerges; Batteries and Secure Energy Transitions (IEA); BNEF Global Energy Storage Growth Upheld by New Markets Storage Innovations 2030 Report; Achieving the Promise of Low-Cost Long Duration Energy Storage; Storage Innovations 2030 Awards

Sodium-ion (Na-ion) Cells Made Advancements in 2025 but Still Face Major Headwinds

Na-ion had a breakout year in ESS in 2025, with NFPP (Sodium Iron phosphate pyrophosphate) sub-chemistry in particular moving from R&D into major product offerings and large-scale BESS deployments. While still dwarfed by Li-ion, Na-ion is a rising competitor that aspires to be a safer, cost-effective alternative in the long term made from abundant, low-cost materials. To capture BESS market share it will have to outpace Li-ion's improvement trajectory on key metrics.

Proposed advantages of Na-ion:

- Safety: Higher thermal runaway trigger temperature
- Cycle life: Na-ion NFPP may exceed LFP cycling
- Lower degradation at hot and cold temperatures
- Wider temp. tolerance decreases aux. power needs
- Improved SOC calibration

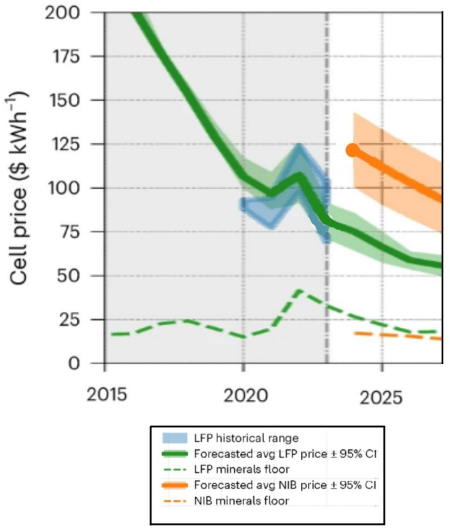
Major drawbacks:

- Volumetric Energy Density (270 Wh/L for Na-ion vs. up to 430 Wh/L for LFP, as reported by Roland Berger)
- Cost $/kWh (near-term)
- PCS optimisation

Developments in Na-ion ESS in 2025

- 50 MW / 100 MWh Na-ion Commissioning by HiNa
- Pilot projects by Peak Energy, Phenogy
- High-profile collapse of industry pioneer Natron
- BYD announces MC-Cube SIB BESS product
- CATL Naxtra product advancement
- Hithium launches hybrid Li / Na product
- Xingkong Na Dazhou Maliu Industrial Park 1GWh Na-ion battery commissioned

COST HISTORY OF NIB RELATIVE TO LFP



COMPARISON OF CHEMISTRY METRICS



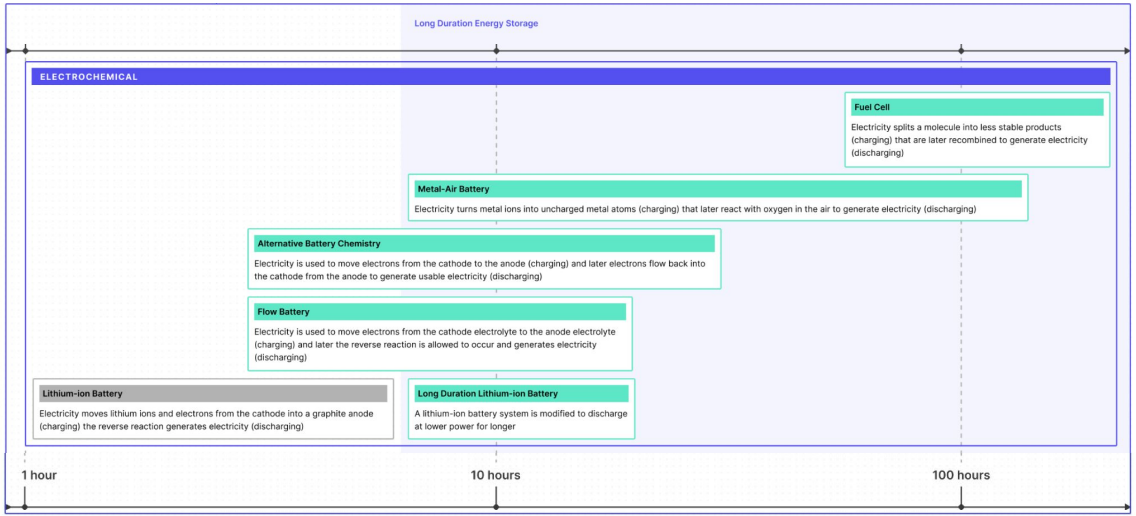
Source: Cell cost chart, Peak Energy, Jim McDowall. Roland Berger (Volumetric Density) (Distinguished Partner)

Cell Chemistry Predicts BESS Duration 'Sweet Spot'

In BESS applications, the duration of the system ranges from 1 to over 100 hours, and cell chemistries tend to have ranges where their cost and performance are most competitive

Li-ion has been the leader in the largest market segment, 2-4 hour projects. Falling costs have led it to be able to compete in 6-hour and 8-hour projects

Alternative chemistries excel at longer durations (8h+), but these markets are at early stages and are still very small relative to the 2-4 hour market.



sightline climate Source: Content provided courtesy of Sightline Climate. Note: Sightline's definition and framework are presented as context for the following charts and are not universally adopted.

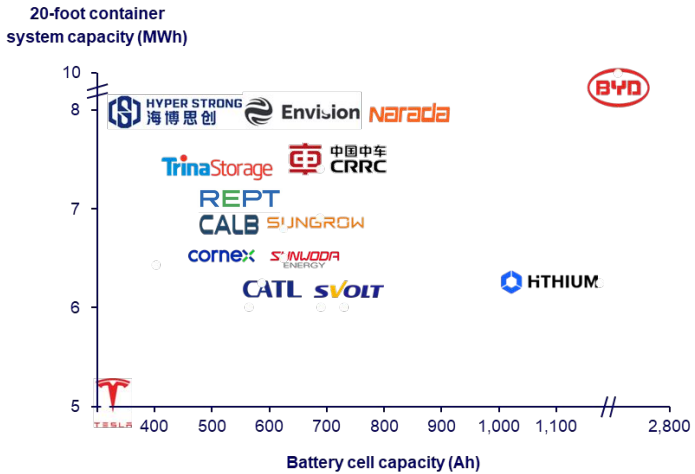
Product Features & Developments

- ESS cells continued to grow ever larger, with some exceeding 1000 Ah, driving 20-foot enclosure densities to exceed 7-8 MWh, although some battery suppliers chose to prioritize quality over density
- Chinese cell suppliers continued to develop their own DC-blocks, while non-Chinese suppliers shifted toward AC-blocks using 3rd-party cells
- Pre-lithiation technology, originally pioneered by CATL, has been adopted by other suppliers to offer zero degradation in the initial years of a BESS

ESS BATTERY CELL CAPACITY BY MANUFACTURERS

Manufacturer	300+ Ah	500+ Ah	600+ Ah
CATL	306/314	587	
BYD	300/320/340/350		2710
EVE	304/306/314	560	628/648
Gotion	300/314/330/340	588	650
CALB	314/392		640
REPT	306/314/320/340/345/392	564/587	625/688
BATTERO TECH	314/324		
HTHIUM	300/314/320	587	1130/1175/1300
鹏辉	314/320	590	
SUNWODA ENERGY	314		625
TrinaStorage	306/314	530/587	
Envision AESC	305/315/350	530	700
SVOLT	325/350/370		684/710/730/770
Narada	305/314/320/340	587	690/783
cornex	306/314/315/320	588	648/650/684/688

LARGEST 20-FOOT ENCLOSURE CAPACITY BY MANUFACTURERS



Source: Content & analysis provided by Wood Mackenzie (Distinguished Partner). For more information, visit https://www.woodmac.com.
Data collected and elaborated from company websites and announcements

Roundup of Developments in Utility-Scale Technology and Products

OEMs moving beyond fixed 20-ft containers toward modular, scalable configurations for flexible site deployment

Manufacturer	Product	System Capacity by Container Size	Illustration	Structural Highlights
FLUENCE A Siemens and AES Company	Smartstack	7.5 MWh/24 ft		Two-layer design: upper battery pod + lower PCS/control cabinet
CATL	TENER Stack	4.5 MWh/20 ft		Two 20-ft containers, each with 4.5 MWh, stacked to form a high-capacity 9 MWh storage system
海博思创 HyPER STRONG	HyperBlock M	3.2 MWh/10 ft		Each 10-ft module offers 3.125 MWh (DC) /3.2 MWh (AC), scalable via 2–8 modules arranged in a "side-by-side + back-to-back" layout
HTHIUM	∞Power 6.25MWh	6.25 MWh/20 ft		Single 20-ft container with 4 modular battery racks (4-hour) or 8 racks (2-hour)
SUNGROW	PowerTitan 3.0	3.45 MWh/10 ft 6.9 MWh/20 ft 12.5 MWh/30 ft		Three sizes available: Flex (3.45 MWh/10 ft), Classic (6.9 MWh/20 ft), Plus (12.5 MWh/30 ft)
TESLA	Megapack 2XL	3.9 MWh/29 ft		Two-container configuration with integrated battery modules, inverters, and thermal management

Source: Content & analysis provided by Wood Mackenzie (Distinguished Partner). For more information, visit https://www.woodmac.com.
Data collected and elaborated from company websites and announcements

AC vs. DC-block

Two competing architectures for battery enclosure have been rising within the BESS industry.

AC Block

PCS is pre-integrated into a single enclosure that outputs AC power directly



Pros:
- Simpler and quicker installation
- PCS included in the product warranty and easier O&M
- Simplified control system

Trends:
- Gaining market share in EU and US market due to design benefits.
- Tesla's Megablock advances MV AC block trend for 2026.

DC Block

The enclosure outputs DC power which feeds an external PCS (bi-directional inverter)



Pros:
- Flexibility to size the PCS
- Lower upfront cost (per-kWh)
- Allows for third party EMS implementation

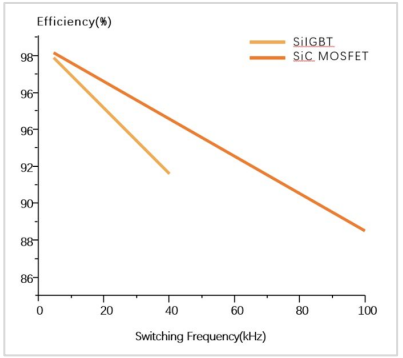
Trends:
- Preferred solution in solar+storage hybridation projects.
- Leads the energy density race at block level into 2026.

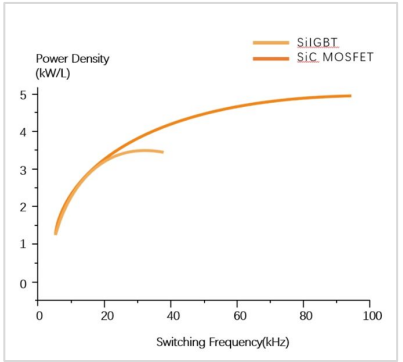
Source: Nor-Cal Controls, Saur Energy, LinkedIn - Drew Lebowitz, Fluence, Energy Storage News

Technology Trends in Energy Storage Power Conversion Systems (PCS)

Higher Efficiency, Grid-Forming, and Digitally Integrated.

- **High-efficiency power electronics**: wide-bandgap semiconductors (e.g., SiC) are increasingly favoured in PCS, as they reduce switching losses, lowering system losses, reducing cooling needs, and enabling better battery usage.
- **Grid-forming capability:** increasing number of PCS are able to replicate the behavior of synchronous generators, providing inertia, frequency regulations, and voltage control. This is crucial as traditional generators retire, enabling ESS to support weak grids, form islanded networks, and allow for high renewable penetration.
- **Digitalization & smart integration**: modern inverters are becoming smart energy management hubs, allowing for AI-driven performance optimization and predictive control. This results in improved ESS safety due to proactive failure detection, better lifecycle management, and better profitability.
- **Modular architecture**: Many leading PCS products offer a modular architecture, in which the PCS is divided into individual sections which can output different power levels. This allows an operator to tailoring the power outputs as different DC racks age unevenly, which is especially helpful following augmentation





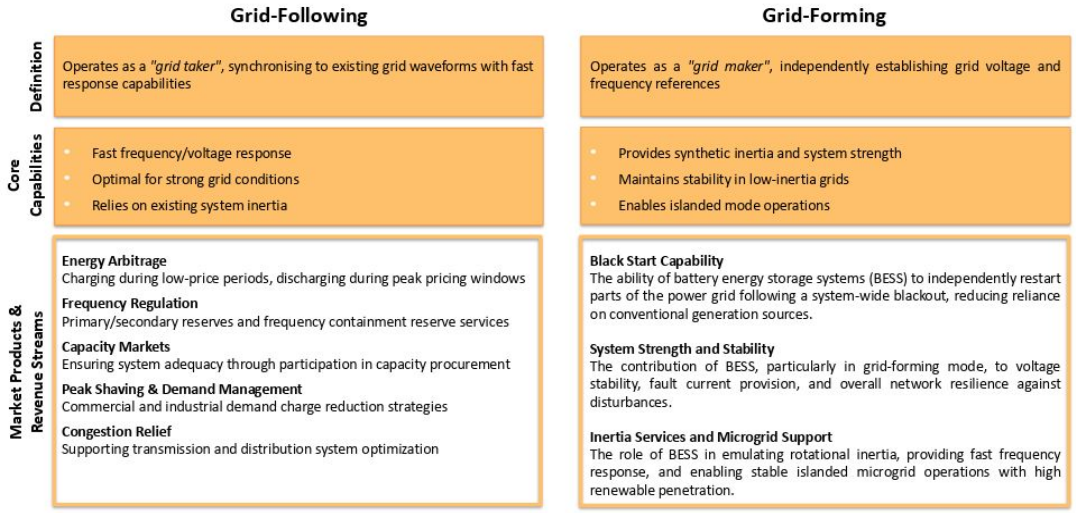
Source: Megarevo, Invergy, MDPI, ESN

Grid-following vs. Grid-forming

Energy storage PCSs come in one of two different configurations:

Grid-following systems are only able to output to an existing, stable grid. They can't operate independently during outages without backups like generators. The vast majority of PCSs for utility-scale storage are grid-following.

Grid-forming systems are able to operating in most conditions as grid-following, but should there be an outage, they can form their own voltage and frequency reference, enabling operation in both connected and isolated ("islanded") modes - like powering microgrids or critical sites during blackouts. This independence makes them essential for resilience in unreliable or decentralized grids.



Source 1: CIGRE-UK

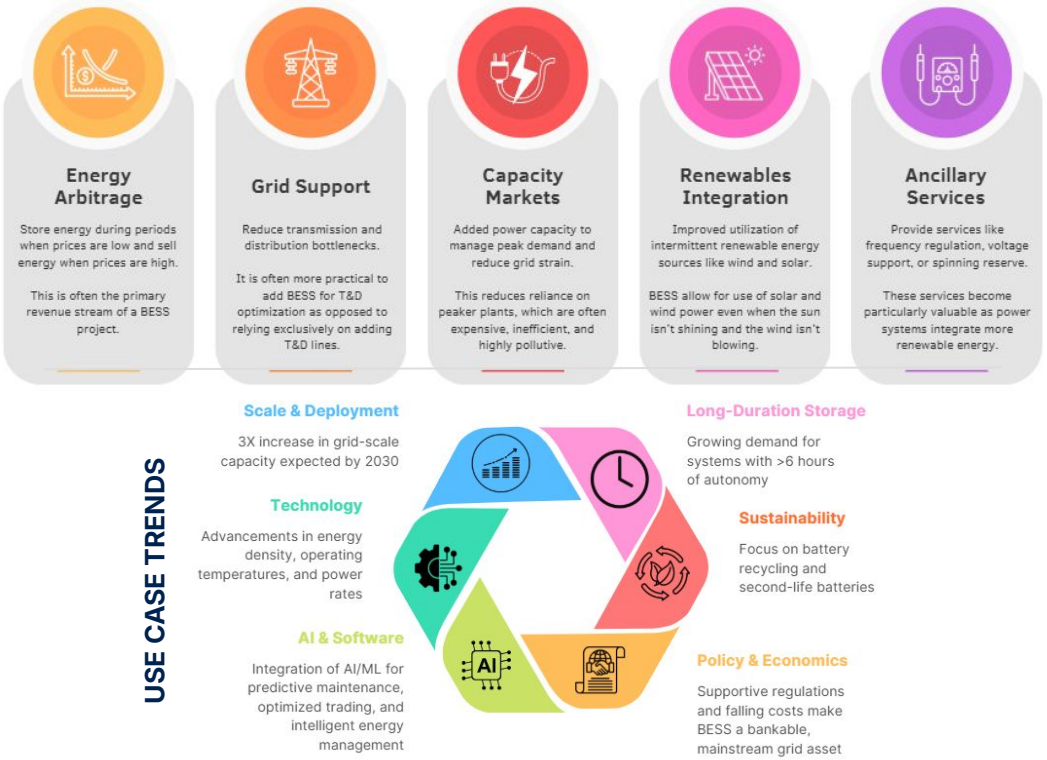
VF | VOLTA FOUNDATION

BESS Use Case Overview

BESS plants justify their capital cost by providing services to the power grid. Unlike PV or Wind, BESS do not create power, so their revenue is derived from contracted and real-time market participation.

Where BESS are connected directly to the grid they are referred to as **Front-of-meter (FTM)**, and when they are connected in parallelwith a load they are referred to as **Behind-the-meter (BTM).** Most Utility-scale BESS installations are FTM while C&I and Residential BESS tend to be BTM.

BESS Use Cases vary widely across markets, but here we have highlighted 5 of the leading revenue mechanisms used by BESS to monetize their operations. Notably, these services can be 'stacked' allowing the BESS to monetize many different revenue streams, either simultaneously or at different times of the day, month, or year.



Revenue Models / Summary of BESS Revenue Drivers (Merchant / Contract)

BESS play a critical role in integrating renewables, providing grid stability, and enabling energy arbitrage. Revenue models for BESS broadly fall into two categories:

Merchant (market-exposed): Relies on wholesale market dynamics (e.g., energy arbitrage, ancillary services like frequency regulation).

Contractual: Secures predictable income through agreements such as tolling (fixed fees for availability), power purchase agreements (PPAs), or capacity payments (e.g., Resource Adequacy in CAISO). Prioritizes stability, though it caps potential returns.

Hybrid models, blending both merchant and contract revenue, are increasingly common, as are **hedge agreements**, which provide revenue floors and other mechanisms in merchant markets. Both of these approaches serve to mitigate risk to the project.

The choice of business model is fundamentally driven by **revenue risk considerations**. The spectrum reflects a trade-off between revenue certainty and exposure to market volatility.

Model	Description and key features	Revenue characteristics
Pure tolling	Owners lease the asset to a third party, transferring dispatch rights in return for fixed revenues. Asset owners retain ownership but give up operational control.	Fixed revenue stream regardless of market conditions.
Rate-based cost recovery	T&D operators own energy storage as grid assets, providing services and recovering costs through regulated cost-based rates.	Regulated cost recovery ensures stable returns; market-based rate services may also be used if compliant with regulations.
Contracted revenue	Asset owners secure long-term contracts with offtakers, such as power purchase agreements (PPAs) or capacity-based payments. Asset owners retain dispatch and capacity rights under auction-based contracts.	Stable, predictable revenue stream over the contract tenor.
Floor-plus-share	In this hybrid model, optimisers (e.g. trading firms) guarantee a revenue floor and share profits above it, blending features of merchant and tolling models, akin to one-way contract-for-difference (CfD) structures.	Minimum guaranteed revenue or profit with additional upside potential. Optimisers cover shortfalls if revenues fall below the threshold.
Pure merchant	Owners charge/discharge electricity based on price signals in competitive markets, often using optimisers who share profits.	Revenue depends on price volatility. Owners benefit from price swings but also face downside risk. Revenue insurance may be used to mitigate risks.



Sources: BNEF, "Energy Storage Tolling: A Primer", March 2025; Macquarie Asset Management analysis.

Source: Macquarie (table)

Roundup of Developments in Commercial & Industrial (C&I) Business and Technology

Business Trends in the C&I sector

- **Revenue stacking** has become a key requirement for many C&I BESS projects to meet investment thresholds, with demand-charge reduction alone often insufficient in mature markets.
- Strong growth is expected through 2026–2036, with industry forecasts indicating high-teens CAGR; in the near term, **data centers are emerging as a fast-growing C&I application**, particularly in the U.S. and Europe.
- **BESS-as-a-Service** and similar business models are gaining traction; instead of high upfront costs of buying and maintaining assets, the C&I customers pay a periodic subscription fee that includes guaranteed asset performance and upkeep.

Technology Trends in the C&I sector

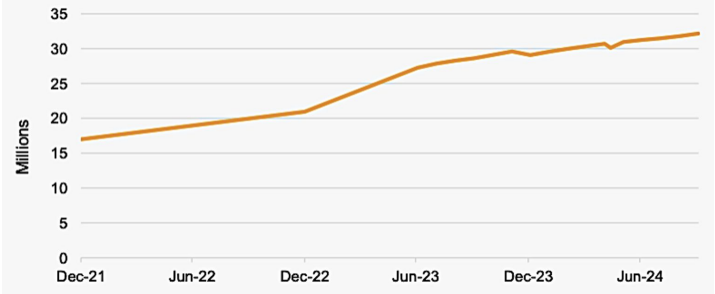
- The C&I market is increasingly served by **modular, integrated AC block systems in the ~100–150 kW / ~200–300 kWh range**, typically featuring integrated inverters, liquid cooling, and hybrid (PV-ready) functionality.
- **LFP chemistry** dominates, with a trend toward larger-format cells and higher-capacity battery modules as suppliers seek to reduce system-level costs and improve energy density.
- **Sodium-ion** remains at an early stage in C&I applications, with limited commercial deployment and no broad cost advantage over LFP evident in 2025.
- **Software and energy management** capabilities have overtaken hardware as the primary differentiator, as core battery hardware has become increasingly standardized and commoditized.

Source: IDTechEx; company announcements

Use-Cases and Revenue Models for Residential and C&I Customers

Residential, commercial and industrial customers are targeting long-term cost savings and improved resilience by investing in and using battery energy storage solutions. These solutions enable the implementation of individual energy strategies, taking into account cost, quality and time trade-offs. The trend of lower system prices and further asset usage optimisation via value stacking (i.e. via VPPs) is an additional growth driver for this segment.

NUMBER OF ACTIVE USERS REGISTERED THROUGH ENERGY RETAILERS INSIGHTS APPS (3)



QUALITY OF REVENUE MODELS FOR RESIDENTIAL AND C&I

	Residential	C&I
Behind the Meter (BTM)		
Tarif		
Peak shaving		●
Load shifting	◑	●
Self-consumption	●	◑
Aggregation		
Revenue stream participation	●	●
Regulatoric		
Decarbonization goals		◑
Electrification incentives	◑	◑
De-Risking Premium*		
Backup power	○	○
Power Quality		○

● good ◑ fair ○ optional

*revenue only if risk occurs

Virtual Power Plants (VPP)

Fundamentals on VPP

Definition: A Virtual Power Plant (VPP) is created by a entity that coordinates the charging and discharging of many small, distributed energy resources (DER, like residential or commercial batteries, but also EVs, thermostats and others) to act as one large battery resource on the grid.

Benefits: Coordinators manage these third-party owned assets, compensating the owners so the collective fleet can participate in larger-scale markets, such as ancillary service markets, that individual, smaller assets cannot access. Additionally, VPPs can be deployed faster to support grid congestion compared to utility scale assets.

Challenges: The success of VPPs is highly dependent on supportive regulatory, policy, and market rules. But also the availability of the right hardware in the infrastructure like smart meters. Additionally, the right communication protocols are need to avoid stranded assets.

State of VPP

Market State - NA: The US reached 37.5 GWh of VPP in 2025 (including batteries and other DER), 61% of the deployments are based on batteries and EVs. Sunrun operates one of the largest VPP with 375 MW / 75,000 home batteries. PG&E to use residential storages based VPP for proactive load shaping, contrasting to former peak shaving interventions, and plans with 412 MW total VPP power in 2025. The implementation of FERC Order No 2222 by the different RTO/ISOs is supposed to further drive VPP growth.

Market State - EU The largest players are Next Kraftwerk with 12.7 GW and Statkraft with more than 10 GW (both including all DER). In the UK, the implementation of BSC Amendment P415 (operational since Nov 25) facilitates the entry of “virtual trading parties” to drive VPP growth.

VPP with Utility BESS: Also large scale utility BESS are aggregated into virtual batteries to enable wider access without the hurle of ownership.

Source: RMI, Utility Drive, Codibly, Openadr,RMI, Electrek,Electrek, Latitude media, Latitude media, FERC, Enel, Next Kraftwerk, Statkraft, Zoeees, terralayr

Mapping LDES Technologies Across Durations

Duration	Representative technologies	Minimum deployment size, MW	Nominal duration, hrs	Representative OEMs
Inter-day	Traditional pumped hydro (PSH)	200-400	0-15	Andritz AG, General electric (24+ hrs)
	Novel pumped hydro	10-100	0-15	Quidnet energy (10+hrs)
	Gravity-based	20-1000	0-15	Energy Vault(2-18 hrs)
	Compressed air (CAES)	200-500	6-24	Hydrostor(8+hrs)
	Liquid air (LAES)	50-100	10-25	High view power (6+ hrs)
	Liquid CO2	10-500	4-24	Energy dome(8-24 hrs)
Multi-day/ multi-week	Sensible heat (e.g. molten salts, rock material, concrete)	10-500	10-200[2]	Rondo energy, Antora(24+ hrs)
	Latent heat (aluminium alloy)	10-100	25-100	MGA thermal(multi-days)
	Aqueous electrolyte (flow batteries)	10-100	25-100	Invinity energy systems,cell cube (2-12) hrs
	Metal anode batteries	10-100	50-200	Form energy(100+ hrs)

Source: LDES Scoping Report

Long Duration Energy Storage (LDES) Technology Use Cases

LDES technologies can play multiple roles in power systems with a high penetration of intermittent renewable energy

LDES technologies as flexibility resources and their role in power systems

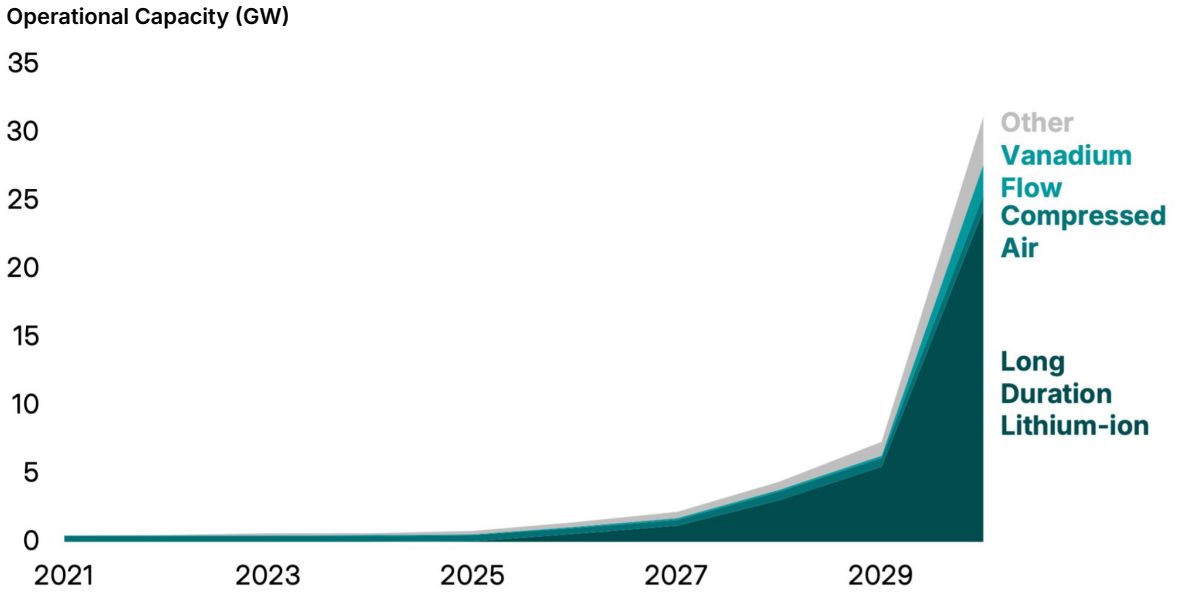
Flexibility options	Functions in the Power System					
	Maintaining stability	Peak capacity	Mitigating grid congestion	Addressing multi day imbalance	Addressing seasonal imbalance	Responding to extreme weather
Dispatchable generation						
Short duration lithium-ion ESS						
LDES						
Demand response						
Enhanced electricity interconnection*						
Transmission line building						

Source: Content & analysis provided by Wood Mackenzie (Distinguished Partner).
For more information, visit https://www.woodmac.com.

Very Suitable Suitable in some cases Not Suitable

Committed Projects Anticipate LDES Growth to 3% of BESS by 2029 from 0.1% in 2025

LDES PROJECT PIPELINE BY OPERATIONAL DATE



0.5GW/4.4GWh of LDES projects are operational outside of China (0.1% by power). Only 91MW/563MWh of that capacity has been installed since 1991, of which 35MW/300MWh came online in 2025 (>14× 2024 additions).

8-hour lithium-ion projects comprise 78% of the project pipeline projections for 2030. However, most LDES policies are technology agnostic and heavily weight bid price and deliverability.

- Policies in California and Ontario, Canada, exclude lithium-ion and could enable early deployments of emerging technologies that reduce tech risk and bring down cost

sightline climate Source: Content provided courtesy of Sightline Climate. Developer-provided COD estimate. Data excludes pumped hydro.

Manufacturing Supply Chain QA/QC for BESS Equipment Buyers

While the majority (72%) of failures is known happen during construction, commissioning, or within the first two years of operation. In 2025, 19% of projects experience reduced returns due to technical issues and unplanned downtime. Integration, Assembly & Construction is a critical phase in BESS risk mitigation.

Market Intelligence

Supply Chain: A macro understanding helps mitigate purchase risks (geopolitical, shortages, etc.)

Regulations: recent and constantly evolving laws & regulations shape the market (US tariff evolution, FEOC compliance)

Pricing: Volatility of pricing is rising by many factors that should be known (balance between oversupply and tariffs)

Technology: Newest technology evolutions are shaping BESS projects (modularization of BESS, new chemistry evolution)

Suppliers & Product Due Diligence

Factory Audit: assess a supplier's Manufacturing Process and the Quality Management System.

Traceability Management System Audit: ensure the ability of the manufacturer to trace its own supply (impact of recalls, delivering specific products,...).

Supply Chain Mapping: Validate that manufacturers can trace their supply chain (derisk the US CBP verification)

ESG Management System Audit: Ensure the BESS is ethically sourced and respecting legislations.

Contracting Support

Tendering Support / RFP: Evaluation of suppliers relies on key aspects that depend on each BESS project. RFP templates can be standardized to qualify suppliers.

Technical Contract Negotiation Support: the BESS industry is getting more and more specialized, technical support is necessary.

QAP & Technical Exhibit: Testing of BESS products during manufacturing depends on the contractual limits set beforehand. In particular, the **Factory Acceptance Test Scope review** is key to ensure a functional BESS.

Conformity Assessment

Pre-Production

- Product conformity assessment
- Pre-production inspection

During Production:

- Production monitoring
- Manufacturing records verification
- Supply chain mapping

Post Production:

- Factory Acceptance Test (FAT)
- Capacity check
- Battery data analytics
- Loading monitoring

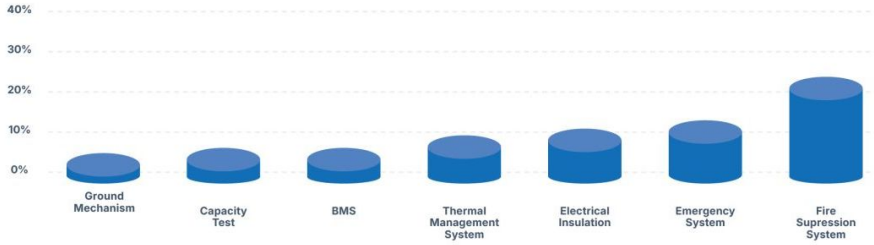
Source: EPRI, ESS-news about Accure report, Energy Storage News, DOE Procurement, FootAnstey

Frequent BESS Non Conformities Found During Factory Acceptance Testing

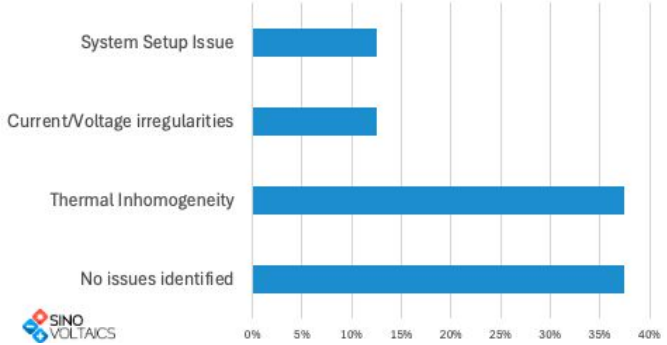
BESS require rigorous testing to identify non conformities (NCs). Most NCs are related to the safety systems of the BESS.

- During the Factory Acceptance Testing (FAT) of BESS production by third party quality control company, the NCs are classified as Critical(*)/ Major(**) / Minor(***) / Opportunity for Improvement.
- Safety systems comprise 20% of non-conformities
- Depending on contract struction, buyer can require corrective actions from the manufacturer for NCs before shipping
- FAT's capacity tests shows that 66% of BESS projects missed at least one acceptance criteria not met.

2025 BATTERY ENCLOSURE NON-CONFORMITIES



FAILURES FOUND DURING CAPACITY TEST DATA ANALYSIS



(*) **Critical**: A defect that is likely in hazardous or unsafe conditions for the individual using the product, likely to cause damages to other products or property or that is generally contravening mandatory regulations.
(**) **Major**: : A defect that may reduce the stability of the product or cause the product to fail to perform its function. Obvious appearance defects. Those are likely to reduce the sales ability of the product.
(***) **Minor**: A defect that doesn't reduce the usability of the product but is nevertheless a workmanship defect beyond the acceptable quality standard

Source: STS LinkedIn, Sinovoltaics & Volytica

Large Scale Fire Testing (LSFT) Became an Established Testing Requirement in 2025

A change in the **2026 Edition of NFPA 855**[1] supplanted **Edition 5 of UL 9540A as the de-facto Large Scale Fire Test.** However, consensus was reached in August of 2025 on a new revision that will bring the UL 9540A test method back into alignment with the intent of NFPA 855 and the model fire codes that reference it.[2]

Standard	Focus	What	Why
UL 9540A Ed. 5 [Edition 6 publication target March 31, 2026]	Thermal runaway behavior, fire and gas hazards, module/unit propagation	Internal propagation, gas composition, ignition susceptibility, flame/heat characteristics	To understand internal failure mechanics and gas hazards.[3] Consensus revisions provide data required to determine separation distances, suppression design, and installation safety
Large Scale Fire Testing (per 2026 NFPA 855, no specific standard referenced)	Fully developed unit-level fire + external exposure risk.	Real-world fire spread, heat flux to exposures, suppression performance, structural risks	Required to determine separation distances, suppression design, and installation safety[4]
UL 9540B Outline of Investigation	Residential ESS fire propagation	Fire severity and spread from a failure of an ESS in a residential setting.	Addresses risk to occupants by evaluating the *"fire propagation characteristics of residential BESS"*[5]
CSA C800 {Note: CSA TS 800 interim specification now incorporated into this document.)	Reliability & QA	ESS reliability under extreme external abuse conditions	Establishes BESS behavior when subjected to abuse resulting in a developed fire condition.[6] Developed to supplement UL 9540A Edition 5.





Source: NFPA Standards Council Decision, UL Standards Activity, UL 9540A, Edition 5. See *Scope*, NFPALink®, UL 9540B, See *Scope*, CSA Group

Notable Advancements in Codes and Standards for 2025

2026 NFPA 855[1,2]

- General requirements applicable to all ESS now found in exclusively in Chapter 4.
- Emergent battery chemistries have been included, formerly falling into the "Other" category. Lead-acid, aqueous nickel-based, and aqueous metal-air batteries now have consistent exclusions throughout.
- Exclusions have been added to Chapter 14 to allow for temporary storage of Li-Ion batteries under certain conditions.
- New requirements for emergency response plans, EV charging systems with integrated ESS, flow batteries, and ESS on barges.
- Annex Section G.8 has been revised to aid in evaluating the potential consequences of an explosion event.
- Decouples UL 9540A (Edition 5 and prior) from Large-Scale Fire Testing. Both are now required for the reduction of prescriptive sizing and spacing - in response to concerns that prior large-scale test requirements and hazard analyses did not consistently capture realistic multi-enclosure failure scenarios and emerging ESS technologies.

2026 National Electrical Code[3,4]

- Sizing guidance clarified for behind the meter ESS, providing for more consistent interpretation and application.
- Allowances for Power Control Systems (PCS) to manage current flow and provide inherent overcurrent protection.
- Expanded guidance on bidirectional power and grid integration

UL 9540, Edition 3 redlines published in 2025[5,6]

- New product certifications after the effective date of September 2024 must comply with Edition 3.
- Significant update to introduce clear definitions and marking requirements for both *AC ESS* and *DC ESS*. Each component in an ESS is now more appropriately defined by its function, rather than physical location.

UL 3601 and UL 1974 represent an emerging focus on battery lifecycle and circularity

- UL 3601 Edition 1 published in July 2025 establishes a framework for measuring and reporting on the sustainability of Li-ion and other secondary batteries. In parallel, UL Solutions now offers an ECOLOGO® Certification fro Circularity of Batteries.[7,8]
- UL 1974 Edition 2, first published in November of 2023 is currently in active status with several changes being proposed. Provides a path for repurposing EV batteries in less-demanding stationary storage applications.[9]

Taken in aggregate, these changes highlight near-term stabilization in safety-related ESS codes and standards, while also demonstrating an industry shift towards maturity and sustainability.

Source: NFPA 855, 2026 Edition, Meyfire Blog, NFPA 70, 2026 Edition, IAEI Magazine, UL Standards and Engagement, Sustainable Energy Action Committee (SEAC), UL 3601, Edition 1, UL Solutions (UL, LLC), UL 1974: Creating a Safe Second Life for Electric Vehicle Batteries

Warranties & Performance Guarantees

BESS warranties and performance guarantees have become more standardized across the industry, and are a requirement for BESS

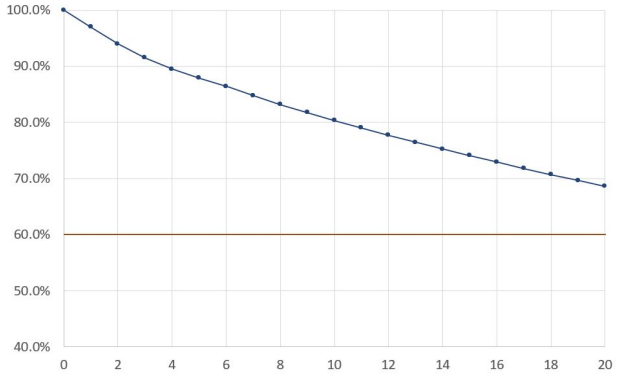
Product warranty (usually between 2 and 5 years)

- Covers defects in materials, workmanship, and serial defects in initial years of operation
- Typically included in both the Battery Supply Agreement, and also in the EPC agreement (whether turnkey or balance-of-plant)

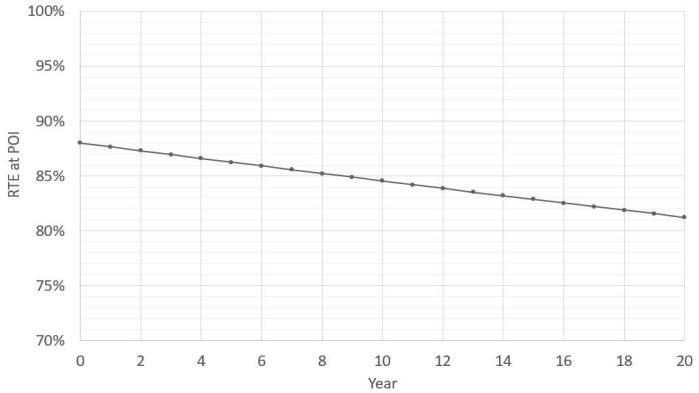
Performance warranty / guarantees (from 10 to 25 years) - tied to extended product warranty

- Energy Capacity Degradation, round-trip efficiency (RTE), and Availability are the key terms, typically covered in a Long Term Service Agreement (LTSA) Tied to strict operating conditions that needs to be fully understood. Important to have flexible performance warranties that reflect operational behavior

TYPICAL 20-YR CAPACITY DEGRADATION CURVE



TYPICAL 20-YR ROUND-TRIP EFFICIENCY CURVE



Source: cellectenergy, www.ess-news.com

Long-Term Service Agreements (LTSA) for BESS

The **LTSA is an agreement** between the Project and battery supplier for l**ong-term performance guarantee (PG), preventative and corrective maintenance.**

LTSA terms have begun to be aligned across major suppliers:

- 20-year term common, 25-year is now frequently offered
- Performance guarantees tend to include:
  - 25-year degradation guarantee to 60-70% SOH based on 1 cycle per day
  - Up to 2 cycles per day (provided annual maximum not exceeded)
  - 20- to 25-year Round-trip efficiency guarantees from 88% at Beginning of Life (at POI) to 82% at End of Life
  - 96-98% Availability Guarantee (after discounting preventative maintenance)
- Leading LTSAs tend to not place any requirements on State-of-Charge (SOC), while lower-tier suppliers may place limits on average SOC
- Most suppliers have moved away from warranty adjusters based on temperature; as long as the system is within the allowable ambient temperature range, it can be operated
- Most key terms in LTSA have corresponding liquidated damages clauses

BRAND	NOTABLE PUBLICLY AVAILABLE PERFORMANCE GUARANTEE TERMS
CATL	Zero degradation in the first five years of use for the Tener product, driven by pre-lithiation
FLUENCE	Providing numerous additional warranties: 99% Availability Guarantee, Dispatchable Energy Guarantee, up to 25-years Energy Capacity Guarantee, up to 25-years Round-Trip Efficiency (RTE) Guarantee, State of Charge accuracy guarantee
BYD	20 to 25 years of warranty on eligible storage projects After 10,000 cycles, the battery retains 70% of its original capacity, which enables us to provide a 12-year warranty
e-STORAGE	25 – year design life span and up to four years zero degradation, 12,000 cycles.
HTHIUM	The warranties against performance degradation and the risk of defects, with coverage of up to 15 years
TESLA	Megapack comes with a 20-year warranty and performance guarantees, ensuring operational capacity throughout the lifetime of the system New Megablock has a 25-year operational life and support for over 10,000 cycles
TrinaStorage	Product warranty, performance warranty (capacity and availability coverage with flexible usage parameters) 15,000+ Cycles lifespan with zero degradation in the first year

Interconnection Bottlenecks Grow; Calls to Prioritize Readiness over First-Come, First-Served

With the BESS market boom, queues to secure BESS grid connection have exploded in key Western markets, and some markets (e.g. Germany) are highly over-subscribed prioritizes with **project applications generally treated by order as opposed to readiness or system value**. Also, the time spent in the queue for projects commissioned in 2024 is over several years, as shown in several US ISO markets.

The Energy Storage Europe Association has called for **prioritization mechanisms** and **differentiated queue management**, and recommendations for making co-location, cable pooling and hybrid grid connection available for all projects.

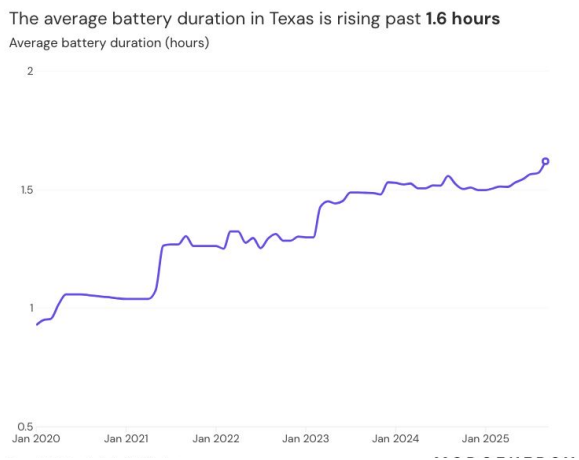
	UK	Germany	Italy	USA	Australia
Current BESS capacity (GW)	7	14.5	1	26	5
Interconnection queue (GW)	61	720	277	374	20
Note	Queue is x2 2030 target	Queue is x2.5 entire 2025 Germany grid capacity	Queue is 18x 2030 target	Only for projects targeting commissioning by 2028	Queue has doubled since last year

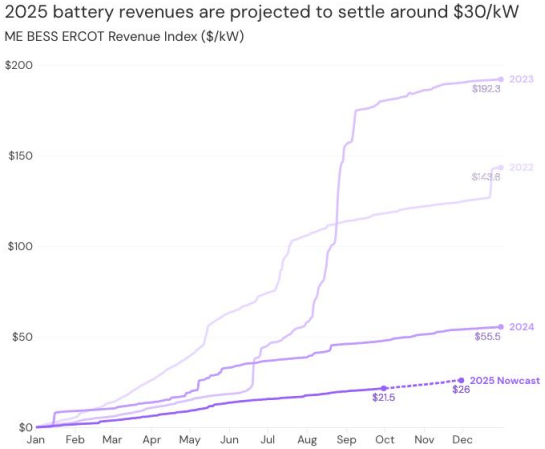


Source: Solar Power Portal, Energy Storage News, Clean Energy Wire, PV Magazine (1), ESS News(1), ESS News(2) , PV Magazine (2), Rated Power, PV Magazine (3), ENVERUS, Renew Economy, Modo Energy

Market Saturation in ERCOT Leads to Revenue Cannibalization

- In 2023, batteries in ERCOT earned an average of USD $168,504 per MW-year from ancillary services
- By 2024, average ancillary service revenues fell to USD $36,317 per MW-year – a nearly 80% decline
- The drop was due to an oversupply of BESS projects that led to more competition in the AS markets and a resulting crash in AS prices
- The change in revenue profile from ancillary services to energy arbitrage favors longer system durations (2hr-4hr systems)
- As such, average system durations in ERCOT continue to rise
- With the shift to more energy arbitrage in the revenue stack and the potential for new ancillary services that require 4hr duration (DRRS & DRRS Plus), the increase in average system duration should persist





Source: Rabobank, Modo Energy, Modo Energy

Regulatory Timeline for Deploying BESS in Major Markets

RFP / Award & Market Incentive

In **Regulated Markets**, where there are specific MW or MWh targets, such as Canada[1] or Spain[2], competitive RFPs or Capacity Auctions are held. These projects are awarded via negotiated offtake agreements.

In **Liberalized Markets**, such as UK and US[3],developers perform interconnection studies and might need to support the cost of upgrading the network. Offtake may be regulated through government or private market contracts.

Across both markets, incentives are being enhanced to allow BESS to access more revenue streams.

Interconnection

The **grid must allow for interconnection** based on BESS specific charge and discharge requirements, sometimes called "grid neutral"[4]. These will be defined by the type of utilisation, and the utility, grid operator, or regulator will define which / if upgrades are required based on them.

The developer may be required to fund some or all of the upgrades depending on the arrangement of the project.

Permits Approval

Projects must be granted various national, state or regional approvals enforced by **Local Authorities Having Jurisdiction (AHJs)**. This may also include consulting with planning or sitting committees, obtaining environmental and community approval and any additional studies such as noise.

Projects must prove compliance with electrical and construction codes.

Local Regulation

Based on the **Local Authorities Having Jurisdiction (AHJs)** interpretation of the code, the project, and its **key components**, such as the BESS, PCS, and control systems, must **comply with certain standards**.

At the moment of writing this report, the most commonly required standards at product level are: UL 9540, UL 9540A. At project level IEC 62933 and NFPA 855 are also normally required.

Source: [1] Energy Storage News, [2] Delfos Energy, [3] PV Magazine [4] FFE

Overview of Global Policy Support for BESS

Regional Summary

China:
China is targeting 180 GW of energy storage by 2027 via a shift to market-based pricing, while simultaneously maintaining a "dual-use" licensing framework for advanced batteries and equipment that is currently under a partial **one-year diplomatic suspension** until November 2026.

US:
In 2025, U.S. policy transitioned to the **One Big Beautiful Bill Act (OBBBA)**, which prioritized domestic manufacturing by strengthening **Foreign Entity of Concern (FEOC)** restrictions and tax credit requirements. While utility-scale storage retained its **30% Investment Tax Credit**, high cumulative tariffs on Chinese imports (exceeding 100% in some cases) have increased project costs by **15–25%**, prompting a strategic shift toward a domestic supply chain.

EMEA:
In 2025, the EU finalized the **Electricity Market Design (EMD) reform and Net-Zero Industry Act (NZIA)**, officially classifying storage as a strategic asset class and mandating the removal of "double charging" fees across member states. The framework sets a benchmark to produce 40% of the EU's battery needs domestically by 2030, supported by fast-track permitting (capped at 12–18 months) for "Net-Zero Strategic Projects.

Africa:
Africa has also formalized its storage transition through the African Union's **Energy Transition Strategy and Action Plan (ETSAP)**. In South Africa the **Renewable Energy Masterplan** aims to localize battery manufacturing. A cornerstone of this shift is **South Africa's Battery Energy Storage IPP Procurement Program (BESIPPPP)**, which has successfully concluded three bid windows to date, securing a total of 1.7 GW of grid-scale capacity.

Overview of Global Policy Support for BESS

By the end of 2024, at least 26 countries had implemented or announced measures to promote energy storage.

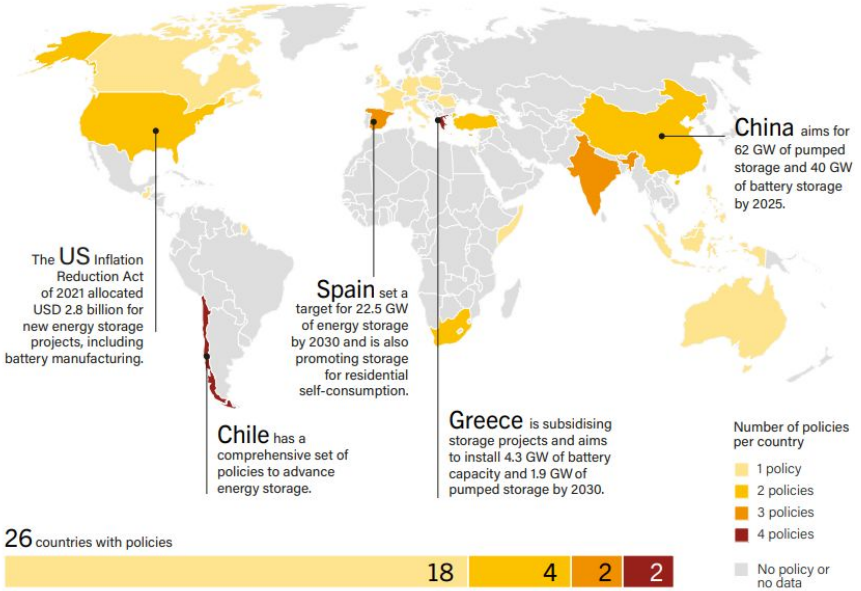
Over half of these countries set specific energy storage targets. **Fiscal and financial incentives** were the **most common policy type**

Focus Areas

- Incentives focus on: Expanding **battery capacity** to enhance **grid stability** and promoting **domestic battery manufacturing** industries
- Incentives apply to both **utility-scale** and **household-level** storage systems

Emerging Trends (2025)

- Policymakers increasingly exploring **long-duration energy storage (LDES)** technologies
- **United Kingdom** and **New South Wales (Australia)** introduced **new mechanisms** to support LDES development in early 2025



Source- Renewables 2025 Global Status Report: Global Overview

Easing Mandates Trigger China ESS Rush This Year but Policies Offer Long-term Support



Revenue source	Policy impact	Reasons
Leasing revenue	Negative	The easing of energy storage mandates has reduced incentives for renewables projects to rent ESS capacities
Price arbitrage	Positive	Widened peak/off-peak spreads in spot market enhance arbitrage opportunities
Capacity compensation	Positive	Capacity compensation and capacity pricing provide a guaranteed return
Ancillary services revenue	Positive	Policies encourage storage participation in frequency regulation, load following, reserves, and other ancillary services

See the **China section** for wider commentary on China ESS policies.

Energy storage remains at the core of China's power transition

China experienced a rush of BESS and renewable energy installations in May, right before the new changes in renewable power pricing mechanisms took effect in June. Installations have declined in the following months, as the market is still digesting the front-loaded demand.

Regulators have also eased the national renewable storage mandates in a recent policy shift, reducing incentives for some renewable projects to rent ESS capacities. However, tender volumes for grid scale ESS projects have remained strong, largely exceeding market expectations. The main reasons are due to policy support:

- Capacity compensation and capacity price from local governments such as Qinghai, Inner Mongolia, Hebei province. This is set to gradually reduce over the coming years
- Raising peak/off-peak price spread in the spot market. For example, the Qinghai government has devoted to widen the price spread sufficiently to cover energy storage operating costs

China's latest plan includes nearly doubling its new energy storage capacity to 180 GW by 2027, up from 95 GW in June. This further confirms that the government still aims to improve the energy system stability even though it has historically outpaced the storage targets, having met its 2025 goal of 30 GW two years early

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com
Installations data from China Energy Storage Association (CNESA).

Changing US Federal Policy Environment

U.S. incentives accelerate domestic battery production while new tariffs, FEOC rules, and China controls force fast supply-chain diversification.

Legislation / Rule	Description	Effects on Stationary Energy Storage
BBBA – Build Back Better Act (2021, proposed)	Proposed climate spending bill; not enacted but informed IRA design.	Set early direction for domestic manufacturing incentives and supply-chain reshoring later implemented under IRA.
ITC – Investment Tax Credit (expanded 2023)	30% tax credit; standalone storage eligible from 2023. Adders raise credit to 40–70%.	Improves BESS project economics; accelerates utility-scale and C&I deployment across the US.
IRA – Inflation Reduction Act (2022)	§45X PTC for domestic battery manufacturing; §48/§45 ITC/PTC for storage.	Anchor policy for BESS deployment and US supply chains; drives gigafactories and project pipelines.
Tariffs – AD/CVD & Section 301 (2024–2025)	Higher duties on Chinese Li-ion batteries, components (e.g. anodes), EVs, and minerals.	Raises import costs; shifts sourcing toward North America and Korean/Japanese suppliers.
OBBA - One Big Beautiful Bill FEOC / PFE Rules (2024–2025)	Limits credits for entities linked to China, Russia, Iran, or North Korea.	Disallows some EV/manufacturing credits; reshapes sourcing, JV structures, and mineral supply.
China Export Controls (2023–2025)	Export licensing on graphite and advanced battery materials/technologies.	Increases supply risk; accelerates diversification, domestic processing, and recycling.

See the **Policy section** for wider commentary on US ESS-related policies.

Source:: https://www.congress.gov/bill/117th-congress/house-bill/5376, https://www.irs.gov/credits-deductions, https://www.congress.gov/bill/117th-congress/house-bill/5376, https://ustr.gov/issue-areas/enforcement/section-301-investigations, https://www.energy.gov/articles/feoc-guidance, http://english.mofcom.gov.cn

One Big Beautiful Bill Act (OBBB) Provisions

Electric Vehicles

- Section 30D – New EV Purchase Credit: The $7,500 consumer credit now ended for vehicles acquired after Sept 2025, cutting the original 2032 timeline by seven years
- Section 25E – Used EV Purchase Credit: The $4,000 credit for used EVs ended for vehicles acquired after Sept 30, 2025, ending seven years earlier than planned.
- Section 45W – Commercial Clean Vehicle Credit: Ended early; only zero-emission commercial vehicles placed in service by Sept 30, 2025 remain eligible.

Advanced Manufacturing

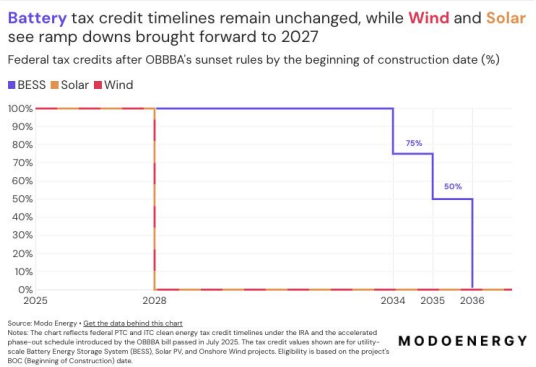
- Section 45X - Advanced Manufacturing Production Credit
- Phaseout timeline retained at 2030–2032, unlike the early sunset for wind/solar credits.
- Tighter domestic content rules: Starting Dec 31, 2026, integrated components (e.g., battery modules) must have at least 65% of material costs sourced fro
- U.S.-produced primary components, increasing in subsequent years.
- New FEOC/PFE restrictions: Beginning July 4, 2025, taxpayers and suppliers cannot be Prohibited or Foreign-Influenced Entities, and credits are disallowed if components are produced with "material assistance" from such entities.
- Refined battery module definition: From July 4, 2025, a "battery module" must include all essential equipment for functionality, narrowing eligibility.
- Added eligible products: OBBB expands eligibility to include certain metallurgical coal production and other industrial components under 45X.

Solar and Wind

- Section 45Y & 48E - Production Tax Credit & Investment Tax Credit: For solar and wind projects, these credits end for any facilities placed in service after December 31, 2027.
- New rules for solar and wind construction: For solar and wind projects beginning construction on or after Sept 2, 2025, developers may only use the Physical Work Test to establish "begin construction" and not the Five Percent safe-harbor method
- The four-year Continuity Safe Harbor still applies until July 5, 2026, after which projects must be in service by Dec 31, 2027 with no buffer period

BESS

- Continues to qualify for the full ITC until 2033, with the potential value of the credit falling to 75% in 2034 and 50% in 2035.
- However, BESS projects are subject to Foreign Entity of Concern (FEOC) provision



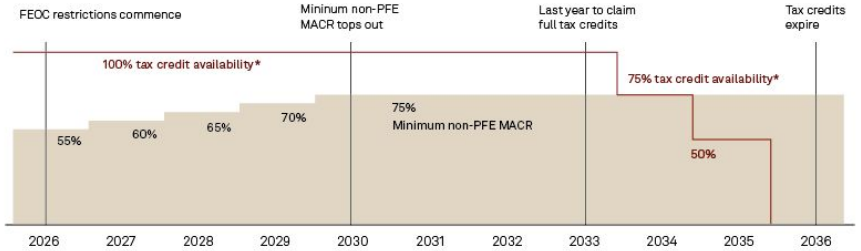
See the **Policy section** for wider commentary on US ESS-related policies.

Source: Moss Adams, Grant Thornton Advisors, Modo Energy

Updated IRA Investment Tax Credit Guidelines (FEOC)

- **FEOC definition**: "Foreign Entities of Concern" are companies owned, controlled, or significantly influenced by foreign adversaries (e.g., China, Russia, Iran, North Korea). 2 types:
  - **Specified Foreign Entities (SFEs)**: Directly owned or controlled by hostile governments.
  - **Foreign-Influenced Entities (FIEs):** Indirectly influenced via board control, debt, licensing, or IP agreements.
- **Material Assistance Rule**: Prohibits projects from receiving significant cost contributions from FEOCs – financial support counts, not just physical components.
- **Material Assistance Cost Ratio (MACR)**: Defines the share of system cost that must be FEOC-free to qualify for ITC
- **Policy impact**: Projects tied to FEOC-linked suppliers may become ineligible for federal tax incentives, including the Investment Tax Credit (ITC).
- **Relevance to BESS**: The globalized battery industry is especially vulnerable, with major suppliers like CATL, BYD, and Gotion potentially triggering FEOC restrictions.
- **High-risk supply areas**: Extraction and processing of critical minerals (lithium, cobalt, graphite), production of cells/modules, BMS components, and inverters/control systems.
- **Key vulnerability**: Even if direct suppliers are compliant, upstream sub-suppliers may not be, requiring deep supply chain due diligence
- **100% recapture risk**: Any payment made to a SFE or FIE **within 10 years of claiming the credit** triggers full ITC clawback, effectively creating a 10-year exposure period for recapture.
- **Industry response**: Non-FEOC companies with U.S. cell/module manufacturing are pivoting from EVs to BESS, including Samsung in Indiana, LG in Michigan, and SK in Georgia.

Major Battery Energy Storage System Milestones under H.R.1



As of Oct. 10, 2025.
* Based on beginning of construction.
FEOC = foreign entity of concern; MACR = material assistance cost ratio; PFE = prohibited foreign entity.
Sources: S&P Global Commodity Insights; public reports.
© 2025 S&P Global.

See the **Policy section** for wider commentary on US ESS-related policies.

Source: Norton Rose Fulbright, Norton Rose Fulbright, EticaAG, Reuters, Reuters,Reuters, S&P Global

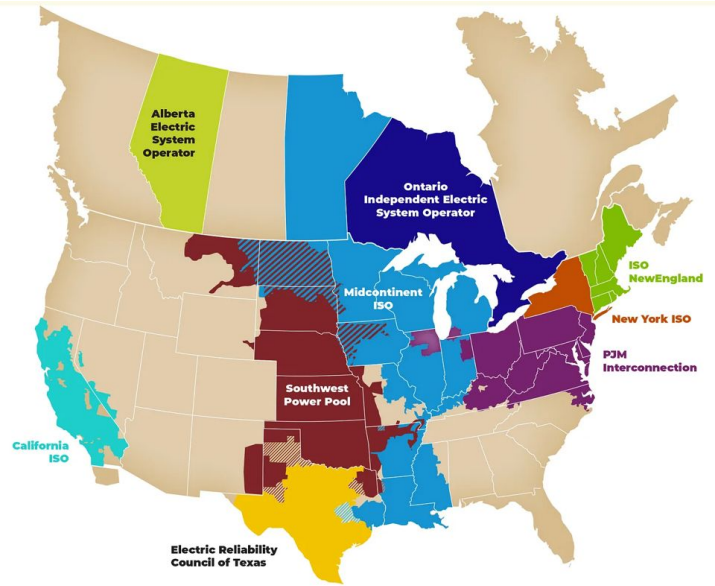
Differing Permitting Processes for Renewable and BESS Integration Complicates Adoption

State law determines whether electricity markets are regulated or deregulated and public utility commissions (PUCs) or independent system operators (ISOs) implement mandates impacting how energy assets are managed, expanded or replaced:

- **Regulated:** Companies need to go their respective state legislatures to get approval for price increases (rate cases) to invest in improvements who test whether costs are prudent and reasonable → **Difficult to modernize or add new power generation methods in states that mandate low prices as there is a higher burden of economic proof required unless there are renewable mandates**

- **Deregulated:** By contrast, electricity markets in deregulated markets managed by independent system operators (ISOs) separate the generation, transmission, and distribution to increase competition and any modernization or renewable integration including BESS is tied to investment returns → **As costs come down, adoption has increased more than in regulated markets as independent power producers (IPPs) can build without utility ownership**

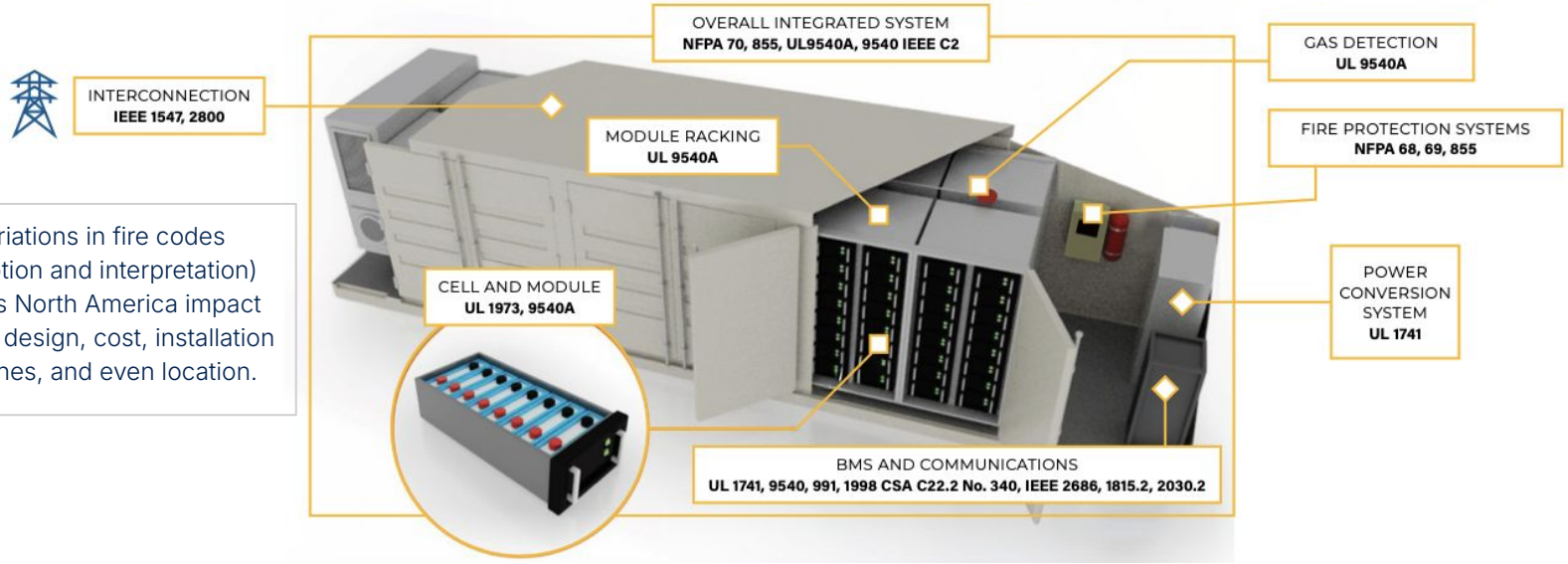
- **Exceptions:** The Texas ERCOT is independent (not subject to FERC) with clear guidelines with installation taking 18 to 30 months while California, with a strong statewide green energy mandate takes 4+ years due to complex permitting and interconnections → **Texas and California represent around 50% of BESS installations in the country with 19 GWh and 59 GWh respectively**



Notes: Tan states/provinces in this map are regulated electricity markets; ISOs/RTOs shown in colour, with ERCOT being entirely within the state of Texas.

Source: ISO/RTO Council (map), Pivot Research, FERC, ERCOT, DOE

Differing Fire Codes Across States Only Adds to the Complexity of BESS Installation



Variations in fire codes (adoption and interpretation) across North America impact project design, cost, installation timelines, and even location.

Despite the recommendations of national baseline models (e.g., NFPA 70 + 855), fire codes for BESS vary from state to state and province to province in the US and Canada, adding complications to operators navigating permitting and local regulations. Fire codes can also have regional differences within state/provincial borders → **Fire codes are adopted through amendments and operators evaluate local codes to de-risk projects and prefer states with predictable permitting environments to reduce delays and compliance costs.**

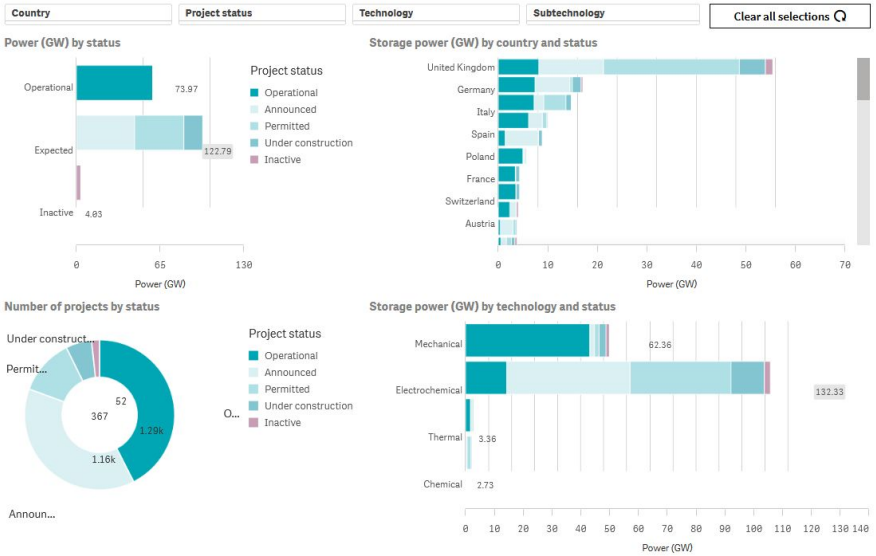
Source: American Clean Power (image adapted from PNNL), Pivot Research, EticaAG

European Energy Storage Policy Framework

Energy Storage a Cornerstone of Many European Power Grids

- **Official recognition:** Energy storage systems are now formally designated as a key component of European power grids and active market participants
- **Market integration:** In December 2025, ENTSO-E published a policy paper detailing electricity market reforms to **fully integrate utility-scale storage**
- **Policy support:** In July 2025, the European Commission issued guidance to **lower energy bills and accelerate clean energy deployment,** explicitly facilitating storage deployment alongside renewables and grid upgrades
- **Monitoring & competitiveness:** The Commission launched the **European Energy Storage Inventory** in March 2025, a real-time dashboard tracking ESS installations and market competitiveness
- **Grid-forming for >1MW generators:** ENTSO-E also released a technical report outlining requirements for generators, including **inverter-based** ones, such as BESS, to **stabilize the European grid.**

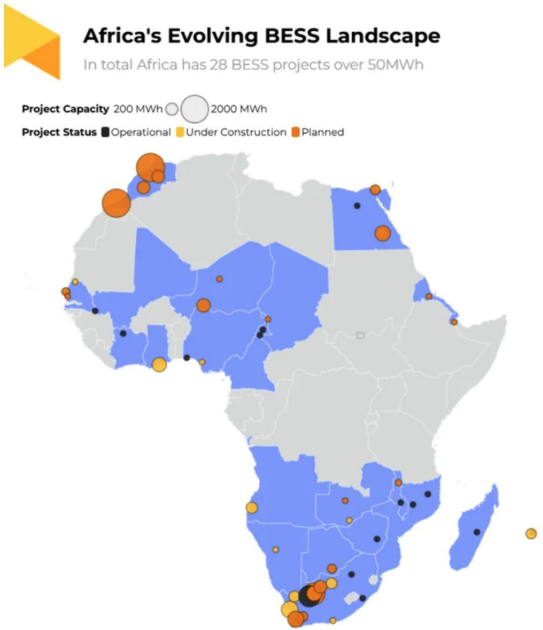
EUROPEAN ENERGY STORAGE INVENTORY



Note: Although there is a broad regulatory framework for BESS installation across EU-members (EU 2023/1542), they do not apply uniformly across all countries. Like the US, some European countries have more predictable and straightforward regulations while others do not.

Source: European Commission; ENTSO-E

African Energy Storage Policy Framework



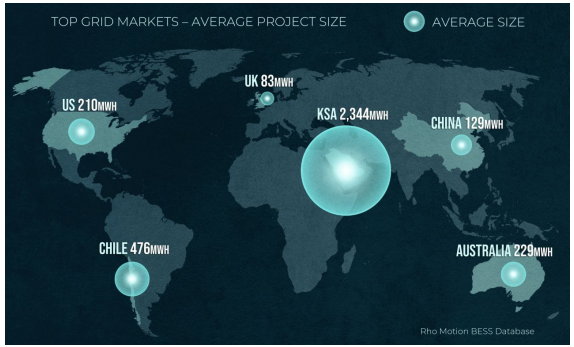
- National energy strategies increasingly recognize the role of storage for grid flexibility and renewable integration. **South Africa's Renewable Energy Masterplan,** approved in 2025, includes policy support for BESS as key tool to manage intermittent solar and wind generation and to enhance energy security
- Similarly, **Morocco's** policy goal of reaching **~52% renewable share by 2030** is directly linked to increased focus on BESS, such as the 1.6 GW standalone BESS project for grid balancing
- Energy storage policy across the continent reflects diverse **national realities, with a small number of leaders** (i.e. South Africa, Morocco, Egypt) driving significant BESS growth, while others are just beginning to embrace the potential as storage prices continue to fall
- **South Africa** is emerging as a key energy storage player on the continent, representing **over 60%of Africa's grid-scale BESS pipeline** in 2025, thanks to its Battery Energy Storage IPP Procurement Program

2025 marks the inflection point where African energy policy begins treating battery storage as core infrastructure

Saudi Arabia Top-Down Renewable Policy, Driven by Solar Integration, Makes it a Fastest Growing ESS Market

- **Saudi Vision 2030** maps out a 50% renewable goal by 2030, requiring 100-130 GW of solar and wind to be deployed
- The Kingdom of Saudi Arabia (KSA) has so far signed over 64GW of renewable PPAs by end of 2025
- This portfolio includes the **lowest solar (1.04 $c/kWh) and wind ($1.34 $c/kWh) PPA prices in the world**, respectively at Shuaiba and Dawadmi.
- In support of renewables integration, the Saudi Ministry of Energy has set a target of 48GWh of BESS by 2030; 8GWh of this was brought online in 2025 with a further 14GWh in active construction and 8GWh in tender, all at major 380kV HV substations
- The **average project sizes seen in KSA are the largest in the world**, at 2,344MWh (nominal) per project
- Four of the operational projects at *Bisha, Jazan, Najran* and *Khamis* are ranked in the current 10 largest BESS in the world
- Recent project awards for KSA BESS projects at Tabuk and Hail were signed at $73/kWh for turnkey ESS - the lowest BESS prices in the world outside of China seen to date.





Note: KSA projects are typically reported in the media and by some analysts based on nominal energy capacities rather than rated or useable energy due to substantial overbuilds in lieu of augmentation. The values quoted by the Ministry of Energy are in rated energy, but each 2GWh rated project has approx 2.5-2.6GWh nominal installed energy.

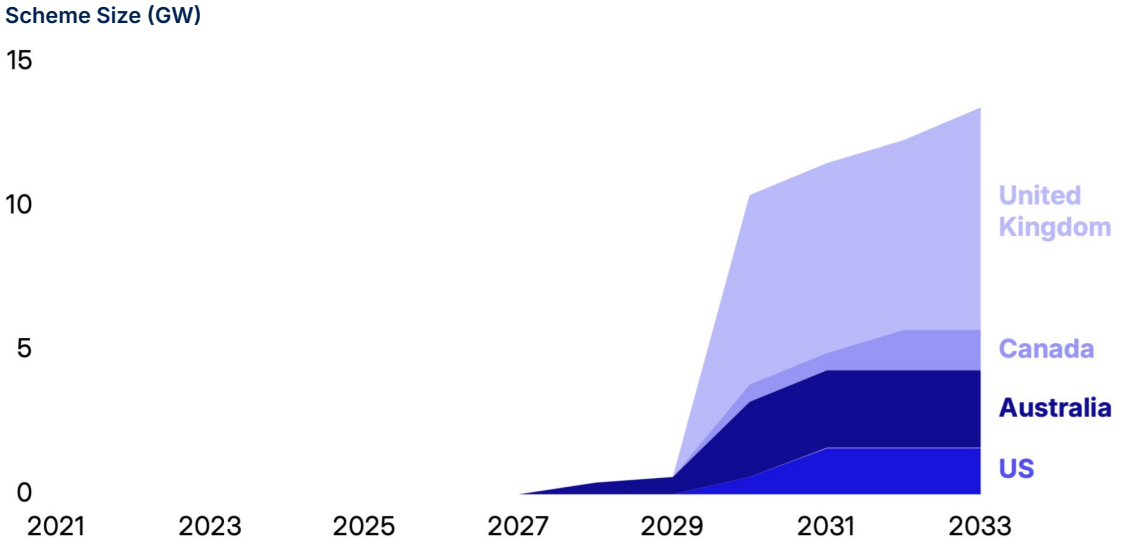
Source: Ministry of Energy, HRH Prince Abdulaziz bin Salman Al Saud FII Keynote, Wood Mackenzie (Distinguished Partner), Image credits: Benchmark Minerals Intelligence (Distinguished Partner), Algihaz

Confirmed Policies Could Guarantee Revenues to 10 GW of LDES by 2030

LDES is heavily policy-dependent and very few projects reach FID without support. Grant programs and government loans have financed many pilot and demonstration projects, and commercial deployment being enabled by policies like cap-and-floor schemes (eg United Kingdom), regulatory mandates (eg California), and centralized procurements (eg California) that guarantee high and stable revenues.

Most revenue guarantees are state-level, including policies in California, Massachusetts, and New York in the US and New South Wales and South Australia in Australia. The UK cap-and-floor scheme is a notable exception.

CONFIRMED LDES POLICY SUPPORT BY GEOGRAPHY



sightline climate Source: Content provided courtesy of Sightline Climate. Note: Includes confirmed policies that support only 8+ hour storage.

LDES: Policy* Support by Geography: US & Europe

	US	Canada	UK	Europe	Spain
Policy	California-centric	Commercialization of Lowest-Cost, LDES	Cap and floor scheme to enable investment and revenue certainty	Long duration energy storage challenge (Germany)	Energy storage legislative draft & grants for storage and thermal/flow systems
Mechanism	Funding via California Climate Investments Initiative	$6.7M invested under Energy Innovation Program	Cap on max ROI for investors and min revenue for developers	Public funding support of $4.6M	$971M of grant support
Target / Metric	2 GW deployed between 2031-2037	Commercialization of lowest-cost LDES	• 4-6 GW by 2030 • 5-10 GW by 2035	Storage for ≥10 hrs with no usage of critical raw materials	€280 million fund for storage, 600 MW+ by 2026
Other LDES Support	US DOE is funding $100 million to pilot projects	Federal investment of $5M for compressed air energy storage Ontario-specific target: 6 GW of 10+ hr duration storage starting 2032	• Capacity market participation • Grid services • Tax relief • UK Battery Industrialisation Centre development: $32M funding for vanadium redox flow batteries (VFRB)	• Germany plans to launch 500 MW of LDES > 8hrs between 2025-2026 • Procurement scheme for "Long Duration Energy Storage System(s)" (Ireland) • Italy: 3 GW target for LDES projects by 2030	National Energy and Climate Plan (PNIEC) targets 22.5 GW by 2030, including thermal storage / concentrated solar power

**Policies as of 2025*

Source: US DOE, California energy commission, Energy Storage News, LDES Council Map

LDES: Policy Support by Geography: Asia & Australia

	China	Japan	South Korea	Australia
Policy	Special action plan for development of new energy storage (2025-2027)	Long-Term Decarbonization Auction (LTDA),METI	2030 K-Battery Development Strategy	Australian Vanadium Limited (AVL) Grant
Mechanism	$35.2B in support of large scale projects	Capacity auction for generation and storage	Large-scale R&D projects worth over 500 billion$ won for commercialization of next-generation batteries	Develop a domestic VRFB ecosystem, electrolyte & processing, funded through a $31 million grant
Target / Metric	180 GW by 2027	Awarded 1.4 GW in 2025	Commercialize lithium-Sulfur, SSB, and lithium-metal batteries by 2025, 2027, and 2028, respectively	Commission a concentrator & high-purity vanadium processing facility
Other LDES Support	Implementation Plan for Promoting high-quality development of the Vanadium Batteries	National subsidies for grid-scale storage by METI	Roadmap for commercialization of the lithium-metal batteries	Battery Tech grants Flow Battery Storage Manufacturing grants

*Policies as of 2025

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing

Applications
- EV
- Stationary Energy Storage
- **Data Centers**
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

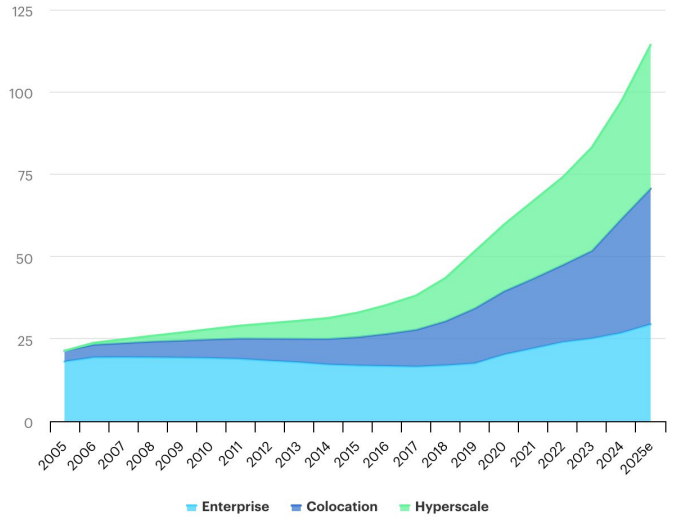
Software / AI

VF | VOLTA FOUNDATION

Data Center Boom & Outlook

- **Global installed data center capacity surpassed 100 GW by early 2025.** AI is a major driver of rising electricity demand relative to traditional data center workloads. This is particularly noticeable in the hyperscale segment, where most new data centers are designed primarily to support AI training and inference.
- **AI data centers** with high-density GPUs **require gigawatt-scale power**, but grid interconnection delays of 2–11 years and capacity constraints are **pushing hyperscalers** such as AWS, Google, Meta, and Microsoft **to build** proprietary data center campuses with **on-site power generation and energy storage**
- **Clean technologies** - often combining natural gas, renewables, and battery storage - will increasingly supplement or **replace constrained grid supply**
- **Batteries**, including UPS, BBU, and BESS, **deliver resiliency**, **smooth** AI-driven **power fluctuations**, **provide grid services**, and **enable time-shifting**; BESS alone could unlock 76 GW of new capacity through rapid backup and peak shaving

Global Installed Data Centre Capacity (GW)



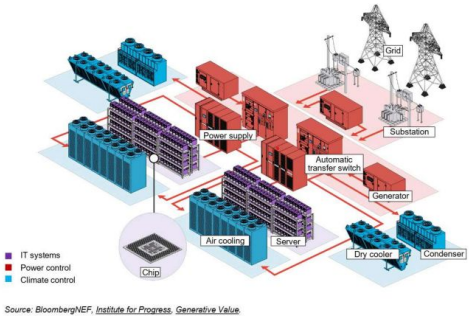
Source: IEA, Flexgen, Traxtech

AI Data Centers (AIDC) vs Traditional Data Centers (DC)

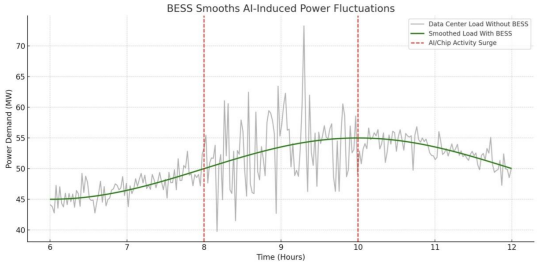
Gen AI data centers use much denser GPU-based compute, more advanced cooling, and more complex power architectures than traditional facilities, with distinct designs for model training vs inference. **Battery energy storage is emerging as a key enabler for these AI data centers by providing fast, flexible capacity, especially where grid constraints and clean power goals collide.**

Dimension	Traditional DC	AI Data Center (AIDC)	Implications
Primary workloads	Web, enterprise IT, general cloud VMs	GPU-heavy AI training and inference	Different compute profile drives design.
Compute hardware	CPU-centric, modest accelerators	GPU/accelerator-centric, very high TDP devices	Shifts power, cooling, and capex mix.
Rack power density	~3–15 kW typical	40–140+ kW for AI clusters	Forces new power and cooling topologies.
Facility scale	MW to low tens of MW; some hyperscale 50–100 MW	Hyperscale campuses often 100 MW–multi-GW, esp. for training	Power and land constraints now central.
Power strategy	Grid + diesel UPS/gensets, limited onsite generation	Grid + large UPS, plus BESS, staged interconnection, and co-location with clean generation	Power architecture is now a strategic differentiator.

Figure 15: A typical data center layout



Source: BloombergNEF, Institute for Progress, Generative Value

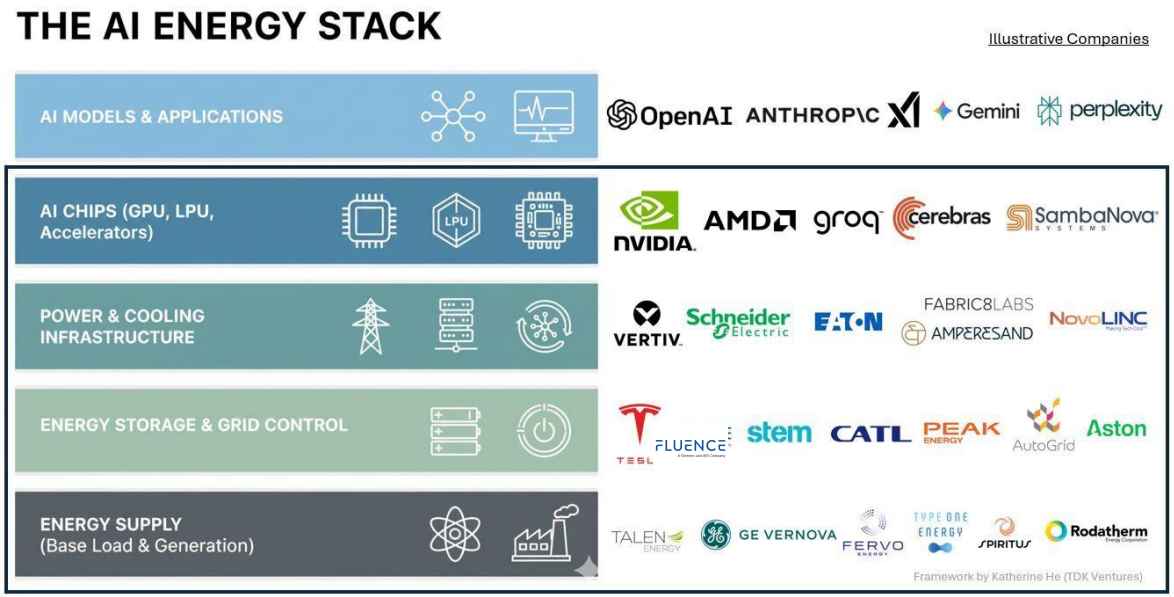


Source: Fluence Energy

Why BESS Matters More for AIDC

- AI clusters create very large, fast-ramping, and relatively inflexible loads, stressing grids and interconnection queues; BESS can act as a "bridge-to-grid" resource to get capacity online faster and smooth load
- As hyperscalers pursue 24/7 clean energy for AI regions, pairing renewables with BESS near or at the site is often the fastest way to deliver firm, low-carbon capacity compared with new gas or transmission

The Energy Ecosystem Underpinning Data Center Development, with Batteries at the Core



Major BESS Deals of 2024-25

Aligned Data Centers announced a landmark 31 MW / 62 MWh BESS deal in October 2025 with Calibrant Energy for a Pacific Northwest campus

PJM awarded interconnection to 23 BESS projects totaling 2.2 GW in December 2025, many co-located or hybrid with data center hotspots in the mid-Atlantic to ease grid strain from AI loads

Source: AI Hit a Wall in 2025. That Wall Is Power, Substack

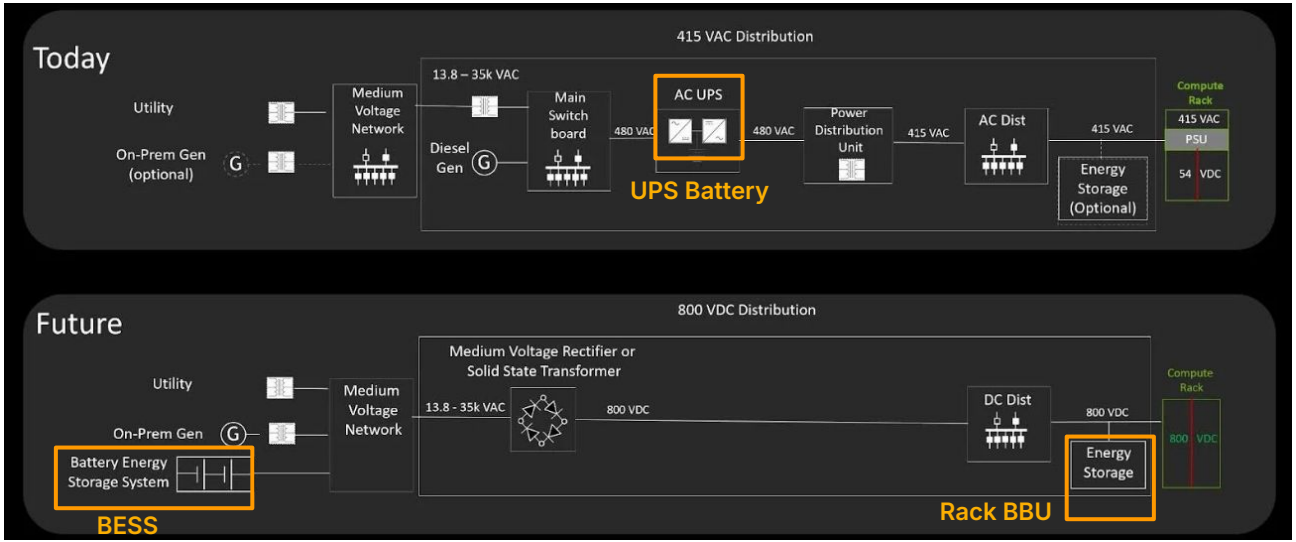
Hyperscaler Events in 2025

Hyperscalers and data-center operators are actively testing and deploying alternatives to lithium-ion especially long-duration and safer chemistries to power AI-era data centers.

Hyperscalers	Battery Integrators	Battery Type	Key Takeaways
Google	ENERGYDOME Our WORLD can't wait.	CO_2 based	**Google** signs its first long-duration energy-storage partnership with Energy Dome to deploy **CO_2-battery technology** across its global operations
prometheus HYPERSCALE	XL Batteries	Flow Batteries	XL Batteries will deploy a 333 kW **Organic Flow Battery** demo at **Prometheus** in 2027, followed by planned purchases of two 12.5 MW / 125 MWh systems in 2028 and 2029.
Crusoe	REDWOOD MATERIALS	Li-ion	Redwood Materials (via its Energy arm) and Crusoe collaborated to power a modular AI data-center via a **12 MW / 63 MWh battery** + solar microgrid
Aligned Adaptive Data Centers	CALIBRANT ENERGY	Li-ion	Calibrant will deliver a **31 MW / 62 MWh** battery energy storage system (BESS) at **Aligned data center** campus in the **Pacific Northwest**.
edged AN ENDEAVOUR COMPANY	tiamat	Na-based	Endeavour's Edged announced a partnership with battery maker **Tiamat** to deliver **Na-based energy storage** for AI data centers and grid applications.

Next-Gen Power Architecture in AI Data Centers and Where Batteries Are Embedded

Batteries are increasingly embedded **across every layer of the modern data-center power architecture**, from facility-level energy storage systems connected to the grid to rack-level battery backup units that sit inches from AI servers. As power densities rise and uptime requirements tighten, data centers are shifting from centralized, AC-based backup architectures toward high-voltage DC systems with distributed batteries that provide faster response, higher efficiency, and greater resilience. This evolution is turning batteries into a **core enabling technology for both power delivery and reliability in next-generation AI infrastructure**.



Today's 415V AC data center (top)

Future's 800V DC power distribution (bottom)

Source: NVIDIA -Building the 800 VDC Ecosystem for Efficient, Scalable AI Factories

Batteries in Data Centers (From Grid Interface BESS to Rack Integrated Backup Units)

Modern data centers increasingly use batteries not just for backup power, but also for grid flexibility, efficiency, and improved power architecture. Battery applications can be grouped into three main tiers:

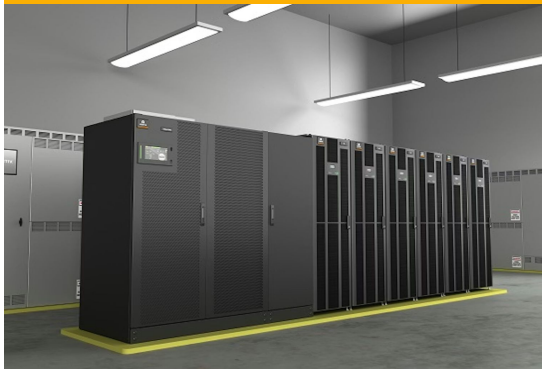
Data Center Grid-interface **Battery Energy Storage (BESS)**



Picture: Tesla Megapack at X AI Memphis campus

Large utility-scale battery systems sit at the **grid interface** of a data center to support peak shaving, frequency regulation and renewable integration.

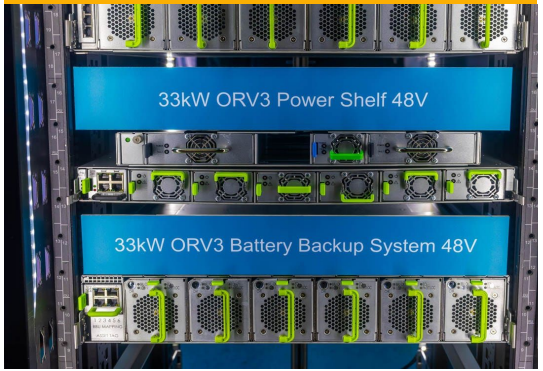
Traditional Batteries Housed **Uninterruptible Power Supply (UPS)**



Picture: Vertiv's UPS unit with LIB

Batteries in the UPS in the data center facility hall, to provide **short-duration ride-through power** during grid outages until generators start.

Rack-Level / Integrated **Battery Backup Units (BBU)**

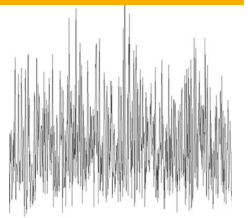
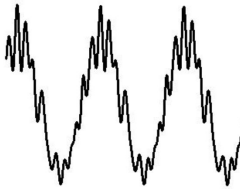
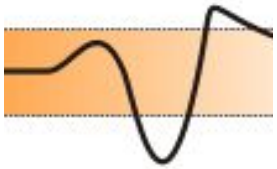
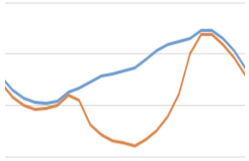
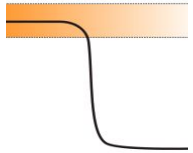


Picture: LITEON ORv3 33kW power Shelf

Batteries integrated to the power rack in the IT hall, moves energy storage **closer to the IT load** to reduce conversion losses and adapt to variable loads, and to support new power architecture without heavy UPS footprints.

Source: Company press releases

Data Center Energy Storage Applications

<100 ms-1s Runtime	1-60 s Runtime	1-10 min Runtime	0.5-4 h Runtime	4-12 h+ Runtime
				
Power filtering	**Synchronous compute loads**	**Brown-outs, grid supply interruptions**	**Demand response, renewables integration**	**Grid resilience**
Supercapacitors, NiZn	Supercapacitors, lead-acid, Li-ion (LTO), Na-ion (NFPP), NiZn	Lead-acid, Li-ion (LTO, LFP), Na-ion (NFPP), NiZn	Li-ion (LFP), Na-ion (NFPP)	Li-ion (LFP), Na-ion (NFPP), flow batteries
In-rack in IT room	Rack-level in power room	Rack-level in power room	Grid/utility input side	Grid/utility input side

Data center energy storage requirements differ by runtime, driving demand for distinct performance characteristics that cannot be addressed by a single battery solution.

Source: ZincFive, Peak Energy, Etica AG

BESS Design Configurations for AI Data Centers

BESS enables differentiated energy storage solutions for AI training and inference, each with distinct operational requirements

BESS Design Parameter	Training Campuses	Inference Campuses
Power Tolerance	Tolerates brief interruptions; requires high instantaneous power delivery	Requires 99.999% uptime; zero-tolerance for interruptions;
Scale & Burst Capacity	BESS can supply multi-MW to GW-scale bursts and manage ramping when large training jobs start or pause; 40-60% load swings common	Sustained high load; 2-4 hour backup for always-on fleets
Response Time	Millisecond ramping management; handles computational bursts within seconds	Sub-50ms cutover; BESS is more tightly integrated with UPS and grid services to ride through faults and provide fast frequency response.
Primary Function	Co-located BESS can support “power-first” sitting near renewables or nuclear, with batteries smoothing variability and supporting microgrid-style operation.; support flexible interconnection	BESS plus smart control can arbitrage time-of-use prices for always-on inference fleets, reducing operating cost without compromising SLAs

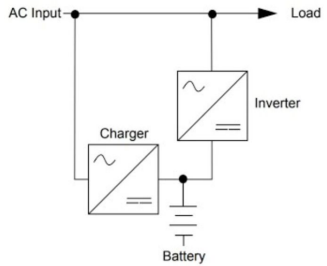
Source: Terakraft, Flexgen

Uninterruptible Power Supply

UPS systems enable data centers to manage incoming utility power abnormalities by providing backup power and power conditioning to critical infrastructure.

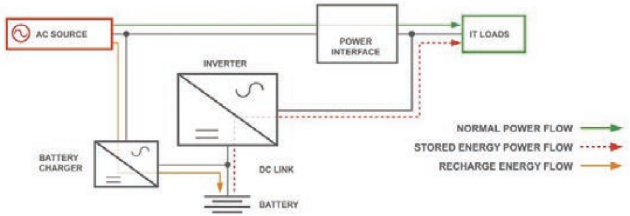
Key Architectures:

Standby (Offline) UPS



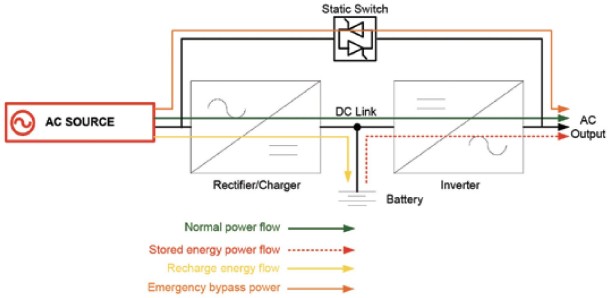
- Lowest cost alternative
- Backup power during incoming utility outage events

Line Interactive (Online) UPS



- Backup power during incoming utility outage events
- Input utility voltage is regulated

Double Conversion (Online) UPS



- Highest cost alternative
- Backup power during incoming utility outage events
- IT infrastructure is fully isolated from incoming utility power

Source: Eaton

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing

Applications
- EV
- Stationary Energy Storage
- Data Centers
- **Aviation, Drones, Space**
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

VF | VOLTA FOUNDATION

Notable Industry Events in 2025

Q1

Supernal (Hyundai subsidiary) unveils their full-scale eVTOL aircraft is undergoing ground testing at Mojave Air & Space Port in California

Pipistrel Nuuva V300 hybrid-electric cargo drone conducted its first successful flight, showcasing early adoption of hybrid electric propulsion for unmanned cargo missions.

Q2

Joby achieved an important milestone by completing the first crewed transition flight of its electric vertical take-off and landing aircraft.

Amprius began the volume rollout of its 450 Wh/kg silicon-anode cells, achieving a significant energy-density milestone for commercial aviation applications.

White House EO and DoD/DoW directive fast-track mass deployment of low-cost, attritable drones, signaling strong demand for domestically produced, high-power, supply-chain-secure lithium batteries

Q3

Beta's Alia all-electric aircraft flew intercity test routes in Norway, demonstrating operational battery-electric flight beyond prototype hover modes.

Archer Aviation and Anduril Industries formed an exclusive strategic partnership to develop a hybrid-propulsion VTOL aircraft for the U.S. Department of Defense

Vertical Aerospace completed the world's first public airport-to-airport eVTOL flight.

Q4

Air delivered its first production-ready cargo eVTOLs featuring a next-generation electrical architecture optimized for high-speed autonomous logistics.

Embreaer's Eve eVTOL completed its first full-scale prototype flight, commencing its intensive flight test program for future battery-electric passenger service.

Beta Technologies files for IPO, NYSE raising over $1 billion and valuing the electric aircraft company around $7.4 billion

U.S. Transportation Secretary Launches First-Ever National Advanced Air Mobility Strategy to Unlock the Future of Flight

Source: Company Press Releases

Notable Regulatory Events in 2025

Q1

EHang receives Air Operator Certificates in China for pilotless human-carrying eVTOLs, marking a first for autonomous eVTOL operations in that jurisdiction

FAA updates powered-lift rules to clear a certification path for eVTOL aircraft, providing formal regulatory guidance for advanced air mobility certification.

Q2

U.S. executive actions direct the FAA to publish draft BVLOS (beyond-visual-line-of-sight) drone rules, aiming to replace individual waivers with a clear BVLOS regulatory framework.

National Aviation Authorities (NAA) Network releases first Advanced Air Mobility aircraft type certification roadmap, establishing coordinated benchmarks for emerging electric aircraft certification globally.

Q3

FAA issues the first FAA certification under its MOSAIC airworthiness rules for an eVTOL aircraft (AIR ONE), opening a formal regulatory pathway for light electric vertical flight.

FAA grants experimental airworthiness certification for the Air One eVTOL prototype, enabling expanded flight testing in the U.S. under updated electric aviation regulations.

Q4

LIFT Aircraft initiates FAA type certification process for its commercial HEXA eVTOL, signaling a transition from experimental to full certification engagement.

FCC bans new foreign drone models including Chinese market leader DJI

Source: Company Press Releases

Understanding the Categorization of Electric Aircraft Across Applications and Classes

Efficiency spectrum

- Fixed-wing CTOL is most efficient (high L/D, long range/high speed); multicopters are least efficient (pure vertical thrust, high disk loading, short range/low speed), with Lift+Cruise and Vectored Thrust hybrids in between.

Design trade-off

- eVTOL architectures balance vertical lift capability against cruise efficiency adding wings/tilt improves range and speed but increases complexity, while pure rotorcraft favor simplicity and urban missions at the cost of efficiency.

Aircraft Type & Configuration	Hover/Take-off Mechanism	Cruise Mechanism & Efficiency (L/D)	Relative Disk Loading & Range/Speed Profile
 **CTOL** (Conventional Take-Off and Landing) [Fixed Wing, Runway]	Runway acceleration for wing lift (Not Vertical)	Wing lift, Prop/Jet thrust (High Efficiency, High L/D)	 [N/A for Hover] | Long Range, High Speed (Inter-city)
 **Multicopter** [Multiple Fixed Rotors, No Wing]	All rotors generate vertical thrust (High Power)	Body tilt provides small horizontal component (Low Efficiency, Low L/D)	 [High Disk Loading (Red Gauge)] | Short Range, Low Speed (Urban Mobility)
 **Lift + Cruise** [Separate Lift Rotors & Cruise Prop, Fixed Wing]	Dedicated lift rotors only (Vertical Thrust)	Wing lift, Cruise prop thrust (Lift rotors inactive/feathered) (Medium Efficiency, Medium L/D)	 [Medium-High Disk Loading] Medium Range, Medium Speed (Regional)
 **Vectored Thrust (Tilt-Rotor/Wing)** [Tilting Rotors/Wing for Lift & Cruise]	Rotors tilted 90° up (Vertical Thrust)	Rotors tilted forward, Wing lift (High Efficiency, High L/D)	 [Medium-Low Disk Loading] Medium-Long Range, High Speed (Regional/Inter-city)

While fixed-wing CTOL remains the gold standard for high-speed, inter-city efficiency, hybrid architectures like Vectored Thrust and Lift + Cruise used in EVTOL aircraft are essential for regional missions, trading increased mechanical complexity for the balance of speed and range required to make urban air mobility viable.

Source: The promise of energy-efficient battery-powered urban aircraft, [Image AI Generated from the source content]

Major Battery-Electrified Aviation Players

Americas

Joby, ARCHER, wisk, EVE MOBILITY REIMAGINED, supernal, overair, PIVOTAL, BETA, SURFAIR, ELECTRA, REGENT, COSMIC AEROSPACE, ELROY AIR, Whisper Aero

Europe

VOLOCOPTER, VÆRIDION, VERTICAL, AUTOFLIGHT, ascendance, PIPISTREL, VOLTAERO, AURA AERO, Heart Aerospace, Delivering Today DRONAMICS, MAEVE AEROSPACE, DUFOUR AEROSPACE, H55

Asia - Pacific

EHANG 亿航, AEROFUGIA 沃飞长空, SKYDRIVE, VOLANT, 亿维特航空 EVT AEROTECHNICS, 时的科技 TCab Tech, VERTAXI 御风未来, VOLAR AIR MOBILITY, SF EXPRESS

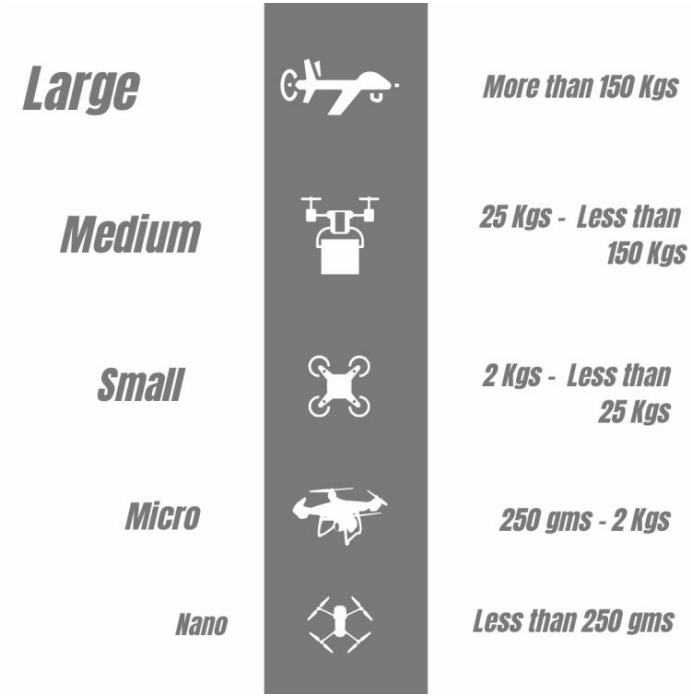
DEVELOPMENT FOCUS

eVTOL | eSTOL/eCTOL

Source: Company announcements

UAS/UAM Segments Highly Coupled by Weight, Specific Application, and Propulsion Type

- In today's UAS/UAM landscape, aircraft below roughly 25 kgs (small UAS) and up through light eVTOL classes are already predominantly battery-native, because electric motors scale efficiently at low mass
- Most UAS/UAM missions are power-limited rather than energy-limited (high takeoff power, short duration), aligning well with batteries' strengths of high power density and instant torque
- Battery improvements push the crossover upward where ongoing gains in cell-level specific energy, C-rate capability, thermal management, and cycle life steadily raise the feasible MTOW threshold where batteries outperform hybrids or fuel systems, shifting progressively larger UAS and UAM platforms into the battery-dominant regime.



As battery technology improves, secondary benefits compound with simpler architectures, lower maintenance, easier certification, quieter operation, faster turnaround via high-rate charging. This makes batteries not just viable but structurally preferred across an expanding share of UAS/UAM weight classes.

Source: A review of powering unmanned aerial vehicles by clean and renewable energy technologies

UAS/UAM Market Overview Active US Fleet - Commercial Fleet Drives Increased Performance & Demand

- Recreational UAS/UAM are typically low utilization and typically does not require battery replacement in its lifetime resulting in new drones as the primary battery demand driver in the segment
- For commercial drones battery wear, not unit sales, drives demand: The commercial/Part 107 sUAS fleet flies far more hours than recreational drones, making battery replacement cycles (months, not years) the dominant source of recurring battery demand rather than new-aircraft builds
- UAS missions prioritize high C-rate, fast recharge, and thermal robustness over long cycle life; Li-ion chemistries are optimized for burst power and mission turnaround, not EV-style longevity

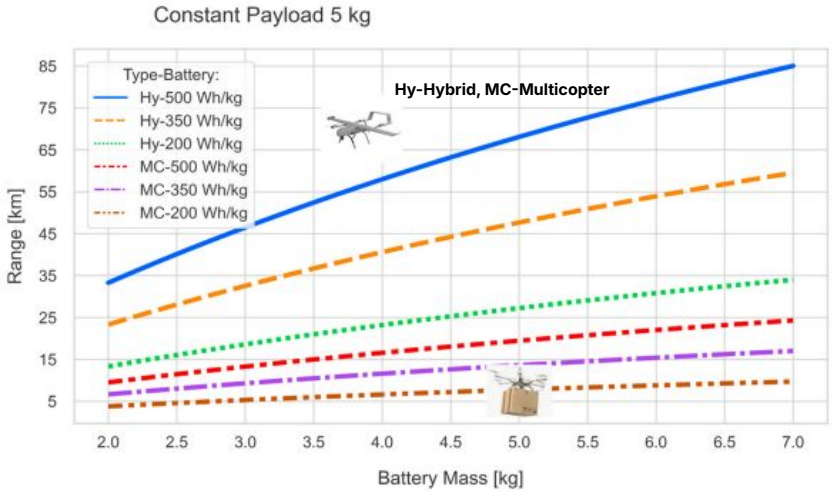
Regulation unlocks battery volume: BVLOS, delivery pilots, and higher utilization rates materially increase battery throughput per airframe, meaning modest fleet growth translates into outsized battery demand growth once regulatory constraints ease

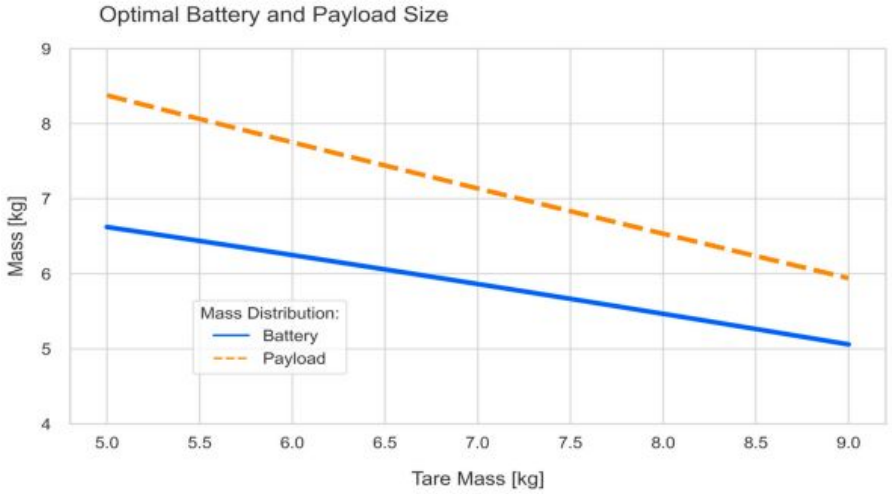
USA | <25 kgs	2025	2026	2027	2028	2029
Recreational	460	480	500	510	510
Rec New Add	20	20	10	0	0
Commercial	395	402	408	411	413
Pack (kWh)	1.0				
Rec (MWh)	20	20	10	0	0
Comm (MWh)*	2,370	2,412	2,448	2,466	2,478
Total (MWh)	2,390	2,432	2,458	2,466	2,478

**Assumes 6 replacements per year*

Source: compendium to faa aerospace forecast fy 2025-2045 emerging aviation entrants: unmanned aircraft systems and advanced air mobility

Batteries Play a Vital in Drone Performance & Provide for System Flexibility

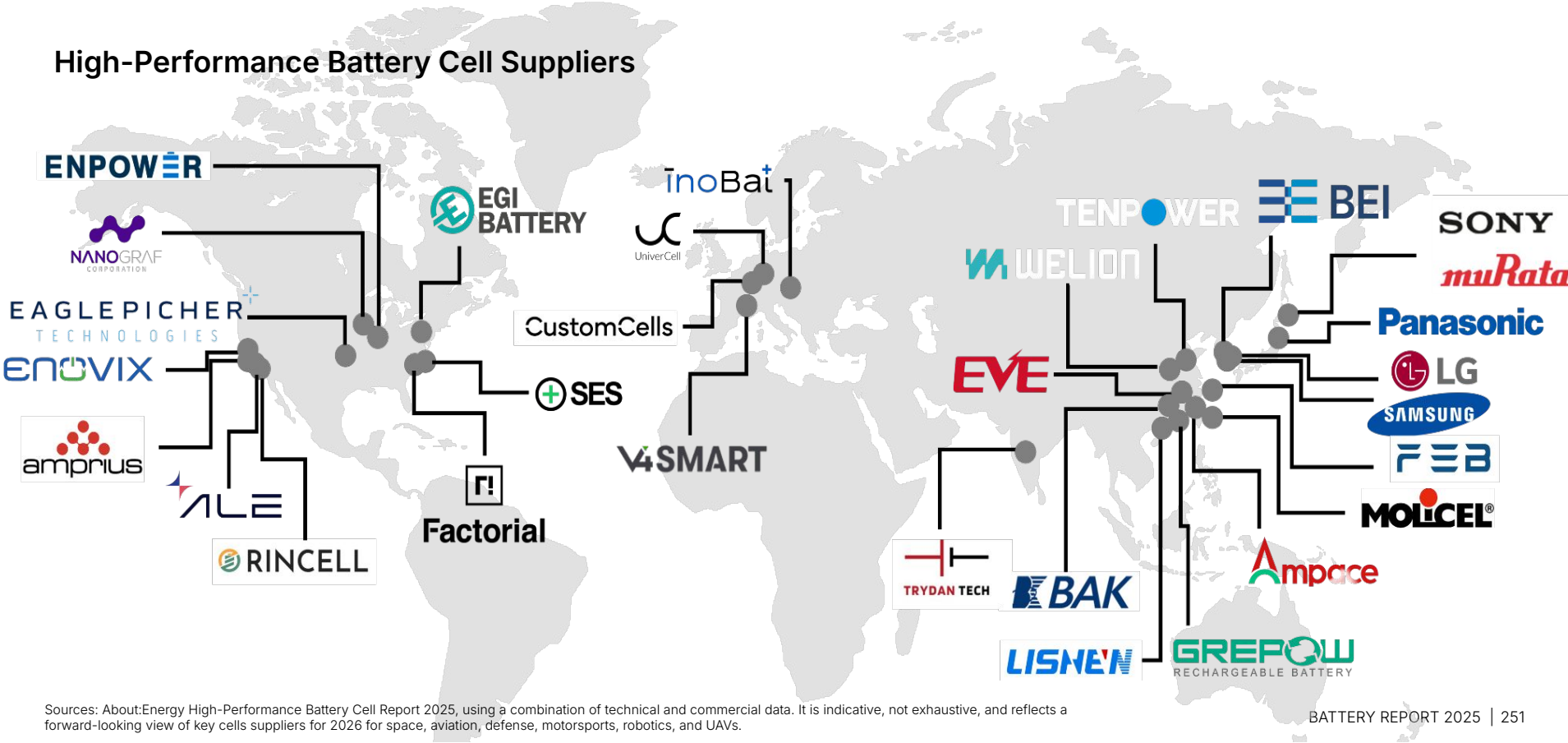




- Range for constant payload roughly scales linearly with gravimetric density improvements in battery-only drone
- Hybrid systems realize greater absolute range improvements over battery-only drones with gravimetric density improvements
- Segmenting battery size across a fleet to optimize for variable payloads and range is likely a better option than variation in the drones (tare) themselves
- Highly variable duty cycles and performance specs present product challenges and market opportunities for battery manufacturers with aviation customers

Source: Analyzing the Impact of Technological Improvements on the Performance of Delivery Drones

High-Performance Battery Cell Suppliers

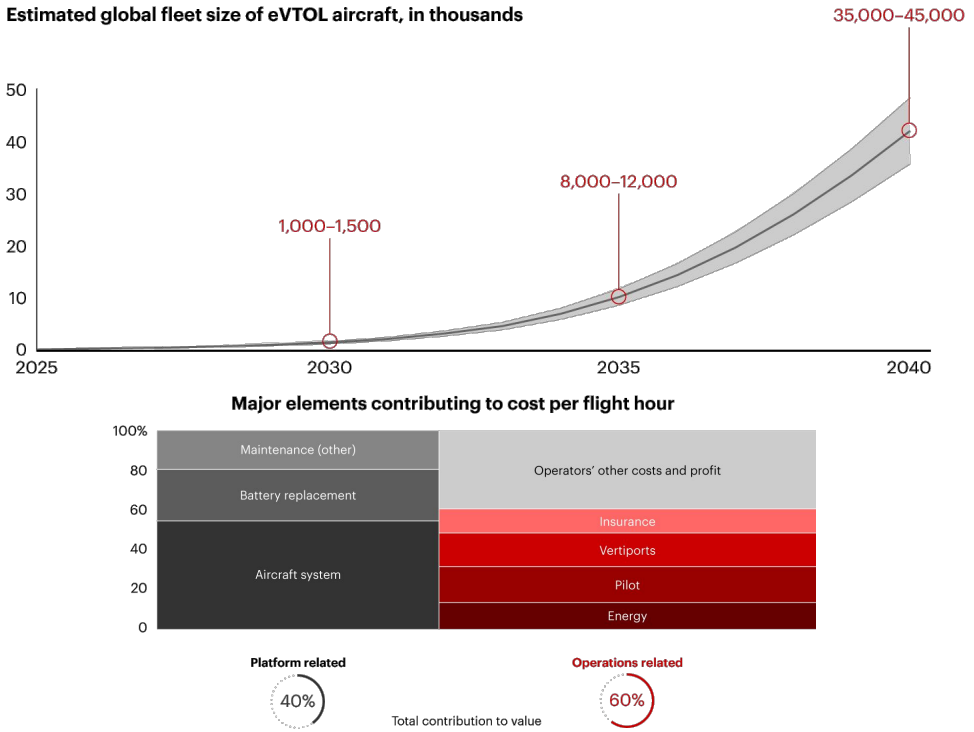


Sources: About:Energy High-Performance Battery Cell Report 2025, using a combination of technical and commercial data. It is indicative, not exhaustive, and reflects a forward-looking view of key cells suppliers for 2026 for space, aviation, defense, motorsports, robotics, and UAVs.

eVTOL 2040 Fleet Size Will Potentially Equal Current Commercial Airliner Fleet

- eVTOL viability hinges on battery energy density and efficiency to meet range and payload requirements (~70–80 mile missions). OEMs are optimizing designs to reduce energy-intensive hover time and overall weight.
- Expensive battery packs with limited cycle life are a significant component of operating costs, and improving lifespan/durability is critical for lowering total cost per flight.
- Although not elaborated in detail in the brief, Bain highlights that battery tech and thermal management are part of broader performance challenges that affect certification, safety, and maintenance planning.

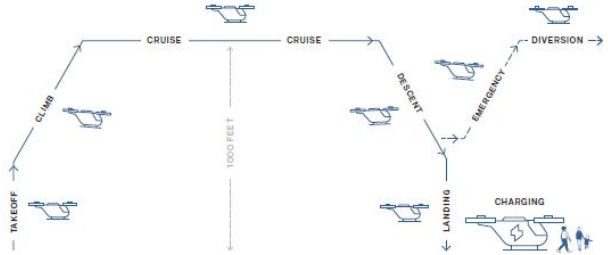
Significant technology improvements are still needed for a relatively small market that may only reach 10-20 GWh per year in the long term



Source: Bain & Company

eVTOL Sub-Application Determines Unique Performance Specifications & Unit Economics

- Air taxi or urban air mobility mission profile defined by high power pulses and asymmetric mission energy demand
- Range of about 30–150 miles
- >4C discharge during take-off pulse
- Fast charging to minimize turnaround prioritize power density



Mission profile details

PULSE TIMES

Take-off pulse:	~4 minutes
Cruise pulse:	~20 minutes
Landing pulse:	~2 minutes

AVG. DEPTH OF DISCHARGE 55%

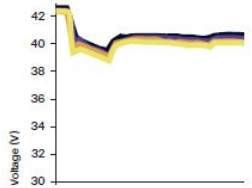
MAX DISCHARGE 5.4C

eVTOL economics tied to mission-count durability, not full DoD cycles

Module Voltage During Mission Profile

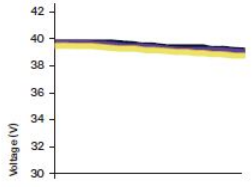
3A: Take-off

eVTOL power profile demands high discharge rates at take-off (up to 5.4C).



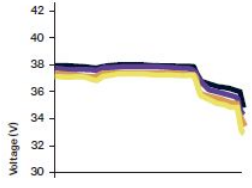
3B: Cruise

Once in air, optimized aerodynamics allow an eVTOL aircraft to fly with limited strain on the battery.



3C: Landing

At destination, an eVTOL must slow to landing speed then discharge power at high rates to safely land.

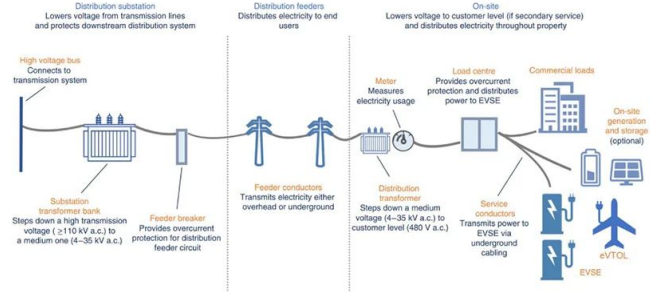


Source: Cuberg Aviation Battery Module External Testing Report - May 2024

eVTOL/Electric Aircraft Charging Requirements Highlight High-Power Infrastructure Necessity

- High-power demand and grid impact: eVTOL vertiports will require megawatt-scale charging capacity (≈1 MW or more per site), far beyond typical loads, meaning significant local grid upgrades and utility planning are needed for reliable operations.
- On-site energy solutions needed: To mitigate grid stress and support frequent high-power charges, integrating on-site energy generation and storage (e.g., microgrids) with renewables is a key strategy highlighted by NREL and industry analysis.
- Infrastructure planning advancing: FAA and industry stakeholders recognize the need to incorporate eVTOL charging nodes into vertiport/airport planning now, with siting, operations, and standards discussion ongoing across credible aviation infrastructures.

Commercial rollouts drive charging network build-out: Global partnerships and pilot projects (e.g., Abu Dhabi's vertiport charging rollout) reflect real-world deployment of dedicated eVTOL electric charging infrastructure to support advanced air mobility services.





Source: National Laboratory of the Rockies (formerly NREL), BETA Technologies

outliers

Pushing the boundaries of science by investing in defense & commercial Space technologies.

Space is the next transformational economy. It has already transformed our digital infrastructure and is now emerging as a frontier for breakthroughs such as in-space manufacturing and orbital data centers. This transformation is driven by dramatic reductions in launch costs: from **US$54,500/kg** during the Space Shuttle era (1981-2011) to under **US$2,720/kg** with SpaceX's Falcon 9 (2015), and is projected to reach **US$100-300/kg** with SpaceX's Starship within the next few years.

Every Earth industry will have a space frontier, including batteries. At Outliers, we are building this ecosystem as one of the top 5 space funds in the world, backing entrepreneurs and working with policymakers to make this vision a reality. Space attracts Outliers. Are you an Outlier?

Explore Outliers' proprietary research tools for analyzing the space economy:

Outliers Space Technology Atlas
https://docs.outliers.fund/space/atlas
A first-of-its-kind tool analyzing 52,579 federal contracts to over 7,625+ private space entities since 2016.

Outliers Scientific Fund Simulator
https://docs.outliers.fund/space
Historical outcomes modeled by valuation multiples across the U.S. space industry over the past 25 years.

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2025 | BATTERY REPORT

INDUSTRY

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Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing

Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- **Robotics**
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Notable Events in 2025 - Humanoids Lead the Headlines

Q1

Apptronik raised $350 million in Series A funding (co-led by B Capital and Capital Factory, with Google's participation) to scale production of its Apollo humanoid robot

Agility Robotics unveiled the next-generation of its Digit humanoid robot with significant upgrades for warehouse work. New features included a more efficient battery

Q2

Fourier Intelligence showcased its GR-1 humanoid robot for the first time in a healthcare setting at RehabWeek 2025 in Chicago. GR-1 demonstrated functional human-like movements and allowed clinicians to interact with it directly. This event highlighted humanoids' potential beyond factories in clinical therapy and patient care

Q3

Boston Dynamics and the Toyota Research Institute (TRI) demonstrated Atlas performing a complex sequence of tasks autonomously using a large behavior model (LBM)

Figure AI announced it had raised over $1 billion in Series C funding at a staggering $39 billion post-money valuation.

Q4

Figure AI introduced Figure 03, its third-generation humanoid robot, as a major leap toward a versatile home and commercial robot.

China's UBTECH Robotics announced it began mass production and delivery of its Walker S2 humanoid robots claiming the world's first large-scale humanoid deployment.

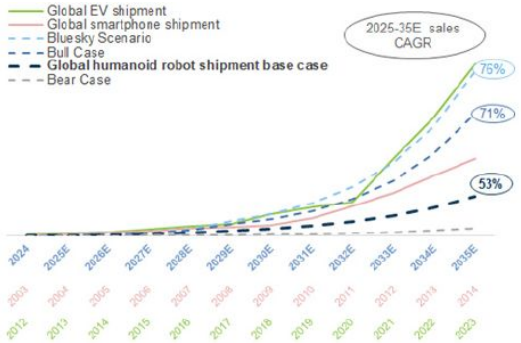
Source: Company Press Releases

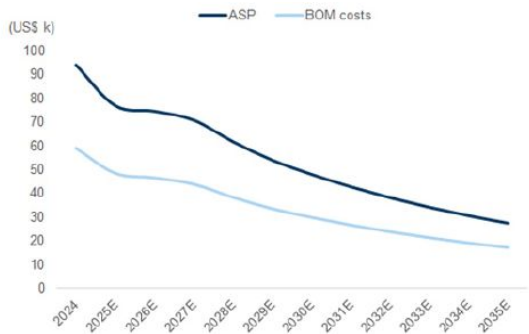
Market Overview - Bipedal Humanoid Robot (BHR) Focus & Battery Demand Impact

- Goldman Sachs 2035 forecast is only 38% industrial applications
- Morgan Stanley's 2050 forecast puts BHR population at 930 million with 90% for commercial and industrial applications
- Segmentation mix will heavily influence battery demand where C&I applications will require more frequent pack replacements
- Goldman Sachs modeled battery at "<1%" of BOM in 2024 (<$600)
- Battery demand KPI will be based on existing fleet rather than current year units sold like EV

1 billion BHRs needing an annual replacement of a 2 kWh pack creates 2 TWh of demand

Global shipment (k units) - new														
	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E	2031E	2032E	2033E	2034E	2035E	2025-35E CAGR
Base case	1.0	3.5	20	51	76	114	171	256	359	502	703	985	1,378	53%
Industrial	100%	100%	100%	100%	100%	100%	100%	95%	84%	69%	56%	46%	38%	
Consumer	-	-	-	-	-	-	-	5%	16%	31%	44%	54%	62%	
Bear case	1.0	1.0	1	4	20	51	76	114	171	256	359	502	703	n.m.
Industrial	100%	100%	100%	100%	100%	100%	100%	100%	100%	95%	84%	69%	56%	
Consumer	-	-	-	-	-	-	-	-	-	5%	16%	31%	44%	
Bull case	1.0	6.8	30	75	148	299	594	890	1,323	1,966	2,924	4,351	6,478	71%
Industrial	100%	100%	100%	100%	100%	100%	63%	53%	44%	37%	31%	26%	22%	
Consumer	-	-	-	-	-	5%	37%	47%	56%	63%	69%	74%	78%	
Blue-sky scenario	1.0	10	40	100	220	484	1,016	1,525	2,287	3,430	5,146	7,718	11,577	76%
Industrial	100%	100%	100%	100%	95%	62%	38%	33%	29%	25%	22%	19%	16%	
Consumer	-	-	-	-	5%	38%	62%	67%	71%	75%	78%	81%	84%	



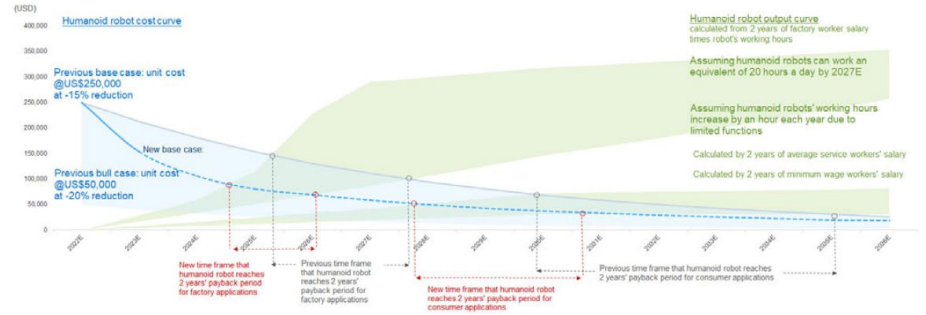


Source: Goldman Sachs, Morgan Stanley

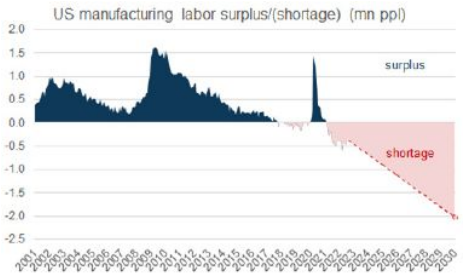
Bipedal Humanoid Robots (BHR) | Market Growth Drivers & Applications

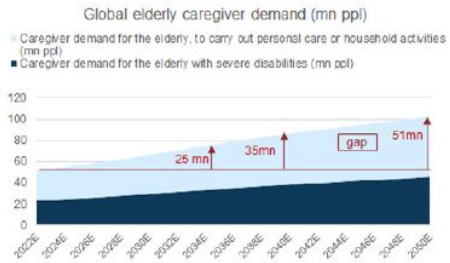
- AI acceleration (end-to-end + multimodal / robot-LLM progress) is speeding iteration and expanding what humanoids can reliably do, pulling demand into real work settings
- Rapid cost/BOM decline improves payback economics, bringing factory deployments earlier and consumer use cases sooner
- Capex + supply-chain buildout (more OEMs, deeper component availability, especially China) is enabling volume shipments and broader market penetration
- Labor constraints + safety/fatality exposure + policy support are key demand drivers, especially for "dangerous/dirty/dull" work humans avoid and regulators prioritize

Near-term applications: structured manufacturing and special operations; longer-term upside: household/elderly care if general-purpose AI proves viable.



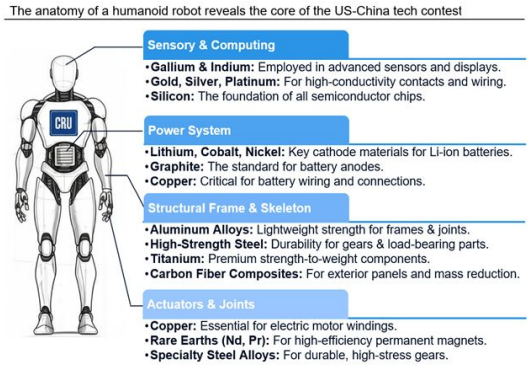
Note: Blue shaded area represents the possible range of humanoid robot ASP cost reduction and the green shaded area represents the possible range of humanoid robot productivity output assuming the robot's efficiency is twice a human worker; the crossing points represent the payback point for humanoid robot.

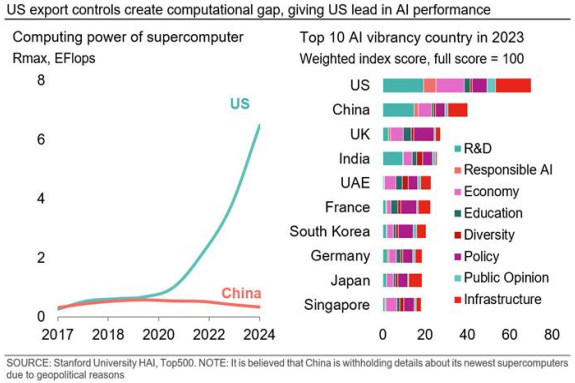


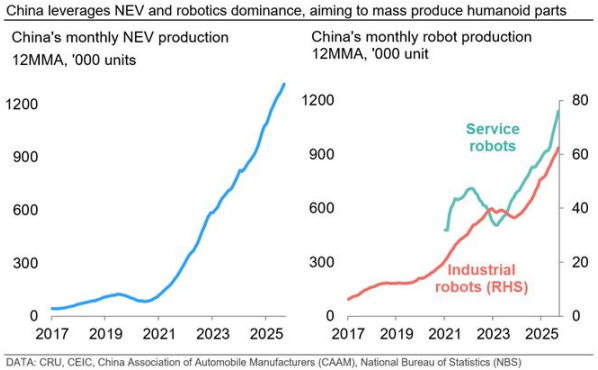


Source: Goldman Sachs, Morgan Stanley

China and US Vying for Control of Humanoid Robot Market







The humanoid robot battle pits US AI leadership against China's manufacturing scale and critical resource control. China is strategically pursuing self-reliance and supply chain capture to dominate this potentially $8 tn market.

The strategic advantage of the US rests heavily on the robot's 'brain', specifically foundational AI models (GenAI, LLMs) and advanced AI chips. China generally lags behind the US in cutting-edge computing power essential for training and deploying sophisticated embodied AI. This is enforced by **US export controls** since 2022, which strategically deny Chinese competitors' direct access to advanced AI chips required for true fluid, complex motion and real-time environment understanding.

China counter-leverages this vulnerability:

- maintaining overwhelming control over rare earth and battery **supply chains**
- manufacturing scale and supply chain depth enable unparalleled speed, flexibility and cost advantages in hardware production
- highly coordinated **national policy strategy**

See the **China section** for wider commentary on China's humanoid robot industry.

A Blue Ocean Market for Advanced Batteries

- Commercial and advanced Bipedal Humanoid Robots (BHRs) overwhelmingly use high-energy lithium-ion batteries (NMC/NCA) or in 48–60 V packs
- Typical humanoids carry ~1–3 kWh of batteries scaling with robot mass (50–80 kg) and payload rather than human-like form factor
- Most packs deliver 2–4 hours of practical operation, with fast charging, autonomous docking, or hot-swappable modules used to maintain high utilization
- A comparative analysis of leading BHRs reveals diverging battery technology strategies balancing energy density, efficiency, safety and operational uptime through architectural choices and chemistry evolution.

Next evolution of BHR links the BMS to the robot's motion planning and sensor data, enabling it to anticipate high power demands in advance, thus significantly reducing the impact of high C-rates on the cycle life of the cells.

Global ex-China humanoid robots

Manufacturer	Boston Dynamics	Agility Robotics	Tesla	Apptronik	Kawasaki Heavy Industries	Rainbow Robotics	1X	Figure	Sanctuary AI
Model	*Atlas*	*Digit (Latest Gen)*	*Optimus Gen 2*	*Apollo*	*Kaleido*	*HUBO2*	*EVE*	*Figure 01*	*Phoenix*
Mass	89kg	<65kg	63kg	73kg	80kg	43kg	83kg	60kg	70kg
Height	1.5m	1.75m	1.72m	1.73m	1.80m	1.20m	1.83m	1.70m	1.70m
Speed	2.5m/s	1.5m/s	2.0m/s	1.0m/s	1.1m/s	0.5m/s	3m/s	1.2m/s	1.2m/s
Degrees of freedom	28	10 + 8 (arms)	28 + 22 (hands)	c.30	34	32	74	41	74
Continuous operating time	1hr	16hr (optimized for logistics)	4hr	4hr	n.a.	n.a.	4hr	5hr	n.a.
Country	USA	USA	USA	USA	Japan	Korea	Canada	US	Canada
Target applications									
Disaster rescue	✓				✓	✓			
Special/hazardous applications	✓		✓	✓	✓	✓			
Patrol							✓		
Logistics	✓	✓		✓			✓	✓	✓
Auto manufacturing			✓	✓					
Healthcare/elderly care			✓	✓			✓	✓	✓
Commercial applications	✓		✓	✓		✓		✓	✓

China humanoid robots

Manufacturer	UBTECH	Fourier Intelligence	AGIBOT	Unitree	Dataa	Xiaomi	Dreame	Chunmi	Leju Robot	KEPLER
Model	*Walker S*	*Fourier GR-1*	*Expedition A1*	*H1*	*XR-4*	*CyberOne*	*Universal Humanoid Robot*	*DaQiang*	*KUAVO*	*K1, S1, D1*
Mass	n.a.	60kg	55kg	47kg	65kg	52kg	56kg	65kg	65kg	85kg
Height	1.70m	1.65m	1.75m	1.8m	1.68m	1.77m	1.78m	1.70m	n.a.	1.78m
Speed	n.a.	1.4m/s	1.5m/s	>1.5m/s	1.4m/s	1.0m/s	0.6m/s	0.6m/s	1.3m/s	n.a.
Degrees of freedom	41	44	45+	20	60+	21	44	36	26	28 + 12 (hands)
Continuous operating time	2hr	>1hr	n.a.	2hr	12hr	2hr	n.a.	n.a.	n.a.	n.a.
Country	China	China	China	China	China	China	China	China	China	China
Target applications										
Disaster rescue									✓	✓
Special/hazardous applications									✓	✓
Patrol			✓						✓	✓
Logistics	✓		✓	✓					✓	✓
Auto manufacturing	✓		✓	✓					✓	✓
Healthcare/elderly care	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Commercial applications	✓		✓	✓	✓	✓	✓	✓	✓	✓

Robot models are updated as of Jan 5, 2024.

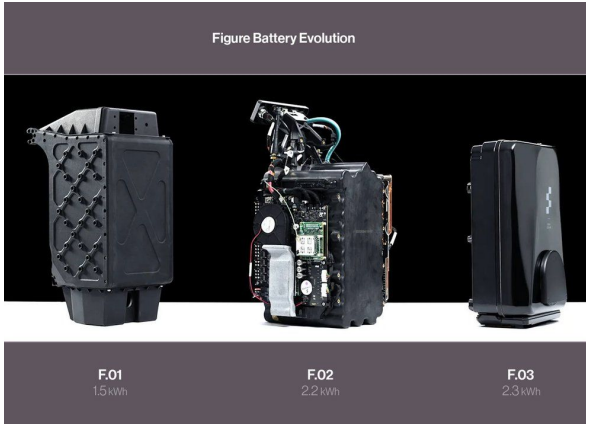
Source: Company data, Data compiled by Goldman Sachs Global Investment Research

Source: Goldman Sachs, Morgan Stanley

Battery Technology is Driving BHR Performance & Economics

Bipedal Humanoid Robots (BHRs) have a unique power profile, distinguishing their batteries starkly from traditional automotive or aviation EVs.





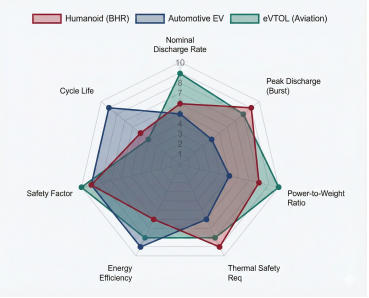
Battery systems are becoming more energy-dense, modular, and tightly integrated with advanced BMS and thermal management, pushing BHRs toward longer duty cycles by improving the battery rather than redesigning other systems

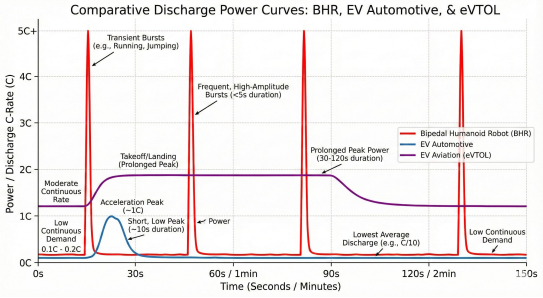
Source: Energy Sources of Mobile Robot Power Systems [Image AI Generated from the source content] , F.03 Battery Development



Battery Technology is Driving BHR Performance & Economics

A Bipedal Humanoid Robots (BHRs) power profile is defined by a low continuous discharge rate (typically ~0.1C) for basal functions like standing, walking and low speed manipulation, interspersed with highly transient high-amplitude power bursts for critical dynamic actions such as jumping, running, lifting heavy loads or compensating for instability (typically ranging from 3C to 5C).





Source: Energy Sources of Mobile Robot Power Systems [Image AI Generated from the source content] , F.03 Battery Development

2025 | BATTERY REPORT

INDUSTRY

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Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing

Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- **Other**

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

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Other Applications Demand Drivers		Battery Innovation That Enables It
AI Smartphones and PCs GenAI features increase battery drain up to 50%. Always-on AI assistants, on-device LLMs, and multimodal processing demand sustained high power. **$298B GenAI smartphone spend | 400M+ units (2025)**	→	**Silicon Anode Tech (Si/C and 100% Si) + NPU Efficiency** Si/C anodes (3-20% Si): 400-500 Wh/kg, shipping in OnePlus 13, Honor, Oppo. 100% silicon anodes: 900+ Wh/L, Enovix AI-1 sampling to OEMs (July 2025) for first pure-silicon smartphone. NPUs counter drain with 5-10x efficiency vs GPU. **Si/C Market: $537M (2025) to $20.8B (2034) | Consumer electronics segment 60% share**
Ultra-Thin Form Factor Race Flagship race to sub-6mm: iPhone 17 Air (5.64mm), Tecno Spark Slim (5.3mm), Samsung S25 Edge (5.8mm). Foldables under 4.5mm. Battery bulk is the constraint. **S25 Edge uses Li-ion = only 3,900mAh | Si-C adopters: 5,000-6,000mAh at same thickness**	→	**Silicon-Carbon Energy Density** 13% higher density vs Li-ion unlocks trade-off: thinner phone OR bigger battery. Oppo Find N5: 4.21mm foldable with 5,600mAh. Honor Magic V5: 5,820mAh at 4.4mm. **Chinese OEMs lead (OnePlus, Oppo, Honor, Xiaomi) | Samsung/Apple lag in adoption**
Wearables and Medical Devices Smart rings, AI glasses, health monitors require extreme miniaturization. Medical wearables (CGM, ECG, SpO2) demand 24/7 reliability and long cycle life. **Wearables: $219B to $493B (2030)**	→	**Small-Form-Factor Solid-State Batteries** Miniaturized solid-state cells ship before EVs (2026 vs 2028+). TDK: 1,000 Wh/L (100x previous). Samsung Electro-Mechanics mass-producing for Galaxy Ring, Watch, Buds (2026). Non-flammable, 50% thinner. **CE captures 40% of solid-state market by 2035 | Wearables = commercialization entry point ahead of EVs**
Sub-10-Minute Charging Expectation Realme GT3: 0-100% in 9.5 min (240W). Realme demos 320W (5-min charge). OnePlus 15: 150W. Thermal management is critical bottleneck at these power levels. **Consumer expectation: charge during coffee break | USB-C PD universal standard**	→	**GaN Chargers + Silicon-Carbon Thermal** GaN chargers 50% smaller, 30% more efficient than silicon. Si-C batteries handle fast-charge heat better than Li-ion - critical enabler for 150W+ charging. **GaN Market: $1.4B (2025) to $3.7B (2030)**
Budget CE and IoT Scale Cost-sensitive segments need alternatives to lithium. IoT explosion demands billions of low-cost cells. Geopolitical lithium/cobalt supply chain risk drives diversification. **CE holds 28.8% of sodium-ion market (2025) | Targeting: IoT, budget wearables, entry phones**	→	**Sodium-Ion Chemistry (Emerging)** Abundant materials, no lithium/cobalt dependency. Better thermal stability. Lower energy density than Li-ion limits use to cost-first applications. BYD, CATL investing. **Market: $527M (2024) to $3.3B (2034)| DOE $15.7M initiative**

- Consumer Electronics leads adoption of solid-state and silicon-anode technologies, helping accelerate commercialization - even ahead of EV timelines.
- Wearables are a strong entry point for next-gen battery tech, with fast iteration cycles and clear performance benefits.
- Battery design innovation is unlocking the next wave of consumer-electronics form factors, enabling thinner, lighter and more powerful devices.

Source: Gartner; IDC; Counterpoint; Enovix; BCC Research; Mordor Intelligence; Coherent Market Insights; Precedence Research; Market.us; PhoneArena; Gizmochina

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INDUSTRY

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Notable Events
Industry Value Chain
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- EV
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- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety

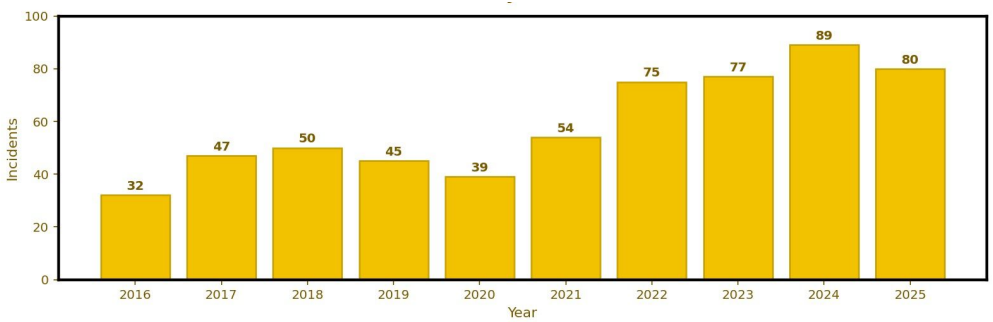
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

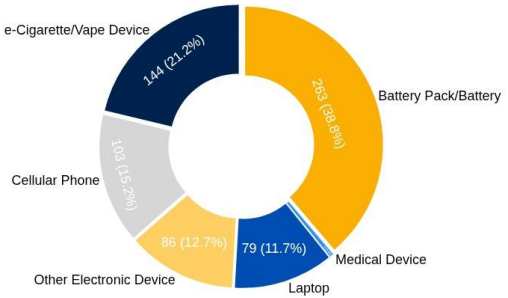
Software / AI

Battery Safety Incidents: FAA and New Directives

NUMBER OF LITHIUM BATTERY RELATED INCIDENTS IN THE US



LITHIUM BATTERY AIR INCIDENTS BY CATEGORY SINCE 2006



Graphs: last updated Dec 15. Source: FAA Incident Website

FAA issued a new Safety Alert for Operators (SAFO 25002) on August 25, 2025 that reinforces guidance relating to the potential hazards for lithium batteries carried by passenger and crew members. This comes amid a rise in 2025 of high-profile onboard battery-related incidents. Incidents include: August 8 incident heading to Dallas where cell phone overheated and began emitting smoke and April 4 incident where a battery pack inside a backpack overheated and caught fire resulting in injury and diverting of the plane. Full list can be seen on the FAA Incident Website.

SAFO 25002 gives many recommendations such as:

1. Recommendation of the use of large amounts of water to cool the battery and suppress flames as the primary response to a thermal runaway event.
2. Review of lithium battery fire fighting processes, procedures, and training including training practices for crewmembers to recognize different lithium battery thermal runaway stages.
3. Review of passenger safety messaging to advise passengers of lithium batteries risk

Notable Large Facility Fires Overview

Date/Location	Facility/Size	Key Details
Jan 16-18 *Monterey County, CA, USA*	**Moss Landing** *300 MW/1200 MWh*	Major fire from a 2020 installation that led to evacuation, environmental cleanup, and decommissioning. See following slide for further details.
Feb 19-20 *Essex, UK*	**Statera Thurrock** *300 MW/600 MWh*	Fire in a single containerized battery while site was under construction.(*Source*)
Jul 14 *Kaohsiung, Taiwan*	**Molie Quantum Gigafactory** *Cell Factory*	Fire in testing facility while batteries were undergoing initial charging protocol. (*Source)*
Aug 30-31 *Monterey County, CA, USA*	**California Flats Solar** *240 MWh*	Four Tesla megapacks ignited at a solar facility. Packs were allowed to burn and fire was contained. (*Source)*
Sep 23-24 *Boulder City, NV, USA*	**Townsite Solar** *360 Mwh*	Two Tesla megapacks ignited at a solar facility. Packs were allowed to burn and fire was contained. (*Source*)
Oct 18 *Munmorah, NSW, Australia*	**Waratah Super Battery** *850 MW/1680 MWh*	Catastrophic transformer failure right before final testing. Decreased capacity to 350 MW. Delayed full deployment until 2026. (*Source)*
Dec 19-22 Warwick, NY,USA	**Warwick BESS** *36 MWh + 17.9 MWh systems*	Fire at single containerized battery. Similar 2023 fire at the site identified water intrusion as root cause. (Source)

As BESS/EV deployment continues to grow, safety continues to be an on the front of minds as large scale thermal events can have big consequences such as release of toxic compounds into the environment and communities as well as downtime of key energy infrastructure.

A BESS specific failure database can be found here.

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Large Facility Fires: Case Study- Moss Landing

The lithium-ion fire at **Moss Landing** (natural gas-generation/BESS storage facility in Monterrey, California, United States) on **January 16, 2025 destroyed 300 MW of the 750 MW battery storage facility and led to an evacuation of ~1200 people in the area**.The region destroyed consisted of Moss Landing's Phase 1 NMC battery system (manufactured by LG Chem) facility that was completed in late 2020 which marks the earliest installation at the site.

No official root cause of the 2025 fire has been found, but **fallout** from the fire **has lead to regulatory involvement** from government agencies such as EPA, DTSA, and others. A timeline of regulatory events can be found below. While BESS regulations has changed significantly since the year this facility was deployed (2020; pre-NFPA 855), this event highlights the importance of strict safety regulations as BESS deployments continue to grow.

Jan 16

Start of fire and evacuation of nearby community. Extinguished Jan 18

Jan 16- 24

Start of air quality, soil and surface water sampling, and multi agency public health assessment group mobilization

Feb 18

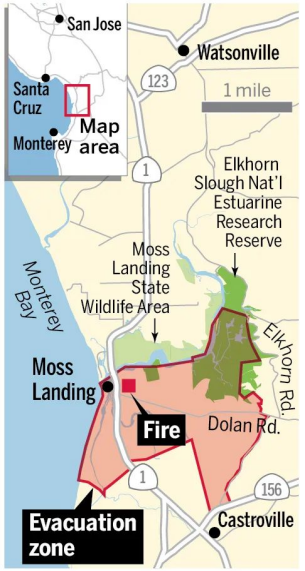
Flare up inside of building occurs. State of California requests EPA lead oversight of site's battery removal work

Feb 22- Mar 13

Battery delinking occurs.

April - Present

Continued decommission and cleanup continues well into December 2025 and is expected in the future.



BAY AREA NEWS GROUP

Source: Moss Landing Battery Fire Data Dashboard; Worst-case scenario: County official calls for 'independent investigation' of Moss Landing battery fire

Battery Safety Relevant Recalls & Incidents: CPSC

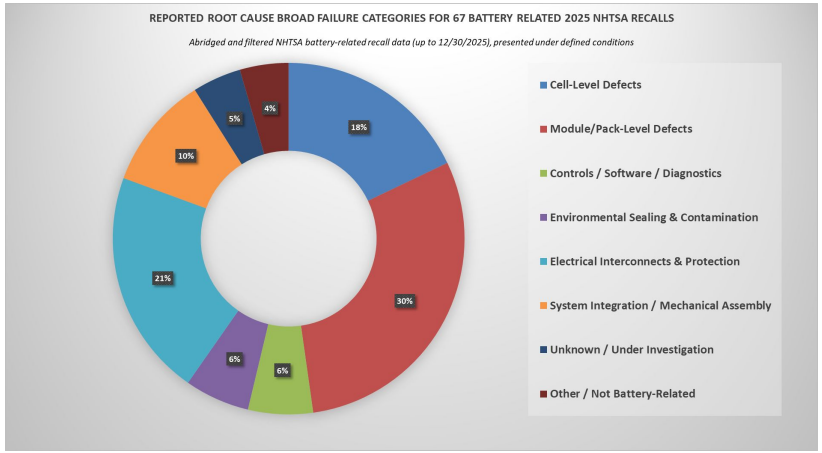
Date	Battery Root Cause	Name of Product	Units	Incidents	Manufactured In
13-Mar-25	Battery internal issue	Sublue Mix underwater scooters and replacement batteries (black batteries only)	~ 40,370	161 thermal/swelling (8 fires, 1 injury, 2 property damages worth $651,400)	China
20-Mar-25	Battery internal issue	VC Group MagSafe Wireless Power Pack Portable Power Banks	~ 89,500	19 fires, 10 minor injuries	China
17-Apr-25	Battery internal issue	Casely Wireless Portable Power Banks	~ 429,200	51 thermal/swelling, 6 minor injuries	China
1-May-25	Battery internal issue	Baseus 65W 30000mAh Portable Chargers (model number BS-30KP365)	~ 55,380	76 (72 swelling, 4 fires, 3 property damages)	China
29-May-25	Battery internal issue	iWALK Magnetic Wireless Power Banks	~ 27,500	15 fires, 10 injuries	China
12-Jun-25	Battery internal issue	Anker PowerCore 10000 power banks (model A1263 only)	~ 1,158,000	19 fires/explosions, 2 minor injuries, 11 property damages worth $60,700	China
17-Jul-25	Battery internal issue	iStore Magnetic Wireless Power Banks (IST-09991/W05 model only)	~ 8,520	3 thermal/explosions, one minor injury, 5 property damages worth $15,000	China
14-Aug-25	Battery internal issue	ESR HaloLock Wireless Power Banks	~ 24,000	9 fires/explosions, property damage $20,000	China
18-Sep-25	Battery internal issue	Arizer Solo II portable electronic vaporizer devices	~ 5,460	9 thermal/explosions	China
2-Oct-25	Battery internal issue	BP125, BatPak 2F and BatPak 3F Power Banks	~ 2,400	2 fires, 1 minor injury, property damage $3,300	China
9-Oct-25	Battery internal issue	ESR HaloLock Wireless Power Banks	~ 19,500	20 fires/explosions, property damage $30,000	China
13-Nov-25	Battery internal issue	Belkin Portable Power Banks and Wireless Charging Stands	~ 83,500 (In addition, ~ 2,385 were sold in Canada)	1 fire in US, 15 fires outside of US, two minor injuries, property damage $37,765	Vietnam/China
5-Dec-25	Battery internal issue	INIU BI-B41 Power Banks	~ 210,000	15 thermal (11 fires, 3 minor injuries, property damage $380,000)	China
20-Mar-25	Electrical hazard posing battery thermal event risk	Aiper Seagull Pro ZT6001 cordless robotic pool cleaners	~ 32,660	19 thermal/fires, 5 property damages	China
24-Apr-25	Electrical hazard posing battery thermal event risk	Huffy Torex 24V Utility Terrain Vehicle (UTV) Ride-on toys	~ 24,700	20 thermal/fires, 5 minor injuries	China
3-Jul-25	Electrical hazard posing battery thermal event risk	Predator 2000W Power Stations	~ 6,500	1 electrical	China
30-Jan-25	Reese's Law (battery ingestion)	Greater Goods Digital Kitchen Scales	~ 349,500	none	China
20-Feb-25	Reese's Law (battery ingestion)	Fjorden iPhone Camera Grips	~ 546	none	China
24-Apr-25	Reese's Law (battery ingestion)	LED Strip Lights	~ 390	none	China
28-Aug-25	Reese's Law (battery ingestion)	CT-ENERGY Lithium Coin Battery Chargers with Rechargeable 2032 Batteries	~ 1,100	none	China
13-Nov-25	Reese's Law (battery ingestion)	Great Lakes Select Button Cell and Coin Batteries	~ 32,600	none	China
4-Dec-25	Reese's Law (battery ingestion)	KTEBO Writing Tablet Toy	~ 10,380	none	China
26-Jun-25	Short circuit	DR Power LiPRO rechargeable lithium-ion battery packs (5.0 Ah)	~ 13,200	2 thermal/fires	China

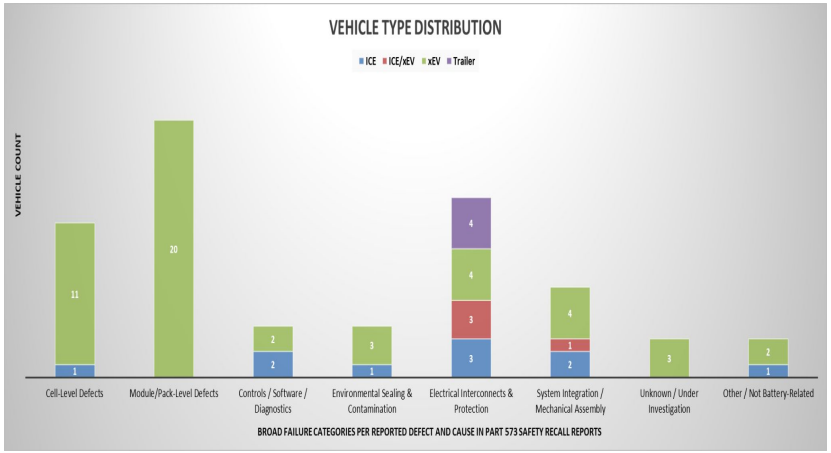
Source: Recalls & Product Safety Warnings | CPSC.gov

NHTSA Battery-Related Recalls, Broad Failure Categories per Reported Defect & Cause - 2025

Per NHTSA recall descriptions, there were approximately 67 battery-related recalls (includes 12V SLI, HV or other battery) in 2025. Each was classified into one of eight defined broad failure categories.

- Module/Pack-Level Defects led in recall frequency with 20 incidents.
- Cell-Level Defects, despite fewer recalls, affected the largest fleet.
- Electrical Interconnects & Protection and Controls/Software issues were significant contributors.
- Impact and frequency didn't always align - categories with fewer recalls can still pose major risk due to large vehicle exposure.





Source: NHTSA Recalls by Manufacturer | Department of Transportation - Data Portal and Part 573 Safety Recall Reports

Trend Comparison: NHTSA Battery-Related Recalls, 2025 vs 2024

Classifying publicly available recall defect and cause into defined broad failure categories appeared to show that Controls, Software or Diagnostics related issues led reported recalls in 2024 relative to Module/Pack-level assembly issues in 2025.

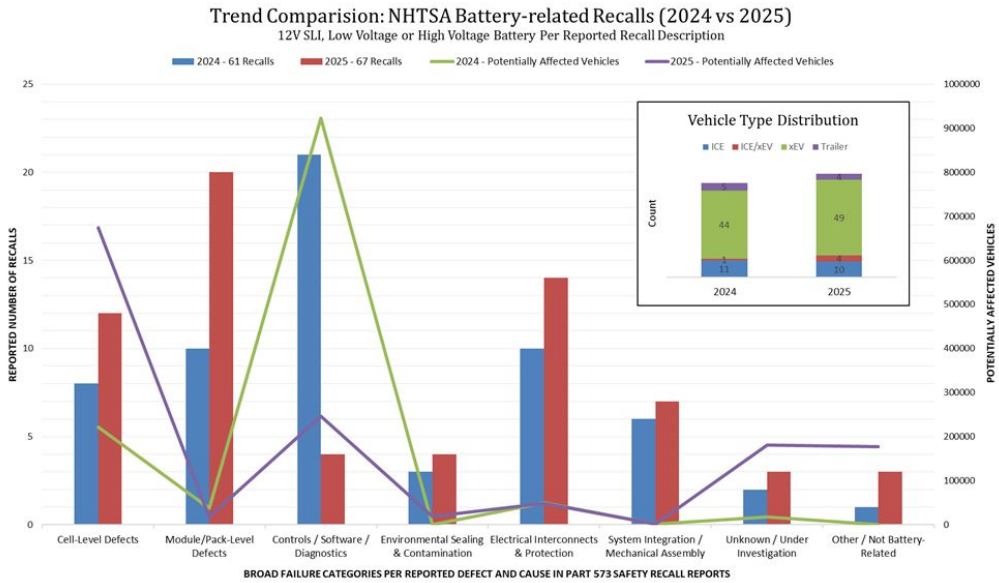
Cell-level issues appeared to lead potentially affected vehicles in 2025. Though fewer in 2025, Controls, Software or Diagnostics related issues affected significant vehicles.

Batteries in xEV vehicles led reported recalls (>70%) relative to those used in ICE, ICE/xEV or Trailers.

Emerging risks from issues related to Environmental sealing & contamination; Electrical interconnects & protection (outside the battery); System integration/Mechanical Assembly.

Approximately 67 reported battery-related recalls in 2025 relative to 61 in 2024.

Distributed nature of potential risk highlights need for safety considerations across layers.



Source: NHTSA Recalls by Manufacturer | Department of Transportation - Data Portal and Part 573 Safety Recall Reports

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Fire Safety Technologies: System

Structural Safety Considerations

Design choices to prevent propagation of events

Design considerations includes pack level choices, integration of systems, material selection, and incorporation of engineering controls.

Example of standards that guide considerations:

- UL 9540
- NFPA 855
- NFPA 68/69

Source [1]

Thermal Management Systems (TMS)

Maintains temperature "homeostasis"

System consists of: Sensors, set point management, cooling apparatus.

Types of cooling:

- Immersion cooling- pack submerged in dielectric liquid
- Liquid cooling- circulating liquid to absorb heat
- Air cooling- fans and blowers force circulated air

Source [2]

Fault Detection and Alarms System

Detects/diagnoses stages of a thermal runaway cascade

System consists of mixture of sensors and alarms/alerts

Types of sensors:

- Gas detection- vent gases
- Thermal detection- temperature anomalies at cell/module/pack
- Voltage imbalance monitoring- flags cells/modules/packs for potential faults

Source [3]

Active Fire Suppression System (FSS)

Reacts to extinguish fires of the system

System consists of automated response that triggers fire suppression agents

Types of suppression:

- Gas based suppression- inert or extinguishing gases
- Aerosol suppression- fine particles to interrupt combustion
- Water-based suppression- water to extinguish fire

Source [4]

Prevention → **Containment**

When designing a battery system, several system-level strategies exist to ensure proper safety against thermal runaway events.

Source:[1], [2], [3], [4]

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EV Battery Safety Regulation / Standards Updates across the Globe

Jurisdiction	Regulation / Standard	2025 Update	Practical Impact
UNECE / Global Interegs: R100 SA05	UN Regulation No. 100 – 05 Series of Amendments	Adds mandatory **thermal propagation safety assessment** / test	Drives pack thermal design changes; affects global EV type approval, risk mitigation mandatory
China GB Standards	GB 38031-2025 – EV traction battery safety	Introduces **"no fire, no explosion"** rule; thermal diffusion & crash tests	Significant redesign of battery safety architecture for China market
EU Environment Europa- Waste Batteries Recycling	Battery Regulation (EU) 2023/1542	Fully replaces Batteries Directive from **18 Aug 2025**	Single, directly applicable EU compliance framework for EV batteries
EU European Commision	Recycling efficiency & recovery methodology - (EU) 2025/606	Harmonised calculation & verification rules adopted **July 2025**	Requires auditable recycling efficiency and recovery reporting
UNECE (Heavy-duty EVs) UNECE sustainable transport	UN GTR-22 on EV battery durability	Adopted in **Nov 2025**; durability metrics for e-trucks	Introduces durability compliance into Heavy-Duty EV homologation
India MoEF: India	Battery Waste Management Rules – Amendment 2025 (amends 2022)	Updates EPR framework and compliance mechanics	Stronger producer responsibility and documentation duties
India MoRTH: India	Battery Pack Aadhaar System – Draft Guidelines	Draft released in **Dec 2025** proposes unique battery lifecycle ID	Digital traceability across EV battery lifecycle

Key Changes in Consumer Electronics Battery Safety Regulation (2025)

Europe

EU: On August 18, 2025, the Directive 2006/66/EC was officially fully repealed so the sole battery regulation framework is EU 2023/1542 which is a comprehensive regulation on battery safety and battery sustainability.

UK: On April 30,2025 the PAS 7055:2025 standard was published which updates safety guidelines such as labels and warnings for button/coin cells up to 32mm in size.

Africa

Kenya: May 5, 2025 was earmarked as the full enforcement of Extended Producer Responsibility (EPR) regulation that outlined clear battery waste producer responsibilities to increase accountability and safety during e-waste disposal. Temporarily suspended but resumed in Dec 15, 2025.

Asia

China: On Jan 8, 2025, CNCA outlined the updated requirements of GB 4343.1-2024 and GB 4706.1-2024 standard which requires more stringent testing of battery-operated devices. Testing includes requirement of battery-operated tools and appliances to be tested with fully-charged batteries in actual operating conditions among others. GB/T 19865-2024 will be rolled out in Aug-2026, that includes updated temperature and battery warning labels for electronic powered toys.

Saudi Arabia: On July 21, 2025, SASO notified draft technical regulation changes to a variety of sectors including E-mobility devices and EVs sold in Saudi Arabia. Regulation changes are to be made to be more inline with internationally accepted standards.

Americas

USA: On January 8, 2025 the CPSC issued draft notice of proposed rulemaking (NPR) for increased safety standards in e-bikes and similar e-mobility products. Withdrew officially on August 18,2025, leaving regulatory advances in e-mobility in the air.

Canada: On Dec 2, 2025 Health Canada issued a notice of intent for the proposal of new requirements for lithium-ion batteries in consumer products.

Key Updates in Electric Aircraft Battery Safety Regulations

Technical Safety Mandates	**Thermal No-Propagation (DO-311A) Mandate** A single-cell thermal runaway event must not propagate to adjacent cells.	**Advanced Venting & Containment** Enhanced requirements for managing toxic off-gassing away from critical aircraft structures.	**Predictive Health Monitoring (BMS)** Shift from reactive safety to predictive "State of Health" monitoring requirements. Not mandatory
Certification Frameworks	**EASA MOC-4 & MOC-5 (July '25)** Standardized Means of Compliance for VTOL Energy Storage Systems, replacing ad-hoc "issue papers."	**FAA Harmonization** Shifted toward aligning with EASA SC-VTOL standards to streamline dual-certification paths.	
Logistics & New Chemistries	**Sodium-Ion Inclusion (IATA/ICAO)** Introduction of specific UN codes (e.g. UN 3551) allows legal transport and testing of Na-Ion prototypes.	**Mandatory 30% SoC Shipping Limit** Strict enforcement for air transport of all lithium and sodium-based batteries to mitigate fire intensity.	





In 2025, the regulatory standards in electric aviation matured significantly pivoting from a case by case approval to a more harmonised and unified regulations.

Source: RTCA DO-311A; UL 1487; EASA MOC SC-VTO;, FAA-TSO C179b

Shipment & Storage - Standards and Regulations

Name	Related to [Shipment or Storage]	Type
UN 38.3	Shipment	Regulation
UL 9540	Storage	Standard
UL 9540A	Storage	Standard
NFPA 855	Storage	Standard
IEC 62619:2022	Storage	Standard
UL 1973	Storage	Standard
IEEE 1635-2022	Storage	Standard
UL 1642	Both	Standard

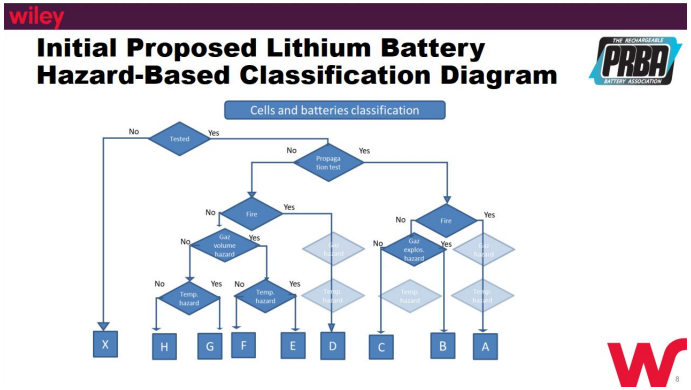
Note: Standards shown are selected from Taqa BelArabi standards Database based on multiple sources: IEC,IEEE, UN, UL, GB, ISO, & NFPA.

Regulations vs. Standards

- **Regulation:** a *mandatory legal requirement* set by a government or regulatory authority to ensure safety, environmental protection, and compliance (e.g., transport rules for lithium-ion batteries). Companies must follow regulations by law.
- **Standard:** is a *voluntary technical guideline* developed by industry organizations, such as IEC or ISO, that defines best practices for battery design, testing, and performance.

Highlighted Regulation - UN 38.3

UN 38.3 remains the anchor. Expect incremental clarifications via **Amendment 1 (2024)** and proposals from **2025** sessions (e.g., fixture/mounting language), while **air rules (IATA/ICAO)** tighten SoC controls by **2026** - all of which affect test planning, documentation (TS), and logistics SOPs
New more **detailed categorization** of battery cells and packs **hazard level** in UN38.3 will be proposed **2029/2030**, involving new testing requirements on cell and pack levels for categorization.



Note: Diagram adapted from PRBA presentation at the International Battery Seminar & Exhibit.

Source: Taqa BelArabi, PRBA, IBS Exhibition

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Key Updates in Residential & Portable Battery System Requirements

- **UL 9540 & UL 9540A:** Covers >20kWh energy storage systems (ESS), with 9540A providing large-scale fire testing to assess risks in residential settings. 2025 update includes more stringent gas and temperature testing.
- **UL 9540B:** A newer protocol for large-scale fire testing of residential ESS. Not currently required.
- **UL 2743:** Specifically for portable power packs (units must be <20kWh), ensuring device-level safety for portable, non-grid use.
- **NFPA 855:** Sets installation rules, becoming stricter in 2025 limiting total stored energy and placement (garages, outdoors, utility spaces, e.g. 10kWh per dwelling and 1kWh if interior portable system) to manage fire hazards, with specific protection (gypsum board) required for unfinished indoor spaces.



Source: BSLBATT, NFPA, UL Solutions

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Fire Code for Stationary Energy Storage System Facilities - New York State Case Study

History and Background	
Early summer 2023	After 3 fires at BESS facilities in Suffolk, Orange and Jefferson County, energy storage projects were under scrutiny from local communities.
July 28, 2023	Governor Kathy Hochul announced the creation of a New York State Inter Agency Fire Safety Working Group (FSWG) to ensure the safety and security of energy storage systems, including making fire code recommendations.
July 1, 2024	FSWG releases the Final Fire Code Recommendations Report taking into account public comments and feedback from subject matter experts and interested stakeholders
July 25, 2025	New York Code Council votes to approve the 2025 NYS Fire Code officially adopted updated energy storage safety codes based on the FSWG's recommendations
January 1, 2026	2025 NYS Fire Code takes effect

In July 2025, the New York State Fire Prevention and Building Code Council formally adopted the 2025 Fire Code of New York State (2025 FCNY). The 2025 Includes significant updates to SECTION 1207 - Electrical Energy Storage Systems (ESS). Key updates include:

- **Independent desktop reviews:** pre-construction/energization to verify design and safety compliance.
- **Central-station fire monitoring** with immediate FD notification, 24/7 coverage, and video monitoring with a 72-hour lookback.
- **Hazard support personnel:** dispatch within 15 minutes, on-site within 4 hours to assist responders.
- **Emergency Response Plan (ERP) required:** plus site-specific training for local fire departments.
- **More requirements around Decommission Plans:** including requirements for post-incident contingency
- **Emphasis on Ongoing Testing:** requires that all safety systems (battery monitoring, ventilation, gas detection, etc.) be tested per OEM guidelines, and records of tests be kept
- **Utility Exemption Narrowed:** broad exemption for utility-owned BESS largely removed with only a few exceptions

Source: NYSERDA, NY-BEST, NY-BEST, FCNY 2025, Empire Report

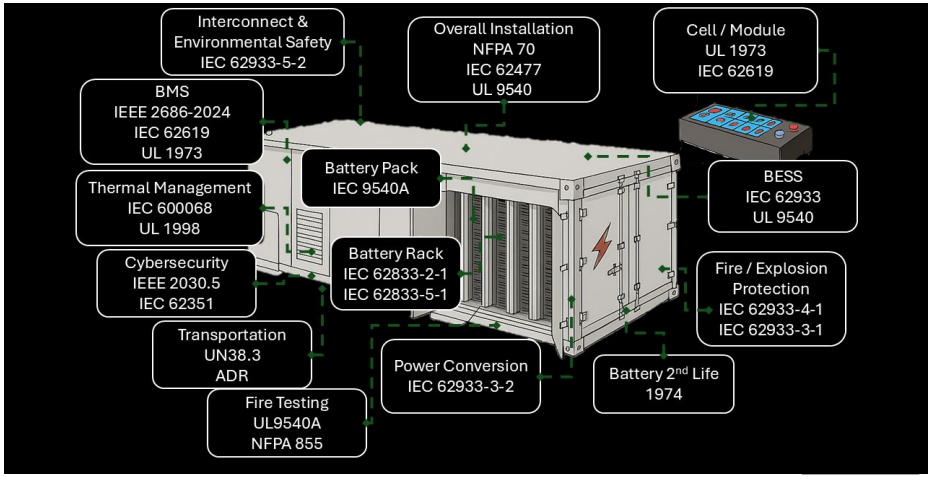
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BESS Safety Regulations and Standards

BESS & Battery Standards in Use

Standards are **not mandatory** unless they are **adopted** by regulatory framework [local, state, national levels]. While standards are not legally binding, they are widely adopted because they help ensure quality, compatibility, and safety - and they often support compliance with regulations.

Important to highlight: current level of battery standards [even for major applications as BESS] represent **the bare minimum** of what is required to ensure the battery system reliability & safety. A good battery system design will always consider **requirements beyond standards** to ensure its performance and safe operation.



Note: Standards shown are selected from Taqa BelArabi standards Database based on multiple sources: IEC,IEEE, UN, UL, GB, ISO, & NFPA.

Source: Taqa BelArabi

Product quality, built in.

Prevent **thermal runaway** by removing dust at the source

Thermal runaway often begins with microscopic dust that weakens cell integrity. Nilfisk vacuum solutions remove hazardous, conductive, and combustible particles in all areas of battery production – helping you protect performance and reduce the risk of malfunction.

And because we support every step of the manufacturing process, our solutions help you maintain cleaner, safer, more reliable operations, from mixing to final pack.



See how we help build quality into every cell.

NILFISK

BESS Safety Regulations and Standards Cont.

	BESS Highlighted New Standards [2025]
NFPA	*NFPA 855: 2026 edition (released 2025)*
GB	*GB 44240-2024 (effective Aug 1, 2025)* *GB 38031-2025 (effective Jul 1, 2026)*
IEC / ISO	*IEC 62933-5-2:2025 | IEC 62933-4-3:2025 | IEC 62933-4-2:2025 | ISO 23625:2025*
UL	*UL 9540 (Edition 3, 2025) | UL 9540A (5th Edition, 2025) | UL 9540B (Outline of Investigation, 2025)*
IEEE	*IEEE 2686-2024 (published Feb 7, 2025) | IEEE 2993-2025*
CEN / CENELEC	*EN 18061:2025*
SAE	*SAE J3327_202509 (2025) | SAE J2929 | SAE J2464 | SAE AS6413 / SAE AIR6840|*
Codes & local requirements	*California Energy Code 2025 (Nonresidential)*
IOGP - specifications for Oil/Gas industry	*IOGP S-753 and IOGP S-753Q (Jan 2025, public review)*

2025 | BATTERY REPORT

INDUSTRY

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Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety

Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

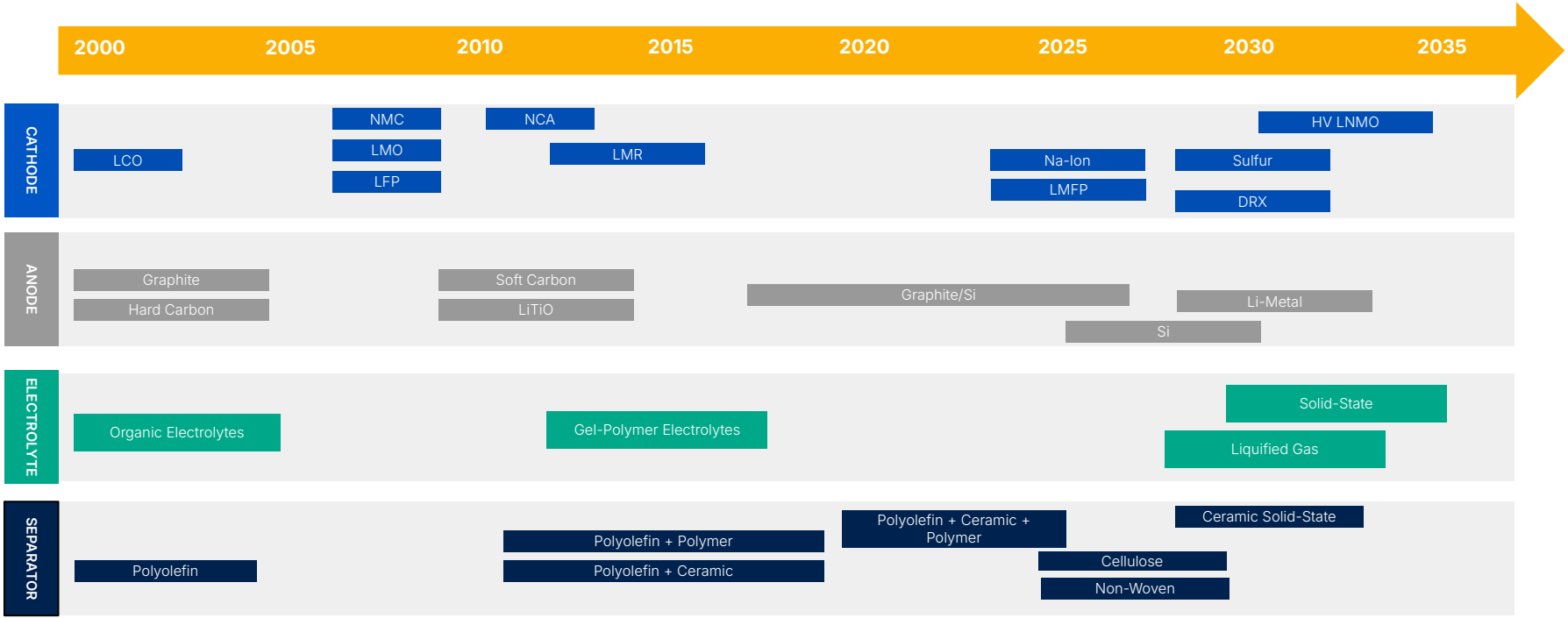
Cell Chemistry Overview

	Anode	Cathode	Electrolyte	Separator	Cell Design
General	The anode affects energy density, cycle life, and charge rate by hosting charge-carrying ions in the charged state.	The cathode determines the battery's capacity, discharge rate, operating voltage, and thermal stability.	The electrolyte, often a liquid or gel, enables ionic transport between electrodes and may act as a chemically active species depending on the battery chemistry.	The separator, a porous membrane, prevents physical contact between the anode and cathode, thereby avoiding short circuits, while allowing ion flow.	The performance of a battery is determined by the properties and interactions of its key components as well as system-level design choices (formulation, electrode loading, cell type).
Example 1: Lithium-ion (Li^+)	Stores ions during charge; releases during discharge (e.g. Li^+ intercalation into graphite, lithium reduction silicon-containing carbon, or plating onto Lithium Metal).	Accepts ions during discharge; releases during charge (e.g. Li^+ intercalation / deintercalation in metal oxides or phosphates such as LCO, NMC, NCA, LFP, LCO, LMO, Sulfur)	Ion transport medium enabling Li^+ movement between electrodes (organic carbonate solvents such as EC/DEC with Li salts, e.g. $LiPF_6$)	Physical barrier preventing short circuits while allowing Li^+ flow (e.g. microporous polymer, often with ceramic coating or solid state ceramic or polymer electrolyte)	Generally can be designed for power OR energy with trade-offs in other performance depending on application.
Example 2: Sodium-ion (Na^+)	Stores ions during charge; releases during discharge (e.g. Na^+ adsorption / intercalation in hard carbon).	Accepts ions during discharge; releases during charge (e.g. Na^+ storage in layered oxides, polyanionic compounds, or Prussian blue analogs).	Ion transport medium for Na^+ conduction (primarily organic electrolytes with Na salts, e.g. $NaPF_6$; some aqueous systems).	Physical barrier preventing short circuits while allowing Na^+ flow (e.g. polymer separator similar to Li-ion).	Generally designed for low cost, safety, and durability, with moderate energy density.
Example 3: Lead-acid (Pb/PbO_2)	Electrode supplying electrons during discharge (e.g. $Pb \leftrightarrow PbSO_4$ via SO_4^{2-} participation).	Electrode accepting electrons during discharge (e.g. $PbO_2 \leftrightarrow PbSO_4$ via SO_4^{2-} participation).	Ion-conducting medium and reactant (aqueous sulfuric acid, H_2SO_4; SO_4^{2-} and H^+ ions).	Electrical isolation with ionic permeability (e.g. porous rubber, polymer, or glass-mat separators).	Generally designed for reliability, recyclability, and low cost.

Source: Battery Report 2023 and 2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

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Timeline of Modern Lithium-ion Cell Chemistry Development



Source: Battery Report 2023 and 2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0)

Battery Performance Metrics: Definitions and Applications (1/2)

Performance Metric	Definition	Improvements Enable
Gravimetric Energy Wh/kg:	The energy provided by the cell divided by its total mass	Enables applications where weight is sensitive (EVTOL, Drone, Wearables, Infantry gear)
Volumetric Energy Wh/L:	The energy provided by the cell divided by its total volume	Enables applications where volume is a consideration (Cars, Personal devices, medical, etc)
Max Discharge Rate:	The highest allowable current, expressed as a multiple of the battery's rated capacity (C-rate), that can be applied during discharge without exceeding the manufacturer's specified voltage, temperature, or safety limits.	Enables applications where power is needed quickly (Battery Backup Units, Missiles, Race Cars etc)
Max Discharge Pulse Rate:	The highest short-duration discharging current (C-rate) that a battery can safely accept for a limited time without exceeding its voltage, temperature, or safety limits.	Enables applications with broad power fluctuations (Grid, CNI, Aerospace, EV, etc)
Max Charge Rate:	The highest allowable current, expressed as a multiple of the battery's rated capacity (C-rate), that can be applied during charge without exceeding the manufacturer's specified voltage, temperature, or safety limits.	Enables applications where reduced downtime is important to the consumer (EV's, EVTOL)
Max Charge Pulse Rate:	The highest short-duration charging current (C-rate) that a battery can safely accept for a limited time without exceeding its voltage, temperature, or safety limits.	Enables applications with high sudden current spikes (Grid, CNI, EV)
Cycle Life (80% BOL):	The number of complete charge–discharge cycles a battery can undergo before its capacity falls below a specified percentage of its original capacity (usually 80%).	Enables applications where cost of ownership, total throughput, and reliability are important (Grid, EV, Aerospace)
Calendar Life:	The total elapsed time (usually in years) that a battery can remain usable while in service, regardless of the number of cycles, before its capacity or performance falls below a specified threshold (often 80% of original capacity)	Enables applications where minimized cost of ownership, guaranteed lifespan, and long mission profiles are important (Aerospace, EV, Grid)
Shelf Life:	The period a battery can be stored (typically at room temperature) without significant loss of performance or safety.	Enables applications where the battery may not be used right away (DOD, CNI)
Operating Temperature Window:	The range at which a battery can operate without any damage to internal components	Enables applications where adverse conditions are common (DOD, Grid, Anything with hot/cold climates)

Source: Battery Report 2023 and 2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0)

Battery Performance Metrics: Definitions and Applications (2/2)

Performance Metric	Definition	Improvements Enable
Coulombic Efficiency	The ratio of charge extracted during discharge to charge supplied during charge in a single cycle.	Understanding long-term capacity fade, lithium inventory loss, and cycle life prediction (EV, Grid, R&D).
Depth of Discharge (DoD) Capability	The allowable fraction of total capacity that can be repeatedly used without accelerated degradation.	Lifetime optimization and usable energy planning (Grid storage, EVs).
State of Charge (SOC) Accuracy	The accuracy with which the battery's remaining charge can be estimated during operation.	Reliable battery management, range prediction, and user confidence (EV, Consumer, Medical).
Round-Trip Energy Efficiency:	The ratio of energy delivered during discharge to energy required during charge	Enables applications where energy losses directly impact operating cost and system sizing (Grid, EV, Storage)
Usable Energy vs. Temperature:	The fraction of nominal energy that can be delivered as a function of operating temperature	Enables applications requiring predictable runtime across climates (EV, Grid, Aerospace, DOD)
Usable Power vs. Temperature:	The maximum deliverable power output as a function of temperature without exceeding voltage or thermal limits	Enables cold-start and high-power operation in extreme environments (EV, eVTOL, Aerospace, Military)
Internal Resistance (DCIR / ACIR):	The effective resistance of the cell that causes voltage drop and heat generation under load	Enables assessment of power capability, efficiency, and aging behavior (EV, Power Tools, Grid)
Resistance Growth Over Time:	The increase in internal resistance with cycling and calendar aging	Enables lifetime power prediction and end-of-life criteria definition (EV, Aerospace, Grid)
Self-Discharge Rate:	The rate at which stored energy is lost over time without external load	Enables long-duration storage, standby systems, and infrequently used assets (Grid, DOD, Backup Power)

Source: Battery Report 2023 and 2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0)

Example Design Ranges of Various Lithium Ion Chemistries (Anode to Cathode Pairings)

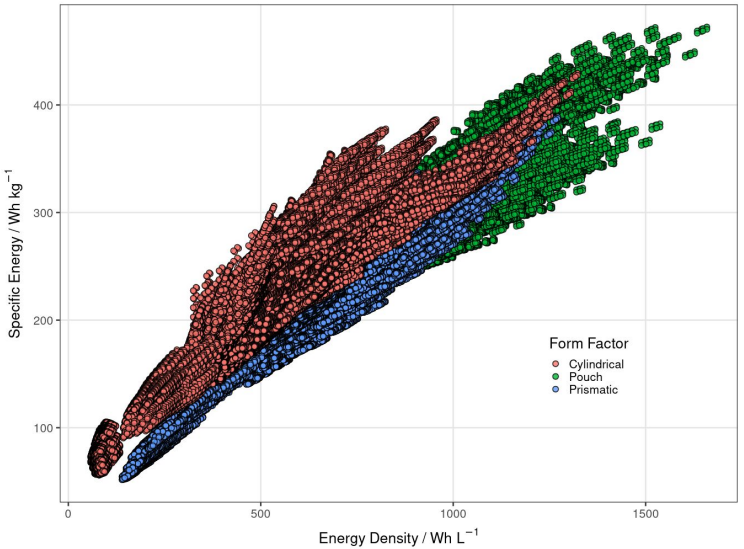
Cathode	Anode	Cell Nominal Voltage (V)	Cathode Capacity (mAh/g)	Cathode Loading (mg/cm^2)	Cathode Binder (%)	Cathode Additive (%)	Cathode Porosity (%)	Anode Capacity (mAh/g)	Anode Binder (%)	Anode Additive (%)	N/P	Anode Porosity (%)	Electrolyte ml to Ah Ratio
LFP	**Graphite (90-100%) + Silicon (0 - 10%)**	3.2	146 - 160	23_- 33	1 - 3	2 - 6	20 - 35	450 - 650	2 - 3	1 - 3	1.04 - 1.26	21 - 38	1.25 - 2.5
LFP	**Metallic Silicon**	3.2	146 - 160	23_- 33	1 - 3	2 - 6	20 - 35	3400	10 - 15	5 - 10	1.1 - 1.9	21 - 38	1.25 - 2.5
LFMP	**Graphite (90-100%) + Silicon (0 - 10%)**	3.7	130 - 150	19 - 32	3.5_- 4	3.5_- 8	23 - 36	450 - 650	2 - 3	1 - 3	1.04 - 1.26	21 - 38	0.8 - 3.3
LFMP	**Metallic Silicon**	3.7	130 - 150	19 - 32	3.5_- 4	3.5_- 8	23 - 36	3400	10 - 15	5 - 10	1.1 - 1.9	21 - 38	0.8 - 3.3
NMC 811	**Graphite (90-100%) + Silicon (0 - 10%)**	3.6	180 - 210	18_- 35	1 - 4	2 - 4	9 - 26	450 - 650	2 - 3	1 - 3	1.04_- 1.26	21 - 38	1.3 - 2.8
NMC 811	**Graphite (90-100%) + Silicon (0 - 10%)**	3.6	180 - 210	18_- 35	1 - 4	2 - 4	9 - 26	680 - 1800	6 - 10	3 - 6	1.04_- 1.26	21 - 38	1.3 - 2.8
NMC 811	**Metallic Silicon**	3.4	180 - 210	18_- 35	1 - 4	2 - 4	9 - 26	3400	10 - 15	5 - 10	1.1 - 1.9	21 - 38	1.3 - 2.8
NMC 811	**Lithium Metal**	3.8	180 - 210	18_- 35	1 - 4	2 - 4	9 - 26	680 - 1800	0	0	1.21 - 1.3	0	1.3 - 2.8
LMR	**Graphite (90-100%) + Silicon (0 - 10%)**	3.7	230 - 260	13 - 22	3_- 5	3 - 5	42 - 56	450 - 650	2 - 3	1 - 3	1.04_- 1.26	21 - 38	2 - 5
LMR	**Metallic Silicon**	3.7	230 - 260	13 - 22	3_- 5	3 - 5	42 - 56	3400	10 - 15	5 - 10	1.1 - 1.9	21 - 38	2 - 5
Sulfur	**Lithium Metal**	2.1	1000 - 1300	4 - 6	1 - 10	3 - 5	50 - 60	3680	0	0	1.5 - 3	0	3 - 5
NFMnO	**Hard Carbon**	3.0 - 3.1	130 - 140	5 - 20	2 - 5	5 - 10	20 - 40	300 - 340	5 - 10	3 - 8	1.05 - 1.3	30 - 60	1.1 - 3.3
NFPP	**Hard Carbon**	2.9 - 3.0	108 - 110	5 - 20	2 - 5	5 - 10	20 - 40	300 - 340	5 - 10	3 - 8	1.05 - 1.3	30 - 60	1.1 - 3.3

**Cathodes/Anode pairings were chosen to highlight differences and from commercially available cells and combinations when possible. Larger List of combination at links below.

Source: Battery Report 2023-2024., Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0), Note: Additional design metrics available at source

Impact of Form Factor on Performance

Form Factor	Volumetric Energy (Wh/L)	Gravimetric Energy (Wh/kg)	Other Key Trade-Offs
Pouch Cells	Highest; Lightweight, flexible thinnest casing and efficient active material packing allows highest Volumetric Energy Density.	Highest; No metal can adding weight allows maximum Gravimetric Energy Density	Fragility (leaking, off-gassing) ; Requies Thermal & Mechanical Management on pack level, no Safety Devices, typically slower stacking manufacturing speed
Prismatic Cells	High; though slightly lower than pouch due to rigid casing and internal clearances.	Medium: Rigid metal casing adds weight relative to pouch, but less than cylindrical on a per-cell basis.	Thermal non-uniformity, Susceptible to swelling, higher cost , Excellent packing efficiency in battery packs, better safety than pouch. Depending on stack vs wind lowest $/kWh
Cylindrical Cells	Lowest; Round shape leaves gaps when packed	Lowest; heavy and rigid Steel or Aluminum casing adds significant weight	Round geometry limits packing efficiency, Best thermal uniformity, mechanical robustness. fastest winding speed for manufacturing. Also lowest $/kWh. Better safety then Pouch

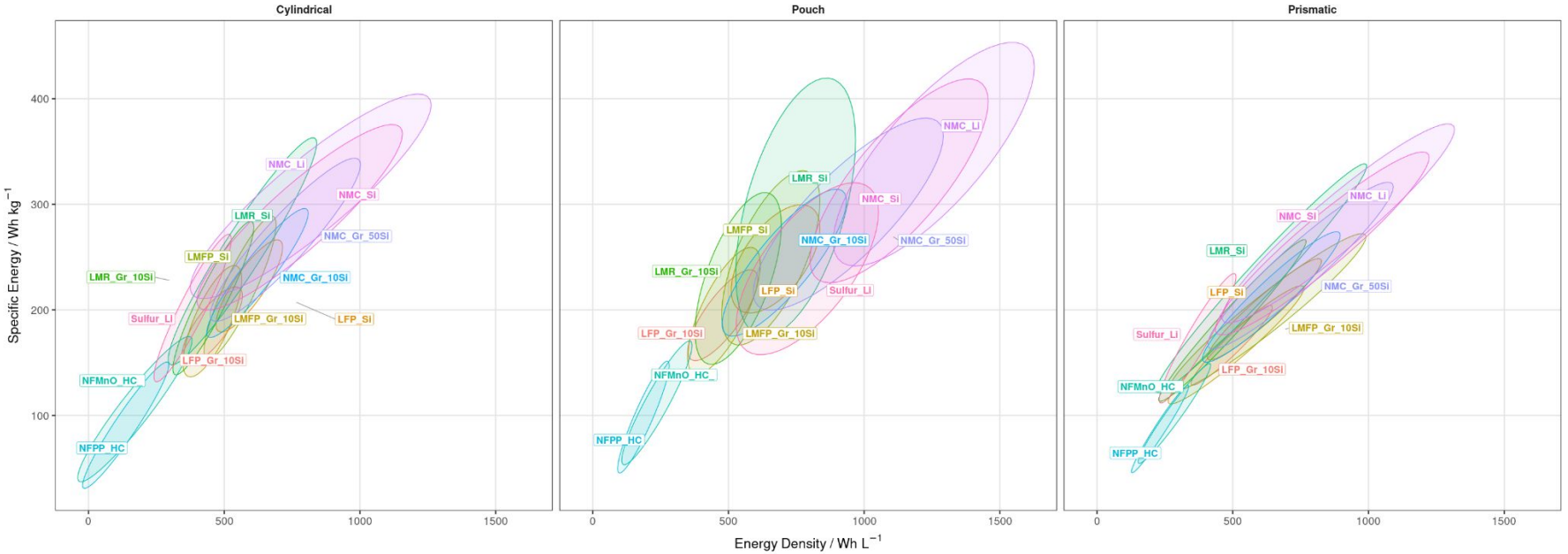


Overall Form Factor selection is **highly contingent on application and needs of the applications or consumer. Novel chemistries favor pouch due to its relative ease of **new material integration** and Wh/kg & Wh/L advantages

Source: Battery Report 2023 and 2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0)

Impact of Cell Chemistry on Different Form Factors (2/2)

Chemistries can have advantages over others given the form factor selected. Not every chemistry performs equally in every form factor.



Source: Battery Report 2023 and 2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0)

Chemistries Influencing Cell Form Factor Choices

Chemistries can influence cell form factor choice, but no clear trend. A cell form factor might be decided by either "Top-down" approach (e.g. OEM) or "Bottom-up" approach (e.g. startups / new chemistries / new technologies). The dimension of cell form factors has been evolved to enhance the performance and drive the cost efficiency for certain space and applications.

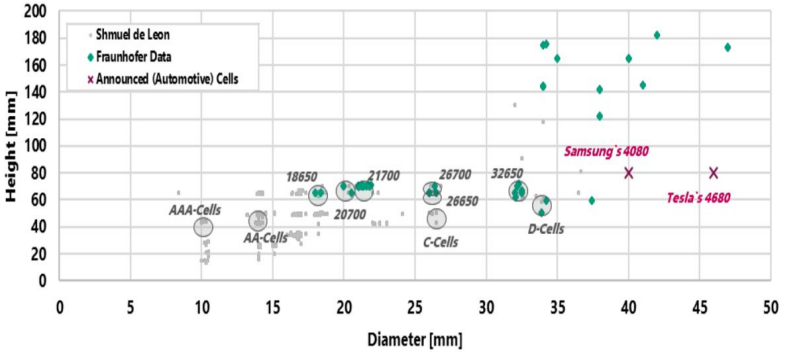
TABLE: DEPENDENCE OF CHEMISTRIES AND FORM FACTORS

Chemistries (Cathode // Anode)	Cylindrical Cell / *e.g.* OEM / main players	Prismatic & Blade Cell / *e.g.* OEM / main players	Pouch Cell / *e.g.* OEM / main players
NMC(NMCA) // Gr.	LGES	CATL, Samsung SDI	LGES, SK On
NCA // Gr.	Tesla/Panasonic, Samsung SDI, LGES	Samsung SDI	
LFP (LMFP) // Gr.	A123, CATL	BYD, CATL/Tesla, Gotion, EVE	A123, Gotion
LCO // Gr.			Samsung SDI
Sodium Cathodes // HC	HiNa, Faradion, TIAMAT SAS	CATL, BYD, Veken	LiFUN, Farasis, GPET
Dominant Silicon Anode	Storedot, Amprius, Enevate		Enovix, Storedot, Amprius
Solid-state (Sulfide, Oxide, Polymer)			QS, SolidPower, Toyota, ProLogium

Color Code:	
	manufacturability, reliability or safety concern
	application & cost rather than technical challenges or manufacturability
	trending

EVOLUTION OF THE CELL DIMENSION OF FORM FACTORS

Form Factor	Evolution of Cell Dimension
Cylindrical cell	18650 --> 21700 --> 4680 --> 46xx (*e.g.* 95, 12)
Pouch cell (long : short ratio)	ratio 1:1 <---> ratio 4:1, and thickness: 4 - 12mm
Prismatic cell (long : short ratio)	ratio 1:1 <---> ratio 4:1, and thickness: 10 - 70mm



Note: this original graph is from source 1

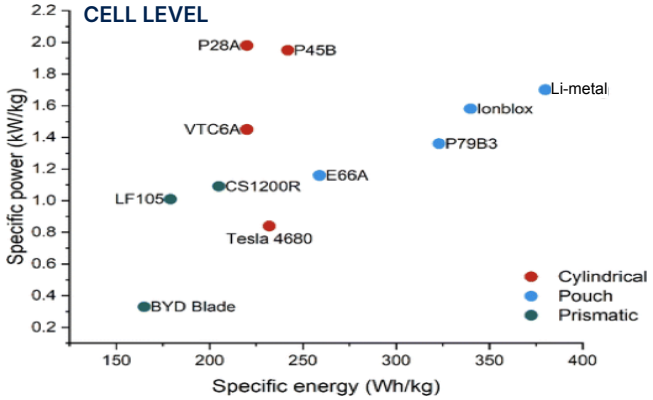
Source: CellForms-Development_perspectives_for_lithium-ion_battery_cell_formats_Fraunhofer_2022.pdf,

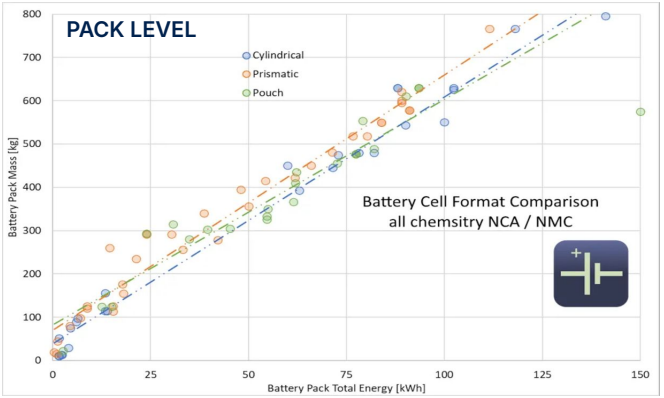
Applications Influencing Cell Form Factor Choice

The choice of cell form factor can be driven by applications, which depend on the requirements including energy density, power capability, safety, space efficiency, thermal management, mechanical stability and scalability. Each form factor offers unique pros and cons for specific application at either cell level or pack level.

TABLE: DEPENDENCE OF APPLICATION AND FORM FACTORS

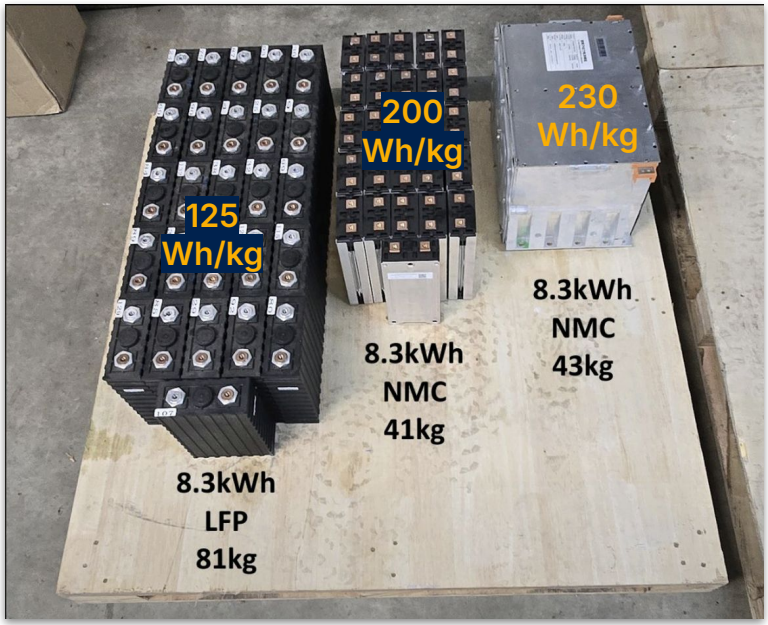
Applications		Cylindrical Cell	Prismatic Cell	Pouch Cell
Mobility	EVs			
	Aviation			
	eBikes/eScooters			
	Defense			
	eVTOL			
Stationary				
Consumer electronics				
Industrial & Services	Power tools			
	Medical devices			
Color Code				
	less selected			
	no clrear trend - all FFs being employed and considered			
	trending			





Source: [1] Formats - Battery Design, [2] *EES Batteries*, 2025, 1, 227-241

Form Factor Chemistry Tradeoff Comparison in Products



This side-by-side comparison highlights the **critical trade-off** in battery design: **Energy Density** vs. **Everything Else** (Safety, Cost, Cycle Life). Safety does not scale with size of cell ("More Ah, more boom")

To get **8.3 kWh** of energy, we can choose an **81 kg LFP pack** (safer, cheaper, longer life) or a **41 kg/43kg NMC pack** (higher energy, lighter weight). This highlights the fundamental tradeoff that many applications make in optimizing for the application.

The choice depends entirely on the **application**. For maximum range/performance (EVs), you choose the biggest **NMC/NCA** cells to maximize packing efficiency and overall pack density (with the least weight/volume). For stationary storage or heavy-duty vehicles where space/weight is less critical, **LFP** offers a cost-effective, longer lasting, and safer solution in addition to a higher total energy throughput.

Source: Redwood, ANL, Nature-lithium-ion battery cathode chemistry, Battery Report 2023-2024 Cell Chemistry, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

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Performance Metrics for Key Battery Chemistries	Lithium Ion								Sodium ion	Lithium Metal	Solid State	Lithium Sulfur
Cathode Anode	High Voltage LCO Gr	NMC Gr	NCA Gr	LFP Gr	LMFP Gr	LMO Gr	High Voltage LNMO Gr	High Ni Majority Silicon	NaMOx Hard Carbon	High Ni Lithium Metal	High Ni Lithium Metal	Sulfur Lithium Metal
Gravimetric Energy Density Wh/kg (cell level)	180-200	250-300	250-280	160-205	190-230	100-150	150-165	325-350	130-160	400-450	300-450	300-500
Volumetric Energy Density Wh/L (cell level)	400-700	650-800	600-750	250-400	400-580	300-400	400-650	750-1000+	150-300	700-1000	700-900	450-650
Cycle Life (C/2+ rate) (>80%)	750	1500	1000	3000	2000	500	750	500	6000	400	500	300
Calender aging (Qual)	Avg	Avg	Avg	Good	Avg	Low	Poor	Low	Avg	Avg	-	Avg
Self Discharge (%/Month)	1.00%	0.25%	2.50%	0.50%	1.00%	2.00%	-	5.00%	0.20%	-	-	1.00%
Charge Rate Capability (Qual)	Avg	Avg	Avg	Avg	Avg	Avg	Avg	Good	Avg	Low	Low	Avg
Discharge Rate Capability (Qual)	Good	Avg	Avg	Avg	Avg	Good	Avg	Good	**Avg	Avg	Avg	Avg
Safety (Active Materials)	Avg	Low	Low	Avg	Avg	Avg	Low	Low	Good	Poor	**Poor	**Avg
Possible Form Factors and Challenges	No Issue	No Issue	No Issue	No Issue	No Issue	No Issue	No Issue	*High Swelling*	No Issue	handling issues	Manufacturing	No Issue
Nominal Voltage (V) Voltage Range (V)	3.6 (3.0 - 4.5)	3.7 (2.5 - 4.3)	3.6 (3.0-4.3)	3.2 (2.5 - 3.65)	3.7 (2.75 - 4.0)	3.8 (3 - 4.3)	4.7 (3.0 - 5.0)	3.5 (2.5 - 4.2)	3.1-3.7 (1.5 - 4.2)	3.7 (2.5 - 4.2)	3.7 (2.5 - 4.2)	2.1 (1.5 - 3)
Cathode Specific Capacity (mAh/g)	274	215	200	170	160	148	147	215	170	215	215	1675
High Temperature Operation (60C+)(Qual)	Low	Avg	Low	Good	Good	Low	Low	Avg	Good	Low	**Low	Good
Low Temperature Operation (10C-)(Qual)	Poor	Good	Good	Poor	Avg	Avg	Avg	Good	Poor	Low	**Low	Poor
Recycle Value (Li, Co, Ni, Cu) for Cost/Effort	Best	Good	Good	Low	Low	Low	Avg	Avg	Poor	**Avg	**Avg	Low

Best 5
Good 4
Avg 3
Low 2
Poor 1

* Cell design and components other than the cathode can make a very large difference in cell performance metrics
* Marker [-] indicates no spec sheet available to make judgement.
Ratings marked with "**"are based on published data but have no commercial cells
For more details and sources, please visit: Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0)

Applications Matched to Preferred Performance Metrics		Market Size and Priority					Lithium Ion								Sodium ion	Lithium Metal	Solid State	Lithium Sulfur
		2024 Market in Billion USD	Priority #1	Priority #2	Priority #3	Priority #4	High Voltage LCO Gr	NMC Gr	NCA Gr	LFP Gr	LMFP Gr	LMO Gr	High Voltage LNMO Gr	High Ni Majority Silicon	NaMOx Hard Carbon	High Ni Lithium Metal	High Ni Lithium Metal	Sulfur Lithium Metal
Aerospace	Planes	426.42	Safety	Wh/kg	Power	Reliability	Poor	Low	Low	Poor	Poor	Poor	Poor	Good	Poor	Low	**Good	Great
	eVTOL	11.10	Power	Wh/kg	Safety	Reliability	Poor	Avg	Avg	Poor	Poor	Poor	Poor	Good	Poor	Great	**Good	Great
	Low Earth Orbit Satellites	12.90	Cycle Life	Wh/kg	Reliability	Safety	Avg	Avg	Avg	Avg	Low	Poor	Poor	Low	Avg	Poor	**Good	Poor
	Medium Earth Orbit Satellites	47.,44	Cycle Life	Wh/kg	Reliability	Safety	Avg	Avg	Avg	Avg	Low	Poor	Poor	Avg	Avg	Poor	**Avg	**Avg
	Geostationary Orbit Satellites	17.24	Cycle Life	Wh/kg	Reliability	Safety	Avg	Avg	Avg	Avg	Low	Poor	Poor	Low	Avg	Poor	**Avg	**Avg
Automotive	Moped	68.64	Wh/L	Cost	Self Discharge	Cycle Life	Low	Avg	Avg	Good	Good	Low	Low	Avg	Avg	Poor	**Poor	Poor
	Motorcycle	84	Wh/L	Cost	Cycle Life	Self Discharge	Low	Avg	Avg	Low	Low	Low	Poor	Good	Low	Avg	**Avg	Low
	Sports Car	89.15	Wh/kg	Wh/L	Power	Cycle Life	Avg	Good	Good	Avg	Avg	Poor	Poor	Good	Poor	Low	**Good	Poor
	Sedan	235.9	Cost	Wh/L	Cycle Life	Self Discharge	Low	Avg	Avg	Avg	Good	Poor	Avg	Poor	Avg	Poor	**Low	Low
	Sports Utility Vehicle	333	Wh/L	Cost	Cycle Life	Self Discharge	Low	Avg	Avg	Avg	Good	Poor	Avg	Poor	Avg	Poor	**Low	Low
	Heavy Duty Trucks	215.54	Wh/L	Wh/kg	Cycle Life	Cost	Poor	Low	Low	Low	Low	Poor	Poor	Avg	Poor	**Avg	**Low	**Avg
	Industrial Trucks	24.72	Wh/kg	Cycle Life	Cost	Self Discharge	Poor	Avg	Low	Low	Low	Poor	Poor	Avg	Poor	**Avg	**Low	**Good
Consumer Electronics	Computers & Tablets	448.76	Wh/L	Safety	Reliability	Cost	Good	Avg	Low	Avg	Avg	Low	Good	Low	Low	Poor	**Poor	**Poor
	Smart Phones & Watches	566.12	Wh/L	Safety	Reliability	Cost	Good	Avg	Low	Avg	Avg	Low	Good	Low	Low	Poor	**Poor	**Poor
	Power Tools & Gardening	39,5	Power	Cost	Safety	Reliability	Good	Poor	Low	Avg	Avg	Low	Good	Low	Low	Poor	**Poor	**Poor
	E-Bikes	48.7	Cost	Wh/kg	Safety	Reliability	Avg	Avg	Avg	Avg	Good	Avg	Good	Low	Good	Poor	**Poor	**Good
Grid	Grid Storage (Balancing)	7.51	Cost	Cycle Life	Reliability	Safety	Good	Low	Low	Good	Poor	Poor	Poor	Poor	Good	Poor	**Poor	**Good
	Residential Storage + Smart Grid	37.6	Reliability	Safety	Cost	Cycle Life	Avg	Low	Low	Good	Good	Avg	Avg	Poor	Great	Poor	**Avg	**Avg
Medical Devices	Defibrillators	11.34	Safety	Reliability	Power	Self Discharge	Avg	Low	Low	Avg	Low	Avg	Low	Good	Poor	Low	**Avg	**Poor
	Surgical Tools	14.26	Safety	Reliability	Power	Cycle Life	Avg	Low	Low	Avg	Avg	Avg	Low	Good	Poor	Low	**Avg	**Poor
	Pacemakers	4.4	Safety	Reliability	Cycle Life	Self Discharge	Low	Low	Low	Avg	Avg	Low	Low	Poor	Poor	Poor	**Good	**Poor
	Monitoring Devices	22.548	Cycle Life	Cost	Safety	Reliability	Low	Low	Low	Good	Low	Low	Avg	Poor	Good	Poor	**Poor	**Poor
Military	Infantry	309.77	Reliability	Safety	Wh/kg	Self Discharge	Poor	Avg	Avg	Poor	Low	Poor	Poor	Good	Poor	Poor	**Good	**Good
	Backup Power		Reliability	Safety	Wh/kg	Wh/L	Poor	Avg	Avg	Poor	Low	Poor	Poor	Good	Poor	Poor	**Good	**Good
	Missiles		Power	Wh/kg	Wh/L	Reliability	Good	Avg	Avg	Low	Low	Low	Poor	Good	Poor	**Good	**Good	**Good
	Drones		Power	Wh/kg	Wh/L	Reliability	Good	Avg	Avg	Low	Low	Low	Poor	Good	Poor	**Good	**Good	**Good

Best 5
Good 4
Avg 3
Low 2
Poor 1

* Cell design and components other than the cathode can make a very large difference in cell performance metrics

Ratings marked with "**"are based on published data but have no commercial cells

For more details and sources, please visit: Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

		Room Temp (20 - 30 C)									Functional Requirements		
Market	Sub-Market	Wh/kg	Wh/L	Max Discharge Rate	Max Discharge Pulse	Max Charge Rate	Max Charge Pulse	Cycle Life (80%)	Calendar Life	Shelf Life	Safety	$/kWh	$ / kWh / Cycle
Aerospace	eVTOL												
	Low Earth Orbit Satellites												
	Medium Earth Orbit Satellites												
	Geostationary Orbit Satellites												
	Unmanned Aerial Systems												
Automotive	Motorcycle												
	Sports Car												
	Sedan												
	Heavy Duty Trucks												
Consumer Electronics	Smart Phones & Watches												
	Power Tools & Gardening												
	E-Bikes												
Grid	Commercial and Industrial												
	Residential												
	Utility												
Medical Devices	Surgical Tools												
	Monitoring Devices												
Military	Infantry												
	Backup Power												
	Missiles												
	Communications												

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For more details and sources, please visit: Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

	Green Enabling or Required
	Orange potentially adds a premium/Tie breaker
	Gray doesn't make money

Best
Good
Average
Poor
Worst

Chemistry		Room Temp (20 - 30 C)									Functional Requirements		
Cathode	Anode	Wh/kg	Wh/L	Max Discharge Rate	Max Discharge Pulse	Max Charge Rate	Max Charge Pulse	Cycle Life (80%)	Calendar Life	Shelf Life	Safety	$/kWh	$ / kWh / Cycle
LFP	Graphite												
LFP	Silicon												
LFMP	Graphite												
LFMP	Silicon												
LMR	Graphite												
Reference Point	NMC	Graphite											
NMC	Gr + 50% Si												
NMC	Silicon												
NMC	Lithium Metal												
Sulfur	Lithium Metal												
NFMnO	Hard Carbon												
NFPP	Hard Carbon												

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Ratings marked with "**"are based on published data but have no commercial cells

For more details and sources, please visit: Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

2025 | BATTERY REPORT

INDUSTRY

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Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- **EV**
- **Stationary Energy Storage**
- **Data Centers**
- **Aviation, Drones, Space**
- **Robotics**
- **Other**

Safety

Cell Design and Materials
- **Li-Ion**
  - **Li-Cathode**
  - Separator
  - Li-Anode
  - Anode
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

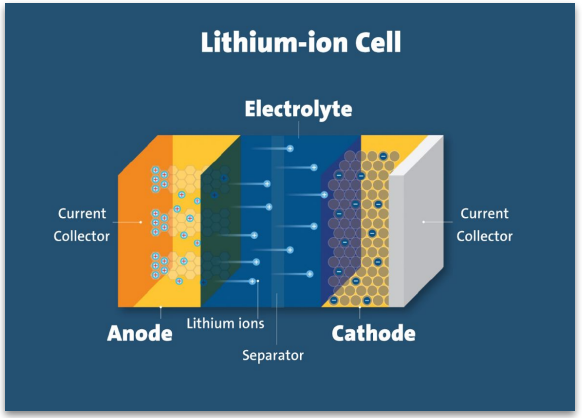
Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Cathode Introduction

Across rechargeable battery systems, the cathode is the positive electrode that primarily impacts a battery's operating voltage, energy density, power capability, thermal behavior, and lifetime. Cathode materials vary widely by battery chemistry and may include metal oxides, phosphates, sulfides, or conversion-type compounds, each offering different trade-offs between performance, cost, safety, and durability.

In lithium-ion batteries, cathodes are most commonly based on transition-metal compounds, such as lithium cobalt oxide (LCO), lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP). The specific metal composition and crystal structure strongly influence voltage, energy density, rate capability, and long-term stability.



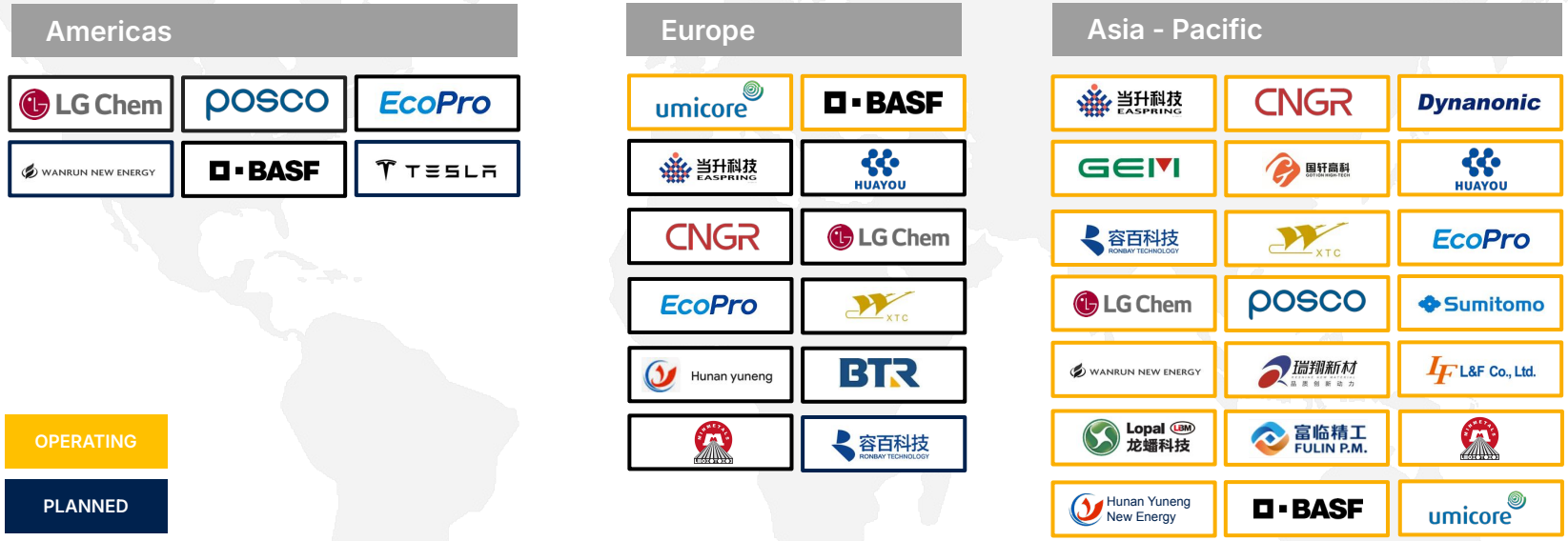
Function of the cathode:
During discharge, ions migrate from the anode through the electrolyte and are accepted and stored in the cathode while electrons flow through the external circuit to provide power. During charge, this process is reversed, with ions released from the cathode and transported back to the anode. The cathode's structure and chemistry govern how efficiently ions can be stored and transported under different operating conditions..

Factors influencing cathode choice:

- **Energy density:** How much energy the battery can store per unit mass or volume, driven by cathode capacity and operating voltage.
- **Power density:** How quickly ions and electrons can move within the cathode structure to deliver high power.
- **Cycle life:** The ability of the cathode to maintain capacity and voltage over repeated charge-discharge cycles.
- **Thermal Stability & Safety**: Resistance to thermal runaway, oxygen release, or structural degradation under abuse or high temperature.
- **Cost & Supply Chain:** Raw material availability, processing complexity, and exposure to critical or constrained elements.

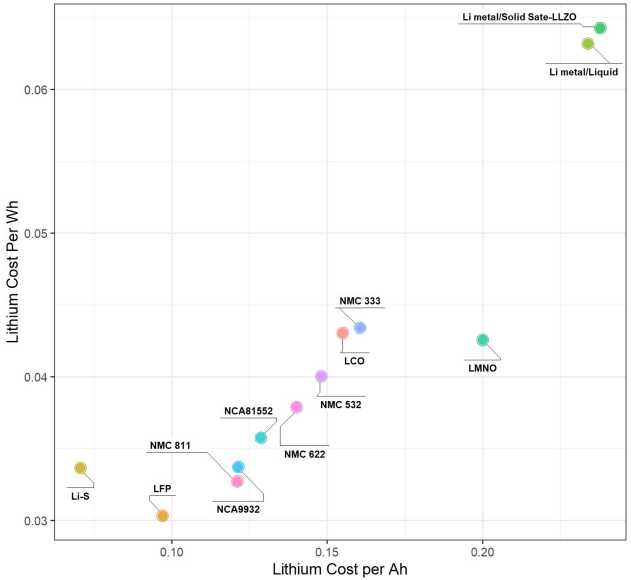
Source: Redwood, ANL, Nature-lithium-ion battery cathode chemistry, Battery Report 2023-2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

Major pCAM and CAM Producers



Source: Company announcements

Chemistry Lithium WH & AH Cost Map - Drive Towards Cheaper Batteries



For more details, please visit: Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0)
***Cost in USD

Current market conditions are demanding cheaper batteries for EV's at the same performance of modern day NMC811 batteries.

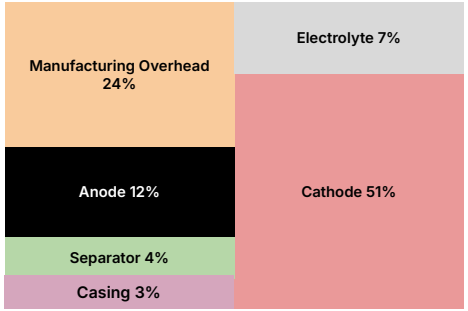
Cost Drivers (see Costs Section for more information)

- Cathode active material (CAM) is major driver, accounting for >~50% of the cell cost
- Lithium Hydroxide (LiOH) or Lithium Carbonate (Li_2CO_3) accounts for > 50% of the CAM cost excluding processing/overhead

Enabling Cheaper EVs

- LFP is the near-term solution for achieving the lowest lithium cost per kWh
- Beyond LFP, manufacturers will need to turn to advanced chemistries, such as lithium-sulfur (LiS), to maintain Cathode cost reductions while improving performance.

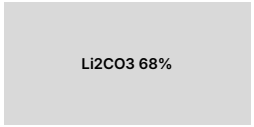
CELL COST BREAKDOWN



NMC811 COST BREAKDOWN



LFP COST BREAKDOWN

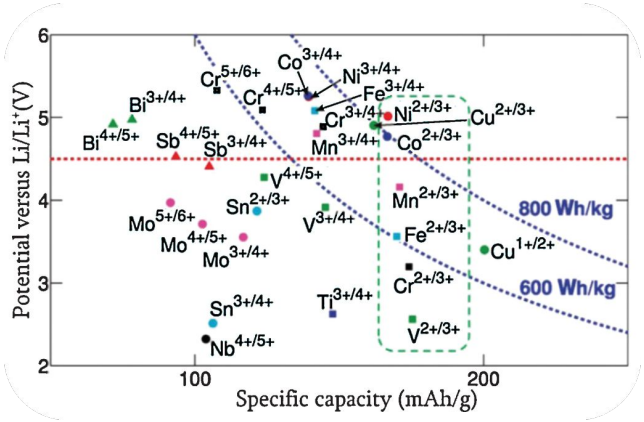


Source: Battery Official, Battery Report 2023 (pg 131), Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

High-Voltage Cathodes - Opportunities, Challenges, and R&D Trends

The theoretical voltage limit of a cathode material is defined by its **active elements' redox potentials.** NCM naturally delivers a higher voltage than LFP because Ni, Mn, and Co ions have higher redox potentials than Fe ions [1].

The **practical voltage limit can be increased** by optimizing particle morphology toward single crystal, tuning element ratios to raise Mn content, and applying doping or coatings to stabilize the crystal structure and minimize side reactions.



[1] Specific Capacity of Cathode Material Only

The high-voltage battery market is growing rapidly, driven by demand for long-range EVs, advanced AI enabled consumer electronics, and high-capacity energy storage. Higher voltage enables greater capacity and more energy delivery per unit of cathode material.

Current high voltage R&D trends focus on **high-voltage LCO**, **single-crystal mid-Ni NCM**, and **LMR**

- High-voltage LCO is well suited for high-energy applications, including AI-enabled consumer electronics and drones.
- Single-crystal mid-Ni NCM leverages high voltage to compensate for mid-Ni's lower capacity while improving safety compare to high-Ni NCM, making it ideal for power supplies in AI data centers.
- Lithium-manganese-rich (LMR) cathodes are an emerging high-capacity option for high-voltage operation, enabled by reversible lattice oxygen oxidation above about 4.5 V. They also use little to no cobalt, which lowers material cost and reduces environmental impact.

To improve high-voltage stability at the cell level, fluorine has been widely introduced across the system, whether in the cathode, as an electrolyte additive, or within the lithium salt itself. But pushing the F content too high can raise HF generation, which becomes a safety risk for the cell. The safe upper limit for fluorine loading still isn't well understood.

Source: Liu et al. Mater. Today 2016

Impact of Nickel Content on the Performance and Applications of NCM and NCA Cathodes

Ni%	NCM 5-series*		NCM 6-series		NCM 8-series		NCM 9-series		NCA 8-series
	Polycrystal	Single Crystal	Polycrystal	Single Crystal	Polycrystal	Single Crystal	Polycrystal	Single Crystal	
Capacity (mAh/g)	155	185	176	190.8	210	195.8	217	214	195
Price (USD/mt) 12/07/25 and %↑since 01/02/25	19,535.2 (71.6%↑) 3C	18,027.7 (32.7%↑) NEV	18,255.6 (39.2%↑) 3C	18,046.4 (24.6%↑) NEV	20,168.8 (32.4%↑) NEV 19,819.2 (16.7%↑) 3C	n/a	n/a		20,499.7 (5.1%↑)
Process difficulty	High-Ni materials must be annealed in O_2, whereas mid-Ni materials can be annealed in air. High-Ni materials require LiOH as the lithium source, while mid-Ni materials can use Li_2CO_3; LiOH may lead to equipment corrosion. High-Ni materials are more sensitive to humidity compared to mid-Ni materials, resulting in higher lithium residuals.								
Advantage	Good performance balance and relatively low cost		Moderate energy density, good cycle life, and safety		High energy density, high stability		High energy density and therefore lower cost per kWh		Good energy density, good rate capability, better stability
Applications	EV, 2-wheelers, 3-wheelers, Consumer electronics		EV, Consumer electronics		EV, Drone, eVTOL, Consumer electronics, Robotics, Low earth orbit (LEO) satellites		Drone, eVTOL, Robot, Solid State Battery		EV, Powertools, Low earth orbit (LEO) satellites

*5-series means there are ~50% Ni in the composition

Source: MTI, MSE, Fangzheng Report, SMM

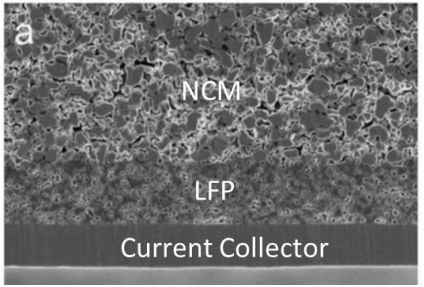
Technology NCM-latest Technology Focus

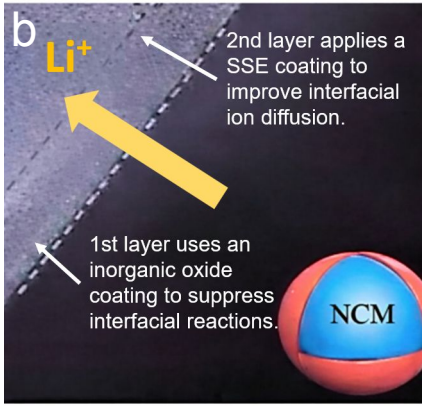
Layered electrode architecture

- This year brought a strong focus on new cathode electrode-level architecture. Manufacturers have been experimenting with layered designs, blended layers, and hybrid layered+blend structures. CATL's Freevoy Super Hybrid, which stacks NCM and LFP in a layered electrode, is set to debut in the Leapmotor D19 in 2026.
- Cathode architecture including current collector (CC)|Blend CAM, CC|CAM1|CAM2 (figure a), CC|Blend A|Blend B, and Blend A|CC|Blend B
- The chemistries in these architectures range across NCM, LFP, LMFP, and sometimes LMR. Each layer can use the same chemistry or mix different ones depending on the performance target. LFP particle engineering is the key to minimize gas evolution in blend CAM system.
- A dedicated interfacial protection layer between the two materials, combined with a film-forming electrolyte, helps suppress undesired reactions at high voltage and stabilizes the mixed-chemistry system

CAM for Dry Process and SSB

- Another major theme is CAM surface coatings design tailored for dry-electrode manufacturing and solid-state electrolytes.
- For NCM, these coatings improve adhesion between the CAM surface and the dry binder, strengthen the conductive pathway with the carbon additive, limit particle agglomeration, and help increase active-material loading. Dry processing is especially important for solid-state systems, particularly those using sulfide electrolytes.
- Teams are also exploring cathode-side coatings specifically for solid-state batteries. Approaches include applying thin layers of solid electrolyte and/or dedicated coating materials (figure b, CATL) that boost ionic transport while reducing interfacial resistance and contact degradation.





Source: Leapmoter D19, CATL Report

Nickel Manganese Cobalt (NMC) Basic Information

NMC - SWOT ANALYSIS

S Strengths	W Weaknesses	O Opportunities	T Threats
Properties and performance: High energy density, low temperature power capability. **Material chain strength:** Strong battery supply chain and high recycle value. **Easy system integration:** Reliable and easy SoC monitoring and easy trade-off between energy density and durability.	**Safety:** High thermal release, dangerous side reactions during cycling, off-gassing, cell swelling. **Health concerns:** Ni, Co hazardous to human and environmental health. **Cost:** Usually high cost/kWh compared to other chemistries. **Challenging to process:** Prone to gellation during mixing.	**Wide variety of composition offers a broad range of use cases:** Long range / high-end EVs, buses, boats, heavy-duty, equipment, power tools. **Materials improvements:** Continuing advances in safety and performance, high-voltage mid-nickel, advances in lowering cost/kWh.	**Safer alternatives:** LFP, LNMO, Na-ion. **Regulations:** PFAS, NMP, safety, material sourcing. **Metals supply chain:** Li, Ni and Co make NMC expensive and prone to high price variability, while mining practices can be environmentally damaging.

NMC remains the go-to chemistry where very **high energy density** is paramount (high-range EVs, eVTOL, drones, ...).

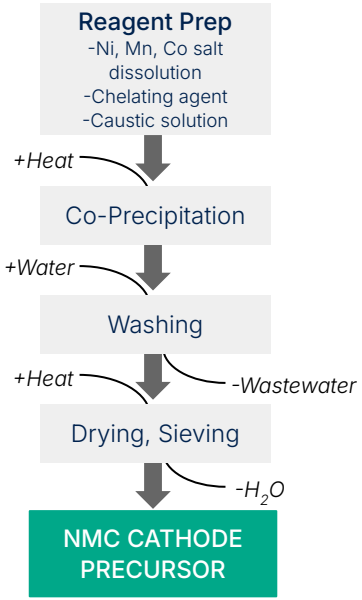
Incremental improvements within all the production processes (single-crystal particles, dopants, coatings, composition gradients, ...) are allowing for more and more favorable trades-off between energy density, safety, durability and cost.

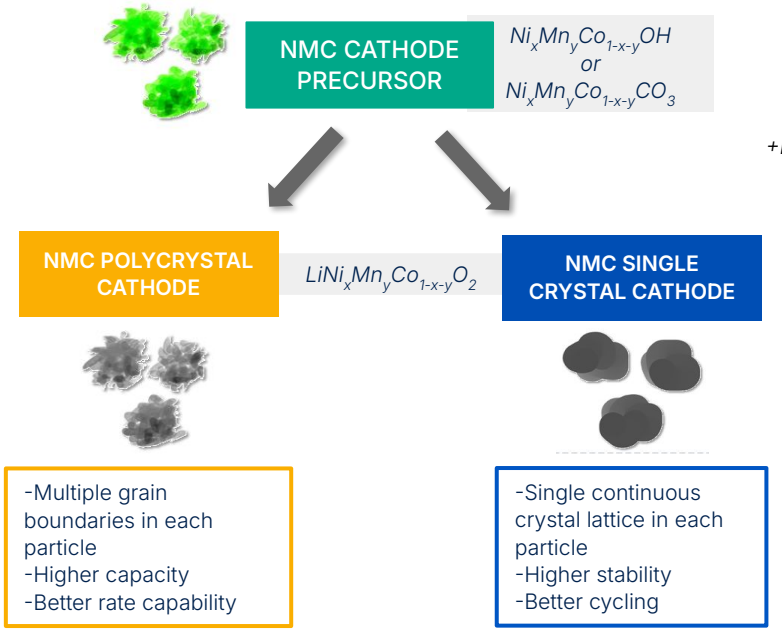
These process improvements allows for **opportunities** to lower the Co-content by (1) increasing the Ni-content above 90%at., aiming for even higher energy densities, and (2) increasing the end of charge voltage without sacrificing durability and energy density with high-voltage mid-Ni compositions.

Source: F. Saaid et al. Heliyon Cell Press. 2024 ; A. Eldesoky et al. J. Electrochem. Soc. 2023

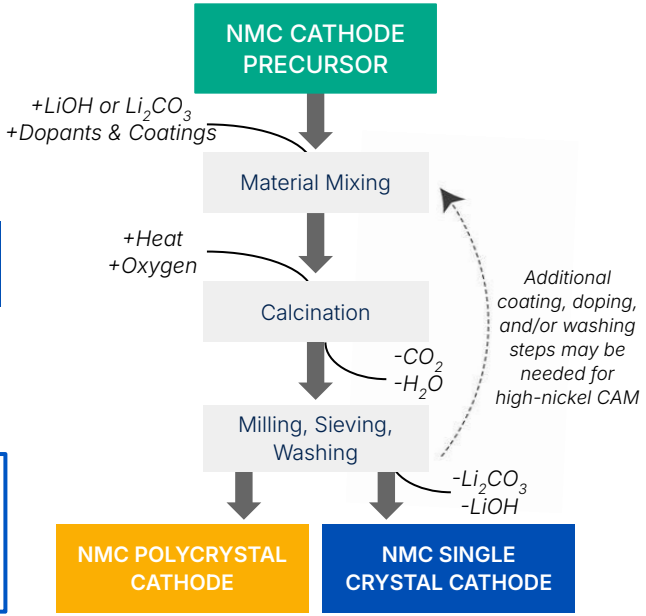
NMC Cathode Active Material Synthesis Process

NMC CATHODE PRECURSOR SYNTHESIS OVERVIEW





NMC CATHODE SYNTHESIS OVERVIEW



Source: Comparison of Single Crystal and Polycrystal → Dahn et al. Chem. Mater. 2009, 21, 1500–1503 → https://pubs.acs.org/doi/10.1021/cm803144d
Precursor Synthesis process → Jing Li et al. J. Electrochem. Soc. 2017, 164 A1534 → https://iopscience.iop.org/article/10.1149/2.0401714jes/pdf

NMC 523 vs 622 vs 811

Mid-Ni NMC variants (NMC622 / NMC523):

- Offer the best overall balance between performance materials/manufacturing costs and stability
- Good for Mid-class/Entry EVs and BESS

High-Ni NMC811 :

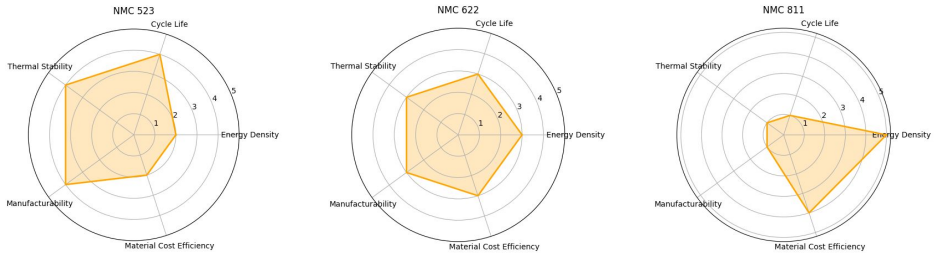
- Maximize energy density, however stability and degradation issues require special engineering (doping/coating, electrolyte additives and BMS control) to be viable
- Valuable for high range/performance applications (e.g, Premium Class of Long-range EVs)

Manufacturing complexity (advance engineering, moisture control, high yield losses and quality control requirements) limits high–Ni penetration

In the China historically mid-Ni NMC chemistries are dominant (especially NMC622), whereas NMC811 is present in niche premium/export EV segment

In the Europe and North America NMC811 is growing the share in EV due to the focus on higher energy density

Parameter	NMC523	NMC622	NMC811
Relative Energy Density	Baseline	Higher (ca. 5-10% vs 523)	Highest (best Wh/kg)
Thermal Stability	Best	Middle	Lowest
Cycle Life	Good	Balanced	Shorter
Charging/SOC	Faster charge, tolerant to higher SoC	Balanced	High SoC accelerate degradation
Material Cost	Higher (30% Co)	Lower than 523 (20% Co)	Lowest (10% Co)
Manufacture Complexity	Easiest	Moderate	Hardest
Technology Approach	Particle morphology, coating, electrolyte additives	Doping/coating, reshaping	Doping/coating, gradient particles, electrolyte additives, BMS control
Application(s) Targeted	Entry class EVs; energy storage	Mainstream EVs	Premium high performance EVs with high range



Source: [1] Y. Ding et al. Electrochem. Energy Rev., 2019, 2, 1-28. ; [2] M. S. E. Houache et al. Batteries, 2022, 8, 70. ; [3] T&E Report 2023: Clean and lean: Battery metals demand from electrifying cars, buses and coaches. ; [4] https://www.adamasintel.com/mid-nickel-ev-batteries-garner-19-market-share-in-china/

NMC Notable Events

January

Jae Young Tech Co has developed recycling process of lithium & Ni-Co-Mn extraction with 85 % recovery rates and lithium purity >99 %

February

KIA has released of EV4 hatchback/sedan NMC variants in Base (58.3 kWh) 410/439 km range and Long Range (81.4 kWh) 610/630 km range

March

Volktec aims to produce NMC cells for e-scooters, e-bikes and chargers by the end of 2025 and EV batteries in the second half of 2026

April

Lion Smart, a subsidiary of Lion E-Mobility has announced that it has released samples of its NMC+ battery platform to selected customers

May

Turntide Technologies has introduced Gen 5 NMC modular battery: 4.5 kWh (100 Ah) or 6.8 kWh (150 Ah), which is securely mountable in 3-axis

June

Sino-Moroccan joint venture COBCO has commenced production of NMC and pCAM at its new plant in Jorf Lasfar, Morocco

July

Nash Energy has joined forces with Rincell Corporation to develop and produce advanced NMC cells domestically in India

August

BlueOval SK, the joint venture of Ford and SK On starts production of NMC cells in Glendale, Kentucky, U.S. for Ford F-150 Lightning and E-Transit

September

LG Energy Solution will supply Kim Long Motor with NMC cylindrical battery cells for e-buses; production is scheduled to 2026

October

Sakuu Kavian dry- printing manufacturing process of NMC811 electrode save CAPEX by 20-50 % & doubles battery lifespan

November

Scientists from UNIST has developed new recycling technique that recovers > 95 % of Ni and Co from old EV batteries

December

PowerCo has started unified NMC cell production at its Salzgitter plant, which will establish capacity of 20 GWh per year

Nickel Cobalt Aluminum (NCA) Basic Information

NCA - SWOT ANALYSIS

S Strengths	W Weaknesses	O Opportunities	T Threats
Properties and Performance: High energy density with excellent rate capability **Long calendar life** due to presence of Aluminum **Structural Stability:** No manganese leaching Mature **production processes** **Strong recycling capability** with recycling methods achieving high recovery rates	**Cost**: High cost due to higher Ni content **Safety**: Thermal stability concerns, particularly at high temperatures due to high Ni content **Capacity Fade**:High Ni content causes susceptibility to loss of oxygen and capacity fade **Complex Manufacturing Process:** Cation mixing, difficulty in ensuring even distribution of Aluminum in cathode	**Use Cases**: Fast charging capabilities for consumer electronics and EVs, High power applications like power tools, forklift, e-trucks, ESS **Production Process:** Innovations in production and doping/coating will reduce cost and increase stability	**Safer Alternatives:** LFP offers lower cost, safer chemistry **Regulations & Supply Chain Volatility:** Co makes NCA expensive and prone to high price variability **Geopolitical Instability:** Trade restrictions, export controls in nations can affect material flow

Nickel Cobalt Aluminum (NCA): Continues to be a prominent technology in electric vehicles and portable electronics.

Development progress: Shifting to ultra high Ni content to optimize energy density, rate capability and thermal stability.

Leading companies: Panasonic and Sumitomo have played key roles in advancing and popularizing NCA batteries across diverse applications including Tesla vehicles. In addition, Samsung SDI, POSCO Future M, BASF SE and EcoPro have emerged as key suppliers in recent years.

Primary use: EV applications, with power tools, e-bikes, and portable electronics making up the rest.

Source: Agus Purwanto *et al* 2018 *Mater. Res. Express* 5 122001

NCA Notable Events

January

BMW iX facelift revealed with more power and range due to it significantly larger 94.8-108.9 kWh NCA battery and achieve 321-374/370- 426/321-366 WTLP range miles xDrive45 / xDrive60 / M70Drive correspondingly

February

Hyundai Motor Company and KIA Corporation signed MoU with Samsung SDI to develop high-performance batteries specifically for robots, with aim of increasing energy density, output and usage time

March

Samsung SDI has started production of next-gen 46-series (4680, 4695, 46100 and 46120) cylindrical batteries contained NCA cathode and Silicon Carbon Nanocomposite anode in Cheonan, South Korea

April

Samsung SDI announced that it received JLR (Jaguar Land Rover Automotive) Quality Award due to their 21700 cylindrical battery with NCA cathode and Si anode

May

Samsung SDI has announced plans to expand & modernise its plant in Göd, Hungary, where they produce sixth-generation (P6) prismatic cells using NCA chemistry with high Ni (91%) content and Si-based anodes

June

Sakuu announced it had validated the performance of its "dry printed" NCA and NMC electrodes, which eliminate toxic solvents and water in manufacturing

July

Samsung SDI has secured 6 of 8 battery supply deals of ₩1T ($726M) to install NCA BESS of total capacity 465 MW in South Korea (South Jeolla Province's Jindo, Goheung, Yeonggwang, Muan & Shinan counties)

August

EcoPro has announced that it cumulative sales of NCA CAM surpassed 300 kt as of the first half of this year (H1 2025); this amount is sufficient to produce around 3M electric vehicles

September

Samsung SDI demonstrates the next-generation Samsung Battery Box 1.7 (SBB 1.7) of 6.14 MWh equipped with NCA cells, which delivers about 17% higher energy density than the previous SBB 1.5

October

Samsung SDI had announced that it has signed a trilateral agreement with BMW group & Solid Power to collaborate on all-solid-state battery (ASSB) project which will be used for BMW i7 test vehicle, which combines Gen5 construction principles (prismatic cells in modules)

November

Samsung SDI won CES 2026 Innovation Award for 18650 battery with NCA cathode and Samsung SDI's proprietary Silicon Carbon Nanocomposite (SCN) anode

December

EcoPro BM started NCA and NCM CAM production in Debrecen, Hungary; the facility will produce 54 kt of CAM that will be enough for around 600 k EV per year

Nickel Cobalt Manganese Aluminum (NCMA) Basic Information

NCMA - SWOT ANALYSIS

S Strengths	W Weaknesses	O Opportunities	T Threats
Combines the strengths of NCM and NCA	**Requires precise control in synthesis to maintain quality**	**High-end EVs with long range and fast charging capabilities**	Competition from NMC, NCA, (high-end EVs) and LFP (cost)
Reduces Co content, lowering costs & Co supply chain dependence	Structural instability due to high Ni content	Integration with high energy density anodes (silicon-dominant)	**Growing safety concerns over high nickel content**
High energy density	High nickel content drives up costs in raw materials, CAM production, and manufacturing processes like CTP.	Power tools requiring high output and fast energy delivery	High sensitivity to nickel prices
Suitable for various cell formats, providing flexibility in design and application	Thermal instability compared to LFP	Drones, EVTOL	
Strong recycling potential for valuable materials			

Lithium Nickel Cobalt Manganese Aluminum Oxide (NCMA): Represent a flavor of next-generation development in lithium-ion batteries, combining the strengths of both NCA and NCM.

Advantage: This chemistry prioritizes high Ni, high energy density, improved thermal stability over NCM, and reduced reliance on cobalt. The ongoing development focuses on optimizing its composition and long-term performance.

NCMA Is Gaining Traction In High-End EVs: Industry leaders, such as LG Energy Solution, Toyota, and Rivian, are spearheading efforts to commercialize NCMA batteries in EVs, with major production facilities in initially in the US.

Source: LG battery lab, Kim et al. J. Power Sources 2023, GM Authority

NCMA Notable Events

January

Aptera Motors have signed a deal with LG Energy Solution with a volume of 4.4 GWh for supply Aptera solar electric car between 2025 and 2031

February

LG Energy Solution is teamed up with Toyota to use the former Ultium Lansing battery plant in Michigan, U.S. to build high-Ni NCMA battery modules

March

All-electric Cadillac Escalade IQL arrives mid-2025 with 460-mile (724+ km) range equipped with 205 kWh NCMA battery

April

LG Chem highlights presentation during the Interbattery 2025 the next-gen LAP (LG Advanced Phosphate) by blending NCMA & LMFP CAM

May

First commercial pickup Isuzu D-Max Electric with 66.9 kWh NCMA battery was revealed with UK deliveries & expected in March 2026

June

Mercedes AMG model GT XX concept based on 1 MWh NCMA battery cell with fast charge (400 km within 5 minutes) was presented

July

Ultium Cells LCC will upgrade its facility in Spring Hills, Tennessee, U.S., which is currently producing NCMA pouch cells for EVs, to the low cost LFP battery cells

August

Posco Future M ships the 1st NCMA CAM produced entirely with domestically sourced precursors to Ultium Cells

September

General Motors Co. adapts its Hummer EV Tech NCMA battery to power the Lunar Rover for NASA's Artemis program; the batteries are meant to last for a decade and a distance of 30,000 km of service life

October

LS L&F has announced the completion of the construction ₩1T factory in Saemangeum, South Korea, which will produce a 20 kt of NCMA pCAM in 2026 and 120 kt by 2029

November

Porsche Cayenne Electric had officially launched, which characterized with 325 km range and powered by 113 kWh NCMA battery with silicon-graphite anodes sourced for LG Chem

December

LG Chem plans to supply Tesla in 2026 with ultra-high Ni (90%) NCMA battery of 600 km range with reduced Co content (less than 5%)

Lithium Cobalt Oxide (LCO) Basic Information

LCO - SWOT ANALYSIS

S
Strengths

Unrivaled volumetric energy density, enabling powerful, compact consumer electronics like **AI-smartphones and wearables**.

Mature manufacturing processes with high yields (>98%) and a well-established global supply chain.

Stable high-voltage platform (3.7-3.9V) ideal for sensitive devices, maintaining consistent power until ~5% charge.

W
Weaknesses

Extreme dependence on cobalt exposing the supply chain to price volatility and ESG scrutiny from its concentrated DRC & Indonesia sourcing.

Inherent **thermal instability** at high states of charge, posing safety risks without advanced BMS.

Limited cycle life (500-1,000 cycles), insufficient for long-life applications like EVs or energy storage.

O
Opportunities

Pushing operating **voltage to 4.55V** via advanced coatings and doping, unlocking **10-15% more ED.**

Growing demand in high-margin, miniaturized applications like medical devices, AR/VR headsets, and IoT sensors.

Development of circular economy, with **recycled cobalt** mitigating primary mining risks and meeting corporate goals

T
Threats

Market share erosion from improving cobalt-free chemistries entering mid-range electronics with 20-30% lower costs.

Intensifying **geopolitical tensions**, including China's export controls and US FEOC policies, disrupting supply chains.

Silicon anodes boosting competitor performance, diminishing LCO's unique ED advantages.

In 2025, LCO maintains its dominance in high-density consumers electronics.

Research Direction: Focus on stabilizing high-voltage operation through material doping and atomic layer deposition to maximize energy density.

Main Players: CAM and cell production is dominated by the APAC region. Largest LCO CAM producer is XTC, which benefits from a vertically integrated supply chain.

Capacity Variation: Steady growth in its core consumer electronics niche.

Impact on Upstream and Downstream: Upstream is pressured by volatile markets and a shift to recycled cobalt, while downstream enables premium electronics but is excluded from high-growth EV/ESS markets.

Source: ICCSino, Counterpoint Research, Shanghai Metal Market

LCO Notable Events

January

Cobalt Institute publish the report Responsible Secondary Cobalt about the major Co losses on both mine site and EoL LCO consumer electronics

February



Democratic Republic of Congo, which accounts for an estimated 77% of global Cobalt production, imposed a 4 months export suspension due to low-price environment

March



Electra Battery Materials Corp. has snagged a non-binding LOI from Canada government for $20M to finish the construction of its proposed cobalt refinery in the Temiskaming area

April

Xerion Advanced Battery Corp. launched a pilot-scale one-step production of 99% refined Co metal by using proprietary DirectPlate™ Molten Salt Electrolysis refining process

May

Cobalt Blue and Glencore contracted to supply Kwinana Cobalt Refinery with cobalt hydroxide locking its 50% feedstock requirements

June



European Union increased financial and technical support of Africa's' mining & named 6 kt/year Kobaloni Energy Zambia refinery as one of strategic initiatives under Critical Raw Materials Act

July

Ateios Systems has announced release RaiCoreTM High Voltage world first PFA-free LCO battery with 15-20% more energy density and more 80% capacity retention after 1000 cycles at 1C

September

Cobalt Blue reported that Kwinana Cobalt Refinery works approval granted; the facility will be established East Rockingham, near the Kwinana Bulk Terminal

October



Democratic Republic of Congo lifts its 8-month suspension on Cobalt export on October 15 2025, introducing a stricter quota system

October

Electra Battery Materials Corp. announced the closing its $34.5M financing and $40M debt equitization; the capital which will allow to construct & commissioning North America's first cobalt sulfate refinery

November

Electra Battery Materials Corporations sign Supply Chain Cooperation Agreement with pCAM company Positive Materials Inc.

December

Cobalt Blue secures $5.3M to advance Kwinana Refinery, Australia's strategic Cobalt processing hub; the final investment decision for this project is planned in 2026

Lithium Cobalt Oxide (LCO) Basic Information

Lithium cobalt oxide ($LiCoO_2$) remains the leading cathode for portable electronics due to its high practical capacity and stable discharge plateau. Pushing charge cut-off voltage above ~4.4 V can further increase usable capacity by extracting more lithium, but it also accelerates degradation, making cycle life a key constraint. LCO is often benchmarked around ~500 cycles, with optimized high-voltage designs and controlled operating windows reaching ~1,000-cycle-class performance. As a result, high-voltage LCO increasingly relies on coatings, dopants, and blends to improve stability and reduce cobalt content. For example, a "2% LAF-LCO" variant reported ~89.1% retention after 100 cycles versus ~44.5% for baseline LCO.

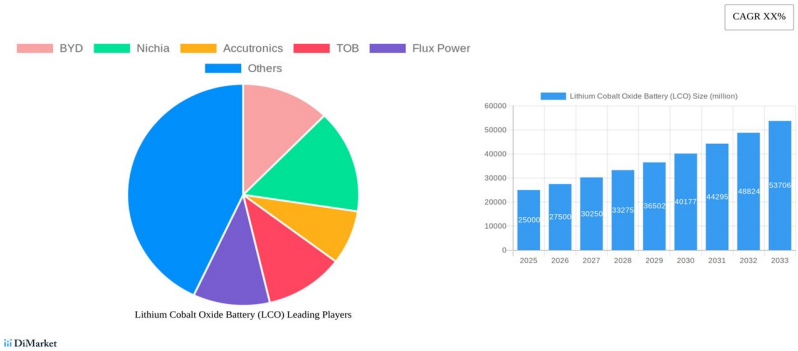
Limit Voltage (V)	4.2	4.3	4.4	4.5	4.6
Capacity (mAh/g)	140	155	170	185	220
Average Cell Voltage (V)	3.91	3.92	3.94	3.97	4.03
Specific Energy (Wh/kg)	457.3	607.6	669.6	733.5	885.9
Specific Energy (Wh/L)	2299	2552	2812	3081	3721
Increase %		11%	10%	9.5%	21%

Based on market study "LCO Co≥60 %, 4.45 V: ~US $27.6 k/ton and China $16.7k/ton in June 2025." Up-stream input cost pressures (Co/Li) continue to push material cost higher.

Main domain: Still the workhorse cathode for 3C/portable electronics – smartphones, laptops, cameras, tablets, many 18650/21700 packs for electronics.

EVs: In 2025, EV cathodes are dominated by NMC and LFP; LCO is *not* a major EV chemistry due to cobalt cost, safety, and cycle life at high load.

Market snapshot: A 2025 market report pegs the global $LiCoO_2$ battery market in the mid–tens of billions of USD with moderate growth, mainly tied to electronics, and under pressure from NMC and LFP in many segments.



Source: Wu et al. J. Energy Chem. 2022,large-battery datainsightsmarket,

Lithium Iron Phosphate (LFP) Basic Information

LFP - SWOT ANALYSIS

S Strengths

Lowest-cost Li-ion cathode chemistry at scale (iron/phosphate vs nickel/cobalt)

Safety: High thermal stability reduces fire/thermal-runaway risk

High Durability: Outlasts high-nickel chemistries in heavy cycling and long-duration applications.

Performance: Tolerates deep discharges, high temperatures, and long idle periods needed for ESS.

W Weaknesses

Lower Energy Density: Limits use in long-range EVs or applications where weight/volume constraints dominate.

Cold Weather Disadvantage: Inferior charging and power delivery in cold climates compared to NMC/NCA and NA-Ion.

Larger Pack Footprint: Requires more mass and volume to achieve equivalent capacity.

Low Recycling Value: Iron-phosphate cathodes offer little recoverable value of components.

O Opportunities

ESS Growth: Price pressure + cycle life tends to favor LFP in mainstream deployments.

Mass Market EV Expansion: Ideal for entry/mid EVs and commercial vehicles where cost beats range.

Non-China Buildout: US, EU, and others are scaling overseas LFP supply chains.

Super-fast-charging: New tech allows super-fast-charging LFP even up to 12C.

Advanced Pack Integration: Structural integration narrows the energy-density gap with high-nickel chemistries.

T Threats

High-Nickel chemistries retain premium segments: Dominate long-range EVs. Cost gap could narrow with nickel price weakness.

Supply Chain Concentration: >95% of global LFP CAM production in China.

Policy/tariff volatility: Impacts economics of imported LFP materials/cells and slowing project pipelines outside China.

Na-ion Alternative: Particularly for ESS if lithium prices increase and are sustained.

Lithium iron phosphate (LFP) demand continued climbing in 2025 (ahead of nickel based chemistries) and, capturing >50% of market share [1].

China's adoption of LFP batteries in EV surged accounting for **>80% of total vehicle deployment** [2] and [3].

LFP appeal is structural: lower materials cost (no nickel/cobalt), strong safety characteristics, and durable cycle life, making it competitive for mass-market EVs and stationary storage(ESS).

Outside China, **automakers and cell makers have expanded LFP programs to improve EV affordability** and reduce exposure to nickel/cobalt, though cost and supply chain remain key hurdles versus China's integrated ecosystem.

Source: (1) Reuters, December 2025; (2) ICCSino, May 2025; (3) IEA – Global EV Outlook 2025

LFP Notable Events

January

ICL signed a JV with Shenzhen Dynanonic to produce LFP for European Market in Spain.

February

Altilium launches LFP recycling in the UK, recovering >97% of Li and 99% of graphite from spent LFP batteries

March

Formosa Smart Energy announced production at its 2.1 GWh LFP battery cell plant in Changhua, Taiwan

April

Foresee Power unveiled it new GO 6 LFP battery pack, offering best-in-class energy density among 6 kWh LFP batteries

May

Nissan cancels its planned ~$1.1 billion LFP battery plant in Kitakyushu, Japan

June

LG started mass production of LFP batteries for ESS in Holland, Michigan U.S.

CATL started mass production of 587 Ah LFP cells for ESS with density volumetric 434 Wh/L

July

Ultium Cells (GM& LG JV) will add LFP at its Spring Hill, Tennessee plant with targeted production for late 2027

August

Tesla signed a $4.3B deal with LG Energy Solutions to supply LFP batteries for U.S. ESS products

September

SK On signs a deal to supply up to 7.2 GWh of LFP batteries to US-based Flatiron Energy for ESS

October

CATL-backed Jiangxi Shenghua New Material will build two high-tap-density LFP plants with total annual capacity 525 kt in Sichuan, China

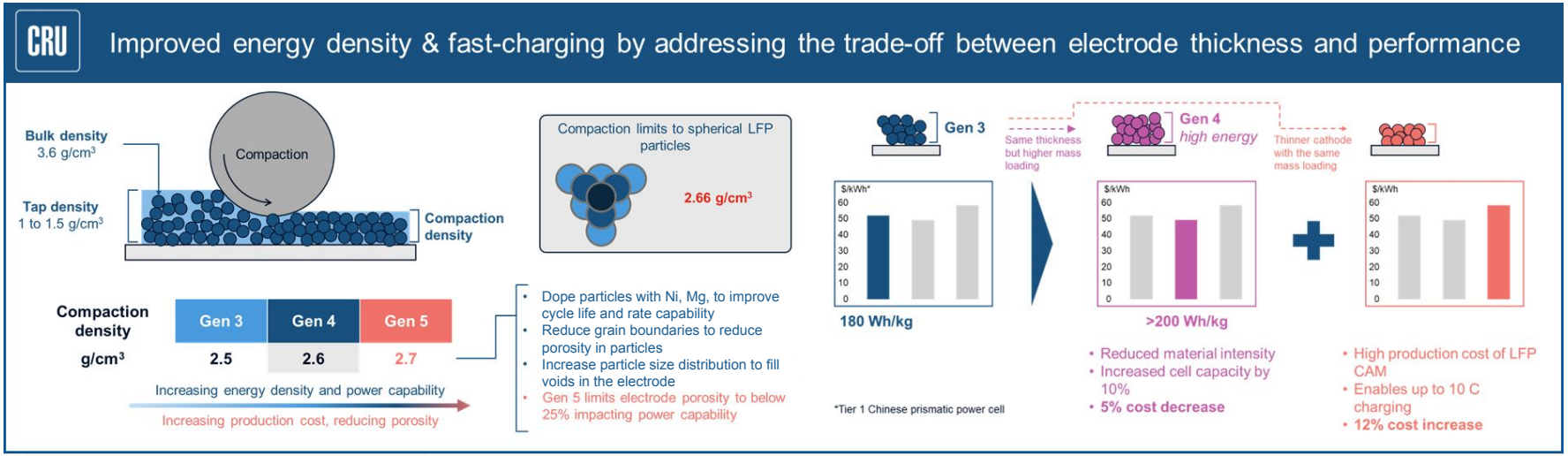
November

CATL and Stellantis JV breaks ground on LFP battery plant in Zaragoza, Spain with target production by end 2026, delivering up to 50 GWh/year

December

Posco Future M will build new LFP plant in S Korea targeting global ESS demand; production of 50 kt LFP CAM targeted for late 2027

High Compaction Density Is Pushing the Limits of LFP



High compaction density can either give more energy density or faster charging; Chinese manufacturers are currently opting for the latter.

See the **China section** for wider commentary on high compaction density LFP

Map of Key Players in Global LFP Production

Americas - Cell Producers

LG Energy, SK on, Ford, SAMSUNG SDI, AESC, TESLA

Americas - CAM Producers

nanoOne, Mitra Chem, Wildcat Discovery Technologies

OPERATING PLANNED

EMEA - Cell

CATL, Gotion, LG Energy, PowerCo, SUNWODA, CALB

EMEA - CAM

当升科技 EASPRING, Hunan yuneng, CNGR, HUAYOU

China - Cell

CATL, BYD, Gotion, EVE, CALB, HITHIUM, SUNWODA, REPT, SVOLT

China - CAM

WANRUN NEW ENERGY, Hunan yuneng, Dynanonic, 富临精工 FULIN P.M., Gotion, Lopal 龙蟠科技

Asia - ex.China - CAM or Cells

Lopal 龙蟠科技, CNGR, posco, NASH ENERGY

China controls >95% of LFP production with an integrated supply chain; US and Europe are in earlier stages of build out with many JVs including Asian technology partners.

Source: Company announcements

Lithium Manganese Iron Phosphate (LMFP) Basic Information

LMFP - SWOT ANALYSIS

S Strengths	W Weaknesses	O Opportunities	T Threats
Higher energy density than LFP	Reduced calendar and cycle life compared to LFP, due to the Jahn-Teller distortion of Mn and metal dissolution into electrolyte.	Mid-to-Long Range EVs Heavy-duty vehicles (trucks and buses)	Lack of industry standardization causes product inconsistencies
Lower cost per kWh than NMC	Poor electrical conductivity lithium-ion diffusion	Blend cathode with NCM for high-voltage batteries	Scaling challenges
Abundance and low cost of Mn	Like LFP, SOC estimation is challenging	Potential to replace LFP in EV applications	Advanced modifications required for LMFP increase process complexity
Higher voltage than LFP	Dual voltage plateau worsens cell consistency, causing mileage data fluctuations in BMS	Improvements similar to LFP	Underdeveloped supply chain
High thermal stability and safety	Limited cathode density		Supply Chain geographically concentrated in China especially for Mn precursor
High voltage platform			
Leverage existing LFP manufacturing processes and infrastructure			

Lithium Manganese Iron Phosphate (LMFP): Emerging cathode material offering high energy density, safety, and cost-effectiveness, ideal for heavy-duty EVs and energy storage systems (ESS).

Research focus: Improving electrical conductivity, lithium-ion diffusion and stability (overcome JanT distortion and metal dissolution) thanks to nanostructuring and morphology control, surface coating (carbon and/or non-carbon), ion-doping (Mg, Y, V, F, I), compositional and structural design (gradient surface layer). Develop green synthesis routes.

LMFP development: Led by major Chinese manufacturers, with new North American companies also advancing LMFP technology for EV and ESS applications

Source: Battery Report 2024,Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

LMFP Notable Events

January



China's commerce ministry on 2 January announced plans to limit exports of LFP and LMFP processing technologies

February

Integrals Powers provided new details on the discharge rates and durability of LMFP CAM for EV battery

March

Firebird Metals has started test work of LMFP CAM (5 out of 100 batches) and has produced its first LMFP batteries for EV

April

Addionics reports on AI based Smart 3D Electrodes which improve the conductivity in L(M)FP batteries, material adhesion and enabling the cell higher density and performance

May

Gotion unveiled world's first LMFP Astroinno Gen-2 battery supporting 10-minute ultra-fast charging 240 Wh/kg energy density, and 93% cold-weather capacity retention at -20°C

June

Integrals Power has signed supply deal with Euro Manganese; under the agreement, the latter will provide high purity $MnSO_4 \cdot H_2O$ from Chvaletice, Czech Republic

July

Taiwan's Industrial Technology Research Institute (ITRI) signed an agreement with Saft for development next gen. LMFP batteries

August

Firebird Metals obtained 2 Chinese invention patents for LMFP CAM and pCAM and EoI from Taza Metal Technologies for purchase 5 high efficient calcination clins for pCAM production from low-grade Mn ore

September

A collaboration between University of Warwick and Polaron has optimised the manufacturing of LMFP for increased cell performance

October

Gotion High-Tech has announced that will begin mass production of next-generation LMFP (260 Wh/kg) in 2026, Volkswagen is Gotion's largest shareholder and plans to equip its own EV

November

A 40,000-ton LMFP CAM project has been announced in Ya'an, Sichuan, P.C.R

December

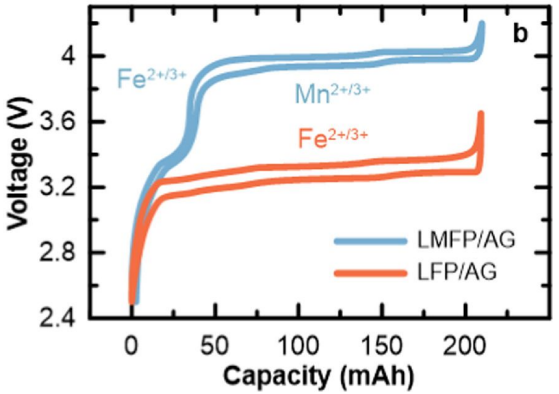
A 130,000-ton LMFP CAM project led by Jiangsu Hengtron Nanotech Co., Ltd has been officially launched in Yinchuan Economic & Technological Development Zone

Differences between LFP and LMFP

Structure
- LMFP partially replaces Fe in LFP with Mn.
- Incorporating Mn into the system raises the redox voltage, resulting in increased overall energy density.

Performance
- LMFP's capacity at low-temperature performance is more stable compared to LFP.
- Both chemistries exhibit similar safety profiles.
- High voltage and high surface area of LMFP limit cycle life due to electrolyte oxidation and Mn-dissolution

Market & Usage
- LMFP-64 (60% Mn content) is the most widely available composition in the market, with research efforts now shifting towards 70% Mn content.
- LMFP is often blended with NMC due to its similar voltage, which improves the safety and reduces the cost relative to NMC.



MN/FE RATIO IN LMFP (NOMINAL VOLTAGE, PRACTICAL CAPACITY, ENERGY DENSITY)

LFP (0% Mn)	20% Mn*	40% Mn	60% Mn	80% Mn	**LMP** (100%Mn)
3.4V	3.44V	3.48V	3.64V	3.96V	3.95V
161.0 mAh/g 534.9 Wh/kg	161.7 mAh/g 553.5 Wh/kg	157.4 mAh/g 557.0 Wh/kg	142.4 mAh/g 515.8 Wh/kg	126.3 mAh/g 459.9 Wh/kg	63.0 mAh/g 230.6 Wh/kg

*20% Mn: $LiMn_{0.2}Fe_{0.8}PO_4$

Source : Guoyuan Securities, Battery Report 2023 (pg125, Argonne NL battery model, Leslie et al. 2024 JES 171 040520

Lithium Manganese Oxide (LMO) Basic Information

LMO - SWOT ANALYSIS

S
Strengths

LMO has better **thermal stability** compared to NMC and NCA.

Low cost, earth-abundant Mn vs Co-based cathodes; good for cost-sensitive markets.

High power density for EVs, power tools and fast charge capability.

Manganese is more abundant and less toxic than cobalt.

LMO is one of the more promising materials for **solid-state** batteries.

High efficiency at low cost.

LMO does not release oxygen as aggressively as LMR at high states of charge.

W
Weaknesses

Mn dissolution & capacity fading, especially at elevated T and high voltage.

Limited energy density vs NMC/NCA.

Poorer high-voltage stability (**>4.3 V**) due to phase changes, surface
damage, and side reactions.

LMO may suffer from capacity fade and and poor efficiency at high power.

Electrolyte side reactions and **HF attack** accelerate degradation.

Cannot compete with LMR in EV range; LMR offers ~33% higher energy density than LFP and vastly outstrips LMO

O
Opportunities

Mn dissolution & capacity fading, especially at elevated T and high voltage; major life-limiting mechanism.

Limited energy density vs NMC/NCA, and even vs some optimized LFP in pack-level systems.

LMO may suffer from capacity fade and and poor efficiency at high power.

Electrolyte side reactions and HF attack accelerate degradation.

Blending LMO with LMR (or NCM) leverages LMO's high power to compensate for LMR's poor rate capability.

T
Threats

Competition from LFP and LMFP: similar safety and cost, but often better cycle life and strong industrial ecosystem.

High-Mn layered/spinel cathodes (LMNO, high-Mn NMC) may capture the Mn-based, high power narrative with higher energy density.

Persistent Mn-dissolution concerns can limit acceptance in long-life EV/ESS without strong mitigation.

Mature, somewhat **"commodized"** chemistry may lead less investor attention vs next-gen cathodes.

Advantage: LMO's advantages lie in its cost-effectiveness, safety, and environmental benefits. its spinel 3D structure gives fast Li^+ diffusion → high power / fast charge, while Mn makes it cheaper and safer than Co-rich cathodes. That combo is why it's strong in tools, e-bikes, and 2–3-wheelers.

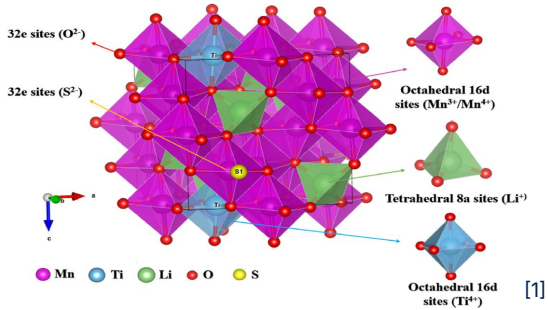
LMO does not current have a big market share: LMO suffers from short cycle life due to high self-discharge rate and capacity fade over many charge/discharge cycles, caused by manganese dissolution and structural degradation. However, some companies have been able to manage this issue with a variety of techniques.

Source: 1. Battery Report 2024 (Pg226); 2. LMR battery technology, article by *S&P Global Mobility*; 3. Zihao Zheng et al, *Langmuir* 2025, 41, 48, 33009–33021

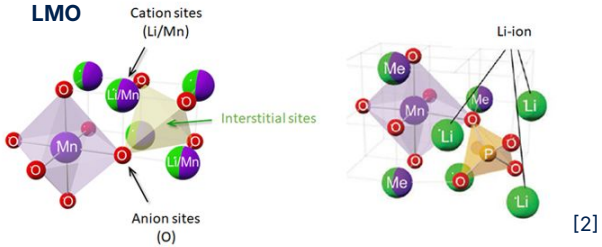
Stabilization of the LMO ($LiMn_2O_4$) Spinel Structure

"The $LiMn_2O_4$ spinel cathode offers a unique combination of 3D lithium diffusion, thermal stability, and cobalt-free chemistry. Although its energy density is limited by Mn^{3+}- induced Jahn–Teller distortion and dissolution, modern doping and surface-engineering strategies enable LMO to remain industrially relevant in high-power, safety-critical, and cost-driven applications." Cation and anion substitution may enhance LMO CAM performance.

- Researchers from University of Illinois Urbana-Champaign introduced a novel method to assess the potential dependent degradation of LMO cathode via manganese and oxygen sensitive scanning electron microscopy which elucidates the complex interplay of acid-base, interphase formation, and oxygen loss in Mn dissolution mechanisms in operating cathodes as a function of potential.[3]
- Researchers from Qingdao University, China has reported the LiB3O5 surface coating to the LMO which mitigates particle cracking, prevents Mn dissolution, and increases the lithium-ion conductivity rate. mitigates particle cracking, prevents Mn dissolution, and increases the lithium-ion conductivity rate.[4]
- GM Global Technology Operations LLC filed a patent on protective coating on Lithium Manganese Rich oxide cathodes (LMR) core with a protective lithium manganese spinel coating, aimed at improving long-term cathode performance in Li-ion batteries.[5]
- DYSON TECHNOLOGY LIMITED has issued a patent, the invention provides a cathode composition for a lithium-ion battery of the general formula: $Li_{1+x}Mn_{1-x}O_2$; wherein the composition is in the form of a single phase having a rock salt crystal structure; and the value of x is greater than 0, and equal to or less than 0.3.[6]



[1]



[2]

Source: [1] O. Nyamaa et. al. Mater. Adv., 2024,5, 2872-2887; [2] Yuji mahara et al, aenm, 2023, 13, 45, 2301843; [3] Dong ok kim et al *J. Mater. Chem. A*, 2025,13, 10540-10549; [4] Rui wu et al. *Langmuir* 2025, 41, 18, 11755–11764; [5] US patent US20250105270A1; [6] US patent US12334551B2;

LMO Notable Events

January

The production of Mn_3O_4 saw a slight increase MoM, with a significant rise YoY. This trend was mainly attributed to the increased production of LMO in March

February

Canmax's spinel LMO cathode material has been sampled to multiple customers and achieved positive validation results.

March

Ford announces a breakthrough with Lithium Manganese Rich (LMR) battery chemistry for its upcoming electric vehicles, and that the chemistry will be scaled and integrated into production

April

Giyani metals has made the first shipment of high purity battery grade manganese to the multiple potential offtakers for testing and qualification from its Demonstration Plant ("Demo Plant") in Johannesburg

May

POSCO Future M (Korea) has completed the development of LMR (Lithium Manganese Rich) cathode materials, and actively scaling up "lithium-manganese-rich (LMR)" cathode materials, seeing them as a strategic growth driver.

June

GM and LG Energy Solution have announced plans to commercialize LMR batteryGM and LG Energy Solution have announced plans to commercialize LMR battery prismatic cells.

July

POSCO Future M officially announced its *LMR cathode materials strategy* targeting entry-level and standard EV markets with improved energy density (~33 % higher than LFP).

August

Stratus materials has transitioned to a second-gen cobalt-free "LXMO-2" CAM and started shipping to customers and partners. the density of this material enables high energy cells, with well over 300 Wh/kg and 700 Wh/liter. demonstrated.

September

Firebird Battery Materials Ltd. forms a strategic alliance with Taza Metal Technologies(one of the few ex-China producers of high-purity manganese sulphate monohydrate) to advance manganese-rich cathode materials.

October

Ampere partners with Stratus Materials in a Joint Development Agreement (JDA) to explore innovative cobalt-free LXMO battery technology for future Renault Group EVs.

November

GM's lithium manganese-rich (LMR) battery technology, developed with LG Energy Solution, won "Battery Innovation of the Year" at *The Battery Show North America 2025*.

December

SAIC has launched the MG4, its first model equipped with an LMO semi-solid-state battery, through its MG sub-brand, marking the inaugural commercial deployment of semi-solid-state batteries.

Source: Various news articles linked above

Lithium Manganese Nickel Oxide (LMNO) Basic Information

LMNO - SWOT ANALYSIS

S Strengths

LMNO has higher energy density than LMO, approaching that of NMC and NCA

High Operating Voltage: ~4.7 V vs. Li/Li^+, enabling high energy density

Cobalt-Free Chemistry: Eliminates Co supply chain risks and reduces BOM cost by ~20% vs. NCM

LMNO offers better thermostability than other high-energy CAM

Higher **charge voltage** cutoff at 4.7 V

Fast Kinetics: 3D Spinel structure allows rapid 3D Li^+ diffusion, supporting high C-rates (fast charging)

W Weaknesses

Lower capacity than NMC-based cathodes

Electrolyte Instability: Severe oxidative decomposition of organic electrolytes at >4.5 V

Higher production cost than for LFP or LMO

Mn Dissolution: Disproportionation of Mn^{3+} into Mn^{2+}/Mn^{4+} leads to active material loss and anode poisoning

Poor performance at low temperatures compared to L(M)FP

Interface Degradation: Formation of thick, resistive CEI layers causing capacity fade

O Opportunities

Thermostability and long cycle life are advantages for BESS

Solid-State Integration: Ideal cathode for solid-state batteries (SSBs) where high-voltage stability is easier to manage

Aviation & High-Power Apps: projects targeting aeronautic sectors due to high power density

Mitigate supply chain risk from cobalt.

HV Electrolyte Breakthroughs: 2025 advances in fluorinated solvents/additives tailored for 5V-class cathodes.

T Threats

NMC has higher energy density and L(M)FP has lower production cost

Rise of LMFP: $LiMn_{1.5}Fe_{0.5}PO_4$ (4.1 V) competes directly for the "mid-range, low-cost" segment with better safety/maturity

LFP Dominance: Continued LFP price drops make it hard for new chemistries to compete on cost alone.

Due to advances in solid-state batteries, other CAM may become more competitive

Raw Material Volatility: While Co-free, reliance on high-purity Nickel exposes it to Ni market fluctuations

Lithium manganese nickel oxide (LMNO): LMNO emerged as advanced version of LMO CAM. With the addition of nickel, it offers a higher energy density and higher cutoff voltage than LMO (4.7 V vs. 4.2 V),

Development of LNMO technology: Began in the mid-2000s, but still exists primarily in cell prototypes and not currently used in EVs. However, growing concerns about the sustainability of cobalt mining and supply chain risks may speed up its adoption.

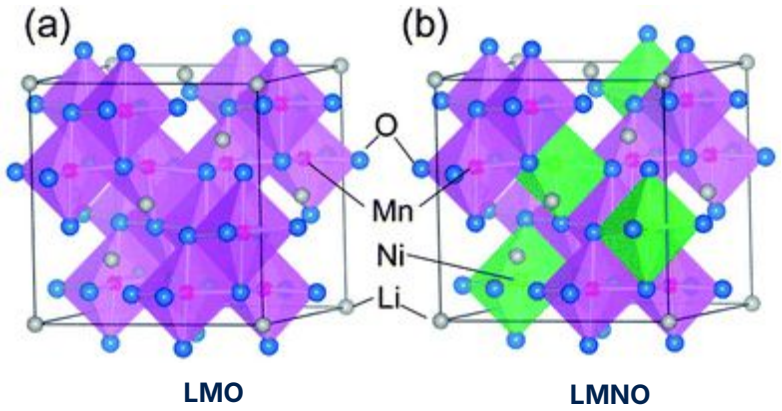
Key players: This technology may soon be implemented in mid/long range EVs, lightweight aviation, drones and BESS. Morrow batteries, Topsoe and NanoOne are aiming to commercialize LMNO technology.

Source: 1. Battery Report 2024 (Pg229); 2. Seokyung choi et al, *ACS Omega* 2024, 9, 17, 18688–18708; 3. Bharti Rani et al. *Sustainable Energy Fuels*, 2025,9, 4262-4285
4. Qiqiang Huang et al, Advanced materials, 2025, 37, 5, 2410006.

LMNO vs. LMO

In LMNO compared to LMO, Mn is partially replaced by Ni and incorporating Ni into the system raises the redox voltage, resulting in increased overall energy density

- LMNO offers a higher energy density, typically around 180-200 Wh/kg, whereas LMO possess a moderate energy density 140-160 Wh/kg
- LMNO has a higher cutoff voltage of 4.7 V, whereas LMO has a cutoff voltage of 4.2 V
- LMNO has improved low-temperature performance compared to LMO



Challenges

LMO:

- Lower energy density → less range for EVs
- Capacity fade due to Mn dissolution at high temperatures

LMNO:

- Higher cost due to Ni
- Slightly reduced thermal stability compared to pure LMO
- More sensitive to electrolyte decomposition at high voltage

LMO (0% Ni)	30% Ni	50% Ni	70% Ni	80% Ni	**LNO** (100% Ni)
4.0 V	4.3V	4.7V	4.8V	4.9V	4.4V
120.0 mAh/g 180.0 Wh/kg	170.0 mAh/g 230.0 Wh/kg	200.0 mAh/g 300.0 Wh/kg	220.0 mAh/g 330.0 Wh/kg	230.0 mAh/g 360.0 Wh/kg	250.0 mAh/g 380.0 Wh/kg

Source: Volta Battery Report 2024 (Slide 230), K. Mukai et al. RSC Adv., 2013, 3, 11634-11639

LNMO Notable Events

January

Renault Austral will use LNMO cell battery, will consume 12 kWh/100 km during WLTP cycle and will be produced end 2028 at Renault factory in Palencia, Spain

February

SeoulTech researchers have introduced a K2CO3 enriched surface on LNMO CAM to improve stability and performance through a KOH-assisted wet chemistry method

March

HyLiST (Hybrid Lithium Metal-based Scalable Solid State Battery Manufacturing) project aimed to develop solid-state LNMO batteries with Li metal anode was launched

April

Researchers from AIT (Austrian Institute of Technology) started working on a MoSiLiB project on developing Li-on batteries with SnS2 anodes and LNMO cathodes on a pilot scale

May

The Battery Technology group at SINTEF achieved a milestone in producing high loading LNMO and Si-C electrodes within IntelLiGent project

June

Work continued on HighSpin project, developing high-voltage LNMO||Si/C cells and modules targeting TRL6 for automotive (2028) and aeronautical (2030) applications

July

Morrow Technologies signed a strategic agreement with SEEL Swedish Electric Transport Laboratory AB for the development of the LNMO battery cells as part of IPCEI initiative

August

NanoOne reported that patent US 12,355,063 on the novel battery assembly using LNMO CAM obtained with OnePot process has been issued

September

Researchers from IMaSE of Technische Hochschule Mannheim and BASF SE published a study of heat generation from LNMO cathodes during cycling

October

Morrow Technologies signed a MoU with Siemens Mobility for the LNMO battery cells joint testing and supply a sample cells with possibility of a long-term supply agreement following successful validation

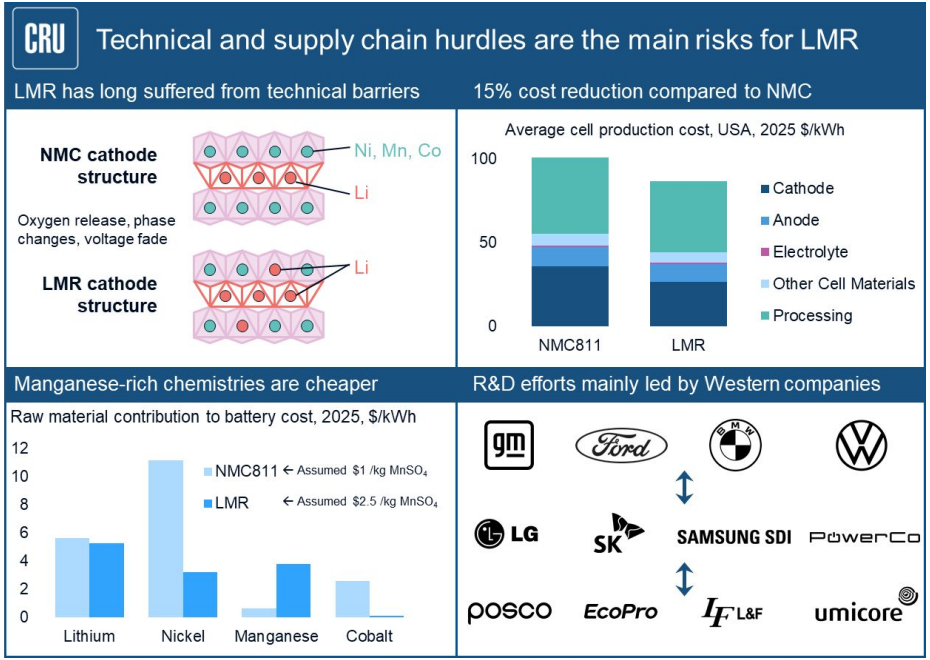
November

Portugal's contribution, known as the NEXTGEN CAM initiative & aimed to manufacture LNMO CAM, was selected by European Commission among 61 other initiatives under a €2.9B package

December

Topsoe chose Sines on the Alentejo coast and Portugal for the LNMO CAM plant within the NEXTGEN CAM project, which is supported by the European Commission's Innovation Funds

Western Companies Are Pursuing LMR as a Potential Alternative to the China-Led LFP Supply Chain



Along with LNMO, lithium-manganese-rich (LMR) cathode chemistry has existed for many years but has suffered from **long-standing technical barriers.** Among other benefits it offers a notionally lower cost compared to NMC and a higher energy density than LFP.

Western auto- and battery manufacturers are pursuing LMR as a technology and associated supply chain that can potentially reduce reliance on China or even compete with it. Ford and GM are the latest companies to plan mass roll-out of LMR for their vehicle line-up, starting from 2028.

The main risk is that LMR is a manganese-rich chemistry. **China dominates the supply of high-purity manganese chemicals** and produces the cheapest product. Some OEMs plan to draw on their future ex.China supply deals, but it will come at a higher cost. However, even when assuming a much higher price for manganese, LMR still comes out cheaper than NMC, as nickel is more expensive.

On the other hand, supply of nickel sulphate and pCAM may remain dominated by China.

LMR has the potential to take over the NMC market in the same way that medium-nickel high-voltage variants have done. It also has the potential to be the low-cost chemistry for North America. When including the US 45X $35 /kWh tax credit, LMR would reach LFP cost levels and would be a viable alternative, given the trade barriers on LFP.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- **EV**
- **Stationary Energy Storage**
- **Data Centers**
- **Aviation, Drones, Space**
- **Robotics**
- **Other**

Safety

Cell Design and Materials
- **Li-Ion**
  - Li-Cathode
  - **Separator**
  - Li-Anode
  - Anode
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Separator Introduction

Across rechargeable battery systems, the separator is a porous, electrically insulating layer placed between the anode and cathode. Its primary function is to prevent direct electrical contact between electrodes while allowing ionic transport through the electrolyte. The separator plays a critical role in safety, power capability, cycle life, and thermal behavior, and is often a key determinant of a battery's tolerance to abuse or failure conditions.Separator requirements vary by battery chemistry, operating temperature, and application, but all separators must balance mechanical integrity, ionic permeability, chemical stability, and manufacturability.

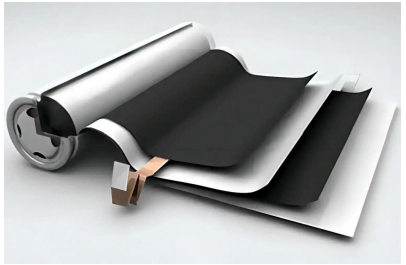
Separators in Lithium-Ion Batteries:

In lithium-ion batteries, separators are most commonly made from polyolefin polymers, such as polyethylene (PE) and polypropylene (PP), produced via dry or wet processes. These materials are chosen for their chemical compatibility with organic electrolytes, mechanical strength, and ability to be manufactured at scale.

Function of the Separator:

During normal operation, the separator:

- Maintains physical separation of the electrodes to prevent short circuits
- Allows ions to migrate through its porous structure during charge and discharge
- Helps regulate electrolyte distribution and wetting within the cell
- Under abnormal conditions, the separator may also contribute to safety mechanisms, such as pore
- shutdown or dimensional stability at elevated temperatures.



Factors influencing Separator choice:

- **Safety & Thermal Stability:** Resistance to shrinkage, melting, or puncture at elevated temperatures; contribution to shutdown behavior.
- **Ionic Conductivity & Porosity:** Ability to support ion transport without excessive resistance, impacting power and fast-charge capability.
- **Mechanical Strength:** Puncture resistance, tensile strength, and dimensional stability under swelling or stack pressure
- **Electrolyte Compatibility:** Chemical stability and wetting behavior with the chosen electrolyte system.
- **Cost & Manufacturability:** Scalability of production processes and compatibility with high-volume cell manufacturing

Source: Redwood, ANL, Nature-lithium-ion battery cathode chemistry, Battery Report 2023-2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

Technology Trends

INDUSTRIALIZED SEPARATOR TECHNOLOGIES

Layer	Separator Type	Material	Advantages
Base Layer	**Dry-Process Polyolefin**	Polypropylene or Polyethylene	Strength, Lowest cost
	Wet-Process Polyolefin	Polyethylene	Low thickness, electrolyte wetting, low cost vs non-polyolefin options
	Nonwoven Fabric	Nonwoven materials made of synthetic fibers: Polyethylene terephthalate (PET), Polyimide (PI)	Porosity, Electrolyte absorption, thermal stability
	Glass Fiber	Often composed of polyethylene or polypropylene with added fillers or ceramic coatings	Thermal Stability, Ionic Conductivity
Coating	**Ceramic Coatings**	Alumina, boehmite, silica	Thermal stability, reduced shrink
	Adhesive Coatings	Poly(vinylidene difluoride) (PVDF), optionally modified (PVDF-HFP)	Adhesion, electrolyte wetting, chemical resistance
	Fiber-Reinforced Coatings	Hybrid coatings combining high-strength fibers (e.g., aramid) with polymer binders.	Strength, thermal stability, reduced shrink
	High-temperature Polymers	Aramids, Polyimides, Polymers of Intrinsic Microporosity (PIM)	Thermal stability, strength, ion selectivity

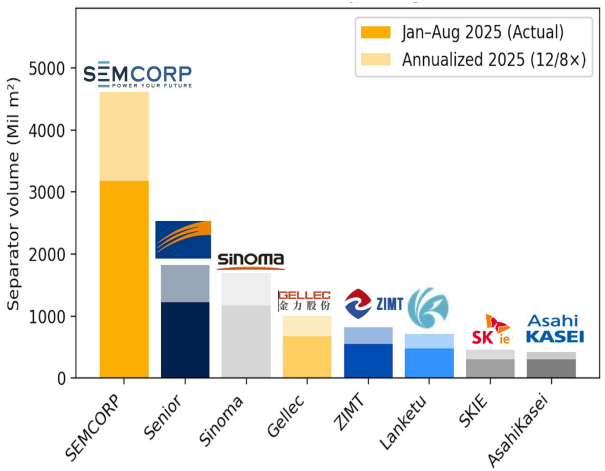
EMERGING TECHNOLOGIES

Who	What	Why
SENIOR 星源材质	Aramid nanofiber composite coatings	Facilitates safety, higher performance than existing ceramic
SEMCORP POWER YOUR FUTURE	Flame retardant separator technology	Enhances safety from reduced risk of fire
SOLVAY	Solvent-free and water-based PVDF binders	Provides ability to laminate multiple electrode layers together, dimensional stability, safety
ARKEMA	PVDF coatings with solvent-free and/or PFAS-free processes	Eliminates of potentially harmful chemicals from process
LG	High-modulus separator designed to withstand Si swelling stress	Allows higher Si content in anode by withstanding swelling stresses
FREUDENBERG	Non-woven separators for ESS	Claims improved cycle life, safety, electrolyte wetting
ProLogium	Fully-inorganic separator and electrolyte battery	Enables liquid-free solid-state,adds safety and flammability performance
SEPION TECHNOLOGIES	Ion selective polymer separators, polymers of intrinsic microporosity (PIM)	Reduces weight, improves energy density, helps reduce impact of transition metals

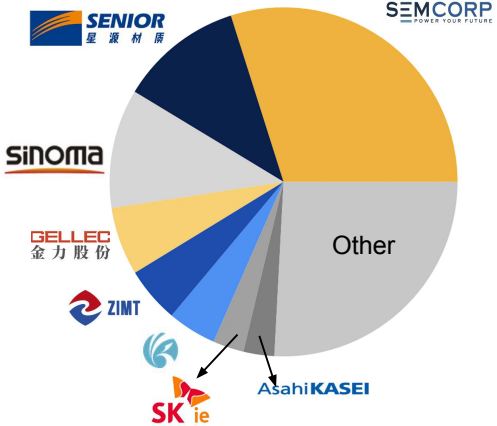
Source: Royal Society of Chemistry, Renewable and Sustainable Energy News

SEMCORP Dominates in Separator Sales, but Other Players Continue to Show Promising Growth

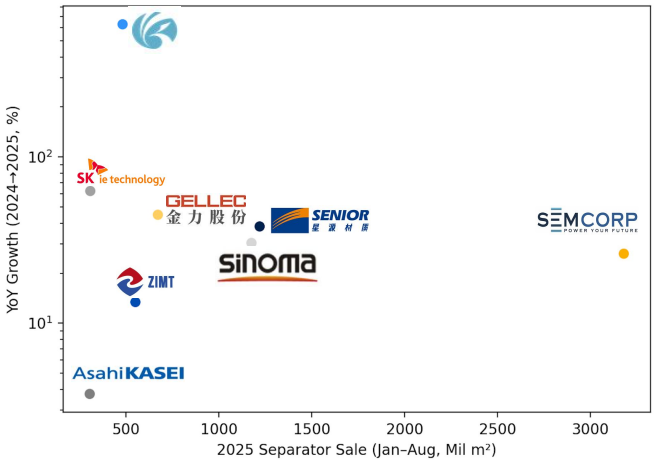
VOLUMES FOR SEPARATOR MFGS



MARKET SHARE



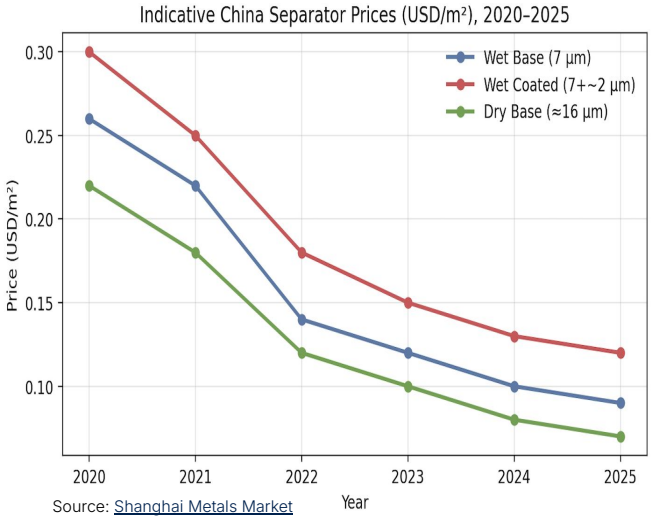
SCALE VS GROWTH



Source: SNE Research

Infrastructure / Supply Chain / Manufacturing

SEPARATOR PRICES STABILIZING ($/m²)



Source: Shanghai Metals Market

China's announced "anti-involution" policy may play a role for 2026 prices

NORTH AMERICA LOCALIZATION



EUROPE LOCALIZATION



(Click on map icons for links)

In Production Under Development

Separator Key Trends + Notable Events

January

Microporous receives $100M award from US DOE to accelerate commercialization of ultra-thin, coated wet-process separators

February

Asahi Kasei breaks ground on HiPore wet-process separator plant in Ontario, Canada (C$1.6B)

Freudenberg announces nonwoven separators claiming improved life, safety, and electrolyte handing

March

24M Impervio separator recognized by Fast Company's 2025 "World Changing Ideas"

April

Natrion announces LISIC-based composite 'active' separator

SKIE supplies base separator films from Korea to LGES in North America, where LG performs ceramic coating - highlighting supply-chain and regulatory complexity

May

Quantumscape announces production of Cobra solid-state separator

June

W-scope Plant construction commences at Nyíregyháza, Hungary plant, W-scope's first European plant

Senior subsidiary INV New Materials announces 1.3 billion m2 facility in Malaysia for base film and coated separator

July

Entek awarded conditional US DOE load for US separator plant expansion

Asahi and Toyota entered into an agreement for Asahi to supply separators from its North Carolina plant

August

Microporous Opens Li-ion separator line in Tennessee, establishing North American supply base

September

Quantumscape and Corning announce ceramic separator co-development agreement

Entek announces majority acquisition by I-squared Capital

October

Nuvola Technology announces SafeCoat separator technology

November

Putailai announces a ~ ¥25 billion expansion in China, adding 20B m^2 of base and 30B m^2 of coated separator capacity (annual) once complete

December

LG, Toray LG completes acquisition of Toray's stake in their Hungary Battery Separator plant

China's new "anti-involution" policy seeks to eliminate "race to bottom", provide stable comp., affecting battery materials generally and separators

Source: company announcements and trade reports (links embedded)

2025 | BATTERY REPORT

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- **Other**

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Cell Design and Materials
- **Li-Ion**
  - Li-Cathode
  - Separator
  - **Li-Anode**
  - Anode
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Anode Summary and Key Points 2025

In 2025, graphite remains the dominant anode material in lithium-ion batteries due to its affordability, long cycle life, mature manufacturing base, and well-understood safety profile. Silicon-based anodes continue to attract strong industry investment as a pathway to higher energy density, primarily through blending with graphite rather than full replacement. Li metal continues to be developed in solid state, lithium sulfur, and other higher energy chemistries.

While silicon offers significantly higher theoretical capacity than graphite, its large volume expansion during lithiation introduces mechanical and interfacial challenges that must be mitigated through materials engineering and cell design. As a result, most commercial progress has focused on incremental silicon integration rather than disruptive anode replacement.

Key points about lithium-ion battery anodes in 2025:

Dominant Material - Graphite: Graphite remains the most widely used anode material, supported by proven performance, manufacturability, and cost structure. However, the global supply chain remains highly concentrated, with China accounting for ~70% of natural graphite production and ~90% of processing capacity.

Emerging technology - Silicon-Enhanced Anodes: Silicon-based anodes are increasingly deployed in graphite–silicon blends to boost energy density while avoiding the safety and stability risks associated with lithium-metal anodes. These approaches offer a pragmatic balance between performance gains and commercial readiness.

Research & Development Focus: Ongoing R&D targets the key limitations of silicon anodes and Lithium metal. For Silicon this include volume expansion, mechanical degradation, and unstable SEI formation. For lithium metal this includes dendritic lithium growth, infinite volume expansion, unstable SEI formation, and manufacturing stability. Other active areas include nano-structuring, advanced binders, engineered conductive networks, and optimized electrode architectures.

Market & Supply-Chain Trends: Concerns around graphite supply security have accelerated efforts to diversify sourcing and develop alternative anode materials, including silicon-rich composites, lithium-metal systems, lithium-titanate (LTO), and hard carbon anodes for sodium-ion batteries.

Source: Ufine, Battery Report 2023-2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

Anode Key Performance Metrics

The selection of an anode material is a critical design decision that directly influences energy density, charging behavior, lifetime, safety, and cost at the cell and system level. While graphite remains the industry benchmark, alternative anodes introduce trade-offs that must be evaluated against application requirements.

Energy Density

Anode materials with higher lithium storage capacity can increase overall cell energy density. Graphite provides stable, moderate capacity, while silicon and lithium-metal anodes offer higher theoretical energy density with increased technical risk.

Cycle Life

Cycle life reflects the anode's ability to withstand repeated lithium insertion and extraction without excessive mechanical or interfacial degradation. Stable SEI formation and mechanical integrity are essential for long-term durability.

Cost

Material cost, processing complexity, and yield directly impact anode economics. Scalable, high-yield manufacturing remains a key requirement for commercial adoption.

Safety

Anode safety is influenced by lithium plating risk, SEI stability, and mechanical robustness. Unstable anodes can contribute to internal short circuits, overheating, and thermal runaway.

Rate

Rate performance describes how effectively the anode supports fast charge and discharge. It depends on ion transport, electronic conductivity, and interfacial stability, and is especially critical for EVs and consumer electronics.

Cathode Compatibility

The anode must be electrochemically and mechanically compatible with the selected cathode to ensure balanced capacity, efficient ion transport, and stable long-term performance.

Manufacturability

Commercial viability depends on how easily an anode material integrates into existing electrode fabrication and cell assembly processes, including slurry processing, coating, calendaring, and formation.

Environmental Impact

There is growing emphasis on reducing environmental impact and supply-chain risk through sustainable sourcing, lower processing intensity, and recyclability across the anode lifecycle.

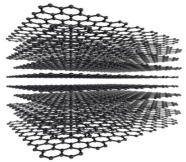
Source: Battery Report 2023-2024, Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

Commonly Used Anode Materials & Performance Tradeoffs

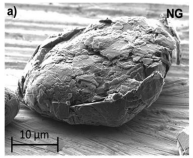
	Graphite (Synthetic & Natural)	Graphite - Si/Siox	Silicon (Si & Sio)	Li Metal
Description	• remains the primary choice for anode materials, • most commonly used in blends with Si/SiO. • structure enables efficient intercalation and supports considerable storage capacity	• utilized in industry for many years and an established component of industrial production, • enables batteries to achieve higher energy densities	• offers higher energy density than graphite • challenges related to volume expansion.	• the most energy dense anode • challenges related to safety and cycle life, often due to dendrite formation.
Pro	• first choice for anode, • good compromise between capacity and durability, • relatively low cost and high availability of raw and recycled materials	• achieving higher energy density compared to graphite, • avoid huge volume expansion	• high theoretical capacity, • higher energy density compared to graphite.	• highest theoretical capacity, • potentially leading to significantly increased energy density,
Con	• limited energy storage capacity, can hinder the development of high-energy-density batteries, • growing supply chain risk	• lower capacity than pure silicon or SiOx anodes, • lower cyclability than common graphite anode (up to 10% Si/SiO for stable lifetime)	• higher cost than graphite (per kg) • significant mechanical degradation and reduced cycle life.	• Prone to dendrite formation during cycling, • posing safety risks • reducing cycle life.

Source: Battery Report 2023 (pg133), Battery Report 2024 (pg236), Battery Talk: Battery Application Break Down 12/31/2025 (Version 3.0

Graphite Basic Technology and Information - Industry-standard Anode Material for Lithium Ion Batteries



Graphite is the dominant active anode material due to its layered structure enabling reversible lithium intercalation. Both natural and synthetic graphite are employed industrially as anode, with properties tailored through processing and surface modification to meet specific cell performance requirements. Fully lithiated graphite (LiC_6) offers a theoretical maximum capacity of 372 mAh/g. Surface engineering (e.g., carbon coating) is widely used to improve conductivity, suppress parasitic reactions, and enhance cycling stability, particularly under fast-charging conditions.

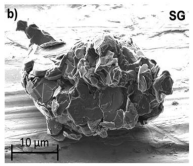


NATURAL GRAPHITE

Production process: Natural flake graphite is mined, beneficiated via flotation, purified to battery-grade specifications, and spheroidized to form spherical purified graphite.

\+ Slightly higher practical capacity and competitive rate performance can be achieved due to favorable particle morphology and increased edge-plane exposure at the particle surface.

– Higher defect density, impurity sensitivity, and broader material source variability can increase surface reactivity and challenge long-term stability and sustainability.

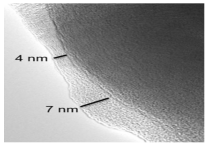


SYNTHETIC GRAPHITE

Production process: Carbonaceous precursors (petroleum and needle coke) are carbonized and graphitized at high temperatures followed by refinement, yielding tailored microstructure.

\+ Higher purity, lower thermal expansion, and better thermal stability lead to higher cycle life.

– High production energy demand and petrochemical feedstock dependence increase cost and environmental footprint.



CARBON COATING

***Production process*:** Liquid- or gas-phase carbon precursors are pyrolyzed at ~800–1100 °C under inert conditions to create a thin, conformal conductive coating on graphite particles.

\+ An optimized thin carbon coating improves electronic percolation and moderates surface reactivity, enabling more stable SEI formation, enhanced rate performance, and improved cycle life.

– Additional processing steps and excessive coating thickness can increase cost and reduce volumetric energy density if not carefully controlled.

PROPERTIES -PERFORMANCE LINKAGE

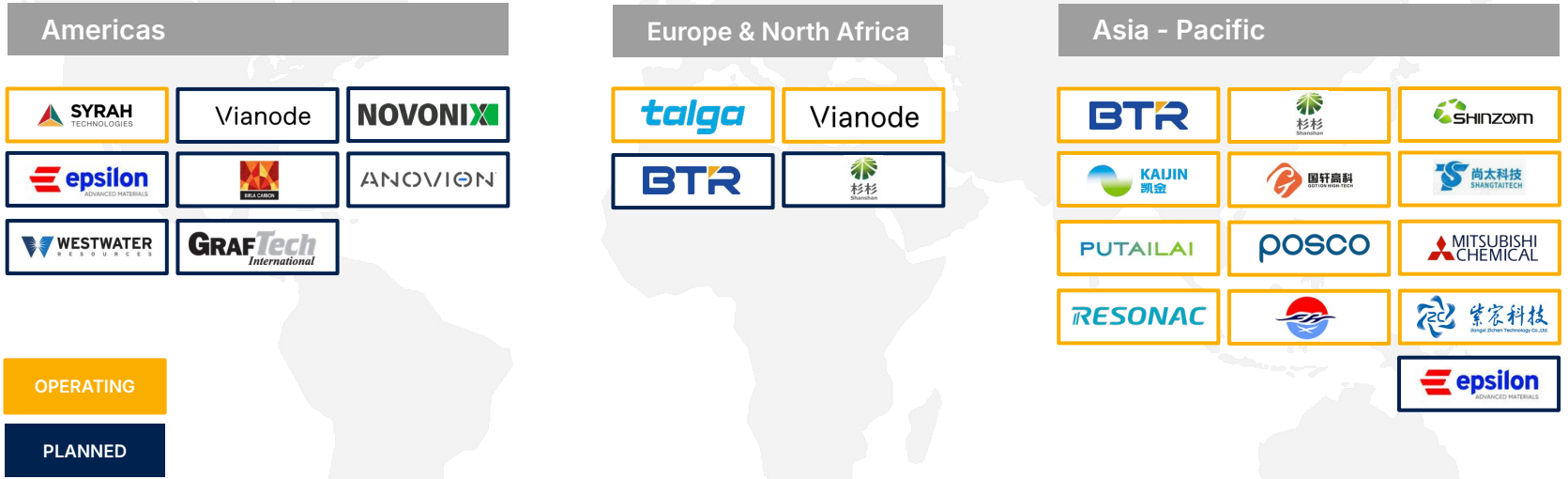
Key graphite attributes - including particle size distribution, tap density, surface area, and metallic/ magnetic impurity levels - govern electrode packing density, SEI stability, lithium-ion transport, and safety, thereby defining critical trade-offs among gravimetric energy density, volumetric energy density, power capability, and fast-charging performance.

APPLICATION-DRIVEN GRAPHITE SELECTION

- High energy density (EV): High tap density graphite with controlled surface area.
- Fast charging: Optimized PSD, edge-plane exposure, and carbon coating.
- Long cycle life / ESS: High-purity, structurally uniform graphite with stable SEI.
- Cost-sensitive systems: Blended natural-synthetic graphite solutions.

Source: Jakob Asenhaeur et al (2020). The success story of graphite as a lithium-ion anode material... *Sustainable Energy & Fuels, 4(11)*, 5387-5416. K Zaghib et al (2003) Purification process of natural graphite... *Journal of Power Sources, 119–121*, 8-15. Seong Jin An et al (2016) The state of understanding of the lithium-ion-battery graphite solid electrolyte interphase... *Carbon, 105*, 52-76. Battery Report 2023. Battery Report 2024

Major Graphite AAM Producers



See Supply Chain section for more information.

Source: company announcements. Only showing major planned operations.

Notable Events: Graphite

January

GM signed a multi-year supply agreement with Vianode with production starting in 2027

February

Northern Graphite is supplying Battery Anode Material (BAM) samples from its LDI Graphite project in Quebec, Canada

May

US department of commerce announced 11.58-721.03% Countervailing Duty (CVD) on active anode material from China

June

Lucid Group entered a supply agreement with Graphite One to secure graphite materials for EV batteries from Alaska, USA

July

US department of commerce announced 93.50-102.72% Anti-dumping Duty (AD) on active anode material from China

August

NextSource Materials Inc. and Mitsubishi Chemical Corporation singed multi-year binding offtake agreement

September

ExxonMobil acquires Superior Graphite's technology and U.S.-based assets to set foot into the synthetic graphite market

October

Nouveau Monde Graphite signed offtake agreements with Panasonic Energy, Government of Canada and Traxys North America

November

Vianode announced $3.2 billion investment in ON, Canada

Stellantis cancels its SG offtake agreement with Novonix and Westwater Resources

Source: Company announcement

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Silicon Basic Technology and Information

Engineered silicon increases anode specific capacity as a blend with or replacement for graphite in Li-ion batteries (LIBs)



Silicon alloys with lithium (fully lithiated silicon (Li15Si4)) to deliver a theoretical specific capacity of ~3,572 mAh/g, approximately an order of magnitude higher than graphite, making it highly attractive for cell energy density. However, silicon undergoes ~300-400% volume expansion during lithiation, leading to mechanical fracture, unstable SEI formation, and rapid capacity fade. Consequently, silicon anodes are implemented through engineered architectures and low-percentage blending strategies to balance energy density gains with cycle life and manufacturability required for EV applications.

SILICON MONOXIDE (SiOx)

Production process: SiOx is produced via high-temperature vapor-phase synthesis followed by condensation and milling to form silicon-oxygen composite powders with controlled oxygen content.

\+ Partial oxidation buffers volume expansion and stabilized SEI formation, enabling improved cycle life and manufacturability compared to elemental silicon.

– Lower active silicon fraction limits achievable capacity gain, typically restricting SiOx usage to low blending ratios (<10%) in anodes.

SILICON IN CARBON (Si-C)

Production process: Si-C composites are produced by embedding nano- or micro-scale silicon within engineered carbon matrices via CVD, or pyrolysis.

\+ Carbon matrices provide electrical conductivity and mechanical confinement to restrain volume expansion, improving cycling stability and rate capability while enabling higher silicon loadings than SiOx.

– Carbon dilution and complex processing reduce gravimetric energy density benefits and increase manufacturing cost.

Metallic SILICON (Si)

Production process: Metallic silicon anodes are produced via metallurgical grinding for micro-silicon or CVD-based deposition of nano-silicon on graphite or current collectors.

\+ High silicon content enables the largest potential increase in anode specific capacity.

– Severe volume expansion and unstable interfacial behavior lead to rapid degradation, limiting direct EV deployment without advanced structural or interfacial mitigation.

PROPERTIES-PERFORMANCE LINKAGE

Silicon anode performance is governed by particle size, oxygen content, carbon architecture, and interfacial stability, which collectively determine achievable capacity, cycle life, and fast-charging robustness.

EV DRIVEN SILICON ANODE STRATEGIES

- **Near-term EV adoption:** Low-percentage silicon blending (primarily (SiOx) for incremental energy density gains.
- **Mid-term pathways:** Engineered Si-C composites to balance capacity and durability.
- **Long-term potential:** Higher silicon loadings enabled by structural and interfacial innovations.

Source: Mazir Ashuri et al (2023) Silicon oxides for Li-ion battery anode... Journal of Power Sources, 559. Iwamura, S. et al (2015) Li-Rich Li-Si Alloy as a Lithium-Containing... Sci Rep, 5, 8085. Zhang et al (2023) Recent advances of SiOx-based anodes... Nano Research Energy, 2(3). Zuo, Xiuxia et al (2017) Silicon based lithium-ion battery anodes... Nano Energy, 31(1), 113–143. P.U. Nzereogu et al (2022) Anode materials for lithium-ion batteries... Applied Surface Science Advances, 9., Battery Report 2023, Battery Report 2024

Silane Precursor for Silicon Additions in the Anode

Silane is used mainly in three ways to incorporate Si in the anode material: forming particles (3D) coating (2D) and nanowires/columns (1D). A more stable secondary phase is used to control the expansion of Si or to act as a substrate.

Strategies to incorporate Si through silane use

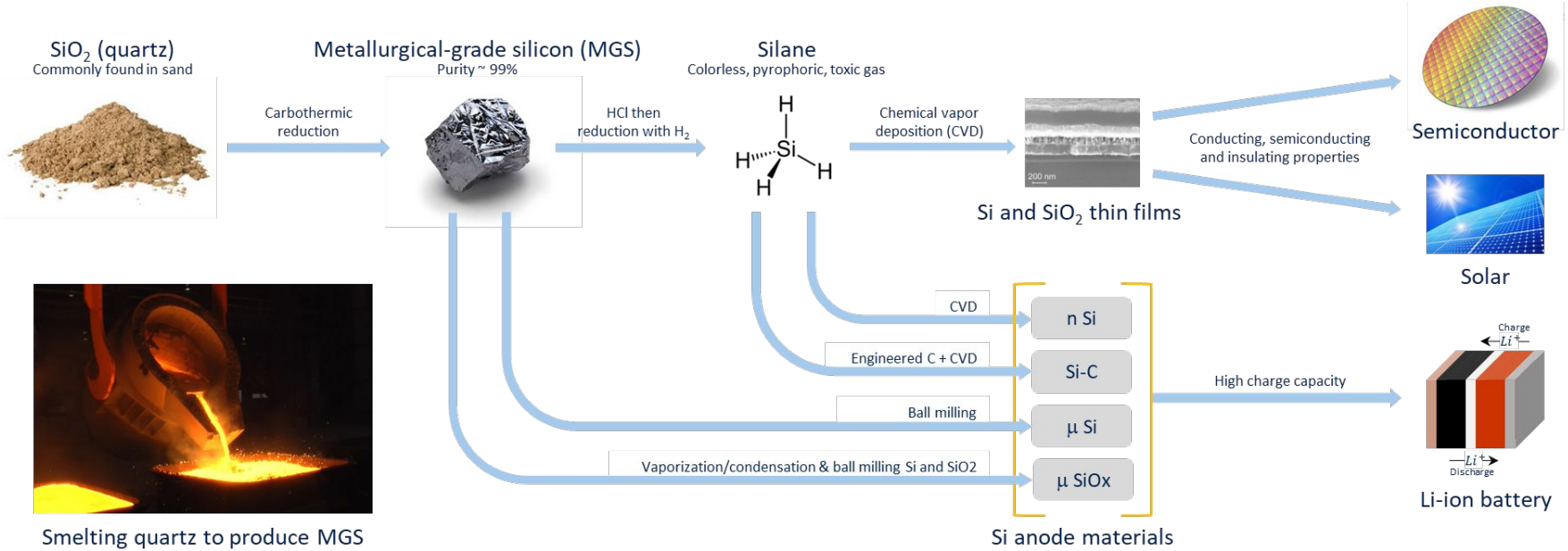
3D particles	CVD can be used to directly grow Si particle as the anode active material such as core shell and yolk shell design principles or simple nanoparticles in the porosity of a matrix e.g., porous carbon
2D coating	Other substrates, usually carbonaceous materials such as CNT, carbon black, etc. can be used to grow a coating of Si through vapor deposition
1D structure	Controlled growth direction and rate can be used to form 1D structures, called nanowires or nanocolumns. The profile shape and chemistry can be managed through temperature and pressure gradients

Source: Toki et al. (2024) Recent progress and challenges in silicon-based anode materials for lithium-ion batteries, Ind. Chem. Mater, 226-269; iestbattery.com

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MGS and Silane (from Sand to MGS and Silane to Silicon Anodes)

Essential in semiconductor and PV manufacturing, MGS and silane are increasingly used in Li-ion battery (LIB) anodes



Source: Favors, Z. et al (2014) Scalable Synthesis of Nano-Silicon from Beach Sand for Long Cycle Life Li-ion Batteries, *Sci Rep, 4*, 5623. Zuo, Xiuxia et al (2017) Silicon based lithium-ion battery anodes... *Nano Energy, 31(1)*, 113–143. P.U. Nzereogu et al (2022) Anode materials for lithium-ion batteries... Applied Surface Science Advances, *9*. Elkem (2023) From quartz to silicon to silicones. Mazir Ashuri et al (2023) Silicon oxides for Li-ion battery anode... Journal of Power Sources, 559

Silicon Key Trends

The focus in 2025 was mainly on Si-C anode types and their increasing market share. Si market events in the US and Europe were focused on industrialization. In China funding of several projects by the government and R&D by the large cell makers were announced which aim to close the gap with the high energy anode technologies by the Western players. Korea has been the meeting point of scaled production and high-energy products.

More western Si anode makers enter the market

In both the US and Europe development of high-energy Si anode startups continues.

In Sep ‘25 Sila starts operation in Moses Lake starting with 2-5 GWh

In May ‘25 Altech Advanced Materials AG commissioned its pilot plant in Saxony

Both western and local players active in Korea

The activities on Si anodes are pushed by component makers notably ramp-ups by Daejoo, Posco and Hansol.

Western companies announcements: Group14 acquires 100% ownership of BAM factory from SK; Nexeon’s announcement of production readiness in Gunsan.

China races to high energy Si anodes

For years, ball milling has been the standard in China to prepare Si-based anodes. A strong focus shift to Si-C in 2025 was publicized.

More than 15 projects were reported in Aug ‘25 to receive investment with focus on high energy SiC anodes and use of CVD to incorporate Si.

Activity on SiOx anodes continue

SiOx is the first class of Si anodes that entered the market but it keeps being improved to increase its mix ratio.

Patent publications by battery producers such as CATL published on SiOx anodes in 2025, and SiOx show that development in this class of materials continues in the market.

Source: ICC SINO, Silicon Anode Battery Technologies and Markets 2025-2035: Players, Technologies, Applications, Markets, Forecasts: IDTechEx oChina's silicon-carbon composite anode material industry, Sila, Altech, other company announcements.

Top 10 Silicon Anode Players - Global Leadership & Operational Milestones (1 of 2)

By late 2025, the silicon anode market has shifted toward industrial-scale production, with leaders commissioning global manufacturing hubs in the US, Korea, and Malaysia to meet the 50% CAGR demand for high-energy EV and consumer electronics cells.

	Sila	Group14	Enovix	Amprius	BTR New Material Group
AAM or Battery	AAM	AAM	Battery	Battery	AAM
HQ	Alameda, CA	Woodinville, WA	Fremont, CA	Fremont, CA	Shenzhen, China
Year Founded	2011	2015	2007	2008	2000
Employees	414	~500	570	99	8,130
Type	Private	Private	Public NAS:ENVX	Public NAS:AMPX	Public (BJSE: 920185)
Total $ Raised	$1.31B	$1.16B+	$220M (Pre-IPO)	$191M (Pre-IPO)	$112M+
Funding Stage, Date	Series G, Jun 2024	Series D, Aug 2025	Public	Public	Public
Valuation / Market Cap	$2.48B-$3.41B	$5.08B-$5.27B	$1,63B-2.66B	~$0.76B	~$5.53B
Technology Approach	Si-dominant composite (Titan Silicon)	Si-carbon composite	3D Structural Cell Architecture	100% Si Nanowire (CVD grown)	Si-C and SiOx composites
Application(s) Targeted	EVs, High-end CE	Auto (Porsche), Mobile	EV, Consumer electronics, ESS (roadmap)	Aero, Defense, Performance EVs	Global OEM supply chain
2025 Progress	Commissioned Moses Lake Facility. Raised $375M to deliver Titan Si	Closed $463M Series D; 100% ownership of Group14 Korea	Scaled Fab2 in Malaysia; positive non-GAAP gross profit	CEO transition; expanded GWh facility in Brighton, CO	70% market share in H1 2024; massive global expansion

Source: Silicon Anode Material Global Market Insights 2025, Global Market Insights, Research and Markets, Top Silicon Anode Materials Market Companies, Sila

Top 10 Silicon Anode Players - Global Leadership & Operational Milestones (2 of 2)

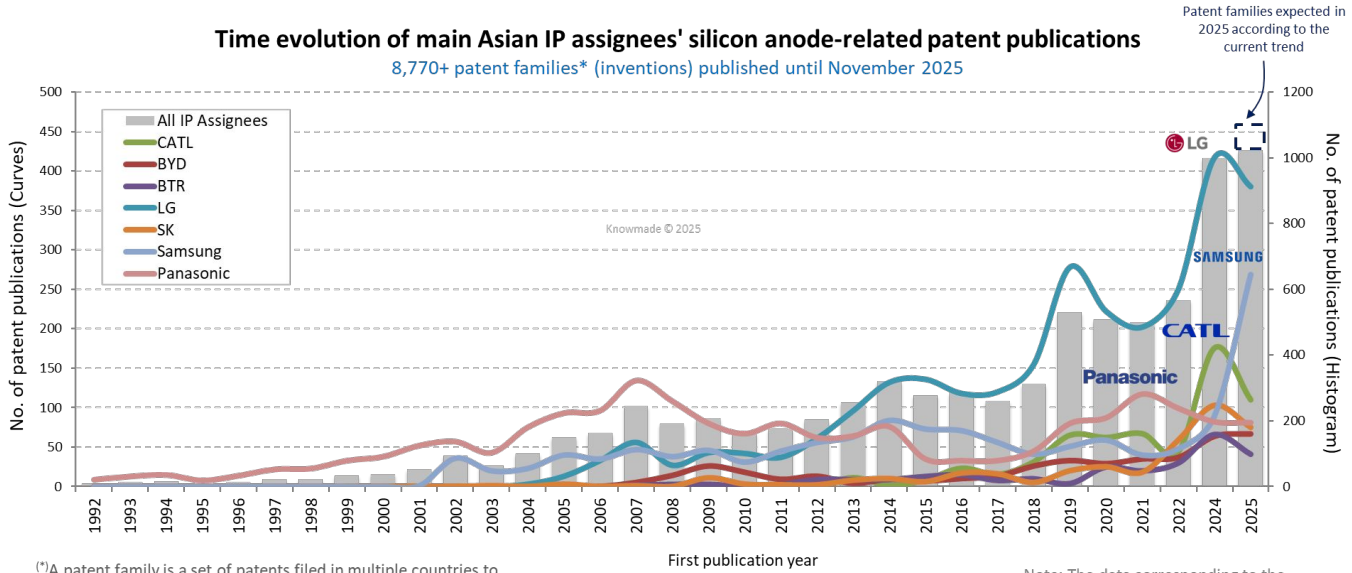
	OneD	Shanshan (杉杉)	IOPSilicon (Tianmulake)	Zhide	Putailai (璞泰来)
AAM or Battery	AAM	AAM	AAM	AAM	AAM
HQ	Palo Alto, CA	Ningbo, China	Liyang, China	Jinhua, China	Shanghai, China
Year Founded	2013	1989	2017	2018	2012
Employees	~50	~10,000+	644	Not listed	6,000+
Type	Private	Public (SHA: 600884)	Private	Private	Public (SHA: 603659)
Total $ Raised	$99M	Not available	Not available	$197M	Not available
Funding Stage, Date	Series C, Jun 2023	Public	Not disclosed	Series D1, Aug 2024	Public
Valuation / Market Cap	$366M	30.25B CNY	Not available	$197M	59.22B CNY
Technology Approach	Silicon nanowires in graphite particles	Si-C, SiOx, Graphite (both)	Si-C, SiOx, hard carbon, Solid Electrolyte Series	Silicon nano-particles in carbon matrices	SiOx/Si-C; integrated coating/foil/equipment ecosystem
Application(s) Targeted	EV	EV, Consumer, ESS	EV, Consumer/ ESS	Consumer electronics, EV	EV, Consumer, ESS
2025 Progress	JDA with Putailai	Indonesia anode plant Phase-1 ~80 kt/y; Si-based mass production advancing	Reported domestic mass production; partner page claims capacity ≈8,000 t/yr	Strengthening the domestic China supply chain for high-end electronics	H1'25 Si-C trial production; JDA with OneD

Others in Top 20

Source: Shanshan 2025 interim, Mitsui Research: OCSiAl collaboration, Putailai trial production, OneDSinanode, IOPSILICON, Silicon Battery Market Size

Time Evolution of Silicon Anode-Related Patent Publications by Main Asian IP Assignees

LG is the IP leader of this silicon anode-related patent landscape.



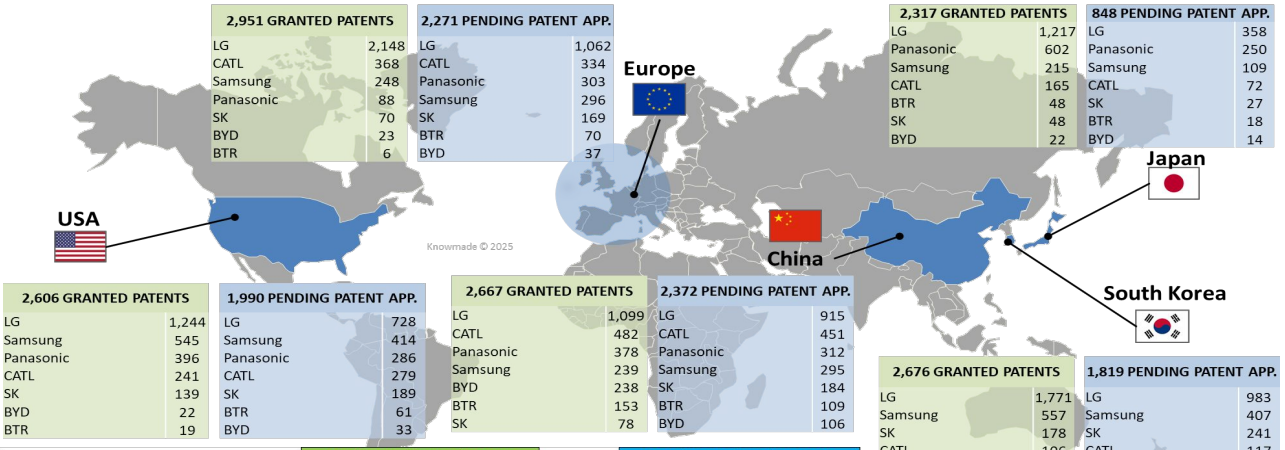
(*)A patent family is a set of patents filed in multiple countries to protect a single invention by a common inventor(s). A first application is made in one country – the priority country – and is then extended to other countries.

Note: The data corresponding to the year 2025 is not complete since patent search was done in November 2025.

Source: Patent search was done in November 2025 by KnowMade, using keywords related to silicon-based anode for Li-ion batteries, IPC/CPCs (H01M, C01B-033, etc.), and assignee names (CATL, BYD, BTR, LG, SK, Samsung, Panasonic) in Orbit (Questel) which provides 100+ million patent documents from 100+ patent offices (USA, Japan, Europe, China, Korea, Taiwan, India, etc.).

Geographical Distribution of Alive Silicon Anode-Related Patent Assets for Main Asian IP Assignees

LG, Samsung, and CATL have a strong and extensive worldwide IP strategy.



				Distribution of granted patents						Distribution of pending patent				
Assignee	Headquarters	Number of patent families	Number of granted patents	USA	Europe	Japan	China	South-Korea	Number of pending patent applications	USA	Europe	Japan	China	South-Korea
All Players		8770+	16370+	2606	2951	2317	2667	2676	12020+	1990	2271	848	2372	1819
CATL	China	870+	1693	241	368	165	482	106	1654	279	334	72	451	117
BYD	China	440+	362	22	23	22	238	15	293	33	37	14	106	28
BTR	China	300+	310	19	6	48	153	31	371	61	70	18	109	41
LG	South-Korea	3240+	9500	1244	2148	1217	1099	1771	5575	728	1062	358	915	983
SK	South-Korea	430+	574	139	70	48	78	178	865	189	169	27	184	241
Samsung	South-Korea	1410+	1899	545	248	215	239	557	1625	414	296	109	295	407
Panasonic	Japan	2050+	2038	396	88	602	378	18	1647	286	303	250	312	2

Source: Patent search was done in November 2025 by KnowMade, using keywords related to silicon-based anode for Li-ion batteries, IPC/CPCs (H01M, C01B-033, etc.), and assignee names (CATL, BYD, BTR, LG, SK, Samsung, Panasonic) in Orbit (Questel) which provides 100+ million patent documents from 100+ patent offices (USA, Japan, Europe, China, Korea, Taiwan, India, etc.).

Key Figures and Recent Positioning of the Main Asian IP Assignees on Silicon-Based Anode Materials

CATL is challenging leading South-Korean companies

		CATL	BYD	BTR	LG	SK	SAMSUNG	Panasonic
Key figures	Number of patent families (inventions)	870+	440+	300+	3,240+	430+	1,410+	2,050+
	Pentadic patent families [1]	30+	1+	2+	400+	10+	60+	1+
Recent IP developments on Si-based anode materials for Li-ion batteries (from 2024-11-28 to the present)	Silicon alone [2]			*				
	Si-based composites [3]	**	*	**	**	**	**	**
	Generic [4]			*	**	*		*

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Notes:

(1) Pentadic patent families are patent families granted jointly in the largest global technology markets, in United States Patent and Trademark Office (USPTO), European Patent Office (EPO), Japan Patent Office (JPO), Korean Patent Office (KIPO), and in the Chinese Patent Office (CNIPA), for the same invention, by the same applicant or inventor.

(2) Silicon alone: this refers to patent families whose core invention relates to Li-ion battery anode materials in which the active material consists solely of silicon, without being explicitly integrated into carbon, graphite, or other composite matrices.

(3) Si-based composites: This refers to patent families whose core invention relates to Li-ion battery anode materials where silicon, SiOx, or another silicon-based active compound is explicitly combined with an additional component such as carbon, graphite, or other inorganic materials.

(4) Generic: This refers to patent families whose core invention involves Li-ion battery anode materials but only broadly mentions silicon, uses unspecified silicon-based materials, or lists multiple Si-based materials in a way.

Quantitative data (number of patent families) are aggregated into two qualitative classes, represented by the symbols * and **, in order to compare players based on orders of magnitude.

Source: Patent search was done in November 2025 by KnowMade, using keywords related to silicon-based anode for Li-ion batteries, IPC/CPCs (H01M, C01B-033, etc.), and assignee names (CATL, BYD, BTR, LG, SK, Samsung, Panasonic) in Orbit (Questel) which provides 100+ million patent documents from 100+ patent offices (USA, Japan, Europe, China, Korea, Taiwan, India, etc.).

Recent IP Developments in Silicon-Based Li-Ion Battery Anode Materials for the Main Asian IP Assignees

Convergence toward structurally and interfacially engineered silicon anodes

CATL	• Industrial, scale-oriented IP targeting silicon's core limits: expansion, SEI instability, low first Coulombic Efficiency (CE), and fast charging. • Focus on confined Si-C composites (porous carbon, conductive networks) with core-shell, graded and elastic coatings. • Emphasis on processes such as: spray drying, CVD, and positioning toward solid-state battery technology.
BYD	• Addressing key technical challenges, including expansion, SEI degradation, conductivity loss, and cycle-life limitations. • Nano/amorphous Si embedded in conductive, porous frameworks, with particular attention to Li^+ transport. • Interface stabilization via coatings and compositional gradients, combined with controlled, scalable synthesis routes.
BTR	• Addressing key technical challenges, including expansion/SEI, low initial CE, gas/safety, rate limits, and electrode processing. • Core concept: confined Si or SiOx in porous carbon or graphite structures, with graded distributions and multilayer coatings.
LG	• A cross-level approach encompassing materials, electrodes and processing aspects. • Engineered Li-Si-O and Si-C composites with multilayer/gradient coatings and controlled particle architectures. • Electrode-level integration (graphite, CNTs) plus prelithiation and impurity/crystal control to improve initial efficiency and stability.
SK	• Positioning toward high-energy Li-ion and solid-state batteries through control of silicon's local structure and interfaces. • Porous silicon–carbon composite materials and chemically engineered silicon (SiO_x and doped Si). • Positioning for solid-state batteries via metal-decorated Si particles to improve conductivity and interfaces with reduced reliance on conductive carbon.
SAMSUNG	• Positioning toward high-silicon-content anodes with balanced performance. • Particle-level engineering: core-shell structures, controlled porosity, and carbon coatings. • Various interface stabilization approaches addressing cycle life, safety, and rate capability.
Panasonic	• Positioning toward high-silicon-content cells in high-energy applications. • Silicon dispersed in carbon or lithium-based matrices, combined with advanced SEI/interface control (F-based, polymer-based, etc.). • Control of porosity, surface coatings, and dopant composition to address trade-offs between efficiency, durability and processing considerations.

Knowmade © 2025

Source: Patent search was done in November 2025 by KnowMade, using keywords related to silicon-based anode for Li-ion batteries, IPC/CPCs (H01M, C01B-033, etc.), and assignee names (CATL, BYD, BTR, LG, SK, Samsung, Panasonic) in Orbit (Questel) which provides 100+ million patent documents from 100+ patent offices (USA, Japan, Europe, China, Korea, Taiwan, India, etc.).

Prelithiation of Silicon Anodes - System-Level Enabler to Offset First-Cycle Lithium Loss in Silicon-Rich Anodes

Prelithiation introduces lithium into silicon anodes prior to cell formation to compensate for irreversible lithium loss during SEI formation and structural accommodation. In high-silicon anodes, significant first-cycle lithium consumption and large volume expansion reduce usable cathode capacity and limit achievable energy density. By supplying lithium in advance, prelithiation improves first-cycle efficiency, enables higher silicon utilization, and stabilizes early cycling behavior. Practical implementation can be achieved through chemical, electrochemical deposition, or lithium additive-based approaches; however, challenges remain related to process complexity, safety cost, and scalability.

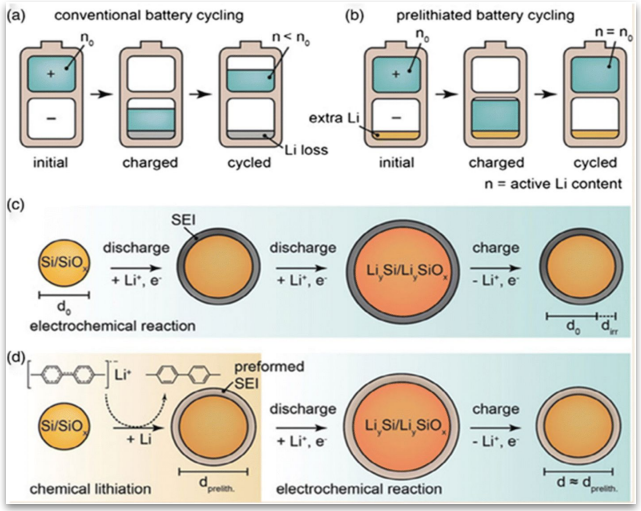
Benefits of Prelithiation:

- **Improves first-cycle efficiency:** Compensates for irreversible lithium loss associated with SEI formation on silicon.
- **Enables higher silicon utilization**: Preserves cathode lithium inventory, allowing increase silicon content in EV anodes.
- **Enhances early-cycle stability**: Reduces mechanical and interfacial stress during initial lithiation.
- **Supports** higher cell-level energy density: Improves active lithium balance in silicon-rich EV cells.

Challenges and Trade-Off:

- **Manufacturing complexity:** Additional processing steps increase cost and integration difficulty.
- **Safety considerations:** Handling lithium-containing materials require stringent process control.
- **Scalability and uniformity:** Achieving controllable, homogeneous prelithiation remains challenging at gigafactory scale.

EV Relevance: Prelithiation is primarily relevant for EV cells targeting higher silicon loadings, where first-cycle lithium loss becomes a limiting factor for energy density and cycle life.



Schematic comparison of conventional silicon anode cycling versus prelithiated silicon anodes, illustrating reduced initial lithium loss and improved lithium inventory retention.

Source: Prelithiation Effects, Prelithiation of Silicon Anodes, Prelithiation strategies Prelithiation Principle

Prelithiation of Silicon Anodes- Methods & Implementation Pathways for Introducing Lithium into Silicon-Rich Anodes

Chemical/ Direct Contact-Based Prelithiation

(lithium supplier via direct chemical contact)

Lithium metal or lithium-rich compounds are brought into direct contact with the silicon anode to introduce lithium prior to electrochemical cycling.

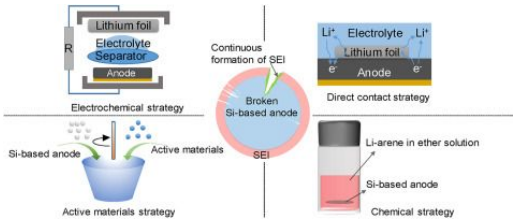
- **Advantages:** Conceptually simple; enables high lithium loading.
- **Limitations:** Challenging safety management, limited lithium dose control, and difficulties in achieving uniform prelithiation.

Electrochemical/In-situ Prelithiation

(lithium introduced during electrode or cell fabrication)

An ultra-thin lithium source (e.g., lithium foil or lithium-containing additives) is incorporated into the anode stack and activated during early cycling or formation.

- **Advantages:** Better integration with existing cell assembly process..
- **Limitations:** Restricted control over lithium delivery and potential variability across electrodes.



ELECTROCHEMICAL VS DIRECT CONTACT APPROACH

Physical Deposition and Manufacturing-Based Approach

(lithium applied via controlled deposition or transfer processes)

Vacuum-based lithium deposition:
Lithium metal is deposited onto electrodes using thermal evaporation or related vacuum techniques to achieve precise lithium dosing.

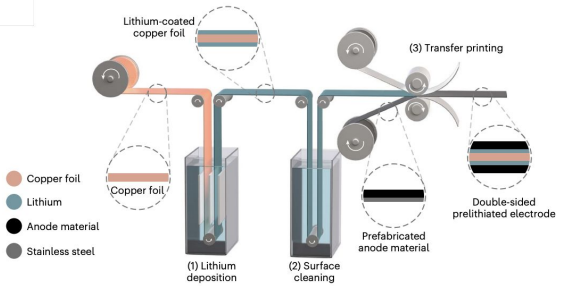
- **Advantages:** High control over lithium quantity and uniformity.
- **Limitations:** Capital-intensive equipment and scalability constraints.

Transfer Printing:
Lithium is first deposited on a carrier substrate and subsequently transferred to the electrode via a mechanical lamination or rolling process.

- **Advantages:** Enables patterned, scalable, and roll-to-roll-compatible prelithiation
- **Limitations:** Increased process complexity and sensitivity to handling and alignment.

Key Trade-offs:

- **Lithium dose control:** Highest for deposition- and transfer-based approaches.
- **Safety and Handling:** Most challenging for direct lithium contact methods.
- **Manufacturability and scalability:** Favor in-situ and transfer-printing strategies.
- **Process integration:** Varies significantly with existing electrode fabrication workflow.



TRANSFER PRINTING

Source: Prelithiation Effects, Prelithiation of Silicon Anodes, Prelithiation strategies

A New Material Player, Production Implementation, Demo Line, Development Grant, and Industrial Standard

Feb 2025

Elevated Materials, a US battery material company, with a manufacturing facility in Germany, is spun out of Applied Materials, manufacturing roll-to-roll lithium thin films for pre-lithiation and Li-metal anodes.

April 2025

CORNEX, a Chinese battery company, debuts a 472Ah BESS LFP cell with “cathode pre-lithium”, a proprietary formula not publicly disclosed. The cell’s energy density is claimed to be 195 Wh/kg.

Sept 2025

Nanoscale Components, a US battery equipment company, commissions its GWh-scale roll-to-roll electrochemical pre-lithiation line for trials of its process equipment.

Graphenix Development Inc., a US battery material company, with a manufacturing facility in the Netherlands, is awarded a $100k grant from the NSF to integrate lithium iron oxide (LFO) into high-Ni cathode material to pre-lithiate its 100% silicon anodes.

CATL and others

The world's first national standard for a lithium supplementation technology was implemented in China, for lithium-rich lithium ferrite (LFO). It was jointly developed by CATL, Gotion, and a host of Chinese lithium and cathode material producers.

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- **Stationary Energy Storage**
- **Data Centers**
- **Aviation, Drones, Space**
- **Robotics**
- **Other**

Safety

Cell Design and Materials
- **Li-Ion**
  - Li-Cathode
  - Separator
  - Li-Anode
  - **Anode**
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Lithium Metal History - The Progenitor of Lithium-Ion

Lithium metal anodes have a long history as **one of the first materials used** in rechargeable batteries, offering a **high theoretical capacity** (3,862 mAh/g) and low electrochemical potential, making them attractive **for high-energy applications**.

Foundational lithium-metal research began in the early 1970s at Exxon, where M. Stanley Whittingham demonstrated the **first rechargeable lithium-metal/titanium disulfide (TiS_2) cell**[2], ushering in the modern era of high-energy battery chemistries. Lithium metal's promise was clear: far higher energy density and dramatically longer shelf life than nickel-cadmium cells, which typically lasted only months. However, by the 1980s it became evident that lithium-metal anodes suffered from **dendritic growth during cycling**[1].

These dendrites could penetrate separators and cause internal short circuits, posing significant risks and making the chemistry difficult to commercialize. In 1977, Canadian company Moli Energy became the first company to bring rechargeable lithium-metal batteries to market, but high-profile safety failures in 1989, resulting in recalls, highlighted the unresolved dendrite problem and ended large-scale commercial efforts for decades to come.[1] As a result, the development of lithium-ion batteries, which use graphite anodes, gained momentum in the 1990s. While graphite offers lower energy density (372 mAh/g), its stability, safety, and longevity made it the standard for commercial applications, enabling the widespread adoption of portable electronics and electric vehicles (EVs).

In recent years, **interest in lithium metal anodes has resurged** due to the growing demand for batteries with higher energy density **for eVTOLs, drones, and aerospace applications**. Research continues to examine ways to address existing challenges associated with lithium-metal, including dendrite formation, interface instability, and limited cycle life. Approaches under study include solid-state and hybrid electrolytes, protective interfacial layers, electrolyte additives, and engineered separators, all aimed at improving plating uniformity and enhancing stability during cycling. While lithium-metal remains a promising candidate for next-generation systems, including solid-state and lithium-sulfur batteries, its practical adoption depends on resolving these technical issues and demonstrating reliable performance under application-relevant conditions.

Source: [1] Moli Energy, [2] Research at Exxon, [3] Lithium Metal Anodes in Solid-State Batteries, [4] Battery Report 2023 and 2024

Lithium Metal Anode Basic Technology and Information

LI METAL - SWOT ANALYSIS

S Strengths	W Weaknesses	O Opportunities	T Threats
High energy density	Limited cycle life	Demand for high energy density batteries	Competition from other technologies (NMC/silicon batteries) and next gen chemistries such as metal-air or lithium sulfur
Lightweight	Low Coulombic efficiency	Aerospace	Safety regulations
Enables other advanced battery chemistries, such as solid-state and lithium-sulfur	Difficulty fast-charging	High-end automotive	Increasing lithium costs and supply chain concerns
	Large volume changes	Defense-related applications (drones)	
	Manufacturability of lithium metal	Advancements in solid-state technology	
	Safety (dendrite formation and high reactivity)		

Lithium metal anodes offer extremely high energy density due to lithium's low weight and high theoretical capacity. However lithium metal technology faces major challenges, primarily related to safety, cycle life, and manufacturability. Lithium metal anodes are prone to dendrite formation during charging, which can cause short circuits, thermal runaway, and fires. Additionally, lithium's high reactivity with electrolytes can reduce cycle life and efficiency.

Compared to traditional graphite anodes, lithium metal anodes can theoretically delivery much higher capacity but are significantly less stable and more challenging to commercialize. Compared to silicon anodes, lithium metal offers higher capacity but lags in safety and durability. In contrast to lithium-sulfur batteries, which may use lithium metal anodes, lithium metal batteries share similar safety concerns but can provide lower production costs and weight advantages.

Many companies are working to mitigate the safety challenges inherent to lithium metal anodes, using techniques such as solid state electrolytes, high-concentration liquid electrolytes, protective coatings, and separator designs that suppress dendrites.

Source: L. Yang et al., J Electrochem Soc, 2024., K. Hatzell et al., Joule, 2024.

Manufacturers Who Have Announced or Plan to Work with Lithium Metal

Lithium Metal Producers



Battery Manufacturers



Automotive Manufacturers Interested



Notable Events: Lithium Metal

January

SES AI signed two new jdcs in early 2025 (up to $10 m total) with unnamed automakers to apply its ai-designed electrolytes in li-metal ev cells

February

Mercedes-Benz began road testing an EQS development car powered by a lithium-metal solid-state pack (with Factorial), moving Li-metal from lab to public roads.

March

Sion Power commissioned a 75 mwh/yr pilot line in arizona for licerion li-metal cells; fully automated 56 ah large-format cells; vacuum thermal evaporation of 2–5 µm li on cu (vs. 30–50 µm foils)

April

Stellantis and factorial reported 77 ah solid-state cells at ~375 wh/kg and 600+ cycles; Stellantis targets a 2026 demonstration fleet using Factorial's fest li-metal batteries.

May

Solid power supplied large-format sulfide solid-state cells enabling a bmw i7 prototype - the first BMW test car running a pure lithium-metal pack.

June

QuantumScape said its "Cobra" ceramic-separator process entered baseline cell production which is a manufacturability step toward Li-metal SSB commercialization.

July

Lyten acquired Northvolt's Gdańsk "Dwa ESS" BESS plant (25,000 m²; Europe's largest), plans immediate restart and to add Li-S–powered BESS; site is equipped to ramp to 6 GWh with footprint for 10 GWh+.

July

Prologium's first gwh-level lithium ceramic gigafactory (taoyuan) began production in 2024; shipments surpassed 2.4 million units by mid-2025, supplying multiple markets

September

Quantumscape + Volkswagen Powerco rode a ducati e-motorcycle with anode-free solid-state cells onto the iaa stage.

October

Pure lithium opened a chicago pilot site to advance li-metal anode manufacturing; alpha-en progressed domestic li-metal methods.

November

Gelion raised £10.5 m to scale lithium–sulfur pouch-cell development (incl. pre-lithiated sulfur) and expand U.S. efforts.

December

QuantumScape Completed installation of key equipment for its Eagle automated pilot line to enable higher-volume solid-state lithium-metal cells, a scale-up milestone toward future GWh production.

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- **Lithium Sulfur**
- Solid-state
- Sodium-ion
- Alternative Chemistries

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- Upstream and Midstream
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Software / AI

Lithium-Sulfur Technology and Information

LI SULFUR- SWOT ANALYSIS

S Strengths	W Weaknesses	O Opportunities	T Threats
Low potential cost (sulfur is abundant; no Co/Ni)	Cycle life still limited (polysulfide shuttle, Li-metal issues)	UAVs, HAPS, small satellites, soldier power	Rapid Li-ion progress (LFP/NMC) and scaling economics
High specific energy potential (gravimetric)	Low volumetric energy at pack level	Long-range e-mobility niches (where weight trump's life)	Na-ion taking low-cost segments
Light weight for flight-critical loads	Low cathode conductivity → heavy carbon/binder loadings	Cost sensitive markets if lean electrolyte designs mature	Regulatory/safety scrutiny of Li-metal
Safer chemistries possible with solid/gel electrolytes	High electrolyte to-sulfur ratios in many designs	Solid/gel electrolytes to suppress shuttle and improve safety	Manufacturing immaturity and capex risk
Strong interest for defense/space/drone use cases	State-of-charge/health estimation is harder than Li-ion	Supply chain diversification away from Co/Ni	Raw material /wet chem processing constraints if not “lean”
			Energy advantage erosion from other advanced chemistries

In 2025, Li-S remains a promising high specific energy chemistry, with visible traction in defense, drones, and space pilots. the core technical push centers on polysulfide-shuttle suppression, lean electrolyte cathodes, protected lithium metal anodes, and polymer/solid electrolytes.

Cycle life and volumetric energy gaps versus best in class li-ion persist, and manufacturing/tooling is still early, but targeted niches (where mass is priced highly) continue to move toward limited deployments.

Source: Argonne, Battery Report 2024 (pg 270), CellVision 2.3

Lithium-Sulfur: Notable Events

Americas

LYTEN, Zeta Energy, conamix, NexTech Batteries

Europe

theion

Asia - Pacific

Li-S Energy, gelion, Gotion, OXLiD, GS YUASA, LG

February

theion

Theion closed a €15 million Series A to scale its crystal-sulfur battery program

March

gelion

Gelion × Max Planck Institute (MPI) announced a strategic partnership to co-develop sulfur cathode active material (CAM) for Li-S (and Na-S), with tech transfer into Gelion's development/ production flow.

May

LYTEN

Lyten announced a US-made drone battery and demoed a >3-hour flight on a 3D-printed UAV; targeting NDAA-compliant DoD supply from its California line.

July

LYTEN

Lyten secured >$200 million additional equity (primarily existing investors), bringing total raised to >$625 million; company says proceeds support acquisitions/expansion for its Li-S business.

October

gelion

Gelion × Tier-one battery maker: April 2025 materials-testing agreement upgraded to a multi-year collaboration to advance Gelion's sulfur CAM toward commercial readiness.

November

Fraunhofer IWS

Fraunhofer IWS (AnSiLiS) announced lithium–sulfur solid-state cell concepts with reduced electrolyte content and a scalable design, reporting early lab validation for lighter, higher-energy, safer batteries.

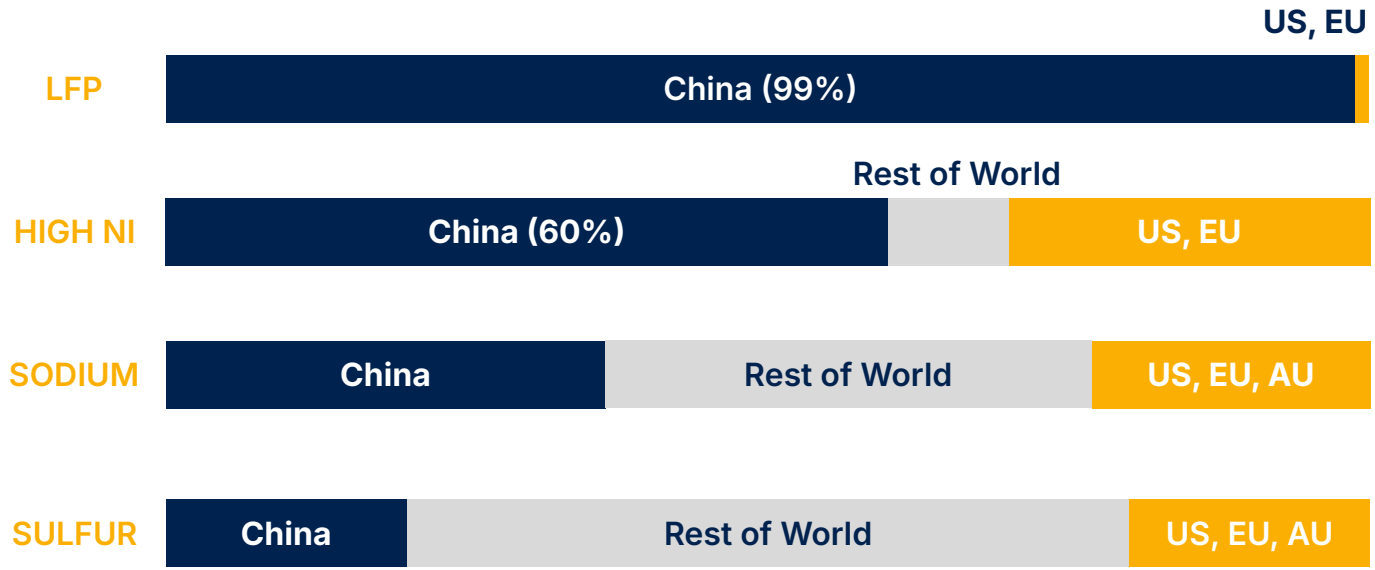
Lithium-Sulfur Battery Bill of Materials

Active	Material Properties	Capacity (mAh/g)	Voltage Range (V)	Tap Density (g/cm^3)	Cycle Life	Prospects & Challenges
Cathodes	Sulfur Carbon	1100 - 1674	1.5-3.0	0.3 - 0.7	50-300	• Safety is better relative to conventional Li-ion • Voltage window prohibitive to pack design • Poor volumetric energy density due to tap density
	SPAN/Inverse Vulcanization	300 - 600	1-2.5	0.4 - 0.6	100-600	• Poor volumetric and gravimetric energy • Limited power density due to nominal voltage
	Lithium Sulfide	1000 - 1166	1.5-3.0	0.3 - 0.7	50-300	• High moisture sensitivity leads to higher costs • Poor volumetric energy due to tap density
Anodes	Silicon	3000 - 4200	0.1-1	0.8-1.0	100-1000	• Poor volumetric energy due to tap density • Feedstock limits costs & quality
	Lithium/ Lithium Alloy	3200 - 3800	0-0.2	0.5-0.7	50-600	• Need to manage high volume change • Limited cycle life reported

Inactive	Material Properties	Description	Prospects & Challenges
Electrolyte	Ether based	LiTFSI salt in ethers / fluoro ethers	• Ethers solubility allows for a broad use of additives and salts for anode stability • Ethers dissolve active CAM material within the cell
	Carbonate based	$LiPF_6$ salt in Cyclic/Linear carbonate mixtures	• Good oxidative stability, but need to manage gas generation/accumulation
Current Collector	Aluminum Foil	Used at Cathode	• At < 1 V aluminum will react with Lithium • Weight of Al significant vs cathode loading
	Copper Foil	Used at Anode	• Copper weight is a significant impact on overall cell weight • Due to chemistry window - Copper should be ok at 0V

Source: 1. Yao, A. Benson, S.M., Chueh, W.C. How quickly can sodium-ion learn? Assessing scenarios for techno-economic competitiveness against lithium-ion batteries. arXiv::2403.13759v3 (2024) ; 2. Shanghai Metals Market (SMM). Metals.com. ; 3. Omenya, A. Sodium-Ion Battery Development. DOE-OE Peer Review (2024). ; 4. Lee, J. Low Cost Sodium-Ion Battery to Enable Grid Scale Energy Storage: Prussian Blue-Derived Cathode and Complete Battery Integration; 2013.

Lithium-Sulfur - A Geographically Agnostic Battery Chemistry

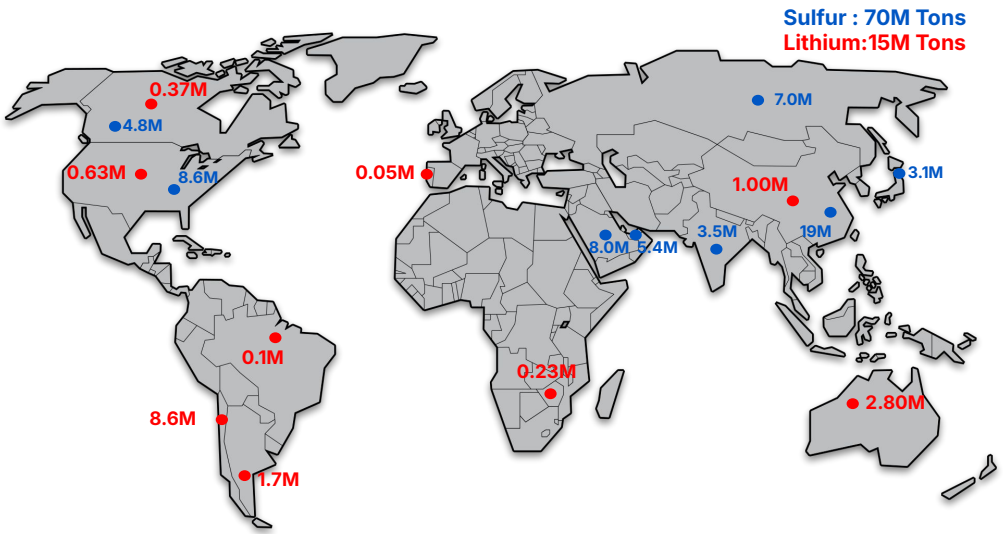


*** Sodium Ion is highly dependent on which cathode/anode pairing.
*** Certain cathode/anode pairings supply chain is heavily leaned towards china

Source: Reuters, Argonne, UFine ,Battery Official,Battery Report 2023-2024

Vast Abundance of Sulfur Is Key to Addressing Long Term Battery Supply Chain Challenges

SOURCES OF ECONOMICALLY RECOVERABLE SULFUR / LITHIUM. [1]



- Sulfur & Lithium are decentralized by region. It is globally available in each country at varying quantities
- Sulfur naturally exists in abundant forms, such as elemental sulfur and sulfide minerals, and is often obtained as a byproduct of fossil fuel refining and natural gas processing. Its established role as a raw material commodity reduces processing requirements, making it an efficient and cost-effective resource for industrial applications like sulfuric acid production and fertilizer manufacturing.
- Lithium-Sulfur batteries adopt manufacturing methods identical to lithium ion, allowing immediate scalability compared to other emerging next generation technologies. Although lithium handling removes mixing, coating, calendering process for anode
- Common advantages: Low temperature operation, 0% or 100% SOC, storage/transport, High Energy, Low Cost, Material Availability
- Common disadvantages: Lower power density vs lithium ion, higher near-term costs, lower nominal voltage, uncertainty around safety and manufacturing claims.

Source: Reuters, ,Argonne, UFine ,Battery Official,Battery Report 2023-*2024*

LYTEN

Powering the Next Industrial Revolution

Strategically leveraging innovative Lithium-Sulfur and proven Li-ion battery technologies.

lyten.com

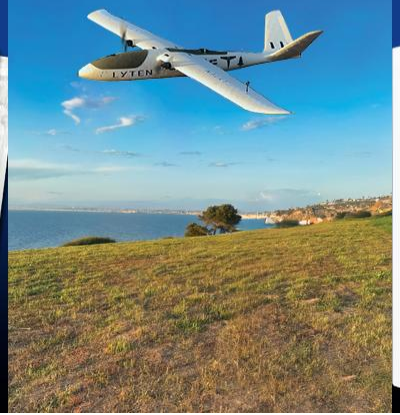
Lithium-Sulfur. Ultra-Lightweight. Locally Sourced.

A high energy density battery that requires to NMC or graphite. Made from abundantly available industrial by-products using a domestically sourced and tariff-proof supply chain.



Autonomous Systems. When Weight and Supply Chain Matter.

Ultra-Lightweight Li-S batteries for UAVs, mobility, and robotics deliver extended range, flight time, and higher payload capacity. Fully NDAA compliant.



Li-Ion NMC. Designed for EVs. Built by Northvolt.

NMC prismatic cells built for automotive. Manufactured in Sweden with 100% clean energy.



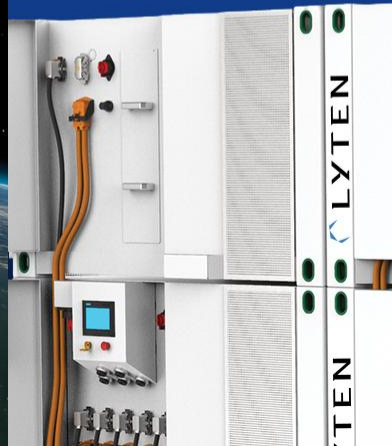
Space. Meet Your Power Source.

Lithium-Sulfur ready to power space infrastructure with a lightweight battery. Launch onto the International Space Station scheduled for January 2026.



BESS. Powering Commercial, Industrial, and Data Centers.

3rd Generation, modular BESS product for microgrids, backup, grid resiliency, peak shaving, and more. Built in Poland.



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Why Solid-state Battery Technology

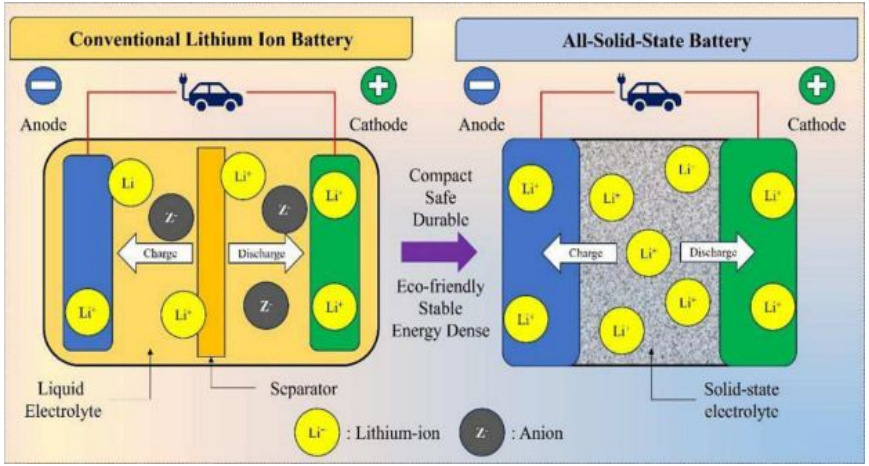
Solid-State Battery:
Represent a high-impact but high-complexity transition requiring coordinated advances in materials, interfaces, and manufacturing.

Demand Drivers:

- **Applications:** Growing demand for compact, safe, high-energy batteries across EVs, consumer electronics, etc
- **Safety:** Reduced flammability risk relative to liquid electrolytes; improved mechanical robustness
- **Energy Density:** Theoretical potential for >400 Wh/kg enabled by lithium-metal anodes (architecture-dependent)

Key Challenges:

- **Interface stability:** Chemical reactions, void formation, and impedance growth at solid–solid interfaces
- **Manufacturability:** Scaling defect-free thin films and multilayer stacks with dry processing and lamination
- **Cost:** High purity precursor requirements and complex processing remain cost barriers



Source: Liu, Y., Huang, Y., Li, H., Peng, Z., & Zhang, H. *Journal of Power Sources*, 2025

Key Trends and Notable Events

The solid-state battery sector is transitioning from breakthrough validation to industrial execution, with commercialization increasingly gated by manufacturability, supply chains, and repeatable scale.

Race to Commercialization

Metric Shift: Focus shifting from cell-level metrics to pack-level safety, integration, and demo deployments

OEM Signals: Major OEMs (e.g., Toyota, VW, BMW) and global SSB developers announcing joint ventures and pilot-line progress toward integration before 2030

China Acceleration: Chinese cell makers accelerating timelines, with rapid pilot announcements and in-vehicle demos (e.g., Dongfeng, BYD)

From Breakthrough to Build-Through

Manufacturing Focus: Shift from lab performance to manufacturability, yield, and high-volume repeatability over one-off hero cells

Process Differentiation: Automation pathways becoming key differentiators (lamination, multi-layer stacking, ceramic processing)

Scale Signals: Companies such as QS, ProLogium, and Solid Power advancing 20–100 Ah demo cells and pilot lines

Supply Chain & Industrial Readiness

Materials Scaling: Scaling solid electrolytes into true commodity materials is now the key gating factor for commercialization

Investor Focus: Investors prioritizing credible scale-up roadmaps over raw energy-density claims

Cost Drivers: GWh-scale economics increasingly determined by SSB-specific tooling, process control, and yield

Source: Summarised from industrial public materials (press releases, official website informations, etc.)

Semi-Solid-State vs All-Solid-State Batteries: Technology Tradeoffs

Semi-solid systems enable faster market entry using existing manufacturing pathways, while all-solid-state architectures offer higher long-term performance at the cost of greater technical and industrial complexity.

Semi-Solid-State

A battery that contains both solid and liquid electrolytes, with solid components making up the majority (over 90%) of the mix.

Commonly consists of liquid solvent + polymeric plasticiser + inorganic compound matrix

ADVANTAGES

- Strong interfacial contact
- Manufacturing compatibility with Li-ion processes
- Near-term deployability

DISADVANTAGES

- Lower volumetric energy density
- Reduced intrinsic safety vs all-solid systems
- Incremental improvement over Li-ion architectures

All-Solid-State

A battery that contains only solid-state phase in electrolytes, can be polymeric/hybrid with inorganic compounds**)

Commonly consists of single layer polymer or composites with fixed & controllable thickness

ADVANTAGES

- Higher intrinsic safety
- Higher potential volumetric energy density

DISADVANTAGES

- Greater R&D maturity required
- Production complexity (new tooling, pressure-managed stacking)
- Stack pressure requirements

Source: About Solid-Liquid terminology *)Yicai | **)*Discov. Electrochem.* 2, 26 (2025) | Also summarised from other previous scientific research outputs

Different Solid-state Battery Philosophies: Tradeoffs and Implications

Solid-state electrolyte philosophies reflect different optimization strategies, balancing performance, manufacturability, and scalability rather than converging on a single universal solution.

Electrolyte Type	Ionic Conductivity	Safety Profile	Manufacturability	Scalability Potential	Primary Challenges
Ceramic-based (Oxides, Garnets)	High (room temperature, materials-level)	High (non-flammable, thermally stable)	Complex (brittleness, high-temperature processing, interface control)	Moderate (process- and yield-limited)	Interfacial resistance, dendrite penetration, mechanical fracture
Polymer-based	Lower (vs ceramics and sulfides; temperature-dependent)	Moderate (improved vs liquid electrolytes, polymer-dependent)	Relatively easy (flexible, roll-to-roll compatible)	High (leverages existing Li-ion manufacturing)	Limited room-temperature conductivity, mechanical stability
Sulfide-based	High (comparable to liquid electrolytes)	Moderate (non-flammable but moisture-sensitive)	Challenging (air/moisture sensitivity, handling requirements)	Moderate (requires controlled environments)	Moisture sensitivity, interfacial stability, processing complexity
Hybrid / Composite	Balanced (engineered tradeoff)	Balanced (composition-dependent)	Moderate (integration of multiple phases)	Moderate (architecture-dependent)	Material integration, interface control, process complexity

Recent Research highlights:

1. Oxford's multi-layer sulfide electrolytes suppress dendrites
2. Harvard's silicon composite anodes improve plating uniformity
3. Korean institute propose universal design standard for SSBs

Source: MD Marine Electric, 2025, Nature Materials, 2025, Tech insights 2024

SSB Hype vs Reality: Common Misconceptions Clarified

Many expectations around solid-state batteries stem from simplified assumptions; real-world performance depends on system-level design tradeoffs rather than electrolyte choice alone.

Common Misconception	What the Evidence Shows
"Solid-state" means all battery components are solid.	Many batteries labeled "solid-state" retain some liquid or gel components*. These are more accurately described as **semi-solid** or **quasi-solid** systems. Fully all-solid-state batteries remain less common and are still under development.
All solid-state batteries require lithium-metal anodes.	Solid-state electrolytes can be paired with **graphite, silicon, or lithium-metal anodes**. Lithium metal offers higher energy density but introduces additional interfacial and stability challenges.
Solid-state batteries inherently deliver the highest energy density.	Higher energy density is **possible**, particularly with lithium metal, but is not guaranteed. Some advanced liquid-electrolyte systems achieve comparable energy density today.
High ionic conductivity alone enables successful solid-state batteries.	While important, ionic conductivity is **only one factor**. Interfacial resistance, mechanical contact, and dendrite suppression are often the dominant challenges.
Solid-state batteries enable faster charging and higher power by default.	Many solid electrolytes exhibit **lower rate capability** than liquids due to interface limitations and transport constraints, particularly at room temperature.

* There is not an industry standard for ther term "solid'state", although there is a new effort in China to create one.

SSB Hype vs Reality: Common Misconceptions Clarified

Solid-state batteries offer meaningful long-term potential, but near-term performance, safety, cost, and timelines are governed by system-level engineering and manufacturing realities rather than electrolyte chemistry alone.

Common Misconception	What the Evidence Shows
Solid-state batteries will double EV driving range.	Vehicle range depends on the total system mass and efficiency, not battery energy density alone. Even substantial improvements in cell-level energy density translate to **incremental, not doubling**, gains at the vehicle level once the weight of the full vehicle is considered.
Solid-state batteries will not catch fire.	Most solid electrolytes are inorganic and non-flammable, reducing certain fire risks. However, **electrical shorts, lithium-metal reactivity, or mechanical failure** can still lead to thermal events under extreme conditions.
Solid-state batteries do not generate gas and therefore avoid toxicity risks.	Trace moisture during manufacturing or operation can lead to gas formation in some systems. For example, **sulfide-based electrolytes may release hydrogen sulfide (H_2S)** under certain conditions, which requires careful materials handling and controls.
Solid-state batteries are a new technology nearing market entry.	Solid-state batteries have existed for decades. Thin-film systems such as **LiPON** are widely used in niche applications (e.g., medical implants, sensors), but **scaling to large-format consumer, EV, or grid applications remains challenging** due to cost and manufacturability.
Cost parity with lithium-ion batteries is imminent.	Achieving cost parity requires **high-volume manufacturing with high yield and stable supply chains**. While progress is ongoing, these conditions have **not yet been demonstrated**.

Manufacturing: Process R&D Innovations

Manufacturing pathways for solid-state batteries diverge sharply between near-term semi-solid approaches that leverage Li-ion infrastructure and longer-term all-solid-state architectures requiring fundamentally new processes and tooling.

Anode Processing

Lithium Anode:
- Li-Cu rolling process
- Physical Vapor Deposition & Thermal evaporation
- Other advanced methods
- In situ Li formation (anode-less variants)

Alternative Anodes:
- Conventional slurry coating
- Dry/solvent-free coating processes

Electrolyte Integration

Semi solid-state
- Electrolyte filling/*in-situ* polymerisation
- Separator impregnation techniques

All Solid state:
- Direct electrolyte coating onto electrodes
- Separate electrolyte layer fabrication with pick-and-place stacking

Cathodes

- Conventional slurry -based coating
- Dry/solvent-free cathode processing

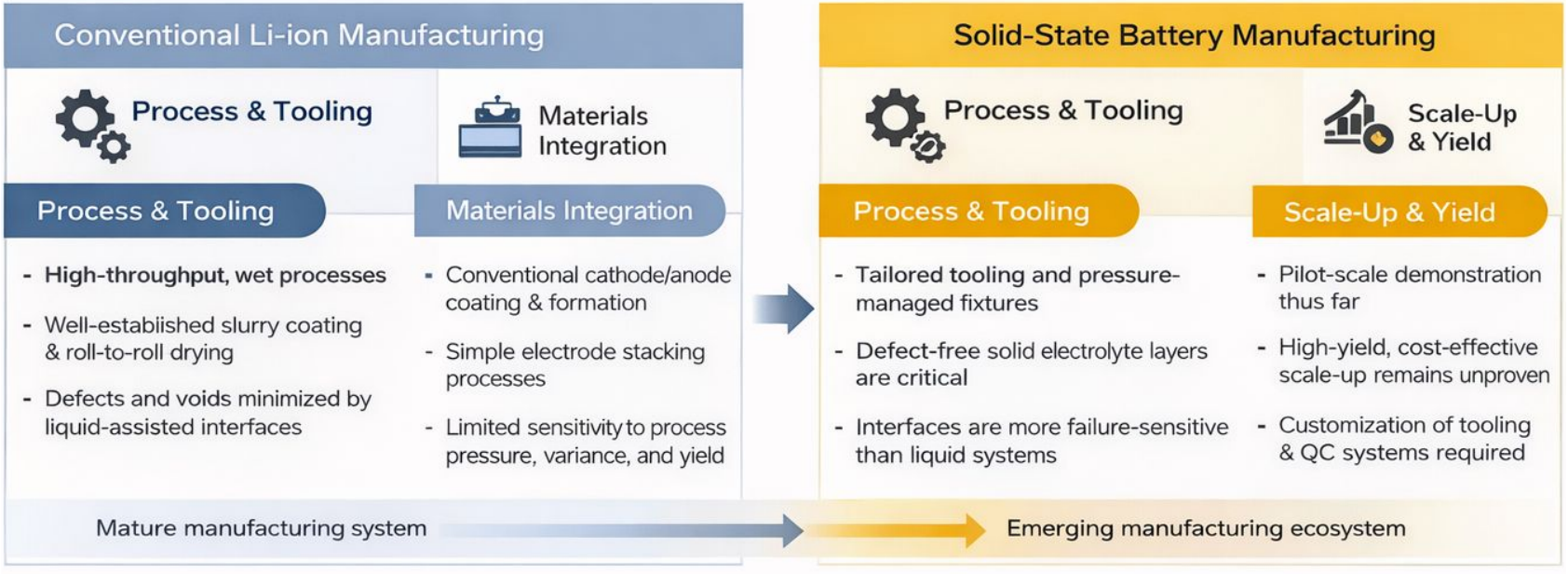
Battery Assembly Process & Misc.

- Adaptation of conventional Li-ion assembly for semi-SSB platforms to enable modular pilot lines
- Purpose-built stacking and pick-and-place architectures for all-solid-state cells
- Automated in-line inspection and AI-driven quality control for real-time process monitoring and yield optimization

Source: Summarised from previous scientific research outputs and industrial public materials (press releases, official website informations, etc.)

Manufacturing Differences Between Solid-State Batteries and Conventional Li-ion

Solid-state batteries introduce fundamentally different manufacturing constraints, where scalable production, yield control, and tooling maturity are as critical as materials performance.



Source: MarketReportAnalytics, EV SSB market

Timeline and Other Announcements of Major Industry Players

January

ProLogium's Dunkirk gigafactory will be built in three stages: construction starting in 2025

February

Mercedes-Benz engineers from the road and racetrack and Factorial cell engineers have worked together on delivering an all-new solid-state battery test program.

April

CATL expects to produce its own solid-state batteries in small series by 2027

May

BMW Group and Solid Power are testing all-solid-state battery cells in a BMW i7

July

QuantumScape and PowerCo expand collaboration to accelerate solid-state battery technology

The solid-state battery cells in the BMW i7 trials featured Umicore's proprietary cathode active materials developed under a JDA with Solid Power

August

BASF delivers first cathode active materials for semi-solid-state batteries to WELION New Energy

September

ProLogium showcases next-gen solid-state battery breakthrough at IAA Mobility 2025, unveils European mass production plan and global collaboration roadmap

October

BMW, Samsung SDI, and Solid Power join forces in the race for all-solid-state EV batteries

CATL denies rumours of 2,000 km SSB mass production in 2027

Sumitomo Metal Mining and Toyota collaborate on mass production of cathode materials for ASSBs

November

NIO drops 150 kWh battery with semi-solid electrolyte production

December

POSCO Future M signs MOU with U.S.-based factorial for all-solid-state battery technology development

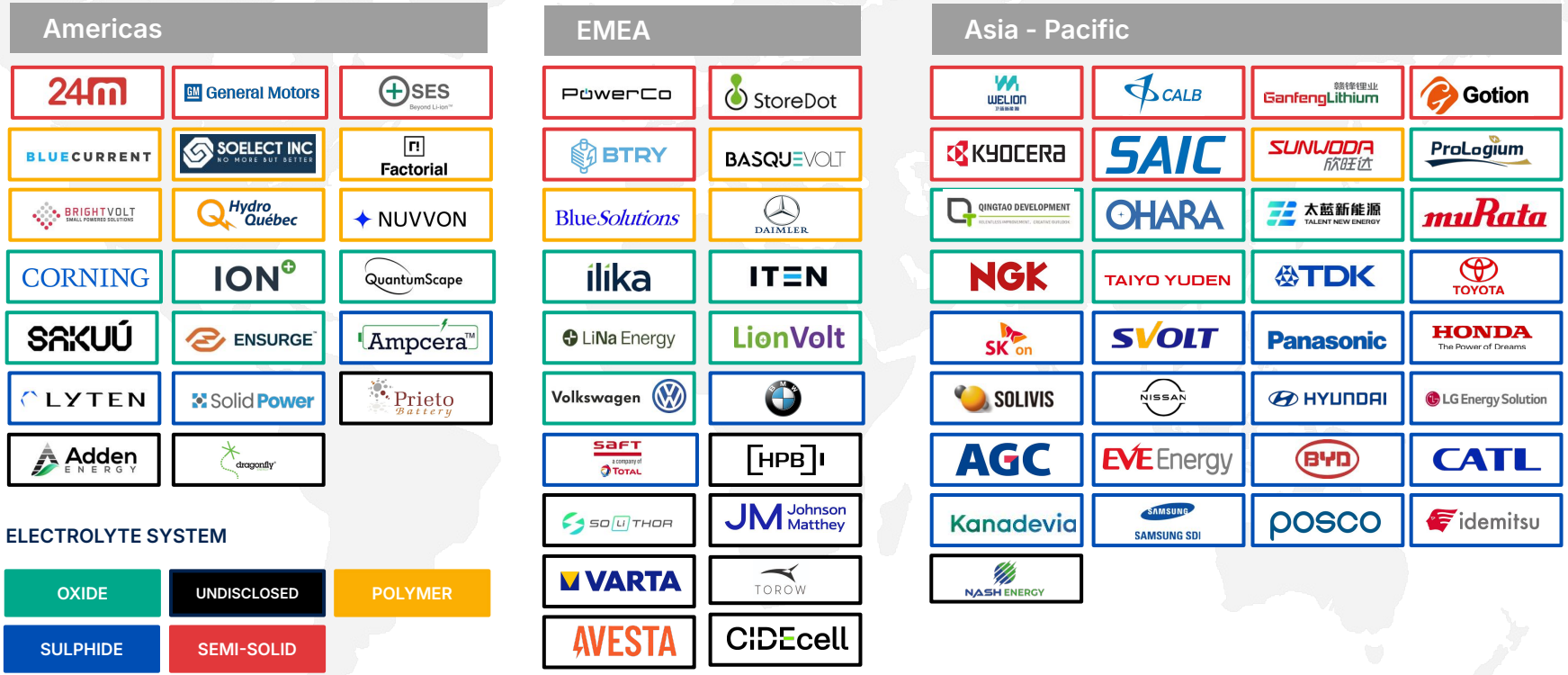
Source: Summarised from industrial public materials and news

Timeline and Other Announcements of Major Industry Players

Region/Country	Company	Target for further development / mass production
Asia - China	WeLion NIO Ganfeng Lithium CATL Gotion Hi-Tech EVE BYD SVOLT Guangzhou's GAC Group ProLogium Taoyuan, Taiwan	2024-2025 (semi-solid-state) 2024-2025 (semi-solid-state) 2025 2027-2028 2027-2030 2026-2028 2027-2033 2028 (start for 2026 for semi-solid-state) 2027-2030 2024-2025
Asia - Japan	Panasonic Toyota (collaboration with Panasonic) Nissan Honda (collaboration with GM & Sony)	2026-2027 2027-2030 2028-2030 2030
Asia - South Korea	Samsung SDI SK On LG Energy Solution	2026-2027 2029 2030
Asia - India	NASH Energy	2026-2027
Americas	Factorial QuantumScape Solid Power	2026 2026-2027 2030
Europe	Blue Solutions (Gen4 technology) Basquevolt ProLogium Dunkirk, France AVESTA Holding PowerCo (collaboration with QuantumScape)	2030-2032 (Previous technologies have been marketed since 2011) 2027 2028 2028-2030 2030

Source: Discov. Electrochem. 2, 26 (2025) | also summarised from industrial public materials (press releases, official website informations, etc.)

Industry Players All Around the Globe



Source: Summarised from industrial public materials (press releases, official website informations, etc.) and websites such as pitchbook, crunchbase, bloomberg, etc.

Main American Solid State Pure Players

The solid-state battery industry has seen significant investment and growth, with diverse electrolyte technologies and notable funding milestones achieved by both established players and emerging startups. We include here only companies mainly focused on solid state batteries.

Company	Electrolyte Technology	Launch Date	Funding, Stage	Notable OEM Partners / Investors	No. Of Patent Families On Solid-state batteries (Up To 2025-12)
24M Technology	Semi-solid	2010	~ 250 M$, Series H	Volkswagen	5
Adden Energy	Undisclosed	2021	≥ 20 M$, Series A	-	2
Ampcera	Sulfide	2017	≥ 10 M$, Seed/Serie A	Ford, NIO	16
Blue Current	Polymer (composite)	2014	~ 130 M$, Series B/C	Umicore	18
Brightvolt	Polymer	2008	~ 42,5 M$, Series B	-	3
DragonFly Energy	Undisclosed	2016	≥ 145 M$, NADASQ Stock	-	4
Ensurge	Oxide/Polymer	2005	~ 75 M€, Oslo stock	Mercedes-Benz	11
Factorial Energy	Polymer/Ceramic	2013	~ 250 M$, Series D	Hyundai/Kia, Mercedes, Stellantis	20
Ion Storage System	Oxide	2019	~ 85 M$, Series A	Toyota	7
Nuvvon	Polymer	2022	~ 5,3 M$, Series A	-	3
Prieto Battery	Undisclosed	2008	~ 32,35 M$, Series E	Hercules Electric Vehicles, Stanley B&D	3
QuantumScape	Oxide	2010	>$1 B$, NYSE Stock	Volkswagen, PowerCo, BMW	55
Sakuu	Oxide	2016	~ 84,3 M$, Series C	NGK, SK, Musashi Seimitsu Industry	4
SoElect	Polymer	2018	~ 14,3 M$, Series A	GM, Lotte Chemical	5
Solid Energy Systems	Semi-solid	2012	~ 600 M$, NYSE Stock	Hyundai, Kia, Honda, GM, LG, SK, Geely, SAIC	3
Solid Power	Sulphide	2011	~ 437 M$, NADASQ Stock	BMW, Ford, Solvay, Samsung, SK	53

*Those highlighted in dark blue are referred to semi-solid state companies

Source: Summarised from industrial public materials (press releases, official website informations, etc.) and websites such as pitchbook, crunchbase, bloomberg, CBInsights, etc.
Patent search performed by Knowmade (Solid-state batteries, reports and monitor).

Main Solid State Pure Players from Other Countries

Company	Electrolyte Technology	Headquarters Country	Launch Date	Fund, Stage	Notable OEM Partners / Investors	No. Of Patent Families On Solid-state batteries(Up To 2025-12)
AVESTA Holding	Hybrid (polymer-inorganic)	Belgium	2023	Undisclosed	-	0
Basquevolt	Polymer composite	Spain	2022	~ 69 M€, Series A + subventions	Iberdrola (utility), CIE Automotive, Enagás (gas utility), CIC Energigune	2
Blue Solutions	Polymer	France	1998	~ 69 B€, Subsidiary of Bolloré	Daimler/Mercedes-Benz, RATP, CEA and Hydro-Québec	54
BTRY	Semi-solid	Switzerland	2023	~ 5,7 M$, Seed	-	0
CIDEcell	Undisclosed	Spain	2025	Undisclosed	-	0
HPB	Undisclosed	Germany/Switzerland	2018	Licensing	-	1
Ilika	Oxide	Great-Britain	2004	> 51 M£, AIM Stock	Advanced Propulsion Centre UK, Nomura International, Artemis	7
ITEN	Oxide	France	2011	~ 140 M€, Equity + loans	SEB, Habert-Dassault	14
LiNa Energy	Oxide	Great-Britain	2017	~ 11,9 M$, Series A	-	11
LionVolt	Oxide	Netherlands	2020	~ 20 M$, Series A	-	7
NASH Energy	Semi-solid	India	2023	Undisclosed	-	0
PowerCo	Semi-solid	Germany	2022	Volkwagen subsidiary	Volkswagen	37
Solithor	Other solid electrolyte	Belgium	2021	~ 10 M€, Seed	-	4
StoreDot	Semi-solid	Israel	2012	~ 226 M$, late-stage VC / pre-IPO	Mercedes-benz, Samsung, Vinfast, Xpeng, Volvo, Ola	4
Torow	Undisclosed	France	2021	Undisclosed	-	1
Tailan New Energy	Oxide (composite)	China	2018	~ 55 M$, Series B	Changan	79
Prologium	Oxide	Taiwan	2006	~ 576 M$, late-stage	Mercedes-Benz, Vinfast, NIO, FAW	27
QingTao Energy Dev.	Oxide	China	2014	> 140 M$	Changan Automobile, BAIC, SAIC	265
Solivis	Sulphide	Asia	2020	~ 19 M$, Series B	-	13
SVOLT	Sulphide	China	2016	> 2,9 Md$, spin-off Great Wall	Xiaomi	241
WeLion	Semi-solid with oxide	China	2016	> 300 M€, Series D	Xiaomi, Huawei, NIO	159

*Those highlighted in dark blue are referred to semi-solid state companies

Source: Summarised from industrial public materials (press releases, official website informations, etc.) and websites such as pitchbook, crunchbase, bloomberg, etc.
Patent search performed by Knowmade (Solid-state batteries, reports and monitor).

Semi-Solid State SWOT Analysis

S
Strengths

Higher technology readiness by leveraging existing Li-ion manufacturing infrastructure

Improved safety relative to conventional liquid-electrolyte systems

Incremental gains in energy density compared to liquid-state Li-ion batteries

W
Weaknesses

Elevated interfacial resistance compared to liquid-electrolyte systems

Continued reliance on liquid components limits long-term differentiation

Unable to fully realize the theoretical energy density potential of all-solid-state systems

Durability and performance sensitivity under extreme operating conditions

O
Opportunities

Long-term platform for next-gen EVs and energy storage

Potential to **reset cost, safety, and performance** benchmarks at scale

Strong **pull from OEMs** and governments seeking step-change innovation

T
Threats

Long development timelines and execution risk

Uncertain **scalability** and cost parity with Li-ion systems

Risk of **over-promising relative** to near-term manufacturability

Source: Summarised from industrial public materials (press releases, official website informations, etc.)

All Solid-state SWOT Analysis

S
Strengths

Highest **potential for intrinsic safety** (non-flammable electrolytes)

Enables lithium-metal anodes and step-change energy density potential

Strong **long-term differentiation** for EVs, aerospace, and high-performance applications

W
Weaknesses

Low manufacturing maturity and limited high-yield production experience

High sensitivity to interfaces, pressure management, and defects

Significant capital intensity and tooling complexity

O
Opportunities

Long-term platform for next-generation EVs and energy storage

Potential to **reset cost, safety, and performance** benchmarks at scale

Strong **pull from OEMs** and governments seeking step-change innovation

T
Threats

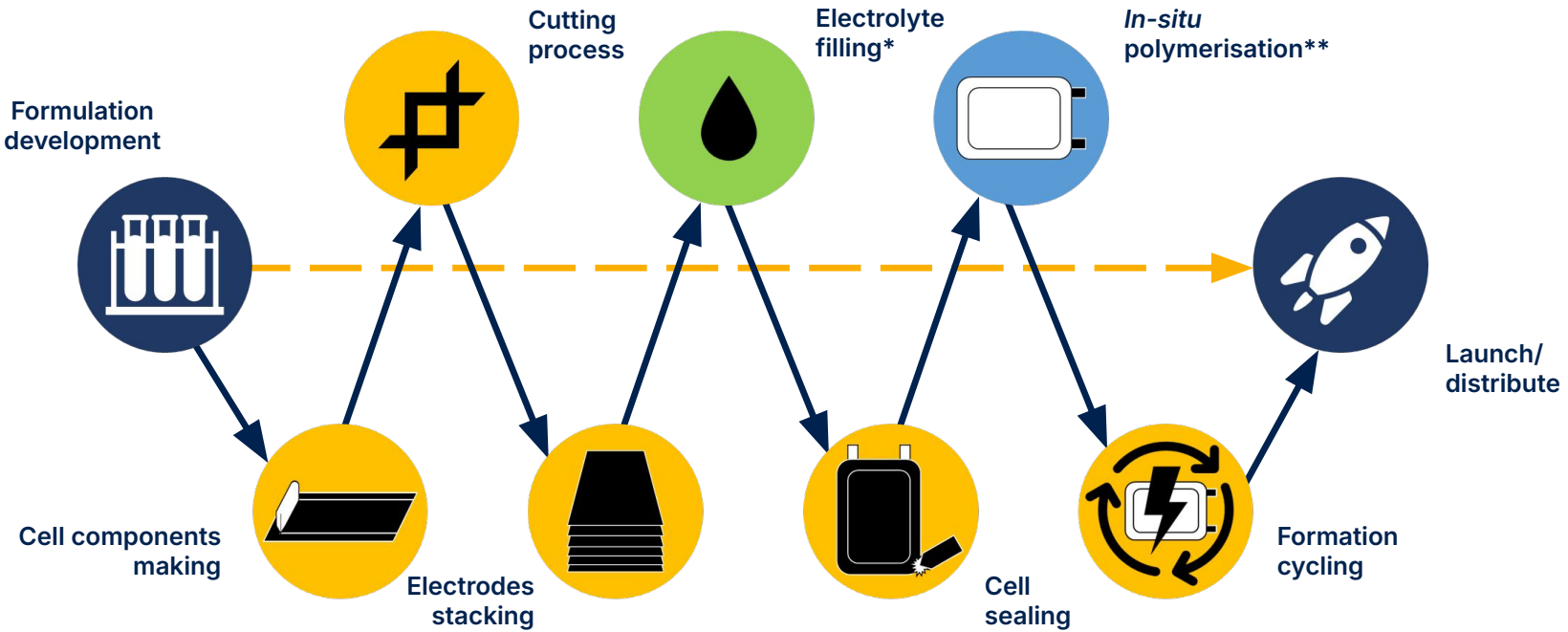
Long development timelines and execution risk

Uncertain **scalability** and cost parity with Li-ion systems

Risk of **over-promising relative** to near-term manufacturability

Source: Summarised from industrial public materials (press releases, official website informations, etc.)

Semi-solid State Manufacturing Characteristics

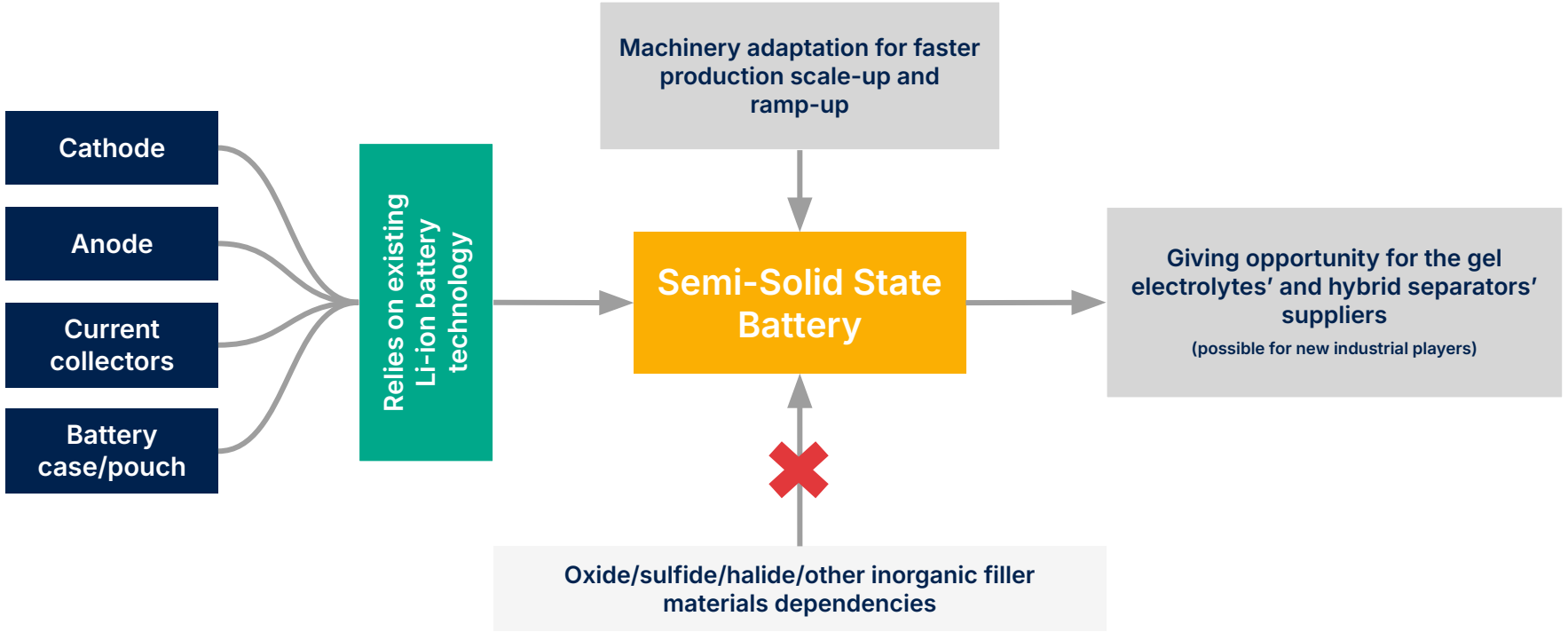


* Similar to liquid state electrolyte (high-modularity and high adaptability in manufacturing line)

** Need less pressure, or even no pressure (more practical)

Source: Adapted from Discov. Electrochem. 2, 26 (2025) | also summarised from industrial public materials (press releases, official website informations, etc.)

Semi-solid State Supply Chain Flowchart



Semi-solid State Industry Players and Investment (Case Study)

Semi-solid-state batteries are being used selectively to bridge the gap between conventional Li-ion systems and future all-solid-state architectures. While they offer near-term improvements in energy density and safety, recent deployments underscore that manufacturing scale, cost structure, and long-term differentiation remain unresolved.

Company	Key Partners / Investors	Strategic Positioning
CATL R&D focus	-	Parallel development of **all-solid-state batteries (long-term)** and **semi-solid-state systems (near-term)**, with semi-solid positioned as a **bridging solution** rather than a final platform.
WeLion Near-term manufacturing	Xiaomi, Huawei	Focused on **early commercialization of semi-solid-state batteries**, targeting incremental gains in energy density while leveraging modified Li-ion manufacturing infrastructure.
NIO Early deployment	WeLion	Deployed a **150 kWh semi-solid-state battery pack** in limited production vehicles beginning in 2024. Program activity was **paused in late 2025**, highlighting challenges in scalability, cost, and sustained manufacturing readiness.

Source: Summarized from industrial public materials (press releases, official website informations, etc.)

Solid-state Batteries Require Additional Critical Minerals

While solid-state batteries promise performance and safety gains, they also expand the critical mineral footprint (including lithium intensity), introducing new supply-chain risks that must be addressed alongside manufacturing scale-up.

Mineral	Primary Role in Solid-State Batteries	Electrolyte / System Context
Indium (In)	Enables stable solid–solid interfaces with high lithium diffusivity	Halide electrolytes (e.g., Li_3InCl_6); interfacial layers
Germanium (Ge)	Enhances ionic conductivity and fast lithium transport	Sulfide electrolytes (e.g., LGPS-type materials)
Gallium (Ga)	Dopant to improve conductivity and phase stability	Garnet electrolytes (LLZO variants)
Lanthanum (La)	Structural backbone element	Garnet electrolytes (LLZO framework)
Zirconium (Zr)	Framework metal providing mechanical and chemical stability	Garnet electrolytes (LLZO framework)
Sulfur (S)	Primary anion enabling high ionic conductivity	Sulfide-based solid electrolytes
Phosphate (PO_4^{3-})	Polyanion unit stabilizing lithium-ion transport pathways	NASICON / LISICON-type solid electrolytes

Critical mineral: A non-fuel mineral or mineral material that faces elevated supply-chain risk and is essential to the manufacturing of products critical to economic or national security.

Solid-state batteries retain the critical minerals used in conventional lithium-ion systems, including lithium, nickel, cobalt, and manganese. Depending on electrolyte chemistry - such as sulfide, garnet, or halide systems - solid-state architectures introduce **additional critical minerals** to enable ionic conductivity, interfacial stability, and mechanical integrity. Interlayers and dopants can further increase material diversity.

Source: [1] Energy Act of 2020 (P.L. 116-260). [2] Resources Policy 111 (2025): 105755. [3] Fraunhofer ISI.

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety

Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- **Sodium-ion**
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

Noteable Events: Sodium

January

STEER

Stanford University study finds Sodium-ion batteries face uphill struggle to beat Li-ion on cost, specifically, against LFP.

March

Altris

Altris announces investment in B1 funding round and collaboration with Volvo Cars for battery energy storage systems.

April

BEDROCK MATERIALS

US based Na-ion start-up Bedrock Materials shuts down less than 2 years after launch. Returns capital to investors.

April

CATL

CATL announced the Naxtra Battery for EVs, achieving 175 Wh/kg, highest amongst all Na-ion batteries.

June

TIAMAT

Tiamat completes 3rd round of fundraising, €22 million from Stellantis, Arkema, MBDA and Endeavour Ventures.

June

ZOOLNASM 众钠能源

Zoolnasm Secures $42 Million in Series A2 round to Boost Sodium-Ion Battery Production.

September

Natron Energy

US based Natron Energy has ceased operations,, halting plans for a giant $1.4 billion factory in Rocky Mount, North Carolina.

September

EVE Energy

EVE Energy launches first grid-scale sodium-ion NFPP battery storage system, enters commercial operations.

October

ALSYM ENERGY

Alsym Energy launches Na-Series, to produce non-FEOC compliant NFPP sodium ion for North America and Europe.

October

UNIGRID™

UNIGRID announces Na-ion battery production capacity at 100 MWh per year through network of battery foundries.

November

PEAK ENERGY

Peak Energy announces contract to deploy 720MWh of Na-ion BESS for Jupiter Power, with 4GWh under reservation.

November

LG Chem

LG Chem partners with Sinopec to co-develop sodium-ion battery cathode and anode materials.

Sodium-ion Bankruptcies / Ceasing of Operations

	Bedrock	Natron
Company History	Founded in 2023 (Chicago), Raised $9M; shut down in 2025.	Founded 2012; raised $300 M+; Michigan pilot (~600 MWh/yr); planned 28 GWh NC gigafactory.
Target Niche & Technology Focus	High-energy Na-ion to rival LFP; incremental gains with trade-offs; lacked clear market fit.	Ultra-durable Na-ion (50 k + cycles, 5-min charge); niche UPS and data centers; low energy (~50–100 Wh/L).
Beginning of Downfall	By Apr 2025, Bedrock's internal modeling and studies concluded that no path to commercial viability existed at current Li-ion costs.	By Aug 2025: UL delays halted $25 M orders; capital dried up; 28 GWh scale-up failed.
Shared Pain Points	• 2023–25 LFP price drop raised bar for Na-ion. • Funding shortfall and long ROI. • High U.S. costs, supply chain gaps, and certification delays. • Asia (CATL, BYD) scaled faster with government support. • Outpaced by LFP and Asian competitors • Capital and regulatory barriers too high for U.S. scale-up.	
Unique Challenges	Early 2025: Incremental R&D gains, no product; short runway made an impossible R&D sprint.	By August 2025: UL delay + $1.4 B factory burden; U.S. supply chain and cost hurdles.
Aftermath	Apr 2025: Orderly shutdown; returned $9 M and state funds; no liabilities; goodwill intact.	Sep 2025: Ceased ops; 95 staff laid off; assets liquidated after 13 years; highlighted U.S. scale-up risks.

BEDROCK MATERIALS

Natron Energy

Key Insights:

- Companies must target unmet needs in new or emerging markets.
- Avoid broad markets with entrenched incumbents without differentiation.
- Avoid long timelines and large capital for commercialization.
- Success demands tech-superiority and market niche alignment.

Na-ion Material / Component Producers

Active	Material Type	Chemical Formula	Capacity | Tap Density | Voltage Window	Producers
Cathodes	Layered Oxide	$NaNi_xFe_yMn_zO_2$ $NaCu_xFe_yMn_zO_2$	125 to 135 mAh/g | >3 g/cc | 1.5 to 3.95V[1,2]	ZOOLNASM 众钠能源, 中科海钠 HiNa BATTERY, BAK 比克电池, EcoPro BM, anandarr
	Layered Oxide	$NaCrO_2$	120 to 125 mAh/g | >3 g/cc | 2.0 to 3.4V[3]	UNIGRID
	Polyanion	$Na_3V_2(PO_4)_2F$, $Na_3V_2(PO_4)_3$,	120 to 130 mAh/g | <2 g/cc | 2.0 to 4.2V[4] 105 to 115 mAh/g | <2 g/cc | 2.0 to 3.4V[5]	TIAMAT, INDI ENERGY, GELON
	Polyanion	$Na_4Fe_3(PO_4)_2(P_2O_7)$,	100 to 110 mAh/g | <2 g/cc | 1.5 to 3.6V[6]	容百科技 RONBAY TECHNOLOGY, 佳纳能源 JIANA ENERGY, 英钠能源 INNA ENERGY, PUNA 瑞扬新能源 RUIYANG NEW ENERGY, 博钠, TIANNA 天钠科技
	Prussian White/Blue	$Na_2Fe[Fe(CN)_6]$ $Na_2Mn[Fe(CN)_6]$	120 to 160 mAh/g | <2 g/cc | 2.0 to 4.0V[7,8]	钠创 NATRIUM, NA 超钠新能源, ALTRIS, MALION 美联
Anodes	Hard Carbon	C	280 to 320 mAh/g | <2 g/cc | 0.05 to 1.0V[9]	BSG, kuraray, BTR, AEKYUNG CHEMICAL CO.,LTD.
Electrolyte	Organic	$NaPF_6$ in Carbonates	N/A	Smooth Way, TINCI 天赐, 新宙邦 CAPCHEM, GTHR

Note: Only including producers reporting Metric Tons scale production in 2025

See the **China section** for wider commentary on Chinese sodium-ion development.

2025 Sodium Ion Battery Players by Region

Americas

- PowerNaP
- Ingevity
- Nanode
- Elementium
- FERMI ENERGY
- MANA
- coulomb TECHNOLOGY
- QUANTUMSHIELD
- ALSYM ENERGY
- TAISPAN
- UNIGRID
- NVTX ENERGY
- ADENA POWER
- INLYTE ENERGY
- ENLIGHTEN
- PEAK ENERGY

Europe

- ALTRIS
- Litona
- TIAMAT
- faradion
- LIONVOLT
- amte power
- VARTA BY CLARIOS
- LiNa Energy
- MOONWATT

Asia - Pacific

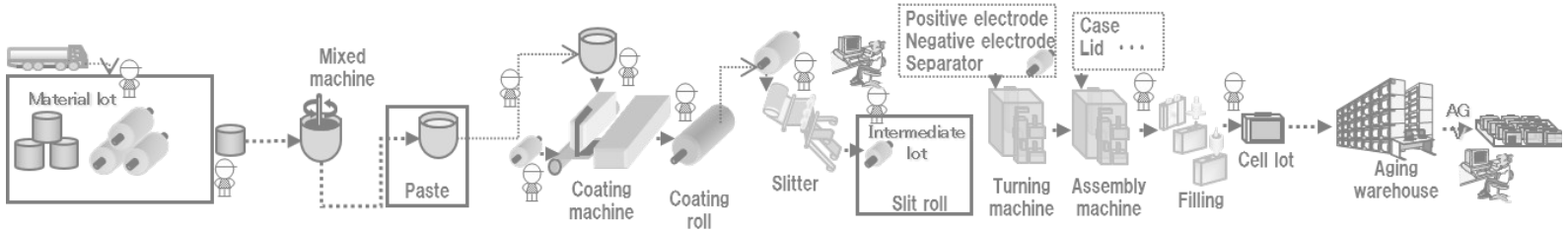
- 钠创 NATRIUM
- Smooth Way
- 容百科技 RONBAY TECHNOLOGY
- INDI ENERGY
- EcoPro BM
- kuraray
- BTR
- BSG
- AEKYUNG CHEMICAL CO.,LTD.
- posco
- LiFUN
- VISION
- ZOOLNASM 众钠能源
- FARASIS
- 华纳新能源 HUANA NEW ENERGY
- 鹏辉 GREAT POWER
- 盘古钠祥 PARAGONAGE
- Gotion
- SODION ENERGY
- CB 中比电池
- AESON POWER
- VEKEN 维科技术
- 中科海钠 HiNa BATTERY
- SVOLT
- HIGHSTAR 海四达
- CATL
- BYD
- EVE
- NO

DEVELOPMENT FOCUS

- MATERIALS
- CELL / PACKS
- FULL SYSTEMS

VF | VOLTA FOUNDATION

Factory Throughput & Cost Effects of Low Wh/L

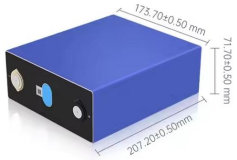


Reference: Li-ion (LFP) factory with capacity: 10 GWh/yr

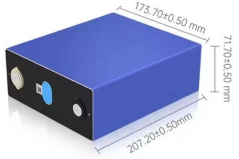
Produces Na-ion (Layered oxide) with capacity: 7.4 GWh/yr

Produces Na-ion (Polyanionic) with capacity: 4.8 GWh/yr

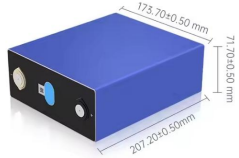
- Cell production throughput is unit / yr based
- Material density (g/cc) and cell VED (Wh/L) directly affect throughput and fixed costs / unit
- While low energy density does not affect applications such as BESS, its impacts production
- Innovations to improve g/cc and Wh/L are vital



Na-ion (Polyanion):
155 to 170 Ah
167 to 187 Wh/L
52% throughput penalty



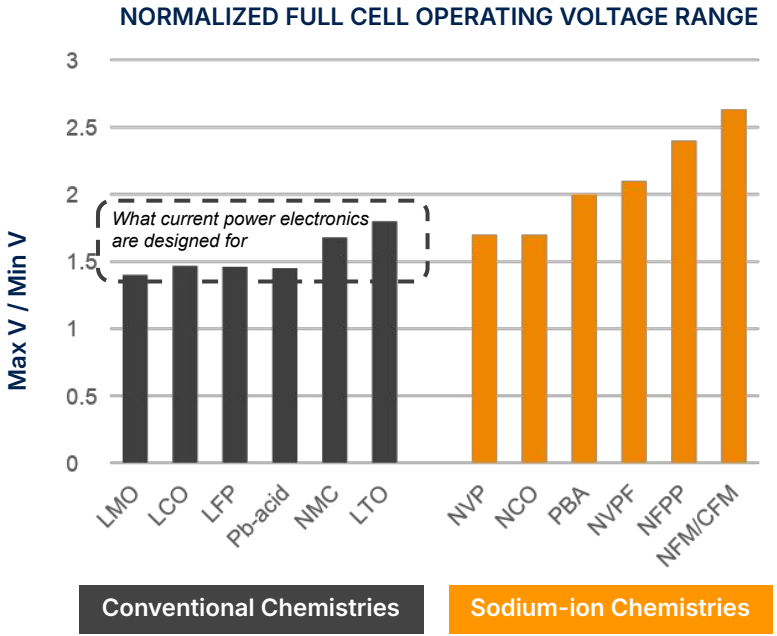
Na-ion (Layered oxide):
210 to 240 Ah
252 to 288 Wh/L
26% throughput penalty



Li-ion (LFP) cell:
314 Ah
390 Wh/L
Reference

Voltage Range Challenges of Na-ion vs Conventional Chemistries

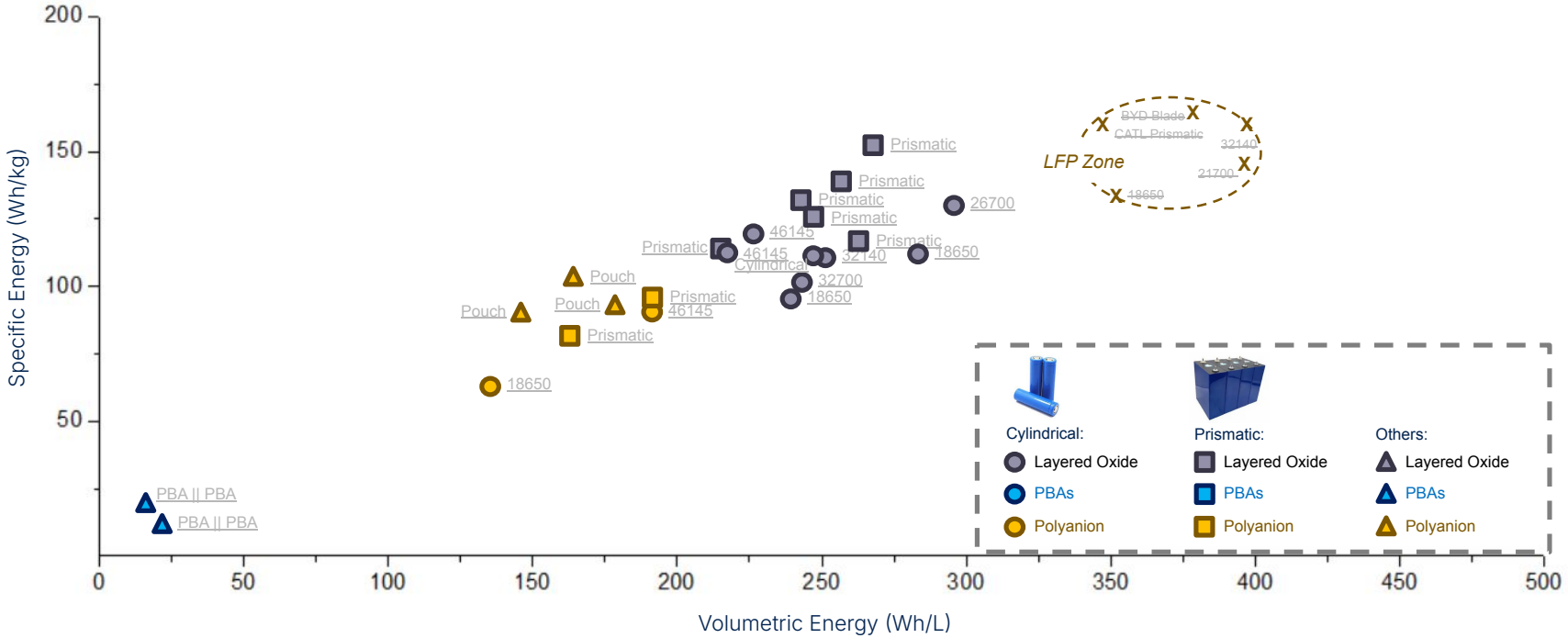
Typical wider voltage ranges of some Na-ion batteries adds complexities where DC-DC converters or inverters operate inefficiently increasing costs and energy losses.



Use-case Examples	Explanation
Data center UPS / Telecom backup	Power conversion requires constant DC voltage. A buck/boost converter needs to be more complex to compensate, reducing efficiency and increases costs.
Grid Connected Storage & BESS	Inverters need a predictable DC link. Wide voltage → inverter either oversized, derated, or added extra DC-DC stage → extra cost.
PV or renewables storage applications	For PVs, the voltage swings mean you can't extract maximum power efficiently without complex controls. Poor MPPT (maximum power point tracking)
EV traction/motive batteries	Motor controllers are optimized for a narrower voltage range (like Li-ion). Wide voltage → more frequent switching between buck/boost → I^2R losses increase.
Battery management complexity	Slopy voltage ranges improve SoC monitoring, but wide ranges require more complex power conversion tools.

Note: A major contributor to Na-ion's wider voltage range is the hard carbon anode, that has a sloped voltage profile, this does not happen in alloy anodes/anodeless full cells (not yet commercialized however).

Reported Energy Densities of Commercial Na-ion Cells vs LFP Reference



Note:Only commercially available cells with Wh/kg & Wh/L reported are shown.

Emerging Applications of Na-ion Beyond Grid Scale BESS

LEAD ACID MARKETS

Major lead acid players have released 12V SLI Na-ion products



Considerations vs Lead-acid:

- Longer lifetimes
- Overdischarge tolerance
- Better cold cranking

DEMAND RESPONSE / PULSE LOADS

Na-ion better than LTO for UPS / datacenter applications



Considerations vs LTO:

- Lower costs per kWh
- Lower footprint required
- Easier system integration

BEHIND-THE-METER ESS

Safety & Longevity drives Na-ion adoption in RESS and C&I BTM storage



Considerations vs LFP:

- High safety that precludes LFP
- Wide temperature operation
- Higher C-rates capable

A Better Battery for Energy Storage

Non-flammable
UL 9540a at the cell level

High-performance
250 Wh/L | 135 Wh/kg
10,000 cycles at 2C / 4C

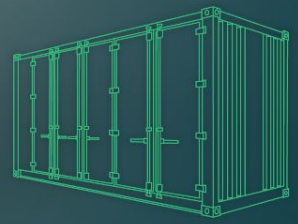
Low-Cost
~90% lower lifetime OpEx costs

Reliable Supply Chain
100% FEOC compliant




Residential


Commercial & Industrial


Utility-Scale

ALSYM ENERGY
Sodium-ion Batteries

Learn more at Alsym.com

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety

Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- **Alternative Chemistries**

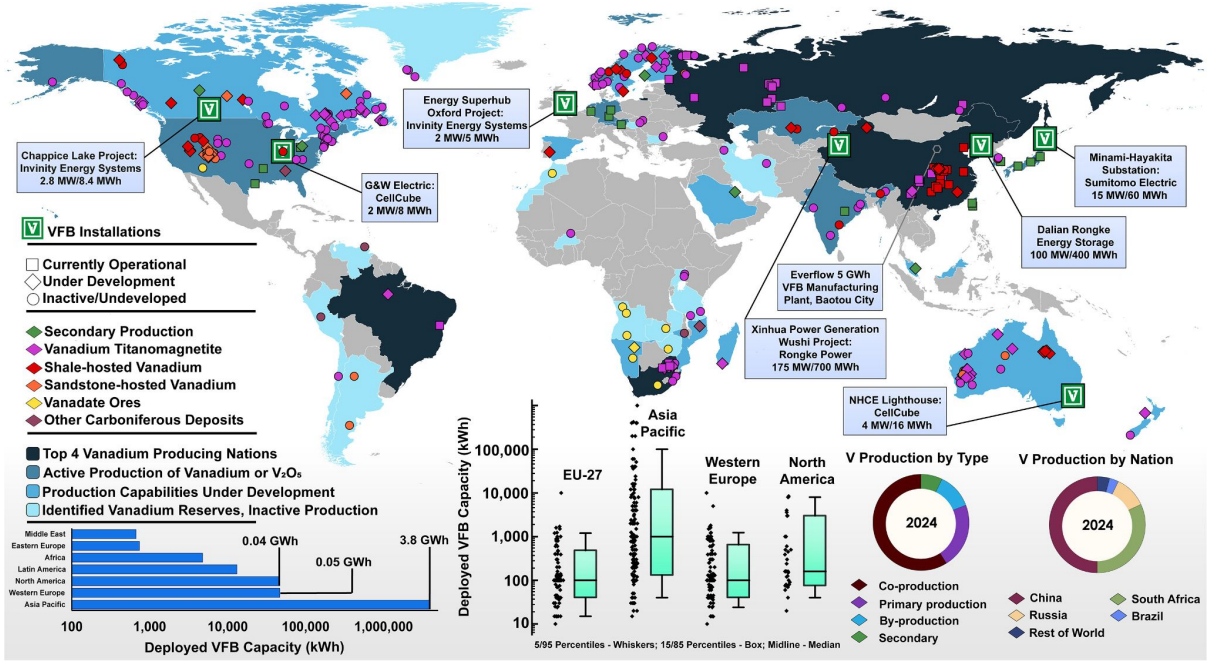
Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

VF | VOLTA FOUNDATION

Vanadium Supply Chain

Vanadium is mined from various countries, with Brazil, China, Russia, and South Africa accounting for 90% of production.



Conservatively, there are about **63,000,000 mT** of vanadium in reserves.

There are 3.94 GWh of operational VRFB globally.

59% of vanadium was produced by co and by-production with steel slag, **17%** from mineral recovery and **24%** from primary production.

Source: Rogers et al. Joule, 2025

LTO Technology: Zero-strain, High-rate Anode

LTO (Lithium Titanium Oxide, $Li_4Ti_5O_{12}$) batteries are those which use LTO instead of graphite as anode material. With a crystal structure that remains highly stable during charge - discharge cycling, LTO is often called a "**zero-strain** material". LTO anodes are characterized by good cycle stability, safety, low-temperature performance, and rate capability, which enable them for applications requiring high power, frequent cycling, and extended cycle life. However, the higher operating potential of approximately 1.5 V vs Li/Li^+ limits specific capacity and nominal discharge voltage.

Key Features

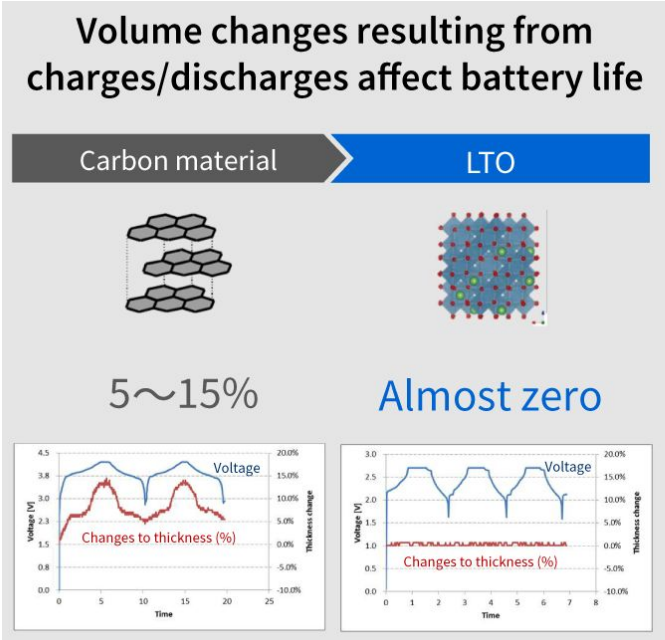


- Safety
- Rate capability
- Excellent cycle life
- Low-temperature performance

Applications

- Electric buses and cars
- Electric ferries
- Railway
- Electric bicycles

Key specifications	
Rated voltage	~ 2.3 V
Specific energy	75 - 100 Wh/kg
Cycle life	> 10000
Paired cathode	NMC, LMO



Source: Toshiba

Source: [1] Frith et al. [2] Zhang et al.

LTO SWOT Analysis

S
Strengths

High cycle life and durability, linked to "**zero-strain**" structure

Safety (low risk of **dendrite** formation) due to the higher working potential (1.55 V vs. Li^+/Li)

Fast charging capability due to **high operating potential** & **fast lithium diffusion** in the spinel

Wide operating **temperature** range

W
Weaknesses

Limited capacity (ca. 175 mAh/g)

Lower battery operating voltage (**~2.3 V**)

High production **cost**

Complex manufacturing

Limited availability

O
Opportunities

High-power applications

Portable electronics

Railway vehicles

BESS

Urban **electric buses**, vehicles where rapid charging is required

T
Threats

Competition from other technologies (NMC/C or LFP/C batteries) and next-gen chemistries

Safety regulations

Increasing **lithium costs** and supply chain concerns

High cost barrier for adoption

Source: [1] Ohzuku et al. [2] Mahek et al. [3] Liu et al. [4] Pohjalainen et al. [5] Wang et al.

LTO Industry Players

Unlike graphite- or nickel-dependent NMC and LFP cells, LTO cells face a distinct supply-chain risk centered on the titanium value chain. While the absence of cobalt and graphite - common bottlenecks in other Li-ion chemistries - initially positioned LTO-LMO cells as politically stable in 2023 supply-risk assessments, this advantage is partially offset by LTO's elevated demand for both lithium and titanium. Both elements carry significant criticality scores and environmental extraction costs.

Americas

- TARGRAY
- microvast
- altairnano
- CLARIOS

EMEA

- Leclanché Energy Storage Solutions
- saft
- AMPOWR

Asia - Pacific

- TOSHIBA
- GREE 格力 Gree Altairnano New Energy
- nichicon
- GO+ GRINERGY
- Zenaji

Source Sustainable Materials and Technologies ; Toshiba, Altairnano, Targray, Microvast, Leclanche, Gree, nichicon, Grinergy, Zenaji, Saft, Ampowr

Niobium Oxide Anode Batteries

Niobium oxide batteries are now entering trials and hitting the commercial market with aim of bringing advanced high power and long life battery solutions to the market with increased volumetric energy density over current LTO by ~50%. Niobium anode development has been supported by major financial backers such as CBMM, Volta Energy Technologies, and Scania Invest in an effort to bring fast-charging / high-power battery technology that meets of the needs of hard to abate segments.

Leading Manufactures

- Toshiba (NTO)
- Echion Technologies (XNO®)
- Nyobolt (NWO)

Specifications

Energy Density	250-330 Wh/L 100-130 Wh/kg
Continuous C-Rate	5-20C
Peak C-Rate	10-60C
Cycle Life to 80% SoH	10,000 - 20,000
Min/Max Temp.	-40°C to 55°C
Avg. Nominal Voltage	~2.25V
Paired Cathodes	NMC, LMNO, etc.

Key Characteristics

Safe Chemistry

Long cycle life

Extreme Environments

Ultra - High Power Density

Fast Charging

Applications

Hybrid



Ideal for hybrid powertrain applications that require high power density and/or mission critical operability in a range of environments.

- Defense
- Mining
- Maritime
- Aviation
- Construction
- Power Generation
- Commercial On-highway

Full Electric



Tailored for high utilization applications where TCO focused KPIs are driven by availability due to fast charging/power & cycle life.

- Mining
- Maritime
- AI Data Centers
- HP UPS/ESS
- Last Mile Vehicles
- AGVs
- Light Rail

Source: Toshiba NTO, Echion Technologies XNO, XNO Whitepaper, Nyobolt NWO

Pilots Surge Across New Flow Battery Technologies/Markets, while Vanadium Deployments Remain Steady in 2025

January

Quino secures $2.6M for commercial pilot site

February

ESS Fleet reaches 2GWh transacted energy

Sumitomo Unveils VRFB

Invinity Energy Partners with Frontier Power

March

Invinity proceeds with LoDES project providing 20.7 MWh to the UK

April

XL Batteries launches grid-scale organic flow battery project

May

Prometheus Hyperscale and XL Batteries partner to deploy long duration energy storage for US data centers

June

Rongke Power delivers world's first commercially used Iron Vanadium flow battery to Aramco

July

Storion and Terraflow form Partnership

TerraFlow announces Texas project

Invinity Establishes Mfg and Supply Agmt

August

Sumitomo deploys demonstration project.

Rongke Power Completes 100MW/400MWh VRB Project

September

Quino and TerraFlow form Strategic Partnership.

Invinity launches data center product

October

ESS and SRP announce project

Form delivers first batteries

Sharp and ESI AP sign MOU

AQUABATTERY signs LOI with Sciven

November

Elestor rewarded project investmen

Quino Energy closes Series A

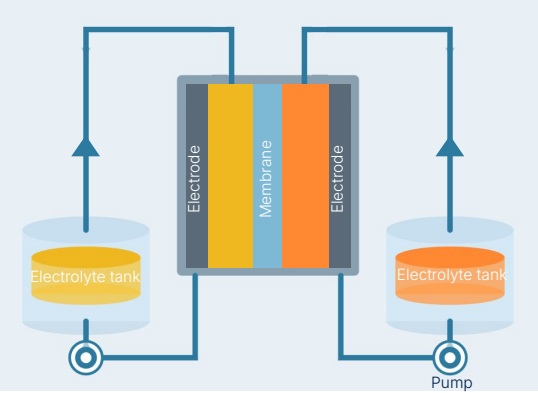
December

EnerFlow plans 1.2 GWh project.

Invinity battery deployed at PNNL Grid Storage Launchpad.

Innovative Batteries – Metal-Air and Flow

Redox Flow Batteries

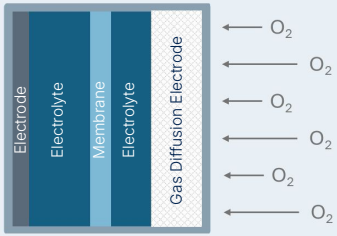


Key Advantage: RFB architecture allows scaling of power and energy density separately

Types: Vanadium (TRL 9), Iron (TRL 4)

Two tanks house the redox active solutions, these are flowed to the cell stack where reduction or oxidation occurs.

Metal Air Batteries

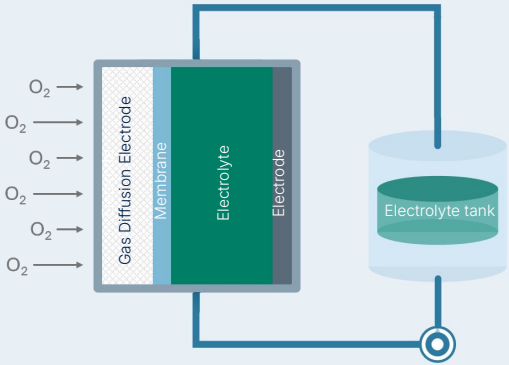


Key Advantage: Metal-air batteries (MAB) have extremely high energy densities

Types: Iron (TRL 4-5), Zinc (TRL 2-4)

MAB employs a gas diffusion cathode for oxygen reduction during discharging. At the anode, metal is oxidized into ions in solution.

Metal Air Flow Batteries



Key Advantage: Metal-air flow batteries (MAFB) combine the scalability of RFB with an increased energy density from the metal air couple

Types: Lithium (TRL 3), Iron (TRL 2)

An MAFB increases the mass transport kinetics of oxygen reduction by flowing while keeping high energy density of MABs.

Source: Shoaib et al. Adv. Energy Mater, 2024 ;Li et al. ACS Energy Lett. 2017 ; Yu et al. J. Mater. Chem. A, 2019. Please see Volta Report 2024 for detailed cell specs.

Industry Players

Metal-Air/Flow Batteries are being developed in a diverse range of geographies due to availability of localized supply chains, safety, and deployment for stationary storage applications

Americas

- noon ENERGY
- ESS INC
- Form energy
- ENERVENUE
- e-zinc
- STORION ENERGY
- TERRAFLOW ENERGY
- VRB ENERGY
- THE BESSt COMPANY
- XL Batteries
- ABOUND
- QUINO ENERGY
- respire energy
- STOREN
- Otoro ENERGY
- Agora ENERGY TECHNOLOGIES
- zenthos ENERGY
- METAL LIGHT
- ENLIGHTEN
- IMABATTERY

Europe

- HalioGen Power
- REDOX
- KEMIWATT
- INVINITY ENERGY SYSTEMS
- cellcube
- BALIHT
- SINERGY FLOW
- elestor
- CEGASA
- ORE ENERGY
- RIVUS power that flows
- redoxblox
- UP
- Jena Flow Batteries
- AZA
- cmblu
- StorTera
- BETTERY

Asia - Pacific

- allegro
- RKP
- I2TR i-battery
- SUMITOMO ELECTRIC Connect with Innovation
- Sthyr Energy
- SHARP
- LINCDYNE
- AQUABATTERY
- AVESS ENERGY
- DELECTRIK
- H2
- FLOW TECH
- weview
- ENERGY STORAGE INDUSTRIES ASIA PACIFIC
- ENERFLOW

METAL AIR | VANADIUM | ORGANIC

IRON | OTHER

sightline climate Source: with support with Sightline Climate (Distinguished Partner).

Just Under $1B Invested in 2024, ~$215M Invested in 2025

The United States federal and state governments accounted for about 60% of investment in metal-air/flow battery technologies in 2024. In 2025, private groups bet on companies focused on long duration energy storage and other governments led the charge in project financing including the first investment as a result of the United Kingdom cap and floor scheme.

Company Name	Funding Amount ($M)	Funding Source (Lead Investor)	Investment Type
ESS	$40	Yorkville Advisors Global (link)	Post IPO Funding
ESS	$31	Inside Investors (link)	Post IPO Funding
Invinity	$33.9	Department of Energy Security and Net Zero (link)	Project Grant
VFlow Tech	$20.5	Granite Asia (link)	Growth
Unbound Potential	$16.9	SRIN-D, Innosuis, Migros Pioneer Fund, Zurich KlimUP (grants), Founderful (lead of conventional funding) (link)	Grants and Pre-Seed
H2, Inc.	$16	STIC Investments (link)	Bridge Financing
Quino Energy	$15	Department of Energy and California Energy Commission (link)	Project Grant
Quino Energy	$10	Atri Energy Transition (link)	Series A
XL Batteries	$7.5	Merrin Investors (link)	Seed
Flux XII	$3.9	Grantham Foundation (link)	Seed
Agora Energy Technologies	$1.8	Natural Resources Canada (NRCan) (link)	Grant
Allegro Energy	$1.1	Australian Government - Department of Industry Science and Resources (link)	Grant
AVESS Energy	$1	Carbon Innovations Grant Program (link)	Series B

sightline climate Source: with support with Sightline Climate (Distinguished Partner).

Flow Battery/Metal-Air Deployments That Came Online in 2025

Vanadium flow batteries led for deployments in operation in 2025, including the largest flow battery deployment in the world. A strong pipeline of projects in development and on order show a more diversified technology profile in the coming years.

Project name	Location	Capacity (MW)	Duration (hours)	Energy (MWh)	ESS provider	Chemistry	Developer / Owner
Viejas Microgrid	Alpine, CA	3.43		9.7	Invinity Energy Systems	Vanadium	Indian Energy
V-iOn Project	La Plana, Spain	0.30	4.0	1.2	Invinity Energy Systems	Vanadium	Gamesa Electric
Saudi Aramco Gasfield Pilot	Saudi Arabia	0.09	11.1	1.0	Rongke Power	Vanadium	
Hami GTIC Shichengzi ESS	Hami, China	100.00	4.0	400.0	Rongke Power	Vanadium	
Nagel Group Germany	Bochum, Germany	0.33	9.1	3.0	CellCube	Vanadium	Nagel Group
Conway Medical Center	Conway, SC	1.00	7.0	7.0	CellCube	Vanadium	Bernhard
G&W Electric Microgrid	Bolingbrook, CA	2.00	4.0	8.0	CellCube	Vanadium	G&W Electric
NETRA VRFB Demonstration	Greater Noida, India	0.50	6.0	3.0	Delectrik	Vanadium	NTPC
Project Nexus	Turlock, CA	0.15	8.0	1.2	ESS	All iron	Turlock Irrigation District
JTC CleanTech One Building	Singapore	0.01	10.0	0.1	VFlowTech	Vanadium	JTC

Source: Fairgreen Climate LDES Tracker

Zinc Batteries Comparison

Safety, sustainability, long storage durations and long battery life are major drivers for growth of zinc battery technologies.

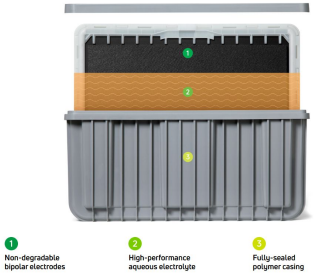
	Zinc Ion	Zinc Nickel	Zinc Bromide	Zinc Air	Li-Ion
Commercial Application	Stationary Storage (3-12 hrs)	UPS (<1hr)[3]	Stationary Storage (3-12 hrs)[2]	Stationary Storage (24+ hrs)	Electric Vehicles; Stationary Storage (1-4 hrs)
Gravimetric Energy Density (Wh/kg)	150[1]	140[1]	60-75[3]	100-400[3]	250-300
Volumetric Energy Density (Wh/L)	100-400[1]	300[1]	60-70[3]	135-1000[3]	650-800
Voltage (V)	1-1.5	1.2-1.9[3]	1-1.8[2]	0.9-1.4[3]	2.5-4.2
Cycle Life	5-10,000[1]	500-1500[1,4]	10,000[2]	500	1500
DoD	100%				80-95%
Calendar Life	15-20 years[1]	15 years[3]	20 years[2]	15-20 years[1]	10
Safety	Non-flammable, not reactive to air or water[3]				Poor
Sustainability Assessment Score		**9.4/10**	**9.5/10**		Poor

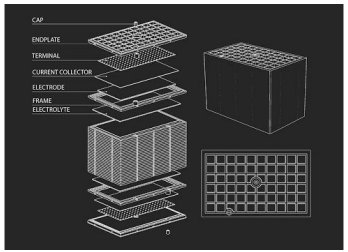
Source: 1 DOE Energy Earthshots Technology Strategy Assessment Zinc Batteries ; 2 https://www.eose.com/technology/ ; 3 Zinc Battery Initiative Presentation; 4 Mitsubishi Electric

Zinc Bromine Batteries

Zinc Bromine batteries have gained commercial traction utilizing the zinc-based aqueous electrolyte to provide safe, durable, and flexible energy storage for 3-12 hour intraday applications

Non Flow Chemistry

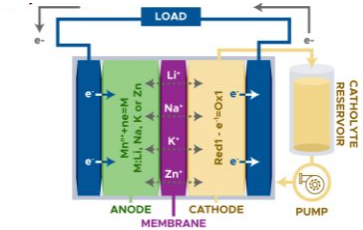




Simple architectures have gained the most traction due to their manufacturability led by Eos Energy Enterprises and Offgrid Energy Labs

Both companies boast mid 80-low 90% round trip efficiency particularly at higher discharge times.

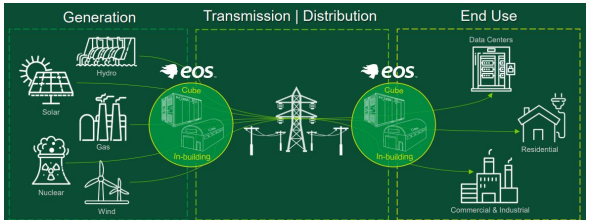
Flow Chemistry



Combining electrolyte tanks with plating of zinc on the anode side of the battery, the flow battery design offers flexibility and scalability in the storage of electricity.

Work on these batteries started with Exxon in the 1970s with companies like Primus Power and Redflow furthering the design though both companies are no longer active

Use Cases



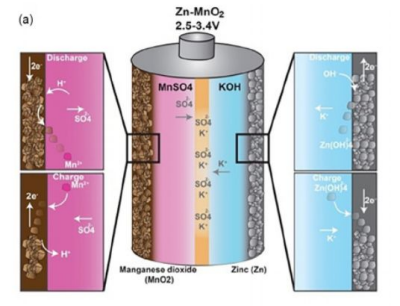
- Behind the meter C&I (e.g. data centres)
- Microgrids, weak-grid and off-grid markets
- Renewable firming and energy shifting

Zinc-ion Batteries

Research in 2025 continues to push zinc-ion batteries (ZIBs) toward greater durability, manufacturability, and commercial relevance.

Basic Chemistry

Zinc-ion batteries are being developed using both near neutral and basic electrolytes. These batteries have a pathway to $50/kWh cell cost level due to the low cost of materials and existing supply chain for the primary battery market. With the theoretical max specific capacity of 308 mAh/g, a lot of up and coming companies and research is being performed to advance zinc-ion batteries to solve manganese dioxide dissolution and improve rechargeability.



Academic Work

Cathode research remains the dominant focus, especially around Mn-based materials to improve cycle life, stability and scalability. This includes:

- Novel cathode materials & hybrid designs (CuO_2, iPOPs, Polyaniline)
- Thinner and more scalable cathodes
- Carbon coating processes and structural tuning (β-MnO_2, α-MnO_2)
- Doping strategies (Ni, Bi, K, Fe, Zn) to improve stability and conductivity
- Adhesion improvements, titanium dioxide surface interfaces, and dissolution shielding approaches (Carboxyl-CNTs, PN-MnO2)
- Hydrothermal synthesis(high valence, polymorphs) and ion-exchange processes adapted for manufacturability
- Vanadium sulfide fundamental studies for alternative chemistries
- Dry-electrode and other manufacturing capabilities

Electrolyte development continues to minimize dendrites and extend lifetime

- Electrolyte additives for suppression of side reactions ($Al_2(SO_4)_3$, Mannitol)
- Hydrogel electrolytes (Polyanionic, Salt-Concentrated) to improve safety and Zn interface stability
- Engineering of cathode–electrolyte interfaces to reduce degradation

Supporting improvements indicate the field is **transitioning beyond core chemistry:**

- Current collector enhancements
- Separator advancements for ion selectivity and safety

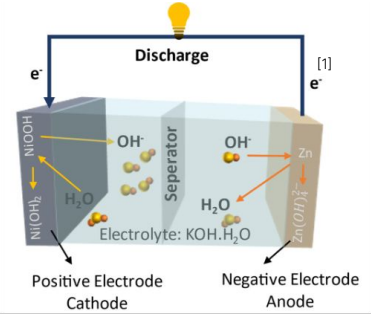
Development of **characterization and data-driven approaches:**

- Characterization of failure modes (in situ, modeling)
- Mechanistic fundamentals to correlate structure and performance
- Incorporating machine learning for material optimization

Nickel Zinc Batteries Continue to Make Inroads

Nickel Zinc Batteries as an alternative to both lead acid batteries and increasingly li-ion batteries for critical infrastructure particularly in dealing with intense AI warble profiles and recent safety concerns for data centers.

Basic Chemistry

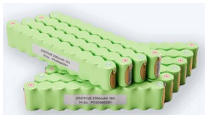


$$Zn + 2NiOOH + 2H_2O \rightarrow Zn(OH)_2 + Ni(OH)_2$$ [2]

Features:
3x power density to lead acid, ½ size, ⅓ weight[3]

Continuous connectivity within a string even with a depleted cell.[4]

Form Factors





Companies such as AEsir technologies are able to use manufacturing lines used by lead acid battery manufacturers due to the similarity in design.

EnZinc similarly plans to utilize existing manufacturing lines through selling their anode sponge and Zinc Nickel design to existing lead-acid manufacturers.

Cylindrical form factors are becoming an additional offering from companies such as ZincFive, Zelos Energy, and GP Energy Tech utilizing adjacent chemistry manufacturing technologies.

Applications

UPS Battery Cabinets [Deployed]
- Covering both centralized and distributed UPS battery backup systems for data centers and other critical power infrastructure in both monobloc and cylindrical formats.

In Server Rack Battery Backup Units [Commissioning]
- Located within the physical server rack of data centers to provide short-to-medium term backup with increasing role of peak shaving from AI warbles.

Intelligent Transportation Service (ITS) [Deployed]
- Installed in roadside and intersection traffic signal cabinets to provide reliable power supply protecting against voltage drops and surges in harsh operating temperatures.

Defense [Trialing]
- Deployed in naval platforms as a main or auxiliary battery to increase performance without thermal-runaway risks.
- Used as an upgrade to existing NiCd batteries for aircrafts.

Industrial Generator Starters [Deployed]
- Dedicated batteries that supply short, high-current bursts; described as Cold Current Amps (CCA), to crank back-up generator engines online.

Source: [1] I.T. Bello et al., EcoMat, 2025., [2] DOE Technology Strategy Assessment, [3] Data Center Dynamics, [4] Best Magazine

Zinc Batteries Notable Events

Industry leaders continue to expand operations; investment targets products to support AI industry, military, and long duration energy storage

February

Gold Peak announces strategic $150M investment in Nickel Zinc batteries for data center and AI applications

March

Zincfive recognized as a top greentech company 2025 by Time Magazine

Eos secures strategic naval base project

April

Anervoir launches NiZn product ZnCore 28 at Global Computing Safety & Security Summit 2025

May

AEsir starts expansion on Joplin, MO manufacturing site to support defense customers

June

Australian team boosts zinc-iodine battery performance with dry process

July

Sthyr Energy raises seed funding to develop zinc-air technology

EnZinc selected for California Energy Commission award

September

Offgrid raises $15M in Series A funding to scale up Zinc Bromine battery operations

October

EnZinc announces JDA with a PbA partner

ZincFive unveils BC 2 product to power AI data centers

Eos expands operations in Pittsburgh with mfg capacity, software hub, and headquarters

November

Eos Energy Successfully Closes $600 Million Convertible Senior Notes Offering

December

ZincFive raises $30M Series F

VF | VOLTA FOUNDATION

Industry Players in the Zinc Batteries Market

Americas

BATTERY MANUFACTURERS

ZincFive, URBAN ELECTRIC POWER, eos, IMPRINT ENERGY, THE BESSt COMPANY, ENZINC, SALIENT ENERGY, eZinc, ZĒLOS, ABOUND

SUPPLY CHAIN

Zochem, Octet Scientific, CELGARD, sabic, TETRA

Europe

BATTERY MANUFACTURERS

AZA, ZINERGY, hilabs, SUNERGY

SUPPLY CHAIN

everZINC+, Brüggemann, GRILLO, IMR METAL POWDER TECHNOLOGIES, Easyl Zinc, delfort

Asia - Pacific

BATTERY MANUFACTURERS

GPET, FDK, ENERGY STORAGE INDUSTRIES ASIA PACIFIC, AmaZinc, PMB DEFENCE, SG, CHILWEE, NGK, OFFGRID ENERGY LABS, BPI 倍特力, melasta, gelion, Energywith

SUPPLY CHAIN

JG CHEMICALS, bdj, NIPPON SHOKUBAI, HINDUSTAN ZINC, Silox, ORLON, Diamonchem, CHILWEE, vedanta, HCCL, UNID, 中国五矿

ZINC ION
ZINC NICKEL
ZINC HALIDE
ZINC AIR
ZINC SALTS
SEPARATORS
ELECTRODE MATERIALS
ELECTROLYTE

Source: linked for every Company Name

Industry-proven Zinc Battery Manufacturers Scaling Manufacturing Capabilities

Following the completion of proof of concepts, efforts are now focused on scaling manufacturing capacity and deliverability avoiding the valley of death to establish a viable expanded solution.

COMPANY	MANUFACTURING / SUPPLY CHAIN PARTNERSHIPS AND ANNOUNCEMENTS
eos	**Eos Energy** is expanding their manufacturing capacity towards 8 GWh with a new **432,000ft^2** manufacturing space in Pennsylvania to accompany their announced headquarters relocation to Pittsburgh, Pennsylvania.(1)
ENZINC+	**Enzinc**$^+$ announced a **Joint Development Agreement (JDA)** with a leading U.S. based lead-acid battery manufacturer to expand on their proprietary zinc microsponge anode technology offering.(2)
Æsir Technologies, Inc.	**ÆSir Technologies** is expanding their Joplin, Montana manufacturing facility footprint along with securing additional state-of-the-art equipment through an awarded Firm-Fixed-Price Contract from BlueForge Alliance.(3)
GPET	**Gold Peak Technology** announced a **USD150M** Letter of Intent (LOI) through their subsidiary, **GP Energy Tech**, to build over stages a state-of-the-art nickel-based manufacturing and R&D campus in the new Johor-Singapore Special Economic Zone (JS-SEZ).(4)

Source: (1)Eos Energy Executes Next Phase of Growth Strategy with U.S. Manufacturing Expansion and New Software Hub Under Project AMAZE; (2)Enzinc+ announce a Joint Development Agreement with leading lead-acid battery manufacturer; (3)Æsir Secures Major U.S. Navy Contract to Expand Battery Production; (4)Gold Peak announces strategic investment in Johor-Singapore Special Economic Zone to capture rapid growth of AI and data centers

$1.3 Billion in Investment for Zinc Batteries

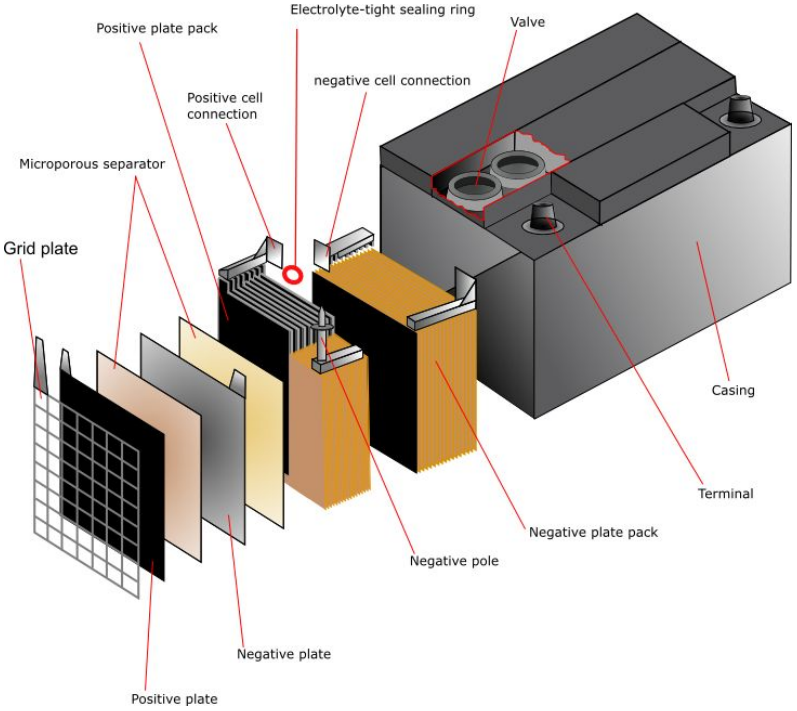
In 2025, investments totaling USD1.3 billion have been announced, with a particular emphasis on expanding advanced manufacturing capabilities for established Zinc battery technology products.

Month	Company Name	Country	Technology	Investment Type	Funding (Usd'm)	Source (Lead Investor)
DEC	EverZinc	Belgium	Zinc Material	Acquisition	Undisclosed	Cerberus Capital
	ZincFive	US	Zinc Nickel	Series F	$30.0	Multiple
NOV	Eos Energy	US	Zinc Air	Convertible Note Offering	$600.0	
	Eos Energy	US	Zinc Air	Public Offering	$458.2	
	Eos Energy	US	Zinc Air	Grant	$24.0	Commonwealth of Pennsylvania
SEP	Offgrid Labs	India	Zinc Bromine	Series A	$15.0	Archean Chemicals Industries
JUL	Eos Energy	US	Zinc Air	Loan	$22.7	US Department of Energy
JUN	Sthyr Energy	India	Zinc Air	Seed	$1.0	Antares Ventures
MAR	Octet Scientific	USA	Electrolyte	Seed	$2.1	ICIG Ventures
FEB	GP Energy Tech	Singapore	Zinc Nickel	Manufacturing	$150.0	Gold Peak Technology Group

Lead-Acid Batteries: Technology Overview

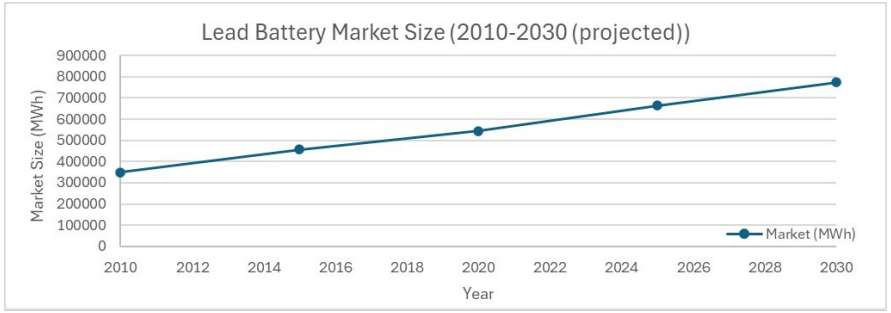
- The lead-acid battery was invented in 1859 by Gaston Planté
- The lead-acid battery is considered to be the first practicable secondary battery and was composed of a pair of spiral-wound lead plates, separated by rubber strips, in a vessel of dilute sulfuric acid.
- Modern lead-acid batteries rely on the same fundamental chemistry but with refined architecture
- The most common formats of lead-acid batteries today are flooded (also called vented), valve-regulated (also called sealed or maintenance free), AGM (activated glass matt), gel, and bipolar, although tubular batteries are used in select markets and applications
- The fundamental discharge and charge reactions for these batteries are:

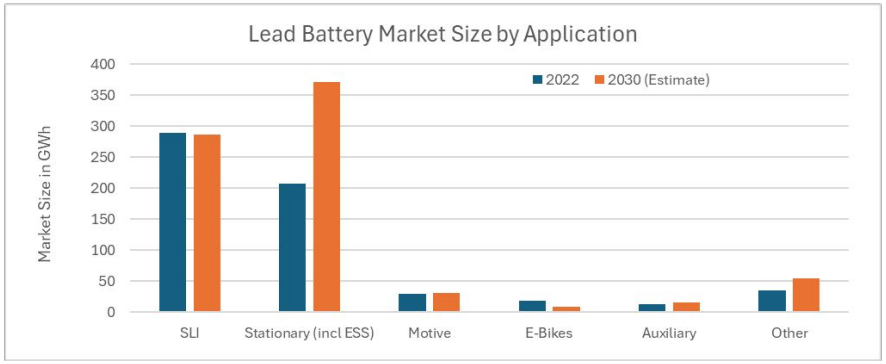
  $PbO_2 + Pb + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$
- Different plate thicknesses and architecture are utilized for distinct applications (e.g. thicker plates are used in deep-cycle applications whereas thinner plates are used in SLI type batteries)
- Ongoing research funded by the Department of Energy is investigating how to improve lead battery performance for ESS applications, especially at longer durations
- Novel applications for lead batteries (and their use in microgrids) is being explored through projects in Europe and Africa



Sample Lead-Acid Battery Schematic

Lead-Acid Batteries: Trends and Notable Events

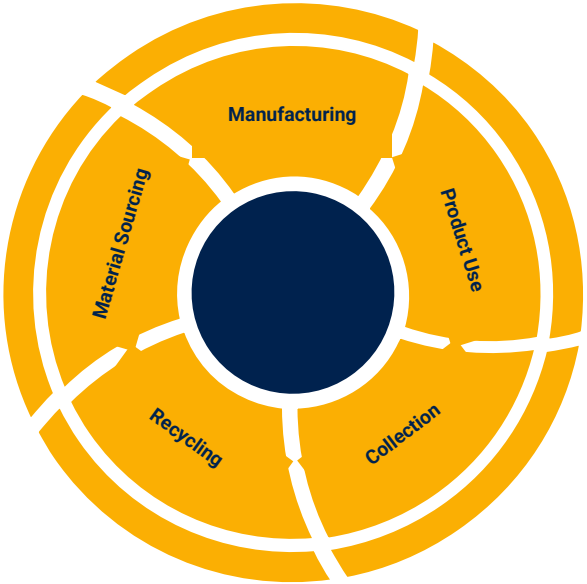




- The lead battery industry is growing, described in numerous market reports, including those from KPMG and CRU
- Key markets for lead batteries are are ESS and backup power (e.g. telecom, UPS, nuclear backup, etc.) and automotive (starter), auxiliary, and motive power
  - Lead-acid batteries are currently the only qualified technology for safety related backup for nuclear power (under IEEE 535);
  - Future growth of SMR technology may require substantial lead-acid batteries, depending on systems
- Key industry events that highlight lead battery technology and its ongoing advancements include Battcon, ELBC (European Lead Battery Conference), BCI Convention, and the Asian Battery Conference among others

Source: :Consortium for Battery Innovation

Lead-Acid Batteries: Supply Chain, Materials, and Recycling



- Lead has recently been included in the USGS list of critical minerals because of its role in battery manufacturing and the associated impacts of that and the recycling industries
- The estimated value of the lead-acid battery market as of 2024 was approximately $50B with growth estimates ranging from 2-7% CAGR, depending on market and application
- In the lead battery industry, the raw inputs to the battery for manufacturing are highly intertwined with the scrap or recycling market.
- Lead batteries have a reported 99% recycling rate, the highest of any consumer product in the United States.
- Recycling rates are high in Europe and Japan while other regions are continuing efforts to increase recycling rate as informal recycling remains a concern
- This strong recycling stream results in more than 83% of lead in US lead battery manufacturing to be sourced from North American recycling facilities, with new batteries averaging at least 80% recycled content.
- Ongoing efforts, demonstrated by the Lead Battery 360 Initiative, a global program led by the International Lead Association (ILA), Battery Council International (BCI), the Association of European Automotive and Industrial Battery Manufacturers (EUROBAT) and the Association of Battery Recyclers (ABR) aims to promote best practices in lead mining, lead production, lead battery manufacturing and recycling, and by encouraging responsible practices along the entire battery value chain through supply chain management and product stewardship.

Source: Circularity of the Lead-Acid Battery Industry

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- **Upstream and Midstream**
- Recycling & Secondary Markets

Software / AI

Battery Materials in 2025: Market and Policy Distortions

Lithium

Bullishness from the BESS sector and policy changes are fueling a price resurgence, but supply curtailments have not fully balanced the market.

Investor sentiment remains weak, but producers continue to advance projects.

Cobalt

DRC export controls are tightening global supply.

Feedstock availability outside the DRC is declining, forcing refiners to reduce rates or shift to alternatives.

Nickel

The market for nickel and nickel sulphate remains in oversupply, driven by Indonesia and China.

Demand in batteries has underperformed due to LFP displacement of nickel-based chemistries.

Manganese

High-purity manganese sulphate remains the dominant input for pCAM production.

Limited alternative feedstock and processing capacity outside China make manganese strategically important for midstream resilience.

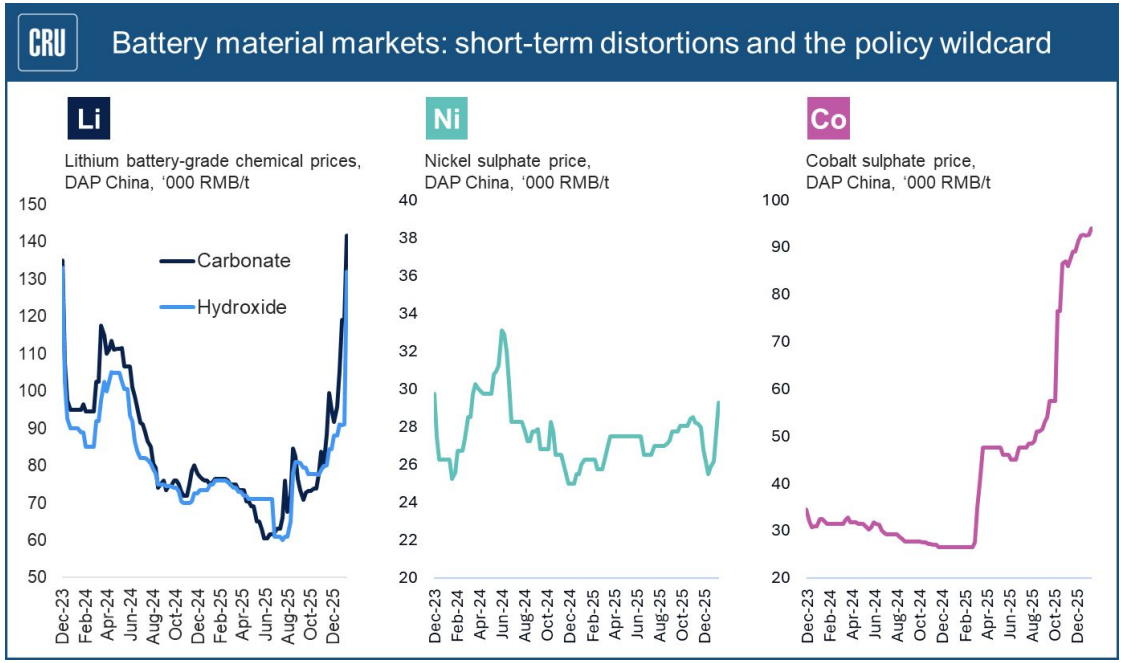
Graphite

Graphite supply chains remain highly concentrated in China with export controls increasing risk.

Diversification efforts continue but progress remains slow relative to demand growth.

Source: Summary of section content

Battery Material Markets Experience Short-Term Distortions in 2025, but Prices Stay Relatively Low.



Markets for the three major battery raw materials in 2025 were driven by short-term distortions - inventory swings and waves of buying - not just supply-demand fundamentals. Policy decisions in resource-rich countries are now a wildcard that can tighten markets quickly.

Lithium: China saw a sharp price rise as inventories fell and LFP cathode material output surged. This is amplified by strong procurement and over-ordering from the BESS value chain, and more recently (Jan 2026) accelerated by changes to China's export VAT rebate.

Cobalt: The DRC introduced a ban on cobalt exports, and then export quotas, but the rollout has been slow. Even before full enforcement, the quota uncertainty tightened availability and supported higher prices.

Nickel: Feedstock costs for nickel chemicals rose, the market was flooded with [non-battery] nickel cathode, and there was an uptick in nickel consumption in NMC pCAM. Despite all of this, prices continued their bearish trend regardless.

Despite the price movements and distortions, prices remain reasonably low compared to previous years, and are still conducive to low battery costs.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

Latest Trends in the Lithium Industry

Investors flee while **producers hold firm**: miners still committing cash to projects

Supply curtailments ongoing for certain mines and refineries, but not yet balanced the market

M&A has slowed this year; company valuations rise on bullish expectations

Government intervention is driving market volatility (China, USA, Zimbabwe)

China has domestic lithium supply reform in its sights: two major mines forced to close

Secondary **lithium from recycling** is already acting as a source of swing supply

China's capacity expansions pipeline puts it on its way to become **largest producer**

Chinese companies are heavily investing in **Argentina and Africa**

Demand is emerging for **lithium intermediates** – sulphate and chloride – for high-end LFP processes

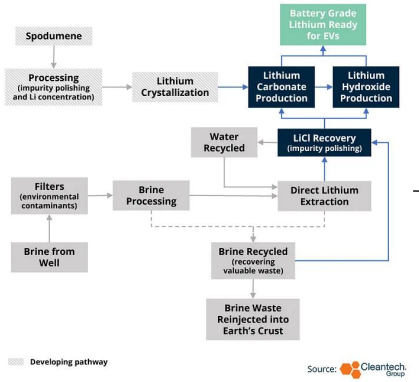
BESS demand fuels bullishness, but value chain is overreacting to perceived demand

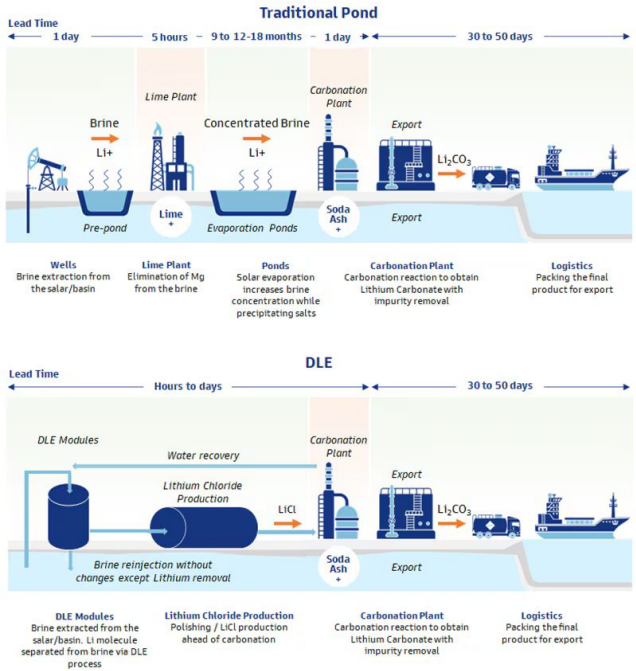
CAM output has surged, and with it, lithium chemical consumption

CAM and Li refining capacity is **expanding outside China**, e.g. Southeast Asia

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

Lithium Production from Spodumene vs Brine: Process, Pros & Cons





	Direct Lithium Extraction (DLE)
Pros	• Continuous production possible • Less impacted by climate/evaporation rates • Can target low-grade brines
Cons	• Some processes still not economically proven • Higher upfront tech integration costs • Limited long-term commercial track record

	Hard Rock
Pros	• Straightforward permitting in some regions • Compatible with existing mining workforce • Strong supply chain + established processing routes
Cons	• Requires blasting and heavy equipment • Transportation of ore adds cost/emissions • Mine closure and rehabilitation obligations

Source: Goldman Sachs, CleanTech

Smackover Lithium Formation's Vast, High-Grade Lithium Brine Deposits Could Fuel US' Lithium Supply Needs



REPORTED ESTIMATED CONC'S

Standard Lithium SWA:
~440–480 mg/L

Franklin Project (TX):
~626–671 mg/L

PARTICIPATING COMPANIES

Standard Lithium, Chevron, TETRA, ExxonMobil, ENERGYX, LANXESS, equinor

High-grade lithium brine resource (200–500 mg/L in key zones)

Group	Status / Estimate
Standard Lithium	DFS published; ~22,500 tpa Li_2CO_3 planned (~2028)
Smackover Lithium (JV)	Long-term vision >100,000 tpa (multi-phase)
LANXESS	Brine processing footprint; exploring lithium co-production
ExxonMobil	Drilling appraisal wells in Arkansas
EnergyX	Expanded acreage (~47,500 acres); DLE pilot deployments
Chevron, Equinor, TETRA	Regional operators → infrastructure, mineral rights, service capabilities
Others coming	Permitting & leasing ongoing across AR/TX

Why Smackover A Big Deal for Lithium

- **High concentration** vs global brine standards
- **High flow rates** & existing O&G infrastructure → lower development costs
- US-based resource **supports IRA incentives** & domestic supply chain goals
- **Compatible with DLE technologies** (adsorption, ion-exchange, solvent extraction)

Strategic Advantages

- **U.S.-based resource** → supports IRA incentives & domestic supply chains
- **Existing** wells, brine handling, disposal & rights-of-way
- **Lower capex/**time-to-market vs greenfield projects
- **Scalable** through modular facilities

Source: USGS - Lithium Smackover Formation, USGS - Lithium resource in the smackover formation brines, Exxon Mobil, Mining - EnergyX Expands US Smackover Acreage

Latest Trends in the Nickel and Cobalt Industry

Governments are intervening to help support the price and value of their national resource and industry

Congo (DRC) banned Co exports in 2025 and will introduce an export quota system

Co prices have surged, the supply-demand balance is tighter, and stocks are at critical levels

Ni market remains in **oversupply**

Indonesian government is gradually tightening supply, mandating higher-value products, requiring annual approvals, and scrutinising tailings management

p/CAM producers scrambling to **secure long-term Co contracts** with non-DRC-dependent suppliers (those with integrated Indonesian Ni-Co resources)

Ternary **p/CAM production has rebounded**, ending a multi-year stagnation in [battery] nickel consumption

The move to **medium-nickel high-voltage NMC** chemistries has dampened Ni and Co demand

LCO battery capacities becoming larger in new electronic devices, but offset by rising voltages

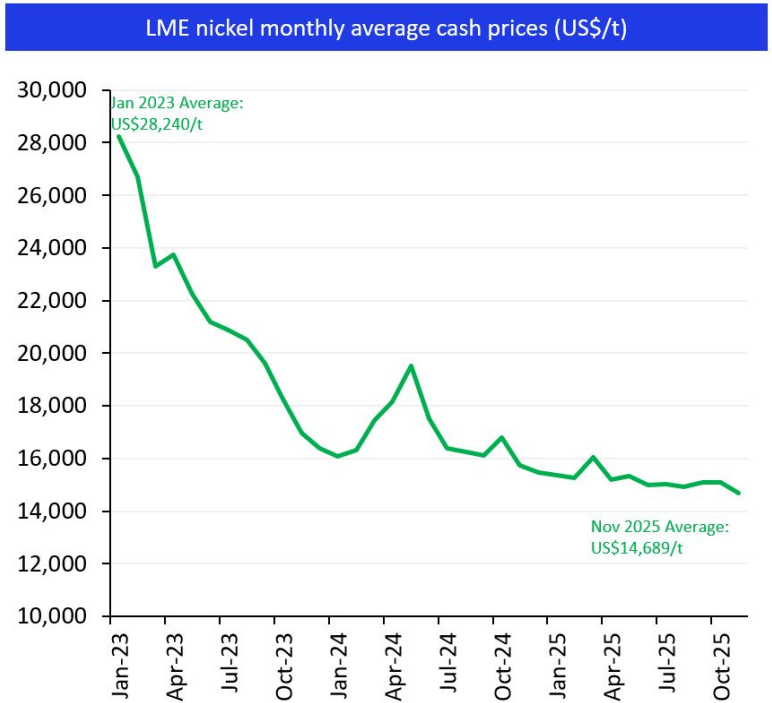
Integrated producers have ramped up **sulphate-to-nickel cathode** (non-battery) conversion, using surplus Ni supply that the battery industry cannot absorb

Rising national defence spending is boosting **Co metal demand**

Rising sulphuric acid costs putting pressure on Ni HPAL, but offset by stronger Co payables

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

LME Nickel Prices Have Halved Since 2023



From January 2023 to November 2025, the LME nickel cash price has fallen by 52%, with the monthly average price declining from US$28,240/t to US$14,689/t.

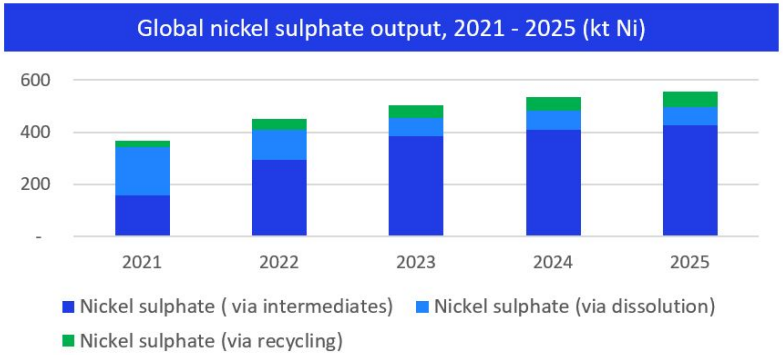
The sharp price correction has been primarily driven by a severe **oversupply of primary nickel products** - including Class I nickel, Class II products (nickel pig iron and ferronickel), and nickel sulphate - mainly originating from China and Indonesia. At the same time, nickel demand growth from the battery sector has been weaker than expected, as the rapid adoption of lithium iron phosphate (LFP) batteries has displaced nickel-based chemistries in mass EV market, mainly in China.

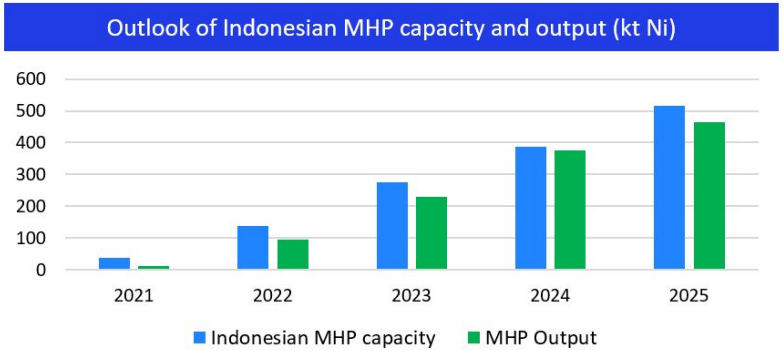
Since 2022, the global nickel market has been trapped in a state of structural oversupply.

China and Indonesia continue to dominate global nickel production, together supplying approximately 2.91Mt Ni in 2025, equivalent to 77% of total global output. Capacity expansions are ongoing in nickel sulphate and nickel cathode production, particularly in Indonesia.

Source: Project Blue, LME

Global Nickel Sulphate Supply is Dominated by China, Primarily Using Indonesian Intermediates





From 2021 to 2025, the largest growth in nickel sulphate supply has come from intermediate feedstocks, including MHP and matte. Nickel sulphate supply from intermediates grew at a CAGR of 28.4% over this period, reflecting the rapid ramp-up of mixed hydroxide precipitate (MHP) and nickel matte conversion capacity, primarily in Indonesia.

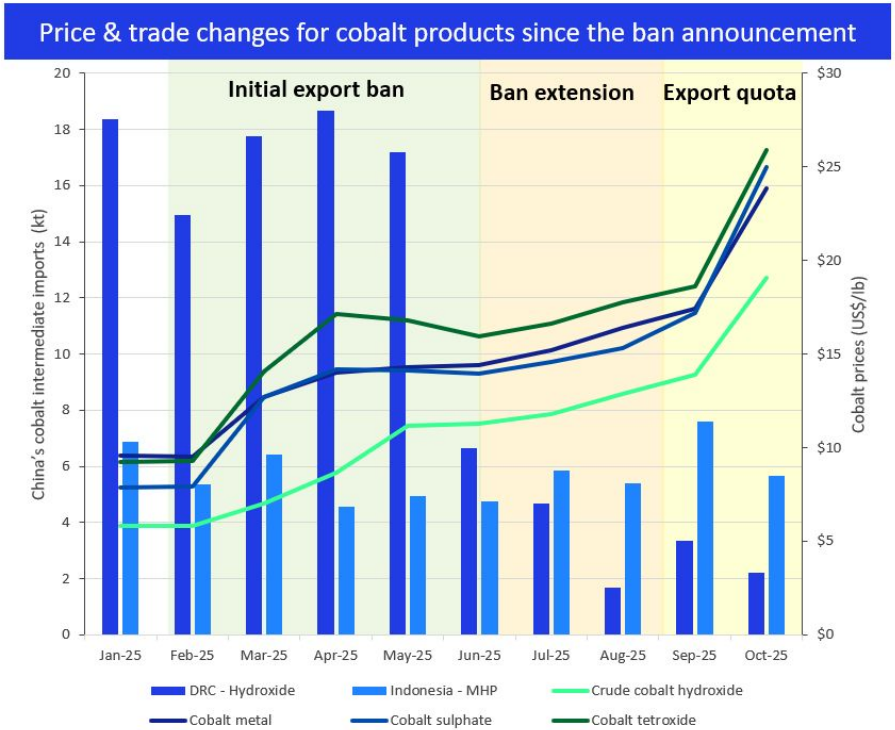
China has been dominating the nickel sulphate (via intermediates) supply in the world, accounting 76% in 2025. Chinese battery chemical producers, including Huayou, CNGR, and GEM, have developed integrated supply chains from intermediates through to cathode active material. Much of this capacity is located in China, based on intermediates produced from HPAL plants, oxygen-enriched side-blowing furnaces (OESBF) matte lines, and matte converted from NPI in Indonesia.

From 2021 to 2025, Indonesian MHP production grew at a CAGR of 142.5%. Since 2021, when Indonesia began producing MHP and feeding it to China's nickel sulphate production, **MHP has become a key nickel feedstock for NCM/NCA pCAMs production.** Its cost advantage over nickel matte, combined with its cobalt content, has made MHP a preferred feedstock in China's battery materials supply chain.

Nickel sulphate produced **from recycled feedstocks** (battery scrap and end-of-life [EOL] batteries) has become an increasingly important source of nickel sulphate supply, accounting for approximately 10.7% of total nickel sulphate output in 2025. Between 2021 to 2025, secondary nickel sulphate supply grew at a CAGR of 24.3%, driven primarily by China's expanding recycling capacity, supported by the legalisation of high-quality black mass imports starting in August 2025.

Source: Project Blue

DRC's Export Ban and Policy Announcements Impacting Global Cobalt Supply Chains



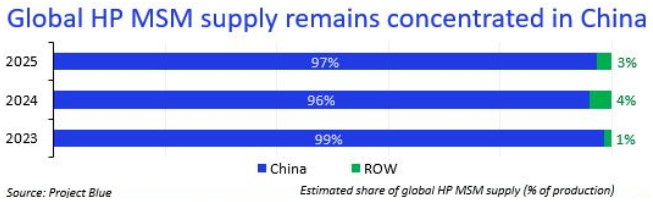
The export ban triggered sharp increases in prices increases across the cobalt market, with key battery chemicals (sulphate and tetroxide) reaching multi-year highs by late 2025, while spot cobalt hydroxide traded at par with, or at a premium to, cobalt metal.

Ongoing depletion of hydroxide inventories outside the DRC have constrained available feed causing Chinese refineries to reduce operating rates. While, increase their reliance on alternative feedstocks, including MHP, scrap, and cathode material.

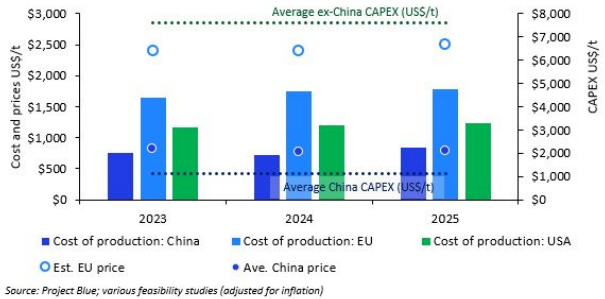
Source: Project Blue

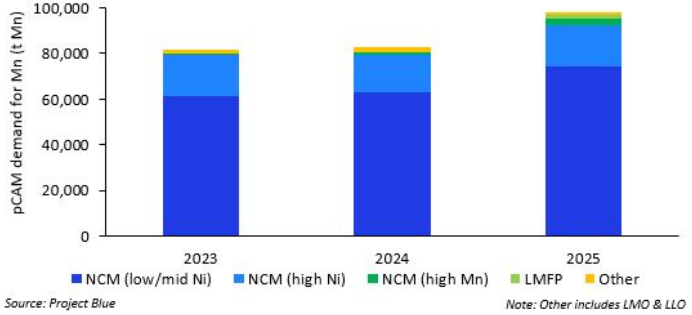
High-Purity Manganese Sulfate Monohydrate (HPMSM) Is the Primary Manganese Input for pCAM

Given the scale advantages embedded in China's cost structure, pCAM production trends in China remain central to global HP MSM availability and downstream cathode material supply.



Supply concentration in China reflects scale advantages that Western projects must achieve to offset higher capital and operating costs.

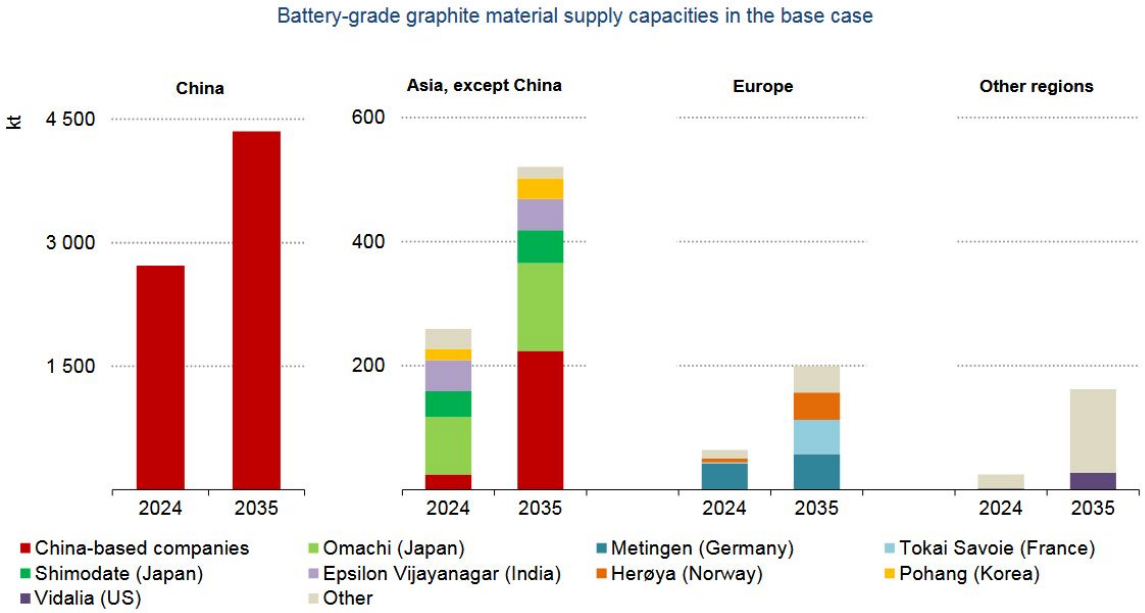




- HP MSM has remained the dominant manganese input for pCAM production in China, supported by large-scale monthly production.
- Sulphate, carbonate, and tetroxide inputs are all consumed at the pCAM synthesis stage and chemically converted during precursor formation, with input selection determined by the target pCAM chemistry and processing route, rather than the final cathode material. Sulphate-based routes dominate conventional NCM pCAM production, while carbonate- and tetroxide-based routes are typically used for LMO and high-Mn pCAM formulations.
- HP EMM (>99.99%) remains the dominant feedstock for tetroxide production and is also used as a starting material in selected HP MSM production routes.

Source: Project Blue

China Still Dominates Graphite Supply Chains



Graphite supply chains are highly concentrated in China.

Geopolitics has been the main near-term barrier, with export controls and tariffs making it worse.

Financing, long lead times, permitting, are major challenges for ex.China graphite producers. Energy costs, cost-competitiveness, and a lack of specialist know-how are other challenges specific to synthetic graphite anode producers.

Efforts to diversify graphite supply are advancing: Synthetic graphite is converging on Indonesia, Morocco, and North America, while natural graphite upstream is expanding in Africa.

See **Chemistry** section for more information.

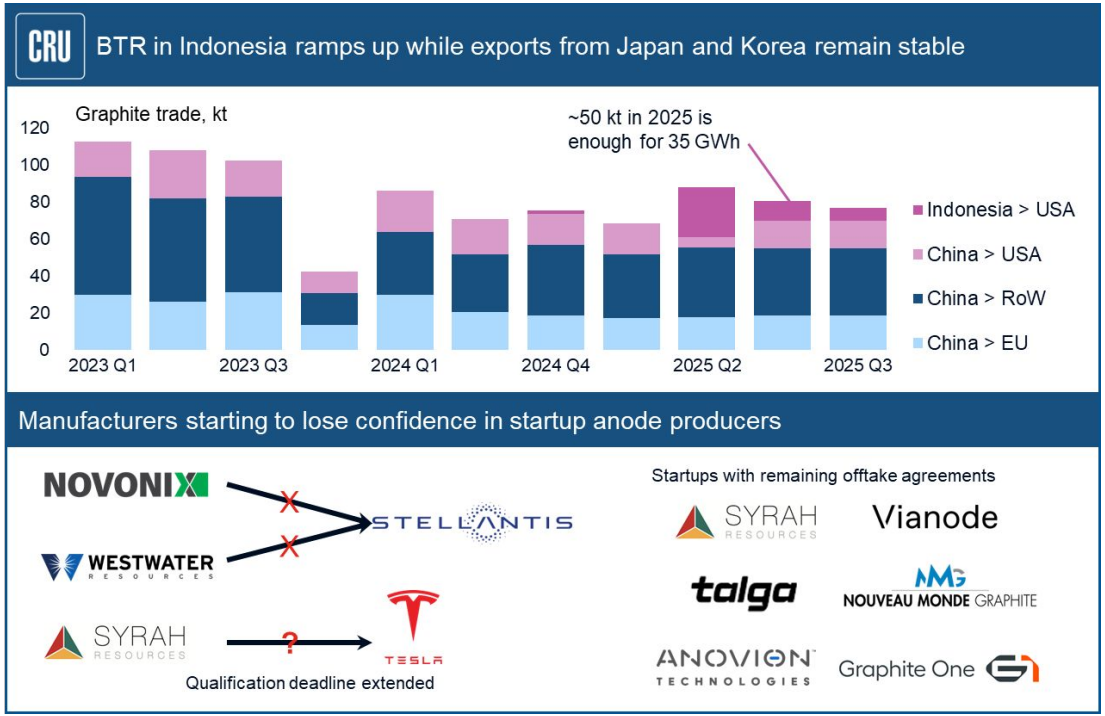
Source: IEA, company announcements

Supply Diversification: Emerging Graphite Producers Outside China in 2025



Source: Company announcements

Ex.China Anode Supply Is Growing, but Led by Incumbent Producers



Startups struggling to qualify material

Global production capacity for graphite anode active material has been overwhelmingly focused on China. Along with successive export controls on materials, equipment and know-how, graphite is an especially critical stage of the value chain. Ex. China sources, though, are being increasingly sought after.

Chinese-origin manufacturers are establishing production in jurisdictions where low energy costs and streamlined permitting facilitate the emissions-intensive production of synthetic graphite.

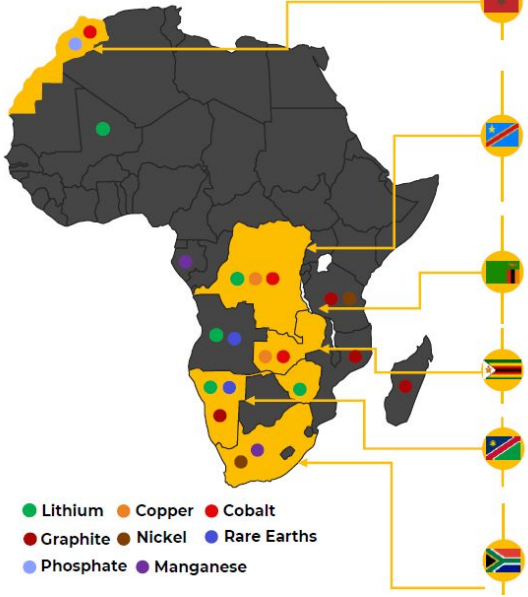
BTR has been ramping up its Indonesian operation and exporting mainly to US customers. Projects in Morocco are also in development.

However, startup producers in Europe and North America have been struggling to qualify their material to the specifications that their auto- and battery-maker customers demand, and the long lead time that this involves. This has already led to some offtake agreements being cancelled or on the verge of being cancelled.

Source: Content & analysis provided by CRU Group (Distinguished Partner), GTT. Japan and Korea trade volumes are not shown here.

Policies Are Aimed at Sustaining African Minerals' Growing Role in the Battery Supply Chain

POLICY STRATEGIES AIMED AT INDUSTRIALISATION AND ATTRACTING INVESTMENTS



- Leveraging automotive capabilities, logistical infrastructure, green energy and EU/US market access through **reliable industrial policy (e.g. industrial SEZs)**

- **Strategic partnerships** with the EU, the US and Zambia to develop a **local battery supply chain through SEZ**
- **Export restrictions**, renegotiation of mining agreements/JVs to increase government stake in mining projects

- **Critical Minerals Strategy (2024-2028)** aimed at local beneficiation through tax incentives and 30% state shareholding in new mining projects
- **Strategic partnerships** with the EU, the US and the DRC to develop a **local battery supply chain through SEZ**

- **Lithium beneficiation policy in line with Vision 2030**, prohibiting export of lithium ore (2022) and concentrates (2027), with a **mandate for lithium sulphate production**; providing tax incentives in SEZs

- **Export ban on unprocessed lithium**, limiting exports, which are subject to government approval

- **Critical Minerals and Metals Strategy (2025)** focused on **regional cooperation** and integration; export **licensing requirements** for certain minerals and SEZs supporting industrialisation

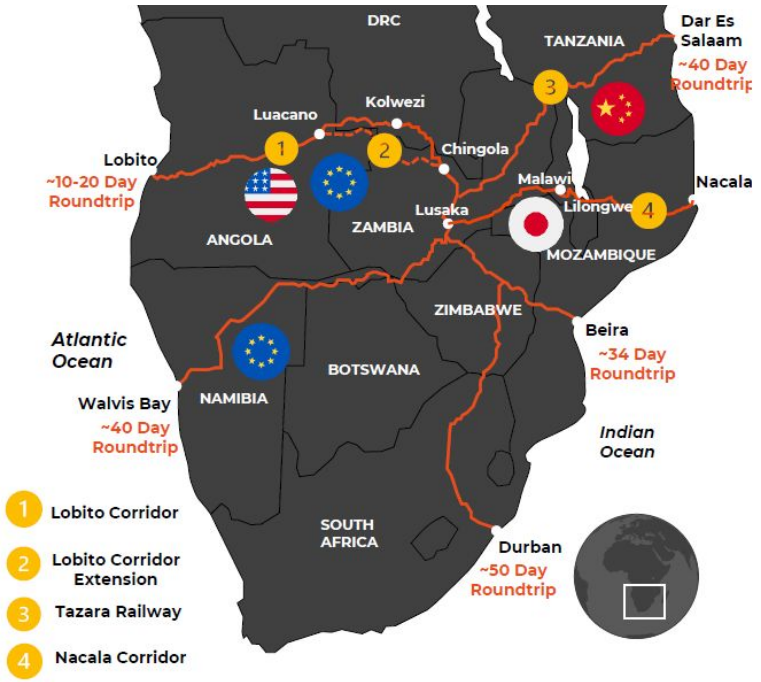
The US, China, and Other Global Actors Are Vying for Control of Key African Logistical Routes

The **African Copperbelt** and Eastern Africa are at the heart of resource geo-economic competition, with **infrastructure projects** backed by global actors vying for access to **critical minerals**:

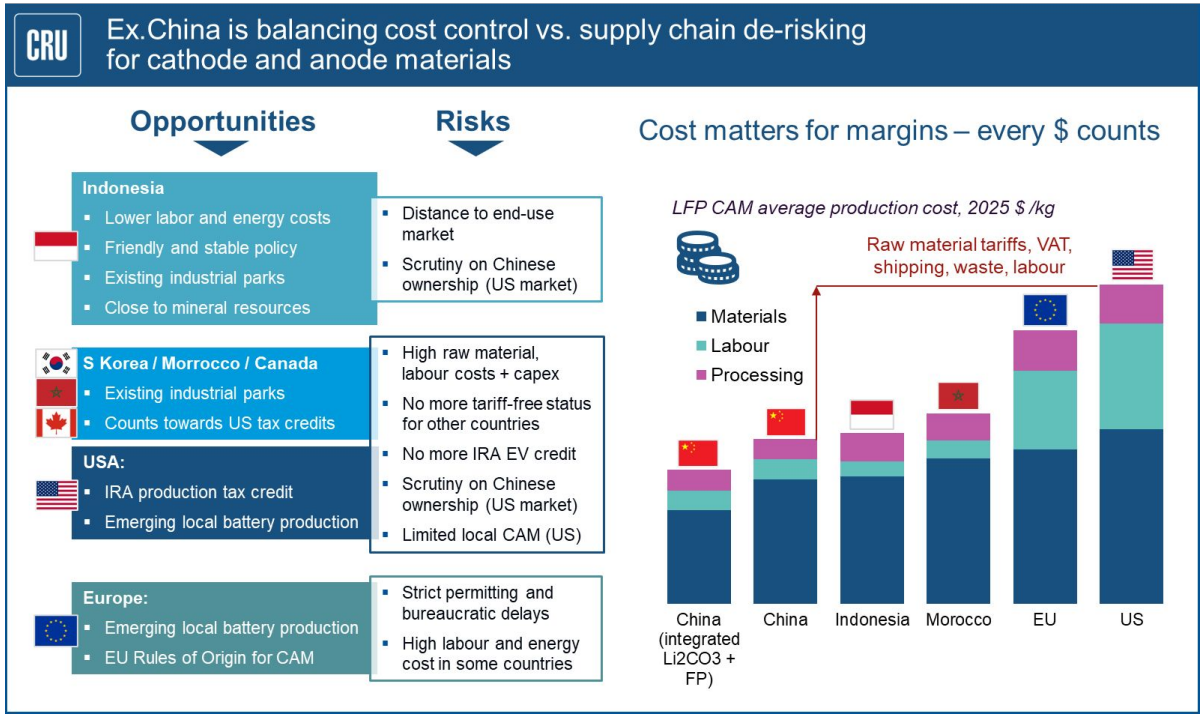
- Lobito Corridor Upgrade
- Modernisation of Tazara Railway
- Nacala Corridor Expansion
- Walvis Bay Corridor Upgrade

Infrastructure and logistical upgrades are key for **value-addition** and **green industrialisation** as they facilitate:

- Regional economic integration and cooperation
- Development of industrial clusters and ecosystems
- Foreign investments and diversification
- Trade connectivity between African and ex-African hubs



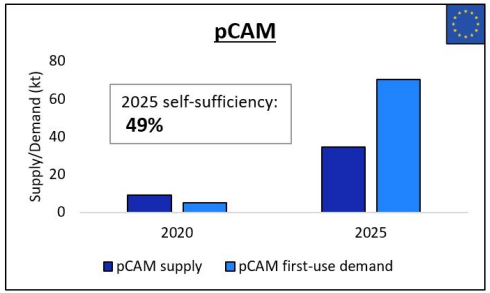
What Is Driving or Holding Back Midstream Capacity Outside China?

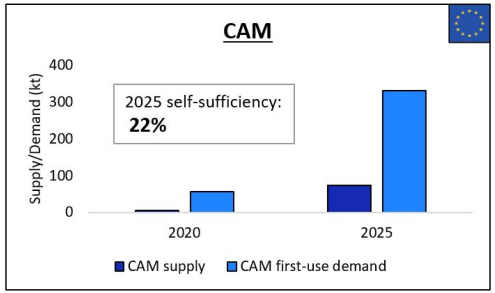


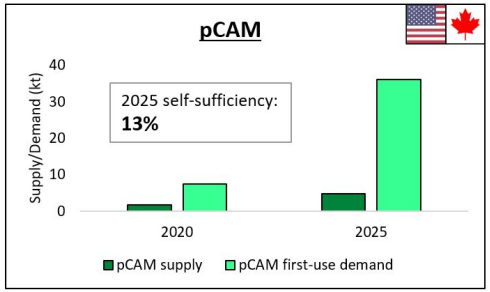
- Asian producers have been pivoting their strategies to capture overseas markets
- Europe and North America are working to nurture a domestic supply chain while adopting policies to reduce reliance on China. China is responding with technology export controls.
- Precursor and cathode material production - the first point of consumption for battery chemicals - is gradually expanding outside China.
- But the **higher costs and investment risks** are deterring more profound investments
- Therefore, supply clusters up to now have been converging on what are seen as low-cost, low-risk countries like Indonesia and Morocco to supply the major markets

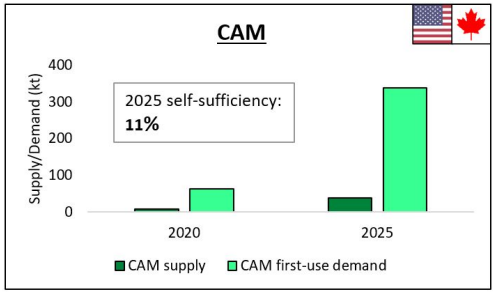
Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

Building Regional Midstream Supply Chains in Europe and North America Remains a Challenge









There is a significant shortage of precursor (pCAM) in Europe and North America, leading cathode active material (CAM) producers to be heavily reliant on imports. This can raise production costs and increase supply chain complexity, which is passed through to cell manufacturers.

A supply shortage also exists for CAM when compared to its first-use demand in battery cell production in Europe and North America, highlighting a strong, structural mid-stream deficit in Western markets.

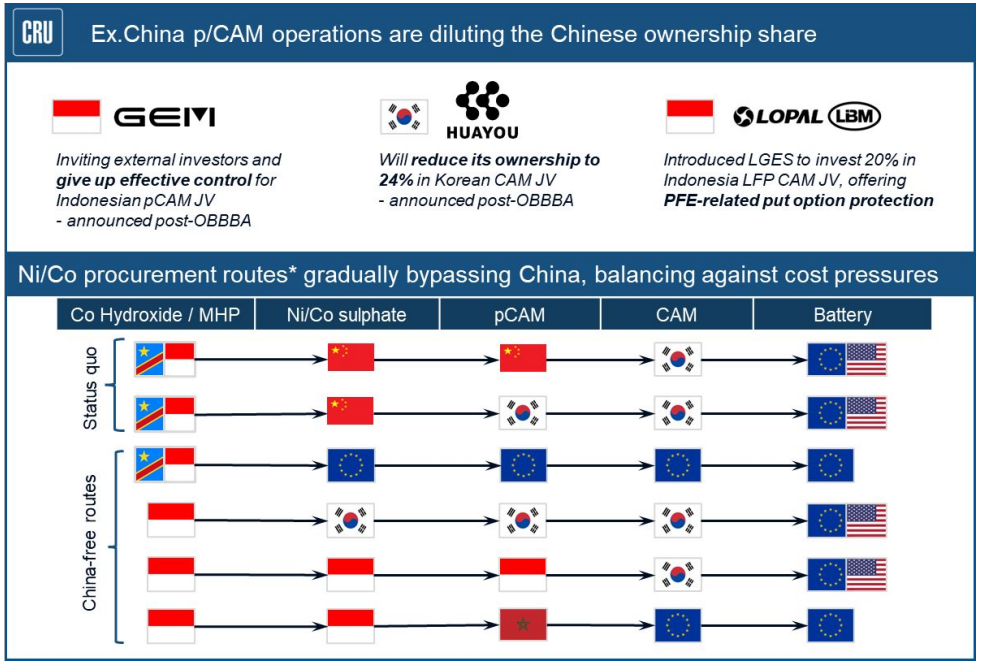
In 2025, many of the South Korean CAM operations that supplied the US market manufactured CAM using pCAM imported from China.

There is a particular shortage of LFP pCAM (iron phosphate) and CAM projected in both regions, where a heavy dependence on China for precursor material will remain. Chinese producers benefit from a highly integrated and mature supply chain further upstream, meaning supply is plentiful and quality standard is high. This presents some key challenges for European and North American markets given a desire for low-cost EVs in these regions. If a desire to move away from Chinese involvement remains, then more must be done to overcome this deficit.

The mid-stream suffers from notoriously tight margins and typically exhibits shorter contract, resulting in more limited visibility of future volumes and cashflow. Appetite for investment is therefore often far reduced compared with the more downstream, value-add areas of the lithium-ion battery supply chain.

Source: Project Blue

The Spirit of 'FEOC' Lives on in Efforts to Build Non-PFE Supply Chains



Under new US tax credit rules, use of Chinese critical minerals now faces looser restrictions for battery makers.

However, in 2025 US automakers and battery manufacturers continue to de-risk their supply chains with **3 strategic choices:**

1. Bypassing geographical China
2. Encouraging dilution of the Chinese ownership share in operations that supply them
3. Shunning Chinese-owned operations altogether

They are balancing this against cost pressures, given the general cost gap versus Chinese supply.

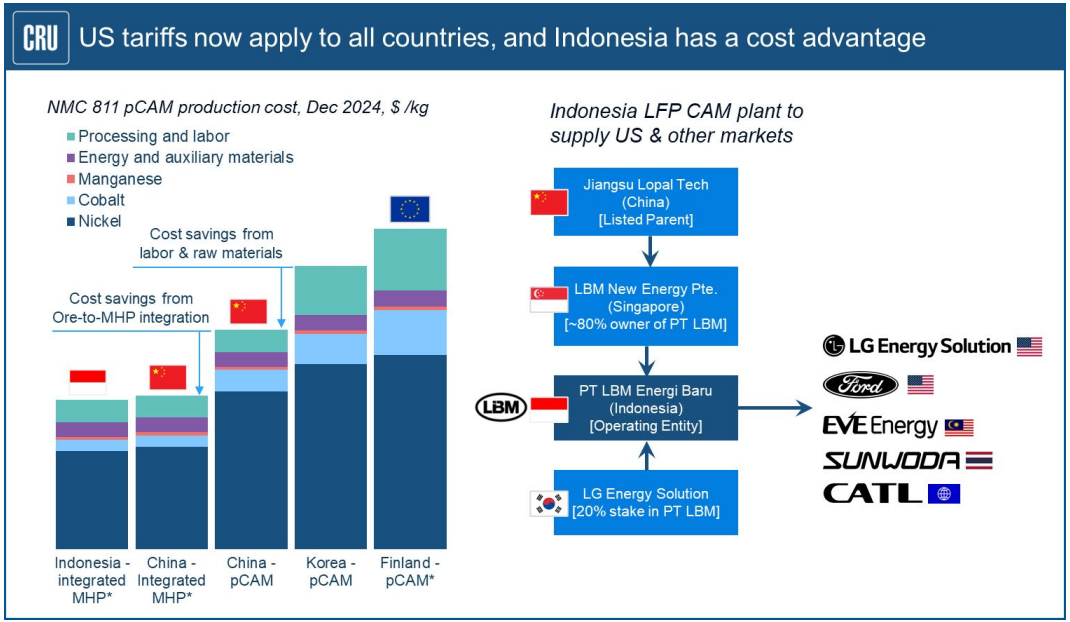
Despite there being a lack of clarity on whether the MACR rule extends beyond CAM, pCAM producers are preparing for a worst-case scenario and using the Biden-era ownership rules as an assumption.

For raw materials, nickel and cobalt are the most critical given the particular dominance of China. The major emerging procurement routes involve Indonesia as a growing vertically integrated supply base, given the availability of MHP.

However, DRC Co hydroxide and Chinese Ni/Co sulphate still retain most market share, given extensive capacity and limited incentives beyond indirect US tax credit benefits for Chinese producers to de-risk and diversify away from the status quo.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.
*Non-exhaustive list of examples

Indonesia Has Emerged as a Key Beneficiary of US Policy Changes



New investment and deals in former US-FTA countries have slowed. Until recently, the Biden-era EV tax credit offered Asian companies two main strategic options:

1. Invest in US-free-trade-agreement countries (FTA) to meet IRA compliance and secure OEM contracts eligible for the EV tax credit
2. Set up in non-FTA countries, forgoing the tax credit but benefiting from lower production costs – a more profitable path for upstream and midstream players not claiming the tax credit directly

Since the EV tax credit is repealed and since free trade agreement status is no longer applicable, production and new investment is now shifting decisively toward cost control, and Indonesia is emerging as a beneficiary.

It has an integrated ore-to-MHP advantage and extending further into the pCAM stage, which offers meaningful cost savings, even compared to China. It has a similar cost profile for LFP CAM and synthetic graphite.

This shift is occurring at the expense of Chinese and South Korean production, as Korean producers face significantly tighter margins than their Chinese and Indonesian counterparts while PFE rules set barriers for Chinese materials entering the US market. It has also slowed new investments and agreements in Morocco and Canada.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com

2025 | BATTERY REPORT

INDUSTRY

VF | VOLTA FOUNDATION

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- **Recycling & Secondary Markets**

Software / AI

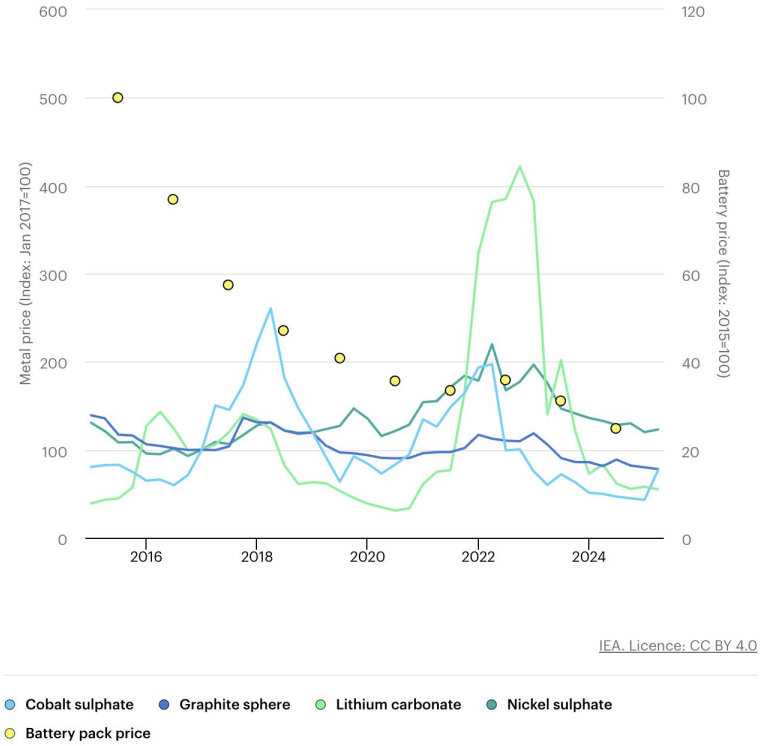
Opportunities & Challenges in the Recycling Industry in 2025

Trade Policy: China's 2025 legalization of black mass imports presents an opportunity for preprocessing recyclers, but composition requirements (e.g., water-soluble fluoride ≤ 0.4% (NMC/LCO) & ≤ 0.1% (LFP)) pose a challenge.

Partnerships: New partnerships between OEMs and recyclers continue to be announced (e.g., BMW with SK Tes in January 2025). These partnerships help secure feedstock for recyclers and help isolate OEMs from the raw material price volatility through fixed-price contracts.

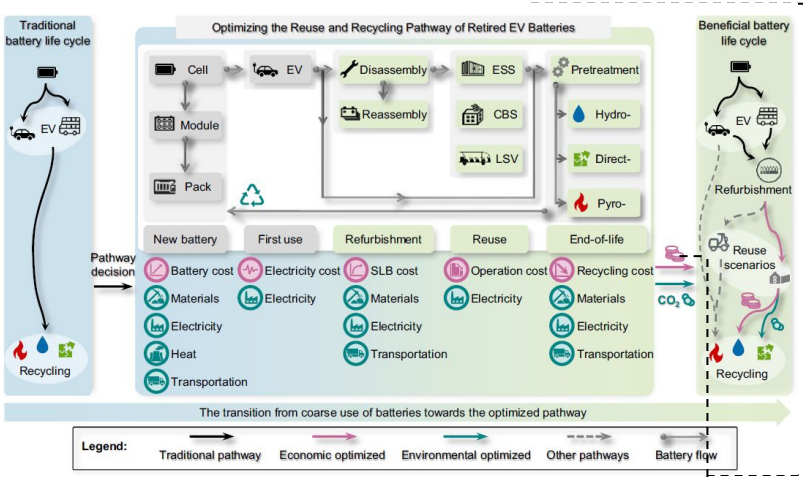
Price Volatility: Metal prices (Nickel, Cobalt, Lithium, etc.) dropped significantly since 2023 and have been volatile over the last decade; however, long-term estimates of value creation potential for recycling are expected to resemble those of the primary metals industry, which shows up to 30% growth.

Overcapacity: Recyclers in both the EU and China face fierce competition and overcapacity, leading to low feedstock levels and utilization rates.



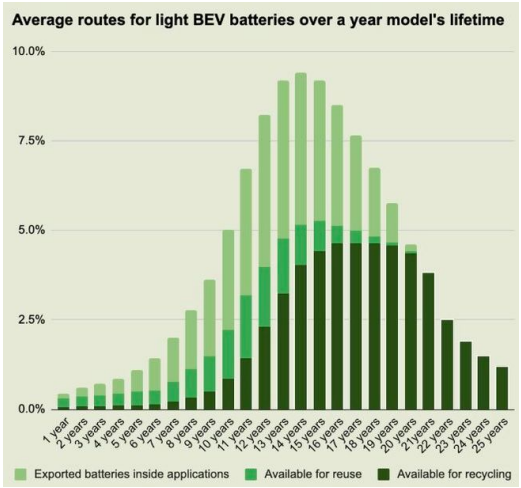
Pathway Decisions: Reuse Versus Recycling

The LIB life cradle-to-grave cycle incorporates new battery production, first use, refurbishment, reuse, and end-of-life (EOL) stages.



Applications in the reuse phase include **energy storage systems (ESSs), communication base stations (CBSs), and low-speed vehicles (LSVs)**. Pink and teal icons illustrate the economic and environmental functions of each stage.

At the EOL stage, pretreatment and 3 recycling technologies are considered, including hydrometallurgical, direct, and pyrometallurgical recycling.



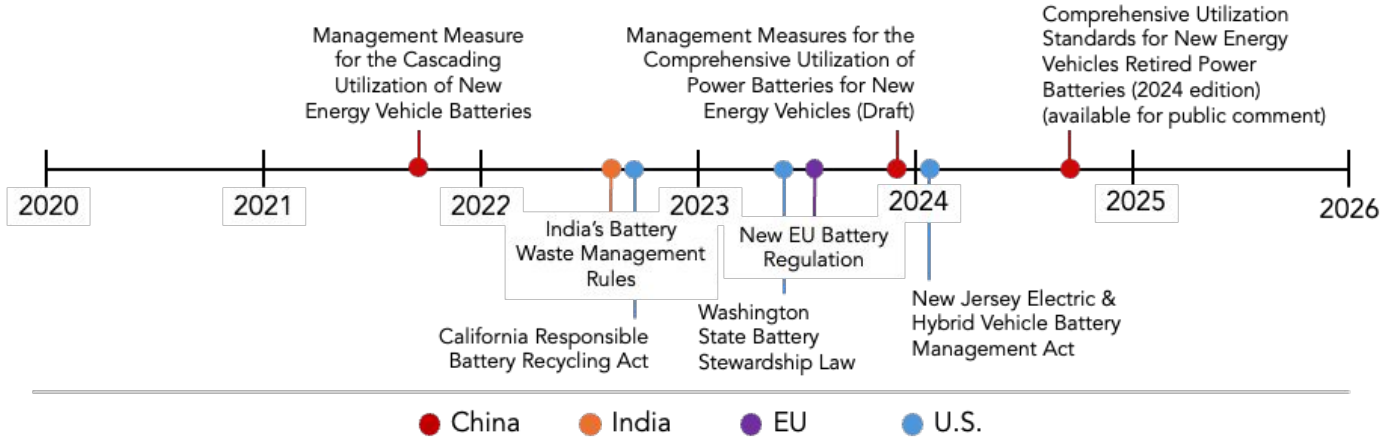
Aggregated anticipated lifecycle of BEV models in Europe and United States

The life cycle of a battery begins with material extraction, refinement, component (cell) production, and assembly into modules and packs. These packs are used in electric vehicles (EVs) during the first use stage, after which the battery packs are disassembled, tested for viability, and reassembled for further use during the refurbishment stage. **The second-life battery (SLB) costs are related to the state of health, residual capacity potential, resourcing, repurposing, amount of retired batteries, refurbishment technology efficiency, and reuse rate.** The operation cost comprises daily maintenance costs and operational costs.

Source: R. Ma et. al (2024) ; CES Online/The Battery Lifecycle Report 2025 by Circular Energy Storage

Strong EOL Management Policies

Individual U.S. states have begun joining the EU, China, and India with strong EOL management policies that include extended producer responsibility agreements (EPRAs).



India's Battery Waste Management Rules (2022): establishes requirements for EPRAs, bans the incineration and landfilling of batteries.
EU New Battery Regulation (2023): sets recycled content standards, recycling recovery targets, and battery passport requirements
China's Comprehensive Standards (2024): updates and adds targets for recovery rates and repurposing annual volume
New Jersey's Battery Management Act (2024): lays out EPR requirements, bans the landfilling of batteries

The EU and India Remain Leaders in Setting Recycled Content Standards, Though Targets Differ in Specificity

Multiple analyses predict that the EU's RCSs may be difficult to achieve given today's recycling technology and feedstock levels, depending on the material.

Thus, many worry that the EU's RCSs could have unintended consequences, like disincentivizing reuse and repurposing, encouraging shorter battery lifespans, and encouraging higher manufacturing waste rates.

Similarly, experts have identified a number of challenges to achieving India's RCSs, including a lack of battery data management infrastructure (and relatedly, battery passports), formal end-of-life battery collection, and technical standards for recycling technology.

EU RCS (NEW BATTERY REGULATION - 2023):

Material	2031	2036
Cobalt	16%	26%
Lead	85%	85%
Lithium	6%	12%
Nickel	6%	15%

INDIA RCS (BATTERY WASTE MANAGEMENT RULES - 2022):

Battery Type	2027-28	2028-29	2029-30	2030+
Portable	5%	10%	15%	20%
Electric Vehicle	5%	10%	15%	20%
	2024-25	**2025-26**	**2026-27**	**2027+**
Automotive	35%	35%	40%	40%
Industrial	35%	35%	40%	40%

Recycling Capacity in China Exceeds That of Other Regions, and the Government is Attempting to Regulate It

China's Whitelist: The whitelist is reserved for companies which meet the government's "Industry Standard for Comprehensive Utilization of Waste Power Batteries of New Energy Vehicles"; the 2024 edition of these standards updates recovery rate requirements (e.g., Lithium target moved from 85% to 90%) and environmental requirements (e.g., fluorine emission recovery rates must be >99.5%).

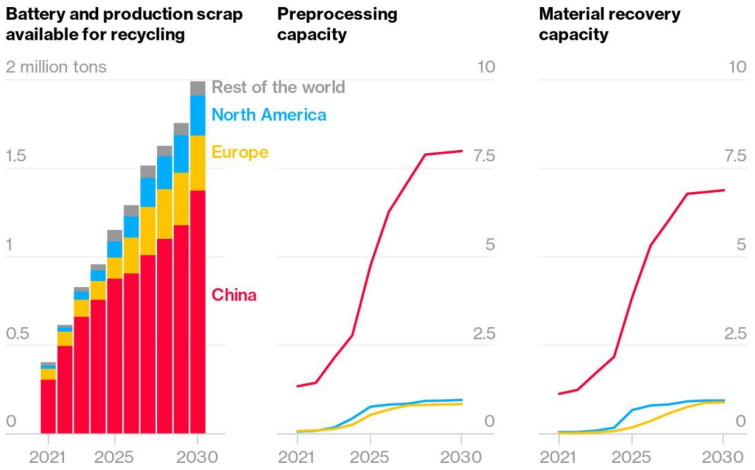
Currently, 156 companies are on the whitelist, compared to an estimated 196,000 battery-recycling-related companies that are operational in China.

Companies not on the whitelist can operate without proper environmental and waste management, lowering their operating costs in a hugely competitive market that is at serious risk for having more recycling capacity than feedstock. Consequently, current utilization rates at whitelisted companies are said to be relatively low.

See **China section** for more information on China's recycling policies and industry.

China's Dominance in Battery Recycling

China has more than half of the world's battery and production scrap, and leads in preprocessing and material recovery capacity



Source: Circular Energy Storage
Note: Pre-processing refers to the steps to turn used batteries to intermediate waste products. Material recovery refers to the process where materials are turned into chemical products for use in battery value chain or other industries.

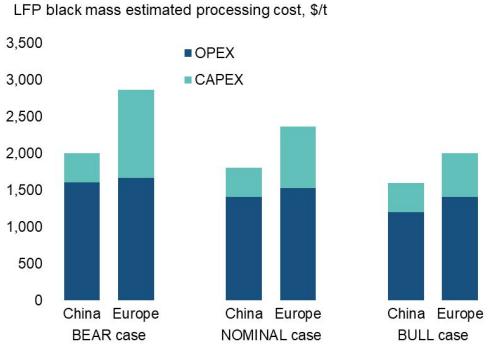
Bloomberg

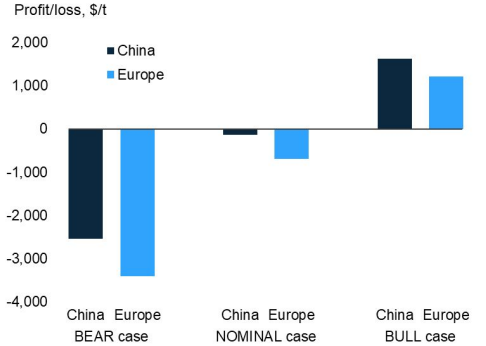
Source: China MIIT, Department of Economy and Information Technology of Hubei Province, Fastmarkets

How Can LFP Recycling Be Profitable?

Economics of LFP recycling rest on a knife edge

Profitability is especially precarious outside China





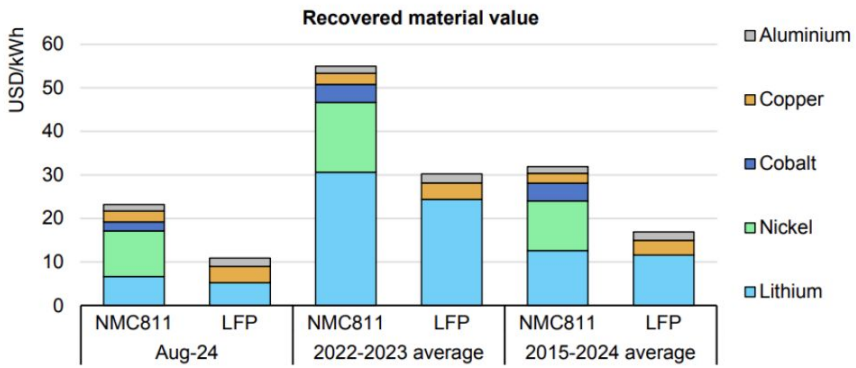
- The **material content value** of LFP is fundamentally less than that of NMC. This poses a complex technical and commercial challenge for recycling as LFP adoption grows globally.
- LFP recycling in China is not so much an issue, despite popular belief, as capex and opex are low, black mass feedstock is abundant, recovery rates are higher for some recyclers, and many companies operate on tolling arrangements.
- However, profitability is especially precarious for operations overseas such as in Europe.
- Technical innovation can mitigate costs and are becoming the key differentiator for recyclers in this cost-sensitive market. But this only goes so far - feedstock costs (black mass and reagents) and revenue (lithium prices) remain the determining factors.
- The path forward may lie in the market increasingly moving towards **closed-loop arrangements** to eliminate recyclers' feedstock costs.
- Policies are increasingly being enacted to encourage/require LFP recycling take place and/or put the burden of recycling on the OEM.

Source: Content & analysis provided by CRU Group (Distinguished Partner), Worley.

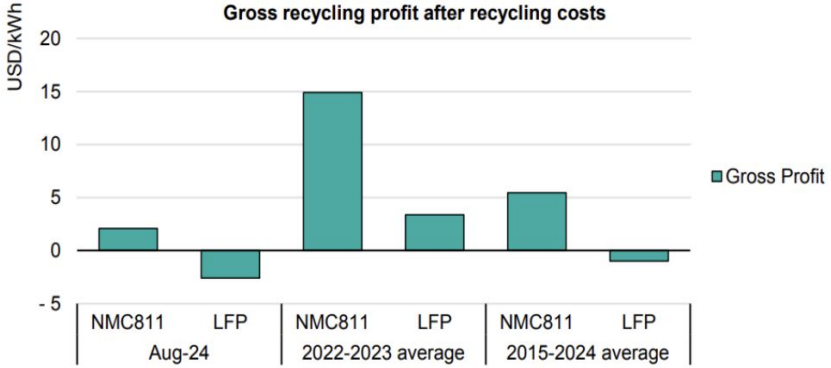
Recycling Profitability Is Heavily Influenced by Changing Material Prices

Because of their material content, NMC batteries have historically netted a marginal profit when recycled while LFP batteries have bore little to no profit. This disparity has in the past encouraged LFP battery reuse when possible to maximize residual value recovery.

AVERAGE RECOVERABLE MATERIAL VALUE OF NMC 811 VS LFP



RECYCLING PROFITS ARE SIGNIFICANTLY LOWER FOR LFP, OFTEN RESULTING IN A LOSS FOR THE RECYCLER



Notes: Analysis using lithium carbonate, lithium hydroxide, nickel, cobalt and copper prices from August 2024, the average prices from 2022-2023, and the average long-term prices from 2015 until August 2024. Based on hydrometallurgy process. Lithium hydroxide prices are used for NMC811 and lithium carbonate prices for LFP. Based on market-based recycling business model. Average domestic material recovery facility capacity in 2023 used – 10 kilotonnes (kt) of battery pack for the United States. Includes black mass purchase cost for each chemistry.

Source: IEA

Environmental Benefits Are Highest for NCM/A Cathode Chemistries & Processes Other Than Pyrometallurgy

Mining of input materials for LFP is less CO_2-equivalent (CO_2e) emissions-intensive than for NMC/A chemistries, resulting in relatively less environmental benefit from recycling LFP than the nickel- and cobalt-based chemistries. Furthermore, pyrometallurgical recycling has been shown to result in greater CO_2e emissions than hydrometallurgical and direct recycling for the same battery cathode chemistry.

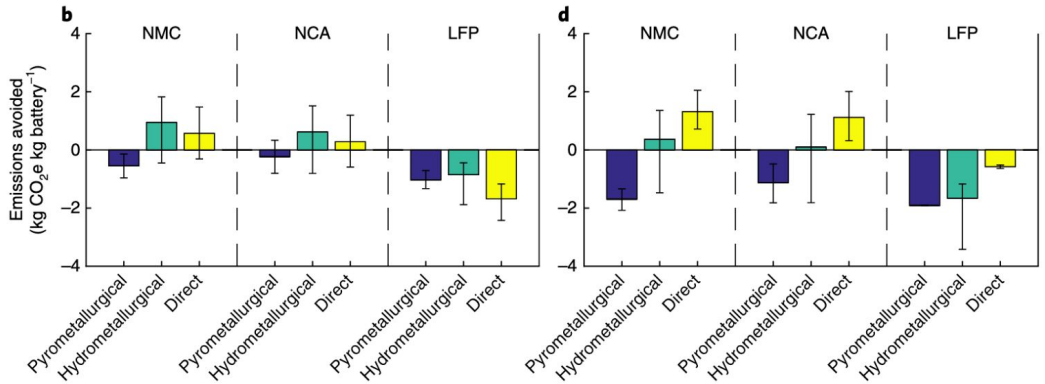


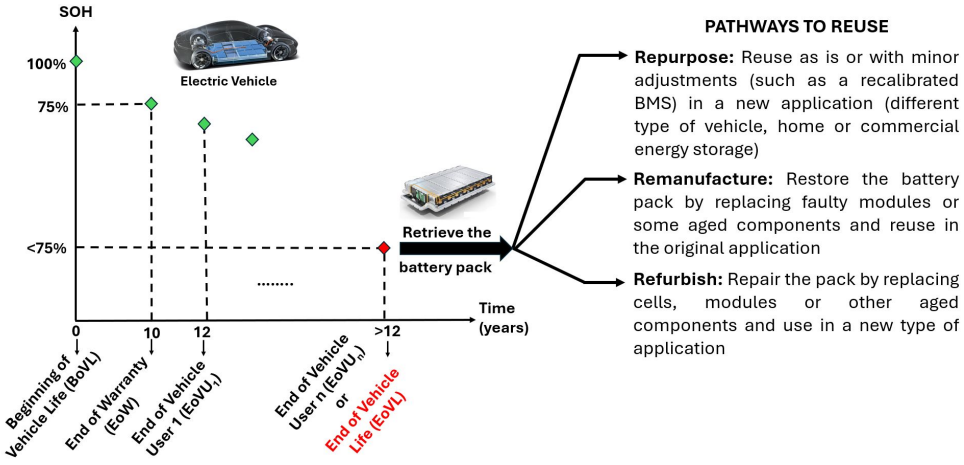
Fig. 3 | Battery recycling emissions. a–d, Medians and 95% confidence intervals for CO_2e emissions per kg less the CO_2e offsets from recovered materials (**a**,**c**), and net CO_2e emissions avoided by using each recycling process (**b**,**d**) for cylindrical (**a**,**b**) and pouch battery manufacturing and recycling processes (**c**,**d**). All processes use US average electricity grid data.

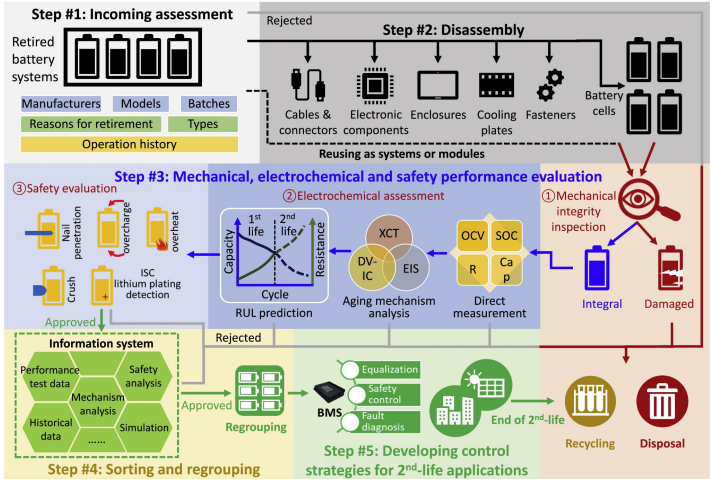
Figure source: Ciez & Whitacre (2019)

Source: Ciez, R.E., Whitacre, J.F. Examining different recycling processes for lithium-ion batteries. *Nat Sustain* 2, 148–156 (2019), Dunn et al. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. *Resources, Conservation, and Recycling 185*, (2022)

Second-life Batteries (SLB): An Overview

The pathway to second-life has 3 steps: receive, then assess to finally redeploy.





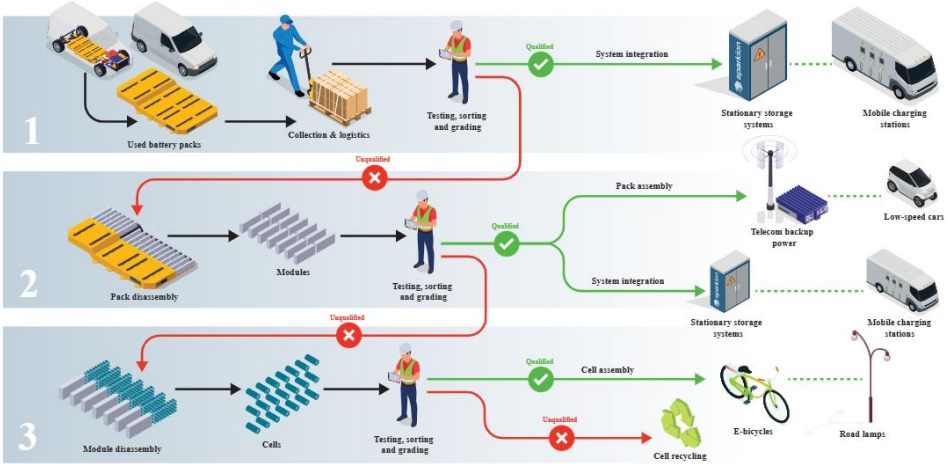
Retired battery assessment procedure involving many costly human-aided steps with inevitable uncertainties.

Battery packs typically consist of series-and-parallel-connected modules, with each module further consisting of series-and-parallel-connected cells. **Packs have "weak" cells which can affect modules and, thus, remanufacturing might extend the majority of the pack's life.** For those with low remaining useful life (RUL), either the entire pack can be repurposed, or only the useful modules/cells can be salvaged and become parts for refurbished packs.

Source: Roy et. al (2025), J. Zhu et al (2021)

Second-life Batteries: Current Applications

Batteries are typically repurposed from a strenuous application (mostly mobility) to less demanding use cases



Repurposing can be done at the pack, module, or cell level: The prospect of disassembling a retired pack is valuable as it can increase the proportion of modules/cells that can be repurposed and also reduce the probability of a faulty or weak module/cell making its way into a second-life use case it is not fit for. To extend the lifespan of batteries, it is **essential to design them in a way that ensures reparability while also creating an ecosystem of repair centers supported by a skilled workforce** that is certified to work with high-voltage systems.

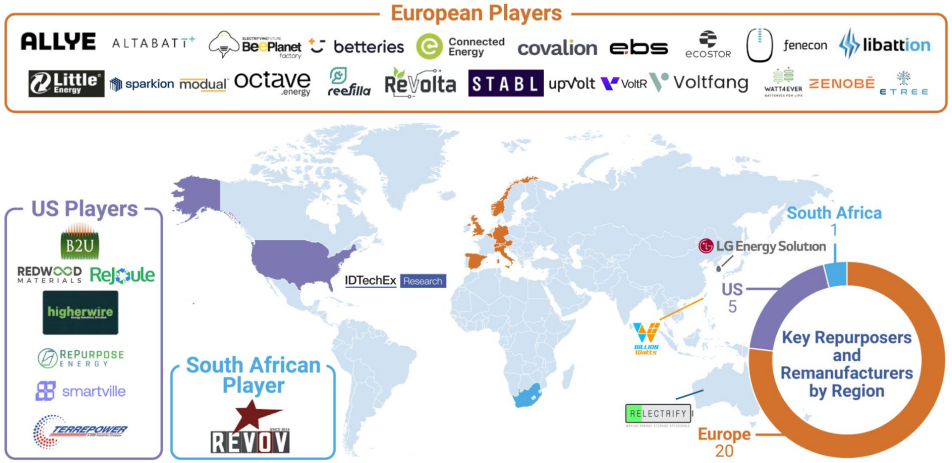
Behind-the-meter Application	Residential	Commercial	Industrial
Renewables Integration	0–150 kWh	0–500 kWh	0–10 MWh
Energy Arbitrage	0–60 kWh	0–500 kWh	N/A
Peak Load Shaving	0–60 kWh	500–4500 kWh	0–4 MWh
Back-up Power	0–40 kWh	0–700 kWh	0–4 MWh
Small Mobility Vehicles	0–15.3 kWh	0–8 kWh	11–25 kWh
EV Charging	0–20 kWh	0–1 MWh	0–5 MWh
Demand Response	N/A	0–2 MWh	0–4 MWh
Microgrid	0.02–2 MWh	2–6 MWh	6–20 MWh

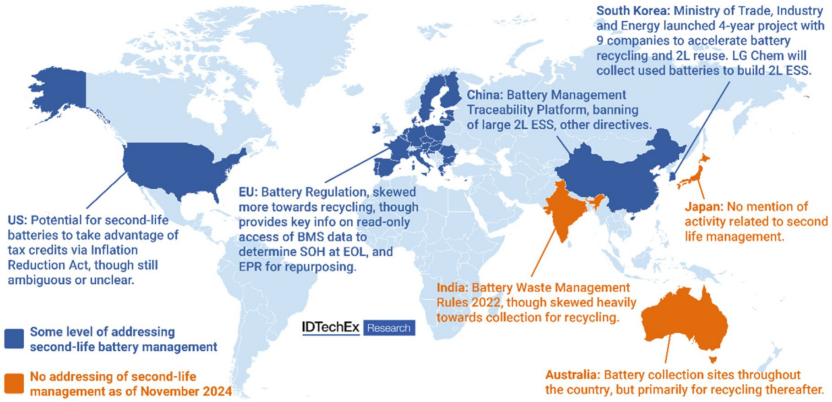
SLB viability: **Green** - suitable, **yellow** - sometimes suitable, **red** - not suitable (economic infeasibility or high C-rates).

Repurposing	Providers (non-exhaustive list)	Offerings
Pack	B2U, RELECTRIFY, ReJoule, smartville, ELEMENT ENERGY	C&I and grid scale BESS, diagnostics
Module	ReJoule, Relyion	C&I BESS, diagnostics
Cell	CURRENTS MARKETPLACE, VoltR, REPURPOSE ENERGY	Retrieving healthy cells from retired packs

Source: Sparkion, Roy et al (2025), Patel et al. 2024.

Second-Life Market Is Growing, Although It Is Challenged by Very Low Cost of New LFP Batteries





- Moment Energy's Luna becomes first repurposed BESS to achieve all key safety milestones
- Relyion completes UL9540A testing for second life EV cells
- B2U is making a 100MWh foray into Texas' volatile energy market
- Redwood Materials built a 63MWh microgrid for AI data center & signed an MoU with GM
- Voltfang to operate large-scale storage facilities for Palladio Partners
- Zenobe powering Extreme E's remote operations using batteries from Stockholm's e-bus fleet
- LG Energy Solution has built and is operating an SL BESS in Ochang, SK
- Valeo & VoltR to power small electric mobility vehicles with SLBs
- DNV & ACCIONA Energía to assess SL BESS against European standards
- ANSYS accelerated Element Energy's BMS design process
- Volkswagen Group, Audi, EON to stabilize grid loads with SLBs
- US DOE cancelled funding for ReJoule & Smartville

Source: IDTechEx

Second-life Batteries: Development/Scale Up Pain Points & Challenges [1/2]

Understanding and addressing the challenges of battery second life is the key to unlocking its potential - transforming the value chain and creating a robust techno-economic pathway for sustainable energy storage solutions

- Understanding second-life challenges is the foundation for unlocking their full potential.
- Addressing these challenges can transform the battery value chain and extend lifecycle benefits.
- A clear techno-economic roadmap enables sustainable and cost-effective energy storage solutions.

ID	Challenge Category	List of Challenges

1	**Technical Challenges**	• Complexity of status assessment & technical performance evaluation
		• Current aging status & initial evaluation
		• Aging Parameters
		  ○ Especially from long-term field and indoor experience
		• Safety
		  ○ Safety and avoidance of thermal runaway
		  ○ Electrical evaluation & prevention of short circuits
		  ○ Prevention of leakage and explosion
		• Performance & reliability
		  ○ Under new operation conditions
		• Battery Model
		  ○ Aging parameters & SOH/SOC models
		  ○ Product sizing & engineering design

2	**Economical Challenges**	• Uncertainty in cost (mainly quantity & quality of batteries) • High logistics cost • Insurance unclarity • High cost of evaluation & preparation for reuse • Uncertainty in lifetime & performance • Ability to provide a consistent business model • TOTAL Cost of Ownership

3	**Battery Standards & Regulations Challenges**	• Still lacking battery checking and usage standards development
		  ○ US
		  ○ EU
		  ○ China
		  ○ Others
		• Existing Standards Complexity of implementation e.g. UI 1974
		• Battery life regulations relating to value during 2nd life
		• Product Testing requirements
		• Lack of Reuse targets
		• Waste rules (often very strict regarding disposal & reuse of EOL battery)

Source: Taga BelArabi

Second-life Batteries: Development/Scale Up Pain Points & Challenges [2/2]

ID	Challenge Category	List of Challenges
4	**Logistics Challenges**	• EOL Batteries transportation cost and Risk during transportation • Lack of safe handling and storage over logistics & value chain
5	**Data Challenges**	• Data availability on real-life battery operational conditions • Data for battery aging models

6	**Startups and new entering plays**	• Providing the needed eco system for
		  ○ Business case development
		  ○ Startup Ecosystem requirements

7	**Ecosystem & Market**	• Ecosystem & market maturity maturity
		  ○ Including localized of transportation supply chain from 1st life battery end-owner to 2nd life enabler (e.g. Repurposing Company)
		  ○ Exclusive contracts between 1st & 2nd life key stakeholders
		  ○ Wellness of OEM's to step into the 2ndl life value chain stage and cover it totally for relevant end-customers



Case Study: Redwood Energy

"Redwood has already deployed its first microgrid powered by upcycled EV batteries. The grid, with **12 MW** of power and **63 MWh** of capacity, is located at the company's campus in Nevada and is being used to power a 2,000-GPU modular data center for AI infrastructure company Crusoe.

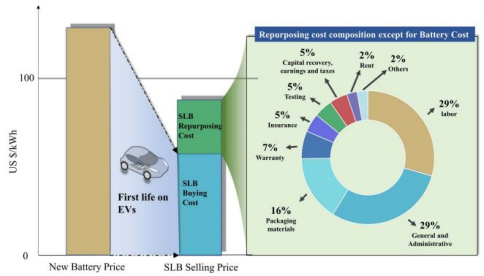
Redwood calls it the **"largest second-life battery deployment in the world"** with enough energy to power "9,000 homes, support 20 Amtrak trips between New York and Washington, D.C., or charge an EV for a 240,000-mile journey - the distance to the moon."

Source: Taga BelArabi, Redwood Materials is giving old EV batteries a second life as microgrids | The Verge

Battery Repurposing: A Budding Industry Facing Fierce Competition

High Cost of Repurposing

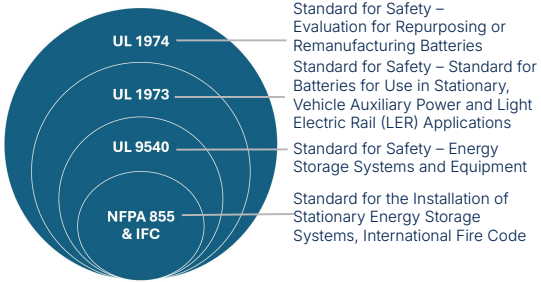
- Used battery buying cost + repurposing cost could exceed the price at which a new battery can be purchased
- **Transportation costs can be prohibitive**, since LIBs are Class 9 hazardous materials (as per DOT)
- **Diagnostics form a major part of the cost** - need to be rapid and accurate
- Data-driven diagnostics at the module and pack level (such as those offered by Smartville & ReJoule) are promising but need to be validated extensively to be generalizable



Selling price comparison between new battery and SLB and the SLB repurposing cost composition (except for battery cost). Source: Li et al. (2023).

Cumbersome Certifications

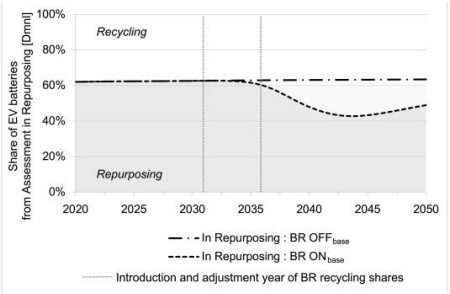
- **Requires cooperation from OEMs but they are unwilling** to share the liability burden
- Certification processes are specific to every cell type - tests need to be repeated even if two cell types are largely identical
- **Inefficient testing** procedures
- UL standards (UL 1974) are not strictly enforced
- **Perceived safety risk**, even though there are no reported thermal events in second life battery assets yet



Regulatory framework (in hierarchical order) for second-life batteries. Source: Roy et al. (2025)

Fragmented Policy

- Currently **the US does not have EPR in all states** (New Jersey passed a bill and 12 others to follow). California's Senate Bill 615 (passed) makes battery digital identifiers mandatory.
- **US DOE's focus has shifted towards supply chain** onshoring, support for circularity withdrawn
- **China prioritizing recycling** over reuse (CATL currently at over 96% Li recovery rate)
- **EU regulation incentivizes recycling more** than repurposing (figure below)

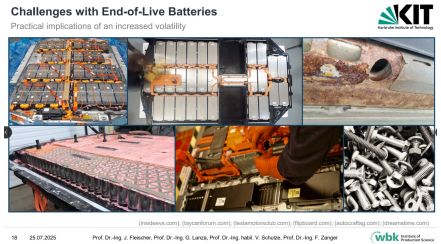


The share of EV batteries 'In Repurposing' and 'In Recycling' under the assumptions of EU Battery Regulation (BR) being absent (OFF) and present (ON). Source: Seika & Kubli (2024)

Source: American Council for an Energy-Efficient Economy (ACEEE), 2025

Battery Dismantling Economics Are Set to Be Transformed with Flexible Automation

Design Variety Makes Dismantling Challenging



First Robotics Are Going Live Across the West

	Entity	Entity Status	Current Operation Status
Hydrovolt	Hydrovolt	Joint Venture	Industrial Scale Operational (Norway)
Mercedes-Benz	Mercedes-Benz	Public (OEM)	Full Closed-Loop Operational (Germany)
BOSCH	Bosch / BLC	Private / JV	Industrial Scale Operational (Germany)
CIRCU LI-ION	Circu Li-ion	Private	In operation in live facilities (Luxembourg)

Manual Dismantling Takes a Prohibitive Amount of Time (1)

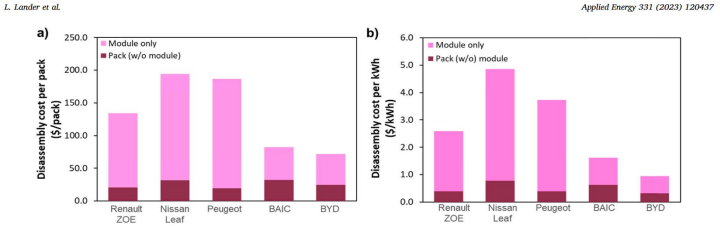
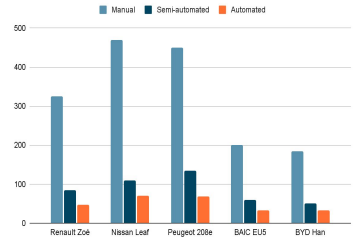


Fig. 1. Disassembly cost (in US$) per pack (a) and per kWh (b) from pack to module level (purple bars) and module to cell level (pink bars) using manual disassembly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Automation Transforms Economics

DISASSEMBLY TIME (1), IN MIN



DISASSEMBLY COST (2)

76%
Reduced labor cost with semi-automated disassembly (2)

47%
Reduced total process cost with semi-automated disassembly (2)

Flexible automation unlocks economically viable battery dismantling by replacing cost-prohibitive manual processes with semi-automated robotic systems.

Source: (1) Robotised disassembly of electric vehicle batteries: A systematic literature review - ScienceDirect, (2) Roland Berger (Distinguished Partner), RWTH Aachen, Battery Monitor 2024/25, p. 63

INDUSTRY

Notable Events
Industry Value Chain
Finance
Costs
Cell & Pack Manufacturing
Applications
- EV
- Stationary Energy Storage
- Data Centers
- Aviation, Drones, Space
- Robotics
- Other

Safety
Cell Design and Materials
- Li-Ion
- Lithium Sulfur
- Solid-state
- Sodium-ion
- Alternative Chemistries

Supply Chain
- Upstream and Midstream
- Recycling & Secondary Markets

Software / AI

VF | VOLTA FOUNDATION

Software/AI Summary

Efficient battery data management emerges as a key differentiator because it is a hard requirement to enable AI in downstream (software) processes - it turns battery data from a potential liability into a **true asset** and **competitive advantage.**

Large Language Models enhance every day productivity, **Large Quantitative Models** (LLMs enhanced by scientific or experimental battery data) enhance scientific rigor and battery experts capabilities - LQMs are available to push battery limits.

The battery industry and academic tech stack is **wide and complex**, each problem has its specific, niche tool to solve it - having a clear overview and understanding on what tools are available and which tools to use for which type of problem **enhances speed** and builds **competitive edge**.

Source: Summary of section content

Software Solutions Across the Battery Lifecycle

Battery Cycling And Material R&D Data Solutions

PEAXY, SANDBOXAQ, VOLTAIQ, Ohm, Polaron, Aris Machina, MONOLITH, BATALYSE, Kmos, MATERA, AIONICS, CITRINE, NOBLEAI, AiiDA, Wildcat Discovery Technologies, TensorFlow, LAMMPS, DeePMD-kit, The Materials Project, PyTorch, MOOSE, Zacros

Multiscale Modelling

COMSOL, PET SILION, GT AutoLion, ABOUT:ENERGY, LIONSIMBA, Ansys, Chemix, PyBaMM, BATEMO, BEST, HEXAGON, AVL, ELECTRODER, slide, ionworks, SIEMENS, mpet, BLAST, BattMo, MATBOX, PyBOP, compular

Manufacturing Process Control

BECKHOFF, Rockwell Automation, camLine, Honeywell, ABB, Palantir, INFICON, Ignition, LEAD, SIEMENS, PDF/SOLUTIONS, SICK Sensor Intelligence, Schneider Electric

Manufacturing Analytics

PDF/SOLUTIONS, SIEMENS, Aris Machina, HEXAGON, PEAXY, VOLTAIC, AmpLabs, APPLIED MATERIALS, eyelit 7, ACCURE Battery Intelligence, AccelionTech

Cell Quality And Inspection

PDF/SOLUTIONS, KEYENCE, Nikon, EXACOM, Waygate Technologies, lumafield, liminal, GLIMPSE, excillum, SMART Battery Analytics, EECO MOBILITY, ISRA VISION

Battery Management Systems (BMS)

ebs, Brill Power, BTE BLACKTEAL ENERGY, fox BMS, BMSer, elysia Battery Intelligence, eatron Technologies, ELECTRA, BREATHE, PULSETRAIN, BattGenie.

Supply Chain

MINESPIDER, circunomics, infyos, Circulor, KEZZLER

Battery Intelligence/Field Analytics

TWAICE, novo, zitara, eatron Technologies, Brill Power, elysia Battery Intelligence, EVIDENT BATTERY, Coulomb AI, ELECTRA, DOYAM, ACCURE Battery Intelligence, reLi, AccuVice, astrolabe, PEAXY, VoltR, volytica diagnostics, PoWerUp Manage & extend batteries life, MICANTIS, ENERGSOFT

ESS Data, Optimisation, and Deployment

Link

Energy Management Systems (EMS)

Link

Different Simulation Techniques for Materials Modeling

Simulation Type	Tools	Technique	Best Use Case
Neural Network Potential (NNP) - Molecular dynamics (MD)	DeepMD-Kit, LAMMPS, GAP	ML-trained potentials for atomistic dynamics	Li/LLZO interface modeling with near accuracy
Kinetic Monte Carlo + Continuum modeling	Kmos, Zacros, MOOSE	Stochastic rare-event + PDE-based mesoscale modeling	SEI growth, electrolyte reduction over long timescales
3D GAN Microstructure Generation	PyTorch, TensorFlow	Deep generative models for realistic electrode structures	To predict tortuosity & porosity for Li-ion transport
Data-Driven High-Throughput	Materials Project, AiiDA ASE	High-throughput ML + physics workflows	Rapid discovery of solid-state electrolytes with high Li-ion mobility

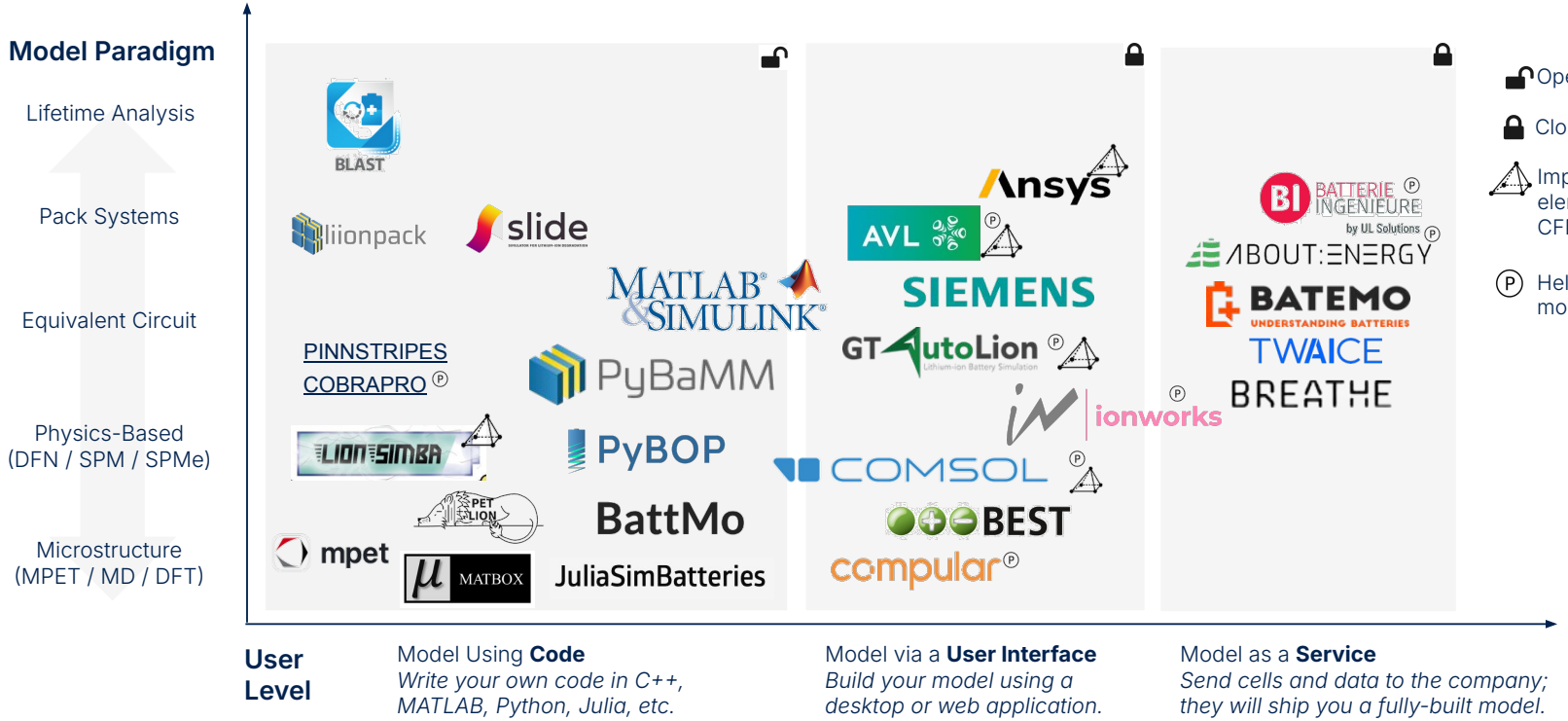
Available Tools

DeePMD-kit · LAMMPS · Kmos · Zacros · MOOSE · PyTorch · TensorFlow · The Materials Project · AiiDA

From Atoms to Interfaces: ML and multiscale modeling accelerate battery breakthroughs, predicting ion transport, optimizing interactions, and enabling data-driven design

Source: Rinon Iwasaki, Naoto Tanibata, Hayami Takeda & Masanobu Nakayama, Communications Materials, 2024 ; Kwangnam Kim, Aniruddha Dive, Andrew Grieder, Nicole Adelstein, ShinYoung Kang, Liwen F. Wan, Brandon C. Wood, Journal of Chemical Physics, 2022 ; Ravi N. Methekar, Paul W.C., Northrop et.al., Journal of The Electrochemical Society, 2011 ; Peter J. Weddle, Evan Walter Clark Spotte-Smith et.al., Electrochimica Acta, 2023 ; , Donal P. Finegan et.al., Nature Communications, 2020 ; Bing He, Shuting Chi, Anjiang Ye, et.al., Scientific data, 2020

Multiscale Modeling Software: From Coding Frameworks to Services



Creating a Digital Twin for Cell to Pack Modelling [1 of 2]

Virtual Cell Design: Accelerate design and chemistry exploration without physical prototypes. **Optimized Pack Configuration:** Tailor battery assembly to specific applications and use cases. **Fleet-Wide Intelligence:** Real-time monitoring of health and performance to get insight into fleet health and safety.

IMPROVING EFFICIENCY, REDUCING COSTS, AND ENHANCING THE RELIABILITY OF BATTERY SYSTEMS

Defining the What, Explaining the How, and Justifying the Why

What is a Digital Twin?
A digital twin is a **dynamic, virtual counterpart** of a single physical asset, enabling real-time monitoring, simulation, and analysis [1].

How does it work?
By leveraging data from sensors and other sources, digital twins can provide valuable **insights** into **performance**, **predict potential issues**, and **optimize operations**

What is the goal?
Enhance products, processes, and systems by applying data science to combined real and simulated datasets



The Three Pillars of a Digital Twin

Three Main Components:

Physical Entity (Physical Twin): The actual asset being monitored

Digital Representation: A virtual model including the asset's current state and usage history

Data Model: The real-time connection allowing data flow, updates, visualization, and analysis between the physical and digital parts

Source: [1]SAE

Creating a Digital Twin for Cell to Pack Modelling [2 of 2]

Virtual Cell Design: Accelerate design and chemistry exploration without physical prototypes. **Optimized Pack Configuration:** Tailor battery assembly to specific applications and use cases. **Fleet-Wide Intelligence:** Real-time monitoring of health and performance to get insight into fleet health and safety.

IMPROVING EFFICIENCY, REDUCING COSTS, AND ENHANCING THE RELIABILITY OF BATTERY SYSTEMS

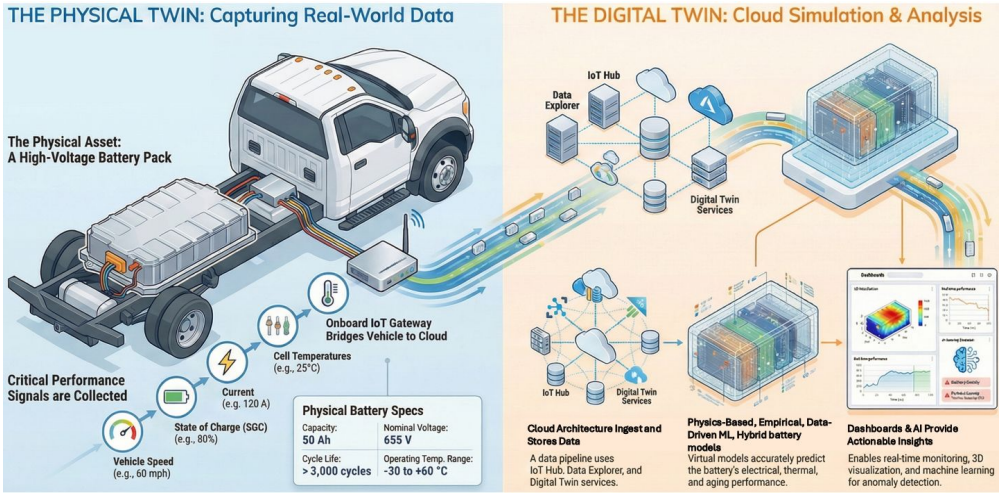
Digital Twin Data Pipeline

The Vehicle Path: The IoT Gateway filters and decodes CAN bus metrics (voltage, temp, SOC) for cloud transmission

The Cloud Path: The IoT Hub routes data into Hot (real-time), Warm (analytics), or Cold (archival) paths based on urgency

Battery Model

The battery modeling for the digital twin focuses on **high-speed, real-time simulation** of the electrical, thermal, and aging behavior of the commercial battery pack. It can be a physics-based, empirical, and data-driven machine learning model



AI Actionable Insights

Digital twin application leverages **AI/ML** primarily for **anomaly detection**, comparing real-time voltage and current data against expected behavior to identify unusual observations for expert review

Regulatory Compliance and Standards 2025

EU Battery Passport Readiness [1]: Digital twin will be the data backbone for **battery passport** regulatory compliance by 2027

New standard for digital twins of vehicle batteries [2]: *DIN SAE SPEC 91487:2025-08* defines terms and characteristics for the use of digital twins for electric vehicle batteries. Users benefit from **common standards and a uniform basis**

Source: [1]EUR_LEX, [2]MHP

Availability of Open Data Repositories and Synthetic Data Generation Accelerate AI/ML Driven Applications

The **availability of open datasets / repositories** and efforts into **standardization** are accelerating several **AI / ML applications** of battery research as the demand for energy storage accelerates. In addition to lab data, increased diversity of available field data is crucial for advancing battery management studies in real-world environments.

Institutional Repositories

Battery Archive

Battery DataHub

Open Datasets

Oxford Battery Degradation Dataset

CALCE - Experimental Test Data

NREL Battery Failure Databank

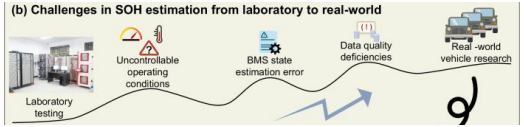
Data Standardization & Tools

BattINFO

LF Energy Battery Data Alliance

Ampworks

The "Lab-to-Field" Gap & Synthetic Data Generation



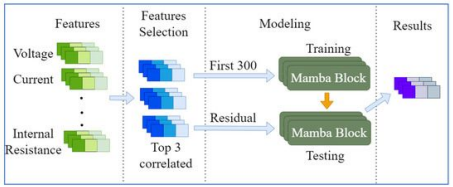
The limited availability of large-scale, high-quality field data is a primary bottleneck for BMS development. This table outlines some latest developments in synthetic data generation that aim to address this:

Architecture	Methodology & Innovation	Lab-to-Field Impact
TimeGAN / RCGAN	Uses Recurrent Conditional GANs to generate multivariate time-series conditioned on auxiliary variables (e.g., Temperature, SOC).	Synthesizes scarce "edge case" data (e.g., extreme cold profiles) to robustify models against unseen field conditions.
CPI-GAN	Embeds "Five Basic Physics Constraints" (e.g., Monotonicity, Energy Conservation) directly into the generator's loss function.	Prevents "physical hallucinations," ensuring generated degradation paths obey thermodynamic laws.
LLMs (SDForger)	"Textualizes" voltage signals, treating time-series forecasting as a natural language token prediction task.	Captures long-range temporal dependencies and enables multimodal analysis (integrating maintenance logs with voltage data).

Example AI / ML Applications

PINNs for Battery Diagnostics: Physics-Informed Neural Networks (PINNs) are **nearly 1,000 times faster than traditional physics models,** making them ideal for real-time diagnostics.

Mamba Model: a more efficient alternative to Transformers, for early Remaining Useful Life (RUL) prediction (trained on CALCE CS2 dataset).



Source: BattGenie, PINNs, NREL, Liang Y, Zhao S., Energies 2024, Liu H, Li C et al., Nat Commun, 2025, Mohanty, Prasanta & Jena et al., IEEE Transactions on Industry Applications, 2025 , Myisha A. Chowdhury, Gift Modekwe, and Qiugang Lu, 2025 , Xiong, Jiawei & Fink et al., Mechanical Systems and Signal Processing, 2023, Cécile Rousseau, Tobia Boschi, et al. NeurIPS, 2025

Turning Test Labs Into Learning Systems – The Strategic Role of Governed Data in Battery Development

As battery R&D accelerates, the industry has moved beyond the 2024 focus of maximizing test throughput. The constraints in 2025 shifted from purely maximising test volume to the quality and structure of underlying data. Automated high-throughput benches now generate continuous cycling and impedance records at volumes that enable AI-driven analysis rather than manual inspection. These datasets underpin AI for science platforms capable of screening and validating new battery materials in as little as **90 days** and **reducing R&D costs by 70%-80%.** Together, these shifts show how structured, traceable test data is turning modern labs into learning systems that accelerate discovery, improve reliability and compound competitive advantage.

Battery R&D Data - Foundational Technologies

Data Foundations	**Standardised Data Models** BDR, FAIR, unified schemas, consistent metadata	**High-Integrity Data Capture** Structured ingestion across cyclers, chambers, sensors	**Automated Data Quality and Validation** ML-driven checks for drift, anomalies, missing context
Test Infrastructure	**Test Plan Design with AI-Guided DOE** Statistical exploration, adaptive experimental design	**Real Time Data Pipelines** Streaming ingestion, event based architecture	**Semantic and Contextual Lab Metadata** Automated tagging, traceability, lineage tracking
AI Applications	**Predictive Diagnostics and Modelling** Cycle life, impedance trends, early fault detection	**Material and Cell Design Acceleration** AI-driven screening pipelines Hours-to-days initial screening,	**Cross Chemistry Learning Systems** Multi-chemistry historical data training large scale models

Focus Areas For 2025 R&D - Test Lab Data And Ai

Futureproofed Datasets for AI and ML - Building a "Data Moat"
Legacy test data often proves hard to use with AI due to uneven execution, missing documentation, and non-standard formats, requiring heavy reprocessing. In contrast, teams that apply rigorous metadata and schemas to test protocols build proprietary datasets that rivals cannot easily match, establishing a "data moat" and lasting edge.

More Efficient Protocol and DOE Design
Access to structured historical data lets teams design charge-discharge profiles, stress matrices and drive-cycle simulations informed by prior outcomes, reducing experimental scatter and speeding up optimisation.

Streamlined Test Data Pipelines That Remove Manual Burden
Streaming platforms replace fragmented file dumps and manual reconciliation. Automated validation and AI-driven quality checks catch drift and errors early, freeing engineers from repetitive data wrangling and accelerating test interpretation.

Source: Material and Cell Design Acceleration, Reducing costs by 70-80%, Standardised Data Models Example (BDF), Automated Data Validation, Real Time Data Pipelines

AI-Powered Automation in the Modern Battery Lab

Speed Revolution
From Years to Days: A Quantum Leap in Discovery Velocity

70% reduction in overall development cycles

- **Material Validation:** Experiment timelines cut from several months to just a few days(PNNL)
- **Material Screening:** AI-driven search completed in 80 hours, a task that traditionally takes years(Microsoft)
- **Cell Design:** Iteration cycles reduced from ~2 weeks to a single day (LG Energy Solution)

Cost Optimization
Driving Down R&D Expenditure and Time-to-Market

50% lower costs for battery testing via high-throughput automation

up to 80% reduction in development costs by leveraging Digital Twins for virtual simulation

Traditional Development: 36-60 months

AI-Boosted Development: 9-15 months

Precision Enhancement
Achieving Unprecedented Purity and Predictive Insight

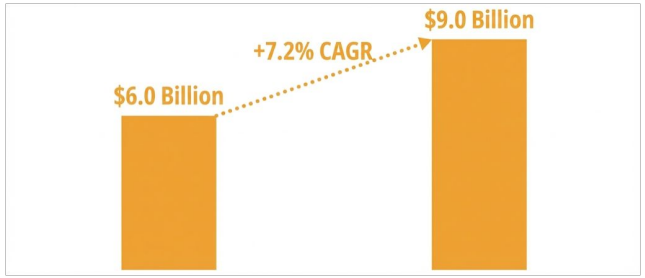
- **Up to 80% improvement in material purity** through automated synthesis protocols (Samsung ASTRAL)
- Enables the **creation of novel, pure material formulas** previously unattainable
- **<1% error rate in AI models** for early prediction of when a battery will enter its nonlinear aging phase

Efficiency Leap
The Emergence of the "Self-Driving"Laboratory

- **Uninterrupted, autonomous operations** for data acquisition and testing
- **Massive parallel experimentation** with real-time, AI-driven "self-adapting" test protocols
- **Fully automated data** collection, analysis, and fault detection, eliminating manual bottlenecks

Source: ODA Cell 2, Aurora Platform, Automated Electrolyte Characterization

Global Lab Automation Market



GLOBALLABORATORYAUTOMATIONMARKETSIZE (USD)

- **Surging Demand:** A definitive market signal for investment in intelligent lab infrastructure.
- **Strategic Capital Deployment:** Fueled by major public and private investment.
- **European Union:** The Horizon program has allocated nearly €200M to automation projects,including the €19.95M FULL-MAP initiative.
- **Tech Sector Entry:** Giants like Google and Microsoft are developing foundational AI models and Digital Twins specifically for materials science.

National-Level Strategy: A New Competitive Frontier

United States

Leveraging its National Lab Network (e.g.,PNNL) via **Genesis Project** to fuse AI with physical sciences, building a data-driven R&D backbone for next-gen energy storage.

European Union

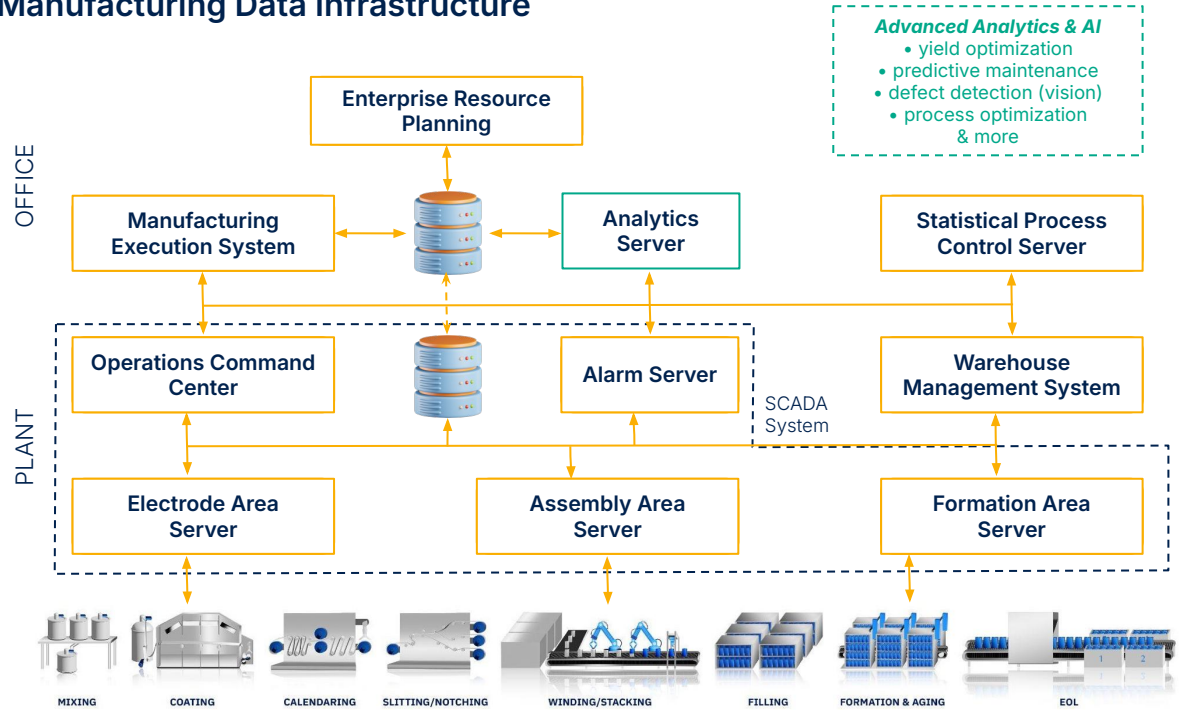
Committings significant public funds to build Sovereign, end-to-end autonomous research platforms (e.g.,**FULL-MAP**) to reduce time-to-market and strategic dependencies.

Asia

Industry champions (CATL, LG, Samsung) are embedding AI at the core of their R&D strategy to out-innovate global competitors and secure market dominance.

Source:1. MarketsandMarkets, 2. Genesis Project, 3. BIG-MAP / Battery 2030+

Manufacturing Data Infrastructure



TYPES OF MANUFACTURING DATA

IoT/FDC
Equipment sensor data collection

Process
Metrology, run card, materials, MES, etc.

Image
X-ray, visible spectrum imaging, optical, etc.

Testing
End-of-line: formation, aging, QC and beyond

Digital Thread / Genealogy
Cell, module, pack traceability; batch, lot, recipe linkage

Sustainability & Compliance Data
Energy consumption, CO_2, footprint, Regulatory reporting (EU Battery Regulation)

Each data type is unique, requiring its own data storage and characterization strategy. For example, images take up a lot of space and may require a unique storage approach.

Manufacturers must integrate inspection, sensors, test, and AI systems into a **unified data backbone** to enable better traceability, real-time optimization and control, and regulatory compliance.

Source: PDF Solutions, Graph from Internal Experts

Advanced Analytics & AI in Battery Manufacturing

The proliferation of sensors and inspection systems has shifted the challenge from data availability to **data utilization. Advanced analytics and AI** are shifting defect detection upstream, enabling **earlier intervention, higher yields**, and **closed-loop process optimization** across the battery value chain.

CLOSED LOOP PIPELINE FOR ADVANCED ANALYTICS: DATA > ANALYTICS/AI > DECISION > ACTION > FEEDBACK

Data Collection

You need to collect all of these for advanced data analytics

IoT/FDC
Equipment sensor data collection

Process
Metrology, run card, materials, MES, etc.

Image
X-ray, visible spectrum imaging, optical, etc.

Testing
End-of-line: formation, aging, QC and beyond

Data Lake

Data Storage

Data Characterization:
Extract characteristics from raw information

Data alignment and harmonization:
Align data from electrode to stacked electrode to assembled cell

AI & Analytics for Decision Support

Most issues are found **at end of line** or **formation/aging**. Insights from **traditional** and **AI/ML data analytics** enable manufacturers to **identify problems earlier, saving time.** This step includes **AI model prep,training, & deployment.**

Action & Control

Data insights now drive real or near real-time process adjustments, automated or operator-assisted, to **prevent drift and stabilize yield.**

Feedback & Monitoring

Continuous feedback ensures model accuracy, retraining, and compliance through monitoring and version control.

Governance & Trust: *Model monitoring, data quality checks, version control, and auditability are expected in production AI systems.*

ANALYTICS APPLICATION EXAMPLES

Overall Yield Dashboard
Centralize data through **yield** trends, key **parameters**, and **equipment performance**

FDC (Fault Detection & Classification) - Identify key **control indicators**

Predictive Maintenance
Minimize downtime across all equipment old and new

Defect Management System (DMS)
Connect all visual inspection to a **central system** and **visualize defects** along the electrode, layer, and cell

Advanced Process Control
Use **tool information and AI** to, for example, direct thick electrode lanes to higher performing winders/stackers

Predict Quality Excursions
Utilize AI/ML to **recognize problems early on**, before formation/aging

Process Control & Tool to Tool Matching
Determine **out of spec tools**, **match** tool performance, & **identify root cause** of tool issues

Analytics for Formation/Aging
Extract key parameters out of complicated formation/aging data

Source: Manufacturers Alliance, Siemens; MDPI, LinkedIn, Diligent, and all underlined content

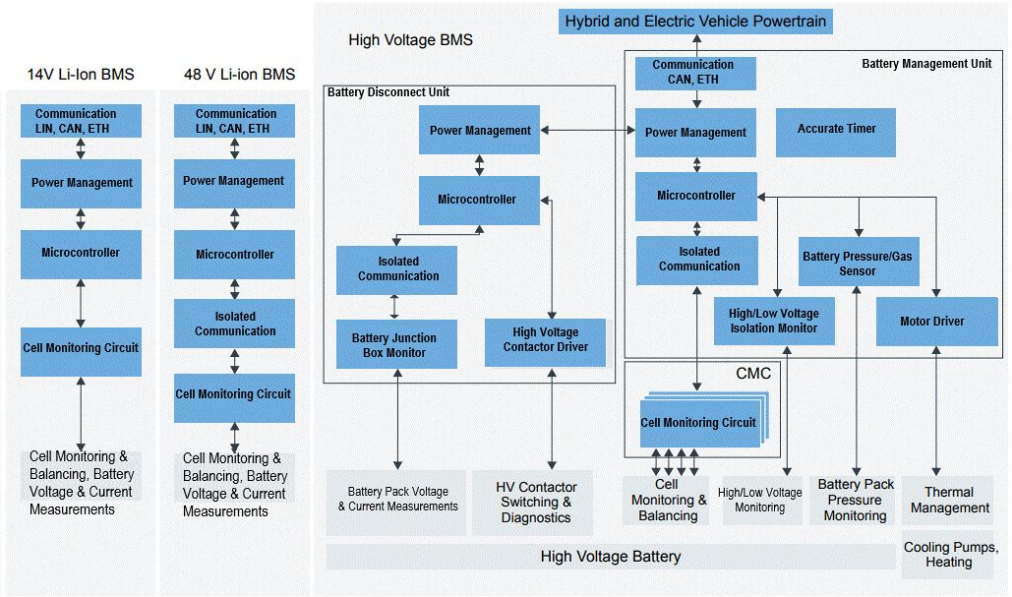
Automotive BMS - Above 12 V BMS Architectures and Requirements

- BMS ensures the operation and the safety of the battery.
- Automotive BMS must comply with the most stringent Safety Requirement as described into **ISO 26262.**
- Cell Monitoring Circuit is matching the numbers of cells stacked in serial in the battery pack, every cell is monitored. Different cell monitoring circuit will cover from a single cell to multiple cells. They will also cover the **cell balancing function.**
- In system, where the control function, run by a microcontroller, is powered from another voltage than the battery pack, there is need for an **isolated communication** between the control function and the cell monitoring circuits. This isolated communication might be through wired or wireless communication.
- BMS will also run the connection and disconnection function from the system. Disconnecting is the higher protection of the battery pack.

Low to High Voltage BMS shared a common architecture. Selection of the proper components is key to run the safe operation, to enhance the stored energy and life time of the battery pack.



A123 Systems' Li-Ion starter battery, open with BMS



Simplified Automotive BMS diagrams [1][2][3][4][5][6]

BMS - Latest Innovations within Estimation Algorithms

Thermal Runaway Detection

The safety philosophy of 2025 has shifted fundamentally from containment to early detection. Recognizing that measuring a temperature spike is often detecting a failure that is already irreversible, the industry has standardized on detecting the precursors to thermal runaway. These precursors - specifically the venting of electrolyte vapors and the generation of decomposition gases - offer a time **window of 5 to 20 minutes before fire occurs.**

Technology Type	Target Parameter	Key Product Example	Detection Capabilities
Chemical Polymer	Electrolyte Vapors (DMC/EMC)	Honeywell BES / BES LITE	Detects "first vent" **5–20 minutes prior to thermal runaway**; specialized coating rejects non-battery gases
Gas Concentration	Hydrogen (H2) 0–16%	Amphenol Telaire T3600	Automotive-qualified H2 detection **post-vent / pre-fire**; provides ratiometric analog output to confirm anode decomposition
Multi-Physics	Pressure, VOC, Humidity, Shock	Metis Cell Guard	Combines environmental parameters to detect pack seal breaches (water ingress) and cell venting simultaneously. Validated by Sandia National Labs as **over 7 minutes faster than hydrogen sensors.**

Cell Balancing

Cell balancing - the process of equalizing the state of charge (SoC) of series-connected cells - remains a critical function of the BMS. In 2025, the industry is witnessing a divergence in balancing strategies, driven largely by the physics of LFP chemistry and the economics of large-format cells.

- **LFP Challenge**: LFP cells have an extremely flat OCV curve, making small voltage differences represent large SoC differences; passive balancing is too slow and heat-intensive for large packs.
- **Active Balancing Rise (2025)**: Solutions like Enerkey's all-time balancing algorithm actively transfer energy (up to 20A), enabling continuous, low-heat balancing.
- **OEM Strategies**: BYD's 2025 Blade Battery uses active equalization (~5A), cutting balancing time ~40% and ensuring consistent full-range capability. BYD's algorithms also determine the "high voltage turning point" of the charging curve which represents the end of the linear charging region. By finding this point, the actual capacity of the cell can be used to equalize cells based on their actual capacities instead of just the nominal capacity.
- **Passive Balancing Use Case**: Several IC suppliers provide solutions that are still preferred in cost-sensitive, smaller systems; example: Infineon TLE9018 provides simple 300mA passive balancing suited for well-matched cells.

Source: Honeywell, Amphenol, Metis Cell Guard - EV Engineering, EnerkeyBMS, JMBatteries - BYD Blade, XRAY - BYD BMS, Infineon

BMS - Diagnostics and Prognostics

BMS diagnostics now leverage multiple paths towards improved fidelity, including **neural networks (AI) deployed onto edge devices and cloud analytics integration.**

Purely on device methods: Claims of real-time capable algorithms to detect li-plating, torn cell tabs, and predict risk of thermal runaway in BMS have been made, although no scaled deployment of these algorithms in large fleets have been claimed.

Linked cloud/edge device methods: It is clear that automotive OEMs are deploying OTA updates to diagnostic algorithms in response to field events, leveraging field data. Fully closed loop processes, between embedded algorithms, to cloud based batch processing capabilities and full fleet context have been proposed, in order to build closed-loop performance on the basis of fleet prognostics.

On Device AI Deployment

Edge AI Accelerator

Leverages powerful Infineon Aurix TC4 Processor, to achieve compute levels necessary for onboard ML features

OTA Update Strategies

Software Updates Over Replacements

Safety recalls are increasingly handled by diagnostic software updates rather than full battery replacements. Example: The Porsche Taycan recall

Linked Cloud And Embedded Solutions

Edge and Cloud Compute to increase accuracy

- Linked ecosystem approach to diagnostics, prognostics, SOH, and RUL
- Adaptive BMS, based on prognostics foundation
- Leverages online and offline compute capacity for batch analytics and increased accuracy, reduced false positives and negatives
- Deploys through OTA updates to calibration

Source: Accelerating eMobility with Automotive Grade AI for Batteries - EE Times, Elysia: Better Software Can Unlock Hidden Potential In EV Batteries, https://www.linkedin.com/pulse/batteries-lets-get-know-each-other-better-elysiabi/, AABC US2025 talks: Uwe Weidemann (Munich Electrification), Tom Maull (Elysia Battery Intelligence)

EMS for Stationary Storages

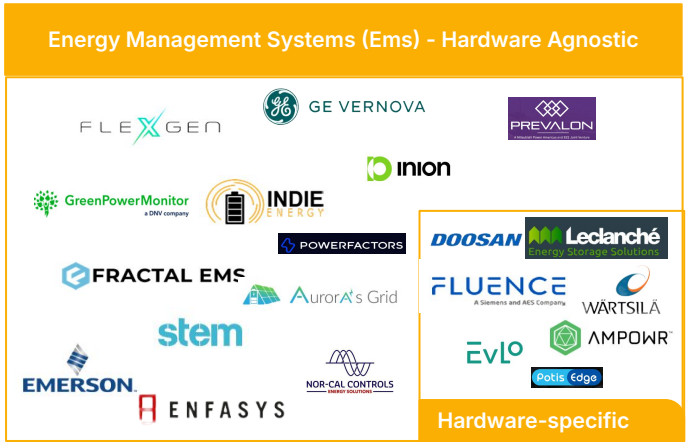
What is an EMS: The Energy Management System is the central software tool in a BESS responsible operational management of the BESS by collecting data from all available sensors and dispatching it based on commands from the grid, optimization or manual input. To achieve this, it coordinates hardware and software components like PCS, HVAC, BMS, fire suppression system and batteries. The costs for the EMS system is around 1% of the CAPEX of the entire system.

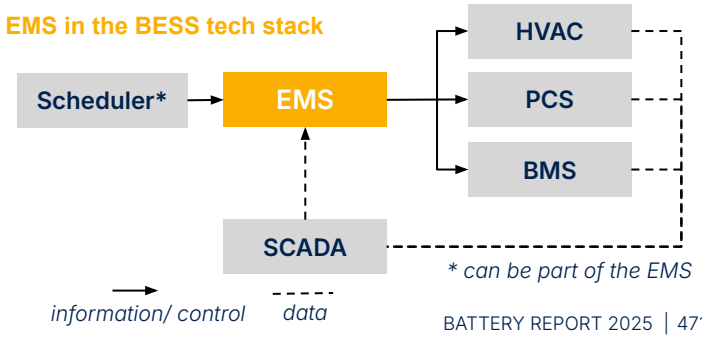
EMS Modularity: The bankruptcy of system integrator Powin in early 2025 highlighted the fact that a BESS is not only a collection of hardware components, but also a variety of software tools which need to operate flawlessly to ensure stable operation.
Retrofitting or upgrading of existing EMS installations in BESS is evolving and makes up to 20% of the overall business for some players. Many EMS providers are hardware-agnostic, some are also system integrators.

Grid Forming Requirements: Developments by different regulatory bodies (NERC, MISO, EU, IEEE) require BESS to provide more and more grid forming services, a step up from grid following only. This requires the EMS to handle additional complexity due to more sophisticated inverter controls software.

Cybersecurity: Important frameworks to consider are NIST 800-53 and NERC CIP, especially NERC CIP-015 requiring real-time security network monitoring and mandatory since this year, and IEC 62443.

The EMS is evolving from a simple control tool to a multi function orchestration layer (forecast, dispatch, grid forming support, market bidding and optimisation), which makes it increasingly relevant for BESS success and and critical to ensure cyber security for grid stability.





Auxiliary Controls - From Enabling Fast Charging in EVs to Optimising Energy Utilisation in BESS

Auxiliary controls such as **thermal management systems (TMS)** maintain battery conditions essential for safe and optimal operation.

Commonly, BESS with capacity below 200 kWh are air-cooled. The HVAC used for air-cooling is often developed independently and can only be integrated separately with the BMS[1,2]. Liquid-cooling on the other hand not only enables better thermal management of the cells, but the TMS is already integrated with the BMS controller and enables effective energy optimisation[3].

While **predictive thermal management** in the automobiles focuses on improving charging efficiency and time[4], stationary energy storages also use **smart thermal management algorithms** to optimise energy consumption by maintaining the desired battery temperature before and during a scheduled charge/discharge cycle[5].

The process involves simulating different thermal management strategies using an available **weather forecast** and **operating schedule** to forecast the battery temperature and energy consumption. The control strategy that results in the **least energy consumption** is chosen by the BESS controller and used for the next scheduled operation[5].

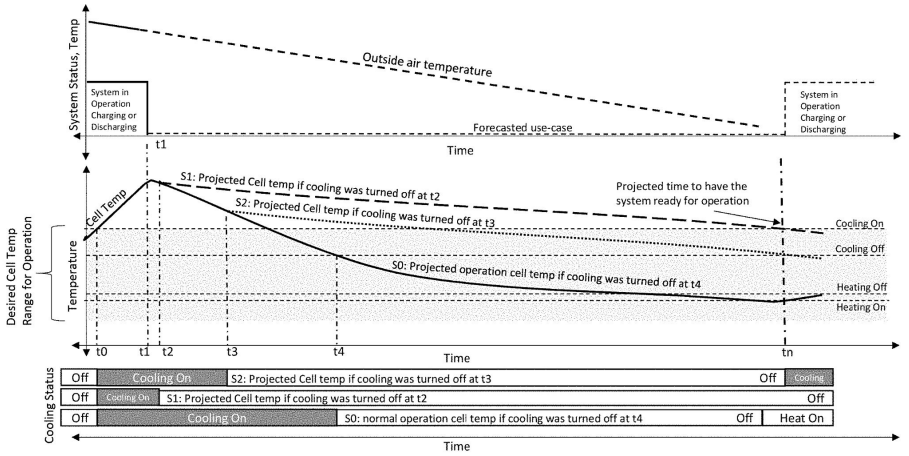


Fig. 5 from (5) compares BESS battery temperature resulting from possible thermal management strategies before a scheduled charge/discharge operation. By simulating several strategies, the one with the least energy consumption or optimum starting condition for the next cycle can be chosen.

Auxiliary controls continue enhancing applications in batteries that are necessary for a balanced and optimal system operation.

Source:(1) Liquid Cooling becomes preferred BESS temperature control option; (2) Battery energy storage systems: thermal management and degradation optimization; (3) SunGrowPower White Paper; (4) Battery Report 2024; (5) Systems and methods for improved battery energy storage system thermal management

Battery Performance & Predictive Maintenance Analytics

Enables bank monitoring to cell level root cause detection

Compared to the traditional BMS, battery analytic solutions can store historical data as well as compare data between racks and banks (racks connected to the same power conversion system). This enables the **detection of banks that are underperforming** in the asset. In the following example an underperforming bank was identified (figure 2) and the underlying root cause identified as cell imbalance due to a limiting cell with lower capacity (figure 1). The **recovery of 10.4% available energy** could be enabled if the single imbalanced rack were repaired, possibly by replacing the weakest module.

- Underperforming bank identified, limited by one single cell
- Cell imbalance due to capacity dispersion found as root cause

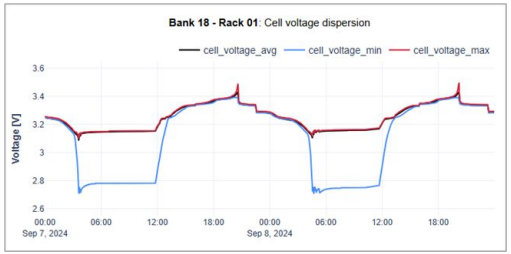


Figure 1. Cell voltage dispersion during operation

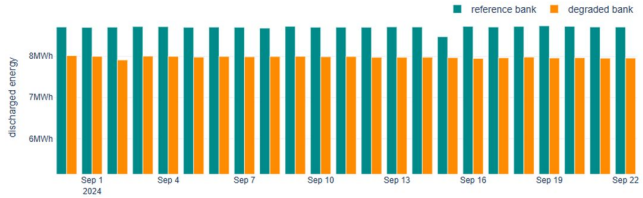
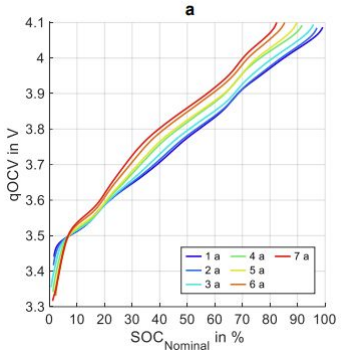


Figure 2. Comparison of discharged energy between banks

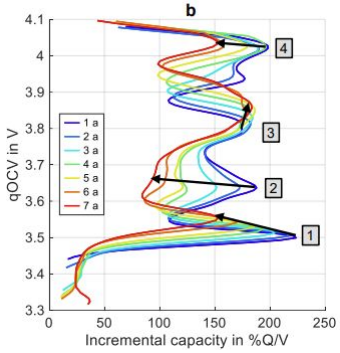
Improves degradation characterization from field data

The open circuit voltage (OCV) curve of a battery contains valuable information about the health of the cell and its two electrodes. While the ideal condition to obtain this curve at is from a low current full charge or discharge, this might not be possible for batteries in operation. A method to **reconstruct an open circuit voltage curve** from partial low-dynamic operational periods has now been demonstrated. This further **enables deeper analysis** of the asset through for example incremental capacity, evaluating different degradation modes.

- Open circuit voltage curves reconstructed from field data
- Tracking of degradation modes possible



Reconstructed qOCV from field data



Incremental capacity analysis to study degradation modes

Source: The true cost of BESS anomalies - PowerUp ;Study: Reconstructing Battery OCV Curves from Field Data - ACCURE

Hazard & Defect Detection

Identifies lithium plating during operation

Lithium plating is one of the most detrimental aging phenomena in batteries, as it can lead to short circuits and in the worst case thermal runaway. High currents at high cell voltage are known conditions to increase this risk (as well as low temperature). Lithium plating can be identified through a **change in the voltage profile** during charging (figure 1). An additional peak can be found when differentiating the data in incremental capacity analysis (figure 2). **AI algorithms can be applied to help identify this peak** during operation, or the change in resistance resulting from the lithium plating reaction.

- Fast charge increase the risk of lithium plating
- Changes in voltage and resistance identified
- AI algorithms improve detection

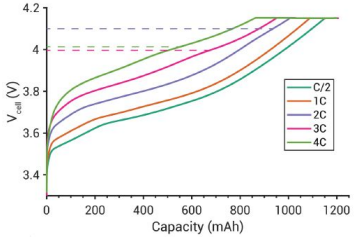


Figure 1. Cell voltage during charging

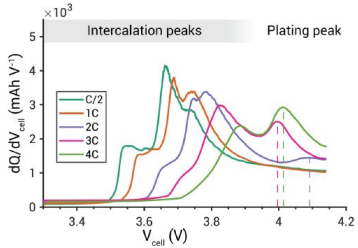
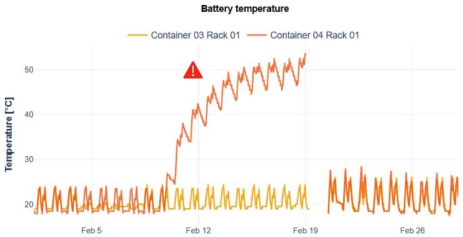


Figure 2. Incremental capacity analysis on cell voltage during charging

Improves the detection of temperature anomalies and its risk factors

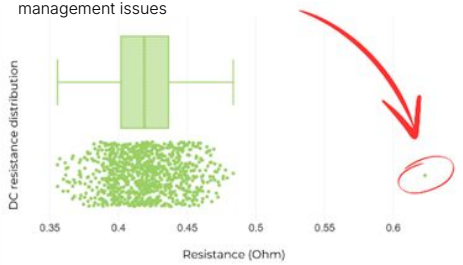
The battery temperature is crucial to consider when evaluating the safety of a battery asset. High temperature can be a sign of abnormal behavior and in the worst-case lead to thermal runaway. Battery analytics can improve the detection of temperature deviation and resolve the underlying problem.

Example 1: Cooling system failure
The thermal management system (HVAC for heating, ventilation and air conditioning) is responsible for keeping the batteries at a good temperature for safety and decreased aging. While temperature variations are expected, as a result of the battery operation, this example shows a **HVAC failure** leading to **unexpected temperature rise**. A combination of an electrothermal model with machine learning enables early and accurate detection of these incidents.



Temperature profile comparing container with and without management issues

Example 2: High resistance outlier
Monitoring resistance over all racks in an asset enables the detection of resistance outliers. In this example a high **resistance outlier** was identified, also resulting in an **extreme temperature rise**. A deeper analysis found an electrical connection fault to be the reason for the abnormal behavior.

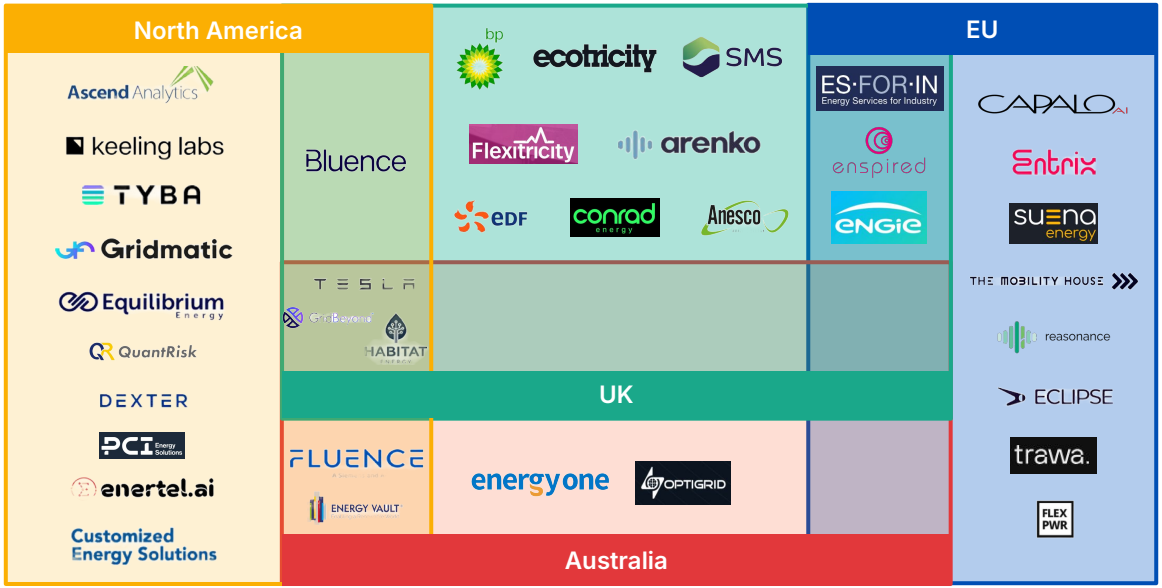


Individual rack DC resistance evolution

Source: Chen et al. "Operando detection of Li plating during fast charging of Li-ion batteries using incremental capacity analysis", Zhu et al. "Intelligent lithium plating detection and prediction method for Li-ion batteries based on random forest model", Safeguarding Battery Storage: AI-Driven HVAC Anomaly Detection - PowerUp, Impact of anomalies on uptime and safety - PowerUp

BESS Tech Stack: ESS Data, Optimization, and Deployment

Optimizers by Region



Monitoring & Data

Cellect, FLUENCE, GreenPowerMonitor, stem, Bluence, POWERFACTORS, ELECTRA

Optimization & Benchmarking

modo, TYBA, Powerline, powerflex, reasonance, encosa, Luxera Energy

System Simulation

Re-Twin Energy, phelas, Gridcog, AURORA ENERGY RESEARCH, Storlytics, MAXWATT

Aggregators

terralayr, ecotricity, BULLFROG ENERGY

Contrary to solar and wind assets, a BESS requires constant managing to generate revenue. Also, **BESS create millions of data points** every day. To optimize the profitability and ensure operation, **a sophisticated tech stack** is needed.

Source: Modo Energy , LinkedIn

BESS: Vulnerabilities & Possible Solutions - Software as a Core Risk and Safety Layer

Regulation Now Targets Software

Virtualization Reliability Standards (2025)
Modernize NERC CIP to cover virtual cyber assets, shared cyber infrastructure and management interfaces, directly addressing software-defined and cloud-like environments.This is relevant for all software systems that support the operation of BESS and are not on-prem.There is a growing distrust in the US against foreign entities of concern (FEOC), leading to an increased scrutiny in technology usage and communication oversight.

EU NIS2 + Cyber Resilience Act (CRA, 2025)
"Secure-by-design" for software: BESS OEMs and software providers must demonstrate that security is built into their development process. This applies to EMS, BMS firmware, PCS firmware, cloud platforms, and all digital interfaces.

SBOM (Software Bill of Materials) is required
Vendors must provide a complete list of all software components inside their product, including open-source libraries and third-party modules. This allows operators to identify whether a vulnerability affects their BESS.

Software-Centric Vulnerabilities

Remote Access Control: Most BESS cyber risks originate from remote-access weaknesses such as OEM support tunnels, VPNs without MFA, or over privileged accounts.

Firmware Update Risks: Insecure or outdated firmware remains a major theoretical risk for BESS, because BMS and PCS firmware directly control safety limits and grid interaction. Improperly secured update channels could, in principle, allow attackers to modify protection parameters. A public incident (2023) exploited a vulnerability in a communication gateway that was used for software updates in home storage.

Cloud Access via API: Cloud-based EMS, fleet platforms, and market-dispatch APIs introduce new digital interfaces that were uncommon in earlier storage installations. As BESS fleets become more software-integrated, API hardening has become an essential cybersecurity focus.

PCS highly critical hardware: All BESS hardware components are vulnerable, but since the PCS communicates with higher and lower level components, it is the most critical and vulnerable component.

In 2025, the number of regulations targeting software integrity increased. For a 400 MWh sized storage, an outage can cost up to $ 1.2 million in monthly losses. **Software is a core safety layer in BESS**, as EMS/BMS/PCS firmware control BESS performance and grid reliability. Software comes with cyber risk (**via risks like remote access, outdated firmware, weak APIs**), operators must evaluate vendors on software maturity (an example checklist on how to implement cybersecurity measures is given here).

Source: energy-storage.news, Fluence, Cellect, Industrialcyber, UL, Eticaag, Öhrström et al, Cyber Resilience Act, Federal Register, CISA, DOE, Brattle

Battery Industry Leveraging AI - Possible Use Cases Across the Battery Lifecycle

Product development
- Engineering workflow orchestration
- Augmented simulations & testing
- Data-driven design iterations
- Document generations (CAD, req. spec.)

Research
- Material discovery
- Recipe engineering
- Accelerated testing
- Automated patent analysis
- Knowledge harvesting

Recovery
- Efficient EOL testing
- Learned battery disassembly
- Waste / feedstock recognition



Battery Production
- Anomaly detection (quality, safety)
- Predictions (quality, maintenance)
- Inspections (quality {vision AI}, processes, machines)
- Automation (processes, operations)
- Planning (shifts, inventory, maintenance)
- Big data analytics & processing

Battery Operation
- Intelligent BMS & TMS
- Charging optimization (charge point locations, battery preconditioning, charging protocols)
- EV range and lifetime modelling
- Field-data analytics
- EV Fleet / BESS asset management
- Safety monitoring, risk prevention
- Energy management & trading

The three main “wishes” of battery AI - disruptive, desirable, difficult to achieve:

The golden recipe with materials discovered or identified by AI.
Find optimal battery material combinations faster and / or better than with traditional trial-and-error methods.

The AI Mastermind that autonomously runs and optimizes a battery production plant.
The battery factory of the future is able to learn, adapt and improve manufacturing performance – without human intervention.

The universal AI-based battery lifetime prediction model applicable to all chemistries.
This could allow precise forecasting for any type of battery, even for new products that have not been physically tested yet.

Source: Accenture at AABC, PDF Solutions (vision AI), GM (AI for charging stations), Voltaiq Panel Discussion at Battery Show NA

Battery Industry Leveraging AI - Published Use Cases, Projects and Solutions in Various Sectors

Material Informatics & Discovery

Polaron, chemix, NOBLE AI, MATH 2 MARKET, HEXAGON, albert, BIOVIA, Schrödinger, Microsoft, umicore, ZEISS

Cell Chemistry & Product Innovation

SANDBOXAQ, NOVONIX, CITRINE INFORMATICS, MORROW, QuantumScape, NVIDIA, SES, Factorial, Schrödinger, Aris Machina, MONOLITH

Large-scale Battery Cell Production & EV Battery Use Cases

CATL, EVE Energy, BYD, TESLA, STELLANTIS, HYUNDAI, SK on, SAMSUNG, SAMSUNG SDI, Envision AESC, NISSAN, MITSUBISHI, TATA, XPENG, LG Energy Solution, BMW, CALB, Ford, NIO

Smart Manufacturing & Shopfloor Solutions

Schneider Electric, SIEMENS, Honeywell, Rockwell Automation, liminal, ROBOVISION, ABB, T Systems, accenture, Capgemini, ethon.ai, PDF SOLUTIONS

Development, Testing & Simulation Tools

ELECTRODER, Sphere, AVL, VERACITY by DNV, IBM, ADDIONICS, DEKRA, BATEMO, AVILOO, Beff, Ohm, CamMotive, ELECTRA

EOL Solutions

greenUnion, RECIRCULATE, CIRCU LI-ION, 邦普循环 BRUNP RECYCLING, VARTA, smiths detection, bower

BMS Hardware & Software

BOSCH, Infineon, eatron, SigmaSense, NXP, SYNTIANT, PULSETRAIN, elysia, HUAWEI

Battery Diagnostics & Asset Management Algorithms

TWAICE, FLUENCE, circunomics, enspired, ACCURE, PowerUp, avathon, elysia, volytica diagnostics, SUNLIGHT, CAPALO AI, Entrix

Source: Accenture at AABC; non-exhaustive list, please click on the logos for details

Applications of Agentic AI in Battery Manufacturing

Agentic AI transforms traditional AI systems into collaborative, autonomous agents capable of executing complex workflows. In battery manufacturing, this paradigm enables **smarter, scalable, and vendor-agnostic analytics.** Large Language models have reshaped agent systems from limited rule-based agents to LLM-powered agents with cross-domain reasoning and natural language interaction.

Applications in Battery Manufacturing

Materials Discovery: University of Bayreuth applies multi-agent systems to accelerate electrolyte innovation.

Battery Management: Electra Vehicles' AI agent translates complex battery data into actionable insights for EV fleets.

Defect Management & Quality Control in Cell Manufacturing PDF Solutions is exploring using AI agents in:

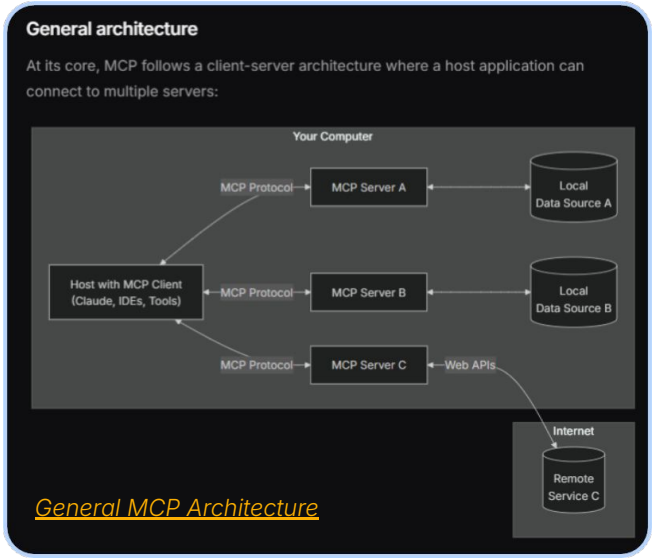
- **Guided Analytics:** Natural language interfaces allow users to interact with battery data intuitively, enabling faster insights and decision-making.
- **Workflow Orchestration:** YAML-based agentic workflows automate complex tasks such as data extraction, transformation, and analysis.

Supply Chain Collaboration: Model Context Protocol (MCP) servers, first popularized by Anthropic, allow new tools to be easily integrated into AI agents, supporting interoperability across battery supply chain ecosystems.

Agentic AI enables scalable, secure, and vendor-agnostic solutions- unlocking new efficiencies and insights in battery cell production, materials R&D, and operational diagnostics.

Key Concepts

- **AI Agents:** Autonomous systems that perform tasks, run code, call APIs, and iterate via feedback.
- **Agentic AI:** Multi-agent systems with memory sharing, role-based behavior, and inter-agent communication.
- **Workflows:** Goal-driven, adaptive pipelines that learn from feedback and enable predictive analytics, diagnosis, and automation.



General MCP Architecture

Bayesian Analysis and Pattern Recognition for Abnormality Detection in Battery Manufacturing

Battery manufacturers are increasingly using **Bayesian analysis** and experimenting combining it with **ML pattern recognition** to detect abnormalities early in production. This hybrid approach improves **defect detection**, supports **predictive maintenance**, and enhances **product quality**.

Key Concepts

- **Bayesian Analysis:** Uses prior knowledge and probability to infer likely causes of anomalies.
- **Pattern Recognition:** ML techniques (e.g., CNNs, autoencoders) identify recurring defect patterns.
- **Hybrid Models:** Combine statistical inference with data-driven recognition for better fault detection.

Example Public Applications

- **BMW & AVL:** Developed a Bayesian Failure Network to trace defect propagation and optimize quality gates.
- **DLR & Helmholtz Institute:** Used Bayesian optimization to model SEI growth and degradation.
- **OSBAD Benchmark:** Compared 15 anomaly detection methods in battery datasets, highlighting Bayesian optimization for tuning and separability. (**Figure 8**)
- **Major Cell Manufacturers** are using Bayesian analysis and pattern recognition for abnormality detection in data.

Detects rare or subtle defects early; Quantifies uncertainty; Scales across chemistries and lines; Improves interpretability for compliance.

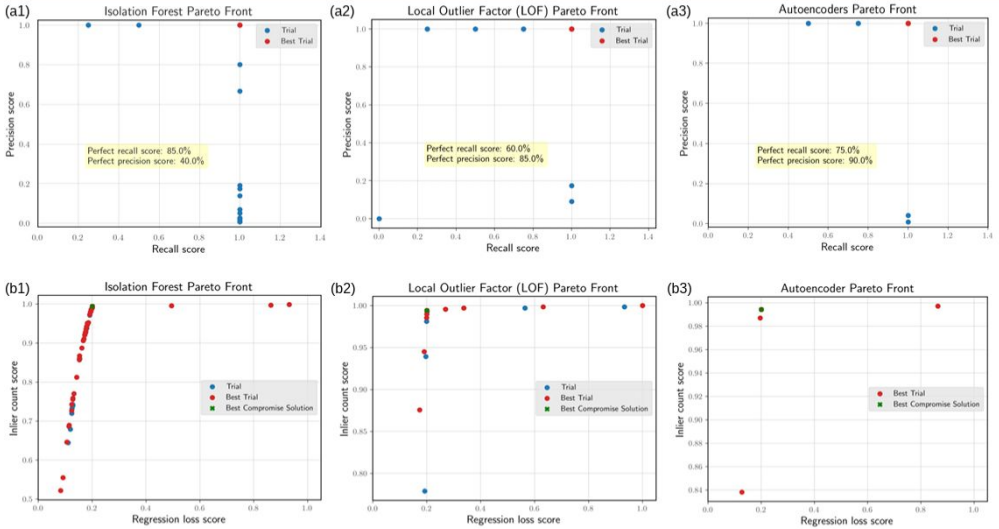


Figure 8: Bayesian hyperparameter optimization for classification and regression objectives across multiple models.

VF | VOLTA FOUNDATION

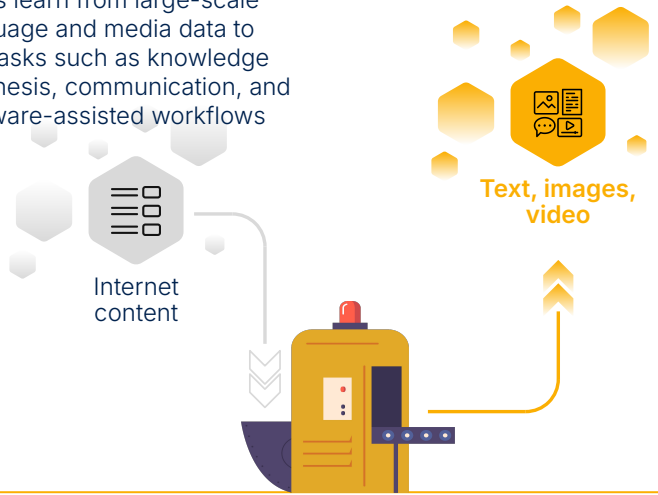
Modeling Paradigms in AI for Battery R&D: Large Language Models (LLMs) and Large Quantitative Models (LQMs)

Different AI model classes address different layers of the battery R&D workflow, from information processing to physics-based prediction

LLMs

- Marketing copy
- Customer service
- Software code
- Media

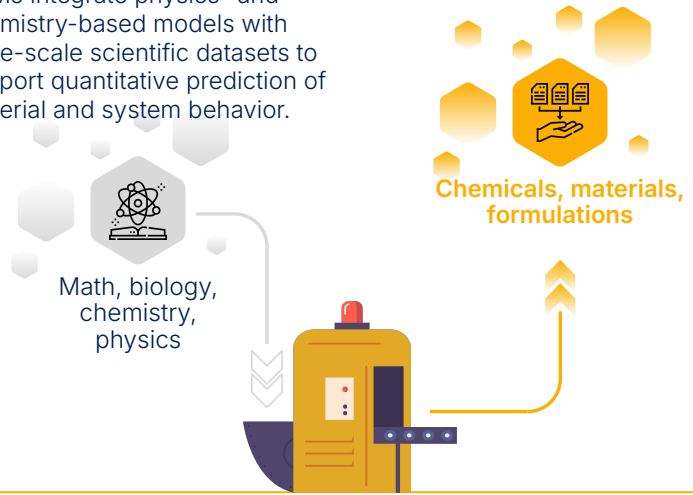
LLMs learn from large-scale language and media data to run tasks such as knowledge synthesis, communication, and software-assisted workflows



LQMs

- Cathodes
- Anodes
- Electrolytes
- Binders

LQMs integrate physics- and chemistry-based models with large-scale scientific datasets to support quantitative prediction of material and system behavior.



Source: The World Economic Forum, Forbes, AIMultiple, Talbot West, IT Pro, Aviso AI

Large Quantitative Models (LQMs) Pipelines - How to Train & Deploy LQM Models Effectively

Pretrain chemistry foundation models on large open source materials datasets, then efficiently fine-tune with targeted, high-fidelity DFT data for battery-specific properties (voltage, stability, ionic transport, interfacial chemistry) to **accelerate discovery-to-deployment**.

END-TO-END PIPELINE

Pretraining Datasets – Large, open multi-domain materials datasets (Materials Project, OC20/OC25, AQCat25)

Self-Supervised Foundation Pretraining – GNNs/ Transformers architectures (e.g. MACE, GNoME) learn universal embeddings

Chemistry-specific Fine-Tuning – Targeted, high-fidelity DFT datasets and narrow chemistry classes (e.g. cathode, solid-state electrolytes)

Validation & Guardrails – DFT/MD benchmarks, uncertainty quantification, physics & chemistry sanity checks

Deployment & optimization – API serving, CI/CD, GPU scaling, Bayesian optimization integration & closed-loop workflows

Next-gen Cathodes

New SSEs

Layered Structures

Key Metrics

- Time-to-candidate ↓ 90% vs. brute-force DFT
- RMSE <0.1 eV for formation energies
- 5× higher validated material hit-rate
- 20× compute cost reduction

Source: GNoME (2023), OMat24 (2024), Open Catalyst Project, JACS Au (2024), AQCat25 (2025), Argonne/IBM (2025)

LQMs and LLMs in Battery Research - Screening Battery Material Candidates

Key Takeaways: Impact on Battery Materials Discovery



- Screen electrolyte, electrode, and SEI materials at scale
- Reduce costly experiments and accelerate innovation
- Enable generative design of next-gen battery chemistries

Examples of Public Efforts

LQM-driven models

- **SandboxAQ –** Large Quantitative Model (LQM) for solid-state electrolyte and cathode discovery.
- **SES –** Uses generative AI to discover new battery electrolyte additives
- **Microsoft –** MatterGen model for AI-driven materials design
- **SDSC –** AI + HPC to screen next-gen battery chemistries
- **Morrow / Citrine –** AI platform to optimize battery materials and manufacturing
- **Factorial –** Uses AI to accelerate solid-state electrolyte development.
- **Aionics –** ML discovery of new electrolytes, additives, and interphase materials
- **NobleAI –** AI for lithium-metal battery materials and electrolyte prediction

LLM-driven models

- **ChatBattery –** LLM tools for electrode material design and analysis
- **ChatSSB –** Large Language Models for Solid-state battery research

SANDBOXAQ™ SES Microsoft Factorial CITRINE INFORMATICS MORROW NOBLEAI

Source: SandboxAQ, SES, Microsoft, SDSC, Morrow/Citrine, Factorial, Avionics, NobleAI, ChatBattery, ChatSSB

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AI-Enabled Knowledge Management and Cognition Development

Knowledge Graphs(KGs) & Semantic Reasoning

KGs establish logical mappings and triadic relationships from cluttered datasets. They model complex dependencies between material precursors, synthesis parameters,and electrochemical performance, enabling advanced semantic search and data inference.

Large Language Models (LLMs) & BatteryGPT

LLMs organize literature, extract data,and provide scientific insights. Retrieval-Augmented Generation (RAG) is a cornerstone technique, grounding the LLM's generative capabilities in verified, domain-specific Knowledge base to mitigate the risk of 'hallucinations.

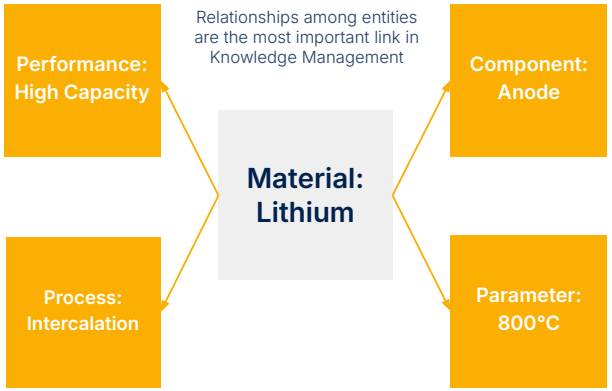


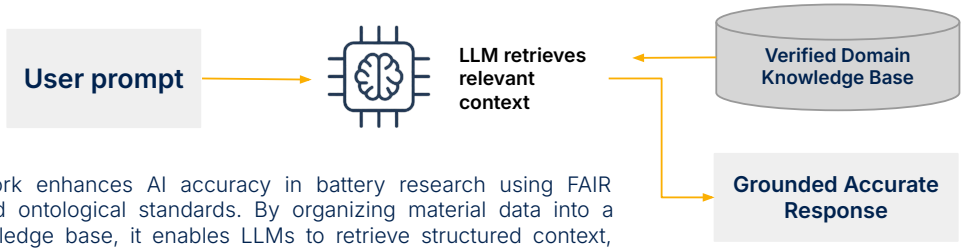
BIG-MAP

Adherence to **FAIR Principles**

Development of **Ontological Standards**

Open Protocols like the **Science Context Protocol (SCP)**





This framework enhances AI accuracy in battery research using FAIR principles and ontological standards. By organizing material data into a verified knowledge base, it enables LLMs to retrieve structured context, ensuring user responses are grounded and scientifically accurate.

Source: github, CBTA Knowledge Base

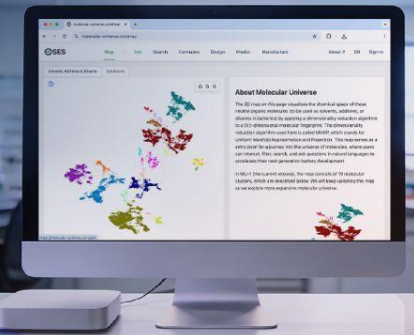
SES

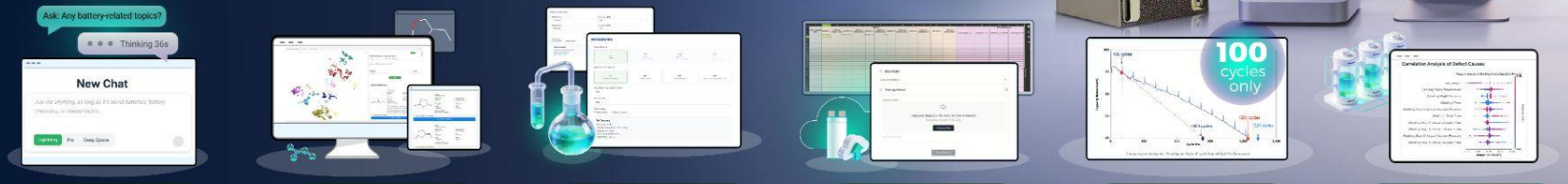
An AI4Science Platform Built by Battery Professionals, for Battery Professionals

This is the reality of today's R&D

$200B+	8–10 year	80%
spent	timelines	failure

Repeat the old ways—or accelerate discovery with **Molecular Universe**, an AI4Science SaaS platform covering the complete end-to-end workflow. It has already helped users discover several breakthroughs including battery materials for consumer electronics, drones, energy storage and EV applications.





Ask › Search › Formulate › Design › Predict › Manufacture

Agentic LLM
Senior scientist level agentic LLM trained on public and private battery domain knowledge

Battery Database
Largest database of battery-relevant properties for battery-relevant molecules

Foundry Integration
Dry and wet automated lab integration including high throughput molecule synthesis, formulation screening and cell performance validation

Simulation Engine
Proprietary high speed and high precision property simulation models including DFT and MD

Cell Performance and Quality Prediction
Machine learning models pre-trained on SES AI internal data and to be further trained using customer data.

Design: impact of material changes on cell performance.
Predict: end of life prediction based on early performance data.
Manufacture: cell quality improvement based on MES data

Why Molecular Universe is the best battery domain AI4Science platform

1. Incubated at a battery company, SES AI, since 2017
2. Offers latest high precision and high speed simulation models, high quality experimental data, and world class domain expertise
3. Available both in cloud (for your convenience) and on-premises (for your security)

Scan to explore!
molecular-universe.com
mu.ses.ai

2025 | BATTERY REPORT

CHINA

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Volta Foundation is the world's largest network of battery professionals. As a global not-for-profit association, Volta Foundation produces publications, networking opportunities, and industry resources to foster collaboration, innovation and advocacy within the battery industry.

Executive Summary

In the last 25 years, China's battery industry has undergone an unprecedented transformation, evolving from a technical latecomer to a dominant global leader. Driven by strategic national policies, from the initial "863 Program" (national NEV technology roadmap) and successive Five-Year Plans to NEV subsidies, China has built a comprehensive advantage across the battery value chain, spanning materials, manufacturing, equipment, talent, and downstream integration. This section deep dives the origins, structure, and sustainability of China's battery ecosystem.

2025 Highlights & Trends

Policy Focus on Market Health and Battery Safety

Removal of mandatory storage allocation exposes true economics, triggering short-term installation volatility, margin compression, and faster industry consolidation

Anti-involution policy: Measures introduced to promoting "quality over quantity", curbing "irrational competition".

New era of battery safety set forth by China's strict GB38031-2025 standards - "no fire, no explosion", effective July 2026.

Continued Supply Chain Dominance

Scale: China produces 86% of all cells globally, with >3TWh of installed nameplate production capacity.

Overcapacity and margin pressure: Intensified domestic competition accelerates overseas manufacturing localization.

Export controls: New restrictions on rare earths, key battery materials, equipment technologies released in 2025, but implementation will be delayed to November 10, 2026 given US-China trade talks.

Capital Allocation Trends

Investment growth: Total publicly disclosed investment projects surpassed RMB 820 billion, with a year-on-year growth rate of over 74%

More selective investment: Capital concentrated in 3 high value segments (Li-ion batteries, materials upgrades, next-gen technology)

Rapid Technology Innovation

Sodium-ion scaling: Commercial deployments expanding across applications: EV, E2W, and ESS.

Semi-solid commercialization: SAIC's MG4 vehicle launched at $14.5k signals readiness for mainstream market.

All-solid-state gaining momentum, but remains in development phase, earliest SOP expected 2026.

2025 | BATTERY REPORT

CHINA

VF | VOLTA FOUNDATION

History
Policy Landscape
Talent & Ecosystem Maturity
Capital
Supply Chain
Technology Innovation

CHINA

History

Policy Landscape
Talent & Ecosystem Maturity
Capital
Supply Chain
Technology Innovation

Pre-2000-2005: Long term Roadmaps Laid the Foundation for Battery R&D and Technology Catch-up

POLICY

Pre-2000

The 10th Five-Year Plan was the first time the central government identified **battery development as a strategic national priority**, establishing targets for the industrialization of electric vehicles (EVs) and their core materials

2000-2001

China's 863 Program (launched in 1987) outlined the national NEV technology roadmap in 2001 known as the "three verticals and three horizontals, 三纵三横". The "three verticals" refer to fuel-cell vehicles, hybrid vehicles, and battery-electric vehicles. The "three horizontals" refer to multi-energy powertrain systems, electric drive motors, and traction batteries

2001-2003

China became a **member of WTO** in December 2001

The government offered **major incentives** for domestic companies to support LIB for vehicle applications, covering up to 75% of the total cost, and up to 85% for smaller companies

2004-2005+

Many **joint ventures** formed between Western and Japanese firms and Chinese battery makers to access incentives and lower labor costs.

INDUSTRY

Pre-2000

1995: BYD founded by Chuanfu Wang, focused on reverse-engineering Japanese NiCd batteries to cut manufacturing costs by 5-6x

1998: Tianjin Lishen founded by Xingcai Qin, and by 2004, operated the most automated production lines in China using equipment imported from Japan

1999: ATL (predecessor to CATL) founded by Robin Zeng, to manufacture batteries for consumer electronics.

2000-2001

2001: BAK founded by Xiangqian Li, and by 2003, it had become one of the global top 10 manufacturers of LIBs

2001: A123 founded to commercialise nanophosphate lithium-ion technology, with an initial commercial focus on power tools

2001: EVE founded by Jincheng Liu, with initial commercial focus on lithium primary batteries

2002-2003

BYD became the first Chinese supplier of LIBs for global brands Motorola (2000) and Nokia (2002), signaling Chinese firms' capability to meet global quality standards. It later acquired Xi'an Qinchuan Automobile (2003) to transition into vehicle manufacturing. BYD IPO-ed in Hong Kong in 2002

2004-2005+

BAK Battery began collaborating with U.S.-based **A123 Systems** to implement advanced mass-production lines

Technological Catch-up: In 2000, China' s lithium-ion battery R&D trailed Japan's by 10 years in terms of technology performance and cost; by 2005, this gap was reduced to less than two years. By 2004, China had already surpassed the U.S. in the number of scientific publications related to LIBs

Source: Developments in Lithium-Ion Battery Technology in The Peoples Republic of China, 2008, From Laptop Batteries to Global EV Dominance: The BYD Story

2006-2010: Rapid Transition from Pilots and Early Commercialization to Real World Deployment

POLICY

2006

The 11th Five-Year Plan formally included the **NEV promotion strategic plan**, shifting the focus of the "863 Program" (a high-tech R&D initiative) toward the industrialization of electric drive systems and lithium-ion batteries

2007-2008

The government established the first formal rule in 2007 for the administration of **NEV manufacturing and sales**, creating a legal framework for new entrants into the industry

The Thousand Talents Plan 千人计划 (2008) recruited overseas top talents, bringing experienced engineers from global automakers into domestic battery firms and accelerating the shift from battery chemistry to automotive-grade EV engineering

2009

Ten Cities, Thousand Vehicles policy,十城千辆 (2009): A landmark NEV program targeting 1000 NEVs per city per year , with a focus on public fleets (buses, taxis, sanitation). It expanded from 10 to 25 cities with ~¥10B in central funding, using fleet procurement to de-risk technology, force scale, and turn NEVs from lab projects into a mature battery and NEV supply chain

INDUSTRY

2006

Gotion founded its battery subsidiary **Gotion High Tech** in 2006, marking its strategic pivot from real estate development into lithium-ion battery manufacturing

2007-2008

The **2008 Beijing Olympics** served as a major showcase for China's NEV industry, debuting ~500 domestically produced NEVs and marking the start of large-scale industrialization

Hong Kong based **EVB Technology (GP Batteries)** producing NiMH and Li-ion batteries became the first facility certified to IATF 16949 and TL9000 in 2008

2009

In 2008–2009, **BYD launched the F3DM**, the world's first mass-produced PHEV, secured a $230M Berkshire Hathaway investment, and introduced the e6, its first pure BEV

Source: Plug-in electric vehicles in China, Battling for Batteries: Li-ion Policy and Supply Chain Dynamics in the U.S. and China

2011-2015 Propelled China onto the Global Stage as the Largest NEV Market

POLICY

2011

China's 12th Five-Year Plan (2011-2015) designated **alternative fuel vehicles**, including EVs, as a strategic emerging industry.

2012

The Energy-Saving and New Energy Vehicle Industry Development Plan (2012–2020) set clear targets: **500,000 cumulative NEV sales by 2015** and an annual production capacity of 2 million units by 2020.

2013

Federal NEV subsidy program extended for 2013-2015

Monetary incentives: Local governments implemented a 1:1 subsidy match

Non-monetary incentives: such as free license plates, road rationing (license plate) travel restrictions, plate quotas, waived tolls, free parking, etc.

2014-2015

Made in China 2025 (2015): This national industrial master plan formalized the ambition to dominate high-tech sectors, setting a target of 70% self-sufficiency in core battery materials and components by 2025

INDUSTRY

2011

CATL split from ATL to focus fully on EV batteries; helped it invest early in large-format NCM power cell, tighten manufacturing control, and win fast automotive qualifications such as BMW

2012

BYD's LFP battery plant obtained ISO/TS 16949:2009 certification, becoming the 1st certified facility in China's EV power-battery sector

2013

Wanxiang acquired bankrupt A123 Systems for $257M, gaining LFP technology, manufacturing know-how, and OEM access, accelerating China's EV battery rise and signaling a shift in industry leadership from the U.S. to China

2014-2015+

Backed by supportive policies and Tesla's patent sharing, a wave of new private **EV innovators entered the market**, like NIO, XPeng, and Li Auto.

China's NEV sales topped 330,000 units, capturing **~60% of global volume**, making China the world's largest NEV market.

Source: A Study of China's Explosive Growth in the Plug-in Electric Vehicle Market, Battling for Batteries: Li-ion Policy and Supply Chain Dynamics in the U.S. and China

2016-2020 Consolidated Supply-Chain Control Through Policy and Scale

POLICY

2016

Beginning in late 2015, **China's battery "whitelist"** limited NEV subsidies to approved domestic suppliers, explicitly excluding Japanese and Korean leaders such as Panasonic, Samsung SDI, and LG Chem. By its end in 2019, Chinese firms had moved into the global first tier, led by CATL and BYD

2017-2018

China's charging-infrastructure plan targeted over 120,000 stations and 4.8 million outlets by 2020, underscoring the state's push to build the ecosystem needed for large-scale EV adoption.

China's Dual-Credit policy shifted NEV growth from subsidy-driven to market-driven. It required automakers to earn "NEV credits" amounting to 10% of their ICE vehicle sales in 2019 and 12% in 2020, forcing both domestic and joint-venture brands to accelerate electrification and providing long-term, stable demand for power batteries

2019-2020

EV subsidies originally ended in 2020 were extended to 2022 to offset COVID impacts, with a ¥300,000 price cap limiting support to mass-market models, except battery-swapping vehicles

INDUSTRY

2016

CATL leveraged the protected domestic market to become the world's largest EV battery manufacturer by 2017. By 2020, Chinese firms collectively controlled nearly 75% of the world's lithium-ion battery production. NCM batteries gained dominance as subsidy policies favored longer-range vehicles.

2017-2018

Tesla used China's 2018 policy opening to build Gigafactory Shanghai and worked with local suppliers like CATL to become part of China's EV and battery supply chain

2019-2020

BYD launched LFP Blade Cell with a cell-to-pack design that significantly improved safety and energy density. This marked the industry pivot back toward LFP chemistry from NCM/NCA.

Following the **Made in China 2025 plan** (launched in 2015), Chinese firms secured near-monopolies on midstream processing, controlling 95% of battery-grade graphite and over 70% of cathode precursor production by the end of this period

Source: China Decade of Dominance in EV Batteries, How China Beat the US in Electric Vehicle Manufacturing

2021-2025 Established Global Dominance in EVs and Batteries

POLICY

2021

NEV Industry Development Plan (2021-2035) targeted 20% NEV penetration by 2025 (achieved early), guaranteeing downstream demand

2022

Guiding Opinions & Implementation Plan for New Energy Storage promotes diverse R&D in technologies like lithium-ion and flow batteries while accelerating the establishment of standards for project construction and operation. It emphasizes integrating storage with power grids to support renewable energy consumption, peak shaving, and frequency regulation

2023

Guiding Opinions on High-Quality Charging Infrastructure enforces strict manufacturer liability and retroactive accountability for accidents. It also mandates optimizing battery performance, researching new battery systems, and advancing cascading recycling technologies.

Export controls on synthetic graphite materials in retaliation for US advanced AI chip export controls to China

2024-2025+

Anti-Unfair Competition Law takes effect, enforcing market order and supporting high-quality development

Export controls expanded to lithium extraction technologies, cathode material processing technologies, lithium ion batteries (>300Wh/kg), Li-ion manufacturing equipment, and graphite anode materials

INDUSTRY

2021

Volkswagen China became Gotion High-Tech's largest shareholder (24%), signaling global interest in Chinese battery tech.

Driven by the lithium price surge, China prioritized sodium-ion battery R&D (2021–2023) as a strategic, low-cost alternative

2022

As early EV batteries entered their retirement phase, the government and industry began exploring standardized recycling models. This included proposing the "**Three-Flow Integration**" management mechanism (unifying physical goods, transfer manifests, and invoices), though the system continues to face implementation challenges

2023

Industry development focus transitions from **Sodium-ion to Solid-State Batteries (The "Next Frontier")**

The China All-Solid-State Battery Collaborative Innovation Platform (CASIP) was officially established in Beijing, uniting government, academia, and industry leaders to overcome technical bottlenecks and accelerate the commercialization of all-solid-state batteries by 2030.

2024-2025+

The **commercial acceleration of eVTOL** (the "Low-Altitude Economy") and humanoid robotics unlocks critical new growth areas. These high-performance sectors demand specialized high-energy-density cells, prompting major manufacturers to diversify their revenue streams beyond the saturated traditional EV market

Source: China's New Energy Vehicle industrial Development Plan for 2021 to 2035, Battling for Batteries: Li-ion Policy and Supply Chain Dynamics in the U.S. and China

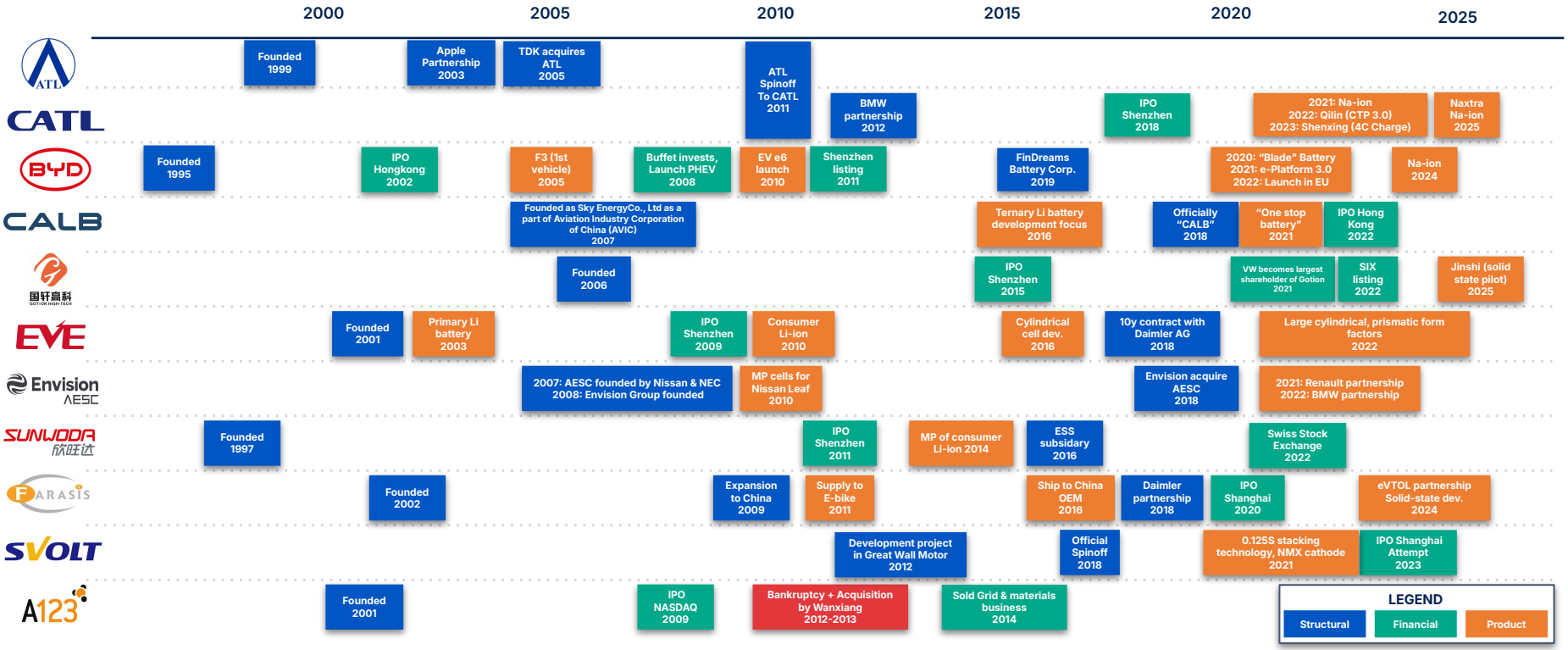
2026-2030 Policy Pillars and Outlook for China's Battery Industry

Policy Pillars (The 15th 5-Year Plan Proposal)	
Overall	Emphasize original innovation in technology and construction of a new energy system that is clean, low-carbon, safe and efficient.
Power System Modernization	Increase renewable energy share and ensure an orderly transition away from fossil fuels.
Advanced Storage & Grids	Strengthen the system's overall coordination, flexibility, security, and resilience by strategically planning pumped-storage projects, vigorously advancing new forms of energy storage, and accelerating the deployment of smart grids and microgrids.
End-use Electrification	Promote green, low-carbon energy consumption and optimize market pricing mechanisms for energy.

Outlook for China's Battery Industry	
Demand Scale	Exceeding 2 TWh by 2030: Storage batteries will outpace power batteries as the primary growth engine.
Global Footprint	Accelerated Expansion: Deepening manufacturing and tech deployment in Europe, SE Asia, and Latin America.
Tech Iteration	Rapid technology iteration: Semi-solid/solid-state, LMFP/Mn-rich chemistries, and SIB commercialize more quickly; LFP and NCM remain dominant for EVs, while LFP leads in stationary storage.
Frontier Apps	Beyond EVs: Surging demand from AI Hardware, Humanoid Robots, and Low-altitude Mobility (eVTOL).
Grid Integration	V2X Assets: EVs evolving into mobile storage units via V2G (Vehicle-to-Grid) applications.
Consolidation	Survival of the Fittest: Market consolidation favoring firms with massive scale and R&D capability.

Source: China's 15th 5 year plan, 工信部:研究编制《"十五五"新型电池产业发展规划》防范低水平重复建设

Key Company Formation, IPO, Technology Milestones



China's Industrial and Technological Strategy Evolved Through Key Eras

	2000-2005 Foundation	2005-2010 Trial Phase	2010-2015 Scale-up	2015-2020 Engineering Peak	2018-2022 Storage Boom	2020-2025 System Innovation	2023-2025 Circularity
Highlight	***No EV Industry Yet***	***Functional, but not competitive***	***Engineering > Research***	***Safety Risks***	***Lifespan > Density***	***System > Chemistry***	***Recycling = Profit***
Tech Status	Mature + Scale Mfg. (3C)	Usable but Immature	Mass Production Ready	Engineering at its Limits	Low-Cost Priority	Non-Material Driven	Economic Driven
Core Technologies	NiMH/ Lead-acid Small Li-ion (3C)	Early LFP & NCM111 Power System Prototypes	LFP Power Batteries NCM523/622 BMS Engineering	High-nickel NCM811 High-compaction LFP CTP Structures	Storage-specific LFP Containerized Systems EMS Integration	CTC/CTP Systems High-speed Coating Solid-state (Pilot)	Industrial Recycling Recycled Material Loop Responsibility Chain
Commercial Results	3C Electronics Era Global Mfg Hub	Public Transit Demos Govt-Driven Projects	EV Mass Production Full Supply Chain	400-600km Range Global Market Leader	Grid-side Storage Exponential Growth	Extreme Efficiency System-level Safety	Resource Security Cost-control Loop
Strategic Focus	Yield & Cost	Validation	Subsidies	Performance	LCOS	Structures	Value

Source: CNESA-ES RESEARCH Energy Storage Industry Research White Paper

CHINA

History

Policy Landscape

Talent & Ecosystem Maturity
Capital
Supply Chain
Technology Innovation

2025 Policy Timeline

January

Implementation of Industry Standards for Comprehensive Utilization of Waste New Energy Vehicle Power Batteries (2024 Edition)

February

Release of Implementation Rules for 2025 New Energy Urban Bus and Power Battery Update Subsidies. The average subsidy for updating city bus will be $11,057 per vehicle, compared to $8,549 (2024).

March

The Government Work Report officially incorporates "Anti-Involution" directives to curb disorderly low-price competition and guide the industry toward high-quality development.

April

Ten ministries jointly released "Guiding Opinions on Transport & Energy Integration," targeting 10% electrification by 2027 and promoting shared green energy corridors.

Released GB 38031-2025 "Safety Requirements for Power Batteries for Electric Vehicles". To be implemented 2026/07/01.

May

Five ministries launched the "2025 NEV to the Countryside" campaign, promoting rural adoption via financial incentives, charging upgrades, and hybrid sales to foster a green mobility ecosystem.

June

Six departments announce regulations on importing recycled black powder raw materials for Li-ion batteries

July

Export control catalogue update adding LFP and LFMP battery preparative technology.

August

New regulations enforce mandatory CCC (China Compulsory Certification) for power banks and lithium-ion batteries, prohibiting the manufacture, sale, or import of uncertified products.

September

Guidance on Promoting High-Quality Development of Energy Equipment emphasizing solid-state battery breakthroughs

October

China's implementation of export controls on key industrial chains such as lithium batteries, synthetic graphite, and rare earths.

November

Suspended the implementation of the export control measures announced in October for a one-year period per latest US-China trade deal.

Pledged to accelerate the implementation of targeted policies and measures to curb "irrational competition" in the power and battery energy storage industry.

December

MIIT mandates carbon declarations for batteries (>2 kWh). A trial runs through 2026, shifting to full coverage in 2027 to align with international standards.

2025 China New Energy Vehicle (NEV) Policy Landscape

Unprecedented Growth

Market Penetration

8.2M NEV Sales

7 Months of 2025: Nearly half of all new car sales

Signs of Overheating

Irrational Competition Emerges

107% – 2024 average combined ratio for NEV Insurers indicating significant underwriting losses and disorder

A Shift in Policy Focus

From Scale to Quality

Government regulating industry

New plans emphasizing:
- Cost
- Monitoring & Production Consistency
- Curbing Disorderly Healthier Development

Future-Proofing the Industry

Alignment and Focus

Focus on core tech & global standards

Aligning with international regulations

Key Policy Pillars

1. Lower Ownership Barriers (Jan)
- Reform NEV insurance through risk-based pricing, universal insurability, and innovative products
- Reduce premium burden; stabilize consumer confidence

2. Strengthen Green & Supply-Chain Sustainability (Feb)
- Enhance power battery recycling and utilization
- Support green upgrading of NEV and intelligent vehicle industries

3. Build Standards for Emerging Technologies (Apr)
- Accelerate standards for AI in vehicles, solid-state batteries, battery swapping
- Reinforce NEV safety, automotive chips, and low-carbon standards

4. Normalize Market Competition (Jul)
- Curb irrational price competition ("anti-involution")
- Strengthen cost/price monitoring and supplier payment discipline

5. Confirm Market Maturity (Aug)
- NEV sales > 8.2M units (Jan–Jul); penetration 45%
- 2025 national NEV penetration target achieved ahead of schedule

6. Anchor Medium-Term Growth (Sep)
- 2025 NEV sales target: ~15.5M units (+20% YoY)
- Expand public-sector NEV adoption, trade-in programs, battery-swapping models
- Continue tax incentives and insurance reforms

Source: https://www.gov.cn/zhengce/zhengceku/202501/content_7001024.htm, https://www.gov.cn/zhengce/202501/content_7001028.htm https://www.gov.cn/zhengce/202502/content_7003408.htm, https://www.gov.cn/zhengce/202502/content_7004966.htm, https://www.gov.cn/yaowen/liebiao/202502/content_7005430.htm, https://www.gov.cn/lianbo/bumen/202504/content_7021759.htm, https://www.gov.cn/zhengce/202507/content_7032374.htm, https://www.gov.cn/yaowen/liebiao/202507/content_7034074.htm https://www.gov.cn/yaowen/liebiao/202508/content_7036200.htm, https://www.gov.cn/zhengce/202509/content_7040551.htm

China's New Energy Vehicle (NEV) Policy Evolution

January

Reforming NEV Insurance

Introduced risk-based premiums and new platforms to solve high costs and coverage gaps.

February

Focusing on a Green Supply Chain

Emphasised improving NEV battery recycling to enhance the industry's competitive advantage.

April

Standardising Future Technologies

Advanced new standards for AI in cars, solid-state batteries, and battery swapping.

July

Curbing Irrational' Market Competition

Implemented measures to monitor pricing and product consistency to ensure fair industry conduct.

August

Exceeding National Sales Targets

The 20% market share goal for 2025 was surpassed ahead of schedule.

September

Setting New Growth & Stimulus Goals

Announced a new 2025 sales target of 15.5 million NEVs.

Key Provisions on Vehicle Acquisition Tax Relief (2024–2027)

Preferential Tax Policies

- **2024–2025:** Full exemption from Vehicle Acquisition Tax
  - Cap: RMB 30,000 per NEV passenger vehicle
- **2026–2027:** 50% tax reduction
  - Cap: RMB 15,000 per NEV passenger vehicle
- **Acquisition date:** Determined by issuance date of statutory sales or import documentation

Eligible Vehicles

- **Vehicle types:** Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs, incl. EREVs), Fuel Cell Electric Vehicles (FCEVs)
- **Passenger vehicle definition:** ≤9 seats (including driver), designed primarily for passenger transport
- **Technical criteria:** Jointly formulated and updated by MIIT, MOF, and STA

Battery Swap Mode (BSM) Provision

- **Tax base:** Vehicle price excluding the power battery where the battery is invoiced separately
- **Condition:** Compliance with battery-swap technical standards and availability of swap services by OEM or authorized operators

Administration & Compliance

- **Eligibility control:** Model inclusion in the official NEV Tax Exemption/Reduction Catalogue
- **Data reporting:** OEMs/importers submit validated electronic vehicle information (tax status and BSM identifiers)
- **Enforcement:** Tax relief granted based on MIIT-validated data; violations penalized under PRC tax law

Source: 中国政府网.政务, State Taxation Administration of the People's Republic of China

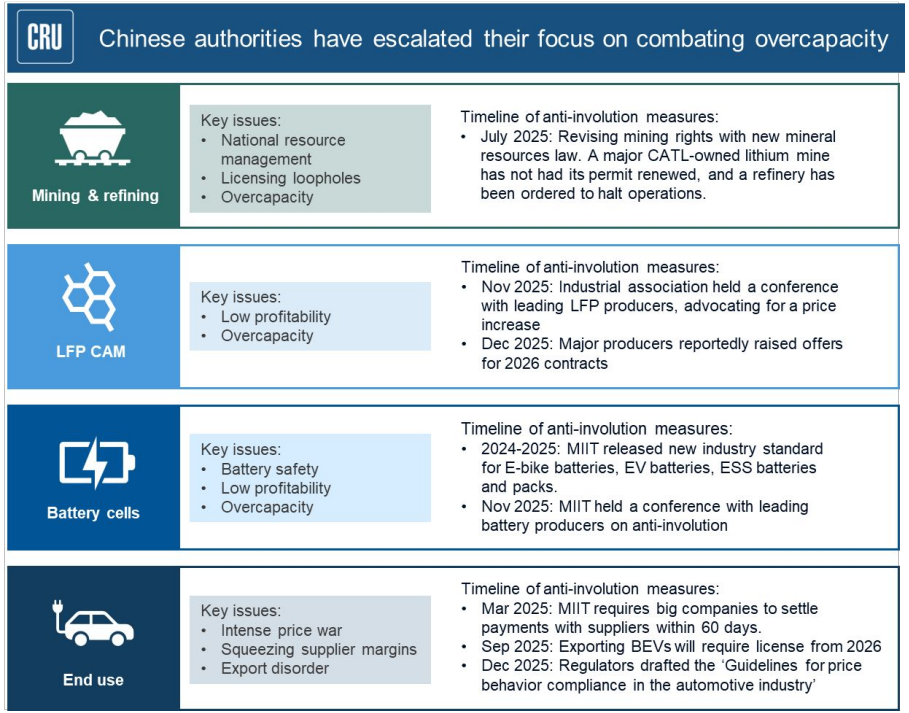
China's Anti-Involution Campaign Targets Overcapacity and Margin Pressure

While domestic consumption growth in China has slowed, external demand is also under pressure due to rising trade barriers. Overcapacity and intense price competition have generally eroded Chinese producers' profitability.

The Chinese government recently introduced various measures to address industrial overcapacity, including within the battery value chain. Commonly referred to as 'anti-involution', these policies focus on 'quality over quantity' and phasing out low-quality, uncompetitive producers. The motivation is also to combat deflation.

As the industries experiencing intense price competition are predominantly driven by private enterprises, and misalignment of incentives from local government complicates the central government's efforts to curb overproduction, the general sentiment in China is that the government will adopt a more gradual and market-led approach to rein in overcapacity rather than resorting to immediate, stringent capacity mandates.

Some private companies are in a concerted effort with their peers to get on board with anti-involution efforts, e.g. LFP CAM producers, while others remain in hyper-competitive segments of the supply chain.



Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

China Releases Most Stringent Battery Safety Standards

The 2025 revision (**GB 38031-2025**) updates and refines the 2020 standard (GB 38031-2020) to reflect technological advancements and a stronger emphasis on real-world abuse scenarios (e.g., fast charging, underbody impacts) and occupant protection during thermal events.

	Test item	GB38031-2020	GB38031-2025	Key differences
Cell level	Safety after fast charge cycle	Not required	300 cycles from 20% to 80% SOC in ≤15 min, followed by short circuit test	New requirement to evaluate safety under rapid charging stress
Pack level	Overcurrent protection Overtemperature protection External short circuit protection Overcharge protection Overdischarge protection	Insulation ≥100 Ω/V	Insulation ≥100 Ω/V (AC: ≥500 Ω/V)	Explicit insulation requirement for AC circuits added
	Thermal Propagation	Alarm signal required before occupant danger (within 5 min of thermal runaway)	Alarm within 5 min of thermal runaway + smoke control documentation for occupant safety (pre- and post-alarm)	Stricter occupant safety requirement; explicit smoke control verification
	Bottom impact test	Not required	10kg hemispherical impactor (30mm diameter steel ball) at 150J ±3J on 3 risk points (front/mid/rear)	New test to simulate underbody collisions

Source: Ministry of Industry and Information Technology of the People's Republic of China communication to understand GB38031-2025 in one picture

China Is Implementing Export Controls to Maintain Its Leading Position

China has increasingly imposed export restrictions on key battery technologies and products.

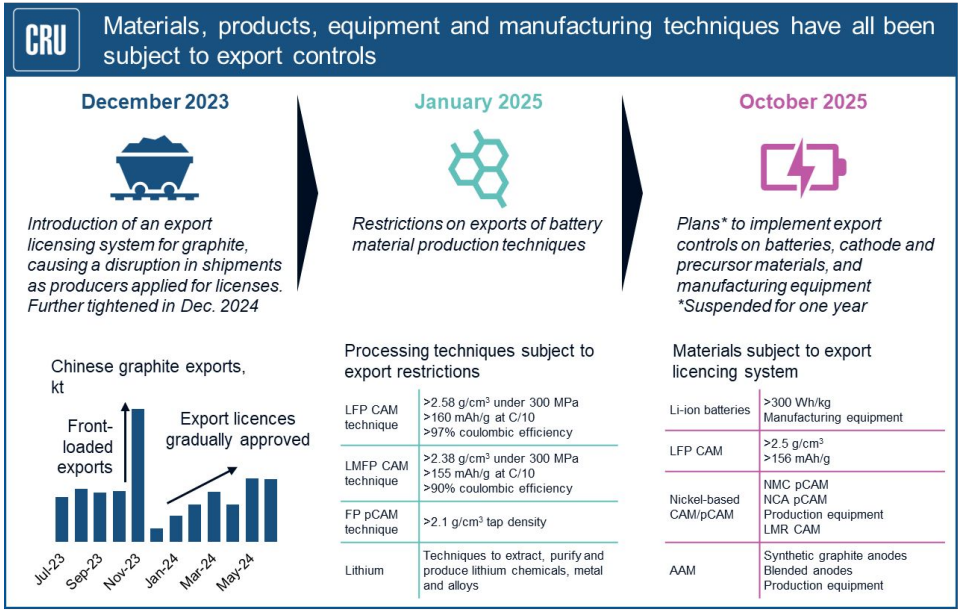
Some products face controls in terms of physical exports, while others are restricted in terms sharing know-how and equipment with foreign entities.

Companies must apply for an export license, even to take their technology and produce it overseas.

The main intentions behind these measures are:

1. Ensure geographical China remains intertwined in global supply chains, and especially in stages of the supply chain that it is dominant in.
2. Ensure only Chinese companies have the know-how and equipment to produce certain high-end technologies.
3. Geopolitical response to protectionist measures by US and Europe.

The latest US-China trade deal includes an agreement that the October 2025 restrictions are suspended by 1 year.



Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

CHINA

History
Policy Landscape

Talent & Ecosystem Maturity

Capital
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Technology Innovation

China’s Battery Talent Ecosystem

China's battery industry has developed a coordinated talent ecosystem - spanning government, industry, academia, and leading companies - that is scalable, replicable, and foundational to long-term competitiveness.

Pre-Employment Education

Multi-tiered structures, modular curricula, and standardized certifications improved talent supply efficiency and shortened onboarding cycles

Career Development Education

Industry–education integration has become a mature model, with close collaboration among enterprises, universities, and industry associations continuously strengthening workforce skills and technical capabilities

Workplace Culture

Strong engineering traditions, sustained R&D investment, and high-incentive mechanisms have created powerful drivers for rapid technological innovation and industrial upgrading

Synergistic Breakthrough Pathways

Government & Associations

- Formulate unified national talent development strategy
- Establish quantitative assessment system, incentivize excellence
- Advocate healthy industry culture, recognize "Best Employers"

Educational Institutions

- Deepen teaching reform, achieve dynamic industry alignment
- Strengthen interdisciplinary training, break departmental silos
- Advance career planning education earlier in curriculum

Battery Enterprises

- Shift from "using talent" to "investing in talent", build full-cycle training
- Build balanced and sustainable workplace culture, optimize workflows

Million-level: 2025 Talent Gap

400K CNY/year: Fresh PHD's Salary

>5%: Leading Firms R&D Investment

Source: Changzhou Battery Technology Association

China's Battery Talent: Regional Evolution Throughout Time

China's battery industry has established a multi-layered talent development system covering pre-employment education, in-service training, and career progression, driven by policy support, industry–education integration, and workplace culture. From 2020–2022, standardized skill certifications and tiered education took shape, with talent concentrated in the Yangtze and Pearl River Deltas.

During 2023–2024, leading firms deepened cooperation with universities through industrial colleges and modular curricula. By 2025–2026, high-intensity work cultures accelerated innovation but raised turnover risks. Regionally differentiated training models have emerged, yet a million-scale talent gap remains the key bottleneck for sustainable industry growth.

Talent Development System Evolution (2020-2026)

Timeline Evolution

2020-2022

System Establishment

- Policy standardization initiated
- Educational tier differentiation
- High regional concentration

2023-2024

Industry-Education Integration

- Leading enterprises engaged
- Modular curriculum formed
- Training base expansion

2025-2026

Culture Transformation

- Talent retention pressure
- Work-life balance exploration
- Assessment system needed

Regional Distribution

Yangtze River Delta — **High**

Representatives: CATL, Shanghai Electric
Features: Highly educated, engineer culture, deepest integration

Pearl River Delta — **High**

Representatives: BYD, Sunwoda
Features: Strong practical skills, high certification rate

Central & Western China — **Growing**

Features: Policy-driven, rapid vocational training growth
Function: Supplying junior technical talent to eastern regions

Impact Hierarchy

Macro: Industry Development

Million-level talent gap
Global leadership in capacity
Talent supply as bottleneck

Meso: Enterprise Competitiveness

High salary & equity incentives
"Extreme effort" drives iteration
High turnover weakens stability

Micro: Individual Growth

Clear career pathways
Continuous skill updates
High pressure causes burnout

Source: Changzhou Battery Technology Association

China's Battery Industry: Geographical Evolution & Strategic Shift

From 2020 to 2025, China's battery industry shifted from coastal concentration to a balanced national layout. The Yangtze and Pearl River Deltas remain innovation hubs, while the Central and Southwest regions emerged as growth leaders leveraging mineral wealth and green energy. By 2025, effective capacity reached **1.7 TWh**, driven by LFP dominance and vertical integration. Supported by "Double Carbon" policies, the industry now moves high-energy production West while maintaining R&D in the East, providing a blueprint for global expansion by leaders like CATL and BYD.

CENTRAL CHINA CLUSTER

Resource-to-Industry Bridge

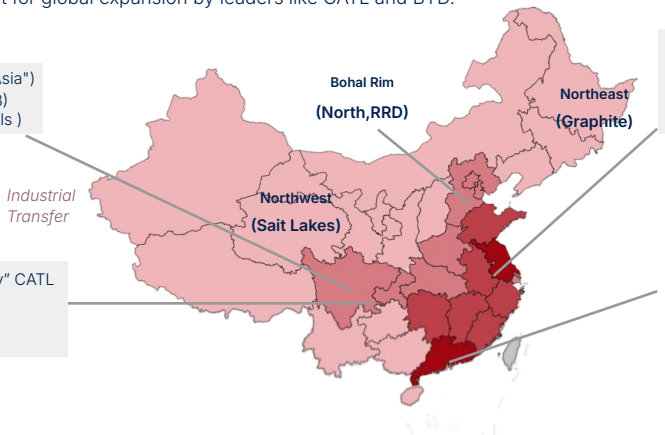
Driven by **"Rise of Central China".**
Specializes in cathode materials & Lithium salt extraction.

Yichun ("Lithium Capital of Asia")
Wuhan/Jingmen (EVE/CALB)
Changsha (Cathode Materials)

Green Energy & Mineral Hotspot (fastest growing)

Powered by Hydro & Minerals.
Focus on Upstream Mining & Mass Scale Cell Mfg.

Yibin ("Power Battey City" CATL partnership)
Chongging (Automotive Heritage, 150 GWh goal)



YANGTZE RIVER DELTA

The Innovation & High-End Engine

Most Mature Chain.
Dominates Mid-stream & Materials
Leads Solid-state/sodium-ion batteries.

Changzhou (94% chain complete, CATL/CALB/SVOLT/SK)
Ningbo (Chery)
Hefel (VW investment in Gotion)

PEARL RIVER DELTA

Highest Enterprise Density.
Focus on System Integration & Recycling (GEM,Brunp).

Shenzhen ("Battery Capital" BYD)
Huizhou (EVE Energy)
Guangzhou (Great Power, ESS)

Regional Agglomeration & Multi-point Expansion

Past: Coastal Concentration → **Present(2025): Balanced National Layout**

Shift from coastal hubs to Central/Western regions leveraging resources &lower costs.Easl/South remain high-tech/transformation leaders.

Tech Diversification Support

LFP (Cost/Safety) Dominant vs. High-Nickel Temary (High-End).
Next-Gen: Sodium-ion pilot (2023) Solid-state progress.

Capacity Expansion

1.7 TWh (Late 2025)

Massive Capacity.
Trend toward Vertical Integration (Mines to Battery).

Policy

"Dual Credit" Policy (Forcing E Carbon Neutrality accelerating ESS.
Strict Recycling "White List".

Resources Drive West
High-energy manufacturing shifts to cheaper, cleaner hydropower.

Innovation Leads East
R&D &Standards remain in Yangtze/Pearl River Deltas.

Global Integration
Top players (CATL.BYD)

Source: 1. 北京伊维碳科管理咨询有限公司, 2. GGII

Collaboration Between Industry, Academia, and Research

Over 36 years (1988–2024), social organizations have bridged China's battery government and industry. **CBIA** and **CIAPS** lead policy advocacy and standard-setting. To drive innovation, the **National Innovation Center** and **CASIP** focus on R&D for materials and solid-state tech. **Auto Battery Alliance and CNESA** optimize the EV supply chain and grid integration. Regionally, the **GDBIA** promotes export manufacturing, while the **JSESA** and **CBTA** enhance grid deployment and Battery Talent Community. **CBHA** fosters the entrepreneurial ecosystem.

North Region (Beijing/Tianjin)

China Battery Industry Association (CBIA)
National policy advocacy & market dev.

China Industrial Association of Power Sources (CIAPS)
Technical standards & research (Tianjin).

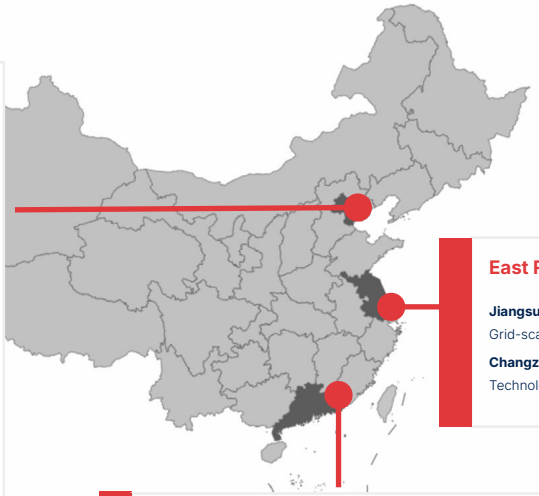
Auto Battery Alliance
EV supply chain optimization.

National Innovation Center
Fundamental breakthroughs in chemistry.

China Energy Storage Alliance (CNESA)
Energy storage policy & grid integration.

ZGC New Battery Technology Innovation Alliance (CBHA)
Innovation hub & venture investment.

Center for Advanced Solid-State Ionics and Batteries (CASIP)
Solid-state battery commercialization.



East Region (Jiangsu)

Jiangsu Energy Storage Association (JSESA)
Grid-scale storage deployment.

Changzhou Battery Technology Association(CBTA)
Technology innovation & Talent Community.

South Region (Guangdong)

Guangdong Battery Industry Association (GDBIA)
Manufacturing excellence & export.

1988	1989	2010	2015	2016	2017	2019	2020	2024
CBIA Beijing	CIAPS Tianjin	CNESA Beijing	Auto Battery Alliance Beijng	Nat. Innov. Center Beijing	CBHA Beijing	GDBIA Shengzhen	JSESA Nanjing	CBTA Changzhou CASIP Beingjing

Source: CBTA Knowledge Base

CHINA

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China’s Battery Investment Journey: From R&D to Global Leadership

China’s battery industry investment has gone through four key phases, transforming from a latecomer in technology to a global leader in production capacity and innovation:

1990s-2005 (Technical Exploration Period)

Private enterprises and research institutes laid the technical groundwork for lithium-ion batteries.

2006-2015 (Policy-Driven Period)

National policies (e.g., "Ten Cities, Thousand Vehicles") fueled industrial takeoff and the rise of key players like CATL and BYD.

2016-2020 (High-Speed Growth Period)

Market expansion and subsidy adjustments triggered industry consolidation, with leading firms dominating the market.

2021-Present

Chinese enterprises led in global capacity, technological breakthroughs (e.g., blade batteries, sodium-ion batteries) and overseas investment.

Three Stages of Policy Evolution:

2016-2020 (Subsidy-Driven Phase)

Regulations stipulate that from 2017 to 2020, except for fuel cell vehicles, the subsidy standards for other vehicle models will be gradually reduced: from 2017 to 2018, they will decrease by 20% on the basis of 2016, and from 2019 to 2020, they will decrease by 40%.

2021-2023 (Transition & Adjustment Phase)

Subsidies were phased out completely, with the dual-credit policy taking over.This policy has exerted a significant impact on the competitive landscape of the passenger vehicle market.

2024-2025 (Market-Led Phase)

Market-oriented pricing mechanisms have matured.Technological advancement has become the sole qualifying criterion.

Source: Exploring Lithium-ion Batteries: China's Rise in the Lithium Battery Industry,China's Power Battery Turbulent 20 Years: From Being Controlled by Japan and South Korea to Global Dominance | Annihilation and Rebirth

Key Policy Variables

New Energy Vehicle Industry Development Plan (2021-2035)

- Energy Storage Electricity Pricing Mechanism: Xinjiang takes the lead in the national layout of the new energy storage industry, with a target of exceeding 20 GW of installed capacity by 2025. **Twenty-three provinces** including Hubei and Heilongjiang are accelerating the industrialization of energy storage. The compensation mechanism for independent energy storage has emerged as the core driving force, and solar-storage hybrid projects have achieved large-scale implementation. Together, these developments depict a new pattern of large-scale development for China's new energy storage industry, shifting from policy-driven growth to a "market-technology" dual-wheel drive model.
- Export Control List: High-end grades of graphite anode materials(including lithium-ion batteries with an energy density of ≥ 300 Wh/kg, high-end artificial graphite anode materials, lithium-ion battery manufacturing equipment, and other controlled items) have been included in dual-use items export controls, forcing investment in overseas local production capacity.(This measure is currently suspended until November 10, 2026.)

On February 9, 2025, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) jointly issued the Circular on Deepening the Market-oriented Reform of New Energy Grid - connected Electricity Prices and Promoting the High - quality Development of New Energy (known as Document No. 136). The document explicitly stipulates that energy storage allocation will no longer serve as a precondition for the approval, grid connection and grid integration of new energy projects, thus bringing an **end to the era of "mandatory energy storage allocation".**

The price of China's power batteries dropped to **CNY 0.45 per Wh in Q3 2024,** a level that is close to or even below the cash cost line of some enterprises. This has intensified competition in the industry and exposed inefficient production capacity to the risk of being phased out.

The **Circular on Deepening the Market-oriented Reform of New Energy Grid-connected Electricity Prices and Promoting the High-quality Development of New Energy**, issued in February 2025, directly triggered the "May 31 Rush Installation Wave" in mid-2025. The policy effect was fully unleashed in May 2025, with newly installed capacity of new energy storage hitting 10.25 GW/26.03 GWh in a single month, representing a year-on-year surge of over 460%.

Source: 30 cents per watt-hour? Lithium battery enterprises face the ultimate test of cost reduction; From "involution" to "money printing": Behind the end of the energy storage price war, a trillion-dollar power value revaluation | Golden Eye

Analysis of the Diversified Financing System

From 2016 to October 2025, there were a total of **578 investment events** with an accumulated investment amount of RMB 134 billion, making lithium batteries one of the most actively invested tracks in China. Among these periods, 2022 saw the highest number of investment events and the largest capital inflow, with 121 transactions and a record-high investment value of RMB 49.53 billion. Investment enthusiasm cooled down in 2024, with 80 events and a total investment of RMB 7.01 billion. However, the investment momentum rebounded from January to October 2025, registering 85 events and a total investment of RMB 6.37 billion.

Series A is the dominant financing round.
In terms of corporate financing rounds, the industry is currently dominated by Series A and Angel rounds, which accounted for **32% and 17%** respectively from January to October 2025. This indicates that new lithium battery projects are emerging continuously, with early-stage investment becoming the mainstream. Next come strategic financing and Series B+ rounds, each accounting for 13%. In addition, Series C and Series D+ rounds are relatively rare, representing 1% and 2% respectively, reflecting that individual projects are moving towards maturity and the project risks are gradually decreasing.

PE/VC constitutes the primary type of investment and financing institutions.
From the perspective of overall investors, PE/VC accounted for **65%** of all investment and financing entities. These institutions value the industry's rapid technological iteration and substantial growth potential, focusing on cutting-edge areas such as solid-state batteries. Next are funds and enterprises, each accounting for 14%. Their primary goal is to conduct vertical investment along the industrial chain, which helps improve capital circulation within the supply chain. Key participating enterprises include **Saudi Aramco, Haiheng Group, Evergrande Green Energy, Geely Holding Group, Shengquan New Energy Co., Ltd., Huamao Technology Co., Ltd., Jiuri New Materials Co., Ltd., Corun New Energy Co., Ltd., Zhejiang Energy Group Co., Ltd., Ningfu New Energy Co., Ltd., and Haitong New Energy Co., Ltd.** Additionally, government investment accounts for 6%. The government plays a role in policy guidance to leverage social capital into key sectors.

Innovative Instruments

Battery-Asset ABS (Asset-Backed Securities)

- Underlying assets: future cash-flows from storage/charging stations
- Example: CATL "Power-Battery Toll-Receipt ABS", RMB 1.5 bn issued, coupon 3.8%
- Rating drivers: battery-degradation curve, operator capability, PPA tenor.

Financial Leasing

- Use case: equipment purchase, line construction
- Key lessors: Far East Horizon, Ping An Leasing, etc.
- Credit enhancement: parent guarantee + equipment mortgage

Green Finance

- PBOC carbon-reduction facility: 1.75% re-lending rate
- Case: Oct 16, 2025,Sunwoda secured a 10-year RMB 67 million policy-based loan from CDB Shenzhen Branch for three energy storage projects.

Source: Enlightenment 2025: Analysis of Investment, Financing, Mergers and Acquisitions in China's Lithium Battery Industry

2025 China Battery Investment Landscape: Larger Aggregate Scale and Higher Entry Barriers

Battery industry investments in China span a broad range of sub-verticals, including battery chemistries, production equipment, cell manufacturing facilities, energy storage supporting infrastructure, and more. Throughout 2025, the investment landscape has shifted toward structure optimization and high-end concentration, with the following key trends emerging:

Structure-optimized fundraising dynamics
According to statistics from the GGII (Gaogong Industry Research Institute), from January to August 2025, there were **183** newly signed and commenced capacity expansion projects in China's lithium battery industry chain, with a planned total investment of **CNY 400 billion**. The lithium battery industry chain is accelerating its transition toward high-quality development amid structural adjustments, exhibiting the prominent characteristics of "accelerated capacity expansion in high-end segments and phase-out of low-end production capacity".

In terms of specific segments, there were **54 capacity expansion projects** for lithium batteries and 23 for solid-state batteries, accounting for 30% and 13% of the total planned capacity expansion projects respectively. Among them, for relatively mature products such as lithium batteries and anode materials, the proportion of commenced projects was higher than that of newly signed projects, indicating that enterprises are focusing more on accelerating capacity construction. For emerging projects such as solid-state batteries and sodium-ion batteries, the proportion of newly signed projects was higher, reflecting enterprises' strategies of seizing strategic positions and pre-empting market opportunities to reserve capacity for the incremental market in the later stage.

Source: GGII

Publicly Disclosed Investment Projects Across the Entire China Lithium Battery Value Chain (2025)

According to incomplete statistics from the GGII, the number of publicly disclosed investment projects the entire China's lithium battery value chain - including lithium batteries and key materials, solid-state batteries, and sodium-ion batteries - exceeded 282 in 2025, with the total investment amount surpassing RMB 820 billion and registering a year-on-year growth rate of over 74%. Lithium batteries and their key materials remained the primary focus of investment, accounting for over 80% of the total investment volume.

Project Type	Number of Projects	Total Investment (CNY 100 million)	YoY Growth Rate	Core Details
Lithium Batteries	64	3485	92%	64 lithium battery projects (RMB 348.5 billion, totaling over 1100 GWh capacity); 114 material projects (positive/negative electrodes, electrolyte, separator, etc., RMB 308.5 billion), dominated by leading enterprises and concentrated in East China and Central China
Li-ion Batteries Key Materials	Not available	3085	127%	
Solid-State Batteries	60	677	-9%	Total capacity of 189 GWh (+23% YoY), mostly pilot and small-batch production lines; key players like SEMCORP and Jinlongyu layout electrolytes and core materials
Sodium-Ion Batteries	42	Over 1000	Significant Growth	Total capacity of over 290 GWh, suitable for energy storage and low-speed transportation; projects clustered in Jiangsu, Jiangxi and other industrial hubs
Others (Recycling, Equipment, etc.)	2	83	Not available	Focus on battery recycling, e.g., the RMB 10.3 billion-level project by Jinsheng New Energy
Total	282	8200	74%	

Source: GGII

Investment Strategy of Leading Enterprises

Strategic Divergence Under the Matthew Effect

Tier 1 (Production Capacity > 100 GWh)

CATL (Contemporary Amperex Technology Co., Ltd.)

- **Strategy:** "Extreme Manufacturing + Raw Material Supply Locking"
- **2024 Capital Expenditure:** RMB 28 billion (year-on-year (YoY) decrease of 15%), while R&D investment reached RMB 18 billion (YoY increase of 25%)
- **Lithium Mine Investment:** Won the bid for Sichuan Lijiagou Lithium Mine with an investment cost of RMB 120,000 per ton
- **Technology Layout:** Parallel development of three routes – solid-state batteries, sodium-ion batteries, and condensed matter batteries

BYD (Build Your Dreams)

- **Strategy:** "Vertical Integration + Global Expansion"
- The full-year **R&D expenditure** in 2024 reached RMB 54.2 billion, representing a year-on-year increase of 35.68%, with the R&D expense ratio standing at 6.97%.
- Third-Party Market Expansion: Blade Batteries supplied to FAW and Toyota, opening up the third-party market

Tier 2 (Production Capacity: 20-100 GWh)

CALB (China Aviation Lithium Battery Co., Ltd.)

- Focus: High-voltage fast charging
- 2024 Milestone: Secured and delivered the world's largest energy storage project order

EVE Energy

- Dual-Wheel Drive Strategy: Energy storage + power batteries
- 2024 Capacity Expansion Investment: announced an investment of **CNY10.8 billion** to construct the world's largest standalone carbon-neutral battery plant, which has a planned production capacity of 60 GWh and focuses on the mass production of LF560K large energy storage cells.

Gotion High-Tech

- Strategic Shareholder: Volkswagen Group China
- Technology Benchmarking: Aligned with German technical standards
- Volkswagen (China) Investment Co., Ltd. announced that it will invest approximately 1.1 billion euros to acquire a 26.47% stake in Gotion High-tech.

Source: CATL annual report 2024; BYD annual report

2025 Distribution Data of EV Battery Listed Companies (By Province)

NO.	Province	Company Name	Stock Code	Listing Board	Core business
1	Guangdong	BYD Company Limited	002594	Shenzhen Main Board	R&D and production of power batteries and energy storage battenies;suppoting batteries for new energy vehicles
2	Guangdong	EVE Energy Co.,Limited	300014	ChiNext Market	Lithium primary batteries,power lithium-ion batteries,energy storage battery systems
3	Guangdong	Sunwoda Electronic Co.,Limited	300207	ChiNext Market	Consumer batteries,power battenies,energy storage batteries and system integration
4	Guangdong	Guangzhou Tinci Materials & Technology Co.,Limited	300073	ChiNext Market	Lithium battery electrolytes,electrolytescathode materials and additives
5	Guangdong	Guangzhou Great Power Energy Technology Co.,Limited	300438	ChiNext Market	Smallithium-ion batteries,energy storage batteries,power battery packs
6	Guangdong	Liuzhou Chemical Industry Co.,Limited	600470	Shanghai Main Board	Production of monoammonium phosphate(raw material for lithium battery precursors)
7	Jiangsu	Biyi Microelectronics Co.,Limited	688405	STAR Market	Lithium battery BMS power management chips,fast charging protocolchips
8	Zhejiang	Wolong Electric Drive Group Co.,Limited	600580	Shanghai Main Board	Motor control,industrial drives,energy storage business
9	Anhui	Gotion High-Tech Co.,Limited	2074	Shenzhen Main Board	Power lithium battery,energy storage battery,lithium resource development
10	Hubei	Farasis Energy(Ganzhou)Co.,Limited	688567	STAR Market	R&D and production of soft-pack power batteries and energy storage batteries
11	Jiangxi	Ganfeng Lithium Co.,Limited	2460	Shenzhen Main Board	Lithium resource mining,lithium salt materialssolid-state battery research and development
12	Sichuan	Tianqi Lithium Corporation	2466	Shenzhen Main Board	Development of lithium ore resources,production of lithium carbonate /ithium hydroxide
13	Chongqing	Shanshan Co.,Limited	600884	Shanghai Main Board	Lithium battery negative electrode materials,electrolytes, positive electrode materials

Listing Board Definitions:

Shenzhen Main Board: Main-tier listing on Shenzhen Stock Exchange (for mature enterprises with stable performance).

Shanghai Main Board: Main-tier listing on Shanghai Stock Exchange (focus on large-cap enterprises).

ChiNext Market: Growth-oriented board on Shenzhen Stock Exchange (for innovative tech/emerging industry enterprises).

STAR Market: Sci-Tech Innovation Board on Shanghai Stock Exchange (for high-tech enterprises with core independent IP).

Source: Summarized from South Money Network,, NetEase News, and StockStar reports (2025); Statistical Scope: A-share listed companies whose core business covers power battery R&D, manufacturing, or key materials (sorted by company registration location);Data Accuracy: Companies are classified by registration location (not production bases) to ensure consistency with regional statistical standards. Note: Hongkong exchange excluded.

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China 2025 Supply Chain Overview

China's battery **raw material sector** shows high concentration and strong external resource dependence. While upstream mining relies heavily on overseas lithium, cobalt, and nickel resources, midstream refining is dominated by Chinese firms. Tianqi Lithium, Ganfeng Lithium, and Yahua Group together control over 75% of domestic lithium processing, while Huayou Cobalt holds more than 30% of global cobalt refining capacity. This structure gives China a competitive advantage in refining and processing, despite its reliance on overseas upstream resources.

China's **battery materials segment** is marked by rapid consolidation and technology-driven divergence. LFP cathodes dominate shipments, given their dominant position in domestic EVs and ESS, while ternary materials continue to lose share. Anodes and separators are highly concentrated, with clear leaders such as BTR and SEMCORP benefiting from scale advantages and high technological barriers to entry. Electrolytes also show rising concentration. Overall, the sector is transitioning toward fewer, larger suppliers with strong cost and process advantages.

The **battery cell and pack market** has reached extreme concentration, with the top ten firms controlling over 93% of domestic share. CATL and BYD form a stable duopoly, together exceeding 70% of market share. Scale, capital intensity, and system integration increasingly define competitive positioning, widening the gap between leading players and the rest of the market with increasing barriers to entry.

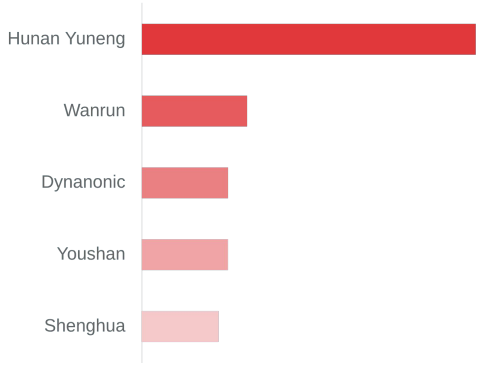
Electric vehicles and energy storage represent the second growth curve of China's battery industry. Chinese companies dominate global EV battery installations and occupy the top tier of energy storage cell suppliers. CATL leads both segments, while emerging players are scaling rapidly in the energy storage market. Cost efficiency, manufacturing scale, and supply chain integration continue to underpin China's global leadership in downstream applications.

Battery recycling is evolving into a scale- and channel-driven circular economy. Market concentration is rising as leading players secure feedstock and integrate with upstream manufacturers. GEM and Brunp lead in both processing capacity and recovery efficiency, with advanced technologies enabling recovery rates above 99% for key metals. Control over recycling channels is increasingly strategic for cost stability and long-term resource security.

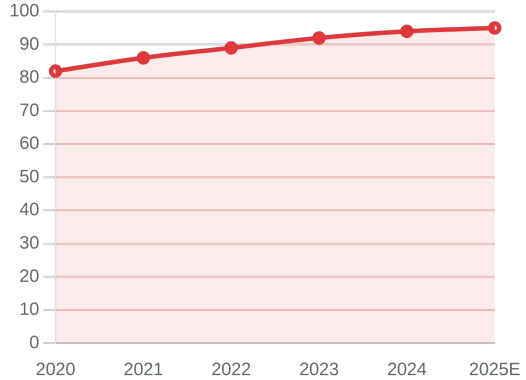
Source: SMM

China's Industry for Cathode Materials (I) - LFP

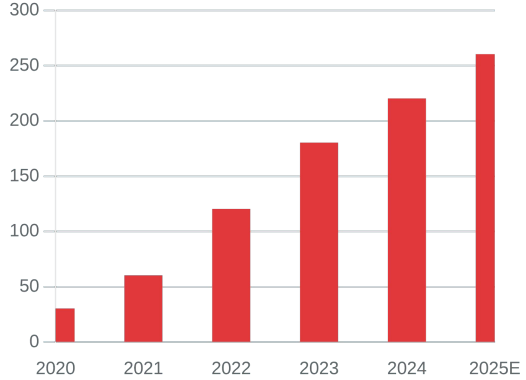
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (10K TONS)



Core Competitive Advantages

Chinese LFP companies possess an integrated industry chain from iron phosphate precursors to finished cathode materials, giving them global competitive edge in **cost control.**

Hunan Yuneng has been the world's #1 for years. Chinese firms continuously innovate in core technologies like **nanonization and high compaction density.**

Industry Overview

In H1 2025, LFP accounted for 77% of total cathode material shipments and over 94% in the ESS sector.

LFP cathode material is one of the most globally competitive segments of the value chain, with generally thin profit margins and intense price competition. The market structure is a "one-superpower, many-strong" model, with Hunan Yuneng leading by a large margin. Chinese companies not only dominate the domestic market but are also actively expanding overseas production capacity.

In terms of technology, 4th generation products with high compaction density have become mainstream, and 5th generation products are entering pilot production.

Source: itdcw, SMM, GGII, EVTANK

China's LFP Cathode Producers Still Face Poor Margins amid Overcapacity

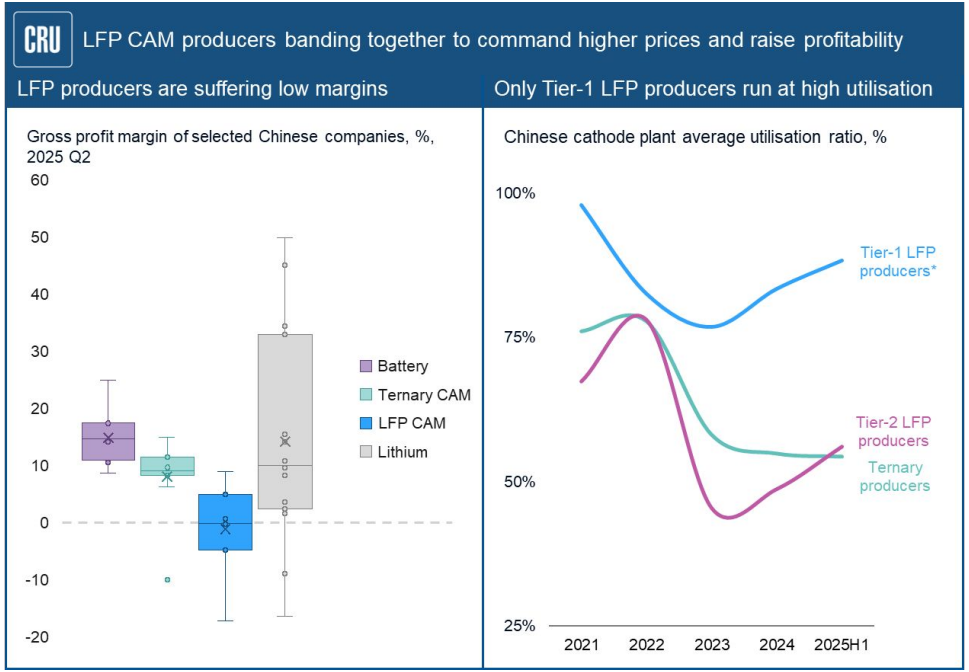
Compared to battery and lithium producers, whose margins are widely dispersed, **almost all LFP producers are struggling to break even**, even including the leading producers with technological advantages that are operating at high utilisation.

Amid rapid demand growth, LFP capacity expansions in China resumed from 2024 H2, led by Tier-1 producers and industry giants from the chemicals and mining sectors. These players aim to capture the market growth and can tolerate lower profitability.

LFP producers are now responding to China's anti-involution campaign and **attempting to take matters in their own hands**. An industry association has launched a LFP cost index and urged companies to raise offers above this level. Leading producers have called for price increases for 2026 contracts. However, ultimately the impact hinges on negotiations with battery customers, who still hold strong bargaining power.

Amid the lithium price rally in Q4 2025, leading LFP producers have suspended several production lines, putting pressure on battery customers that refuse to accept CAM prices linked with lithium prices.

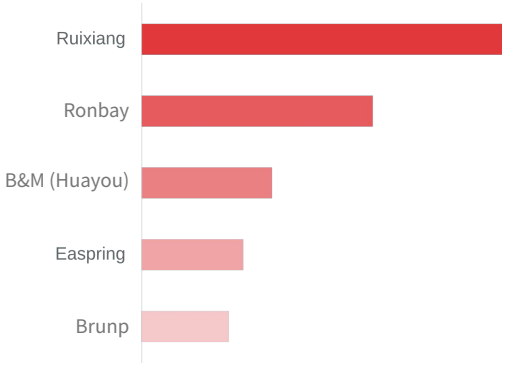
Meanwhile, although most ternary (NMC/A) cathode producers are also operating at low utilisation rates as demand continues to undershoot expectations, profitability remains generally higher than that of LFP producers since ternary batteries are mainly used in high-end vehicles. With demand stagnant from 2023, ternary producers have already cancelled their planned projects and shifted to LFP production.



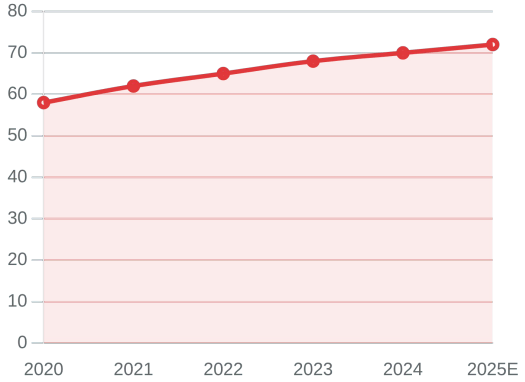
Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

China's Industry for Cathode Materials (II) - NCM

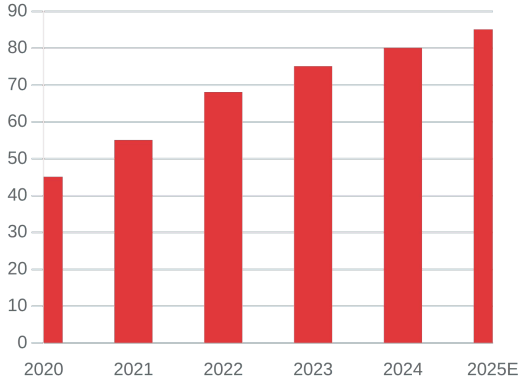
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (10K TONS)



Core Competitive Advantages

Chinese NCM companies have achieved breakthroughs in **high-nickel and high-voltage mid-nickel** technology. These products have achieved mass production and entered the mainstream international supply chain.

NCM precursor companies have a **vertical integration** advantage with Ni and Co mineral resources and processing in Indonesia.

Industry Overview

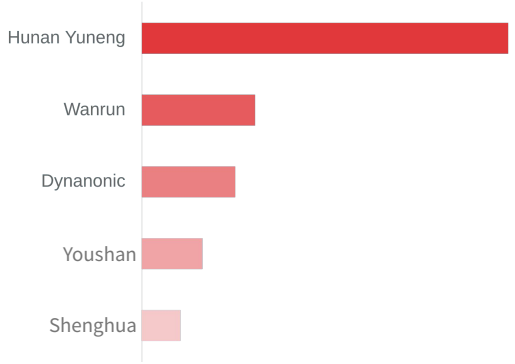
Although the NCM cathode market is being squeezed by LFP, it still holds an important position in the **high-end EV battery sector**. Innovations and added value continue to increase under the trend of high-nickel and high-voltage mid-nickel.

In H1 2025, Nantong Ruixiang ('Reshine') jumped to the top of the industry with mid-nickel high-voltage NCM materials, capturing about 25% of the market. Ronbay maintained technological leadership in high-nickel and ultra-high-nickel NCM materials. The top ten firms account for over 85% of the market, showing higher **concentration** than the LFP sector. Chinese NCM companies are actively **expanding overseas**, with Ronbay building production bases in South Korea and Europe.

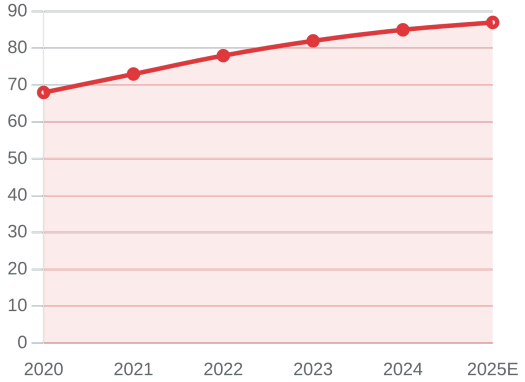
Source: itdcw, SMM, GGII, EVTANK

China's Industry for Cathode Materials (III) - Overall

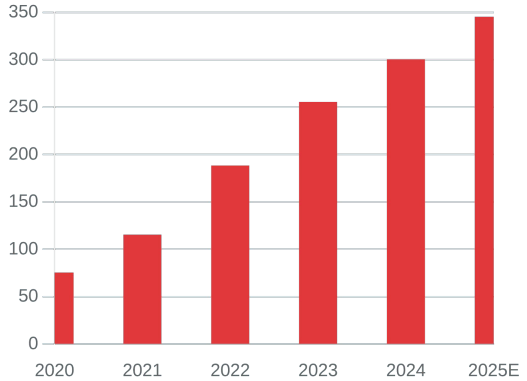
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (10K TONS)



Core Competitive Advantages

Chinese cathode material companies have formed a **diversified product matrix** including LFP, NCM, LCO, and LMFP, covering all application needs. Through **vertical integration** from "resources-precursors-cathode materials-recycling," they have built cost advantages and supply chain resilience. Leading companies are actively expanding overseas.

Industry Overview

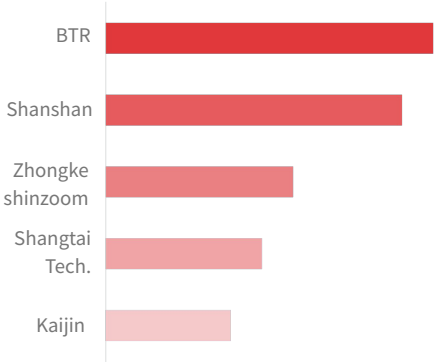
China's cathode material industry has formed the world's most complete product system. In H1 2025, LFP accounted for 77% of total cathode material shipments, with NCM making up about 20%. This diversified portfolio allows Chinese companies to flexibly meet the needs of different application scenarios.

Leading companies like Hunan Yuneng, Ronbay Technology, Dynanonic, and Wanrun New Energy have consolidated leading positions. Technological iteration continues to accelerate with ultra-high-nickel and mid-nickel/high-voltage materials, while solid-state battery cathode materials achieved ton-level shipments.

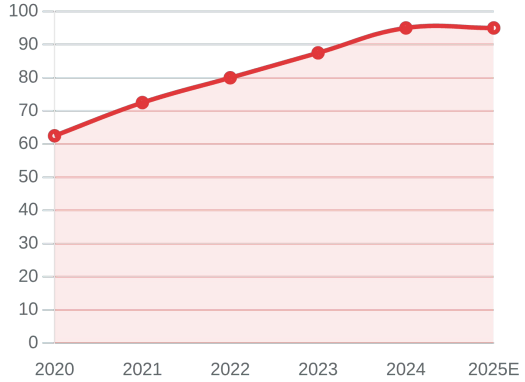
Source: itdcw, SMM, GGII, EVTANK

China's Industry for Anode Materials (Graphite)

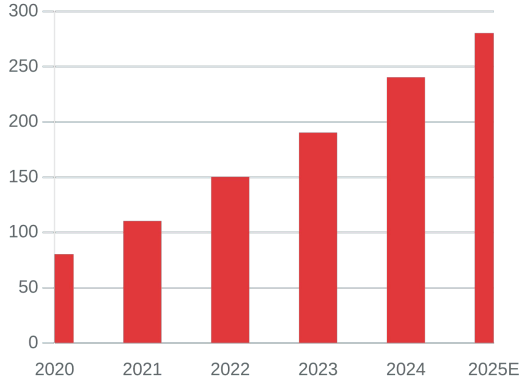
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (10K TONS)



Core Competitive Advantages

Chinese graphite anode enterprises control the complete industry chain from natural graphite mining to artificial graphite manufacturing, creating threefold advantages in **technology, cost control, and production scale**. BTR dominates the natural graphite sector with 63% global market share, while Shanshan has led the artificial graphite sector for years. The top five firms hold 70% of the global market.

Industry Overview

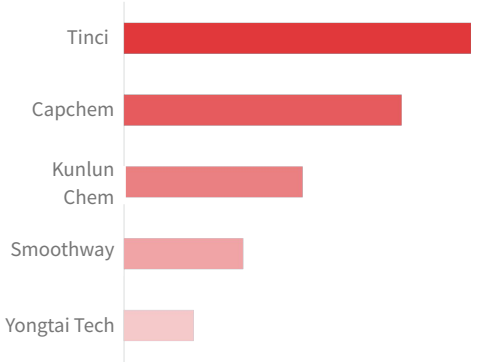
China's graphite anode industry has leaped from a follower to a global leader. Shipments surged from just 192,000 tons in 2018 to over 2.08 million tons in 2024, with a compound annual growth rate exceeding 60%. In H1 2025, artificial graphite shipments reached 1.17 million tons, accounting for 91.7% of all graphite anode shipments.

Industry concentration has steadily increased, with CR5 holding around 70% of the market. BTR and Shanshan have formed a duopoly, each with production capacity exceeding 300,000 tons. Chinese firms not only meet domestic demand but also export significantly to Japan, South Korea, Europe, and the Americas. Technologically, Chinese companies are continuously investing in cost-cutting graphetization processes and cutting-edge areas like silicon-carbon anodes.

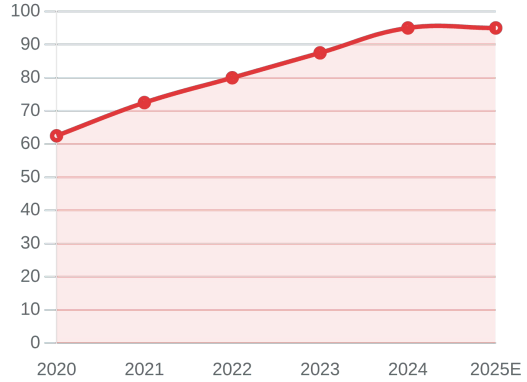
Source: itdcw, SMM, GGII, EVTANK

China's Industry for Electrolyte

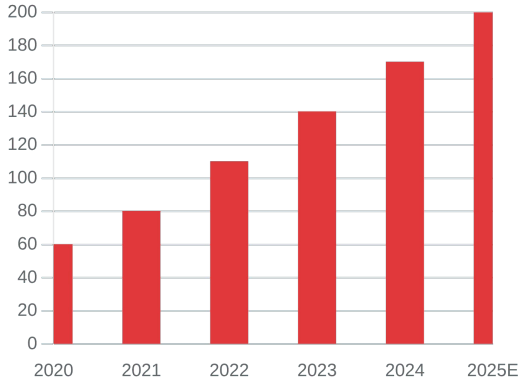
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (10K TONS)



Core Competitive Advantages

Chinese electrolyte enterprises **control the complete industry chain** from lithium salts, solvents, to additives, with obvious cost advantages. Chinese enterprises are also leading in **new electrolyte** and solid-state battery electrolyte fields.

Industry Overview

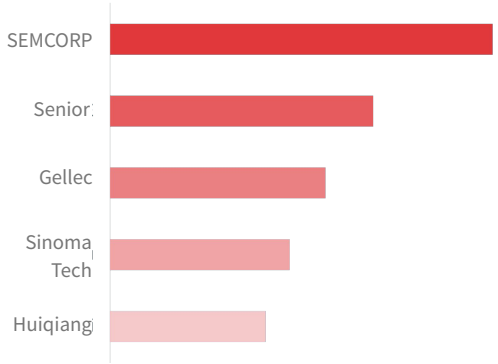
Electrolyte is a critical material for lithium-ion batteries, with Chinese enterprises having formed a global monopoly pattern. 2024 global electrolyte shipments were approximately 1.5 million tons, with Chinese enterprises accounting for over 93% market share. Capchem and Tinci have achieved absolute dominance through technological innovation and capacity expansion.

In market structure, Tinci leads with 33% market share, with Tinci following at 14%. The top five enterprises account for about 90% of the market, showing extremely high industry concentration. Technologically, Chinese enterprises are continuously innovating in lithium hexafluorophosphate and additives. New electrolytes such as solid-state battery electrolytes have entered the commercialization stage.

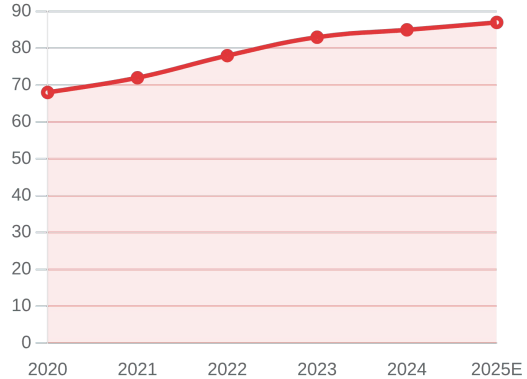
Source: itdcw, SMM, GGII, EVTANK

China's Industry for Separator

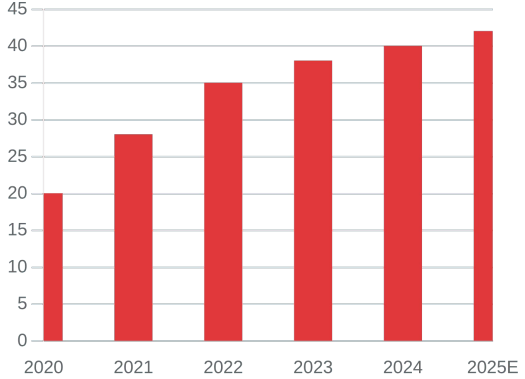
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (BILLION SQM)



Core Competitive Advantages

Chinese separator enterprises master multiple process technologies including dry and wet processes, with products covering high-end applications. Leading enterprises like SEMCORP and Senior Technology Materials have **global-leading production scale,** with obvious cost competitiveness. Chinese enterprises are continuously **innovating in ultra-thin separators and ceramic-coated separators**.

Industry Overview

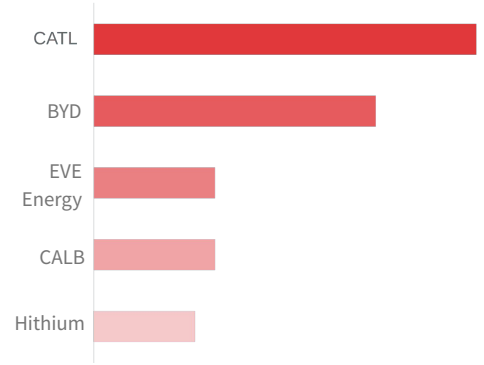
Separator is a core component of lithium-ion batteries, with Chinese enterprises having occupied absolute advantage in the global market. 2024 global separator shipments were approximately 4 billion sqm, with Chinese enterprises accounting for over 87% market share. SEMCORP, Senior Technology and other enterprises have achieved dominant positions.

In 2025, SEMCORP leads with 45% market share, with Senior following at 19%, together accounting for 64% of the market. The top five enterprises account for about 87% of the market. Technologically, Chinese enterprises lead in dry, wet, and ceramic-coated separators. Ultra-thin separator products have achieved commercialization, with thickness reaching below 5 micrometers.

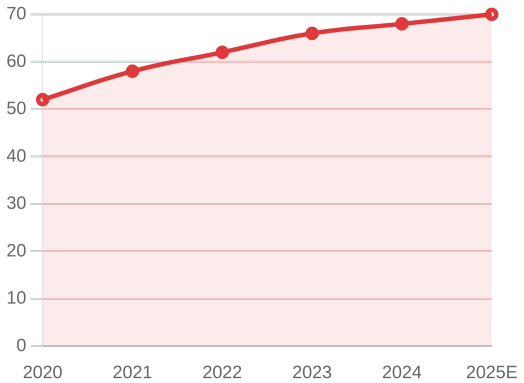
Source: itdcw, SMM, GGII, EVTANK

China's Industry for Battery Cells

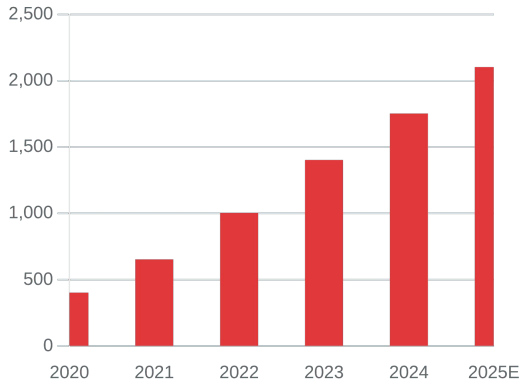
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (GWh)



Core Competitive Advantages

Chinese battery enterprises control the complete industry chain from materials to batteries, with obvious **cost and technology advantages.** Leading enterprises like CATL and BYD have the largest global production scale, while leading in LFP, Blade Battery, and CTP technologies. Chinese enterprises are also actively expanding overseas capacity in Europe, North America, and Southeast Asia.

Industry Overview

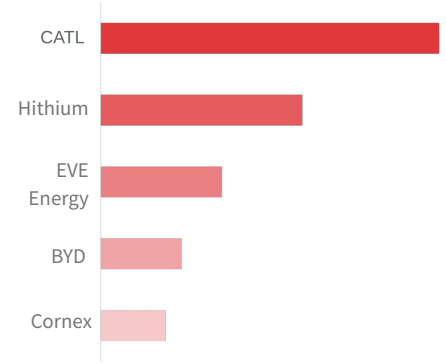
Chinese battery enterprises have become the world's largest battery manufacturers. 2024 global lithium-ion battery capacity was approximately 2500 GWh, with Chinese enterprises accounting for over 70% capacity. CATL and BYD have global-leading production scale.

CATL leads with 38% market share, with BYD following at 28%, together accounting for 66% of the market. The top five enterprises account for about 70% of the market. Technologically, Chinese enterprises lead in LFP, Blade Battery, CTP, and Qilin Battery routes. Chinese battery enterprises' global market share has reached 70%, becoming the most competitive segment in the global battery industry chain.

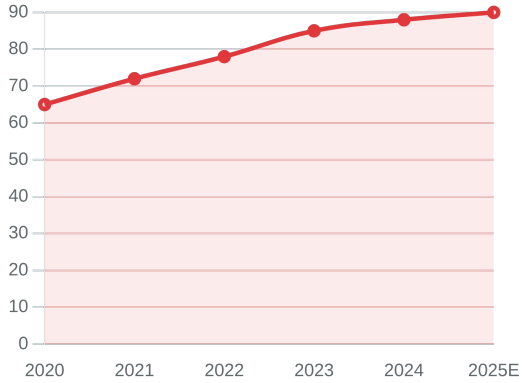
Source: itdcw, SMM, GGII, EVTANK

China's Industry for Energy Storage Systems

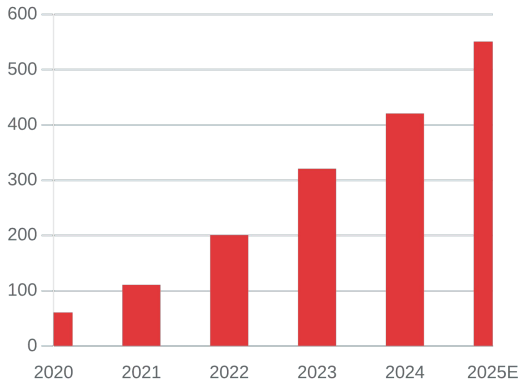
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (GWh)



Core Competitive Advantages

Chinese energy storage battery enterprises lead globally in LFP battery technology, with obvious **cost advantages**. Leading enterprises like CATL and Hithium have the global-largest production scale, with obvious advantages in long-cycle-life and low-cost.

Chinese enterprises have built up a large export network as almost all of the overseas market is served by Chinese ESS batteries.

Industry Overview

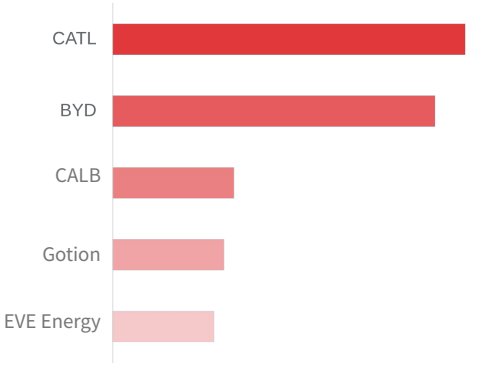
Chinese energy storage battery enterprises have become the world's largest energy storage battery manufacturers. 2024 global energy storage battery capacity was approximately 500 GWh, with Chinese enterprises accounting for over 90% capacity. CATL, BYD and other leading enterprises have global-leading production scale.

CATL leads with 42% market share, with BYD following at 25%, together accounting for 67% of the market. The top five enterprises account for about 90% of the market, showing extremely high industry concentration. Technologically, Chinese enterprises lead in LFP long-cycle-life batteries, liquid cooling technology, and energy management systems. CATL's latest energy storage batteries have a cycle life exceeding 10,000.

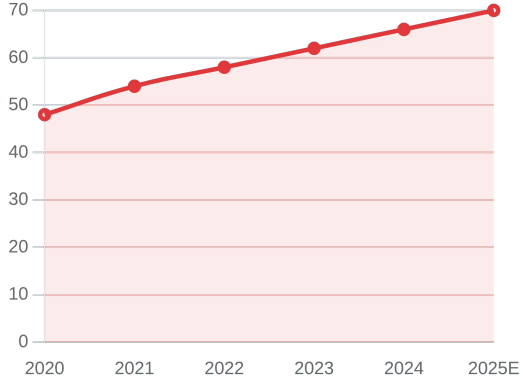
Source: itdcw, SMM, GGII, EVTANK

China's Industry for EV Batteries

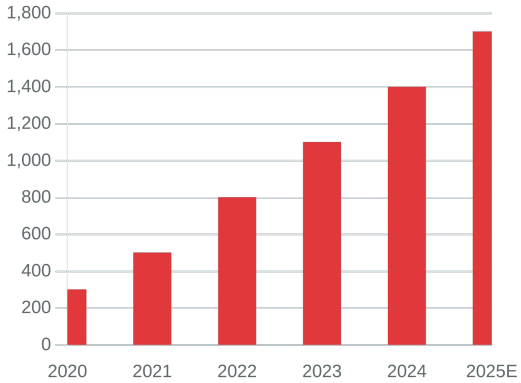
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (GWh)



Core Competitive Advantages

Chinese EV battery enterprises lead globally in LFP, Blade Battery, CTP technology. Leading enterprises like CATL and BYD have global-largest **production scale, with obvious advantages in cost and performance**. Chinese enterprises are also actively expanding overseas capacity, building production bases in Europe, North America, and Southeast Asia.

Industry Overview

Chinese power battery enterprises have become the world's largest power battery manufacturers. 2024 global EV battery capacity was approximately 2000 GWh, with Chinese enterprises accounting for over 70% capacity. CATL, BYD and other leading enterprises have global-leading production scale, with obvious advantages in technological innovation and cost control.

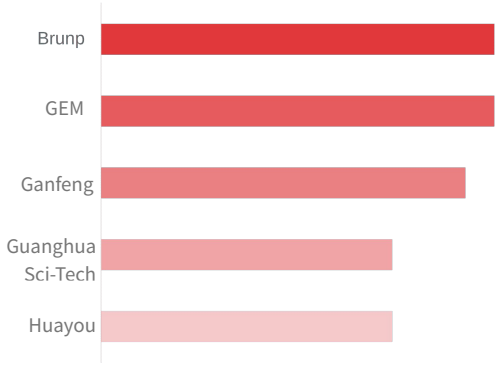
CATL leads with 35% market share, with BYD following at 32%, together accounting for 67% of the market. The top five enterprises account for about 70% of the market. Technologically, Chinese enterprises lead in LFP, Blade Battery, CTP, Qilin Battery and other multiple technology routes. CATL's Qilin Battery and BYD's Blade Battery have achieved commercialization.

Source: itdcw, SMM, GGII, EVTANK

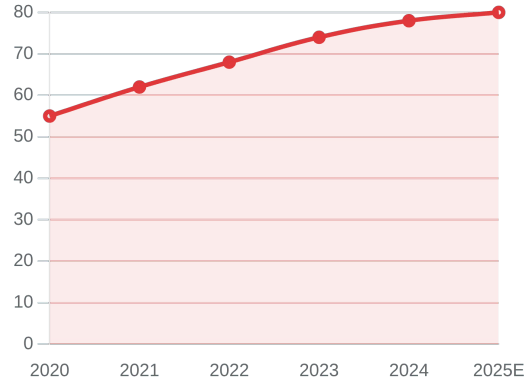
VF | VOLTA FOUNDATION

China's Industry for Recycling

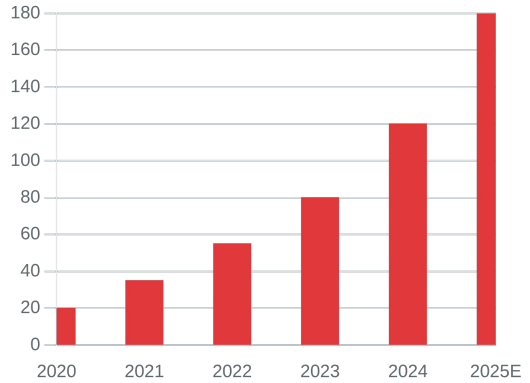
DOMESTIC MARKET SHARE TOP 5 (2025 H1)



CHINESE SHARE OF GLOBAL MARKET



CAPACITY EXPANSION (10K TONS)



Core Competitive Advantages

Chinese battery recycling enterprises possess a complete industry chain in recycling networks, dismantling technology, and regeneration. Enterprises like Brunp Recycling and GEM have a unique advantage on the resource side through the **"recycling-regeneration-cathode material" closed-loop model.** China is expected to process 3.6 million tons of used batteries in 2025, accounting for 80% of the global market.

Industry Overview

Battery recycling in China is entering a phase of rapid expansion. Since MIIT released the first recycler whitelist in 2018, industry participation has accelerated; by 2024, five whitelist batches cover 156 licensed recyclers, and the market is projected to reach US$78 billion by 2025.

Leading players are scaling rapidly. For example, Brunp, CATL's recycling arm, processed over 120 kt of batteries in 2024, with 270 kt of capacity in operation. An additional 300 kt+ is under construction, with longer-term plans targeting 1,000 kt. Technologically, multiple routes - including hydrometallurgy and direct regeneration - achieve >95% recovery rates for nickel, cobalt, and manganese. China's ~80% global market share underpins a closed-loop lithium battery lifecycle.

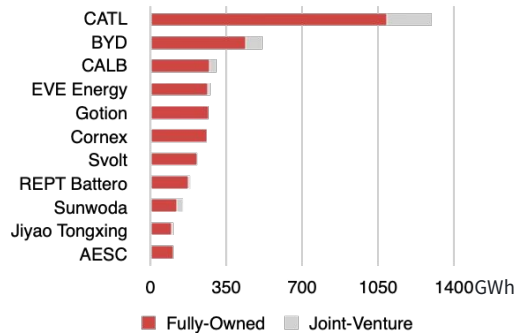
Source: itdcw, SMM, GGII, EVTANK

Closer Battery-Automaker Collaboration: Joint Ventures, Co-development and Vertical Integration

Chinese battery–automaker partnerships are deepening: **Joint ventures** remain the dominant early- to mid-stage collaboration model, particularly with state-owned automakers such as SAIC, GAC, Dongfeng, and FAW, leveraging strong capital support to build dedicated cell or pack capacity. This JV model continues to expand, with projects including CATL–Chang'an (2022), CATL–BAIC (2024), and CALB–Leapmotor (2025) progressing steadily.

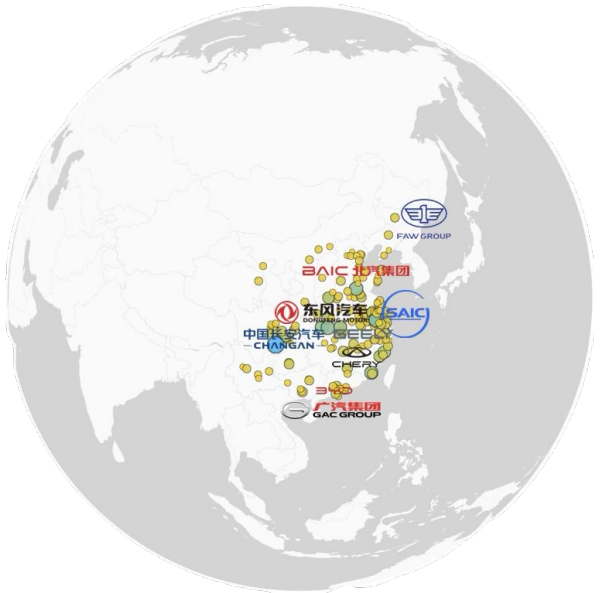
Beyond formal JVs, battery manufacturers also **co-develop automaker-specific cells**, such as Gotion's Volkswagen-standard batteries. In parallel, some full-stack automakers are vertically integrating battery production: FinDreams supplies BYD and third-party OEMs, while Geely consolidated its battery operations in 2024 under Jiyao Tongxing.

DOMESTIC BATTERY MANUFACTURING CAPACITY BY OWNERSHIP STRUCTURE



Note: *This chart includes only operating and under-construction capacity.*

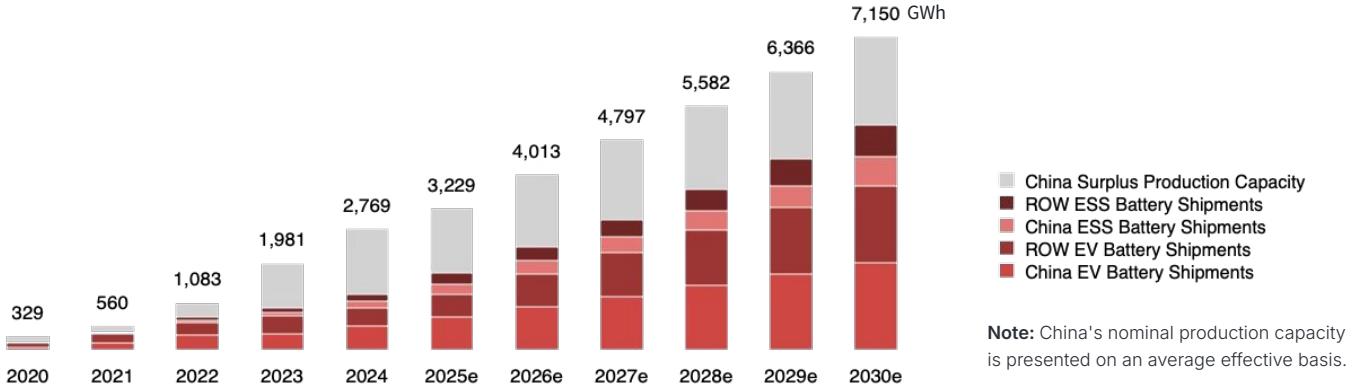
GEOGRAPHIC DISTRIBUTION OF BATTERY MANUFACTURING PLANTS AND SELECTED CHINESE AUTOMAKER HEADQUARTERS



Source: New Energy Terminal

Overcapacity & Global Balance: China's Nominal Battery Production Capacity Exceeds Global Shipments

CHINA'S NOMINAL BATTERY PRODUCTION CAPACITY VS. GLOBAL EV & ESS BATTERY SHIPMENTS



Note: China's nominal production capacity is presented on an average effective basis.

Overcapacity: China's nominal battery production capacity already exceeds both domestic and total global shipments.
As of 2025, based on publicly available information, nominal domestic capacity surpasses 3 TWh, with over 3.5 TWh under construction or planned.

Intensifying competition has driven **strategy divergence**: leading manufacturers continue Li-ion expansion, while others delay or cancel EV battery projects and pivot toward **ESS, consumer batteries or next-generation technologies** such as sodium-ion, solid-state, and eVTOL batteries.

Meanwhile, Chinese battery companies are accelerating overseas manufacturing in APAC and Europe to localize production and mitigate evolving tax and trade risks.

Source: GGII report referenced in the 2025 CATL Global Offering, New Energy Terminal

‘Trump 2.0’ Trade Wars Force Rapid Supply Chain Realignment and De-Risking

New OBBB Rules & Tax Credit Timelines
New legislation updates the 45X tax credit framework with a strict sunset clause. Credits for battery and solar components remain at 100% through 2029 but face a sharp phase-out starting in 2030, dropping to zero by 2033.

Tightened IRA Localization Regulations
To qualify for subsidies, manufacturers must meet escalating non-FEOC localization thresholds. The requirement for battery components jumps from 60% in 2026 to 85% by 2029, forcing a rapid decoupling from Chinese supply chains.

China's Counter-Moves: Retaliation & Export Control
In response to US restrictions, China leverages its upstream dominance by implementing strict export controls on critical inputs - specifically Rare Earths, Graphite, and Battery technologies - creating supply bottlenecks for Western manufacturers.

Fluctuations in Tariffs & Material Prices
The trade war creates a bifurcated market: overseas prices face a "security premium" due to high tariffs and restructuring costs, while Chinese domestic prices remain low due to trapped excess capacity and "involution".

Material Assistance Cost Ratios

Bipartisan Policy Center

Year	Clean Electricity PTC*/ITC** (48E and 45Y)	Solar Components (45X)	Wind Components (45X)	Inverters (45X)	Battery Components (45X)	Critical Minerals (45X)
2026		50%	85%	50%	60%	0%
2027	45%	60%	90%	55%	65%	0%
2028	50%	70%		60%	70%	0%
2029	55%	80%		65%	80%	0%
2030	60%	85%		70%	85%	25%
2031	60%	85%		70%	85%	30%
2032	60%	85%		70%	85%	40%
After 2032	60%	85%		70%	85%	50%

- * - Production Tax Credit
- ** - Investment Tax Credit

Source: Bipartisan Policy Center, congress.gov

Global Strategy & Footprint of Chinese Battery Supply Chain Enterprises

Europe: Powering the Automotive Heartland

- **Strategy:** Deep Integration & Localization. Direct investment in gigafactories to establish a local presence.
- **Objective**: Supply legacy automakers (BMW, Mercedes-Benz, VW) directly, reduce logistical risks, and comply with local content rules.
- **Key Projects:** CATL plants in Germany, Hungary, Spain; EVE Energy in Hungary; CALB in Portugal.

North America: Navigating Policy with Innovation

- **Strategy:** Asset-Light & Policy-Driven Models. Adapting business structures to navigate regulations like the Inflation Reduction Act (IRA).
- **Objective:** Maintain market access while minimizing political and regulatory risks for partners.
- **Key Projects:** CATL's technology licensing & service model with Ford (Michigan).



Middle East & Africa: Tapping New Frontiers

- **Strategy:** Resource & Energy Storage Deployment. Securing critical minerals and supplying massive grid-scale storage projects.
- **Objective:** Lock in essential resources (cobalt from DRC) and capitalize on renewable energy ambitions (Saudi Vision 2030).
- **Key Projects:** Chinese suppliers for Saudi Arabia's Red Sea & Bisha giga-storage projects; Gotion & CNGR building a battery hub in Morocco for EU/US markets.

Asia & South America: Securing the Full Value Chain

- **Strategy:** Resource Control & Regional Hubs.Full-stack investment from mining to manufacturing.
- **Objective:** Secure upstream raw materials (Indonesian nickel, South American lithium) and build production bases for emerging Asian EV markets.
- **Key Projects:** CATL's integrated nickel project in Indonesia; Gotion's LFP plant in Vietnam for VinFast; Huayou's material JVs in South Korea.

Source: 1. Global EV Outlook 2024 2. Benchmark Mineral Intelligence

Global Strategy & Footprint of Chinese Battery Supply Chain Enterprises (Cont.)

Part 1: The Toolkit - Core Cooperation Models

Direct Investment

Building wholly-owned plants for localized, end-to-end manufacturing. (e.g.,CATL in Europe)

Joint Ventures

Partnering with local industry leaders to share risk, capital, and market access. (e.g.,EVE with Daimler Truck in the US)

Technology Licensing

Providing proprietary technology, equipment,and services to navigate policy barriers. (e.g., CATL with Ford)

Upstream Integration

Acquiring stakes in or developing global mineral assets to guarantee raw material supply. (e.g., Chinese firms in South America's 'Lithium Triangle')

Part 2: The Road Ahead

Supply Chain Regionalization

The global model is shifting towards resilient, diversified networks ('Europe for Europe,''North America for North America') to mitigate geopolitical risk. Chinese firms are central to building these new regional ecosystems.

ESG as a Hard Requirement

With initiatives like the EU's 'Battery Passport,'sustainability is now a non-negotiable for market access. Chinese leaders are proactively shaping these global standards through the Global Battery Alliance (GBA).

The Next-Gen Technology Race

Cooperation will intensify beyond current production to focus on joint R&D in next-generation technologies like solid-state and sodium-ion batteries to secure future leadership

The Imperative of Global Cooperation

For China, a global footprint is a necessity:

Inherently Global Supply Chain: The battery value chain is geographically dispersed by nature.

Upstream Resources: Critical minerals like lithium, cobalt, and nickel are concentrated in specific regions, requiring international partnerships to secure supply

Downstream Markets: Application markets are global, demanding localized production and service to meet customer needs and navigate trade policies.

BENCHMARK Source: 1. Global EV Outlook 2024 2. Benchmark Mineral Intelligence (Distinguished Partner)

CHINA

History
Policy Landscape
Talent & Ecosystem Maturity
Capital
Supply Chain



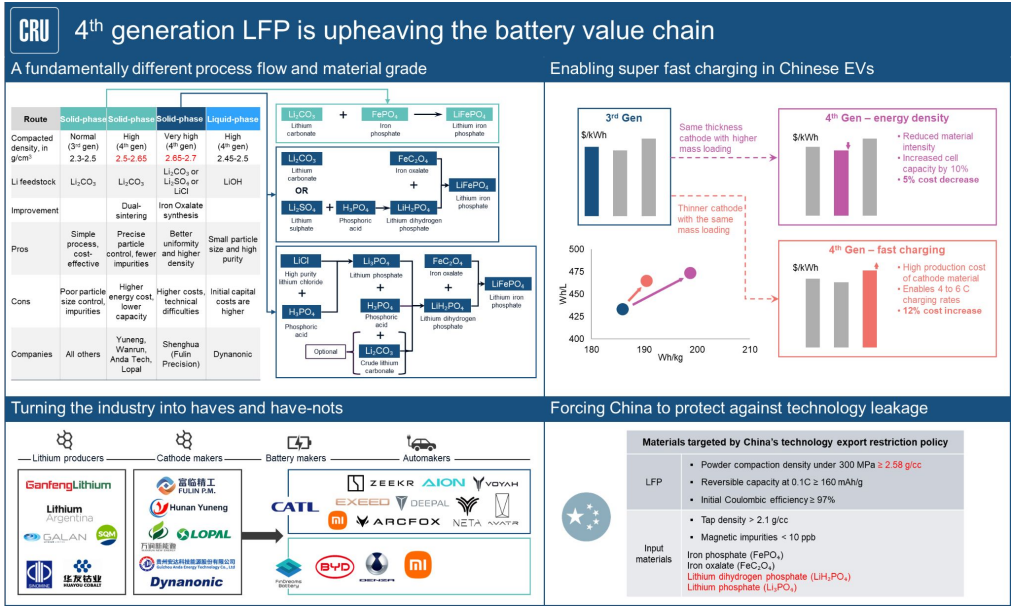
Technology Innovation

4th Generation LFP Has Far-reaching Impacts

LFP cathode continues to improve in hands of Chinese innovators. It is now in its 4th generation and constitutes a technological breakthrough and a fundamentally higher material standard.

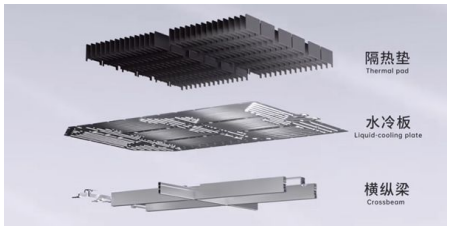
Its emergence has far-reaching implications on global battery investments, supply chain structures, market competition and geopolitics.

- High-compaction-density LFP is enabling **super-fast charging in EVs** in China and narrowing the performance gap versus other chemistries.
- Only a handful of manufacturers are capable of producing or procuring this material, turning the LFP cathode, battery and EV sector into **'haves and have-nots'** and driving consolidation.
- **China's export restriction policy** on high-end LFP technology is ensuring it will remain in the hands of Chinese companies, while non-Chinese firms generally take longer to achieve and scale up similar cost and technical advancements for LFP.
- The different nature of the cathode production route means that it is **shifting raw material feedstock demand** from conventional chemicals to alternative ones, especially for lithium.



From Cell-to-Module to Cell-to-Pack & Cell-to-Body

In 2022, CATL released the Qilin battery using Cell to Pack Gen3 technology, which is the same platform used by the Xiaomi SU7 battery. The new design replaces separate crossbeams, liquid cooling plates, and thermal pads with a multi-functional sandwich structure incorporating an elastic interlayer. Another key feature is the use of built-in micro-bridges, which accommodate cell swelling and improve battery reliability throughout its operational lifetime.



THERMAL & MECHANICAL PROPERTIES INTEGRATION





BUILT-IN MICRO BRIDGES



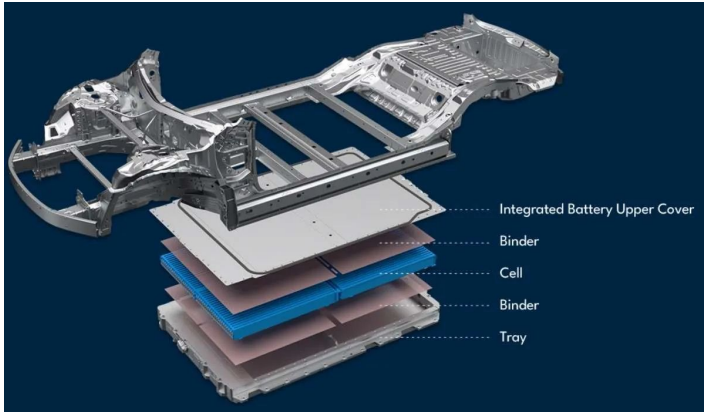
ABSORB CELL SWELLING

Source: 集成度全球新高，宁德时代发布麒麟电池

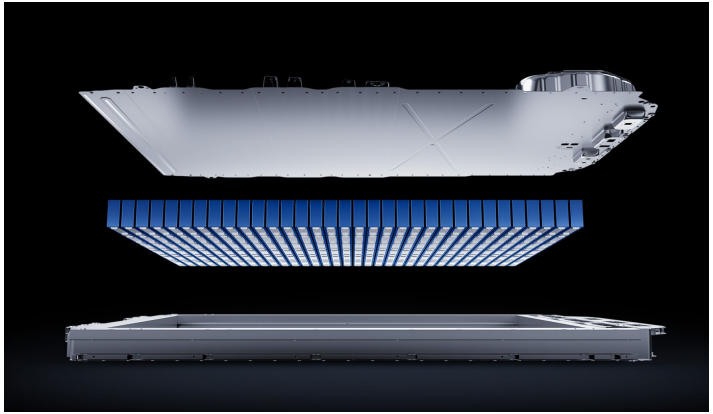
From Cell-to-Module to Cell-to-Pack & Cell-to-Body

BYD's and Xiaomi's Cell to Body (CTB) technology is a structural innovation that integrates the battery pack directly into the vehicle's body. This integration significantly increases the structural rigidity due to higher torsional stiffness. It also optimizes space utilization, achieves a higher volumetric utilization rate, and improves vehicle handling by enabling a 50:50 front-rear weight distribution and a lower center of gravity.

BYD CELL TO BODY BATTERY



XIAOMI CELL TO BODY BATTERY



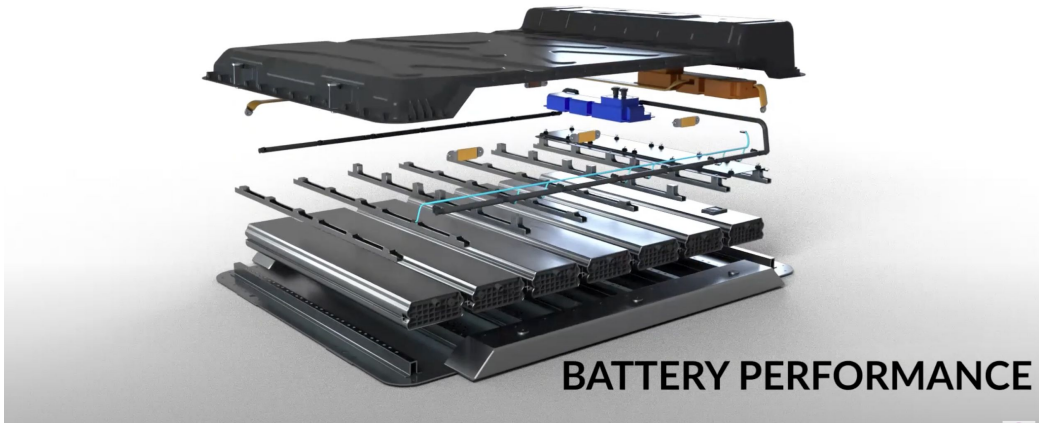
Source: Cell to Body - Battery Design, XiaomiEV

Cell to Body (CTB) Battery Pack Cover Hybrid Material Process

Technology Description: Uses variable-thickness (VRB) structures and orthogonally woven glass fiber-reinforced polymer (OW-GFRP) bonded together to form a hybrid structure.

Key Advantages / Features: ~3x more lightweight than metal structures, while maintaining stiffness requirements.

CTB BATTERY PACK COVER HYBRID MATERIAL PROCESS APPLICATION EXAMPLE



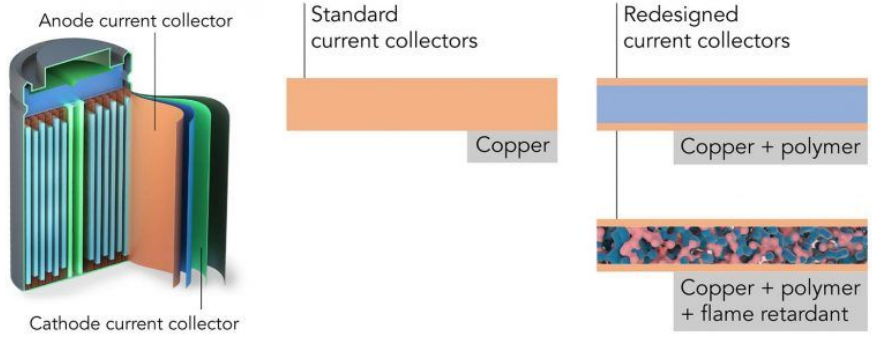
Source: Cost-effective glass fiber battery enclosure to combat EV weight issues | Automotive Powertrain Technology International

Composite Current Collector Technology

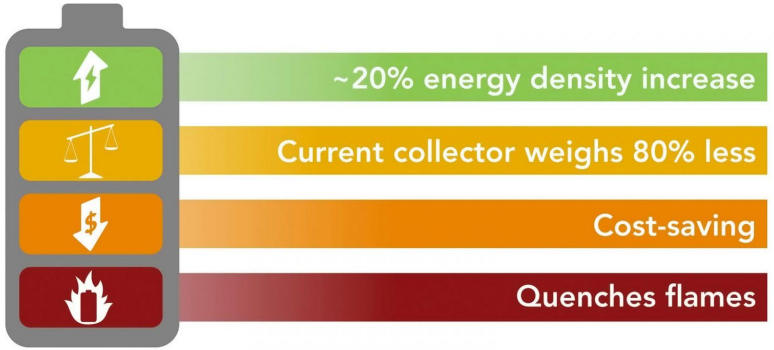
Technology Description: Adopts a "metal-polymer-metal" sandwich structure, where the polymer base film is typically PET or PP, and coated with nanoscale metal layers via magnetron sputtering or electroplating.

Key Advantages / Features: Increases energy density, improves risk to thermal runaway (reduced short circuit risk)

COMPOSITE CURRENT COLLECTOR SCHEMATIC DIAGRAM



COMPOSITE CURRENT COLLECTOR APPLICATION EXAMPLE



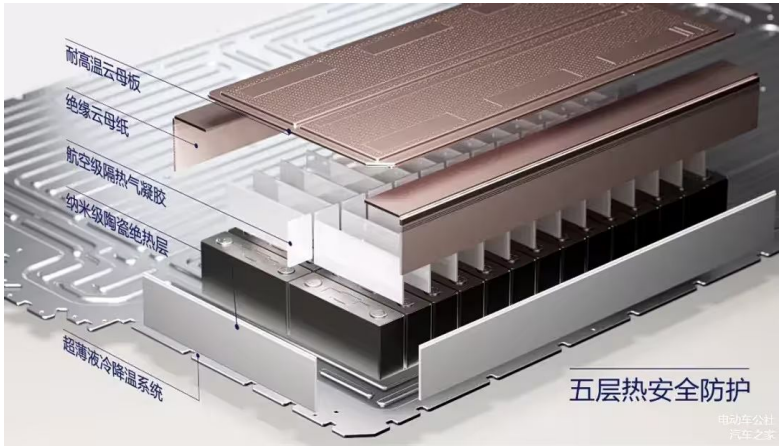
Source: Redesigned Current Conductors Boost Lithium-Ion Battery Efficiency and Safety

‘Thermal-Electric Separation’ & Multi-Layer Insulation

Technology Description: 1. Thermal-Electric Separation: Orients cell vent downward and terminals upward, separating thermal runaway exhaust from high-voltage pathways. 2. Multi-Layer Insulation: Wraps each cell with aerogel, ceramic, and mica layers. 3. Harness Integration: Integrates wiring into a "wireless high-voltage box."

Key Advantages / Features: 1. Prevents high-voltage arcing during thermal runaway, improving overall safety. 2. Creates a "safety cocoon" to effectively block thermal propagation. 3. Reduces manual labor, lowers failure rates, enables smart management system.

"THERMAL-ELECTRIC SEPARATION" & MULTI-LAYER INSULATION APPLICATION EXAMPLE (HUWEI GIANT WHALE BATTERY)



Source: Autohome: 电动车公社

China is a Major Pioneering Player in eVTOL & Humanoid Robots

The 'low-altitude economy' and humanoid robots are pushing lithium battery technology to new performance limits. Currently, solid-state/semi-solid-state batteries are widely regarded as the most promising long-term technological pathways to achieve substantially higher energy density and safety, although their large-scale commercialization will take time to realize.

Performance	Specific Goals & Challenges	Solutions & Development Trends
Energy Density	Low-altitude economy: Breakthrough to 400Wh/kg in the short term, long-term target of 500Wh/kg. Humanoid robots: Advance from 250-300Wh/kg to over 350Wh/kg.	Material Systems: Adopting high specific energy materials like high-nickel cathodes and silicon-carbon anodes. Ultimate Path: Developing solid-state/semi-solid-state batteries, theoretically capable of exceeding 500Wh/kg.
Power & Fast Charging	Meeting the instantaneous ultra-high power demands (high-rate discharge) for eVTOL takeoff/landing and intense robot movements.	Cell Design: Adopting full-tab design to reduce internal resistance. System Management: Upgrading the Battery Management System (BMS) and optimizing output strategies.
Safety	The low-altitude economy requires aviation-grade absolute safety (PPB-level failure probability). Humanoid robots must ensure close-range personal safety.	Intrinsic Safety: Using solid-state electrolytes to prevent thermal runaway at its root. System Protection: Applying system solutions like "thermal-electric separation," multi-stage insulation, and intelligent early-warning BMS.
Adaptability & Lifetime	Cell form factor must adapt to robots' irregular body and complex structure Meet cycle life (target 600+ cycles) requirements under long-term, high-frequency use.	Structural Innovation: Adopting pouch cell packaging and "hybrid architecture" battery packs for customization. Process Optimization: Delaying degradation through material and process innovation.

Source: 电池产业蓄势第二次跨越式增长, 人形机器人电池成新增长极

Over the Past Five Years, NCM Cathode Materials for Power Batteries Have Undergone Rapid Evolution

Trend	Key Directions	Driving Factors & Current Progress
High-Nickel & Cobalt-Reduction Technology Path	Nickel content rapidly increased from NCM 523/622 to NCM 811 and above. "Ultra-high nickel (Ni ≥ 90%)" and "low-cobalt / cobalt-free" have become clear directions.	Increase Energy Density: Higher nickel content delivers higher capacity. Reduce Cost & Risk: Decreases reliance on expensive cobalt with unstable supply chains.
Performance Enhancement & Structural Innovation	To address the structural stability issues of high-nickel materials, core modification technologies like "single-crystal" structures, "concentration gradient" design, and "surface coating & bulk doping" have been developed.	Solve High-Nickel Bottlenecks: Improve cycle life and safety. For example, gradient structures can suppress microcracks. Technology Integration: NCMA (nickel-cobalt-manganese-aluminum) materials further stabilize structure through aluminum doping.
Market & Application Diversification	Forms a "duopoly" with lithium iron phosphate (LFP), but their market shares fluctuate. NCM focuses on high-end passenger vehicles and long-range models.	Cost-Effectiveness: After subsidy phase-outs, LFP made a strong comeback in mid-to-low-end vehicles and energy storage due to cost advantages. Scenario Matching: NCM maintains its position in performance and long-range scenarios due to its high energy density.
Supply Chain & Cost Control	Companies are accelerating "upstream resource integration" and promoting "large-scale production" to reduce costs.	Ensure Supply Security: Secure key mineral resources (e.g., nickel, lithium) through equity investments, joint ventures, etc. Technical Cost Reduction: High-nickel, low-cobalt formulations are themselves a primary cost-reduction path.
Cutting-edge Technology Exploration	"Lithium-rich Manganese-based" cathodes and cathodes compatible with "solid-state batteries" have become R&D hotspots for next-generation tech.	Break Energy Density Ceiling: Lithium-rich manganese-based materials have a much higher theoretical capacity than current NCM. Adapt to System Change: Solid-state batteries require solving interface stability issues between the cathode and solid electrolyte.

Source: 动力锂电池市场发展情况及趋势, 电子产品世界

Resurgence & Dominance: LFP is the Dominant Chemistry in the China Battery Market

Trend	Key Directions	Driving Factors & Current Progress
Market Position & Cost Advantage	**Significant Cost Edge:** LFP batteries maintain a clear cost advantage, with cell-level costs ~30% lower than NMC/NCA batteries, reaching around $95 per kWh in 2023. The LFP battery market was valued at $17.54 billion in 2023.	The phase-out of subsidies shifted focus to cost-effectiveness. Supply chain stability (free from expensive cobalt/nickel) and safety advantages (high thermal stability) are key drivers. Major automakers like Tesla, Volkswagen, and Ford are adopting LFP.
Material Innovation & Performance Enhancement	**Overcoming Intrinsic Limits:** R&D focuses on solving LFP's low electronic/ionic conductivity. Advanced doping (e.g., Vanadium-Sulfur) and coating technologies (e.g., carbon-silica dual-layer) are widely applied to boost conductivity and stability. **Nano-Engineering & Morphology Control:** Precise synthesis methods (e.g., hydrothermal) and the use of additives like graphene and carbon nanotubes optimize particle structure for better lithium-ion diffusion and rate capability.	The drive for higher energy density, longer cycle life, and faster charging for EVs pushes continuous material modification. These innovations aim to narrow the performance gap with NCM while retaining LFP's cost and safety benefits.
Manufacturing & Supply Chain Evolution	**Upstream Integration & Cost Control:** Leading producers are integrating upstream into raw materials (lithium, iron, phosphorus) to secure supply and manage costs, which constitute the largest expense in LFP production. **High-Tap-Density Products:** To meet demand for higher volumetric energy density (especially for EVs), the industry is shifting towards high-tap-density LFP. This is becoming a key differentiator and is dominated by leading manufacturers with technical expertise.	Intense competition and price pressures make vertical integration critical for profitability. The rapid iteration of battery cell design (e.g., towards larger energy storage cells) creates demand for superior material grades.
Future Outlook & Competition	**Performance-Driven Segmentation:** The traditional LFP market is splitting. High-tap-density LFP will maintain competitiveness in mainstream markets, while its successor, Lithium Manganese Iron Phosphate (LMFP), is poised to capture the premium segment with its ~15-20% higher energy density.	The industry evolution is shaped by the need for higher energy density at low cost. LMFP represents the natural upgrade path within the phosphate family. Recycling of spent LFP batteries is gaining importance for a sustainable supply chain.

Source: MySteel

LMFP Cathode Development Progress

Performance Goal: Achieve a 15-20% higher energy density than LFP batteries while maintaining similar safety and cost advantages.

Market Need: Fulfill gap between lower-cost LFP and higher-energy, but more expensive and less safe nickel-rich ternary (NMC) batteries.

Application Expansion: Develop LMFP for use both as a stand-alone cathode and in blended cathodes with NMC materials to create a performance-cost-safety balance.

Time Period	Key Developments & Trends
Early 2020s	LMFP gained significant attention as a next-generation cathode material by combining the high safety and low cost of Lithium Iron Phosphate (LFP) with the higher voltage and energy density of Lithium Manganese Phosphate (LMP). It was positioned to address the energy density limitations of mainstream LFP batteries.
2021-2023	Research intensified to solve fundamental issues hindering commercialization, primarily low intrinsic electronic/ionic conductivity and the "voltage decay" problem during cycling. The emergence and evolution of an anomalous "third discharge platform" was identified as a key cause of energy density loss over time.
2024-2025	This period marks a critical turning point. Leading material companies began building large-scale production capacity (e.g., plants with tens of thousands of tons annual output). The first LMFP batteries entered the market, initially in applications like electric two-wheelers. The industry consensus formed that 2025-2026 would be the period for large-scale market adoption.
2025-Present	A clear industry trend emerged where major producers are strategically shifting new investments beyond traditional LFP towards both next-generation LFP and LMFP. Concurrently, advanced modification strategies like ionic doping (e.g., Zinc gradient doping) and the use of 3D continuous mesoporous carbon frameworks have shown success in enhancing conductivity and, more importantly, effectively suppressing the voltage decay issue.

Source:【磷酸錳鐵鋰電池技術】與【精準反應製程與應用技術】專題:材料世界網-工業材料雜誌, 《工業材料雜誌》2025年3月號推出「磷酸錳鐵鋰電池技術」與「精準反應製程與應用技術」兩大專題:材料世界網, 我院新能源材料与电池团队在国际学术期刊上发表磷酸锰铁锂研究最新系列成果

China's Sodium-Ion Battery Industry Has Rapidly Progressed from Laboratory Research to Mass Production

Large Scale Energy Storage

Landmark projects are in operation, such as the first large-capacity sodium-ion battery energy storage station in China in Nanning, Guangxi, and the world's largest sodium-ion battery energy storage project (100 MWh) by Datang Hubei.



Electric Commercial Vehicles

HiNa Battery released the world's first sodium-ion battery solution for commercial vehicles; CATL's "NaXin" battery is used for heavy-duty truck start-stop.



Two-Wheeled EVs

Brands like Yadea have released multiple sodium-battery electric vehicle models, promoting the replacement of lead-acid batteries.

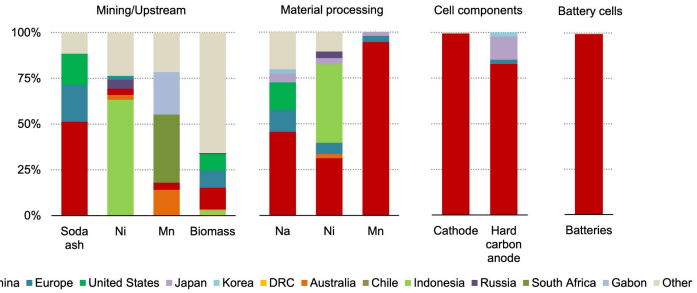


Source: 钠离子电池行至量产前夜_国内行业动态_省工信厅, 钠新电池+双核架构！宁德时代开启多核时代, 雅迪冠能Q50钠电版电动车

China Dominates the Early Sodium-ion Supply Chain

Sodium-ion battery (SIB) technology has progressed rapidly across research, industrial development, and early commercialization. The technology is at a pivotal transition point - moving from prototype demonstrations and pilot production toward broader commercial adoption and full industrial scale-up. China is dominating sodium-ion battery supply chain and has deployed some SIB pilot projects in various applications.

GEOGRAPHICAL DISTRIBUTION OF THE SODIUM-ION BATTERY SUPPLY CHAIN



CHINESE SIB PILOT PROJECTS IN VARIOUS APPLICATIONS

Date	Market Category	Project / Product	Location	Scale / Specification	Companies Involved	Remark
2024-06	**ESS**	Datang Hubei Sodium-ion ESS Phase 1	Qianjiang, Hubei	50 MW / 100 MWh (to 200 MWh)	China Datang, HiNa	World's first large-scale commercial application of sodium-ion for stationary energy storage
2025-05	**ESS**	Baochi Lithium–Sodium Hybrid ESS	Yunnan	200 MW / 400 MWh	CSG Energy Storage; China Southern Power Grid	China's first large scale lithium–sodium hybrid energy storage power station.
2023-04	**EV**	Chery EV with CATL SIBs	China	N/A	Chery, CATL	
2023-12	**EV**	JMC A00-class EV	China	251 km range	JMC, Farasis	
2023-12	**EV**	JAC Huaxianzi SIB version	China	252 km range	JAC, HiNa	
2025-01	**E2W**	Na-ion battery powered Two-Wheeled EVs	China	Mass-produced /48V24Ah	Yadea, Huayu Sodium battery	Mass-produced consumer-grade product

Source: P_Li, Q.; Ulissi, U.; Liang, Z.; Chen, X.; Guo, B.; Zhang, X.; Ouyang, C. Progress and Prospect of Industrialization of Sodium-Ion Battery in China. Advanced Energy Materials.

Semi-Solid State Battery Technology is Ready for the China Market

On August 5, 2025, Chinese automaker SAIC unveiled the 2nd generation of its MG4, which can be powered by a semi-solid-state battery jointly developed by SAIC and Qingtao New Energy. In December, SAIC MG announced it had delivered the first MG4 with the new technology at a price point of $14.5k.

The positive electrode uses lithium-rich manganese-based materials (LMO). The company claims that liquid electrolyte content is reduced to 5%, which will significantly reduce the risk of combustion and improve cycle life.

Safety Performance



Electrical Performance

Power: -20 °C, power is not limited between 25% and 100% SOC;

Charging: -20°C, from 10% to 80%, within 43.2 minutes;

Retention: -20 °C, 1C discharge, the capacity retention > 100%, and the energy retention > 91%;

Cycle life: 3,000 cycles at room temperature with a 1C charge and discharge.

Source: BiliBili - MG4预售发布会

All-Solid-State-Batteries are Still in Development Phase

So far, only some China OEMs have publicly released their SOP plans for solid state batteries. Three of them choose sulfide electrolyte in their technology stack due to the technology's ionic conductivity and manufacture feasibility. By now, sulfide-based battery have become the mainstream route worldwide, Japan, South Korea, Europe, the United States and China have increased their R&D investment in sulfides.

OEM	Solid State Battery Technology	SOP Plan
SAIC 上汽集团 SAIC MOTOR	High Nickel cathode + Si/C anode + Polymer electrolyte	2026
GAC 广汽集团 GAG GROUP	High Nickel cathode + Si/C anode + **Sulfide**/Halide electrolyte	2026
蔚来 NIO	High Nickel cathode + Si/C anode + **Sulfide**/Polymer electrolyte	2027
中国一汽	High Nickel cathode + Si/C anode + Halide electrolyte	2027
BYD 比亚迪汽车	High Nickel cathode + Si/C anode + **Sulfide** electrolyte	2027

Reason 1: High ionic conductivity

- Ionic conductivity : 32 mS/cm
- Ion transfer number : ~1

Reason 2: Easy to manufacture

- A continuous ion pathway can be formed in the composite electrode by cold pressing
- A compact electrolyte film can be formed by cold pressing

Source: 2025第二届中国全固态电池创新发展高峰论坛

Evolution of Si-based Anode Development

Material and Structural Innovation: The evolution from simple mixing to sophisticated nano-/micro-structures like core-shell, yolk-shell, and specially designed porous carbon frameworks has been central to managing volume change.

Process Advancement: The shift from traditional ball milling of metallurgical silicon to CVD-based processes has been key for achieving uniform silicon distribution and consistent, high-quality production at scale.

Supply Chain Integration: Leading companies are increasingly adopting integrated production strategies, controlling key upstream materials like porous carbon and nano-silicon to ensure performance and reduce costs.

Time Period	Key Developments & Trends
2020-2021	Increased interest in silicon as the core technology to break the energy density bottleneck of graphite anodes, due to silicon's ultra-high theoretical capacity (4200 mAh/g). The main research focus was on solving the fundamental challenge of silicon's large volume expansion (~300%) during charging and discharging, which causes rapid battery degradation.
2022-2023	Chemical Vapor Deposition (CVD) emerged as a leading preparation method. This technique involves depositing nano-silicon particles into a porous carbon framework, which effectively buffers volume expansion. Companies like Group14 advanced this technology internationally. Pre-lithiation technologies became critical to overcome the initial capacity loss (low first-cycle efficiency) of silicon anodes. The first gigafactory-scale production plans were announced, marking the transition from R&D to pilot and early commercial production.
2024-2025	Widespread adoption in consumer electronics (smartphones, laptops) occurred, driving initial mass production and cost reduction. Formal entry into the power battery market began, with automakers like Tesla (4680 battery), BMW, and IM Motors launching vehicles using Si-C anodes. Research focused on advanced structural design (e.g., "sieving-pore" carbon structures) to further improve stability and fast-charging performance.
2025 Onwards & Future Outlook	The industry is working towards large-scale cost reduction by optimizing key raw materials like porous carbon and silane gas, and scaling up CVD equipment. It is increasingly considered the preferred anode for next-generation all-solid-state batteries. Applications are expanding into new fields such as low-altitude economy (eVTOLs) and humanoid robots, which demand very high energy density.

Source: 锂电硅碳负极材料，拐点时刻; 硅碳负极放量在即产业链降本成关键; 祝贺何家兴在Nature communications上发表筛分型硅碳最新成果！

ACADEMIA

VF | VOLTA FOUNDATION

Volta Foundation is the world's largest network of battery professionals. As a global not-for-profit association, Volta Foundation produces publications, networking opportunities, and industry resources to foster collaboration, innovation and advocacy within the battery industry.

Section Summary

Lithium-ion and Lithium Metal batteries

- Manganese-rich analogues of NMC and LFP have cost and energy advantages if their stability and conductivity can be managed.
- The allure of pure energy density of lithium metal continues to motivate metal plating and electrolyte research.

Simulating Real-world Conditions

- Batteries can operate for decades, more research is emerging that spans long timescales or accelerated aging.
- The way we use batteries is considerably more complex and varied than the standard way that we test them (0 to 100% cycles), understanding these differences opens up new use cases and better lifetime predictions.

Sodium and Other Ions

- Sodium-ion batteries are becoming a mature technology, but they still finding their home in the energy storage economy.
- Research in charge carrying ions beyond lithium and sodium (such as potassium, zinc, fluoride) is focused on the discovery and engineering of electrode materials and electrolyte–solvent systems.

2025 | BATTERY REPORT

ACADEMIA

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Research Trends
Seminal Literature
Fundamentals
Lithium-ion
Solid State Batteries
Battery Degradation and Performance
New / Alternative Chemistries
Fast Charging & Extreme Fast Charging
Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

ACADEMIA

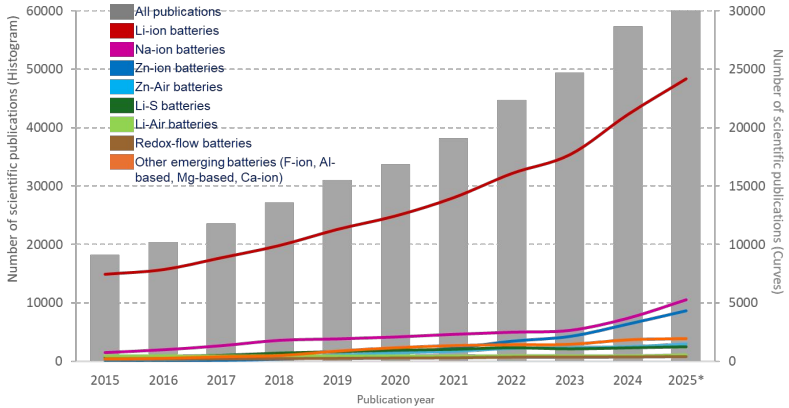
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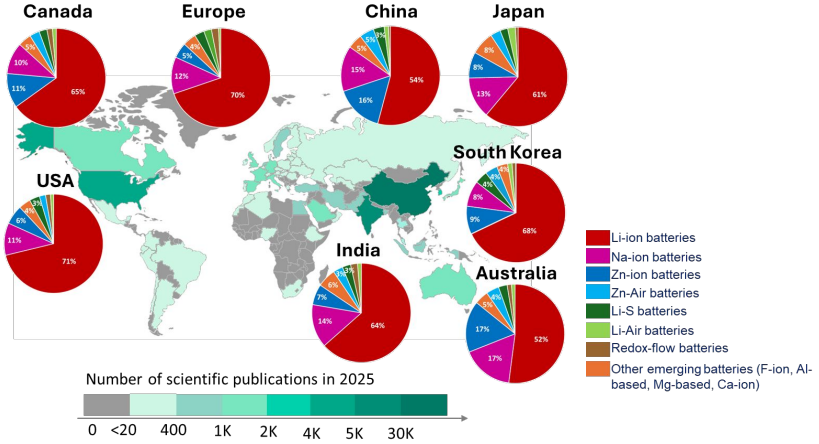
Growth in Publications Driven by China and India & Researches on Li-Ion, Na-Ion and Zn-Ion Batteries

- The number of publications **continues to increase in 2025 across all major battery technologies**, particularly for **Li-ion, Na-ion, and Zn-ion batteries**.
- In 2025, most scientific publications are authored by **Chinese entities**, far ahead of those based in India, the United States, Europe, South Korea, Japan, Canada, and Saudi Arabia.
- For each of these leading countries, **all major battery technologies** are well represented in scientific publications.

TIME EVOLUTION OF PUBLICATIONS ON BATTERIES



RESEARCH VOLUME BY COUNTRIES IN 2025



Source: Knowmade. Publications searches and statistics were done on Scopus by Knowmade,
*Publication searches were done in December 2025 and extrapolated for the whole year.

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Electrolyte, Safety, Anode and Cathode Are the Most Published Topics

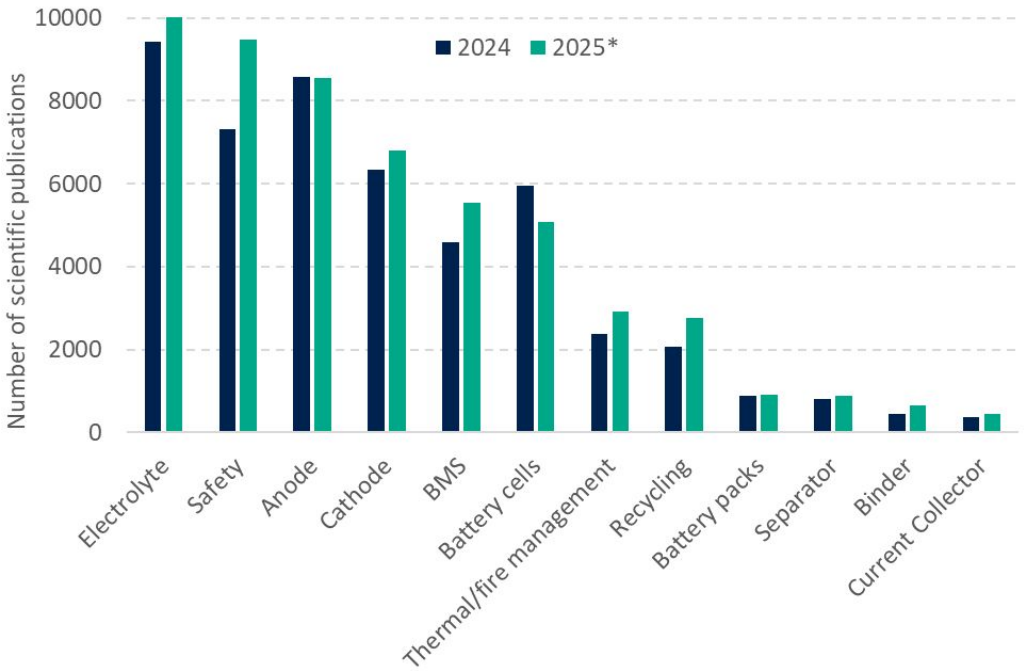
Electrolyte, safety, anode, and cathode are the most published topics. Scientific publications on battery electrolytes increasingly focus on **solid-state and gel systems**, as well as **high-voltage formulations** achieved by tuning solvents, salts, and additives.

A notable acceleration is observed for publications related to **safety, battery management systems (BMS), thermal/fire management, recycling, and binders** between 2024 and 2025.

In contrast, research activity on other components such as the electrolyte, anode, cathode, and separator remains relatively stable.

Developments on binders are **driven by new PFAS regulations and the pursuit of greener electrode manufacturing**, focusing on dry processes and non-PFAS binder alternatives.

SCIENTIFIC PUBLICATIONS SPLIT BY BATTERY COMPONENTS



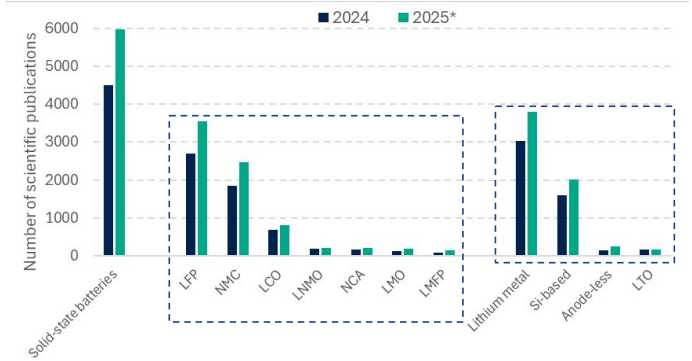
Source: Knowmade. Publications searches and statistics were done on Scopus by Knowmade.
*Publication searches were done in December 2025 and extrapolated for the whole year.

Solid-state Batteries Dominate 2025 Research

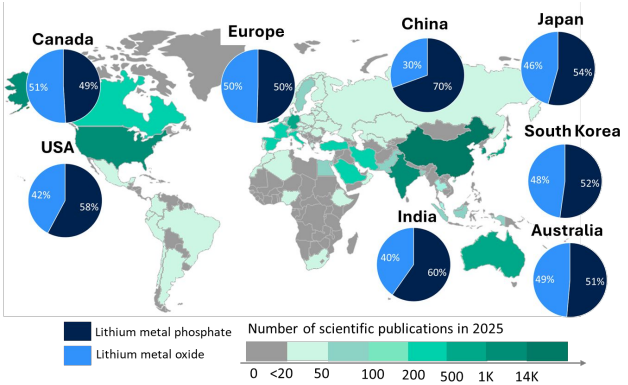
With Continued Focus On Key Cathode And Anode Materials And Strong Leadership From China

- Strong growth of publications for Solid-State Batteries (SSB) which dominates Li-ion research.
- Balanced activity across cathode and anode chemistries: **LFP and NMC** remain the most studied cathode materials, while **lithium metal and silicon-based** anodes drive innovation toward next-generation Li-ion cells.
- **Regional specialization in research**: China leads by volume, dominantly on lithium metal phosphates, while Europe, the USA, India, and South Korea show a balanced interest between Lithium metal phosphate and Lithium metal oxide chemistries, reflecting diverse industrial strategies.

PUBLICATIONS SPLIT BY Li-ION BATTERY TECHNOLOGIES



RESEARCH VOLUME ON Li-ION BATTERY BY COUNTRIES IN 2025*



Source: Knowmade. Publications searches and statistics were done on Scopus by Knowmade.
*Publication searches were done in December 2025 and extrapolated for the whole year.

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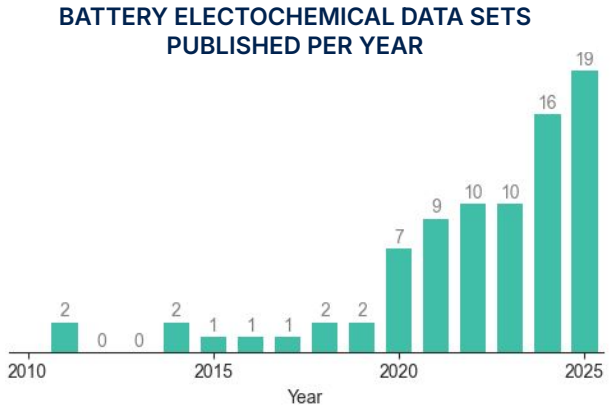
Starting an Era of Open-Source Battery Data and Tools

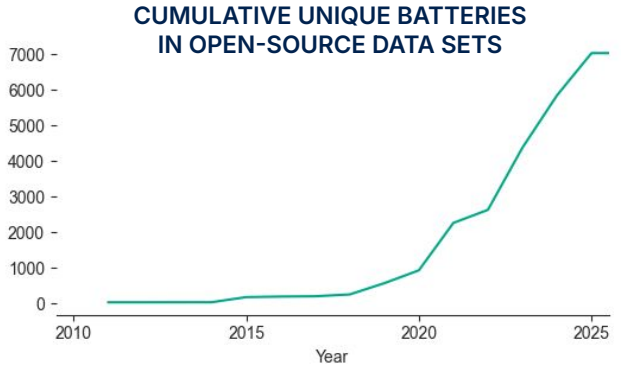
More and more open-source data sets, tools, codebases, and collections are being published every year as the global push to make FAIR (Findable, Accessible, Interoperable, and Reusable) data and code available for scientific research continues to grow.

Collating all easily discoverable battery data, analysis, and code resources published through 2025 results in a collection of:

- Battery data from 7,040 distinct battery cells and millions of cycles
- 4 imaging and tomography libraries for 2D and 3D microstructural data
- 7 safety and thermal runaway entries including 2 databases
- 21 battery modeling codebases for simulating battery electrical, thermal, and aging behavior from electrode-scale to macro-scale
- 23 battery data analysis codebases for processing, plotting, model fitting, and machine-learning feature extraction of raw battery test data

Please contribute your own data and code to keep growing this community of open-source research! **https://github.com/pauljgasper/awesome-battery-data**





Source: AIR Scientific Principles: https://www.go-fair.org/fair-principles/

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Milestones in the Invention of Rechargeable Lithium-ion Batteries

1970s

Stanley Whittingham
1970's: Demonstrates the first cathodes capable of intercalating lithium using TiS_2 [1] and other dichalcogenides[2].

Michel Armand
1970's: Introduces the concept of a "rocking-chair" battery, which stores energy by shuttling ions between different anode and cathode intercalating materials[3].

1980s

John Goodenough
1980: Employs the use of cathode materials ($LiCoO_2$) capable of reversibly intercalating Li^+ at high voltages [4].

Rachid Yazami
1983: Shows successful intercalation of lithium into graphite using polymer electrolytes [5].

Akira Yoshino
1985: Demonstrates a rechargeable Li-ion battery using a carbonaceous material as the anode while working for Asahi Kasei Corporation[6].

1990s

Sony
1991: Releases the first successful commercial Li-ion battery [1991].



Picture taken from Sony Archives

Advances in lithium-ion materials, Now ubiquitous, continue with new cathode chemistries, such as **LTO**[7], **NMC**[8], and **LFP**[9].

Current

2019 Nobel prize in Chemistry
Awarded "for the development of lithium-ion batteries".



Continued development
Fundamentals, materials, and applications of Li-ion batteries. Revisiting old grand challenges (e.g., Li metal anodes) with new tools and approaches.

Source: [1] Whittingham, *Science*. 1976 [2] Whittingham, *Prog. Solid St. Chem* 1978 [3] Mauger et al. *J. Electrochem. Soc*. 2020 [4] Mizushima et al. *Mater. Res. Bull*. 1980 [5] Yazami, *J. Pow. Source*. 1983 [6] Profile of Akira Yoshino [7] Ferg et al. *J. Electrochem. Soc*. 1994 [8] Delmas et al. *Solid State Ion*. 1992 [9] Padhi et al *J. Electrochem. Soc*. 1997

TiS_2 - The First Lithium-ion Intercalation Electrode and the Invention of the Lithium-Based Battery



In **1972**, Stanley Whittingham conducted the first lithium-ion battery electrochemical measurements at Exxon Research and Engineering Co. Whittingham's invention was disclosed in patents in 1973 and in academic journals in 1976.

Whittingham's cell design, **TiS2//Li**, used a positive electrode that did not initially contain lithium, meaning the cell was in a pre-charged stage and relied on lithium insertion during operation. Due to the moderate electronegativity of sulfur, TiS2//Li has a modest average voltage of 2.2V. **Incredibly, his first reported cell cycled 1100 times with more than 80% capacity retention!**

While neither his cathode (TiS_2) nor his anode (Li metal) would go on to be adopted in commercial rechargeable lithium batteries, this battery left an indelible mark on human history.

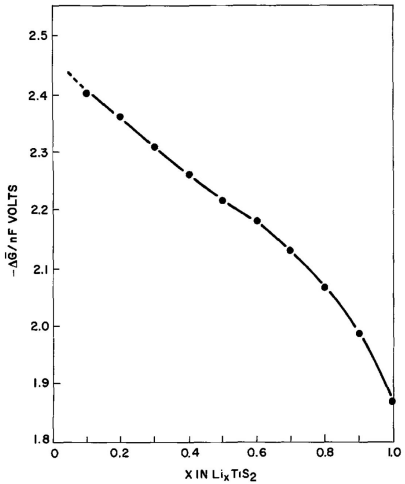


Fig. 2. Partial molar free energy of formation of Li_xTiS_2

Those familiar with the Nernst equation will recognize that the y-axis is simply the familiar E(V)

In 2019, Whittingham was awarded the **Nobel Prize in Chemistry** "for the development of lithium-ion batteries".

Source: [1] Whittingham, Chalcogenide battery. US patent 4,009,052, 1973. [2] Whittingham *Science* 1976. Whittingham *J. Electrochem. Soc.* 1976. [3] Whittingham *Nat. Energy* 2021.; [4] Binghamton University

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$LiCoO_2$ (LCO) - The First High-voltage Intercalation Cathode



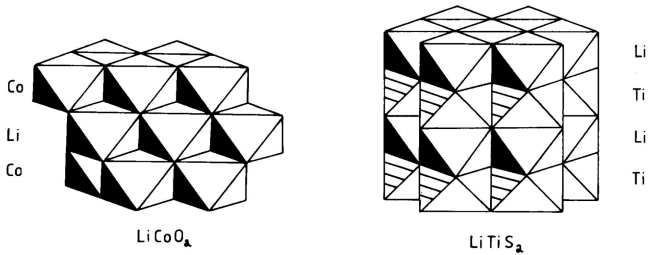


FIG. 1
Idealised structures of $LiCoO_2$ and $LiTiS_2$

In **1980, John Goodenough's** team at Oxford unveiled the oxide cathode **LiCoO2** as a high-voltage lithium-ion intercalation material.

There is no more powerful way to describe this discovery/invention than as follows: 45 years later, one can safely bet that the device you are using to read this Battery Report is powered by LiCoO2.

The layered structure of $LiCoO_2$, not unlike that of $LiTiS_2$, would later be compositionally altered through elemental substitutions to form the NMC and NCA material classes.

In 2019, Goodenough was awarded the **Nobel Prize in Chemistry** "for the development of lithium-ion batteries".

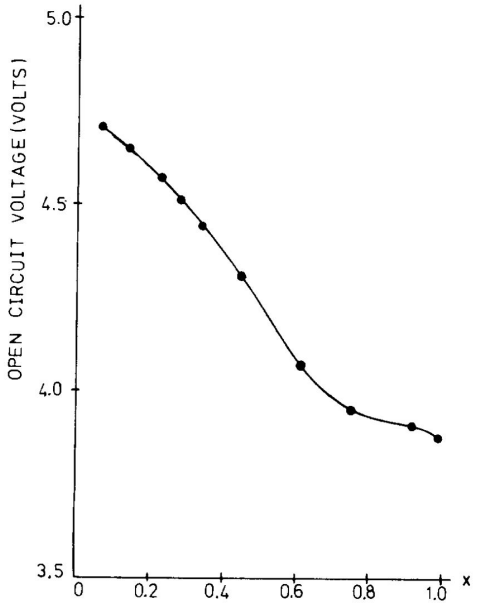


FIG. 3
Open circuit voltage versus composition x for $Li_xCo_{1.01}O_2/Li$

$LiFePO_4$ (LFP) and $LiMn_xFe_{1-x}PO_4$ (LMFP) - Olivine Phosphates with Two-phase (De)Lithiation

Goodenough's group in UT-Austin reported various metal phosphates in three publications in J. Electrochem. Soc. in 1997. Amongst these, they identified $LiFePO_4$ and $LiMn_xFe_{1-x}PO_4$ as inexpensive and non-toxic candidates for Li-ion battery cathodes.

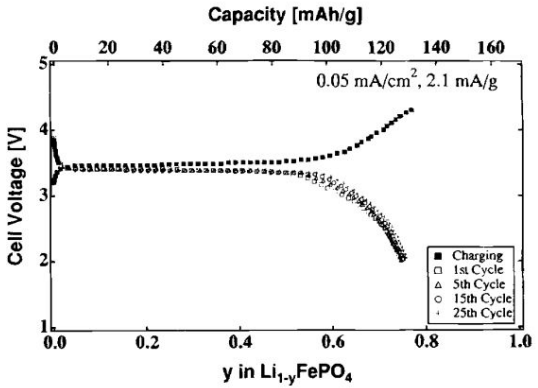
Li atoms in LFP can be reversibly extracted at **3.4 V vs. Li^+/Li**

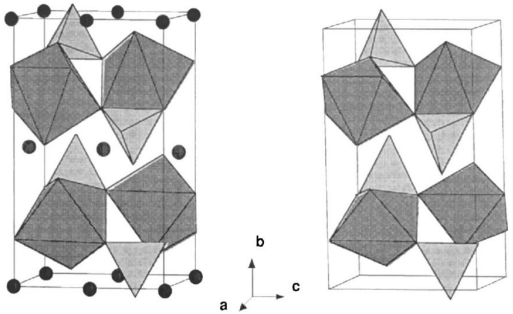
Insertion voltage is independent of state-of-charge

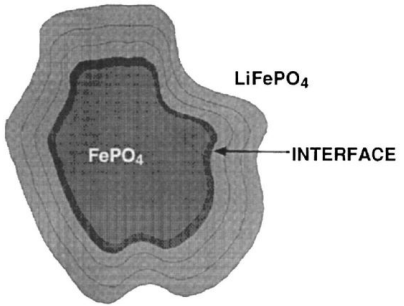
Similar **olivine crystal structure** between $LiFePO_4$ and $FePO_4$

Voltage ($Fe^{3+/2+}$ = 3.4 V, $Mn^{3+/2+}$ = 4.1 V) is within the carbonate electrolyte stability window

Mechanism is proposed to be an inwardly moving **two-phase coexistence** of $LiFePO_4$ and $FePO_4$







Source: [1] Padhi, Nanjundaswamy, Goodenough *J. Electrochem. Soc.* 1997, 4, 1188. [2] Padhi, Nanjundaswamy, Masquelier, Okada, Goodenough *J. Electrochem. Soc.* 1997, 5, 1609. [3] Padhi, Nanjundaswamy, Masquelier, Goodenough *J. Electrochem. Soc.* 1997, 8, 2581.

$LiMn_2O_4$ (LMO) - A Cheaper Alternative to LCO that Struggles with Transition Metal Dissolution

Despite its limited capacity and Mn dissolution, $LiMn_2O_4$ remains an economically attractive cathode that has found use in lower-end applications in China.

$LiMn_2O_4$ exists as cubic structure and can reach a **theoretical capacity of 148 mAh/g**

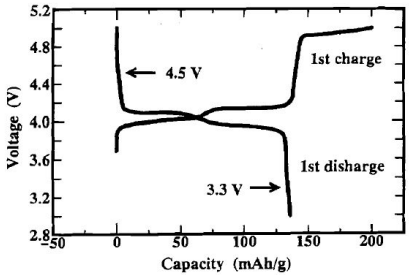
Mn_2O_4 spinel provides tetrahedral sites for Li insertion at 4.1 V and 3.9 V

Cubic structure allows for isotropic expansion and contraction

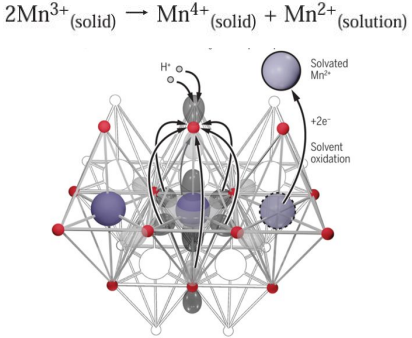
When Li stoichiometry is > 1, cubic symmetry reduces to tetragonal

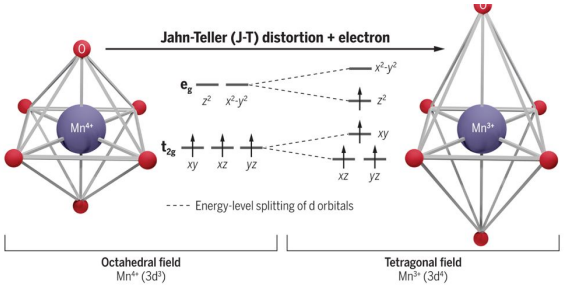
$LiMn_2O_4$ has **poor stability with electrolyte due to Mn dissolution**

Jahn–Teller distortion leads to non-isotropic expansion and loss of structural integrity



Typical charge and discharge curves for a Li || $LiMn_2O_4$ cell [4]





Source: [1] Thackeray, M. M., et al. *Materials Research Bulletin* 19.2 (1984): 179-187. [2] Asl, H. Y., & Manthiram, A. (2020). *Science*, *369*(6500), 140-141. [3] Thackeray, M. M., Shao-Horn, Y., Kahaian, A. J., Kepler, K. D., Skinner, E., Vaughey, J. T., & Hackney, S. A. (1998). *Electrochemical and Solid-State Letters*, *1*(1), 7. [4] Yongyao Xia et al 1997 J. Electrochem. Soc. 144 2593 [5] Gummow, R. J., De Kock, A., & Thackeray, M. M. (1994). Improved capacity retention in rechargeable 4 V lithium/lithium-manganese oxide (spinel) cells. *Solid State Ionics*, *69*(1), 59-67. [6] Nitta, Naoki, et al. "Li-ion battery materials: present and future." *Materials today* 18.5 (2015): 252-264.

$Li[Ni_{1-x-y}Mn_xCo_y]O_2$ (NMC): Layered Metal Oxide High Energy / Power Cathode

First reported in 1999, after a decade of research into unary and binary transition metal oxides, ternary NMC has become one of the most commonly used cathode classes from the layered oxide materials because it offers both high voltage and high capacity.

Li atoms in NMC can be reversibly extracted at **~3.8 V vs. Li^+/Li**

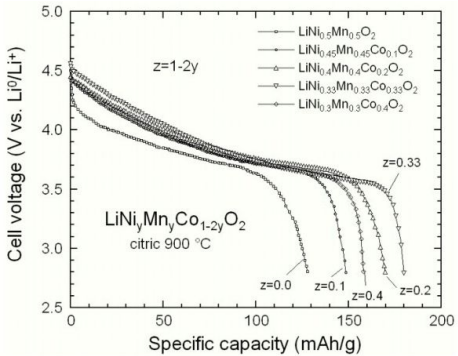
Specific capacities of up **~220 mAh/g** have been reported

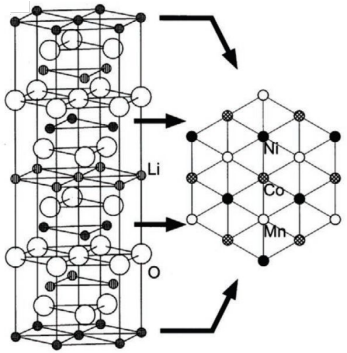
Layered crystal structure similar to LCO

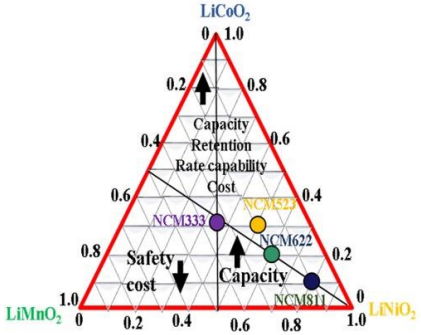
Li intercalates between the metal layers, not all Li can be removed or the structure would collapse

Compositional versatility allows **tuning performance and stability**

Ni improves capacity, Co improves conductivity, and inactive Mn stabilizes the structure







Source: [1] J. Power Sources 1999, 81-82, 416-419; [2] Nat. Commun. 2020, 11, 1550; [3] Adv. Energy Mater. 2020, 10, 1903864; [4] J. Power Sources 2003, 119, 644; [5] Materials 2016, 9, 595

1st Commercially Viable Li-ion Battery Using Petroleum Coke as a Stable Anode



In **1985, Akira Yoshino** at Asahi Kasei Corporation developed the first **commercially viable lithium-ion battery**, using petroleum coke as the anode. A byproduct of petroleum refining, petroleum coke can reversibly intercalate Li-ions at a low potential of ~0.5 V v. Li^+/Li without structural degradation.

Its amorphous carbon regions act as joints, pinning the layers together to provide structural integrity. While these regions limit capacity, the material's stability and durability made it the first commercially adopted anode, paving the way for reliable, long-lasting rechargeable batteries.

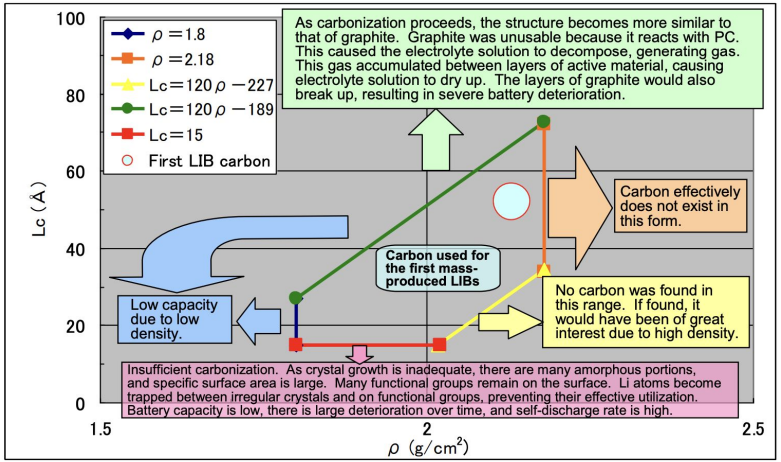


Figure 4. Carbonaceous material suitable for LIB discovered by Dr. Yoshino In 1985

In 2019, Yoshino was awarded the **Nobel Prize in Chemistry** "for the development of lithium-ion batteries".

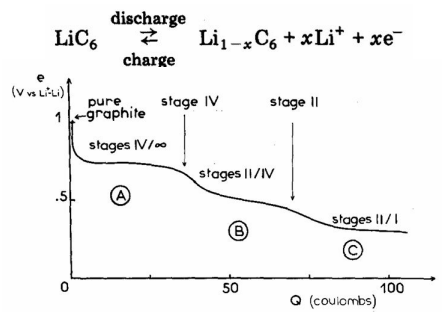
Source Yoshino, A. Nat Energy 6, 449 (2021), Xie, A retrospective on lithium-ion batteries. Nat Commun 11, 2499 (2020); [1] Nobel Prize, [2] Asahi Kasei

Discovery and Commercialization of the Graphite Anode

Yazami and Touzain first demonstrated the electrochemical intercalation of lithium into graphite with a polymer electrolyte in 1983 [1]. Since then, graphite has become the preferred anode in lithium-ion batteries.

FUNDAMENTALS

Graphite is an allotrope of carbon with sp^2 hybridization where graphene sheets are linked together through relatively weak Van der Waals forces [1]. Li intercalates into graphite (inserts itself between graphene layers) in stages. In the final stage, a stoichiometry of LiC_6 is reached, corresponding to a **theoretical specific capacity of 372 mAh g^{-1}** [2].



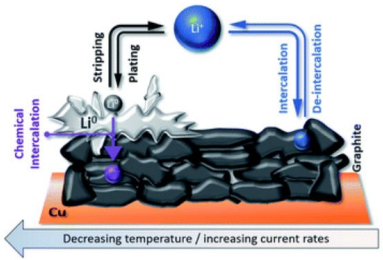
OCV of graphite || Li system

CHALLENGES

Limited rate capability in the lithiation process (charging) can result in lithium plating on the graphite surface, leading to short circuits [2].

First cycle irreversible capacity loss due to electrolyte reduction and formation of solid electrolyte interphase (SEI).

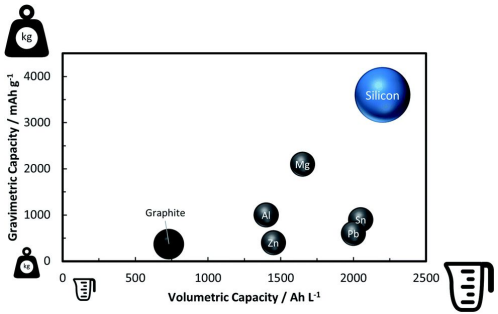
Graphite is unable to be recycled via traditional pyrometallurgy or hydrometallurgy [2].



RECENT DEVELOPMENTS

Natural vs. synthetic graphite: while synthetic graphite is often more expensive than natural graphite, it benefits from higher purity and better thermal stability [2].

Embedding silicon/silicon oxide into graphite leads to increased energy densities. Silicon has a theoretical energy density of 3578 mAh g^{-1} [2].



Source : [1] Yazami, R., and Ph Touzain. "A reversible graphite-lithium negative electrode for electrochemical generators." *Journal of Power Sources* 9.3 (1983): 365-371.
[2] Asenbauer, Jakob, et al. "The success story of graphite as a lithium-ion anode material–fundamentals, remaining challenges, and recent developments including silicon (oxide) composites." *Sustainable Energy & Fuels* 4.11 (2020): 5387-5416.

Carbonate Electrolytes - The Most Used Solvents for Commercial Li-Ion Batteries

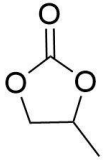
CYCLIC CARBONATES

Propylene carbonate (PC)

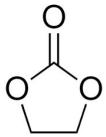
Between 1950s and 1990s, typical electrolytes consisted of various lithium salts dissolved in PC [1]. PC demonstrates strong solvating ability and has a high oxidative stability above 4.0 V_{Li}. Unfortunately **PC can cointercalate with lithium into graphite, leading to graphite exfoliation,** which limits its practical application.

Ethylene carbonate (EC)

Initially, PC was preferred over EC because EC has a melting point of 37 °C. To overcome this high melting point, EC is often mixed with linear carbonate esters such as dimethyl carbonate and diethyl carbonate [1]. Dahn et al.'s discovery that **EC forms a stable solid electrolyte interphase (SEI)** was key to enabling the graphite anode [2]. EC-based electrolytes combined with graphite anodes increased energy density of LIBs by 30–50%.



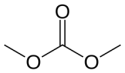
propylene carbonate (PC)



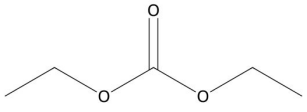
ethylene carbonate (EC)

LINEAR CARBONATES

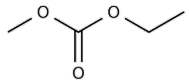
Linear carbonates are typically used as co-solvents with their cyclic counterparts. In 1994, Tarascon and Guyomard first added DMC as a cosolvent to EC [3] [4]. Linear carbonates have relatively low boiling points, viscosities, and dielectric constants. Therefore, **they are often used to improve ionic transport** in the electrolyte. Surprisingly, when combined with cyclic carbonates, the stability window of the resulting mixture is increased [5]. Other popular linear carbonates include DEC, EMC, and PMC.



dimethyl carbonate (DMC)



diethyl carbonate (DEC)



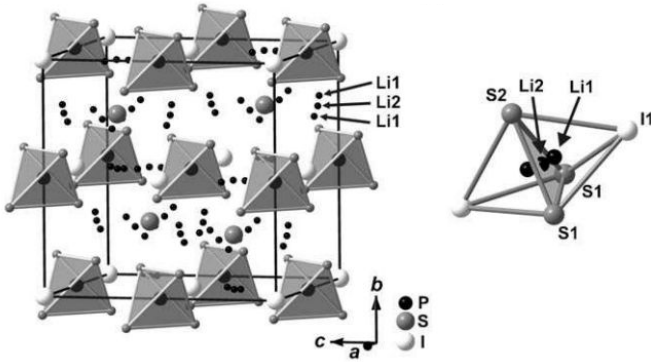
ethyl methyl carbonate (EMC)

> "Within the various brands of lithium ion cells, ... the formulas remain proprietary information; however, the overwhelming majority of these are apparently based on two indispensable components: EC as the solvent and $LiPF_6$ as the solute. In most cases, one or more linear carbonates, selected from DMC, DEC, or EMC, are also used as cosolvents to increase the fluidity and reduce the melting point of the electrolyte." [5]

Source : [1] Xu, K. *Nat Energy* (2021), [2] Rosamaría Fong et al J. *Electrochem. Soc.* (1990) ; [3] Guyomard, D.; Tarascon, J. M. J. *Electrochem. Soc.* (1993) ; [4] Tarascon, J. M.; Guyomard, D. Solid State Ionics (1994) ; [5] Xu, Kang. *Chem. Rev* (2004)

Lithium Argyrodites (Li_6PS_5X) - Solid Electrolytes with High Li^+ Mobility



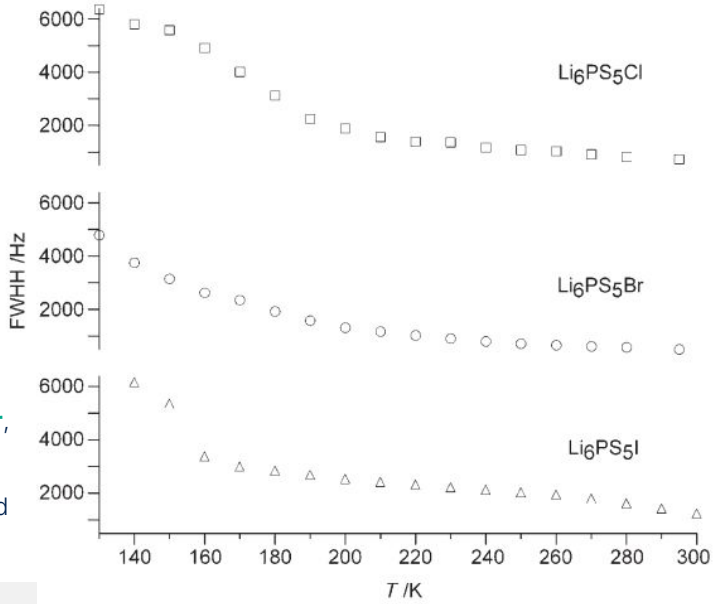


Crystal structure of Li_6PS_5I

In **2008**, **Hans-Jörg Deiseroth** at the University of Siegen in Germany introduced **Li_6PS_5I**, **Li_6PS_5Br**, and **Li_6PS_5Cl** as argyrodite lithium superionic conductors.

The team based their materials on the mineral argyrodite Ag_8GeS_6 because of its high mobility and conductivity of Ag^+ ions and the similar ionic radii of Cu^+ (74 pm) and Li^+ (73 pm) to Ag^+ (114 pm).

Li_6PS_5X development showed that crystal engineering could produce Li^+ conductivities (10^{-2} to 10^{-3} S cm^{-1}) approaching that of liquid electrolytes.



Static ^7Li NMR full-widths at half-height for Li_6PS_5X as a function of temperature.

Source: Angewandte Chemie 120.4 (2008): 767-770. [2] Chemical Reviews 120.10 (2020): 4257-4300.

2025 | BATTERY REPORT

ACADEMIA

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Research Trends
Seminal Literature

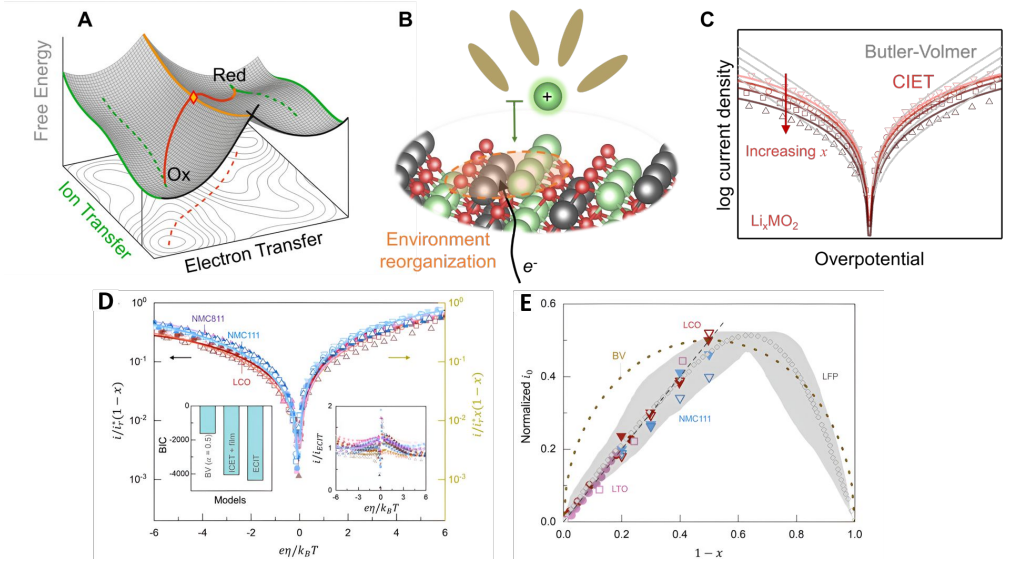
Fundamentals

Lithium-ion
Solid State Batteries
Battery Degradation and Performance
New / Alternative Chemistries
Fast Charging & Extreme Fast Charging
Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

VOLTA FOUNDATION

Lithium-on Intercalation by Coupled Ion-electron Transfer (CIET)

- Coupled Ion-Electron Transfer (CIET) theory is proposed and tested, **unifying ion and electron transfer mechanisms** to provide a more complete picture of the reaction.
- In experiments on common cathodes like $LixCoO_2$ and LixNMC, it was shown that **current rises linearly** with lithium vacancy and does not follow Tafel's law in overpotential dependence, a finding that **contradicts Butler-Volmer (BV) model.**
- The **predictive power** of the CIET model was demonstrated by collapsing hundreds of data points onto a universal curve using a small set of **intrinsic material parameters.**
- A **linear decay** in capacity with increasing current, a distinct signature of a CIET-limited reaction, was revealed by rate capability measurements across eight different electrode materials.



The conventional view that battery performance is **diffusion-limited** is challenged by this work, proving that the **interfacial reaction could be a key bottleneck** in commercial cells.

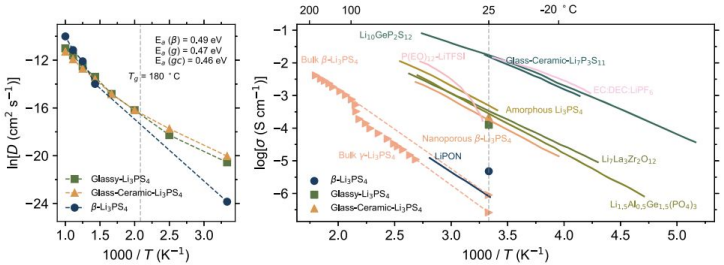
Source: Zhang, Yirui, et al, *Science* (2025)

Inherent Limits on Ion Transport In Solid-state Electrolytes

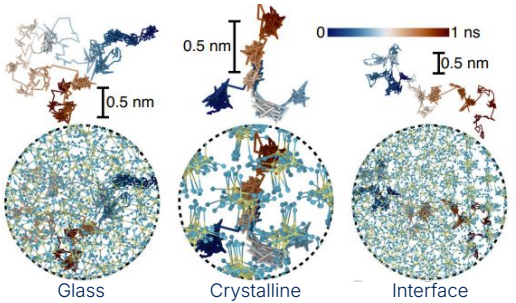
Ionic mobility within solid-state electrolytes strongly depends on a materials structural and energy landscapes as well as site connectivity. In disordered glassy solids and glass-ceramics, variations in local bonding and coordination create a **heterogeneous potential energy surface** that removes the directional bias of ion motion found in most crystalline materials.

Disordered phases and interfaces exhibit **improved ionic conductivity** by facilitating lithium-ion exchange between disordered and crystalline phases and **enhancing cooperative migration** of lithium ions within the crystalline phase. Due to the complexity of the local coordination environments of disordered systems, machine learning is utilized to relate atomic dynamic properties to local structure.

Here, the term 'softness' is used to connect ion hopping dynamics and the amount of structural disorder. Disorder is a mechanism that can improve ion mobility as the lithium ions are more likely to rearrange.



Temperature dependence of lithium diffusion and comparing ionic conductivity of systems with varying degrees of disorder.



Lithium migration trajectories across phases with varying degrees of disorder.

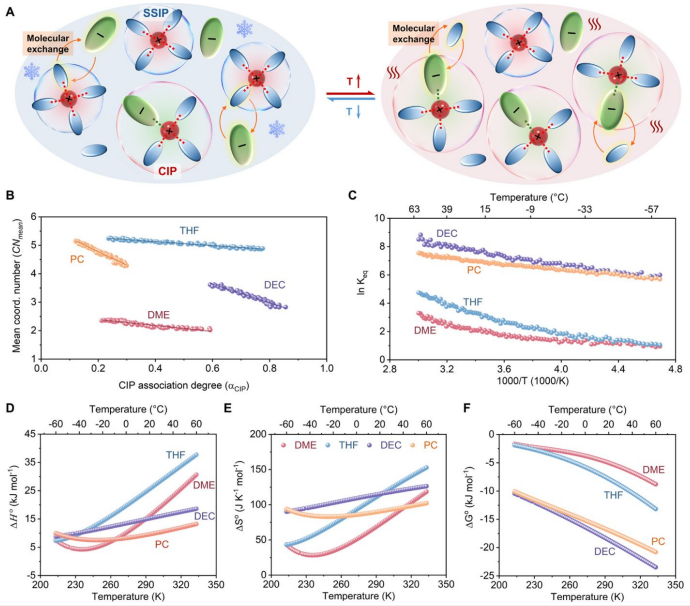
Disorder can create a **more uniform energy landscape** that increases the number of mobile ion carriers and enables cooperative diffusion. A machine learning structural descriptor termed **'softness' connects diffusion dynamic characteristics to insights about ionic conductivity** and the development of advanced solid-state battery electrolytes.

Source: Chen, Z., Du, T. Krishnan, N. M. A. et. al. *Nature*, 2025.

Linking Solvation Equilibrium Thermodynamics to Electrolyte Transport Kinetics for Lithium Batteries

Lai et al. systematically studied the structural evolution of ion–solvent and ion–ion local coordination in both carbonate- and ether-based Li^+ electrolytes, and combined in-situ FTIR and Raman spectroscopies to investigate the temperature-responsive solvation equilibrium. Li^+ solvation can either be found in a **solvent-separated ion pair (SSIP)** or a **contact ion pair (CIP)** configuration, with both coexisting in a thermodynamic equilibrium that varies with temperature and composition.

Compared to ether-based electrolytes, carbonate-based electrolytes showed a preference for CIP association. **The solvation equilibrium thermodynamics were linked to transport kinetics**, with the dimethyl ether (DME) electrolyte exhibiting the highest conductivity and Li^+ diffusivity due to its higher solvent-separated ion pair (SSIP) concentration and lower average coordination number. Moreover, the **contact ion pair association reaction** was found to closely link to the **Li+ transference number** across different temperatures, with ethers exhibiting higher Li^+ transference numbers.



Thermodynamic solvation equilibrium properties offer new descriptors for quantifying **dynamic solvation structure**, and were shown to closely link to the **Li+ transference number** of electrolytes through the changes in their **Gibbs free energy**.

Source: Lai, Jianwei, et al. *American Chemical Society* (2025)

2025 | BATTERY REPORT

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Research Trends
Seminal Literature
Fundamentals

Lithium-ion
- **Cathode**
- Anode
- Electrolyte

Solid State Batteries
Battery Degradation and Performance
New / Alternative Chemistries
Fast Charging & Extreme Fast Charging
Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

Pinning Effects of Heavy Elements for the Structural Stability of Ni-Based Layered Oxides

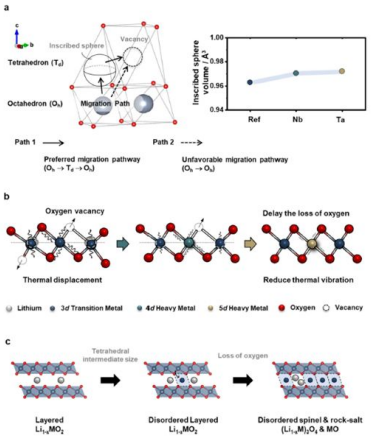
Pinning effect: Nb^{5+} and Ta^{5+} exhibit the same oxidation state identical ionic radii but differ in atomic weight, exhibiting reduced atomic displacement, reinforced Ni–O bond strength, and expanded Li slab spacing to improve electrochemical performance

Performance improvement: The specific capacity was observed to increase in the order of Ref-NMC < Nb-NMC < Ta-NMC over the voltage range of 2.8–4.3 V, further supported by the differential capacity (dQ/dV) curves. Such a tendency remains over subsequent cycles.

PINNING EFFECT

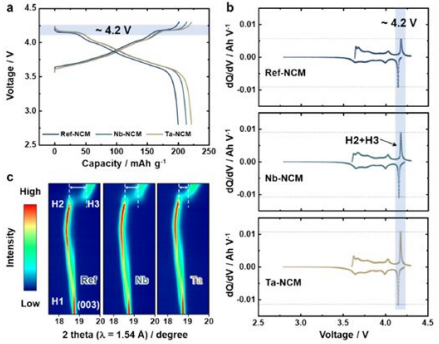
The stabilizing effects were more pronounced for Ta-doped NMC, highlighting the role of atomic mass in modulating the structural and thermal stability of the material

The synergistic effects of heavy element doping includes enhanced structural stability, smoother phase transitions, suppressed lattice collapse, and delayed thermal decomposition



PERFORMANCE IMPROVEMENT

In situ XRD and dQ/dV analyses indicate the H3 phase is stabilized through the pinning effect of Nb and Ta, resulting in a prolonged voltage plateau and enhanced electrochemical stability at high voltage



Source: W. Lee et al. *ACS Energy Lett.* (2025).

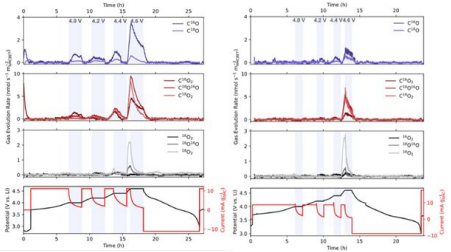
Surface Oxygen Drives Electrolyte Degradation at Ni-rich Battery Cathodes

Gassing observation: the detection of gaseous species evolving from an operating LIB with chip-based electrochemistry mass spectrometry is demonstrated to observe O_2 evolution from a NMC811 cathode and electrolyte solvent degradation to CO_2 and CO

Degradation mechanism: isotopically labelled NMC is investigated to monitor where lattice oxygen is incorporated into electrolyte oxidation products, which identifies a previously unobserved deleterious catalytic CO oxidation mechanism

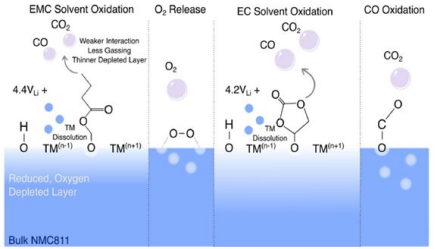
ON-CHIP ELECTROCHEMICAL MS

- Observation of isotope-labelled O_2 provides concrete evidence that molecular oxygen is released from the NMC811 lattice at potentials greater than 4.3 V
- An EC-free electrolyte was tested with ^{18}O-labelled-NMC811 vs. Li. The O_2, CO_2 and CO evolution rates during this cycling can be seen, showing no CO_2 (nor CO, nor O_2) during the 4.0 V vs. Li potential hold, unlike with EC



DEGRADATION MECHANISM

- The identified catalytic CO oxidation mechanism drives the removal of oxygen from the cathode lattice. Given that CO is reported to evolve from numerous processes in LIBs, the presence of such an active species will have significant deleterious effects on the overall performance of the cathode.

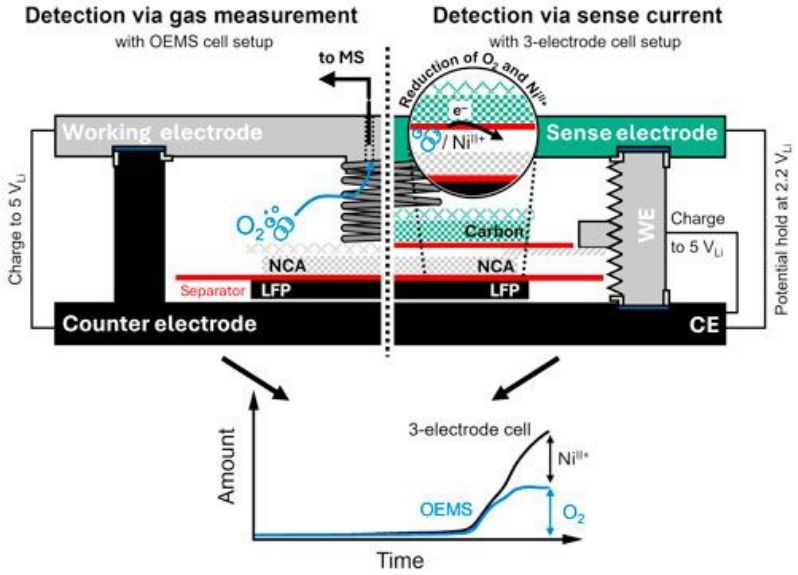


Source: I. Stephens et al, *Preprint* (2025)

In Situ Measurement of Electrolyte Oxidation via Mass Spectrometry and Three-electrode Cells

Compared to an expensive Online Electrochemical Mass Spectrometry (OEMS) test, a 3-electrode cell using the positive electrode material of interest as the working electrode, an LFP counter electrode, and a Vulcan carbon sense electrode can directly measure the net current flow of undesired side reactions at low cost.

However, there are multiple possible parallel side reactions that may occur between an electrode and electrolyte; separating the contributions of oxygen reduction and dissolved TM ions to the sense electrode current does require calibration via the more expensive OEMS measurement.

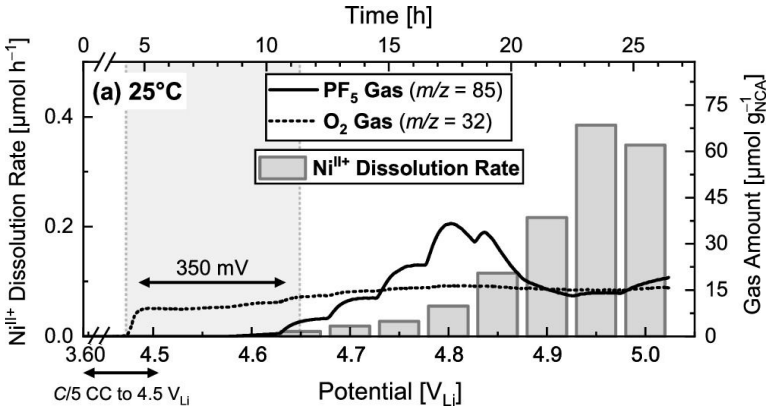


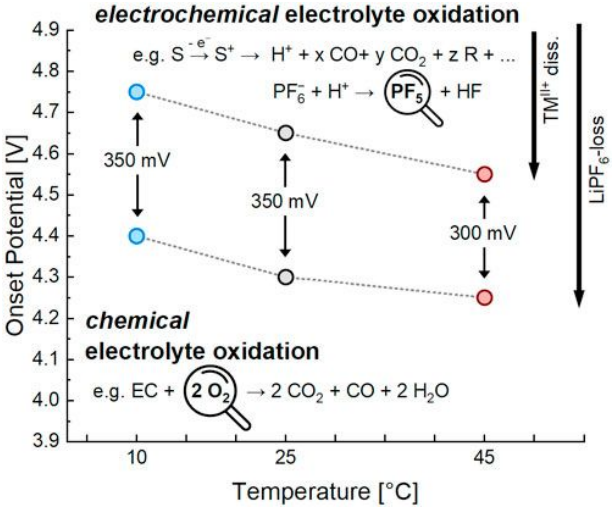
This method paper demonstrates an **economical method to directly quantify evolved oxygen and transition metal (TM) dissolution** from electrolyte oxidation reactions **using a 3-electrode cell with a voltage-controlled sense electrode** to selectively measure lattice oxygen and dissolved TMs.

Source: Reuter L., *J. Electrochem. Soc.* (2024)

Measuring Chemical and Electrochemical Electrolyte Oxidation

Measurements of transition metal (TM) fluoride salt solubility in common electrolyte solvents and TM dissolution caused by the introduction of free protons (mimicking electrochemically-produced free protons via acid) conclusively demonstrate the electrochemical nature of TM dissolution, and provide a pathway for electrolyte design optimization to mitigate TM dissolution and extend battery lifetime.





Using temperature-dependent in-operando hard X-ray absorption spectroscopy, Reinschlüssel et al conclusively separate contributions of *electrochemical* and *chemical* electrolyte oxidation, showing that **electrochemical electrolyte oxidation** is directly linked to the dissolution of transition metals from the positive electrode, while **chemical electrolyte oxidation** is caused by reaction with oxygen, and leaves transition metal dissolution unaffected.

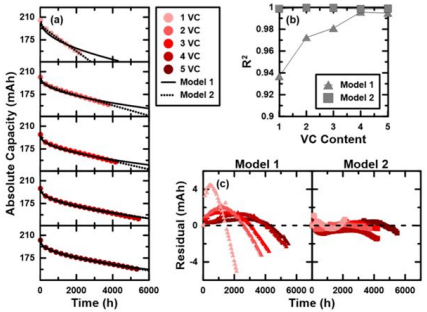
Source: Reinschlüssel et al, *J. Electrochem. Soc.*, (2025)

Understanding Capacity Loss in LFP/Graphite Pouch Cells at High Temperature through Modelling

Modelling innovation: A novel "AB" model was proposed to interpret capacity loss incurred by lithium inventory loss and transition metal dissolution. This model directly reflects the dynamics of SEI growth rate as a function of SEI thickness and Fe dissolution from the cathode. Constant-rate (linear) iron dissolution, assumed by the model, is validated via chemical analysis of aged cells.

Mechanism reflection: Through the "AB" modelling of the capacity vs time of LFP/graphite cells, it is reaffirmed SEI growth and the effects associated with transition metal deposition as the predominant mechanisms of capacity fade in LFP/graphite cells cycling at higher temperatures

"AB" MODEL

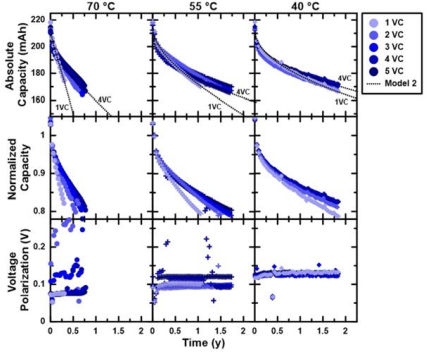


Model 1:
$Q(t) = Q_0(1-At^{1/2})$

Model 2:
$Q(t) = Q^0(1-A(1+Bt)t^{1/2})$

A: lithium inventory loss to SEI growth
B: iron deposition to accelerate inventory loss

CAPACITY LOSS INTERPRETATION



Observation:
Fitted curves using model 2 are shown superimposed on the absolute capacity loss plots

Conclusion:
In LFP/graphite cells, **Li inventory loss due to SEI growth, accelerated by transition metal deposition,** is the predominant degradation mode

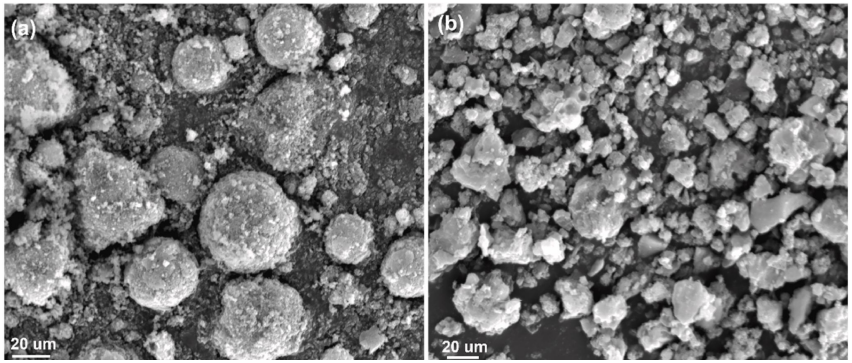
A comprehensive look at the performance of the LFP pouch cells introduced above showing the absolute capacity loss, normalized capacity loss, and voltage polarization at 40, 55, and 70 °C.

Source: Black et al, Journal of The Electrochemical Society, 2025, 172, 090503

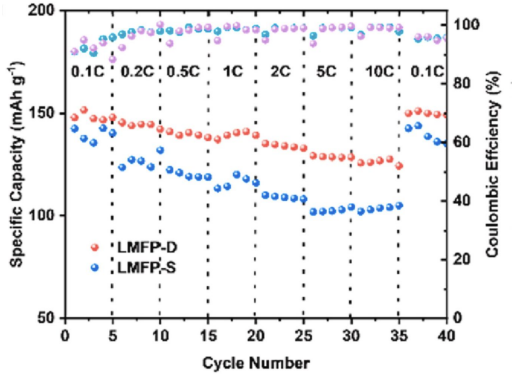
Advancements in Lithium Manganese Iron Phosphate

Towards fulfilling commercial requirements

LMFP (Lithium Manganese Iron Phosphate) is continuing to gain traction as a promising cathode active material due to its potential for low cost, high safety, and higher energy density relative to LFP. However, it suffers from low electronic conductivity, slow lithium-ion diffusion, and low tap density [1]. Mitigation strategies commonly applied include morphology control, elemental doping, and surface coating. Chen J. (2026) explains the impact of LMFP particle morphology on Li-ion diffusion and electrochemical stability, concluding that a porous and spherical secondary structure increases ionic kinetics by improving contact with the electrolyte. Furthermore, a homogeneous distribution of Mn enhances structural stability by suppressing Jahn–Teller distortions.



SEM images of (a) spherical morphology and (b) irregular morphology [2]



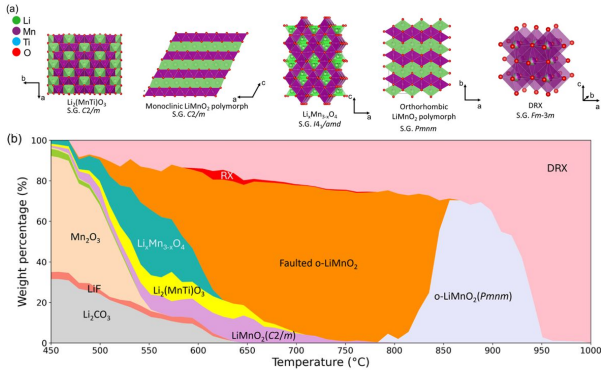
Rate test of cell with CAM particles with spherical morphology (LMFP-S) and irregular morphology (LMFP-D) [2]

A successful strategy to mitigate downsides of LMFP is morphology modification achieved through synthesis optimization, which yields a **spherical, porous structure**. This specific structural improvement has been demonstrated to significantly **enhance cyclic performance** by facilitating better lithium-ion diffusion and electrolyte contact.

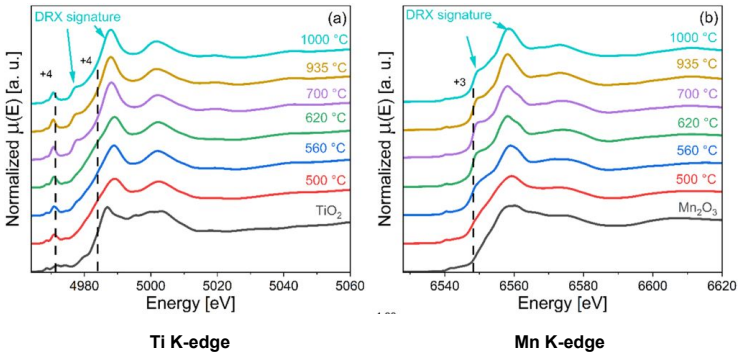
Source: [1] Gonçalves, J. M., et al. (2025), [2] Chen J. (2026)

Understanding the Synthesis of Disordered Rock Salt (DRX)

Disordered rock salt (DRX) oxides and oxyfluorides represent a promising class of cathode materials due to their **exceptional compositional flexibility**, including Ni- and Co-free variants that achieve capacities exceeding 250 mAh/g. For systems containing Mn and Ti (such as $Li_{1.1}Mn_{0.8}Ti_{0.1}O_{1.9}F_{0.1}$), the former serves as the primary redox-active species, while the latter plays a stabilizing role by accommodating local distortions within the lattice. In situ synchrotron X-ray diffraction (XRD) reveals that **DRX formation proceeds through multiple ordered rock-salt-related crystalline intermediates**, beginning at 480 °C and homogenizing by 950–1000 °C. Complementary ex situ X-ray absorption spectroscopy (XAS) on quenched reaction intermediates show that Ti is incorporated into the DRX framework at lower temperatures than Mn (~700 °C vs. 950–1000 °C), highlighting how **both in situ XRD and ex situ XAS are complementary** measurement techniques to study the formation pathway of DRX.



(a) Crystallographic structure of reaction intermediates (b) Weight fraction of precursors and intermediates formed during synthesis



(a,b) Ti and Mn K-edge XAS spectra

Combining in-situ XRD during DRX synthesis **with ex-situ XRD/XAS** on quenched intermediates enables **tracking of intermediate formation and final DRX framework**, and reveals how temperature governs Transition Metal incorporation.

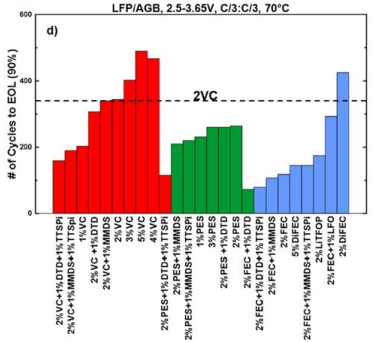
Source: Z. Liang et al (2025).

Additive Screening of LFP/Graphite Pouch Cell for High Temperature Cycling at 70 °C

Mechanism reflection: Lithium loss is driven by growth of the SEI on the negative electrode, which is catalyzed by Fe dissolution from the positive electrode, **forming a well–passivated SEI and mitigating Fe dissolution throughout lifetime decrease lithium loss.**

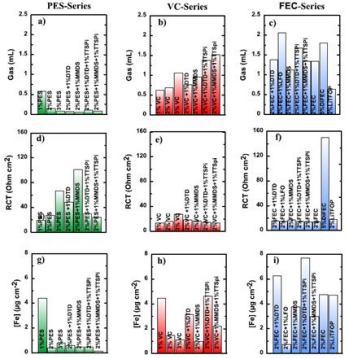
Lifetime improvement: 25 electrolyte combinations were evaluated to address inferior cycling performances of LFP/Graphite cell compared to the NCM operated at high temperatures, indicating the **increase of VC concentration can result in longer lifetimes**

HIGH TEMPERATURE CYCLING (70 °C)



- It is evident that the VC-series has the best lifetime, followed by the PES-Series, and then the FEC-Series
- A significant improvement in the lifetime of LFP/graphite pouch cell cycled at high temperature (70 °C) achieved by doubling the VC concentration to 4%

POST LONG-TERM CYCLE METRICS (70 °C)



Gassing

Charge transfer resistance

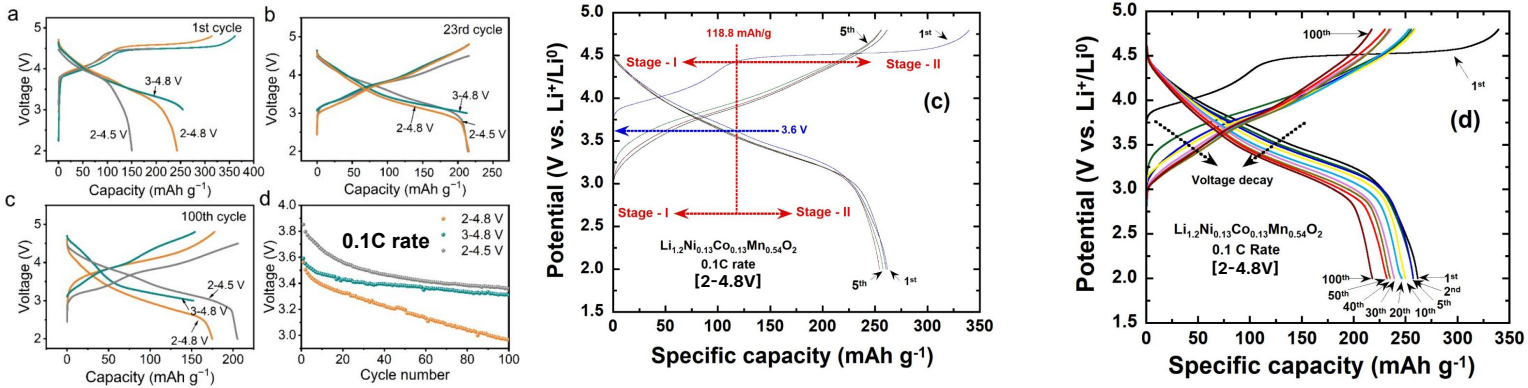
Fe dissolution

Vinylene carbonate (VC) at 4–5% (w/w) was found as the most effective additive for improving the lifetime of LFP graphite pouch cells during cycling and storage at high temperatures

Source: Journal of The Electrochemical Society, 2025, 172, 020536

Simple Voltage Control Method to Enhance LMR Lifetime

Li- and Mn-rich layered cathodes such as $0.5LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2 \bullet 0.5Li_2MnO_3$ may deliver initial capacities exceeding 250 mAh/g, due to the participation of anionic oxygen redox from the Li_2MnO_3 phase at voltages above 4.5 V. While **operation above 4.5 V induces lattice oxygen release** and accelerated voltage fade, **improved voltage stability** is only achieved **at the cost of reduced accessible capacity**. Below 4.5 V, there is a sloping voltage profile associated with $Ni^{2+/4+}$ and $Co^{3+/4+}$ oxidation, while above that voltage there is a plateau from irreversible Li_2MnO_3 activation and lattice oxygen release. Similarly, voltages below 3 V leads to irreversible $Mn^{3+/4+}$ redox. As a result, the wide **2–4.8 V window simultaneously triggers Mn oxidation and $O_{2(g)}$ formation**, leading to the most severe voltage decay, while narrow windows such as **3–4.8V and 2–4.5 V significantly mitigate degradation pathways** at the expense of accessible capacity. Limiting the upper cutoff voltage to 4.5 V also allows for a **gradual activation of the Li_2MnO_3 phase**, fully accessing that capacity after about 20 cycles.

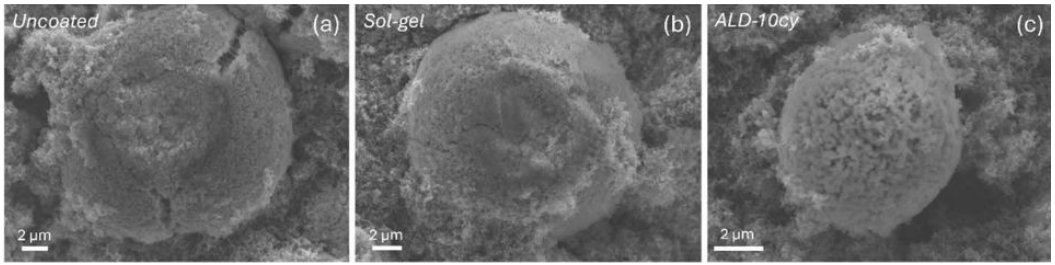


Voltage window tuning of Li- and Mn- rich layered cathode enables controlled access to Mn and O redox, **mitigating cation migration and oxygen release**. Even under a restricted window (<4.5 V), **Li_2MnO_3 activates gradually with successive cycles**, optimizing voltage stability and accessed capacity.

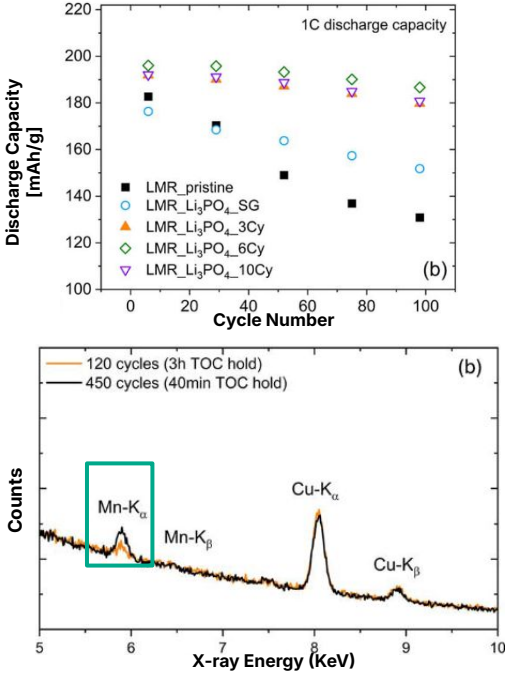
Source: [1] A. Abdel-Ghany et al (2025). [2] M. Yuan et al (2024).

Measuring and Mitigating Transition Metal Dissolution from Mn-rich Cathodes

A Li_3PO_4 surface coating was applied to $0.7LiMn_{0.5}Ni_{0.5}O_2 \bullet 0.3Li_2MnO_3$ to suppress Mn dissolution, **a common degradation pathway for any Mn-containing cathode**; the coating was applied via sol-gel and atomic layer deposition (ALD) to determine the effect of processing technique. While both techniques provided some surface protection, **ALD produced a more uniform Li_3PO_4 layer than sol-gel processing**, underscoring the role of coating methodology. Surprisingly, this nano-scale coating led to **substantially suppressed micro-scale particle cracking and pore/void formation** over cycling. However, capacity fade after 450 cycles is still linked to Mn deposition (observed in EDS analysis of graphite anode), highlighting that residual Mn deposition still dominates long-term capacity fade and the **need for additional mitigation strategies** beyond surface coatings, such as cathode surface dopants and electrolyte modifications.



SEM images of cathode recovered after 120 cycles: (a) uncoated, (b) coating via sol-gel, and (c) coating via ALD



(Top) Discharge capacity at 1C, [2-4.8]V, in full coin cells (Bottom) EDS analysis of graphite anode recovered after 120 and 450 cycles

A carefully processed layer of Li_3PO_4 to Mn-rich cathodes mitigates capacity fade, impedance rise, pore/void formation, and particle-scale damage; however, it **does not mitigate voltage fade**. It also **does not solve the fundamental challenge of Mn-dissolution** over long term cycling.

Source: S. Mallick et al (2025).

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Research Trends
Seminal Literature
Fundamentals

Lithium-ion
- Cathode
- **Anode**
- Electrolyte

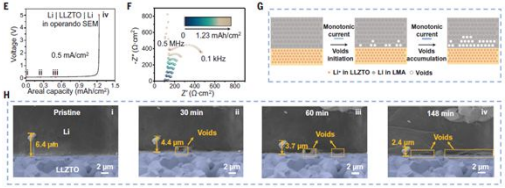
Solid State Batteries
Battery Degradation and Performance
New / Alternative Chemistries
Fast Charging & Extreme Fast Charging
Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

Fatigue of Li Metal Anode in Solid-state Batteries

Methodology: using operando scanning electron microscopy and phase-field simulations, the failure of SSBs is closely linked to the fatigue of the lithium metal anode, which markedly contributes to interface degradation and dendrite growth in SSBs

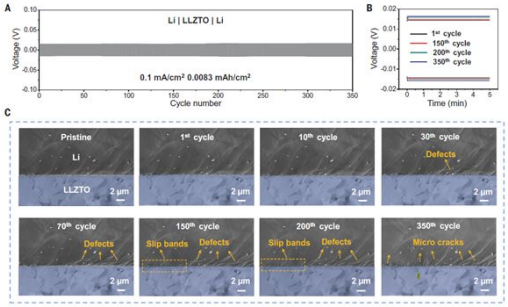
Conclusion: the identification of Li metal fatigue in SSBs clarifies the origin of cell failure and offers an opportunity to establish a quantitative correlation among current density, capacity, mechanical properties of Li metal anodes, and lifespans of SSBs

INTERFACE EVOLUTION CHARACTERIZATION



- During Li stripping, a Li atom undergoes electron loss and transforms into Li^+, traversing the Li/LLZTO (solid electrolyte) interface and creating a vacancy
- As stripping proceeds, vacancies accumulate at the interface, leading to void formation and subsequent voltage increase

FATIGUE OF LI METAL ANODES



- When the fatigue test reaches a certain cycle, da/dN increases to infinity, indicating the final fracture induced by fatigue
- A higher cyclic stress results in a faster slope increase and shorter cycle lives like the effects of increasing the current density on the cycle life of SSBs
- The analogous patterns of voltage cycle number curve and the evolution of crack lengths in metallic fatigue suggest a shared fatigue-driven failure mode

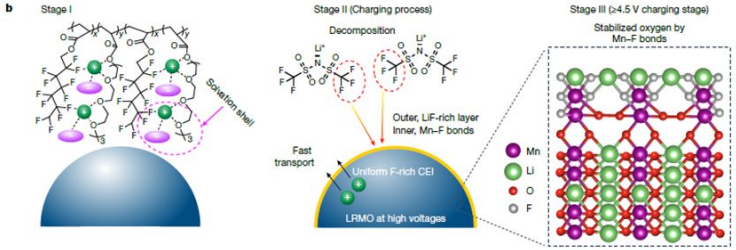
Source: Science 388, 311-316 (205)

Tailoring Polymer Electrolyte Solvation for 600 Wh kg^{-1} Lithium Batteries

Electrolyte Feature: the polymer electrolyte creates an anion-derived F-rich CEI/SEI to protect the lithium-rich metal oxide cathode by suppressing surface oxygen escape, structural transitions, and electrolyte decomposition

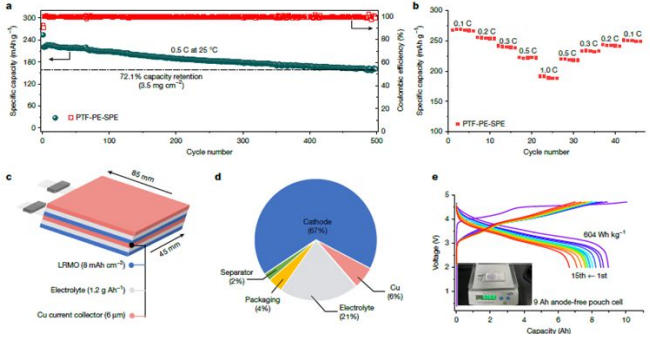
Electrochemical Performance: this quasi-solid-state polymer demonstrates a reversible high-areal-capacity cycling in pouch cells. The pouch cells exhibit an energy density of 604 Wh kg^{-1} and excellent safety under a nail penetration at a fully charged condition

F-BASED ELECTROLYTE



- The strong coordination between Li$^+$ and ether oxygen generates anion-deficient solvation, whereas the poor oxidation stability of PE polymer electrolytes causes interfacial decomposition

ELECTROCHEMICAL PERFORMANCE



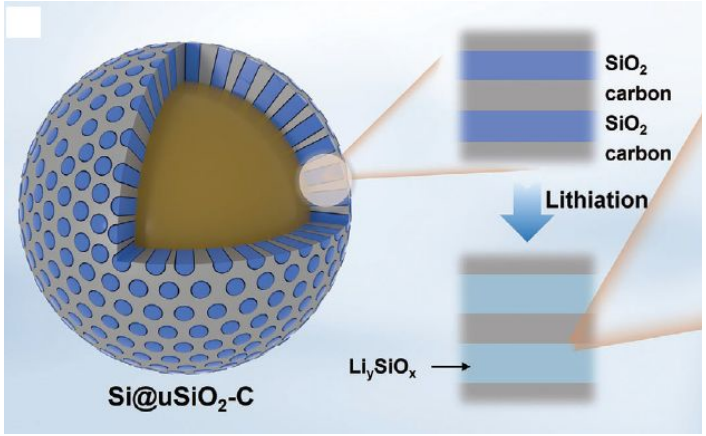
- The assembled lithium-rich metal oxide-based lithium metal batteries delivered a high initial CE of 91.8% at 0.05 C and charge/discharge reversibility (CE = 99.7%) at 1.0 C after more than 200 cycles at 25 °C

Source: Nature, 646, 2025: 343-350.

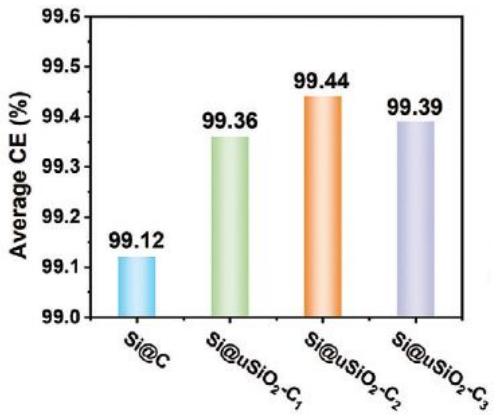
Performance Enhancement of Nanosilicon Anodes via Binary Coating

Thin coating on nanosilicon comprised of binary materials, **carbon and silicon oxide**, provides complementary benefits of enhanced electronic conductivity and mechanical rigidity. Optimized coating thickness is **15 nm**; 7 nm thick coating fails to adequately protect the SEI during cycling while 40 nm coating introduces additional overpotentials.

SILICON PARTICLE AND COATING MORPHOLOGY



AVERAGE COULOMBIC EFFICIENCY IN CYCLING



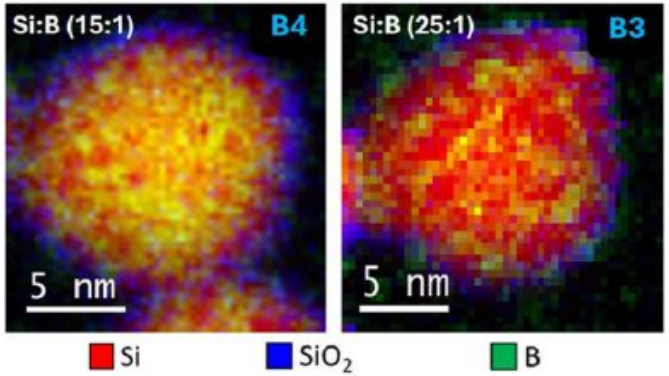
Source: Z. Sun, Q. Yin, S. Zhou et al.

Performance Enhancement of Nanosilicon Anodes via Boron Doping

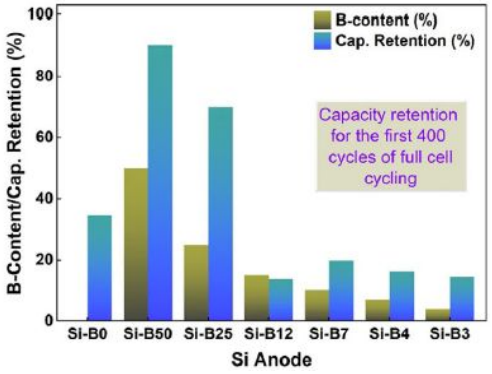
B-doping lowers the expansion of the silicon nanoparticle and improves its electronic conductivity.

Surface **B-dipoles** coordinate with **Li_2CO_3** to create a physical barrier against electrolyte improving passivation.

SILICON:BORON PARTICLE MORPHOLOGY AND DISTRIBUTION



CYCLING CAPACITY RETENTION VS B-CONTENT



Boron doped nanosilicon coated with **lithium carbonate** improves cycle and calendar lifetimes of silicon through enhanced mechanical stability as well as unique chemical stability afforded by **B-dipole** formation at particle surface.

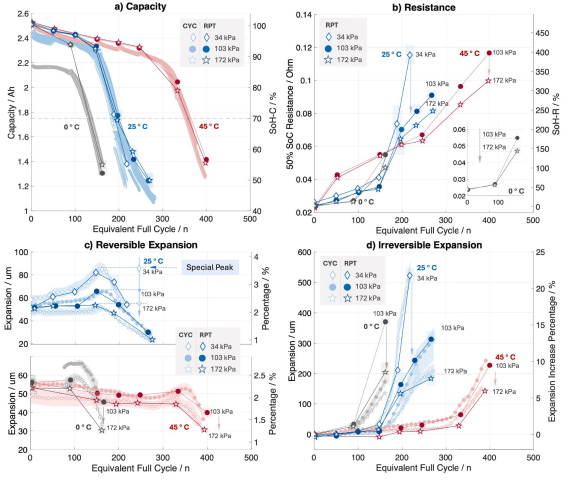
Source: P. R. Adhikari, G. F. Pach, J. Quinn et al.

Impact of Pretension, Temperature, C-Rate and State-of-Charge Window on Degradation of NMC|SiGr

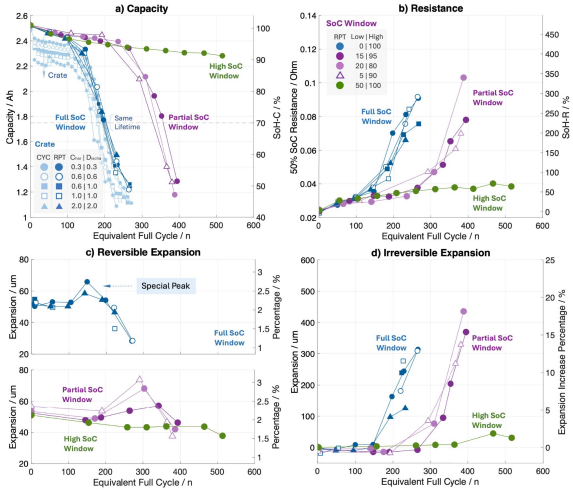
Si-Gr anodes achieve higher energy densities but can exhibit rapid capacity fade, resistance growth, and complex expansion behavior under various cycling conditions. Wan et al (2025) investigated the effects of stress factors like pressure, temperature, state-of-charge (SoC) windows, and charge rates (C-rates) on the evolution of expansion, resistance, and capacity behavior over the lifetime of the battery. Their findings on the optimal range(s) of these stress factors can **guide battery pack and BMS design**.

They also performed ICA and DVA and identified **LLI and LLI + LAM_{NE} (particularly silicon) as the primary causes of pre-knee and post-knee degradation**.

IMPACT OF PRESSURE & TEMPERATURE



IMPACT OF SOC WINDOW & C-RATE



Moderate pretension forces (34–172 kPa) are beneficial as they effectively reduce reversible expansion, irreversible expansion, and resistance growth with minimal impact on capacity fade. **Elevated temperature (45 °C) extends NMC/Si-Gr cycle life** despite an initial increase in resistance, and the lifetime impedance increase under 45 °C is dominated by SEI resistance. Operating in a **narrow SoC window at high SoC minimizes capacity loss**. Degradation is **minimally impacted by charge rates up to 2C**.

Source: Z. Wan et al., eTransportation (2025)

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Lithium-ion
- Cathode
- Anode
- **Electrolyte**

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Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

Liquid Organic Electrolytes for Li-Rich High-Voltage Batteries

Design Class	Concept	2025 Focus
LHCE / HCE	High Li-salt concentration + weakly coordinating diluents → anion-rich solvation, inorganic SEI/CEI, high anodic stability	Li-metal || NMC811 pouch cells under lean electrolyte (≤2–3 g Ah^{-1}), CE >99.5%, gas suppression)
Weakly Solvating Ether Electrolytes	Ether-rich, weakly solvating + fluorinated diluents → anion dominated solvation, dense inorganic SEI	Li // NMC811 stack cells (thin Li, lean electrolyte), hundreds of cycles, low gas evolution
Additive-Engineered Interphase Electrolytes	Targeted inorganic-forming additives (e.g., $MgHPO_4$ phosphates) → multi-layer CEI/SEI	LNMO (5.0V) with $MgHPO_4$ additive, high-rate retention; cocktails for LCO 4.6 V and Li-rich oxides.
All-Fluorinated Electrolytes	Replace carbonates with fluorinated solvents/cosolvents → F-rich interphases, high oxidative stability	Li-rich Mn-based cathodes at high cut-off voltage, retention ~ 85% vs ~ 50%, suppress lattice oxygen loss
Flame-Retardant LHCE	LHCE + flame-retardant components → non-flammable, robust SEI/CEI	NMC811||graphite at ~4.5 V, near unity CE, low fade, passes flammability tests
Liquefied-Gas & Aggregate - Rich Electrolytes	Low-boiling liquefied gases + aggregate-rich structures → ultra-wide temp range, high-voltage stability	Li-metal cells > 4.4 V, improved low-temp performance, reversible interphase formation

Source: [1] Hansen Wang, Xiaolin Yan, Rupeng Zhang et al., *Nature Nanotechnology*, 2025 [2] Luo Zhang, Haodong Zhao, et.al, *NanoScale*, 2025 [3] Yuyu Ban, Feng Hai, Weicheng Xue et.al., *Journal of Materials Chemistry A*, 2025 ; [4] Ganesh Raghavendran, Alex Liu, Oleg Borodin et;al., *Energy Environmental Science*, 2025 ; [5] Recoverable aggregate-rich liquefied gas electrolytes for enabling high-voltage lithium metal batteries

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Lithium-ion

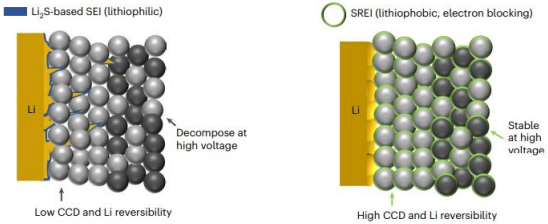
Solid State Batteries
- **Li-Metal**
- Polymer
- Anode-free

Battery Degradation and Performance
New / Alternative Chemistries
Fast Charging & Extreme Fast Charging
Artificial Intelligence and Machine Learning
Battery Management System (BMS)
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Battery Safety

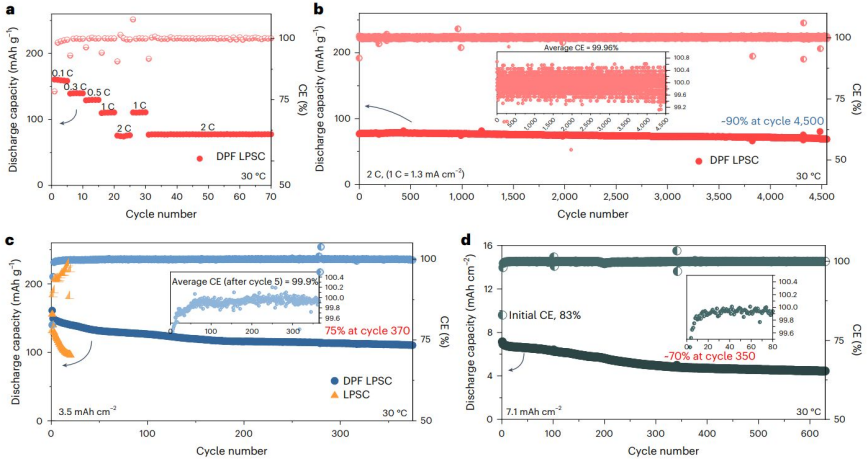
Solid Reductive-electrophile Interphase (SREI) Layers

- Reductive electrophiles form thin, electron-blocking interphases (SREIs) on solid-state electrolyte surfaces. This interphase **suppresses lithium dendrite growth** and **prevents SSE degradation** - improving stability and reversibility by separating the Li metal from the SSE.
- SREI-protected ASSLMBs can deliver **4,500 cycles** at a moderate loading of 1.3 mAh cm^{-2} and **over 600 cycles** at a high loading of 7.1 mAh cm^{-2} at 30 °C and 2.5 MPa.
- Potential benefits of SREIs also apply to metal oxide cathodes by extending their **stable operating voltage up to 4.5 V**, offering a scalable, self-limiting alternative to thick artificial interlayers or a high-pressure assembly.

A highly **lithiophobic** and **electron-blocking** all-inorganic LiF–$Li_xP_yO_zF$ (LPF) layer was generated on the surface of sulfide SSE particles to improve electrochemical stability for both the cathode and anode.



Schematic of the "electrochemical electrophile reduction" strategy.



Electrochemical performance of LPSC with DPF and LPSC without DPF. a) Rate performance data and cycling performance b) at 2C, c) 3.5 mAh cm^{-2} loading, and d) 7.1 mAh cm^{-2} loading.

Source: Nature Materials 24.3 (2025): 414-423.

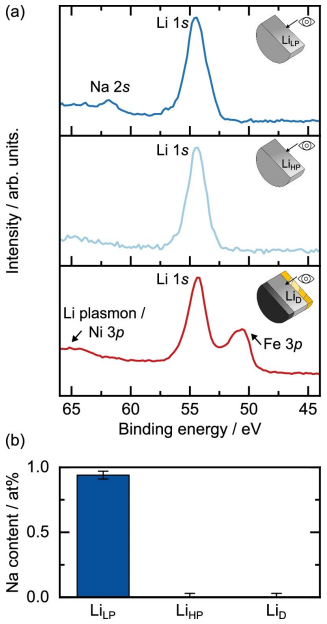
Impact of Lithium Metal Impurities on Lithium Stripping Behavior

Lithium metal foils for solid-state batteries typically have impurities, such as sodium, in the 0.1% to 1% range. TOF-SIMS and XPS data reveals that for reservoir-free cells, lithium electrodeposited onto the negative current collector is **significantly purer** than commercial foils because of selective ion transport of Li^+ through the solid electrolyte.

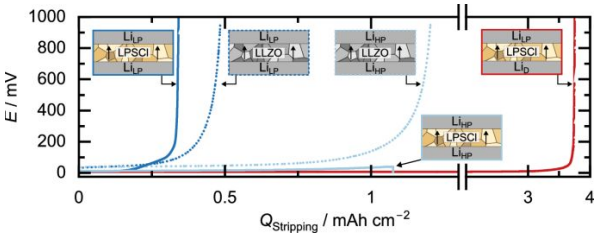
Electrochemical testing of low-purity and high-purity lithium foils showed that impurities negatively affect accessible discharge capacity by **accumulating at the solid electrolyte interphase** and **causing kinetic hindrance**. Sodium-rich layers restrict lithium diffusion and create voids which localize current flow and increase interfacial resistance. This work does contrast with findings from other studies, but this could be explained by samples with different mechanical properties.

The role of microstructure and mechanical properties is therefore a major focus for future work. Although electrodeposited lithium exhibited higher stripping capacity than both foils, the **purity relationship does not necessarily extend** to deposited lithium films.

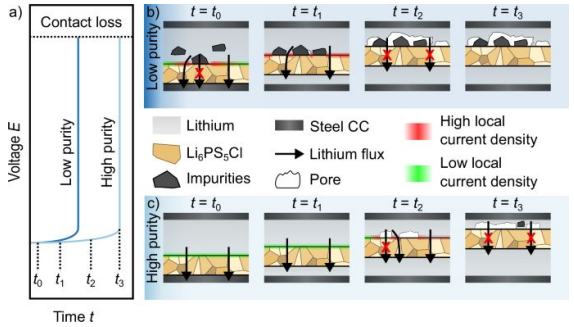
Purity of lithium metal plays a **critical role** on stripping performance for lithium foils in solid-state batteries and **should always be specified** when reporting cell data.



Measurement of impurity content in various lithium samples. a) XPS spectra and b) calculated sodium content.



Influence of impurity content on accessible lithium capacity during stripping.



Impact of lithium purity in (reservoir-free) solid-state batteries. a) Voltage profile and interface evolution of b) low-purity foil and c) high-purity foil.

Source: [1] Nature Communications 16.1 (2025): 5395. [2] Energy Storage Materials 74 (2025): 103975.

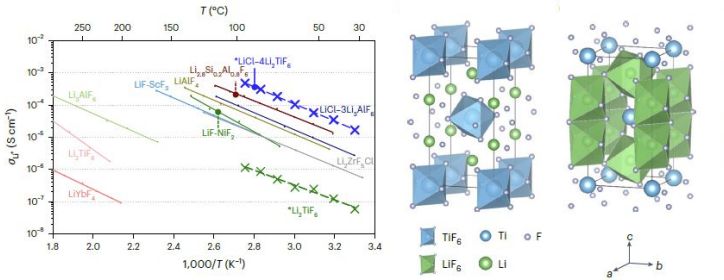
Five-Volt-Class High-Capacity All-Solid-State Lithium Batteries

Strategy and performance: Achieved >5 V operability and ultrahigh areal capacity (35.3 mAh cm^{-2}) in ASSBs using a **fluoride solid electrolyte, LiCl–4LTF**, with high Li^+ conductivity (1.7×10^{-5} S cm^{-1}).

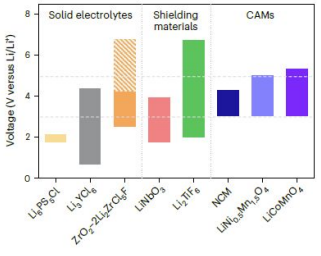
Mechanistic insight: Synchrotron X-ray analyses and theory reveal that the >100x Li^+ conductivity enhancement over Li_2TiF_6 arises from **increased Li^+ concentration and interfacial Cl substitution**, predominantly at surface/interface regions.

Interfacial stability: As a 5 V–stable shielding layer, LiCl–4LTF enables **excellent rate and cycling performance of spinel cathodes** (e.g., 106 mAh g^{-1} at 2C with 75.2% retention after 200 cycles), outperforming unstable LNbO coatings.

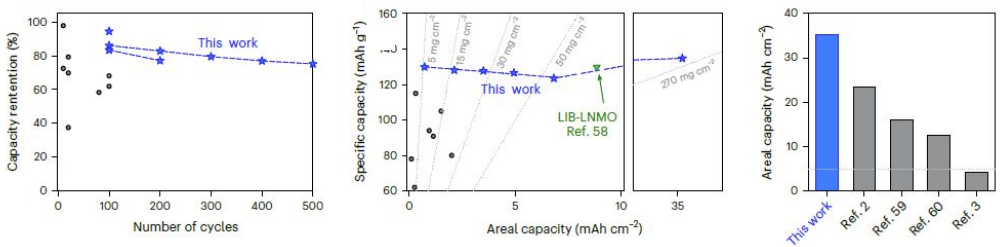
Versatility: Effectiveness is validated across **high-voltage spinels** (LNMO, LCMO, LFMO), **low-voltage extended operation** (258 mAh g^{-1}), and **pouch-type full cells**.



Arrhenius plots of Li^+ conductivities and crystal structures of Li_2TiF_6 with TiF_6



Electrochemical stability windows



Comparison of cycling performance with LNMO electrodes in ASSBs

By combining exceptional >5 V oxidative stability with fast Li^+ transport, LiCl–4LTF enables record-high areal capacity and stable high-voltage operation across multiple ASSB architectures, establishing a broadly applicable interfacial design paradigm.

Source: Son et al., *Nature Energy*, 2025

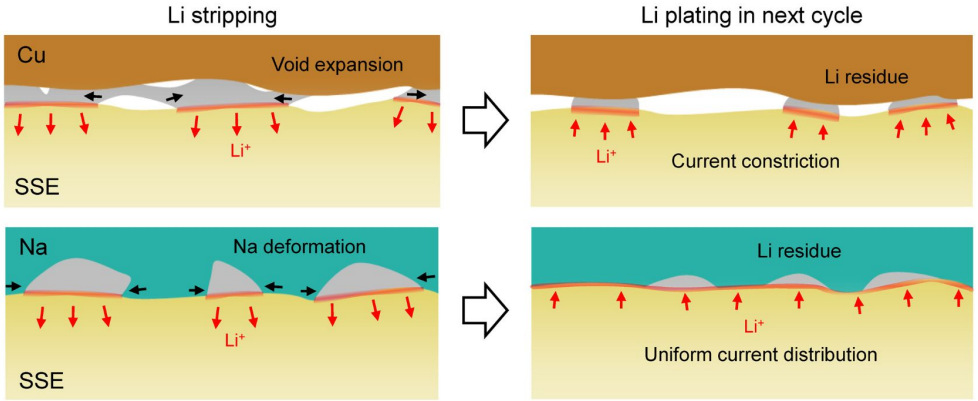
Deformable Sodium Metal Current Collectors for Lithium Solid-state Batteries

Traditional anode-free solid state batteries rely on a rigid current collector to deforms lithium into a thin film geometry as it plates and strips. A new approach is reported here based on a **deformable sodium current collector** where the lithium is allowed to deform the current collector instead, **promoting low-pressure void-free cycling** that allow for free morphology lithium grain growth. However, the processability of sodium current collectors remains a challenge.

Cells were tested in both the half cell and full cell geometry with argyrodite Li6PS5Cl SSE used as a model system.

In the half cell geometry, lithium-copper and lithium-sodium cells were cycled under varying low (0.8-8.1 MPa) pressures. The lithium-sodium cells were found to exhibit significantly improved cyclability and lower internal resistance, which was attributed to the deformability and improved contact of the sodium current collector.

In the full cell geometry, the authors identified a regime (2.5 - 8.1 MPa) sufficient to deform the sodium current collectors (but below the traditional 10 MPa pressures used for steel or copper current collectors) that demonstrated high coulombic efficiencies. Interestingly, they observe that **contact retention, rather than lithium uniformity, seems to drive increases in performance**.



Deformable sodium current collectors provide excellent void resistance and lowered interfacial resistance compared to traditional copper current collectors.

Source: Yoon et al., *Matter*, 2025

Grain Selection Growth of Soft Netal in Electrochemical Processes

The effects of lithium grain size, selection, and growth on the kinetic limitations of lithium metal batteries are still poorly understood. A new chemo-mechanical-thermal model is proposed to understand the mechanisms governing the selection of each grain.

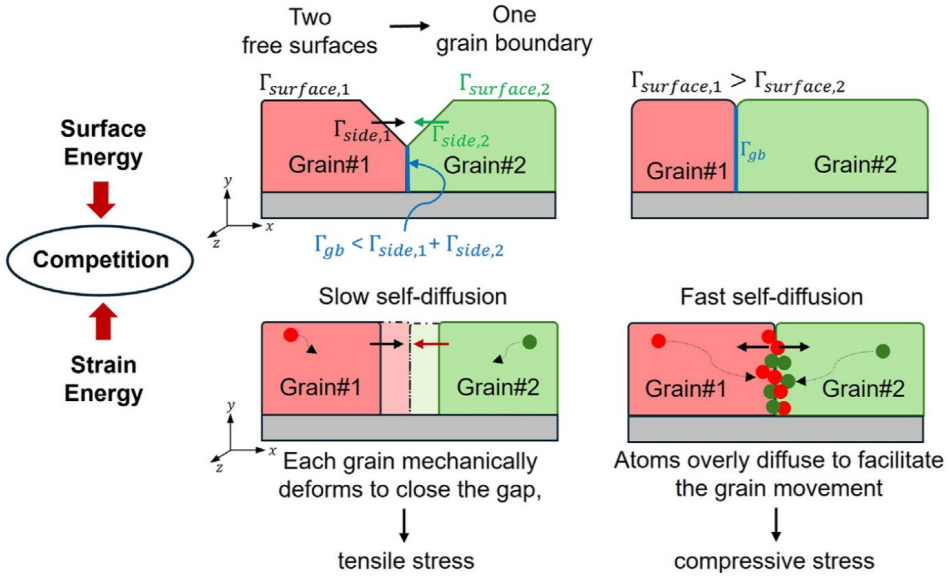
The total energy of a grain can be described in terms of surface energy, lattice strain, and thermal energy.

$$U = \Gamma_{surface} + F_{strain} + F_{thermal}$$

By finding the difference in total energies between grains, a predictive model can be built to determine grain selection.

The authors find that **commonly applied stresses (~10 MPa) are sufficient to modify the lithium grain selection criteria, as are temperature changes** as small as the difference between room temperature and 80C. The thermal model results were validated by an experimental full cell setup, which found a texture transition from (001) towards (101) grain preference within the temperature change.

When the model is instead used to inspect sodium and potassium, the authors found that high-diffusion grains are preferred for room temperature operation at a wide variety of stresses, indicating good compatibility for solid state batteries.



Grain selection between the lithium metal (101) and (001) orientations can be predicted, allowing for better control of diffusion kinetics in solid state batteries.

Source: Zhang et al., *Joule*, 2025

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Lithium-ion

Solid State Batteries
- Li-Metal
- **Polymer**
- Anode-free

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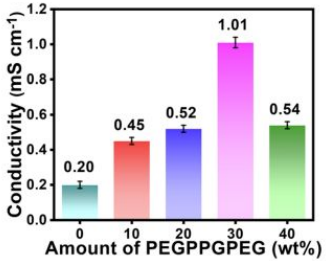
Ionic Liquids as Designed Components of Solid Polymer Electrolyte Architectures

The intentional **functional integration of ionic liquids** (ILs) into polymer networks and polymers with designed confinement enables lithium and beyond-lithium solid polymer electrolytes to reach reasonable room-temperature **ionic conductivity (>10^{-4} S/cm)** and to balance the trade-off with mechanical strength and interfacial instability.

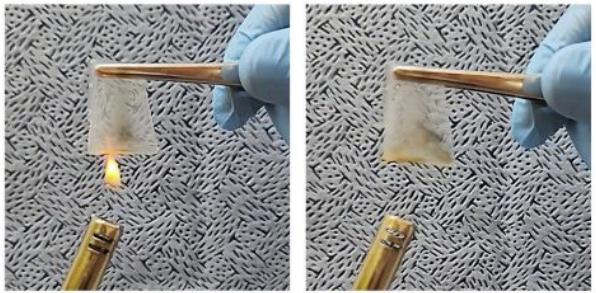
Ionic liquid incorporation not only acts as a plasticizer, but has been shown to improve contact at metal interfaces, suppress dendrites and brittle fracture, improve thermal stability, and enable self-adaptive, viscous behavior. The structural integration of ILs to polymer networks produces a “liquid-like” matrix that enables high ionic conductivity within a **mechanically robust** electrolyte film.

In sodium systems, IL incorporation can be used to alter the anion-polymer interactions to **increase cation diffusivity**. Novel blending strategies have enabled long cell cycling and **excellent fuel-cell performance**. In potassium systems, ILs enabled ionic conductivity above 10^{-3} S/cm and positivity influenced **stable SEI** formation.

Solid polymer electrolytes that structurally integrate ionic liquids have emerged as a key design trend that has enabled room-temperature conductivity, improved ion coordination and mobility, and stable metal anodes in beyond-lithium solid-state batteries.



Room-Temperature ionic conductivity of sodium quasi-solid polymer electrolytes upon varying amount of plasticizer.



Flammability test photos of fabricated composite IL-polymer lithium electrolyte films

Source: [1] Kala, V. S., Soni, C. B., Sungjammenla, et. al. *J. Mater. Chem. A*. 2025. [2] Chen, J., Ebrahimi-Koodehi, S., Iliev, B., et. al. *J. Mater. Chem. A*. 2025. [3] Makhlooghiazad, F., Mejia, L. M. G., Rollo-Walker, G., et. al., *J. Am. Chem. Soc.* 2024 [4] Chae, W., Earmme, T. *ACS Omega*, 2025

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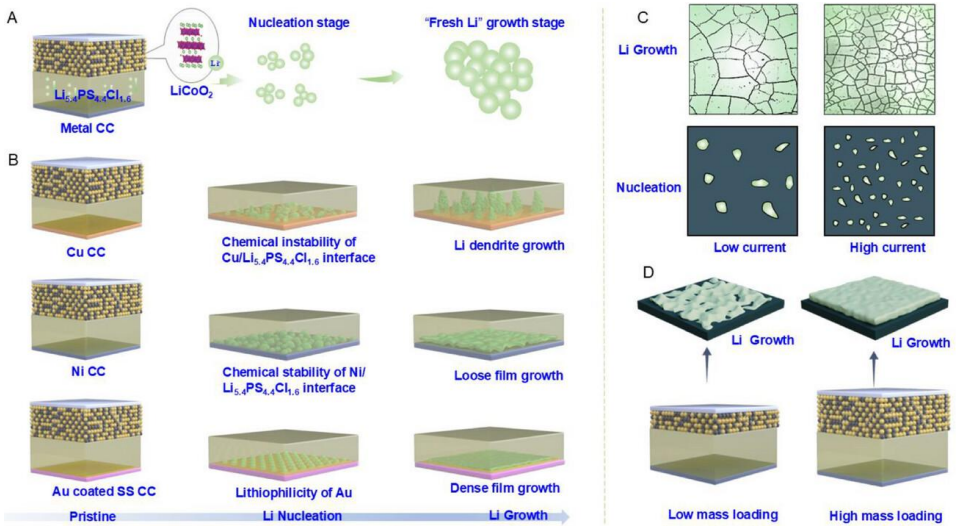
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Effects of Substrate, Current Density, and Li+ Supply in Sulfide-based Anode-free Solid-state Batteries

Lithium nucleation and growth was examined in anode-free $Li_{5.4}PS_{4.4}Cl_{1.6}$ (LPSC)-based batteries using cryo-TEM and electrochemical measurements. Lithium metal was plated onto TEM grids of various materials, which acted as substrates/current collectors, under varying current and mass loading conditions.

Cycling demonstrated that **highly lithiophilic materials are ideal substrates for anode-free systems**, and that ideality is maintained even with very thin seed layers (20 nm). Surprisingly, copper was found to be unsuitable for sulfur systems, resulting in mossy or ball-like plating.

Low mass loadings, shown in previous Li-excess solid state battery work to extend cycle life (due to low volume change), are observed to promote heterogenous lithium nucleation in the anode-free case, though the exact mechanism is unclear.



Sulfide-based solid-electrolytes can be unsuitable in combination with Cu electrode systems due to Cu_2S byproducts, and may show artificially poor nucleation in low mass loading systems.

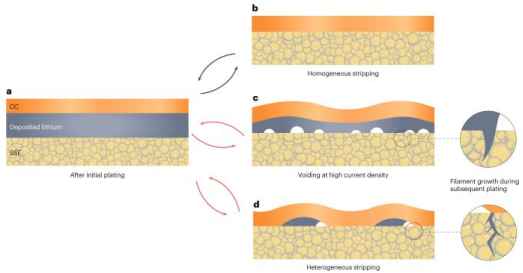
Source: J Wang, Y Liu, M Ye, G Wang, C Xu, H Zhu Small, 2025

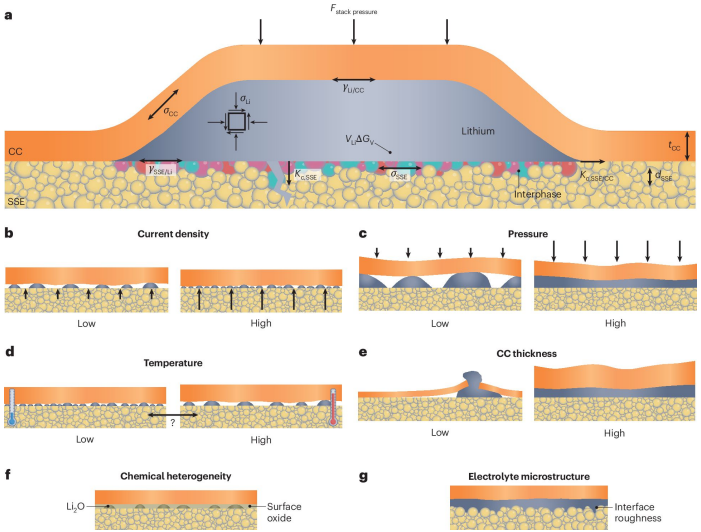
Anode-Free Solid-State – Anode Plating and Stripping Mechanisms

One promise of solid-state batteries is anode free architectures. Understanding the mechanisms of anode plating and stripping is critical to fulfilling this promise.

In anode-free cells, **lithium plating and stripping cause large volume changes at the current-collector/solid-state electrolyte interface, generating significant mechanical stresses**. Because these cells contain no excess lithium, any lithium loss also has a greater impact on performance than in conventional designs.

Achieving uniform lithium deposition depends on several factors, including current density, applied pressure, temperature, current-collector and electrolyte thickness, material homogeneity, and interfacial surface morphology. In contrast, uniform lithium removal during discharge is primarily governed by current density and the ability to maintain a homogeneous stripping environment.





Understanding the mechanisms of lithium plating and stripping in anode-free solid state batteries is critical to unlocking the full promised potential of solid state batteries.

Source: Sandoval, S.E., Haslam, C.G., Vishnugopi, B.S. et al. Electro-chemo-mechanics of anode-free solid-state batteries. Nat. Mater. 24, 673–681 (2025)

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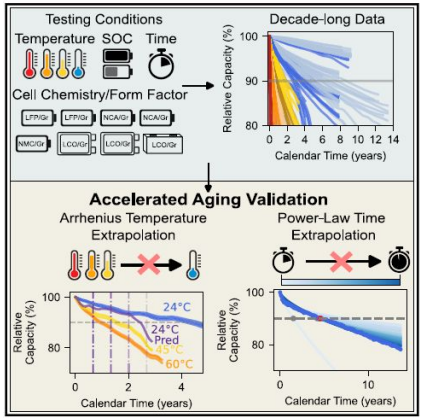
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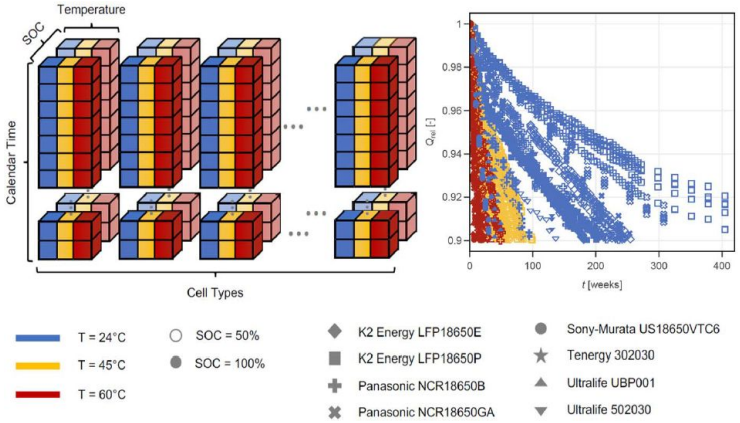
Battery Degradation and Performance
- **Calendar Aging**
- Cycle Aging
- Performance

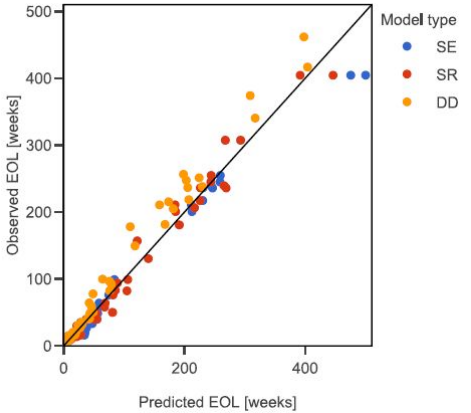
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Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

Stanford 11-Year Calendar Aging Study

Researchers at Stanford published a dataset (available open-source) with 8 commercial cells from 5 manufacturers calendar aged over 13 years, showing significant time-varying nonlinearity, cell-to-cell variability, and cell-type dissimilarity. They highlighted the shortcomings of widely-accepted storage time and temperature dependencies on calendar aging, i.e., power-law exponents and the Arrhenius law,, respectively. They also compared 3 different models to predict the EOL and capacity trajectories of unseen cells, unseen temperatures & unseen cell types: semi-empirical (SE), symbolic regression and data-driven (DD) models.





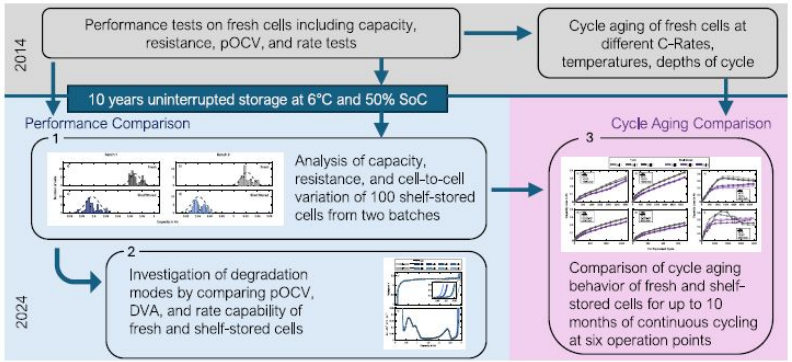


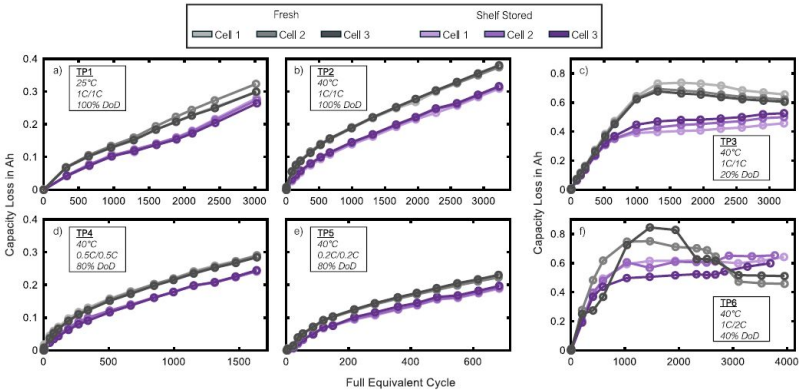
For long storage times, **capacity fade predictions require more sophisticated models** than the Arrhenius law and power-law exponents. **In unforeseen conditions, the SE model excels** in predicting EOL, whereas **for unseen cell types the DD model was effective** in predicting the degradation trajectory.

Source: [1] X Cui et al., *Journal of the Electrochemical Society* (2025), [2] V. Lam et al., *Joule* (2025)

Effect of 10-Year Uninterrupted Storage on Cell Performance

Researchers from TU Munich analyzed capacity loss and resistance change immediately after ten years of uninterrupted shelf storage at 50% state of charge and 6°C on 100 commercial 26650 LFP/C cells. Compared to fresh cells, stored cells show less cycle aging after ten years of storage when operated continuously up to 3000 full equivalent cycles at various operating conditions. Only when cycled at low depths of discharge at medium state of charge does the capacity loss exceed that of fresh cells, due to absent recovery behavior observed for fresh cells under these operating conditions.



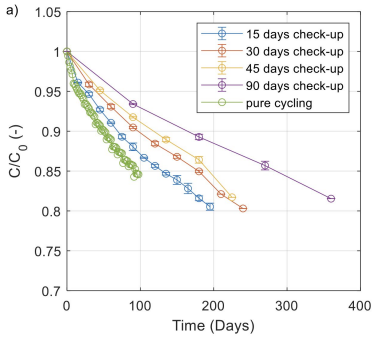


Shelf-stored LFP cells can be used in applications just like fresh cells, without any additional precautions.

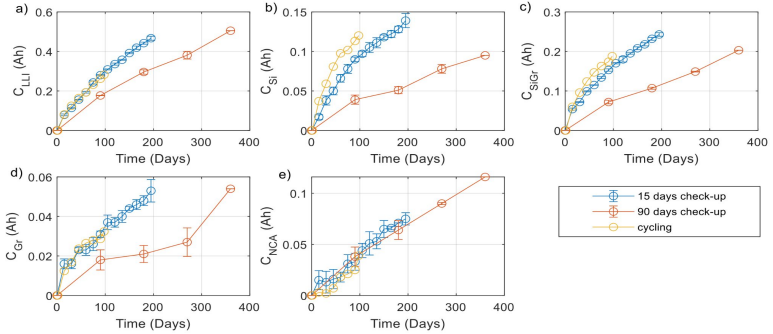
Source: V. Vachenauer et al., Journal of Power Sources (2025)

Impact of Check-up Cycles on Calendar Aging

Cells with silicon–graphite anodes and Ni-rich layered-oxide cathodes are a key next-generation high-energy Li-ion architecture, but their calendar-aging response differs from conventional commercial cells, motivating updated design and operating strategies for lifetime and safety.In Si-graphite/Ni-rich Li-ion cells, check-up frequency strongly influences calendar aging. 15-day check-ups caused ~2× more capacity loss than 90-day check-ups after 200 days of storage. Storage charging method (open-circuit, daily charge, float) had minimal impact on capacity fade, check-up frequency dominates. Calendar and cycle aging are coupled, not linearly additive. Diagnostics (Differential Voltage Analysis) indicate dominant modes are LLI + Si-anode LAM. More frequent check-ups delayed CID (Current Interrupt Device) activation, likely due to pressure relief during cycling and cool-down.



Capacity fade over time of cells with different check-up frequencies and cells aged with cycle test



Evolution of different ageing modes with time. (a) LLI, (b) LAM in silicon, (c) LAM in anode, (d) LAM in graphite and (e) LAM in cathode.

Minimize and standardize check-up intervals, and always report them. Otherwise, you may be measuring check-up–induced degradation rather than true calendar aging.

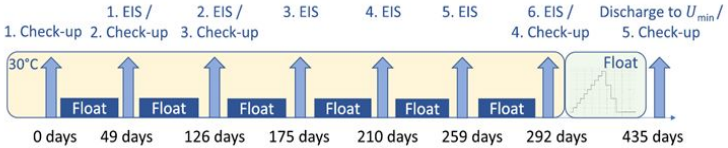
Source: Laresgoiti, I., Yi, H., Koster, D., Karimi, F., Yang, J., Schulte, D., & Figgemeier, E. (2024). Calendar ageing of commercial 18650 cells with nickel-rich cathode and graphite-silicon anode: Influence of check-up. Journal of Energy Storage, 98, 112918.

Float Current (Constant Voltage) Measurement of SEI Growth and Electrolyte Oxidation

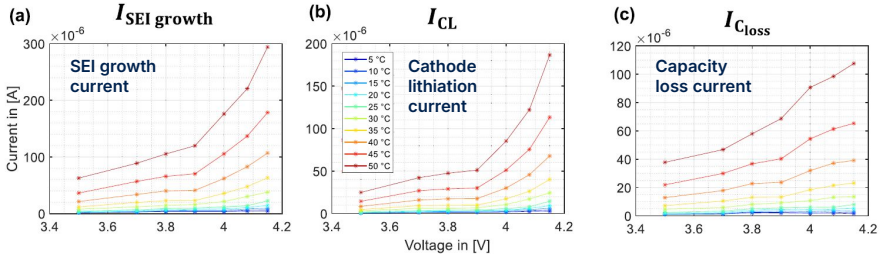
Float current measurements combined with voltage slippage analysis deconvolutes reductive/oxidative electrolyte/interface reactions at both electrodes.

- *Quantitative analysis* of measured currents during repeat voltage holds (I_{float}) on **Samsung Gr|NCA cell** at varying voltages and temperatures **combining voltage slippage analysis, ICP-OES and EIS** to deconvolute float current as SEI current ($I_{SEI\ growth}$)and electrolyte oxidation current (I_{CL}).
- Li-ion battery capacity loss occurs from LLI due to SEI growth, while Li inventory and capacity increases due to electrolyte oxidation.
- *Voltage slippage* is the drift of anode and cathode potentials with ageing. It is a crucial analysis for quantitative current splitting.
- **$I_{SEI\ growth}$ dominates I_{CL}; both increase with high voltage and temperature**
- This technique is broadly applicable for Li-ion batteries with slippage analysis increasing in complexity for next generation batteries (e.g. silicon anodes with hysteresis, stress potential coupling etc.)

FLOAT TESTING PROTOCOL



FLOAT TEST CURRENT MEASUREMENTS AT VARYING VOLTAGE AND TEMPERATURES



Source: M. Azzam, A. Aydin, C. Endisch, D-U. Sauer, M. Lewrenz

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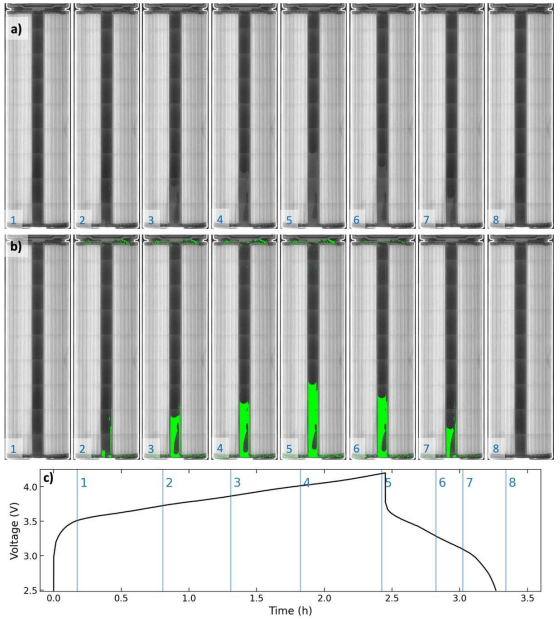
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Electrolyte-motion Induced Salt Inhomogeneity and Heterogenous Lithium Distribution

The work provides the first **operando three dimensional imaging of electrolyte motion in cylindrical cells**, giving direct experimental evidence that electrolyte is expelled through **in plane flow along the anode**, a central assumption of the **EMSI mechanism**.

The study shows that electrolyte redistribution is strongly shaped by **cell geometry, pore filling ratio, anode composition, and gravity**, revealing **asymmetric regions** that can become locally **depleted during discharge** and locally **saturated during charge**.

It demonstrates that EMSI driven salt inhomogeneity can appear even at moderate rates and that some effects can partially reverse when the cell rests at low state of charge.



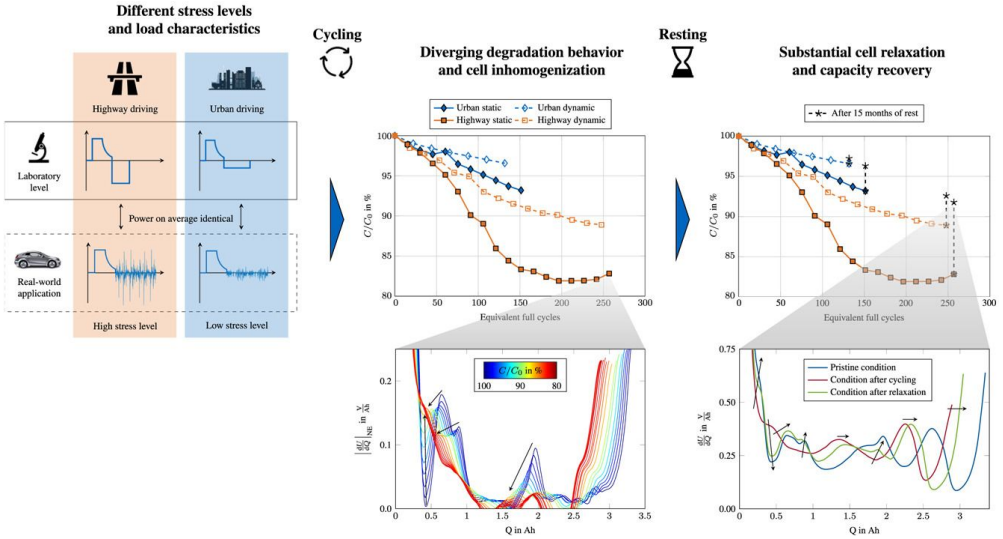
Operando 3D imaging shows electrolyte is expelled along the anode, confirming (reversible) EMSI and revealing geometry driven

Source: [1] Bond et al., JES, 172, 030512 (2025), [2] Butler et al., JES, 172, 060526 (2025), Petursdottir et al., JES, 172, 100504 (2025)

Dynamic Cycling versus Constant-current Cycling

EV lifetime is often assessed with static constant-power aging tests, while real driving is dynamic with long rests. This work shows such tests can **overstate degradation** because a large part of the measured "aging" is reversible.

- If this reversible part isn't separated out, aging tests and models will underestimate real-world lifetime and mislead design and warranty decisions.
- Four 18650 NCA/Si-Gr cases (static vs. dynamic urban/highway; same average power; 60% DoD) show faster apparent capacity loss and resistance rise under static cycling, attributed to reversible anode lithiation/electrolyte inhomogeneity.
- After ~15 months low-SOC rest, cells recover ≈52% of the capacity loss and ≈66% of the resistance rise, informing accelerated-test designs that incorporate rest and separate apparent from true aging.



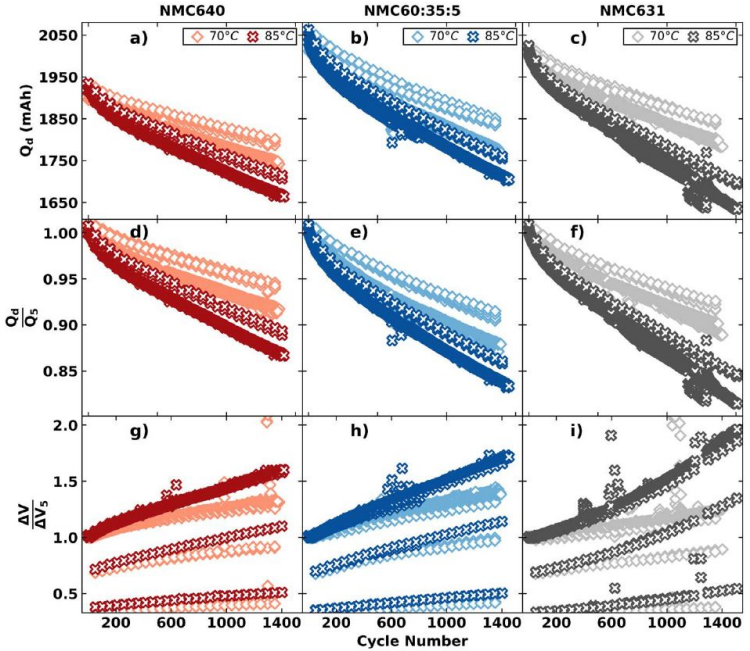
Static cycling can overstate degradation, since long low-SOC rest reverses a large fraction of observed capacity/resistance changes.

Source: Schreiber et al., *Journal of Energy Storage*, 2025.

Accelerating Aging by Testing Above 85 °C

- Specially designed 18650 cells with Gr|NMC640, Gr|NMC63.50.5 and Gr|NMC631 chemistries balanced at 4.05 V containing LiFSI electrolyte underwent cycle life testing at C/3 and C/20.
- Operating temperatures ranged from 20 °C to 100 °C with an upper voltage cutoff of 4.0 V (prevents electrolyte oxidation).
- Loss of lithium inventory and minor impedance growth are the only aging modes, enabling square root of time capacity decay and an equitable comparison across cells.
- Cells operated at lower temperatures show an initial rise in capacity with cycling.
- Best cells retain 87% capacity after 1400 C/3 cycles even at 85°C.

By designing cells to only have a **single degradation mechanism** even across chemistries, we can directly compare high temperature durability.



Discharge capacity and voltage gap evolution with cycling for varying NMC chemistries.

Source: C. Floras, S.M. Maher, K. Tuul, J. Harlow, M. Bauer, J. R. Dahn

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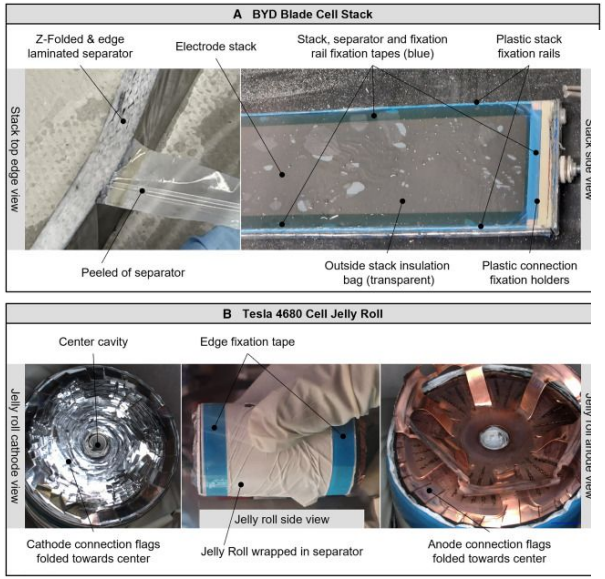
Comparison between Design and Performance of a BYD Prismatic Cell and Tesla Cylindrical Cell

Bridging the gap between lab-scale experiments and larger commercial cells is a key challenge in academic research. Battery cell manufacturers do not typically disclose information on state-of-the-art processes. Disassembling discharged cells inside a glovebox for characterization, electrochemical testing, and documenting internal structure can reveal valuable insights.

Teardown analysis of a BYD Blade prismatic cell and Tesla 4680 cylindrical cell allowed for comparison of their electrical, mechanical, material, and process designs. The BYD cell displays **half the energy losses per volume** as the Tesla cell at the same C-rate. The Tesla cell uses **laser welding** and BYD cell uses **laser and ultrasonic welding** for electrode contact.

The BYD cell uses a **LFP cathode** with a graphite anode, whereas the Tesla cell uses a **NMC811 cathode** with a graphite anode containing **PAA** and **PEO binders**. A manufacturing sequence is proposed for both cells.

Battery teardowns provide useful data on internal design, material selection, and performance, but must be done with **extreme caution to avoid thermal runaway**.



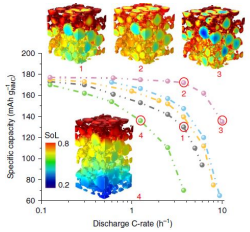
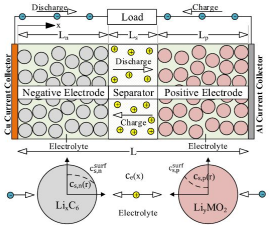
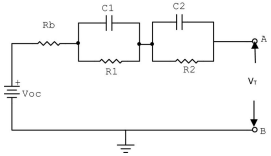
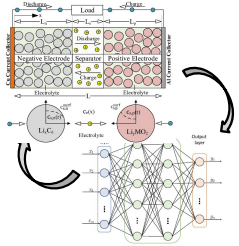
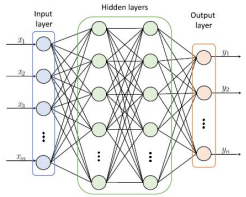
Images of the internal electrode configurations and features for both cells.

OVERVIEW OF GENERAL CELL PROPERTIES AND DIMENSIONS

	Tesla 4680 cell	BYD Blade cell
General		
Nominal capacity, Ah	23.125	135
Nominal energy, Wh	85.56	432
Nominal voltage, V	3.7	3.2
Voltage window, V	2.5–4.3	2.6–3.65
Weight	355 g	2.7 ± 0.3 kg
Volume, mL	133	1,216
Energy density (gravimetric), Wh/kg	241.01	160
Energy density (volumetric), Wh/l	643.3	355.263
The areal capacity of the cathode (calculated), mAh/cm^2	4.99	2.393
Dimensions		
Diameter/length, mm	46	965
Height, mm	80	90
Thickness, mm	–	14 mm
Can wall thickness (sides), mm	0.4	0.3
Separator, µm	10	12
Anode coating thickness, µm	125	65
Copper substrate foil thickness, µm	10	10
Cathode coating thickness, µm	75	70
Aluminum substrate foil thickness, µm	20	20
No. of separator layers	2	78
No. of cathode sheets (coating on both sides)	1	38
No. of anode sheets (coating on both sides)	1	39

Source: [1] Cell Reports Physical Science 6.3 (2025). [2] Journal of The Electrochemical Society 170.12 (2023): 120536. [3] Electrochimica Acta 471 (2023): 143341.

Modeling: From Fundamental Physics to Data-Driven Methods

	3D Microstructural Model	Electrochemical Model (P2D)	Equivalent Circuit Model (ECM)	Hybrid Models	AI Models
					
Description	3D microstructure-resolved physics-based battery model of high fidelity	Physics-based model based on porous electrode theory	Based on electrical components: resistors, capacitors and voltage sources	Combines features from different model types: e.g: P2D & AI, ECM & P2D, ...	Full black-box models
Pros	• Appropriate for electrode design and manufacturing	• Insights into internal battery physics and ageing mechanisms • Suitable for extrapolation	• Low computational effort (appropriate for µC) • Simple parameterization and validation	• Increase of accuracy of P2D or ECM models	• Suitable to reproduce very complex phenomenon, not representable by analytic equations
Cons	• Complex techniques for microstructure definition • Very big computational effort	• Complex parameterization and validation of internal parameters	• Not suitable for extrapolation • No insights into internal battery physics	• Increase of model complexity	• Not suitable for extrapolation • Requires large amount of data

Source: [1] X. Lu et al., NATURE COMMUNICATIONS | (2020) 11:2079, [2] H. Tu et al., Applied Energy 329 (2023) 120289, [3] B. W et al., Energy and AI 1 (2020) 100016, [4] L. Yan et al., Energy and AI 20 (2025) 100478, [5] M. Doyle et al., Journal of the Electrochemical society, 140(6):1526–1533, 1993, [6] A. Jokar et al., Volume 327, 30 September 2016, Pages 44-55

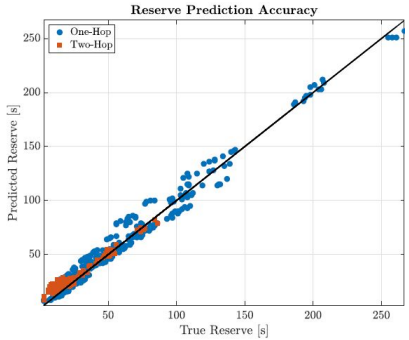
Equivalent Circuit Model with Lithium Depletion (LD) Term for High-Power Discharge (eVTOL) Model

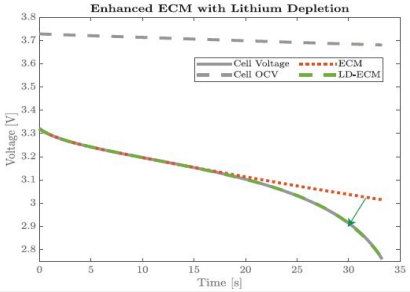
Challenge
The classical **Equivalent Circuit Model** (ECM) fails to reproduce sudden voltage decreases at low SOC (relevant for eVTOL applications).

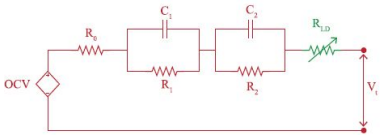
Proposed approach
Additional **diffusion resistance (RLD)** in series to the RC elements is introduced (LD-ECM) in the equivalent circuit. The new term is parameterized through a set of of experimental aging data composed by constant current pulses (CCP), full discharge (FD) and multi power pulses (MPP). A LUT identification methodology with parameter regularization is introduced.

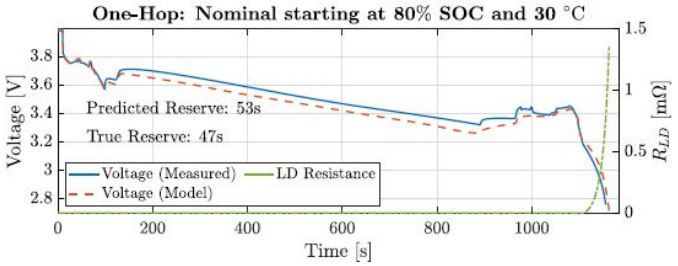
Main Results
The model is validated against a data set of over 150 flights that cover wide conditions (from 30 ºC to 60 ºC and up to 8C of current rate) for eVTOL aircraft.

Reserve time is suggested as the metric to track accuracy. A standard deviation of **6.2s** over all tested duty cycles is achieved. However, maximum errors of up to **20s** are observed.









Adding an additional diffusion resistance element in the Equivalent Circuit Model can capture battery behaviour at low SOC and improve model accuracy. However, lower temperatures (< 30°C) and battery degradation have yet to be addressed on their impact on model performance and accuracy.

Source: A. Goshtasbi et al,, Journal of Power Sources 620 (2024) 235188

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New / Alternative Chemistries
- **Sodium-Ion / Na-Metal**
- Zn/Mg/Ca (Divalent) Ion
- Li-S
- Potassium-Ion
- Flow
- Fluoride-Ion
- Aluminum-Ion
- Metal-Organic Frameworks

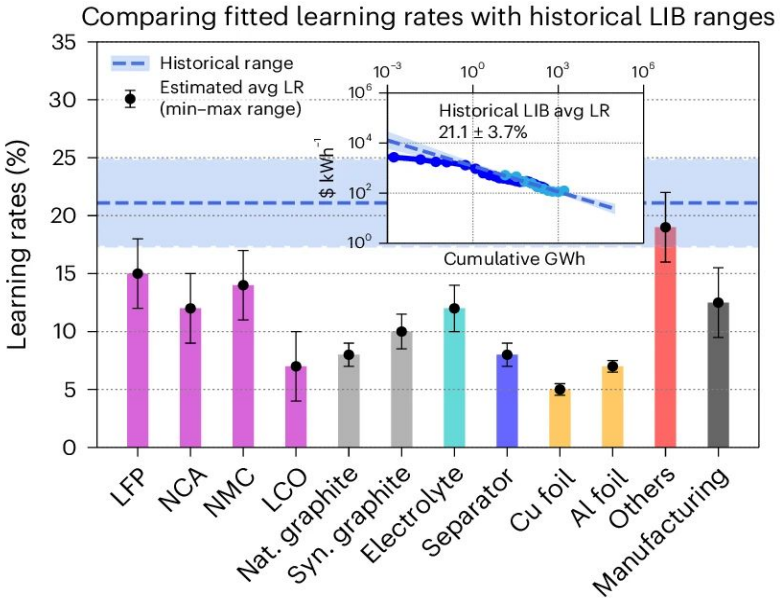
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Sodium-ion Technology Roadmaps and Scenarios for Techno-economic Competitiveness against LIBs

Cell price parity does not translate into total cost of ownership parity because market value also depends on revenue impacts, long term durability and reliability, and the complexity of thermal management and battery management systems.

Yao et al. show that sodium ion can reach cost parity with low cost lithium ion chemistries such as LFP in the 2030s if energy density and materials efficiency improve.

Their scenario modelling indicates that engineering improvements drive competitiveness more than scale and that sodium ion becomes more attractive when lithium or graphite prices rise.

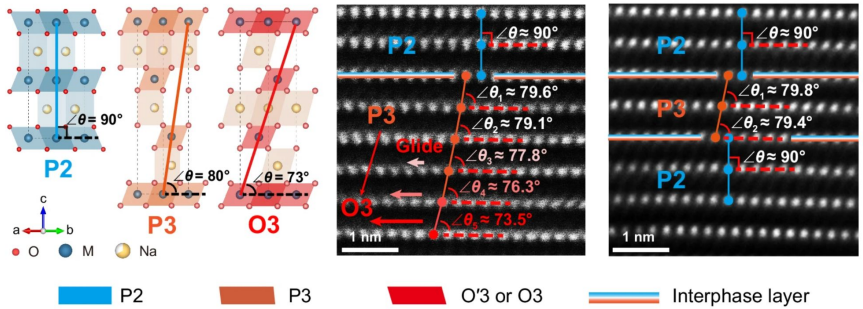


Source: Yao et al., Nature Energy, 10, 404–416 (2025)

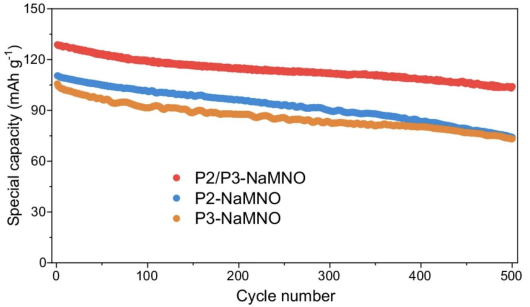
Intergrown O-type and P-type Sodium Layered Oxides

Enhancing stability via interphase engineering

Sodium-ion batteries, being commercialized, are on the track of improvement to cover more and more applications. To achieve that, requirements on higher energy density and cycling stability are often highlighted. Utilizing intergrown P2/P3 and P/O structures in Na-ion batteries is improving electrochemical stability due to synergic effects in biphasic composites. However, interlayer gliding causing phase transitions eventually leads to deterioration of the performance. Zhou X., et al., (2025) demonstrates the possibility of the restraining the phase transitions by interphase engineering, which **enhances cycling stability and rate capability**.



The difference between phase changes with different phase distributions: P3 phase transforms into O phase which can be mitigated by modifying phase distribution.



Cycle performance over 500 cycles demonstrating higher initial capacity and capacity retention for P2/P3 structures

Interphase engineering is an important part of optimizing active materials with bulk phase transitions. By elucidating gliding degradation mechanism for intergrown Na-ion oxides, it has been demonstrated that changing **phase distribution** results in avoiding unfavorable phase transitions.

Source: Zhou X., et al., (2025)

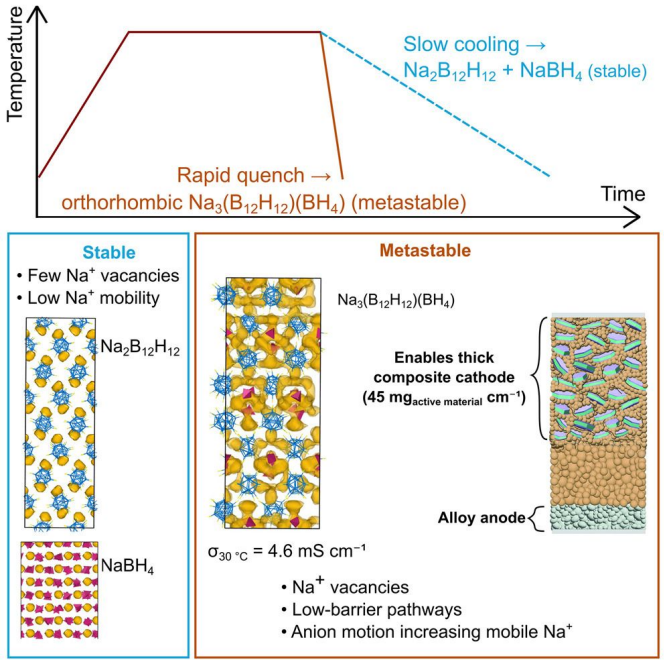
Metastable Sodium Closo-hydridoborates for All Solid-state Batteries with Thick Cathodes

Rapid cooling of sodium hydridoborate precursors from the high-temperature formation window produced a metastable orthorhombic **$Na_3(B_{12}H_{12})(BH_4)$ phase**, confirmed by XRD and NMR. Slow cooling causes the material to revert to $Na_2B_{12}H_{12}$ and $NaBH_4$. The **orthorhombic phase only persists when kinetically trapped**.

Faster cooling increased uniformity of the sodium environment and reduced the presence of precursor-like signatures. Ionic conductivity measurements showed that conductivity increased with cooling rate, reaching **4.6 mS cm^{-1} at 30 °C** for the quenched material, along with a lower activation energy. Electronic conductivity remains several orders of magnitude lower.

Electrochemical testing of composite cathodes showed the metastable phase **reduced tortuosity** and **lowered areal resistance** compared with chloride-only electrolytes. Thick $NaCrO_2$ (45 mg cm^{-2}) paired with Sn as the cathode and anode delivered reversible areal capacities up to 3.5 mAh cm^{-2}. Cells maintained cycling stability when a chloride coating was used to prevent oxidation of the electrolyte, and full cells continued operating at temperatures down to –15 °C.

Kinetic stabilization of a metastable anion-dynamic framework through **quenching unlocks fast Na^+ transport** and enables high-loading sodium solid-state batteries.



Source: Oh et al., *Joule*, 2025.

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Research Trends
Seminal Literature
Fundamentals
Lithium-ion
Solid State Batteries
Battery Degradation and Performance

New / Alternative Chemistries
- Sodium-Ion / Na-Metal
- Zn/Mg/Ca (Divalent) Ion
- Li-S
- Potassium-Ion
- Flow
- Fluoride-Ion
- Aluminum-Ion
- Metal-Organic Frameworks

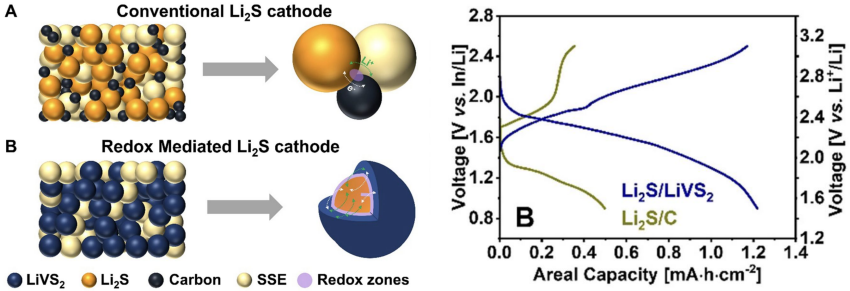
Fast Charging & Extreme Fast Charging
Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

Strategies Enabling Li-rich Sulfur Cathodes in ASSLSBs

Traditional Li-S batteries consist of an S_8:C composite cathode, liquid electrolyte and separator, and a lithium metal anode. Soluble intermediate cathode discharge products as well as dendrite growth are two operational roadblocks which all solid state lithium sulfur batteries may (ASSLSBs) solve. However, ASSLSBs cathodes, typically Li_2S, still have sluggish kinetics and poor electronic conductivity.

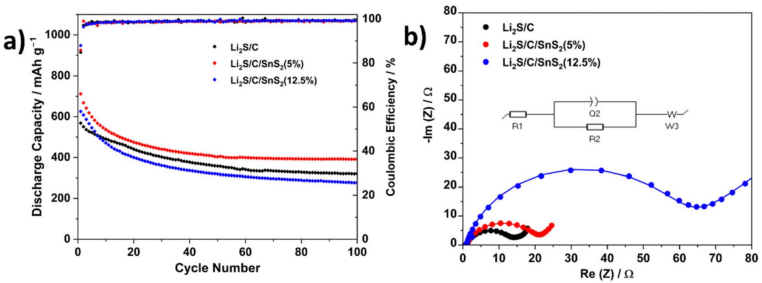
Interfacial Redox Mediator for ASSLSBs

$LiVS_2$ core-shell cathode composites facilitates both electron and Li^+ transport, improving the typically sluggish kinetics of Li_2S reactions. Cells achieved 5.3 mAh/cm^2 at a S mass loading of 10 mg/cm^2. [1]



SnS_2 Additive for Improved Electronic Conductivity

Recent work showed that low amounts of SnS_2 as an additive helps catalyze conversion to Li_2S during charge while also improving electronic conductivity in coin cells. [2]



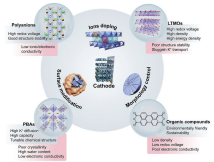
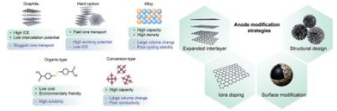
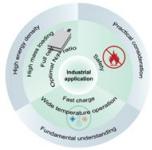
Compositing metal materials into Li-rich sulfur cathodes **improves discharge kinetics, cycle life, and electronic conductivity** in ASSLSBs

Source: [1] Kwok et al., Energy & Environmental Science (2023), [2] Mohammad et al., Energy Advances (2025)

10 Years Development of Potassium-ion Battery

Development status: most improvements are achieved under laboratory conditions (e.g., K metal-based half-cells and low mass loading of active materials), and the performance of PIBs in full cells is still far from the requirements for commercial applications

Recognized weakness: A critical insight bridging the academic research and the commercialization of PIBs is urgently needed to guide future research in this field. More efforts are required to explore the deep mechanism and prompt commercialization of PIBs

Cathode	• PBAs cathode can achieve fast charging and higher capacity, but how to control the water content in the crystal to improve performance is still a challenge • LTMO cathodes show higher operational voltage and higher energy density, but the dissolution of transition metal causes an unstable interface and poor structure stability • Polyanion cathodes show high redox potential, but the poor electronic conductivity limits its rate performance	
Anode	• For the anode, graphite with lower intercalation potential, high CE, less volume expansion, and low cost is the best choice for PIBs. But how to improve cycling stability and rate performance also needs more effort. • Various strategies, including nanotechnology, morphology control, surface modification, and element doping, are proposed to prompt electrochemical performance of electrode materials.	
Application	• All these progresses are still in the academic research and tested under half-cell. More efforts are needed to explore the deep mechanism and prompt commercialization of PIBs, and some possible directions are outlined for future research of PIBs	

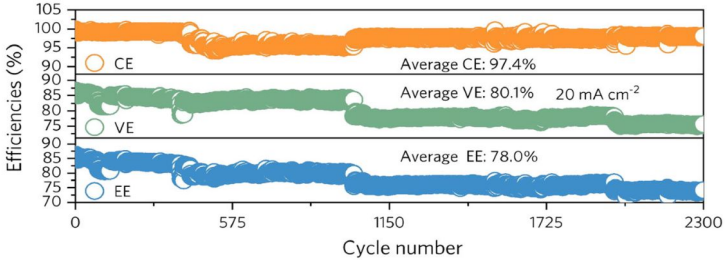
Source: Adv. Mater. 2025, 37, 2416717

Predeposited Pb Nucleation Sites Enable Highly Reversible Zn Electrodes

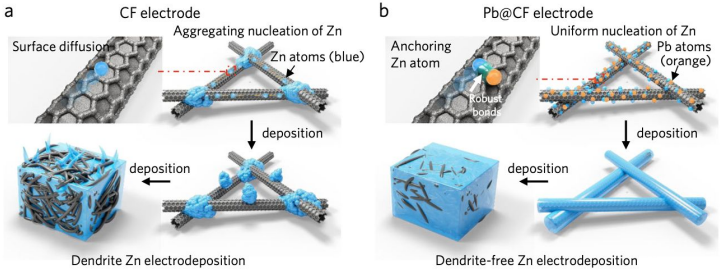
Hu et al. address poor Zn reversibility in aqueous Zn–Br flow batteries by introducing an in situ Pb predeposition strategy that creates uniformly distributed, zincophilic nucleation sites on carbon felt.

The engineered Pb sites pin Zn nucleation, enforce uniform plating, and suppress parasitic hydrogen evolution, enabling dendrite-free Zn growth under high areal capacity operation.

As a result, the modified electrodes sustain 23 Ah cm^{-2} over 2300 h with an average Coulombic efficiency of 97.4%, substantially outperforming unmodified Zn electrodes.



Long-term cycling stability of Zn–Br flow batteries with Pb@CF electrodes.



Pb nanoparticles guide uniform Zn nucleation and dendrite-free growth.

Pb nucleation sites enforce uniform Zn plating, suppress hydrogen evolution, and unlock highly reversible, dendrite-free Zn electrodes at high areal capacity.

Source: Hu, Y., Min, Z., Zhu, G. *et al.*, Nat. Commun., 2025.

Cu-N Redox Cathodes for All-solid-state Fluoride-ion Batteries

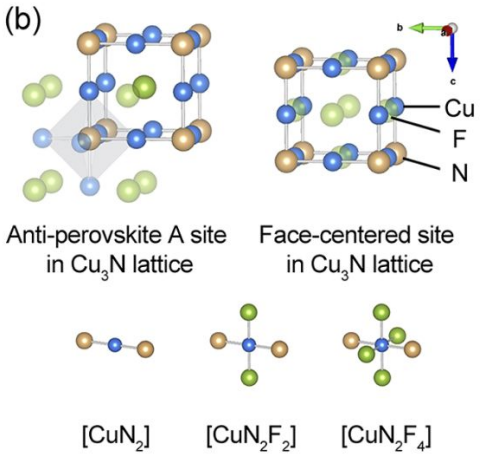
Pb | PbF_2 || F^- (solid electrolyte) || Cu_3N

Zhang et al. demonstrated that **Cu_3N** can function as an intercalation-type fluoride-ion cathode by leveraging its **anti-ReO_3** structure, intrinsic **anion vacancies**, and **linear N–Cu–N coordination.**

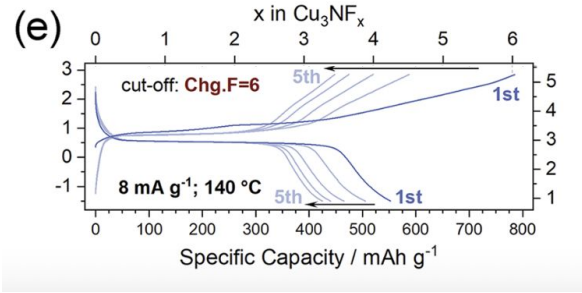
This framework accommodates up to 6 F^- per formula unit, delivering **~550 mAh g^{-1} at 8 mA g^{-1}** in all-solid-state cells operated at 140 °C.

Unlike conventional conversion-based fluoride cathodes, Cu_3N accesses coupled Cu/N redox within a rigid lattice, **enabling high reversible capacity** without catastrophic volume change.

The stabilization mechanism of molecular nitrogen species and the precise crystallographic accommodation of excess fluoride ions at high states of charge remains unclear because the SSE interferes with proper in-situ quantitative XRD analysis.



Fluoride accommodation sites in the Cu_3N lattice during electrochemical fluorination.



Charge–discharge profile of Cu_3N at full fluorination (Chg.F = 6).

Cu_3N enables intercalation-type fluoride storage via coupled Cu-N redox, delivering exceptionally high reversible capacity without conversion-driven volume collapse.

Source: Zhang, D., Yamamoto, K., Cao, Z. et al., J. Am. Chem. Soc., 2025.

Atomic-level Modulated Selenides Lattice for Ultra-stable Rechargeable Aluminum-ion Batteries

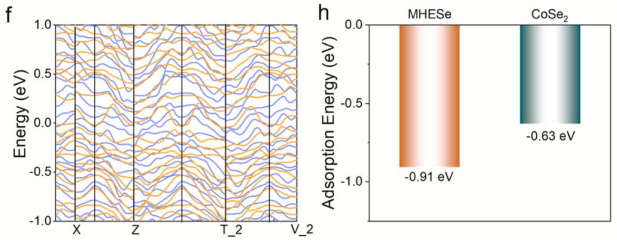
Al | $AlCl_3$-EMICl || Al^{3+} || MHESe

Sun et al. design a **high-entropy selenide cathode ($MHES_e$)** that stabilizes Al^{3+} storage under extreme charge density through atomic-level electronic and structural disorder.

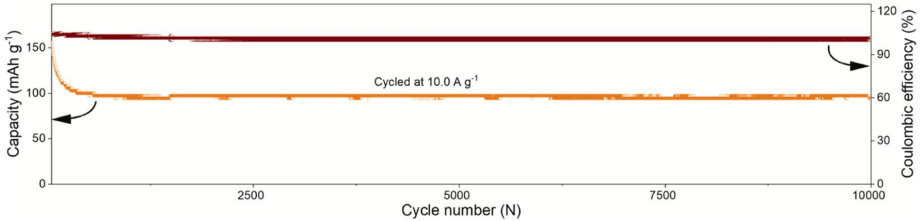
Multi-cation entropy broadens the metal d-band and delocalizes electrons, reducing the Al^{3+} migration barrier from 1.09 eV ($CoSe_2$) to 0.57 eV, **enabling rapid ion transport without lattice fracture.**

Consequently, $MHES_e$ delivers **~155 mAh g^{-1} initially** and retains **~95 mAh g^{-1} after 10,000 cycles** at 10 A g^{-1}, demonstrating ultra-stable, high-rate aluminum-ion storage.

Synthesis relies on a precise, **high-energy ball milling process** under high-purity argon and utilizes **multiple heavy metal precursors**, which may complicate large-scale manufacturing and environmental safety.



f. Density of states of MHESe compared with $CoSe_2$. h.Calculated Al^{3+} adsorption and migration energetics in MHESe and $CoSe_2$.



Long-term cycling stability of MHESe at 10.0 A g^{-1}.

High-entropy lattice engineering enables fast Al^{3+} transport and ultra-stable cycling under extreme charge density.

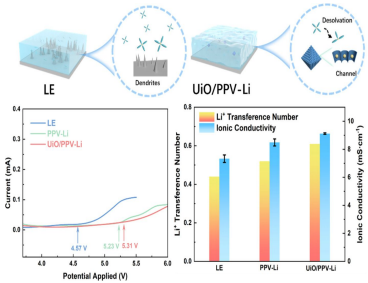
Source: Sun, C., Long, Y., Liu, P. *et al.*, Nano Energy, 2026.

Mktg Approved - DB

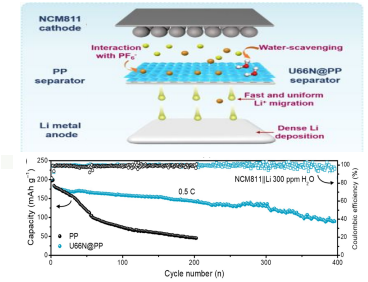
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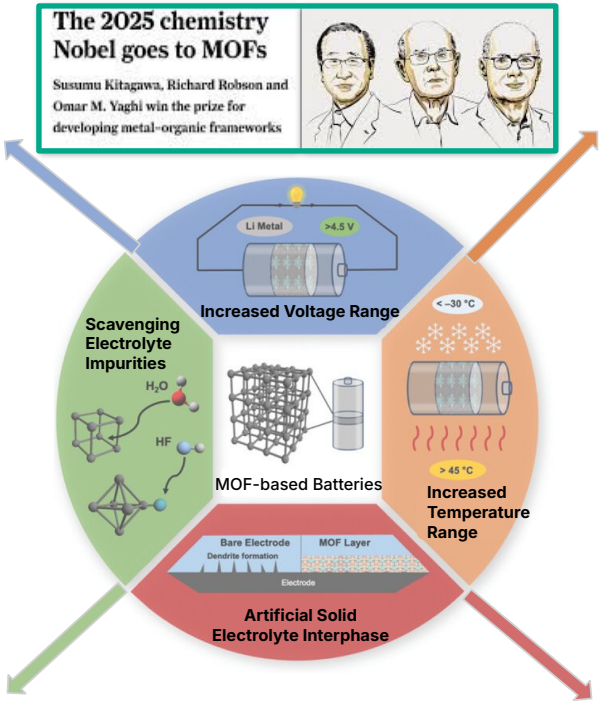
Recent Trend in MOF and Its Derivatives for Energy Storage Applications

UIO/PPV-LI GEL ELECTROLYTE WITH HIGH CONDUCTIVITY, WIDE ELECTROCHEMICAL WINDOW AND FLAME RETARDANCY

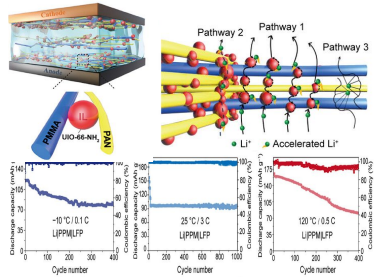


AMINO-FUNCTIONALIZED UIO-66-NH2 SCAVENGES WATER AND STABILIZES NI-RICH LI BATTERIES

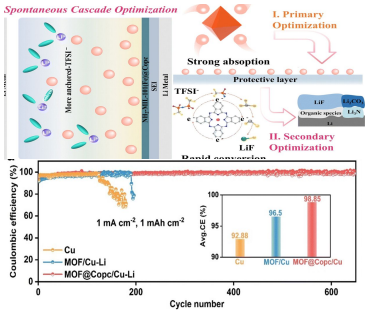




MOF–IONIC LIQUID POLYMER ELECTROLYTES WITH MULTICHANNEL ION TRANSPORT FOR WIDE-TEMPERATURE OPERATION



DUAL ANION–CHARGE ENRICHMENT VIA MOF@COPC ENABLES LIF-RICH SEI FORMATION

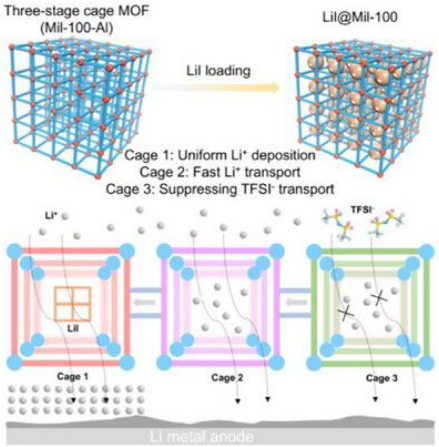


Source: [1] Mu A. U., et al. Adv. Sci. 2024, 11(2), 2305280 ; [2] Xie M.,et al. Energy Storage Mater. 2025, 82,104551 ; [3] Feng L., et al. Adv. Mater. 2025, 37(45), e12360. [4] Wang Y., et al. Energy Storage Mater. 2025, 77, 104217. ; [5] Zhen F., et al. Energy Environ. Sci. 2025, 18(10), 4690.; [6] The 2025 Chemistry Nobel

Halogen-driven Ion Transport Homogenization in 3D Hierarchical MOF for Ultrastable Solid-state LMB

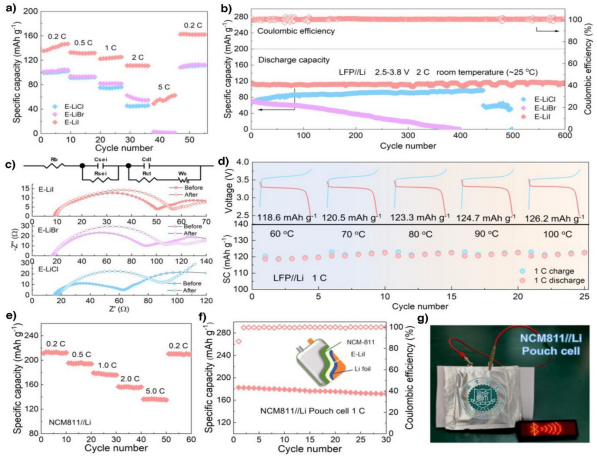
The hierarchical pore channels of MIL-100 confine LiI to form a conductive ionic network, while its triple-level cross-linked multi-stage porous restricts $TFSI^-$ anion mobility, enabling rapid Li^+ transport and uniform deposition by optimizing ion flux and suppressing space charge effects.

The LFP/E-LiI/Li cell delivers **~120 mAh g^{-1}** and maintains **stable cycling for 600 cycles at 2C** without noticeable capacity decay, and also sustains strong performance **at high temperatures (60–100 °C)**. When paired with NCM811, the E-LiI electrolyte enables a pouch cell to exhibit excellent capacity and stable cycling at 1C, successfully powering an LED panel.



MECHANISM

PERFORMANCE



Halogen-engineered 3D MOF electrolytes deliver uniform lithium transport and plating, enabling ultrastable, fast-charging solid-state LMB.

Source: Zhang X., et al. Angew. Chem. Int. Ed. 2025, 64(37), e202511822.

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Research Trends
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New / Alternative Chemistries

Fast Charging & Extreme Fast Charging

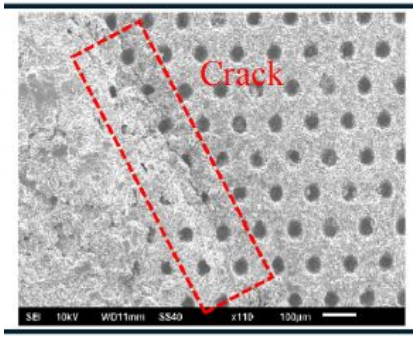
Artificial Intelligence and Machine Learning
Battery Management System (BMS)
Recycling
Battery Safety

Laser Ablation, Carbon Nanotubes and SEI Modification via Customized Formation

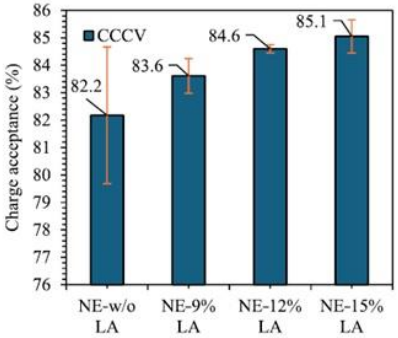
Laser ablation of graphite anode and incorporation of **carbon nanotubes** (CNTs) in NMC811 cathode improves charge acceptance under 10-15 minute fast charge.

- Graphite laser ablation enhances Li^+ ionic transport through lowered tortuosity and improved wetting.
- Using CNTs in NMC811 composite cathode improves electronic conductivity and mechanical rigidity.

GRAPHITE - 12% LASER ABLATION



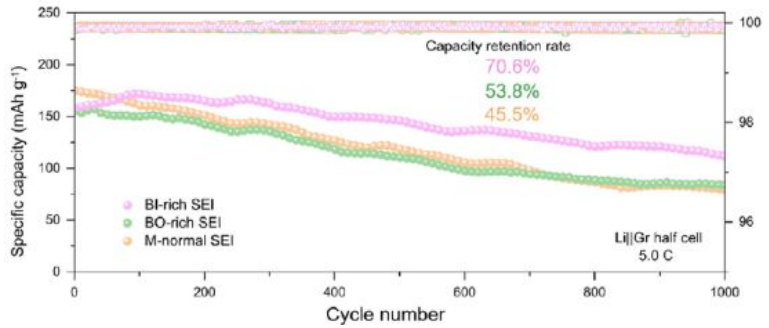
5C CCCV CHARGE ACCEPTANCE



Custom formation cycling of graphite between **1.05V - 2V** including potentiostatic holds promotes formation of inner LiF rich bilayer SEI for enhanced Li^+ transport and mechanical rigidity preventing dendrites.

- Preferential $LiPF_6$ salt decomposition is favored at high potentials in custom formation protocol forming layered SEI.
- Solvent decomposition is favored under traditional formation protocol for mosaic-like SEI.

5C CYCLE LIFE PERFORMANCE



Source: G. Veennam, A. Singh, A. R. Dunlop et al., S. Wu, Y. Zhang, H. Liang et al.

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Research Trends
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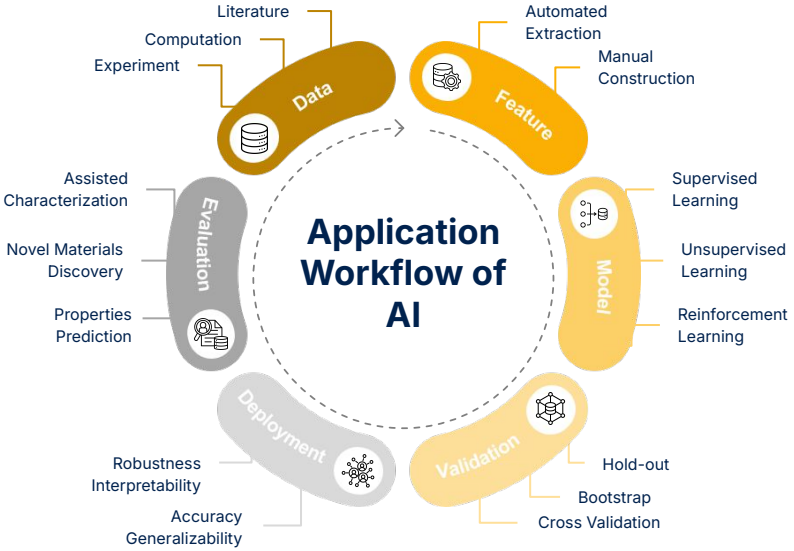
Artificial Intelligence-Driven Development in Rechargeable Battery Materials: Progress, Challenges, Perspectives

What the paper covers:

- Comprehensive review of **AI/ML methods applied across the battery materials lifecycle**, including materials discovery, formulation/process optimization, and performance prediction.
- Focus on electrodes, **electrolytes, interfaces (SEI/CEI), and full-cell performance,** spanning Li-ion and beyond-Li systems

Major challenges:

- **Data scarcity, inconsistency, and bias**, especially for degradation, interfaces, shelf life, and long-term cycling
- Limited **model transferability and interpretability** across chemistries and operating conditions
- Gap among **materials discovery, manufacturing process,** and **cell performance**



Key progress:

- ML models enable **faster screening and design** of cathodes, anodes, and electrolytes using composition-, structure-, and physics-informed descriptors
- Growing integration of **DFT + ML** and **data-driven surrogate models** to reduce computational and experimental cost
- Early success in **property prediction** (voltage, stability, ionic conductivity, cycle life)

Future directions:

- Development of **foundation models**, standardized datasets, and automated data extraction
- **Closed-loop workflows** combining AI, simulation, and (semi-) autonomous experiments
- Greater emphasis on **explainable AI**, uncertainty quantification, and real-world validation

AI is transforming rechargeable battery materials development by enabling closed-loop workflows that integrate data, models, and experiments to accelerate discovery, optimization, and insight generation.

Source: Hu *et al., Advanced Functional Materials*, 2025.

Application-oriented Design of Machine Learning Paradigms for Battery Science

Ying Wang of Fudan University summarizes the current state and possible future directions of machine-learning in battery science, listing key recent advances in:

- High energy density batteries
- Solid-state electrolytes
- Fast-charging electrolytes
- Calendar lifetime prediction
- Recyclability

To further accelerate battery R&D using machine-learning, there are several research frontiers to continue pushing:

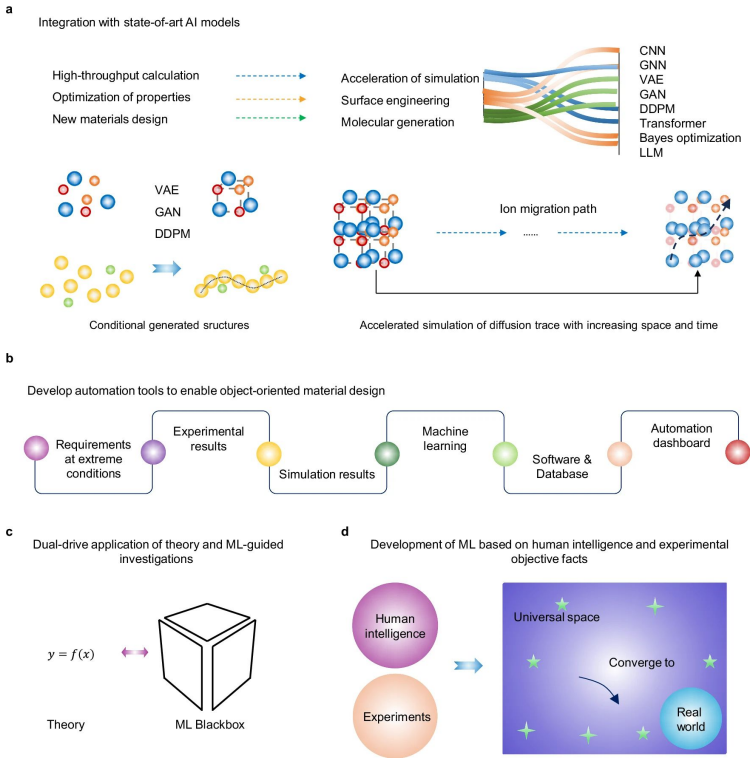
(a) The integration of state-of-the-art AI models for molecular generation and simulation acceleration, including high-throughput calculation, optimization of properties, and new materials design at all length scales.

(b) Developing automation tools by integrating hardware, software, database management, and data analysis and modeling to accelerate discovery.

(c) Coupled development of new analytical theory and physics-informed ML investigations to develop and test new hypotheses.

(d) 'Human-in-the-loop' discovery, using ML guided by hard-to-encode human intelligence and experimental evidence.

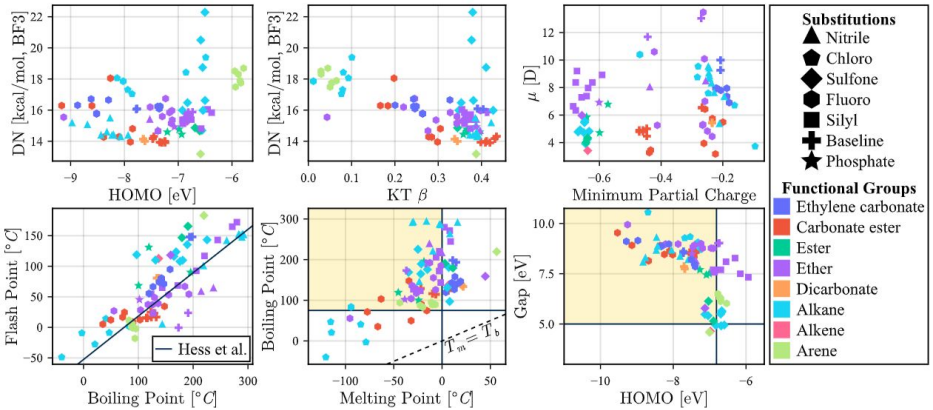
Machine-learning has already transformed battery research, impacting academic and industrial work in nearly all stages of battery development and application. Future progress lies not just in applying the current suite of methods, but also pushing the boundary with new technologies alongside the development of new theory, using automated data collection and modeling to generate and test hypotheses.



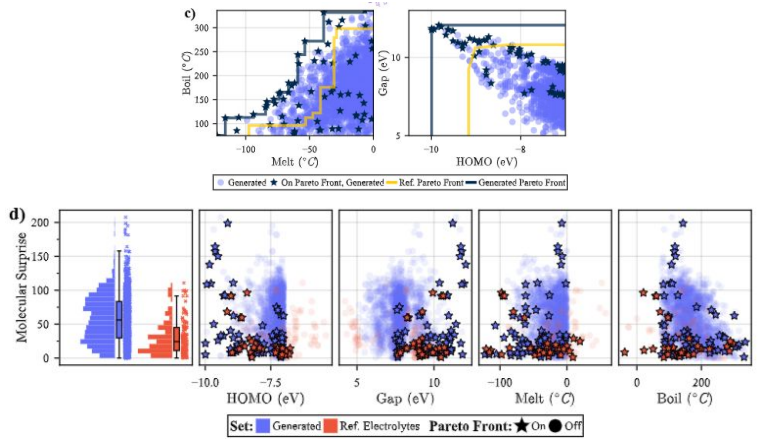
Source: Ying Wang, *npj Computational Materials*, 2025, 11(89)

Foundation Models for Discovery and Exploration in Chemical Space

Molecular foundation models will hopefully accelerate scientific discovery by making the prediction of molecular properties possible at scale, enabling screening of hundreds of millions of candidate molecules for a given application with a relatively small computational cost. Wadell et al not only demonstrate how to implement a molecular foundation model for battery electrolyte discovery, defining a new 'molecular surprise' metric to guide the search for novel compounds, but also describe in detail how to build the data set and train the foundation model in a computationally efficient manner.



Screening of 90 million electrolyte solvent molecules using 8 NVIDIA A100 GPUs in 8 hours (estimated cost of ~$160 to $260 USD on AWS, p4d.24xlarge instance; screened candidates would need further validation using DFT, MD, and experiment). While there is no ground truth for many properties of the evaluated molecules, predicted properties conform to known physical relationships.



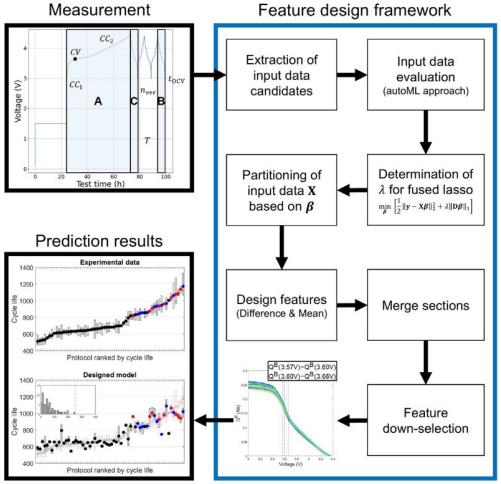
(c) 63 candidates are found that push both chemical and electrochemical stability.
(b) 'Surprising' molecules push boundaries, while many reference electrolytes that are aligned with design rules currently used by electrolyte scientists are less surprising.

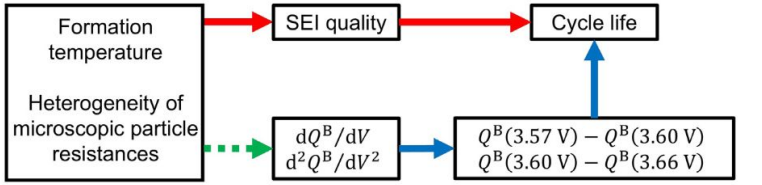
Molecular foundation models enable rapid and cost-effective screening of 100s of millions of molecules to empower the discovery of new materials.

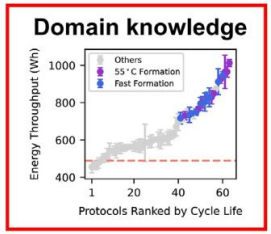
Source: Wadell et al, *arXiv*, 2025, 2510.18900

Systematic Feature Design for Cycle Life Prediction of Lithium-ion Batteries During Formation

Rhyu et al demonstrate how to filter high-dimensional raw current-voltage-time electrochemical data for regions of high statistical significance, produce candidate features and then down select based on domain knowledge, and then finally prune down to data-driven statistical features that can be directly explained by mechanistic models to ensure robustness and potentially allow extrapolation to new materials with minimal data.

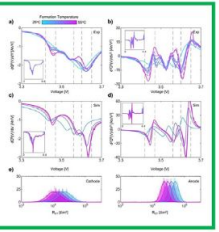


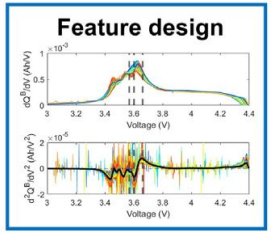




Physics-based investigation

- The impact of temperature and heterogeneity of particle resistances on dQ^B/dV and d^2Q^B/dV^2 curves
- Use **distributed resistance model** under various **formation temperatures**



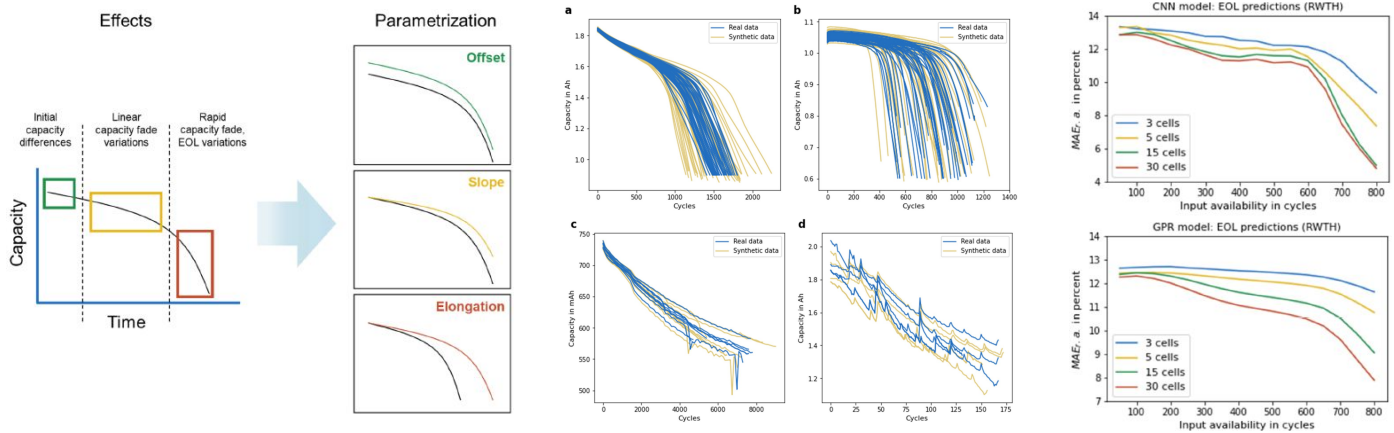


Using only formation data (from Cui et al), cycle life during accelerated aging can be predicted within 10% error using just 2 mechanistically informed features in a random-forest model, directly connecting statistical modeling with theory to enable explainable and trustable predictions.

Source: Rhyu et al, *Joule*, 2025, (9)5, 101884

Fast Data Augmentation to Improve Degradation Trajectory Prediction

Data-driven degradation prediction models can suffer from the inadequacy of high-quality training data. Li et al (2025) mitigated this issue by **generating capacity fade curves synthetically using 3 parameters: Offset** (governs cell-to-cell manufacturing variability), **Slope** (related to the rate of capacity fade) and **Elongation** (determines the occurrence of the "capacity knee" and the EOL). Training datasets were constructed by: (a) **augmenting**, and (b) **partially replacing seed data** (from the lab and field) with synthetic data. The viability of this method was demonstrated by successfully predicting the trajectory with deep and traditional ML models - CNN and GPR, respectively, though its performance in higher dimensional feature spaces remains to be seen.



Cell-testing efforts can be reduced by at least 50% by substituting synthetic data into an existing dataset. The **addition of synthetic data showed an increase in prediction accuracy**, while the partial replacement of real data with synthetic data led to similar model performances using limited data.

Source: W. Li et al., Energy and AI (2025)

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New / Alternative Chemistries
Fast Charging & Extreme Fast Charging
Artificial Intelligence and Machine Learning

Battery Management System (BMS)

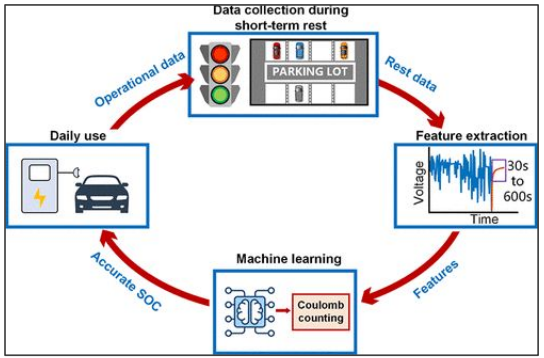
Recycling
Battery Safety

LFP State-of-Charge Estimation: Still a Problem

Challenges for state-of-charge estimation:
Voltage-based method suffers from path-dependent behavior + strong hysteresis + flat OCV plateau
Current-based method suffers from high sensitivity to initial SOC + sensor offset/noise + accumulated error.

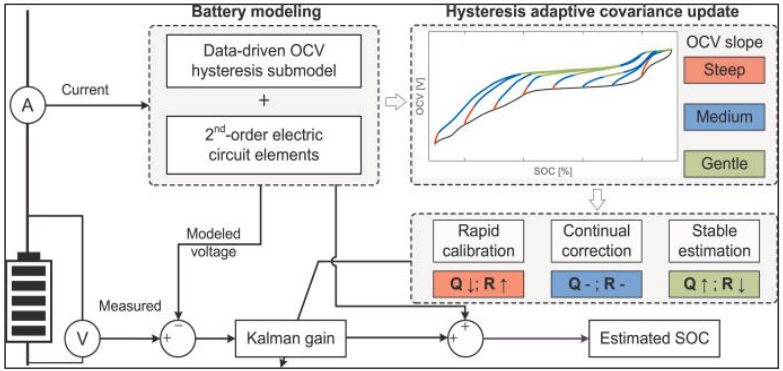
Che et al. keep **current-based method** as the backbone and periodically reset SOC using short (30–600 s) rest segments in normal driving; A ML model uses recent current, voltage, and temperature history to correct the initial SOC

- keep error <3.25% over >430 conditions using only low-frequency signals, suitable for on-board BMS.



Yan et al. propose a **voltage-based hybrid model**: an LSTM hysteresis OCV model (SOC history + temperature) + a 2-RC ECM, with a slope-adaptive Kalman filter that adjusts covariances by OCV slope.

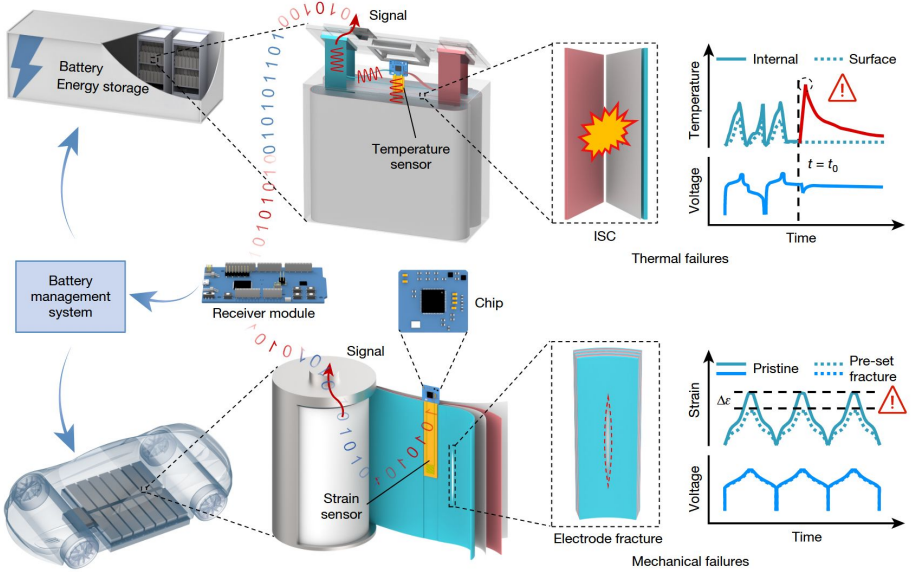
- Across varied temperatures/currents/partial cycles, >95% of samples reach SOC MAE <0.56%;
- RMSE is ≈46% lower than two benchmark state-of-the-art models.



Source: [1] Che et al., ACS Energy Lett., 2025; [2] Yan et al., eTransportation, 2025.

Wireless Transmission of Internal Hazard Signals

- Conventional BMS only “sees” surface signals; many internal thermal/mechanical failures stay invisible until it’s too late.
- This work first shows **a practical, integrable sensor** to monitor internal hazard signals in commercial cells with minimal impact on performance.
- Embed ultrathin temperature and strain sensors plus a tiny chip on current collectors; use the cell tabs for power-line communication (no extra wires or feedthroughs).
- Internal temperature/strain mapping reveals strong non-uniformity and detects electrode fractures and internal short-circuit events much earlier than surface voltage/temperature, providing valuable **extra warning time** for safety control.

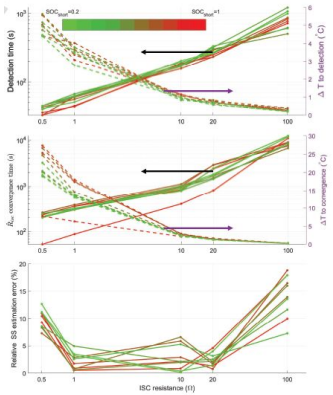


Wireless internal sensing provides a fundamentally new and direct window into battery safety, enabling earlier and more informative detection of internal thermal and mechanical hazards than conventional surface-based BMS signals.

Source: Fan et al. Nature volume 641, pages 639–645 (2025).

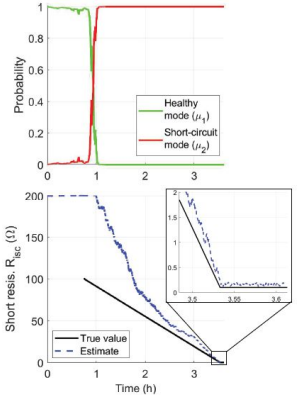
Fault Detection and Short Resistance Estimation in Parallel Connected Lithium-ion Batteries

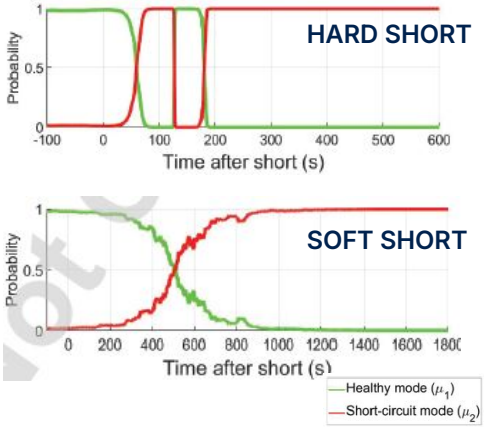
ISC detection in parallel connected cells challenging because in large packs, unmeasured internal currents can obscure charge loss and voltage drop measurements from the faulty cell. Researchers at the University of Michigan used the **Interacting Multiple Model (IMM) technique combined with unscented Kalman filters (UKFs)** to estimate the probability for the occurrence of an ISC and the short-circuit resistance. It relies on dynamic electrothermal models both for the healthy and short-circuit modes to calculate the *mode probability*.



Detection time, temperature rise, and steady state error

IMM's performance with ISC resistance evolving from 100 Ω to 0.1 Ω in ~3hrs





IMM can successfully detect and estimate a wide range of ISC resistances before large temperature rise in a pack (less than 6°C before detection) - validated on 50 synthetic scenarios in which one cell in a 46P pack underwent an ISC during a drive cycle.

Source: H. Movahedi et al., Journal of Dynamic Systems, Measurement, and Control (2025)

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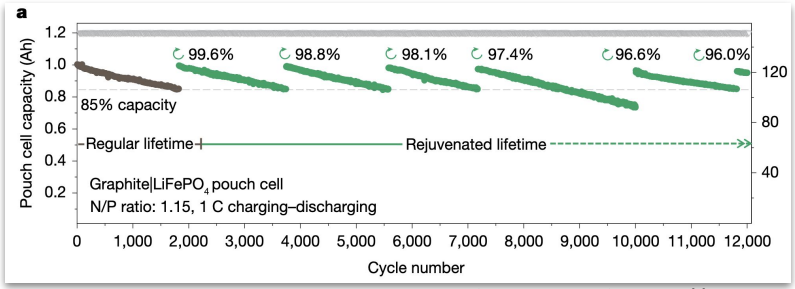
Recycling

Battery Safety

Cell Regeneration by Injection of Lithium Donor

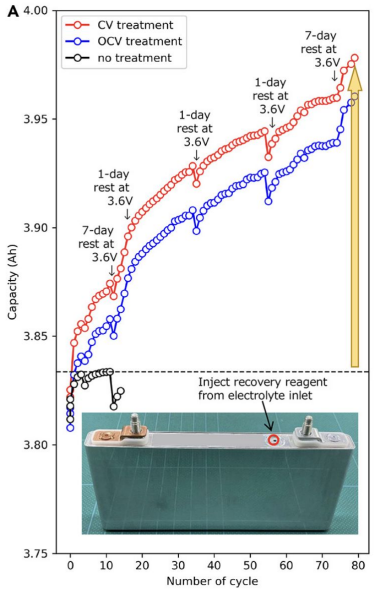
Researchers have introduced a novel method for **regenerating spent cells** by introducing a **lithium donor**

- Introducing salts that **irreversibly liberate lithium ions** into the electrolyte replenishes reserves lost during standard cell formation processes
- Prismatic- and pouch-scale cells can be revived **without any required post processing** or **cell tear down**, streamlining the cell recycling process
- The process has been demonstrated in traditional Li-ion cells, Li-S cells containing SPAN electrodes, and anode-free cells.
- Cell recovery can be further optimized with tailored polarization cycles to re-insert lost lithium



1.0 Ah pouch cell repeated capacity recovery after injection of $LiSO_2CF_3$ [2]

Spent 4.00Ah Graphite|NCM cell recovery after donor injection using different protocols[1]



Injection of lithium donors into spent cells and packs shows promise as a **streamlined, single step method to rejuvenate spent cells after cycling.** Additionally, the method is **cell chemistry independent** and can be further optimized with **cell-specific polarization steps.**

Source: [1] Ogihara et al. Joule (2024), [2] Chen et al. Nature (2025)

Why Material Recovery Matters

Addresses critical raw material scarcity (Li, Co, Ni, Mn), material recovery reduces environmental impact and mining dependence and supports circular economy and sustainable battery manufacturing.

Recovered Materials & Uses

Cathode metals: Li, Co, Ni, Mn → Battery-grade salts (Li2CO3, NiSO4)

Anode materials: Graphite recovery & purification

Current collectors: Cu and Al foils

Electrolyte components: LiPF6 and solvents (partial recovery).

Industry Relevance

Supports EV battery supply chain security

Reduces carbon footprint vs. primary mining

Enables compliance with EU Battery Regulation & ESG targets

Critical for next-generation sustainable batteries

Industry Trends (2025)

Growing adoption of hydrometallurgical recycling for higher recovery efficiency

Rise of direct cathode regeneration for LFP &

LMO-based batteries
Integration of automation and AI for cell sorting & process optimization.

Source: [1] Asad ali et al, j.jenvman. 2025, 391, 126512; [2] Xiaotu Ma et al, *Nat. Rev. Clean Technol.* 2025, 1, 75–94; [3] BK Biswal et al, *Chem. Soc. Rev.*, 2024, 53, 5552-5592.

Material Recovery: Key Approaches

Physical Pre-treatment

Discharging, shredding, and separation

Recovery of:

- Cu & Al foils
- Black mass (Li-Ni-Co-Mn rich fraction)
- Graphite

Hydrometallurgy

Acid/alkaline leaching of black mass selective separation via:

- Solvent Extraction
- Precipitation
- Ion exchange

Recovers Li, Ni, Co, Mn with high purity

Most widely adopted industrial route

Pyrometallurgy

High-temperature smelting (>1200 °C)

Recovers: Ni, Co, Cu (alloy phase)

Limitations:
Lithium mostly lost to slag
High energy consumption
Limited compositional control

Direct Regeneration

Preserves cathode crystal structure

Re-lithiation and surface reconstruction

Benefits:

- Lower energy input
- Higher value retention

Challenges:

- Feedstock variability
- Process scalability

Source: [1] Asad ali et al, j.jenvman. 2025, 391, 126512; [2] Xiaotu Ma et al, *Nat. Rev. Clean Technol.* 2025, 1, 75–94; [3] BK Biswal et al, *Chem. Soc. Rev.*, 2024, 53, 5552-5592.

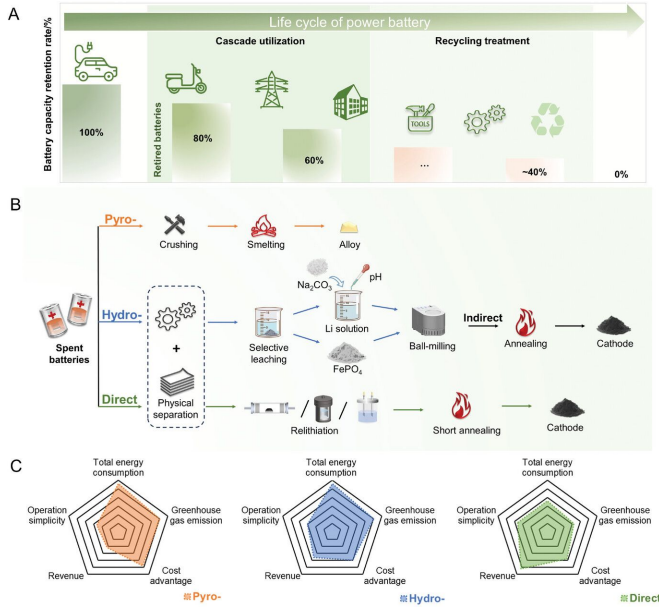
Life Cycle of Lithium Iron Phosphate (LFP)

This review by J. Yan et al summarizes the life cycle of LFP, noting the key economic and environmental advantages that can be achieved using a direct regeneration recycling approach, as opposed to older pyrometallurgical and hydrometallurgical recycling methods.

Spent LFP, after its first, second, or multiple cascading uses, may be direct recycled through either extraction from the cell, separation, and processing, or through simply supplementing a cell's lithium inventory. Specific mechanisms for LFP degradation are reviewed and used to explain the pros and cons of these various direct recycling strategies.

The status of various direct recycling and upcycling of LFP into LMFP technologies are summarized, with alternative directions discussed.

LFP batteries retain value throughout their life cycle - from use and cascade reuse to end-of-life recycling, with **direct regeneration** enabling the **most economical and sustainable** closure of the loop. Many possible direct regeneration approaches exist.



A) The full life cycle of LFP power batteries.

B) Schematic diagram of three recycling methods for spent LFP batteries: **pyrometallurgy** (Pyro-), **hydrometallurgy** (Hydro-), and **direct regeneration** (Direct).

C) Radar charts of three recycling methods for spent LFP batteries: pyrometallurgy ("Pyro-"), hydrometallurgy ("Hydro-"), and direct regeneration ("Direct").

Source: J. Yan, J. Qian, Y. Li, L. Li, F. Wu, R. Chen, Toward Sustainable Lithium Iron Phosphate in Lithium-Ion Batteries: Regeneration Strategies and Their Challenges. Adv. Funct. Mater. 2024, 34, 2405055.

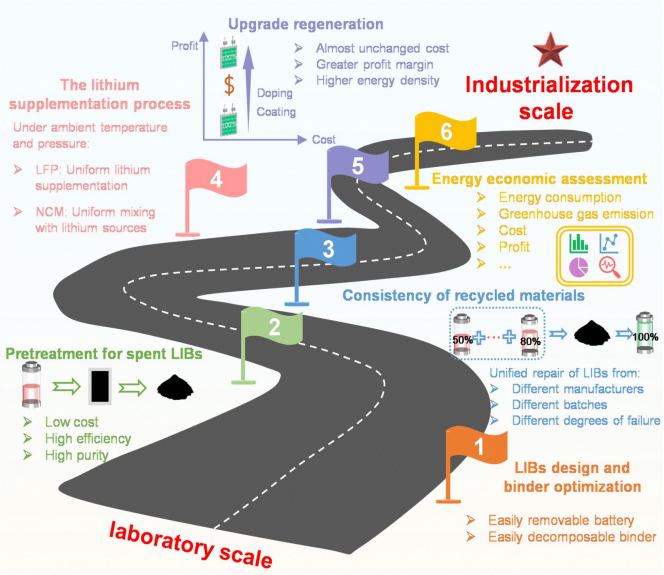
Direct Regeneration of Cathodes

Importance of direct regeneration

- Lower energy consumption compared to hydrometallurgy/pyrometallurgy.
- Preserves the crystal structure and morphology of cathode materials.
- Reduces chemical waste and processing steps
- Enables high-value recycling of LFP, LMO, NMC, NCA, LCO.

Economically viable: Lower energy consumption vs. conventional routes.
Technically superior: Preserves crystal structure enabling multi-chemistry recycling.
Environmentally sustainable: Minimal waste and reduced processing complexity.

ROAD MAP FOR LAB TO INDUSTRIAL SCALE



Source: [1] Runxin wang et al. *J. Mater. Chem. A*, 2026, 14, 909-935; [2] Changhao Li et al. *Mater. Horiz.*, 2025,12, 4065-4091



Can We Make Battery Recycling Safer and Smarter?

UL Research Institutes' Electrochemical Safety Research Institute is at the forefront of safe lithium-ion battery recycling.

Discover our pioneering recycling research aimed at preserving the integrity of cathode materials using eco-friendly solvents, and how we turn science into action by sharing knowledge and raising awareness about safe recycling.

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Scan to learn more about our research or visit:
UL.org/ESRI
NFP.ElectrochemicalSafety@UL.org

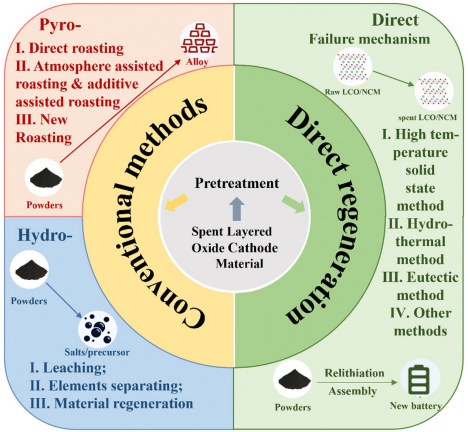
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Direct Regeneration of Cathodes (Cont.)

Regeneration Mechanisms

- Lithium re-insertion into depleted cathode lattice.
- Reduction of Mn^{3+} to Mn^{4+} (in LMO) to suppress Jahn–Teller distortion.
- Grain boundary healing during annealing.
- Surface passivation for improved stability.

CONVENTIONAL RECYCLING V/S DIRECT REGENERATION OF CATHODES



Source: [1] Runxin wang et al. *J. Mater. Chem. A*, 2026, 14, 909-935, [2] Changhao Li et al. *Mater. Horiz.*, 2025,12, 4065-4091

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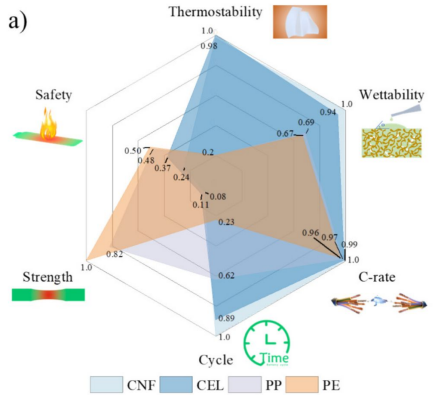
Battery Safety

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Separator Safety Improvements

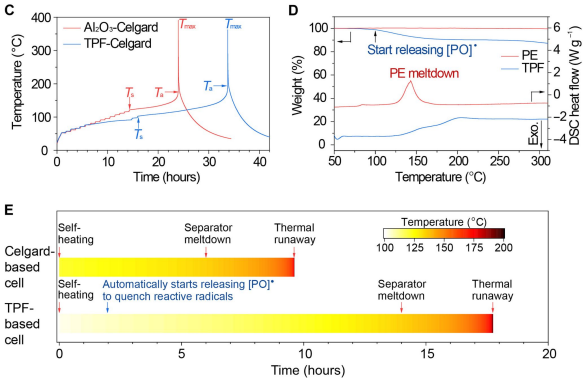
Comparing separator materials in commercial cell formats

In cylindrical 21700 cell formats made from cellulose (cel) and cellulose nanofibers (cnf) show improved performance and thermal stability metrics, however additional functionality is still required to match the strength and safety of polyolefin materials. [1]



Modifying commercial separators: smart membranes that resist thermal runaway

Engineering separators coated with polymeric materials that are engineered to react with thermal runaway products dramatically increase the time to thermal runaway. [2]



Modifying commercial separators with novel materials **extends thermal runaway windows**, and thus overall cell safety, **more than next-generation separator materials** such as cellulose or cellulose nanofibers.

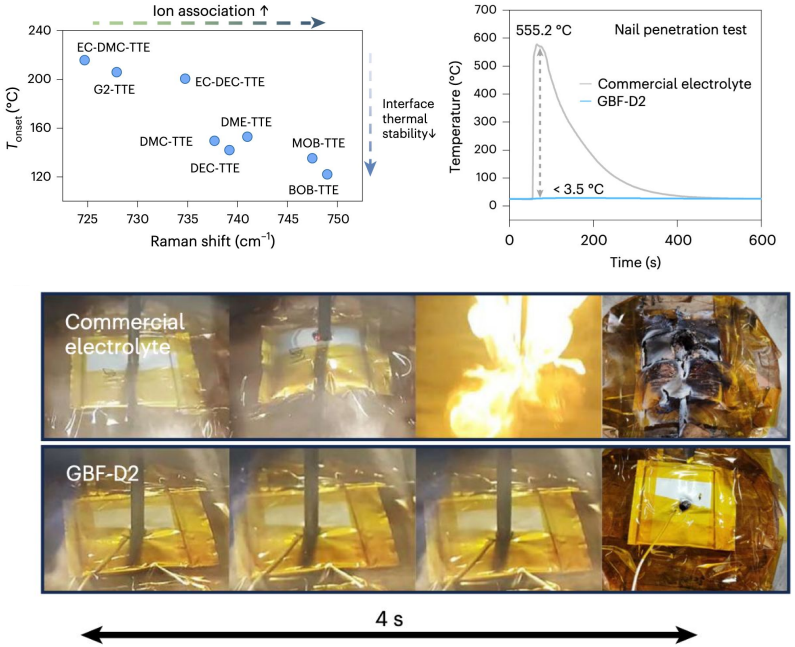
Source: [1] Yang et al. Journal of Energy Storage 112 (2025), [2] Zhang et al.,Sci. Adv. (2023)

Improving Electrolyte Safety with Solvent Design

Converse to traditional electrolyte design heuristics, **weakly solvating electrolytes** were shown to **dramatically decrease flammability and thermal runaway** in Li-ion cells

Creating an electrolyte with weak Li ion solvation at low-temperature and strong, irreversible Li solvation at high temperature isolate reactive species during thermal runaway.

After examining 20 solvent-ion pairs, a two-solvent system of 1-methoxybutane (MOB) and diglyme (G2) with 1M LiFSI showed improved capacity retention during cycling and dramatic reduction in temperature evolution during nail penetration tests.



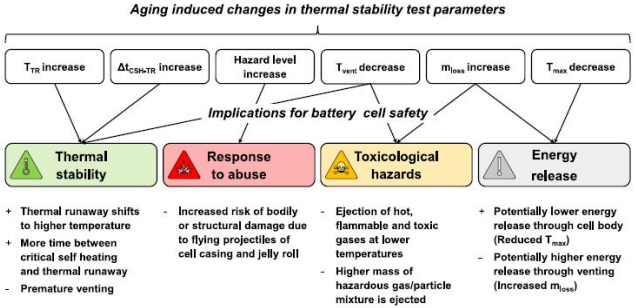
Solvent systems with **weaker, temperature dependent** Li ion solvation can be used to make **inherently safer, commercially relevant Li-ion batteries.**

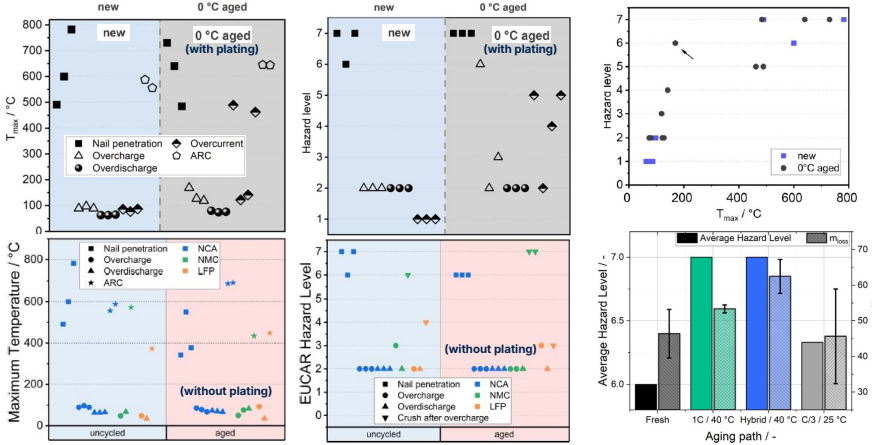
Source: Sun et al, Nat Energy (2025)

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Safety of Aged Cells vs. Fresh Cells

Commercial NCA, NMC and LFP cells were comprehensively assessed to understand how the reactivity of cells in the presence and absence of lithium plating - induced by cycle aging at 0 °C & 45 °C, respectively - affected the results of safety testing methods: mechanical (nail penetration, crush), electrical (overcharge, overdischarge), and thermal (accelerating rate calorimetry or ARC) abuse tests. Their findings emphasize the need to **examine aged battery safety across diverse empirical techniques, degradation modes, and chemistries**.





Aged cells with dominant Li plating exhibit decreased safety behavior, while those with dominant SEI growth behave similar to uncycled cells, with the exception of having a higher likelihood of causing **Hazard Level 7** (unhindered venting of gases during thermal runaway).

Source: [1] Y. Preger et al., Journal of the Electrochemical Society (2025), [2] G. G. Gerosa et al., Journal of the Electrochemical Society (2025), [3] D. Stiller et al., Journal of Power Sources (2025)

TALENT

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Volta Foundation is the world's largest network of battery professionals. As a global not-for-profit association, Volta Foundation produces publications, networking opportunities, and industry resources to foster collaboration, innovation and advocacy within the battery industry.

Executive Summary

Scale Is Accelerating

Europe's battery supply chain is expected to grow from 62,000 jobs today to 200,000–300,000 by 2030.

In the US, the industry is projected to add 84,000–125,000 jobs by 2032.

Globally, the battery value chain could support 5–10 million additional jobs by the end of the decade.

Demand Is Diversifying

Near-term EV market volatility is moderating EV-specific hiring, but global battery consumption is still expected to double between 2025 and 2030.

Hiring demand is broadening beyond EVs, with faster growth in battery recycling, grid-scale and distributed energy storage, advanced chemistries, and digitally enabled manufacturing.

Skills Are the Constraint

More than 80% of manufacturers report difficulty finding qualified candidates, especially in manufacturing, process engineering, automation, and applied technical roles.

Gaps in workforce readiness and uneven training pipelines are becoming structural barriers to scaling production.

Capability Is the Advantage

In response, leading companies are reorganizing around cross-functional, digitally enabled teams that combine chemistry, engineering, software, automation, and sustainability.

As hiring expands but skills gaps persist, organizations that invest in adaptable, continuously learning teams are likely to gain a lasting competitive edge over the next decade.

How to Read This Section

This section is designed as a reference guide to **workforce and talent dynamics in the battery industry in 2025.** Readers can jump to different subsections depending on their interests.

- Battery Training and Workforce Development Highlights
  Discover institutions leading workforce development and training around the world.
- Explore Emerging Trends
  Understand where hiring demand is moving beyond electric vehicles.
- Policy and Immigration
  Learn about developments in US immigration policy and their impact on current and future battery workforce.
- Compensation, Benefits, and Industry Sentiment
  Uncover trends on pay dynamics, mobility, and retention pressures affecting hiring outcomes.
- Skills and Training Gaps
  See where workforce readiness is lagging industry needs and why talent availability is becoming a structural bottleneck.
- Workforce Development, Education, Research, and Access & Advancement
  Get an overview of training programs, career pathways, workforce research, and inclusion efforts shaping the future talent pipeline.

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Workforce Landscape
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Compensation & Benefits
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Workforce Research
Access & Advancement

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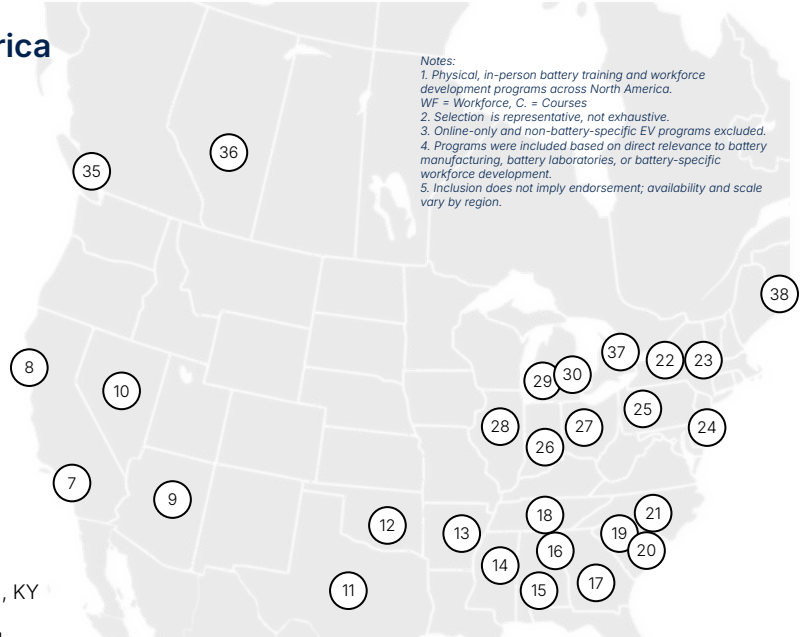
Workforce Landscape

Emerging Trends
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Industry Sentiment
Skills & Training Gaps
Educational Development
Workforce Research
Access & Advancement

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Battery Training & Workforce Development Highlights in North America

North America is growing battery manufacturing and recycling capacity, driving demand for technicians, engineers, and production leadership across the value chain. Workforce initiatives are increasingly **anchored around national labs, industry consortia, colleges, and regionally funded training programs** tied to gigafactory and recycling ramp-ups.



USA

National

1 DOE – Battery Workforce Initiative (BWI)
2 NAATBatt – Workforce Committee
3 Argonne National Labs – Battery WF Challenge
4 National Renewable Energy Laboratory (NREL)
5 SAE International – Battery Training
6 National Fire Protection Association (NFPA)

West Coast

7 UC San Diego SPEC – Battery Boot Camp, CA
8 Electrochemistry Foundry – Workforce Training, CA
9 Future48 – Workforce Accelerator, AZ
10 Nevada Tech Hub – Workforce Development NV

South & South East

11 Universal Technical Institute (UTI) – Battery, TX
12 Tulsa Tech – Battery Recycling, OK
13 LithiumLearns & LithiumWorks, AR
14 AccelerateMS – Battery Training, MS
15 AIDT – EV & Battery Manufacturing Support, AL
16 Alabama Mobility and Power (AMP). AL
17 Georgia Quick Start – Battery WF Training, GA
18 ORNL – Battery Manufacturing Facility, TN
19 Carolina Battery Institute, SC
20 readySC – Battery Manuf. WF Training, SC
21 NC Com. College System – LIB Program, NC

East Coast & Midwest

22 NENY – Battery Academy, NY
23 Energy Storage Engine, NY
24 NJ Clean Energy – WF Development Training, NJ
25 Penn State – BEST, PA
26 Battery Innovation Center (BIC), IN
27 Ohio State – BATTERI, OH
28 Argonne Natl Lab – Battery Training Hub, IL
29 U-M – Battery Lab, MI
30 Henry Ford College (HFC) – Batter Curriculum, MI
31 Elizabethtown Community & Technical College (ECTC), KY

CANADA

32 Canadian Battery Innovation Center (NRCan), National
33 Upskill Canada / Palette Skills – Battery Boost, National
34 Clean Energy Safety and Training Council (CESAT), National
35 UBC Okanagan – Battery Innovation Centre, BC
36 Western Canada – Battery Consortium (WCBC), AB
37 St. Clair College (Windsor) – Battery Manufacturing Curriculum, ON
38 Canadian Battery Innovation Centre (CBIC), Halifax, NS

MEXICO

39 Technológico de Monterrey
40 GIZ & CAMEXA
41 PEM & RWTH
42 Tecnológico Nacional de México
43 Instituto Politécnico Nacional (IPN)

This slide shows original research conducted by Battery-News.com. Sources include European Commission & EU programme portals, EIT InnoEnergy / European Battery Alliance Academy, ALBATTS & VOLTAGE project platforms, national ministries and public workforce agencies, applied research institutes and pilot lines, universities and VET providers, and official programme websites and announcements (2023–2025).

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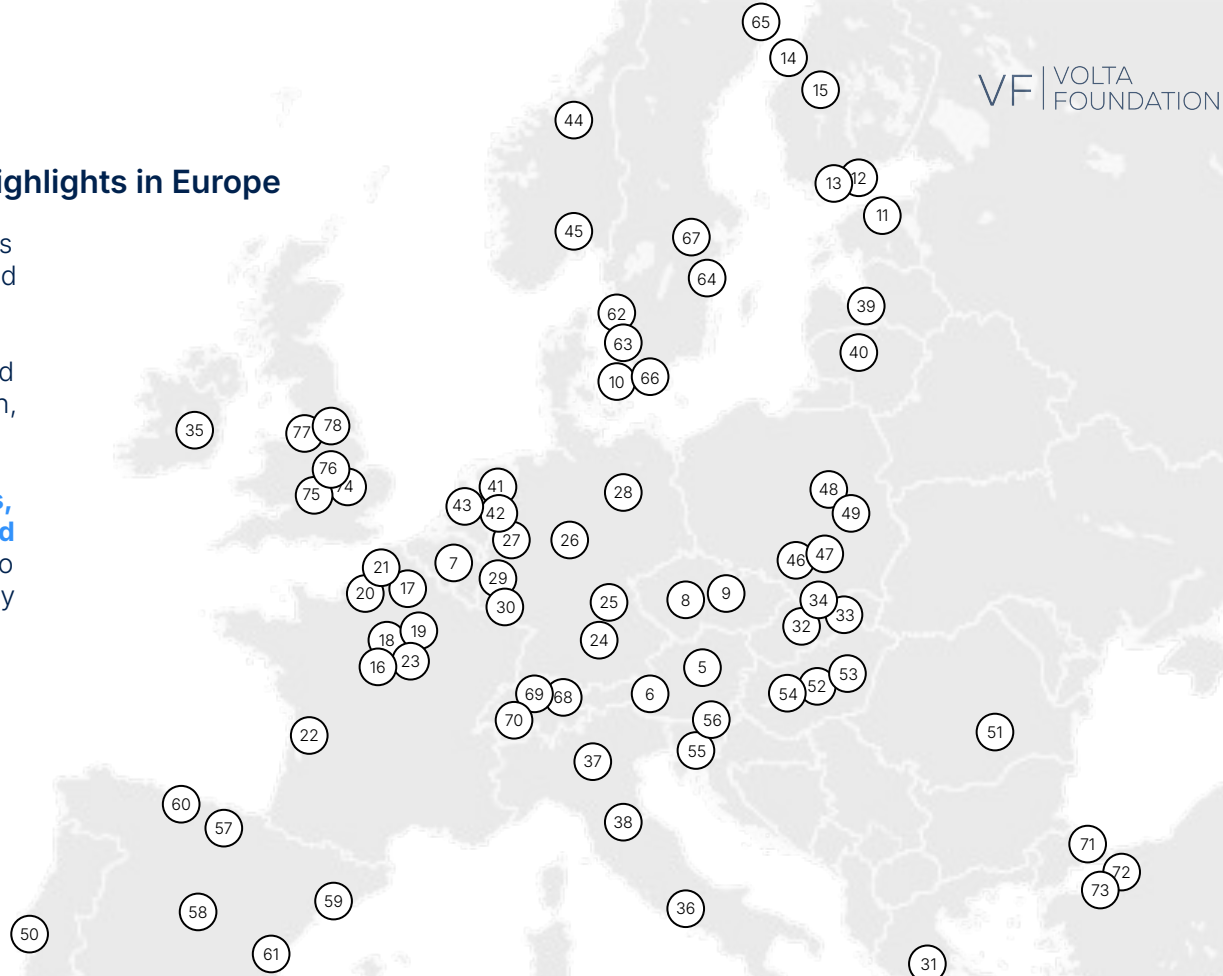
Battery Training & Workforce Dev. Highlights in Europe

Europe's battery workforce development is strongly shaped by industrial scale-up and regulation-driven localization.

Training initiatives are concentrated around cell manufacturing, pack & BMS integration, and recycling.

Initiatives are anchored **industrial alliances, pilot lines, technical universities, and publicly funded training programs** linked to gigafactory ramp-ups and circular-economy requirements.

1 — 78



The corresponding training and workforce development programmes are presented on the following page.

This slide shows original research conducted by Battery-News.com. Sources include European Commission & EU programme portals, EIT InnoEnergy / European Battery Alliance Academy, ALBATTS & VOLTAGE project platforms, national ministries and public workforce agencies, applied research institutes and pilot lines, universities and VET providers, and official programme websites and announcements (2023–2025).

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Battery Training & Workforce Development Highlights in Europe

EUROPEAN LEVEL (EU)
1 BattValue - Professional Courses
2 European Battery Business Club (EBBC)
3 INNO Energy & EBA Academy
4 VOLTAGE – Vocational Training

Austria
5 Materials Center Leoben (MCL) – Materials
6 Technical University Graz – Safety Courses

Belgium
7 EnergyVille – Battery Trainings

Czechia
8 CEITEC – Battery Materials & WF Training
9 Czech Battery Cluster – WF & Skills Program

Denmark
10 Danish Battery Society – Battery Trainings

Estonia
11 TalTech – Battery Applied Teaching

Finland
12 Aalto University – Battery Industrial Courses
13 Finnish Minerals Group – Value Chain C.
14 University of Oulu – Battery Courses
15 VTT – Battery Battery Technologies

France
16 CEA Liten – Battery Training Courses
17 Douvrin Battery Training Center
18 IFP Training – Battery Manufacturing
19 INSTN – Battery Training Courses
20 L'Ecole d.I. Batterie – Battery Manufacturing
21 PFA – Electro'Mob WF & Skill Development
22 Université de Bordeaux – Summer School
23 UIMM – Vocational Battery Training Programs

Germany
24 B3 – Bavarian Battery Education Network
25 BayBat – M.Sc. Battery.Materials & Technology
26 Battery LabFactory Braunschweig
27 Fraunhofer FFB – European Learning Lab Bat.
28 KOMBiH – Battery Qualification
29 PEM Motion – Battery Training Metro
30 RWTH Aachen – M.Sc. Bat. Science & Techn.

Greece
31 CERH – Professional Training

Hungary
32 Óbuda University – Battery Manufacturing C,
33 University of Debrecen – Battery Training C.
34 University of Miskolc – Practical Training

Ireland
35 Engineers Ireland – Battery Trainings C.

Italy
36 ENEA TEMAF – Material Characterization
37 Politecnico di Milano – Battery WF Upskilling
38 Unibo – M.Sc. in Battery Ecodesign

Latvia
39 Riga Technical University – Applied Education

Lithuania
40 Kaunas University – Engineering Program

Netherlands
41 BatteryNL – Next Generation Education
42 Holst Center – Battery WF Upskilling
43 TU Delft - Battery & Energy Storage Courses

Norway
44 NTNU – Engineering Education
45 SINTEF – Battery & Energy Storage Training

Poland
46 AGH – Li-ion Battery Technoloy Course
47 Jagiellonian University – Battery Chemistry
48 NobleProg – LIB Training Course
49 MEERI – Advanced Battery Training Courses

Portugal
50 ATEC Academia de Formação – Sector Train.

Romania
51 POLITEHNICA Bucharest – BMS Education

Slovakia
52 InoBat Academy – Training Programs
53 SARIO – Battery Workforce Initiatives
54 Technical University of Kosice – Bat. Training

Slovenia
55 National Institute of Chemistry – Courses
56 University of Ljubljana – Advanced Batteries

Spain
57 CIC energiGune – Basque Battery Hub C.
58 CSIC – Battery Storage Applied Training
59 IREC – Battery Courses
60 Kirleo – Battery Schhol
61 University Jaume – Batter Training

Sweden
62 Chalmers – Battery Courses
63 GTC – Battery Centre Gothenburg
64 KTH – Battery Specialization
65 Lulea Tech. University – Battery Prod.
66 RISE – Battery WF Upskilling
67 Uppsala University – Battery Courses

Switzerland
68 EMPA – Battery Storage Training
69 ETH Zurich – Battery Education
70 Innosuisse – Battery Skills and WF

Turkey
71 Pendik Borsa – Vocational Awareness
72 Sabanci University – Battery Campus
73 TÜBITAK RUTE – Streams Skills Hub

United Kingdom
74 ECT - Battery Courses
75 Faraday Institution – Skills & Trainings
76 National Bat. Training & Skills Academy
77 UKBIC – Hands-on Trainings
78 Warwick Manufacturing Group – Bat C.

Notes:
1. Physical, in-person battery training and workforce development programs across Europe. WF = Workforce, C. = Courses
2. Selection is representative, not exhaustive.
3. Online-only and non-battery-specific EV programs excluded.
4. Programs were included based on direct relevance to battery manufacturing, battery laboratories, or battery-specific workforce development.
5. Inclusion does not imply endorsement; availability and scale vary by region.

This slide shows original research conducted by Battery-News.com. Sources include European Commission & EU programme portals, EIT InnoEnergy / European Battery Alliance Academy, ALBATTS & VOLTAGE project platforms, national ministries and public workforce agencies, applied research institutes and pilot lines, universities and VET providers, and official programme websites and announcements (2023–2025).

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Heatmap for Battery Jobs - Qualitative Outlook of Job Creation Potential by Region & Value-Chain Segment

Region	*Role*	Raw Material	Active Material	Cell	Pack & BMS	Application EV	Application BESS	2nd-Life & Repair	Recycling
Asia	Mgmt	++	+++	+++	+++	+++	++	+	++
	R&D	++	+++	+++	++	+++	++	+	+++
	Prod	++	+++	+++	+++	+++	+++	++	++
Europe	Mgmt	+	++	++	+++	++	++	++	+++
	R&D	++	++	+++	+++	+++	+++	++	+++
	Prod	+	++	++	+++	++	++	+	++
North America	Mgmt	++	++	++	+++	++	+++	++	+++
	R&D	++	++	++	+++	++	++	+	++
	Prod	+	++	++	+++	++	+++	+	+++
Central & South America	Mgmt	++	+	+	+	+	++	+	+
	R&D	++	+	+	-	-	+	-	+
	Prod	++	+	+	+	+	+	+	+
Africa & Middle East	Mgmt	++	+	+	+	++	++	+	+
	R&D	++	-	+	+	++	+	-	+
	Prod	++	+	+	++	+	++	+	++

The **heatmap shows clear regional specialization in battery job creation.** Asia dominates across most value-chain segments, while Europe and North America show growing employment in manufacturing, integration, and recycling driven by localization policies. Africa and South America remain concentrated in upstream raw materials with limited downstream industrialization.

The **assessment reflects** announced and operational capacity, project pipelines, investment activity, and policy frameworks. Upstream ratings capture resource availability and processing intensity, while downstream ratings reflect growth in electric mobility, BESS, and circular-economy activities.

Relative Job Creation Potential*

-	+	++	+++
low	*moderate*	*high*	*very high*

Mgmt *– Management, commercial, integration*
R&D *– Research, engineering, development*
Prod *– Manufacturing, operations, technicians*

* Ratings reflect relative job creation intensity by region, role, and value-chain segment; they do not indicate technological leadership or absolute employment levels.

This slide shows original research conducted by Battery-News.com. Sources include PEM Motion analysis [IEA; U.S. DOE & NREL; European Commission; Natural Resources Canada; industry associations; public project announcements and (2023–2025)]

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Battery Workforce Outlook

U.S. / North America

The U.S. battery industry for light-duty vehicle batteries, manufacturing, and recycling, is projected to create **84,000 to 125,000 domestic jobs by 2032**, according to the ICCT.

Europe

The battery supply chain in Europe currently supports ~62,000 jobs and could grow to **202,800 to 312,000 jobs by 2030**, according to New Automotive.

Global / Asia / Sub-Sectors

Globally, the battery value chain could sustain **5 to 10 million additional jobs by 2030**, according to the World Economic Forum, the Global Battery Alliance and Worldmetrics (2025).

The global battery industry's ability to scale will hinge increasingly on workforce availability and capability.

Source: 1.New Automotive 2.The ICCT 3.World Economic Forum 4.Worldmetrics,

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The Battery Workforce Landscape: Rising Demand in High Growth Sub Sectors

The battery industry's long-term trajectory is no longer anchored solely to EVs. Fast-growing segments, including battery recycling, energy storage and advanced chemistries, are expanding rapidly and reshaping where workforce needs are emerging.

Market Segment	Trend in 2025	Roles Affected
Electric Vehicles	Temporarily softening of EV sales, policy, and capital, complicate near-term role creation.	EV assembly technicians, vehicle-integrated pack engineers, automotive battery designers, test technicians
Grid Storage & Integration	Accelerating as renewables penetrate global power systems and AI data demand surges.	Systems & BESS integration engineers, controls/software engineers, safety & compliance specialists
Battery Recycling & Circularity	New roles driven by materials scarcity, stricter regulation, and materials scarcity.	Recycling process engineers, materials recovery specialists, environmental & sustainability analysts
Advanced Chemistries	New material developments enable new applications & shifting manufacturing needs.	Materials scientists & electrochemists, cell R&D and prototyping engineers, validation/QA specialists
Gigafactory Operations & Ramp-Up	Mass industrialisation beyond prototype stages requires new skill pipelines.	Manufacturing process engineers, production engineers, equipment maintenance, validation/QA specialists
Cross-Functional and Hybrid Roles	Multi-disciplinary teams blending chemistry, engineering, software, are sought after.	Systems engineers, techno-economic analysts, hybrid electrochemistry-software-automation specialists
Digital Manufacturing & Automation	Smart factories and digital twins enable further cost-downs necessary for competition.	Automation engineers, simulation/digital-twin specialists, MES/data engineers, APC experts
Battery Management & Software	Increasing system complexity and lifetime demands warrant advanced diagnostics.	Embedded software, firmware, diagnostics and sensor-integration engineers

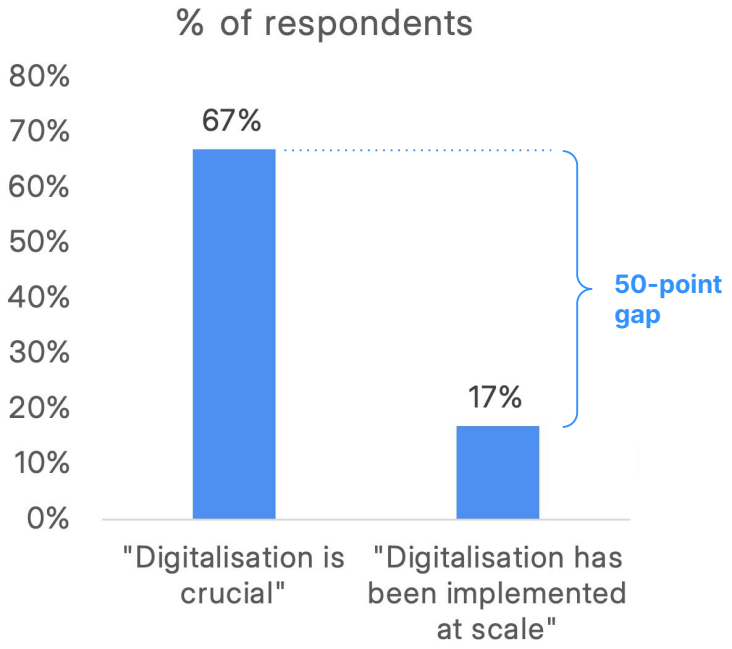
BloombergNEF Source: 1. Bulbat, 2. BloombergNEF (Distinguished Partner), 3. McKinsey, 4. IEA, 5. Capgemini, 6. S&P Global, 7. UKRI, 8. McKinsey

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Digitisation as a Driver for Job Growth

What we are seeing

- Manufacturing needs automation, data infrastructure, analytics, and advanced control.
- Growing roles: automation engineers, simulation & digital-twin specialists, data-driven process engineers.
- 67% of manufacturers say digitalisation is crucial; **yet only 17% have implemented digitalisation at scale.**
- Large adoption gap means hiring plus upskilling is the fastest path to productivity and quality gains.



Manufacturers can bridge the 50-point gap between recognizing digitalisation's importance and successfully scaling it by prioritizing the recruitment and upskilling of specialists in automation, digital twins, and data-driven process engineering.

Source: 1. McKinsey 2. Capgemini

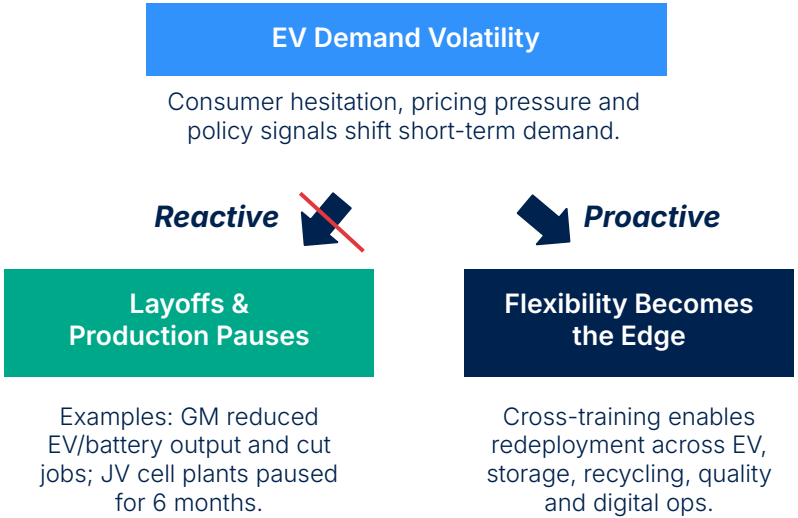
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EV Slowdown Reveals Lack of Cross-Training

What we are seeing

- EV demand uncertainty is prompting some OEMs and suppliers to slow EV and battery production and trim EV-linked headcount.
- This exposes a structural issue: **narrower specialisation makes it hard to redeploy teams toward adjacent spaces**, including grid storage, recycling, efficiency and quality improvements.
- Research shows cross-training builds labour flexibility and is especially valuable under demand uncertainty.

During turbulent market conditions, resilient companies will train their workforces to become effective in a variety of product markets.

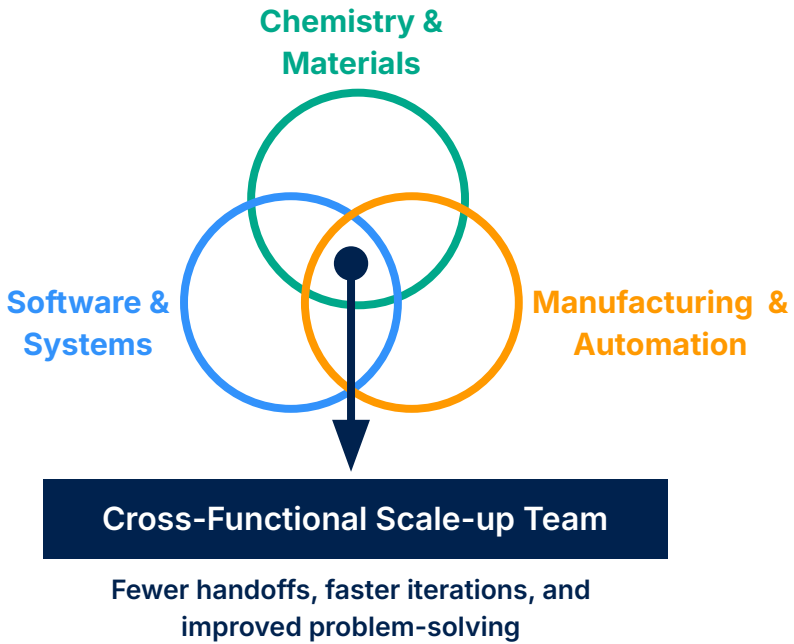


Source: 1. McKinsey 2. Capgemini

Skills Gaps Are Pushing Battery Manufacturers to Reorganise Around Blended Teams

What we are seeing

- Skill shortages span manufacturing, electrochemistry, battery management systems (BMS) and product/system design.
- Leading employers are building cross-functional teams that blend chemistry, engineering, software, automation and sustainability.
- Research organizations find interdisciplinary work increasingly dominant and tending to achieve higher impact.



Cross-functional teams are becoming a competitive advantage, helping battery companies move faster from R&D to scaled production despite widening skills gaps.

Source: 1. CAR 2. CIC energigune 3. Nature 4. Smartsuite

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Visa Policy Trends in 2025

The H-1B visa is used by U.S. battery companies seeking specialized talent. The path to securing these visas became increasingly complex in 2025 as the U.S. government updates its stance on high-skilled immigration. The situation remains fluid. Notable events are highlighted below.

Jan. 17, 2025

DHS Modernization Rule

DHS final rule takes effect, modernizing H-1B and shifting to a beneficiary-centric lottery [1]

Jan. 20, 2025

Political Divide on H-1B

Split over preserving H-1Bs for STEM shortages vs. restricting them to protect U.S. workers [2]

Sept. 4, 2025

Hyundai Georgia Incident

ICE raids a battery-plant, questioning hundreds working under visas not permitting hands-on labor [3]

Sept. 12, 2025

Tesla Hiring Lawsuit Filed

A class-action alleges Tesla favored lower-paid H-1B workers over U.S. citizens in hiring and layoffs [4]

Sept. 20, 2025

$100,000 H-1B Fee

A presidential proclamation imposes a new $100,000 fee on H-1B petitions filed after Sept 21 [5, 6]

Sept. 29, 2025

China Launches K Visa

China introduces the K visa, offering STEM graduated a job-offer-free pathway as an alternative to the noew costlier US H-1B [7]

Oct. 3, 2025

First Lawsuit Challenging H-1B Fee

A coalition of unions, educators, and recruitment groups files suit to block the new $100,000 fee [8]

Oct. 20, 2025

USCIS Issues Fee Update

USCIS clarifies the fee applies only to new petitions from outside the U.S., not to extensions or changes of status [9]

Dec. 2, 2025

State Dept. Memo on Enhanced Vetting Directive

Enhanced résumé and online-presence screening required for all H-1B cases [10]

Dec. 23, 2025

DHS Finalizes New H-1B Rule

DHS finalizes a wage-weighted H-1B lottery favoring higher-paid, senior roles for FY 2027; legal challenges expected [11, 12]

Source: [1] uscis.gov [2] Reuters, [3] ice.gov, [4] Reuters, [5] whitehouse.gov, [6] BBC, [7] Reuters, [8] Reuters, [9] Forbes, [10] Reuters, [11] federalregister.gov [12] Forbes

What Happened at the Hyundai-LG Battery Plant Construction Site in Georgia?

On September 4, 2025, U.S. Immigration and Customs Enforcement (ICE) led a multi-agency enforcement operation at the Hyundai–LG battery-plant construction site in Ellabell, Georgia, questioning approximately 475 foreign workers. ICE stated that many had entered under visa categories that do not allow hands-on industrial labor.

Over 300 South Korean nationals were later repatriated. The raid halted installation and commissioning work and is expected to delay the plant's startup by two to three months.

This incident highlighted a **structural gap in U.S. visa pathways for short-term, highly technical industrial specialists needed during giga-scale factory construction.**



Ellabell, Georgia, U.S., September 4, 2025 in a still image taken from a video. U.S. Immigration and Customs Enforcement/Handout via Reuters.

Scaling domestic battery manufacturing requires leveraging global technical expertise to bridge the local skills gap. Since current visa restrictions create significant bottlenecks, **transforming immigration policy into a competitive advantage is essential for securing a domestic workforce.**

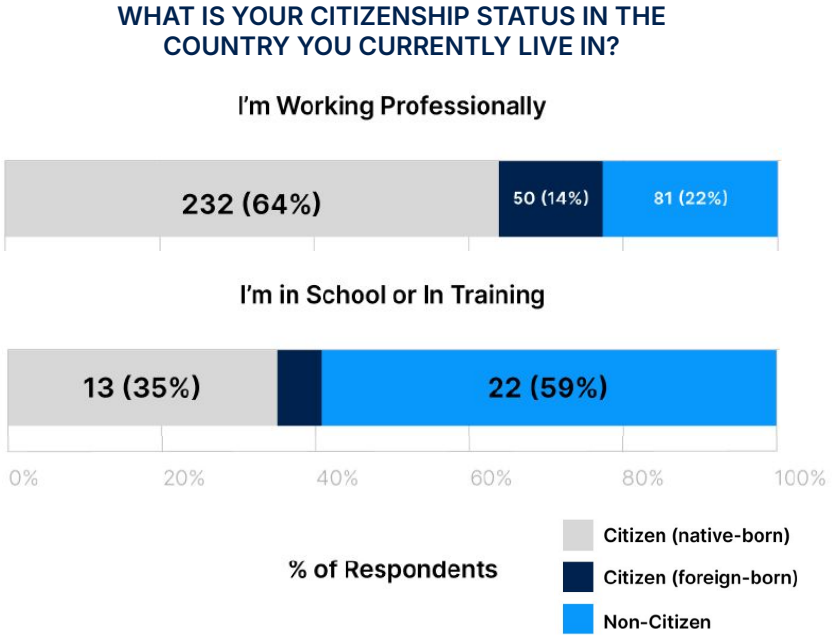
Source: [1] ice.gov, [2] Reuters, [2] Ground News, [3] Ground News, [4] Ground News, [5] Ground News.

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Why Does Visa Policy Matter?

The VF Battery Talent Census showed that:

- **36% of U.S. battery professionals are non-citizens or foreign-born**, with 8% of them holding H-1B visas.
- Nearly **60% of students in battery-relevant academic programs are international**. These students represent the future talent pipeline for the battery industry.
- Hiring managers consistently cite "immigration/visa issues" as one of the top barriers to filling technical roles.



U.S. battery manufacturing depends heavily on globally mobile technical workers. Sudden visa-related disruptions can directly slow factory ramp-up timelines and impact domestic EV supply chain goals.

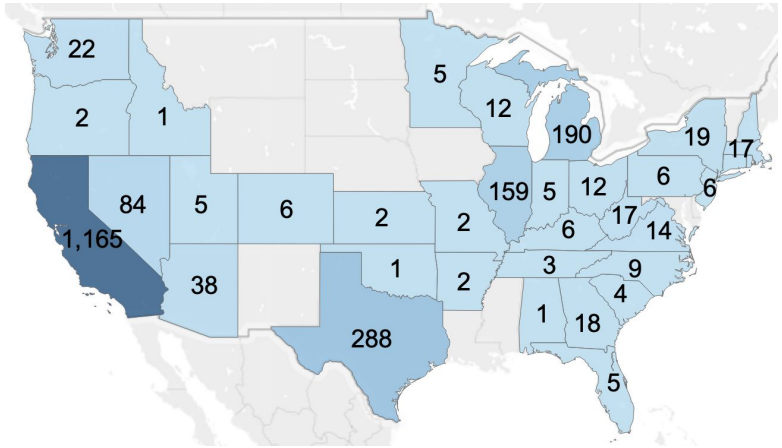
Source: [1] Battery Talent Census, [2] ice.gov, [3] Reuters.

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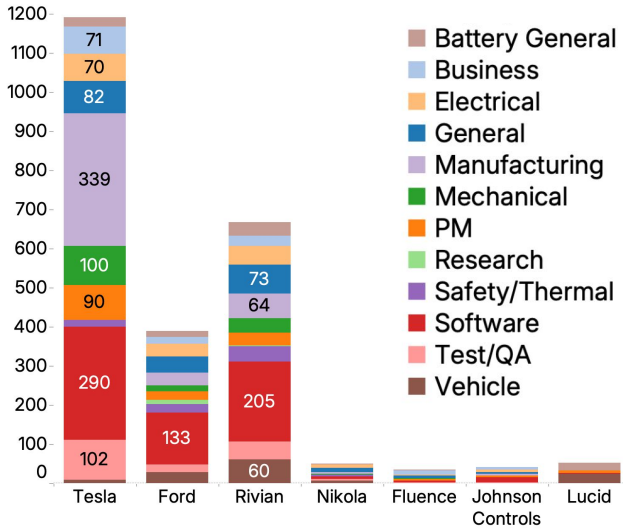
We Analyzed Publicly Available H-1B Data to Study Trends in Compensation, Roles, and Companies

H-1B applications are concentrated in California, Michigan, and Texas. The majority of applications are filed by automotive OEMs: Tesla, Ford, Rivian, and Lucid. Smaller startups also rely on H-1B hires, including Quantumscape, Form Energy, Ascend Elements, Joby Aviation, Sila, Enovix, and Lyten.

H-1B APPLICATIONS BY STATE (2024)



H-1B APPLICATIONS BY COMPANY (2024)



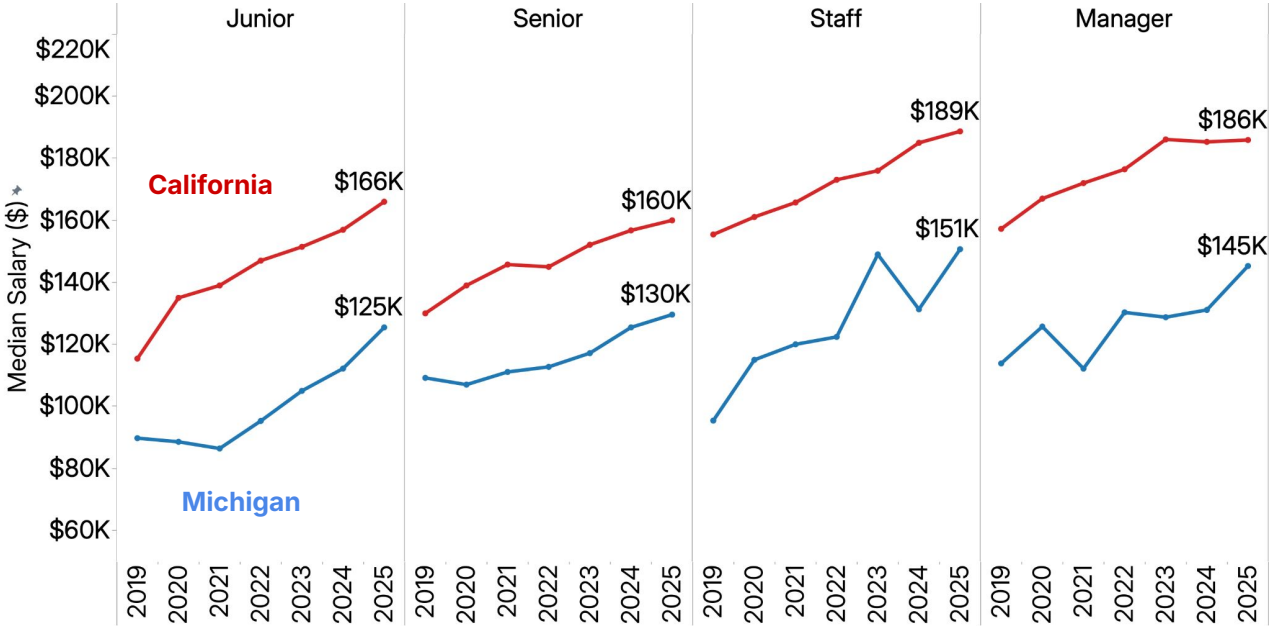
A full list of companies, roles, and salaries, is available **here**.

Source: H-1B application data, including companies, titles, and salaries, is publicly available through h1bdata.info. We analyzed the data using a custom Python-based data processing pipeline. The source code is available on GitHub.

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Base Pay for H-1B Holders Continue to Rise

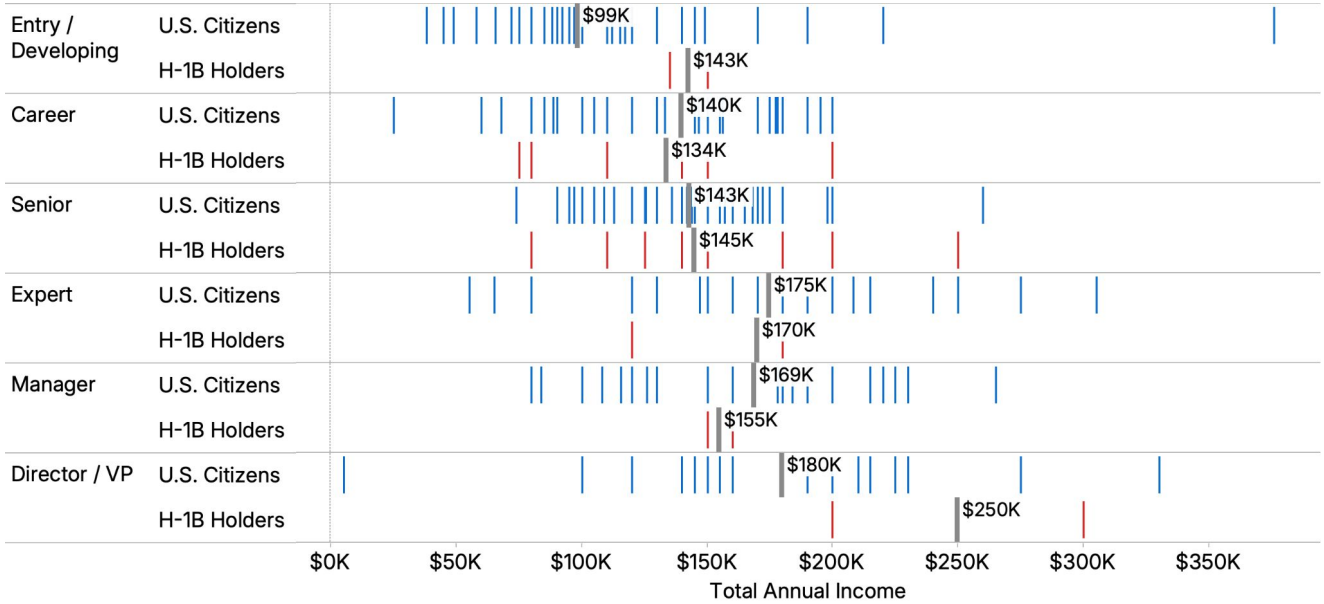
Gap between California and Michigan pay also persist and may be attributable to differences in cost-of-living.



Source: H-1B application data, including companies, titles, and salaries, is publicly available through h1bdata.info. We analyzed the data using a custom Python-based data processing pipeline. The source code is available on GitHub.

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Battery Industry H-1B Visa Holders Are Not Being Underpaid Compared to U.S. Citizens



H-1B visa holders are not being utilized as "cheap labor" compared to U.S. citizens according to this dataset. These results suggest that H-1B talent is being hired for specialized and high-value roles.

This analysis represents original work for the Battery Report. The raw dataset used is obtained from the Battery Talent Census.
Total Annual Income is based on responses to the question "What is your total income over the past 12 months?" Inset labels show median annual income within each group.

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Global Compensation Landscape

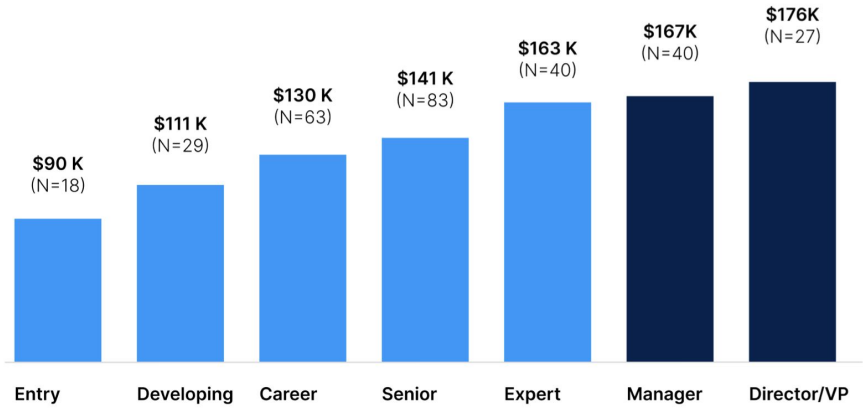
United States
- Highest compensation across nearly all career levels
- California leads in U.S. compensation

Europe (Germany, Sweden, UK, France)
- Lower nominal salaries vs U.S.
- Purchasing power parity (PPP) adjustment narrows gap
- Stronger alignment between age and salary progression, reflecting more structured pay ladders

Canada
- Salaries trail the U.S. but are competitive within N.A.
- PPP adjustments bring compensation closer to U.S. levels for mid-career roles

India
- Lowest nominal salaries among the countries surveyed, but PPP adjustments improve relative purchasing power

AVERAGE BASE SALARY FOR BATTERY PROFESSIONALS IN THE U.S. BY LEVEL



The U.S. remains the global salary leader, even after adjusting for PPP. European systems favor tenure-based progression, while U.S. salaries reward mobility and performance. Compensation disparities influence global talent mobility toward U.S. hubs.

Source: Battery Talent Census.

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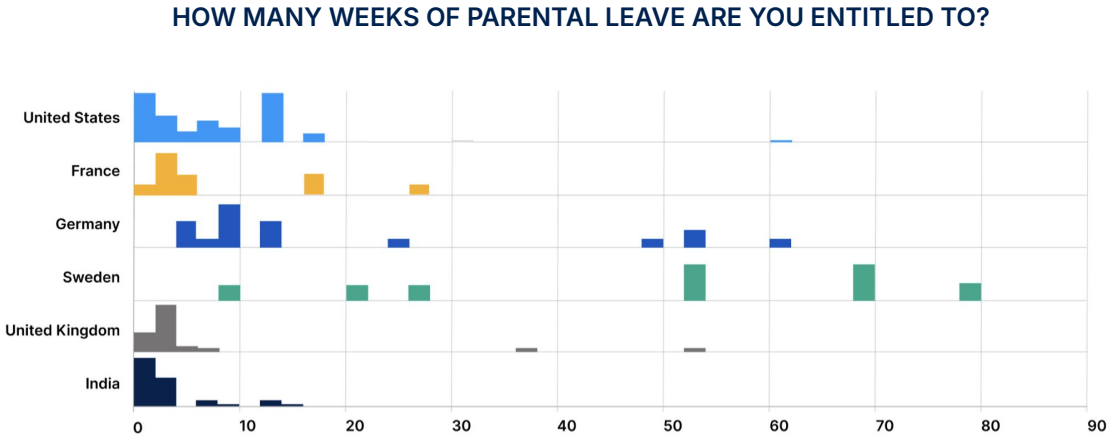
Global Bonuses, Equity and Benefits

Worldwide Trends

- Fewer than 23% of employees receive bonuses >$10k*
- Equity (stock options) is common in U.S. and Canadian startups, less common in Europe and India.

Benefits Across United States

- Low prevalence of non-core benefits:
  - Education reimbursement: ~10%
  - Childcare reimbursement: ~5%
  - Wellness stipends: <25%
- Parental leave:
  - 27% receive none
  - 66% receive fewer than 8 weeks
- Paid time off: median is 4 weeks



Source: Battery Talent Census . *The 23% statistic is based on U.S. data from the Census; however, the trend broadly aligns with global talent surveys.

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Global Bonuses, Equity and Benefits

Europe (Germany, Sweden, UK, France)

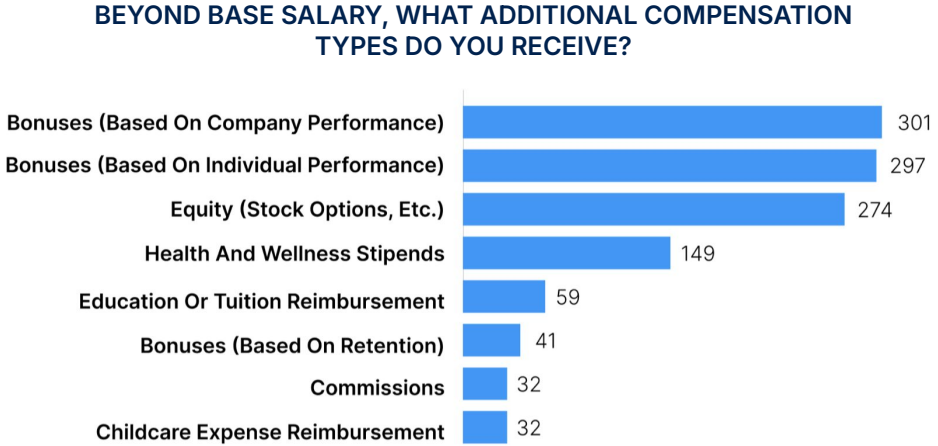
- Most generous parental leave and PTO allotments globally (5–7+ weeks).
- Stronger social benefits reduce reliance on employer-provided perks.

Canada

- Benefits resemble a midpoint between U.S. and Europe, with better public healthcare support reducing dependence on employer healthcare plans.

India

- Wide variability in benefits; global companies offer stronger packages, while domestic firms may lag in wellness and parental leave.



Benefits such as leave, well-being programs, and education support, vary far more widely across countries than salary. Europe consistently outperforms other regions in non-salary benefits.

Source: Battery Talent Census

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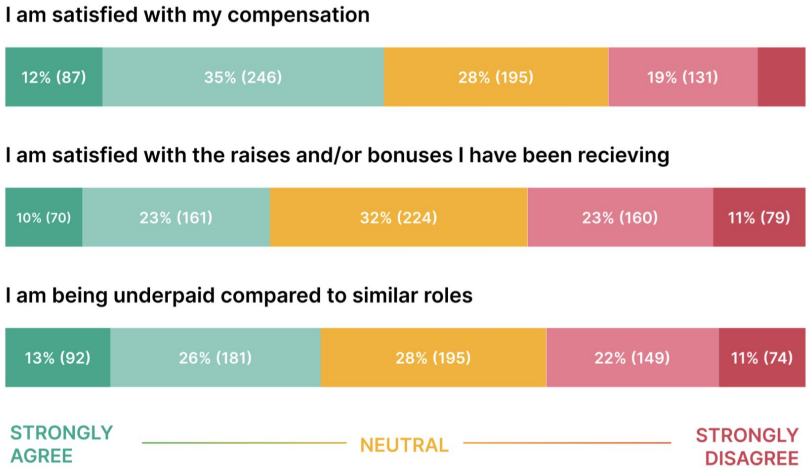
Pay Satisfaction (Global View)

Across regions, salary attracts talent, but benefits, pay equity, and transparent progression retain them. The gap between these two remains the primary global retention challenge.

Pay Satisfaction Across Regions

- <50% of respondents globally feel satisfied with their compensation.
- Underpayment sentiment is strongest in the U.S. and Canada, where market-based pay leads to expectations of faster progression.
- European respondents express slightly higher stability satisfaction but still cite compensation transparency issues.

Many workers' pay expectations do not match reality. Despite pay premiums, a third of professionals believe they are underpaid. Furthermore, less than 50% are satisfied with their compensation, and less than a third are satisfied with their raises and bonuses.



Source: Battery Talent Census

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Workforce Landscape
Emerging Trends
Policy & Immigration
Compensation & Benefits

Industry Sentiment

Skills & Training Gaps
Educational Development
Workforce Research
Access & Advancement

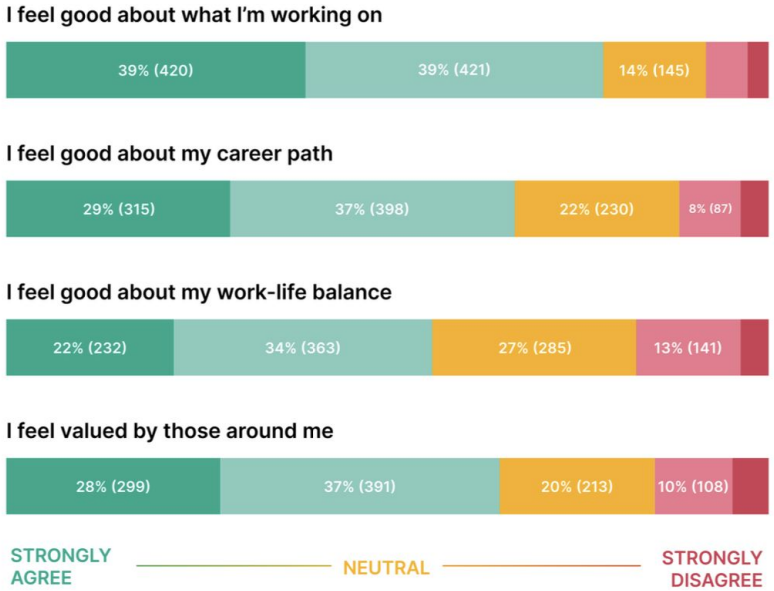
VOLTA FOUNDATION

Industry Sentiment & Workplace: Strong Engagement, Positive Career Outlook

Overall industry sentiment among battery professionals is positive, with **strong alignment around purpose, engagement, and career optimism.**

Across roles and career stages, respondents report high levels of satisfaction with their work, interest in their field, and feeling valued by colleagues. Sentiment trends upward with seniority, suggesting that experience, autonomy, and role clarity contribute to more positive perceptions over time.

RESPONSES TO WORKPLACE SENTIMENT QUESTIONS



Source: Battery Talent Census

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Industry Sentiment & Company: Strong Engagement, Mixed Retention Signals

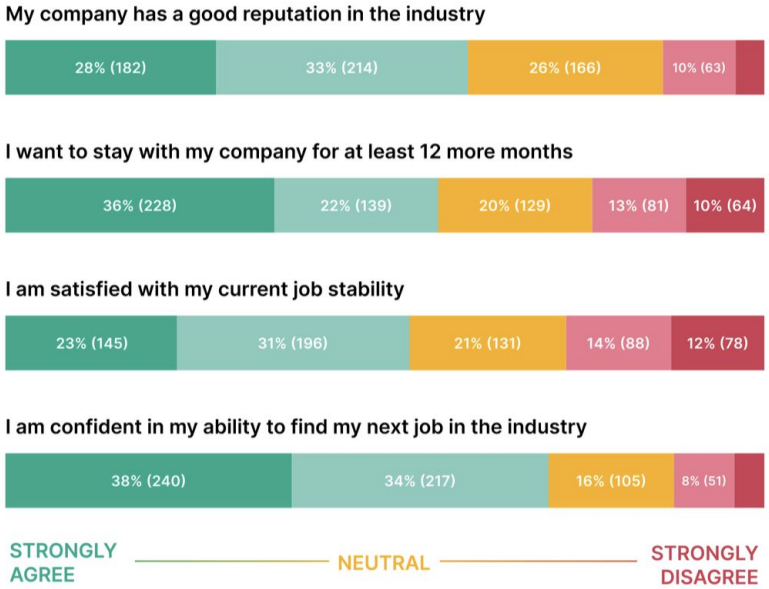
Job satisfaction in the battery industry remains high, but **confidence in job stability and near-term retention is more mixed.**

While most respondents report satisfaction with their current roles, only 54% indicate satisfaction with job stability, and 58% expect to remain with their current employer over the next 12 months.

At the same time, 60% believe their company has a strong reputation within the industry, and a majority of professionals report high labor-market confidence, with 72% expressing confidence in their ability to find another role within the battery sector.

These responses point to a workforce that is engaged and employable, but increasingly mobile.

RESPONSES TO COMPANY SENTIMENT QUESTIONS



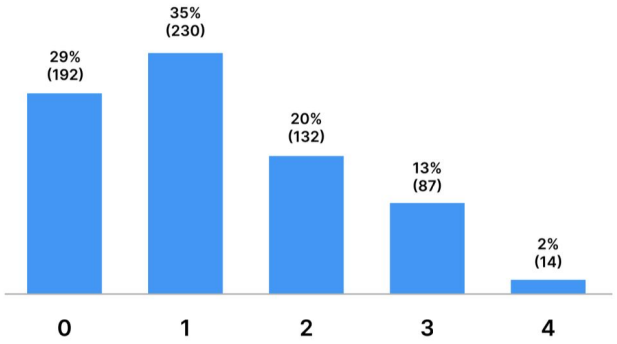
Source: Battery Talent Census

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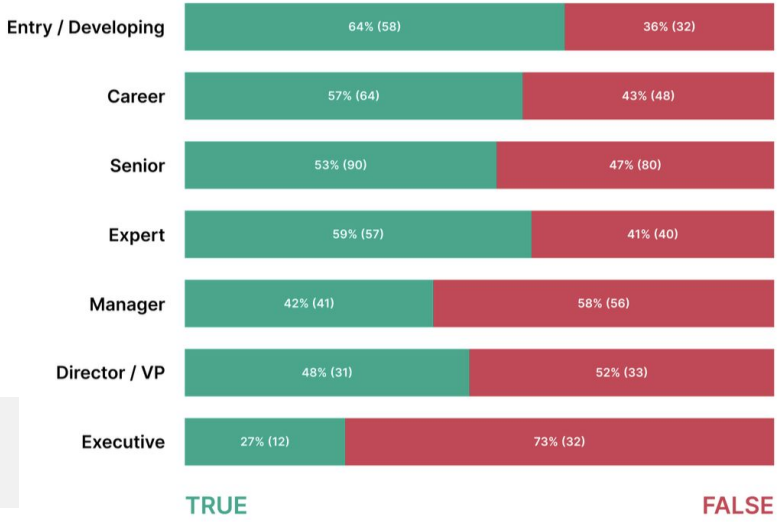
Industry Sentiment & Mobility: Short Tenure and Frequent Job Changes

Only 29% of professionals report staying with a single employer over the past five years, and **average tenure is approximately 2.3 years**, indicating limited long-term attachment to individual companies. Job-seeking activity is widespread: about 50% of professionals report actively looking for new opportunities, with mobility highest among early-career roles.

HOW MANY TIMES HAVE YOU CHANGED EMPLOYERS IN THE LAST FIVE YEARS?



ARE YOU SEEKING NEW JOB OPPORTUNITIES?



These patterns point to a highly dynamic workforce, where **frequent job changes and active job-seeking are common**, especially among early-career professionals.

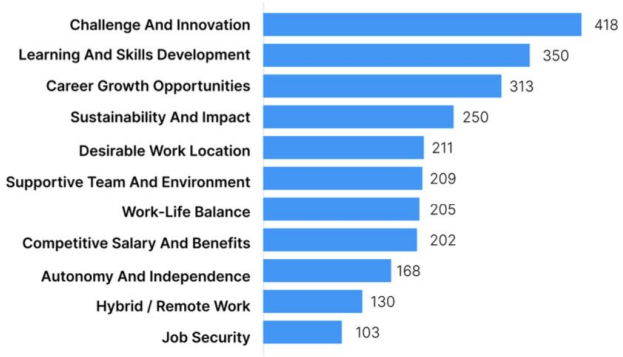
Source: Battery Talent Census

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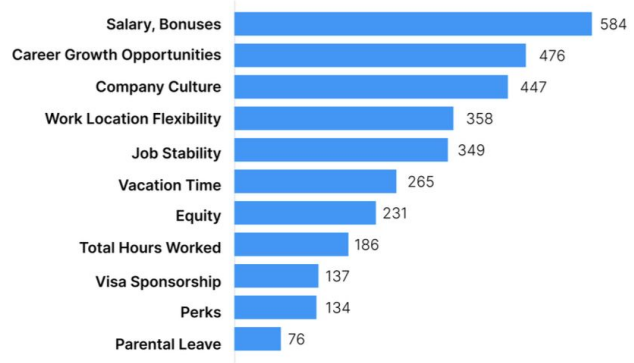
Industry Sentiment & Mobility: Why Do People Leave vs. Why They Join?

Survey responses show that innovation, learning opportunities, and career growth rank highest among reasons for joining a company. In contrast, salary and bonuses, company culture, and work-location flexibility rank highest among factors influencing decisions to accept a similar role elsewhere.

WHY DID YOU CHOOSE YOUR CURRENT ROLE & COMPANY



IF YOU WERE OFFERED A SIMILAR ROLE WITH A DIFFERENT COMPANY, WHAT FACTORS WOULD INFLUENCE YOUR DECISION TO ACCEPT THE OFFER?



Together, these findings reveal a clear retention mismatch: **professionals join for innovation and growth, but leave for compensation, culture, and flexibility.**

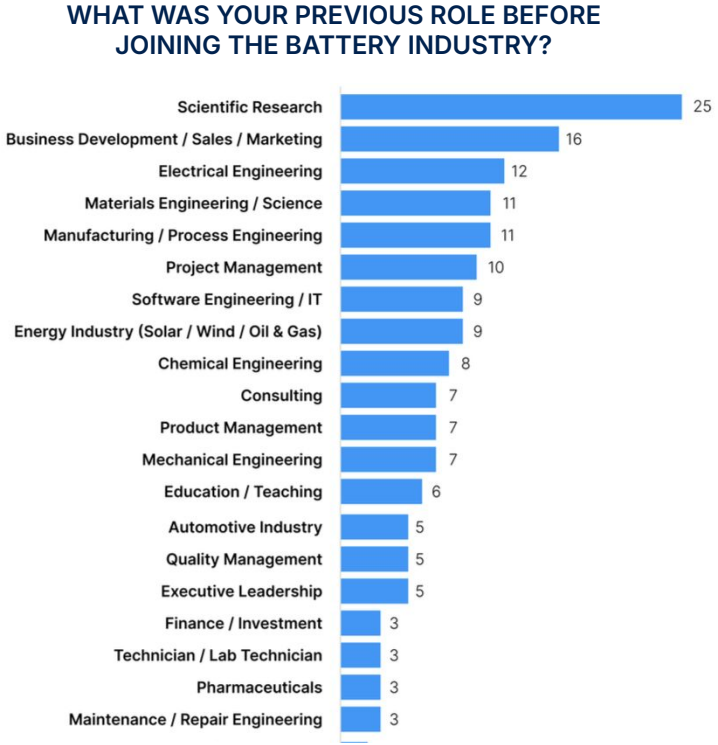
Source: Battery Talent Census

Industry Sentiment & Mobility: Previous Roles

A majority of battery professionals entered the industry from outside fields, reflecting strong cross-industry mobility.

2 in 3 enter the battery field from other industries.

Prior experience most commonly comes from research, engineering, business, and adjacent technology roles, highlighting the industry's ability to attract talent with transferable skills. This pattern underscores the battery sector's porous boundaries and its reliance on cross-disciplinary expertise to build and scale the workforce.



These patterns underscore the battery sector's porous boundaries and dependence on transferable skills.

Source: Battery Talent Census

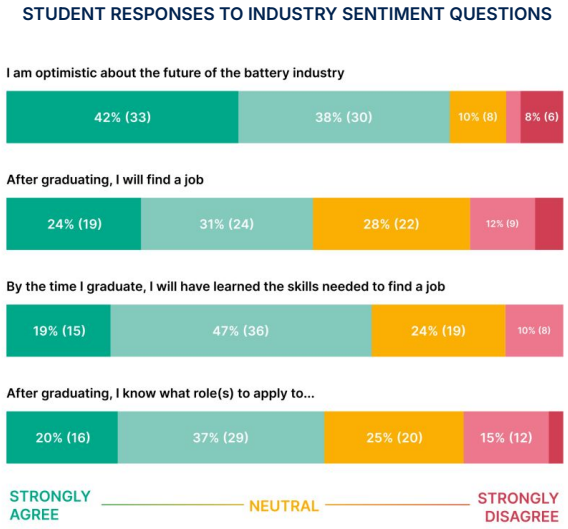
VOLTA FOUNDATION

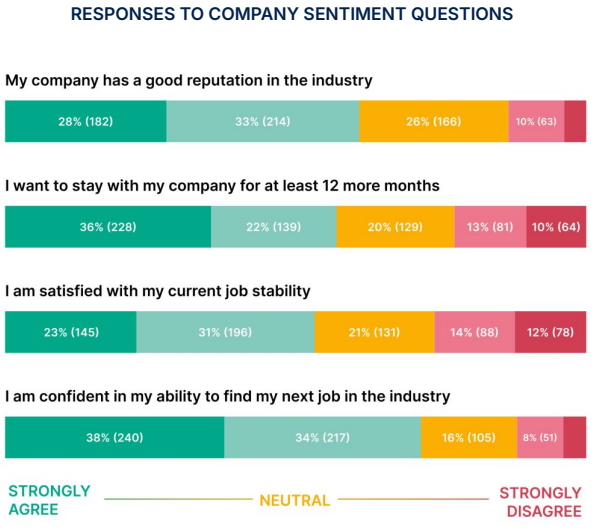
Academic and Student Sentiment

Students reported general optimism about the future of the battery industry, with **80% expressing positive sentiment but only 55% confidence in their ability to find a job after graduation.**

34% of students expressed neutrality or doubt that they will graduate with the skills needed for employment and 43% expressed neutrality or doubt about knowing which roles to apply to.

In contrast, 72% of workers in the battery industry are confident in their ability to find their next job, indicating that direct experience improves confidence and that there is room for clarifying industry roles and career pathways.





Source: Battery Talent Census

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Workforce Landscape
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Skills & Training Gaps

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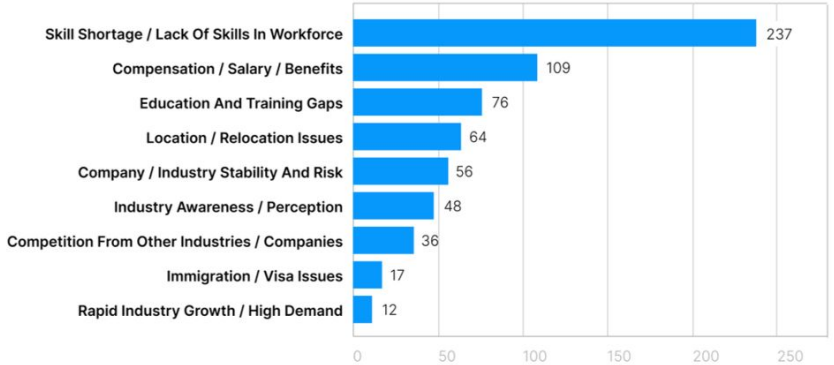
VOLTA FOUNDATION

Skills and Training Gaps: Leading Constraints on Battery Industry Growth

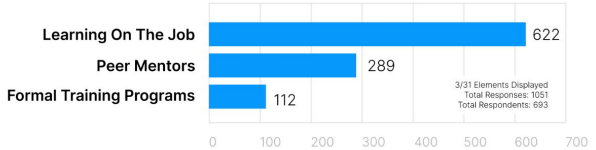
Employers consistently report difficulty filling roles due to persistent skills gaps and insufficient training pipelines, particularly for manufacturing, process, and applied technical positions.

These workforce limitations are cited alongside cost and supply-chain challenges as key barriers to growth, underscoring talent readiness as a structural, not short-term, constraint on industry expansion.

IN YOUR OPINION, WHAT DO YOU THINK ARE THE MAIN BARRIERS TO HIRING SKILLED TALENT IN THE BATTERY INDUSTRY?



WHEN YOU FIRST STARTED YOUR ROLE, HOW WERE YOU TRAINED?



These patterns suggest that **insufficient training infrastructure is limiting the speed of factory ramp-up.**

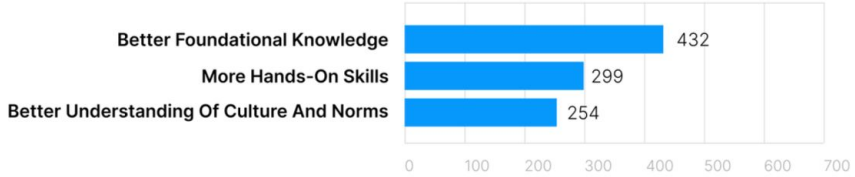
Source: Battery Talent Census

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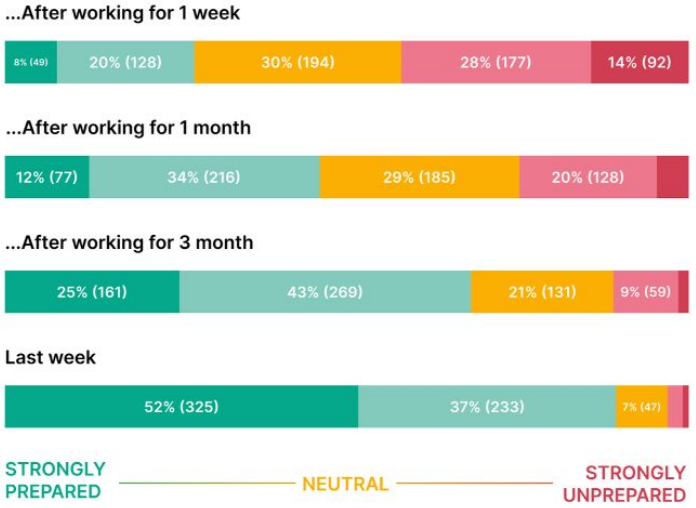
Training Gaps Are Slowing Workforce Readiness

Survey responses show that many battery professionals feel underprepared when they first start their roles, with preparedness increasing only after several weeks or months on the job. When asked what could have improved performance on day one, respondents most frequently cite stronger foundational knowledge, more hands-on skills, and better understanding of workplace culture and norms.

WHEN YOU FIRST STARTED IN THE BATTERY INDUSTRY, WHAT COULD HAVE IMPROVED YOUR JOB PERFORMANCE ON DAY ONE?



WHEN YOU FIRST STARTED YOUR ROLE, HOW PREPARED DID YOU FEEL?



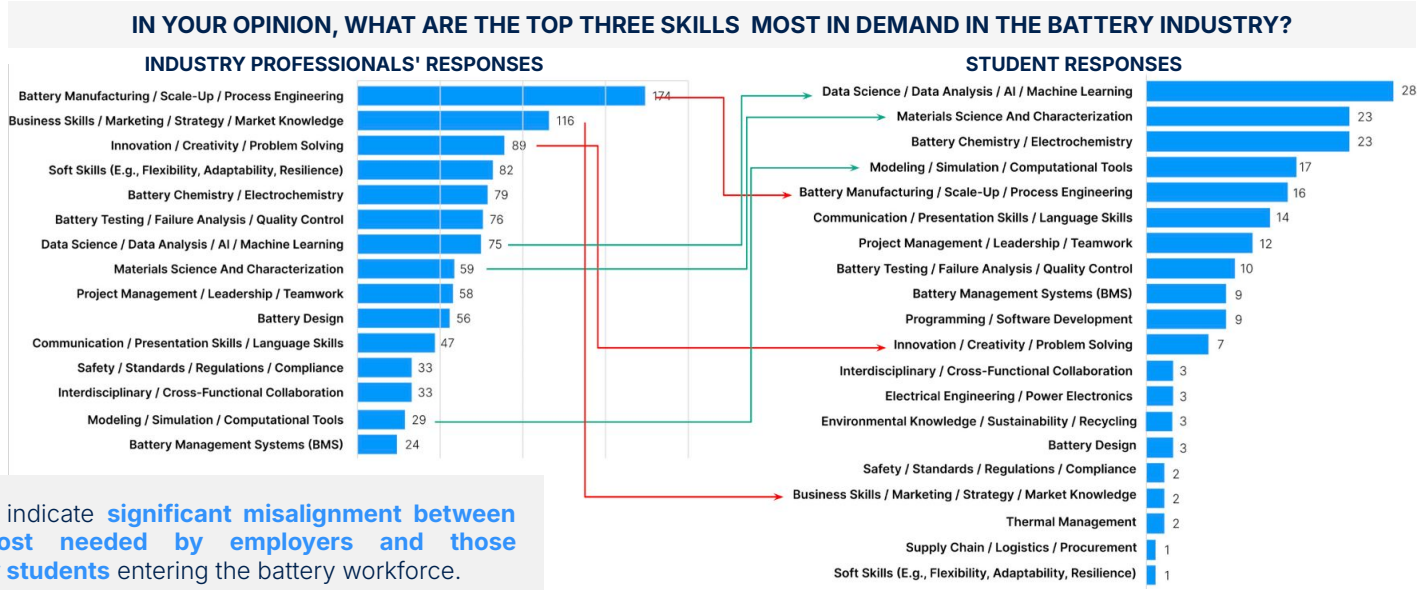
These patterns highlight a **gap between initial workforce readiness and the skills required for effective performance** in battery roles.

Source: Battery Talent Census

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Disconnect Between Hiring Demand and Talent Pipeline Expectations

Industry professionals identify battery manufacturing, process engineering, and production scale-up roles as the most in-demand skill areas. In contrast, student respondents most frequently prioritize data science, materials characterization, electrochemistry, and modeling-oriented skills, with comparatively less emphasis on manufacturing and operations-focused roles.



These findings indicate **significant misalignment between the skills most needed by employers and those emphasized by students** entering the battery workforce.

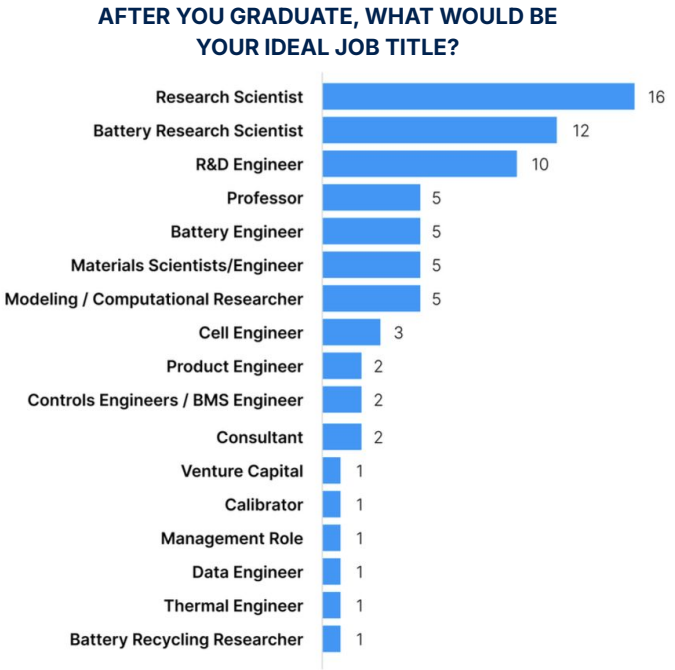
Source: Battery Talent Census

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Students' Career Aspirations Remain Heavily Concentrated in Research and R&D Roles

Students overwhelmingly cite research-focused positions, such as research scientist and R&D engineer, as their ideal post-graduation roles.

In contrast, few students express interest in manufacturing, process engineering, or equipment-focused roles, even though these positions represent some of the most acute talent needs across the battery value chain.



This concentration of student interest highlights a **persistent gap between student career expectations and the roles most critical to industry scale-up.**

Source: Battery Talent Census

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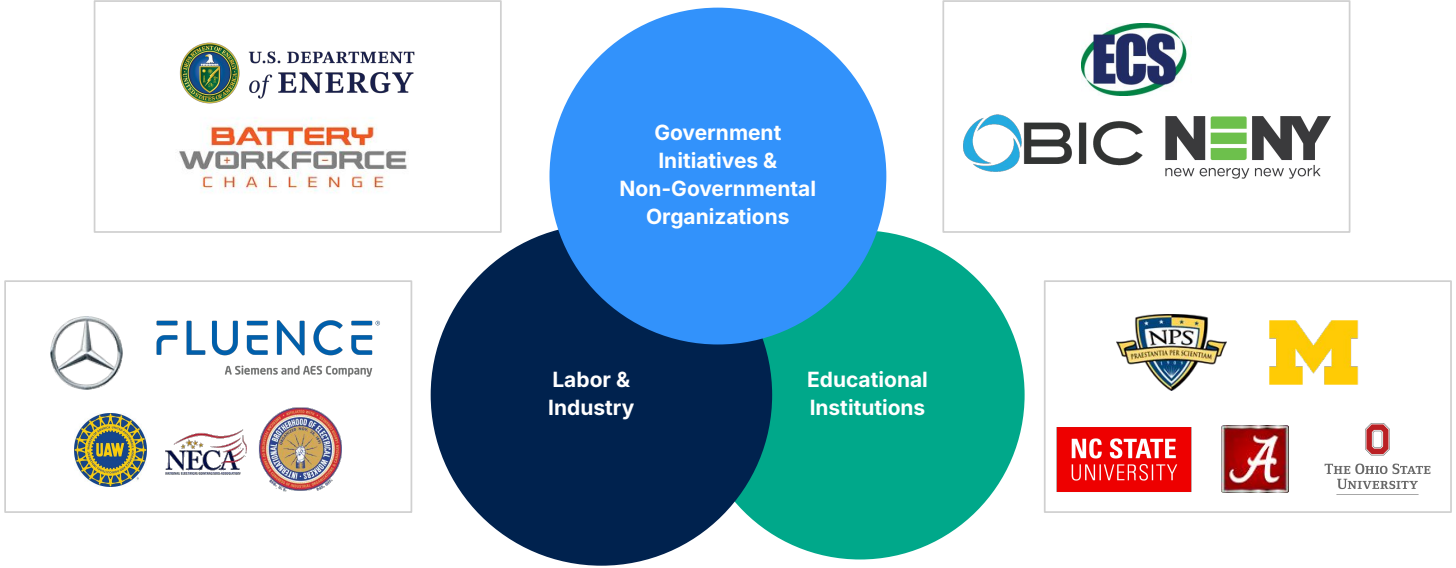
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Workforce Landscape
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Access & Advancement

Educational Development Programs: Overview of Key Players



Successful education initiatives have leveraged public and private sectors to meet the needs of a growing industry and often involve governments, nonprofits, labor groups and academia.

Source: Companies are linked above

From Class to Career: US Government-led Initiatives and Non-governmental Organizations

Battery Workforce Initiative

Goal: "Speed up development of high-quality training, starting with existing examples to develop consensus on core training needs; then develop training for use by companies and local training providers."

Outcomes: Interim report and National Guideline Standards for the Battery Machine Operator occupation.

Key Stakeholders:

- Dept. of Energy
- Dept. of Labor
- AFL-CIO
- Li-Bridge Alliance Members

Battery Workforce Challenge

Goal: Develop the battery workforce through four areas: The Battery Workforce Challenge Collegiate Competition, Regional Workforce Development, Career Connected Learning, and STEM Education.

Outcomes: Develop a talent pipeline across skills and education levels.

Key Stakeholders:

- Dept. of Energy
- Argonne National Laboratory
- Stellantis
- Academic Partners
- Industry Suppliers

Li-Bridge

Goal: Bring together private industry, national laboratories, and the federal government. A key piece of this gap is the limitations of the existing workforce.

Outcomes: Identifying key workforce needs in collaboration with partner organizations.

Key Stakeholders:

- Dept. of Energy National Laboratories
- NAATBatt International
- New York Battery & Energy Storage Technology Consortium (NY-BEST)
- New Energy Nenus

From Class to Career: US Educational Institutions

New Energy New York

Programs led by Binghamton University supported through funding from the NSF and EDA to create a sustainable economy in upstate New York focused on education and workforce development.

Electrochemical Society

Hosts battery courses taught by leading experts from industry and academia in materials, electrochemistry and lithium batteries.

University of Michigan

Along with strong programs in engineering and chemistry, the school offers a battery cell manufacturing course through its online professional certificate program.

Naval Postgrad. School

Focused on research, outreach, curriculum development, and training programs within the broader DoD energy security field.

University of Alabama AMP

Focused on workforce development among students, researchers, scholars, and faculty.

These represent a small selection of the US academic initiatives and joint initiatives between academia, NGO, and government.

From Class to Career: Labor and Industry Led Initiatives

Labor Union Workforce Development Programs

United Auto Workers: An award from the DOE to the UAW Region 6 and UAW Center for Manufacturing a Green Economy (UAW-CMGE) will further develop the High Road Battery Training Program in partnership with the Sparkz corporation.

IBEW-NECA: One example program is the Clean Transportation and Advanced Manufacturing Electrical Training Trust which enables apprenticeships in these key topic areas

Industry Training Programs

Numerous vehicle manufacturers offer internal training programs including Mercedes and Volkswagen.

Battery companies and ESS companies also frequently offer opportunities for training and scholarship like East Penn Manufacturing, Fluence, among many others.

Conferences and Short Courses

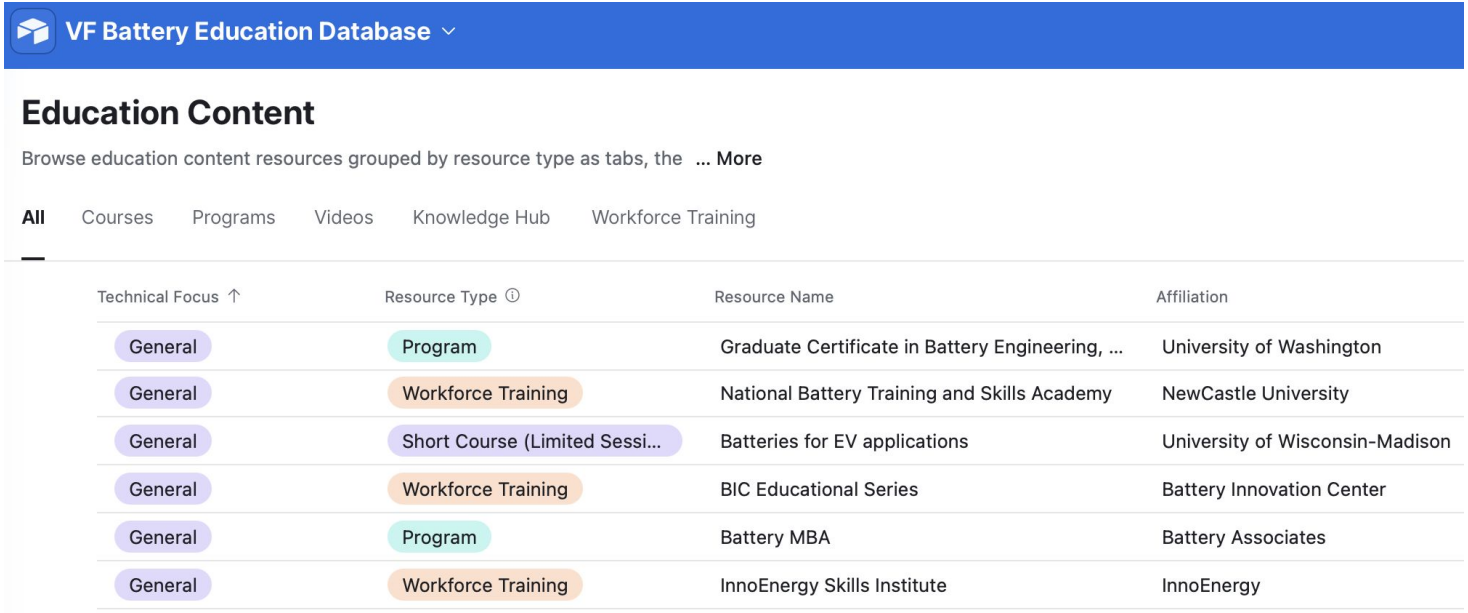
Battcon: Offers classes every year on topics like stationary battery basics, evaluating DC arc flash and battery safety issues, and NERC compliance

The Battery Show: current workshops include Battery 101, Battery Safety, China Battery Technology trends and numerous others

Battery Innovation Center in Indiana: hosts monthly courses on topics such as Battery Fundamentals, Battery 101, Cell Manufacturing, Testing & Validation, Micro-grid, BMS, Current Battery Standards, Second Life Applications, and Current Technological Trends

Volta Foundation Battery Education Database

The VF Battery Education Database is an open-access, community-led resource for discovering battery educational content available for learners *today*. What's highlighted: high-quality online courses, degree programs, wikis, books, and more.



VF Battery Education Database

Education Content

Browse education content resources grouped by resource type as tabs, the ... More

All | Courses | Programs | Videos | Knowledge Hub | Workforce Training

Technical Focus	Resource Type	Resource Name	Affiliation
General	Program	Graduate Certificate in Battery Engineering, ...	University of Washington
General	Workforce Training	National Battery Training and Skills Academy	NewCastle University
General	Short Course (Limited Sessi...	Batteries for EV applications	University of Wisconsin-Madison
General	Workforce Training	BIC Educational Series	Battery Innovation Center
General	Program	Battery MBA	Battery Associates
General	Workforce Training	InnoEnergy Skills Institute	InnoEnergy

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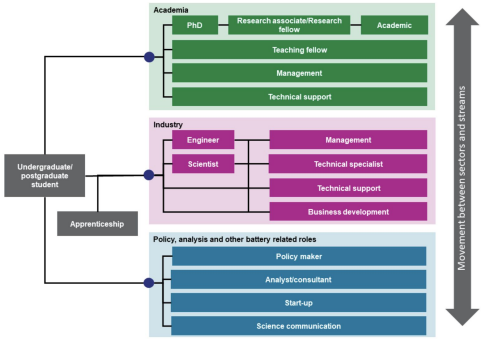
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Resources for Understanding Career Pathways

Preparing the future battery workforce requires defining **career pathways** across the value chain and for different educational tracks.
Here are a few resources that stood out in 2025.

Battery Career Portfolio

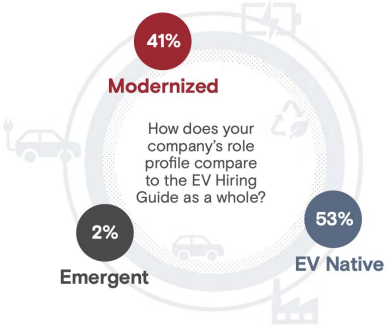
Available Now



THE FARADAY INSTITUTION

Electric Vehicle Hiring Guide

Available Now



MD Learn

ECONOMIC GROWTH INSTITUTE
UNIVERSITY OF MICHIGAN

Battery Workforce Framework

Expected to Launch in 2026



NANOVERSE BATTERY COURSES

NAATBatt INTERNATIONAL

Workforce Research

As the energy transition accelerates, the industry faces a **critical shortage of skilled labor and a significant misalignment between talent aspirations and operational needs**. The following reports highlight the urgent need for strategic workforce development in 2026.

World Energy Employment 2025

>50% of firms and unions reported critical hiring bottlenecks; 60% of companies experienced labor shortages.

US EV Automotive Workers

7% of current auto workers face high disruption, but clear “transition pathways” are possible.

Battery Talent Census Report

Students fixate on R&D roles, while none surveyed listed manufacturing or process engineering as their ideal job.

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How Many Workers Are Needed for Cell Manufacturing?

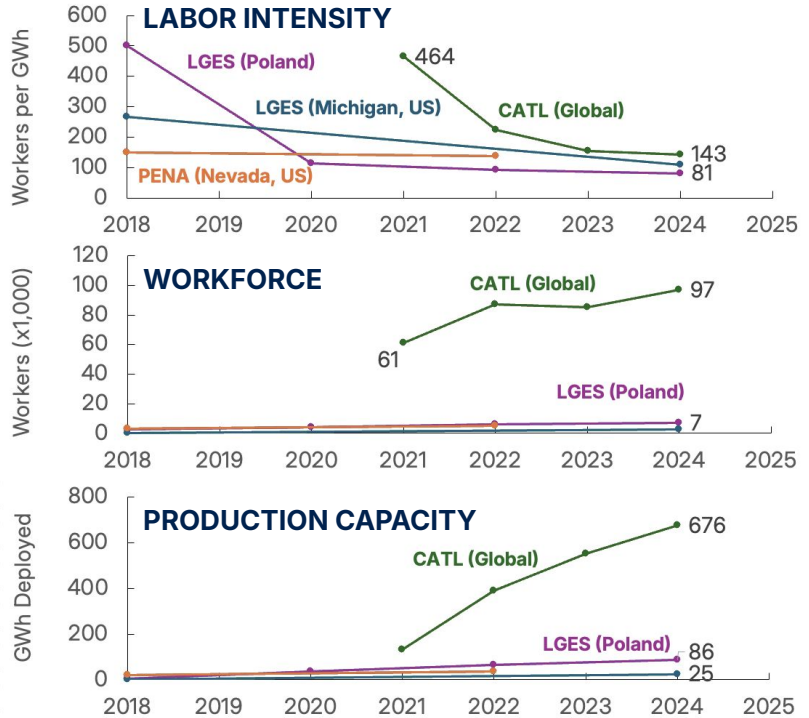
Battery cell manufacturing **labor intensity peaks during production ramp-up, often exceeding 400 workers per GWh.**

As production capacity scales, process automation and process maturity improves efficiency, requiring fewer workers per GWh.

At steady-state production, **the labor intensity declines sharply,** with **best-in-class plants approaching 80 workers per GWh**:

- CATL (Global): 143 workers/GWh[1]
- LGES (Michigan, US): 108 workers/GWh[2,3]
- PENA (Nevada, US): 137 workers/GWh[4,5]
- LGES (Wrocław, Poland): 81 workers/GWh[6]

Data summarizes publicly-available employment and factory production data from company reports, press releases, and news reports. The data was compiled and summarized by Krish Lulla (krishisd@umich.edu) as part of an independent research project at the University of Michigan. Production capacity corresponds to realized or deployed capacity, not promised capacity.



Sources: 1. CATL, 2. LG Energy Solution, 3. Battery Technology Online, 4. NAATBatt, 5. Automotive Manufacturing Solutions, 6. LG Energy Solution.

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Prominent Women Leaders Shaping the Future of Batteries

Across manufacturing, research, innovation, and circularity, women are leading at every stage of the battery value chain. The leaders highlighted here represent just a few of the many driving technical and strategic progress in this rapidly evolving industry.

Manufacturing



Celina Mikolajczak

Battery Executive & Industry Advisor

Veteran battery engineer and manufacturing executive. Known for leading quality, safety, and scale-up programs at companies including Tesla, Uber, Panasonic, and Lyten.

Academia & Research



Shirley Meng, PhD

Chief Scientist, Argonne Collaborative Center for Energy Storage Science

World-renowned researcher driving innovation in next-generation materials and workforce development.

Solid State Technology



Susan Stone

CEO, Blue Current

Pioneering solid-state battery technology using polymer-ceramic hybrid electrolytes, prioritizing both safety and performance.

Liquified-Gas Electrolyte



Jungwoo Lee, PhD

CEO & Co-Founder, South 8 Technologies

Driving commercialization of South 8's liquefied-gas electrolyte technology to enable safer, higher-energy batteries.

Recycling & Circularity



Megan O'Connor, PhD

Founder & CEO, Nth Cycle

Advancing a more sustainable and resilient battery supply chain through the pioneering of low-emission electro-extraction processes for critical metal recovery.

Prominent leaders were determined based on individuals who are regular keynote speakers at events, have been features on women in batteries podcasts and articles, or have been highlighted by other organizations.

Building an Inclusive Future for the Battery Workforce

In 2025, diversity and inclusion efforts gained international traction as organizations like WGBI expanded into new regions and industry events continued to highlight equity and leadership across the global battery workforce.

January 2025

WGBI Women in the Global Battery Industry

Latin America Chapter Launch

May 2025

BATTERY WORKFORCE CHALLENGE

Year 2 Competitions

July 2025

VF | WOMEN IN BATTERIES CONFERENCE

2026 Women in Batteries Conference

Sept. 2025

BATTERY TALENT CENSUS

Report Published

Oct. 2025

THE BATTERY SHOW NORTH AMERICA

Women in Batteries Meet-Up

Women Entrepreneurs Panel

Dec. 2025

aabc advanced automotive battery conference

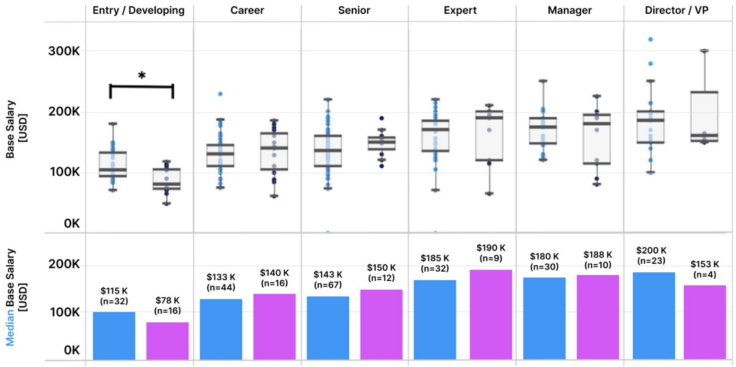
Women in Batteries Meet-Up

Pay Differences and Perceptions at the Entry / Developing Level

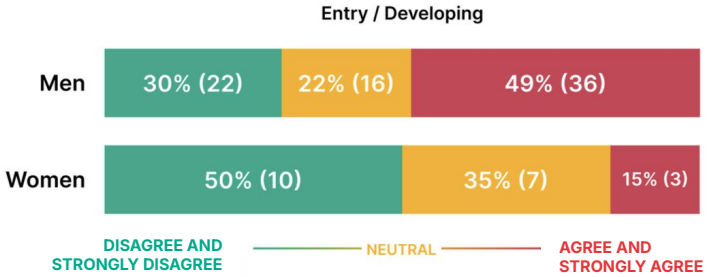
At the entry/developing level, women are paid 30% lower on average ($78k for women versus $115k for men), a statistically significant difference. The pay gap appears to narrow at higher levels, with comparable pay at senior, expert, and leadership levels.

For the same group of women who were paid 30% less than their male peers, 85% felt they were paid fairly or perhaps even overpaid. Only 15% of these women felt that they were being underpaid. Meanwhile, 50% of men in the same category felt that they were being underpaid.

WHAT IS YOUR ANNUAL BASE SALARY?



"I AM BEING UNDERPAID COMPARED TO SIMILAR ROLES"



Women at the entry-level are more likely to be **underpaid**, while **believing that they are being paid fairly.**

Source: Battery Talent Census

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POLICY

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Volta Foundation is the world's largest network of battery professionals. As a global not-for-profit association, Volta Foundation produces publications, networking opportunities, and industry resources to foster collaboration, innovation and advocacy within the battery industry.

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POLICY

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North America
Europe
Asia
Legal

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POLICY

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North America

Europe
Asia
Legal

The USA's Decentralized Battery Governance Framework (3-Pillar Model)

Unlike the EU's centralized regulatory structure, the U.S. operates a decentralized, parallel system. Battery compliance arises from the intersection of federal and state industrial incentives, voluntary safety standards administered through NRTLs, and sector-specific operational rules across transport, buildings, and consumer safety. The result is a **flexible** but **fragmented** framework driven more by market forces than by unified regulation.

Industrial & Market Incentives

- **Federal-Level**
  IRA 45X Advanced Manufacturing Tax Credit
  IRA 30D Clean Vehicle Credit
  IRA 48C Advanced Energy Project Credit
  IRA 48E Clean Electricity Investment Credit
  DOE Loan Program Office (LPO)
  Bipartisan Infrastructure Law (BIL)
  Defense Production Act (DPA)
- **State-Level**
  State Tax Credits
  Property Tax Abatements & Sales Tax Exemptions
  Workforce Training Grants
  Clean Energy Procurement Support
  Utility Rate Incentives for Gigafactories
- **Local / Utility-Level**
  Cheaper Land, Industrial Bonds
  Utility Rebates for Large Energy Users
  Municipal Fast-track Permitting

Core Safety Standards

- **Electric Vehicles**
  UL 2580 Batteries for Use in EVs
  SAE J2464 EV Li-ion Battery Abuse Testing
  SAE J2929 EV Battery System Safety
- **Energy Storage Systems**
  UL 1973 Batteries for Stationary/ Industrial Use
  UL 9540 Energy Storage Systems
  UL 9540A Thermal Runaway Propagation Test
  NFPA 855 ESS Installation Standard
- **Consumer Electronics**
  UL 1642 Li-ion Battery Cells
  UL 2054 Household & Commercial Batteries
  ANSI C18 Consumer Batteries
- **Two-wheelers**
  UL 2271 Batteries for Light EVs
- **Marine**
  ABYC E-13 Li-ion Battery Systems
  USCG NVIC Li-ion Batteries on Commercial Vessels
- **eVTOL & Aerospace**
  RTCA DO-311A Rechargeable Li-ion Batteries
  RTCA DO-160G Environmental Test Procedures

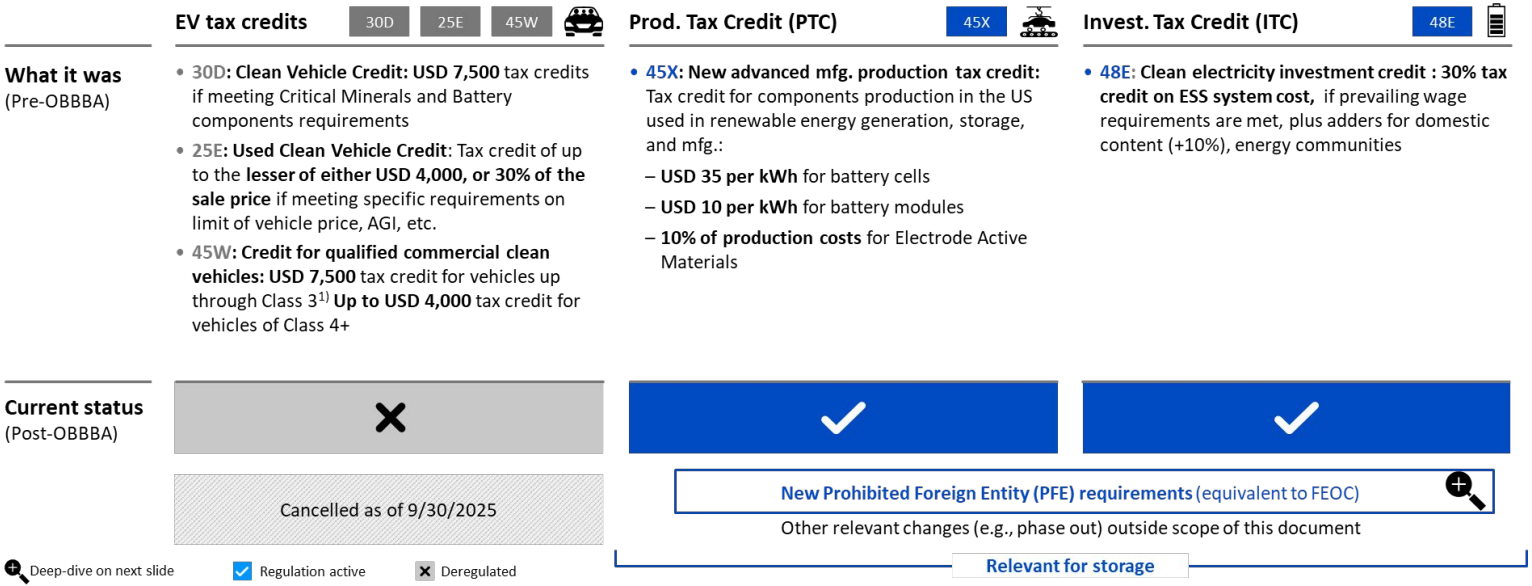
Legal & Operational Rules

- **Transport & Workplace Safety**
  DOT / PHMSA (UN 38.3 + HMR Transport Rules)
  OSHA + NRTLs (UL / CSA / TÜV / Intertek)
- **Vehicles & Mobility**
  NHTSA / FMVSS (Vehicle Electrical Safety)
  EPA & CARB (GHG / ZEV Compliance)
- **ESS in Buildings & Infrastructure**
  IFC / IBC (Fire & Building Codes)
  NFPA 855
  Local AHJs
- **Consumer Electronics**
  CPSC (Consumer Product Safety Commission)
  Retailer Compliance Programs
- **Marine & Aviation**
  USCG / ABYC E-13 / NVIC 02-19
  FAA

Source: IRA; BIL; DOE; DOT; NHTSA; EPA; CARB; UL; NFPA 855; CPSC; FAA

Post-OBBBA, EV Tax Credit Is Removed, Production & Investment Tax Credits Remain but with New Requirements

Trump 2.0 One Big Beautiful Bill Act (OBBBA) impact on selected IRA tax credits



1) <14,000 lb GVWR

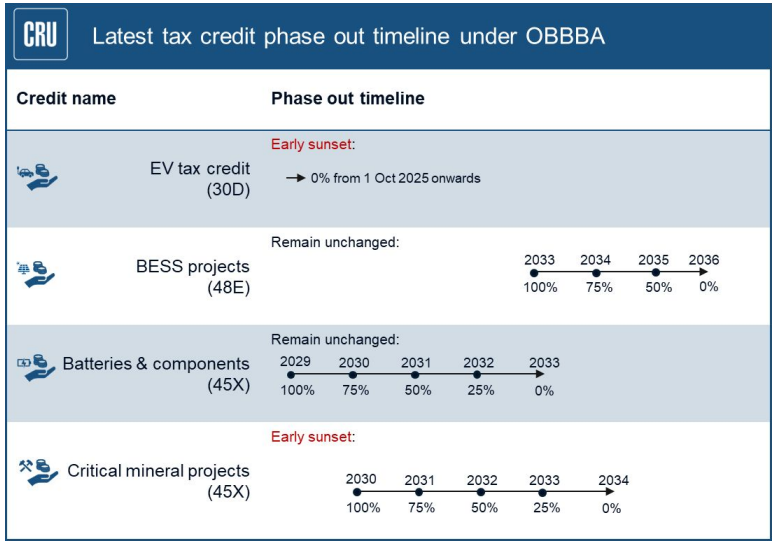
Source: Content & analysis provided by Roland Berger (Distinguished Partner). For more information, visit https://www.rolandberger.com/en/Insights/Global-Topics/Battery.

The One Big Beautiful Bill Act Overhauls US Clean Energy Incentives

Industrial subsidies mostly retained, albeit with sourcing rules.

On 4 July 2025, President Trump signed the One Big Beautiful Bill Act (OBBBA) into law, a sweeping package that significantly rolls back many of the Biden-era clean energy incentives under the Inflation Reduction Act (IRA).

- The **$7,500 EV tax credit is repealed**, but its sourcing requirements live on through the new Prohibited Foreign Entity (PFE) and Material Assistance Cost Ratio (MACR) rules, now applied to the production (45X) and investment (48E) tax credits.
- Using **Chinese critical minerals carries looser restrictions** for battery producers, but the restrictions tighten over time.
- **Most Chinese-origin companies are excluded** from accessing the production tax credit for their US-based battery projects due to their classification as PFEs - akin to the Biden-era 'Foreign Entity of Concern' designation.
- Existing **LFP battery technology partnerships are shielded**, such as Ford-CATL, but new partnerships face disqualification.
- **Stricter investment tax credit rules** make it harder for energy storage projects to qualify from 2026 onwards if they start construction beyond 2025.



Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

New US Tax Credit Rules: Triggering Criteria and Exemptions

Three core disqualifying triggers under Sections 45X and 48E:

1. Project ownership or control by a PFE;
2. Any licensing or financial agreements granting PFEs operational control;
3. Material assistance exceeding the MACR threshold.

… but three key **exemption rules** apply for the 45X and 48E

Exemption criteria	45X (AMPC)	48E (ITC)
Licensing agreement	• Licensing agreements signed before 4 July 2025 are exempt from PFE effective control rules, as long as they are not modified after that date.	
Material assistance	• Materials sourced under binding contracts signed before 16 June 2025 can be excluded from MACR calculations. • These materials must be placed in service or incorporated in a downstream product sold before 1 January 2027.	• Materials sourced under binding contracts signed before 16 June 2025 can be excluded from MACR calculations. • These materials must be placed in service or incorporated in a downstream product sold before 1 January 2030.
Construction start date	n/a	Projects that begin construction before 31 December 2025 are exempt from MACR rules.

Existing agreements temporarily shielded

The final OBBBA text introduces three important exemptions to minimize the disruption for existing contractual and supply chain arrangements, including:

- Existing licensing agreements
- Existing PFE material supply contracts
- Energy storage projects starting before end-2025

For energy storage projects, eligibility for the Investment Tax Credit depends on the construction start date, not the placed-in-service date. Projects that begin construction before 31 December 2025 are exempt from MACR thresholds. Those starting on or after 1 January 2026 must meet escalating sourcing requirements.

Currently, BESS projects are still governed by an earlier IRS guidance from January 2025, which defines construction start based on two criteria:

1. **Physical Work Test**: Requires meaningful physical work to begin on- or off-site (e.g. custom equipment manufacturing).
2. **5% Safe Harbor Test:** Met when at least 5% of total eligible project costs are incurred through binding contracts or expenditures.

On 15 August, the IRS issued updated guidance to restrict the use of the 5% test for large scale solar and wind projects. Although BESS projects are explicitly excluded, similar limitations may be extended at a later stage.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

PFE Is the New FEOC

Chinese involvement is better tolerated

The new PFE framework builds upon and broadens the earlier FEOC restrictions by introducing a two-tiered system:

1. Specified Foreign Entities (SFEs), and
2. Foreign-Influenced Entities (FIEs)

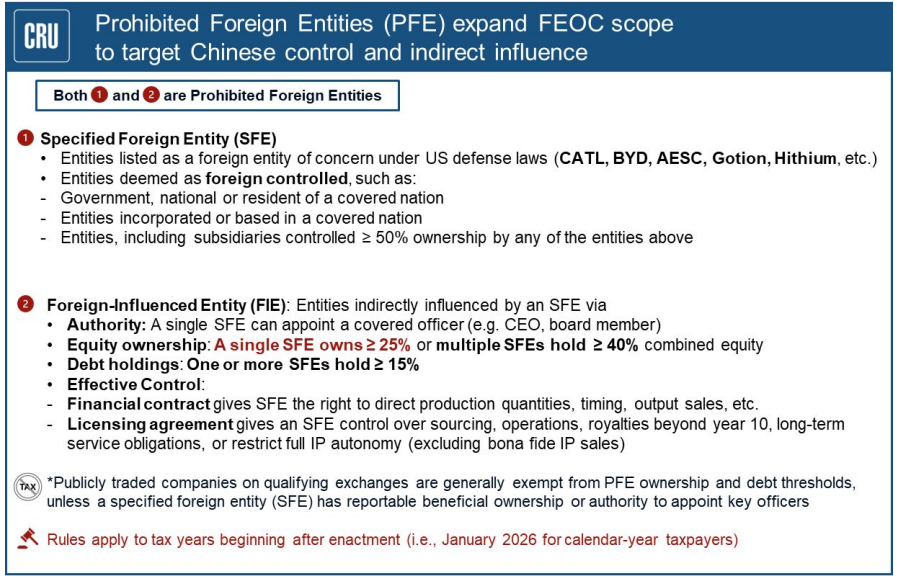
The ownership threshold has led to Chinese p/CAM companies diluting shares in overseas JV projects or providing PFE-related put options as protection to their joint venture partners.

This broader scope allows regulators to assess not only equity ties but also debt, licensing, and operational influence. Under these new definitions, battery projects operated by Chinese-origin companies, such as AESC (on US regulator's watchlist), are expected to be classified as SFEs and disqualified from accessing the 45X production tax credit.

A key distinction between the FEOC and PFE regimes lies in their **tolerance of PFE participation** in the supply chain.

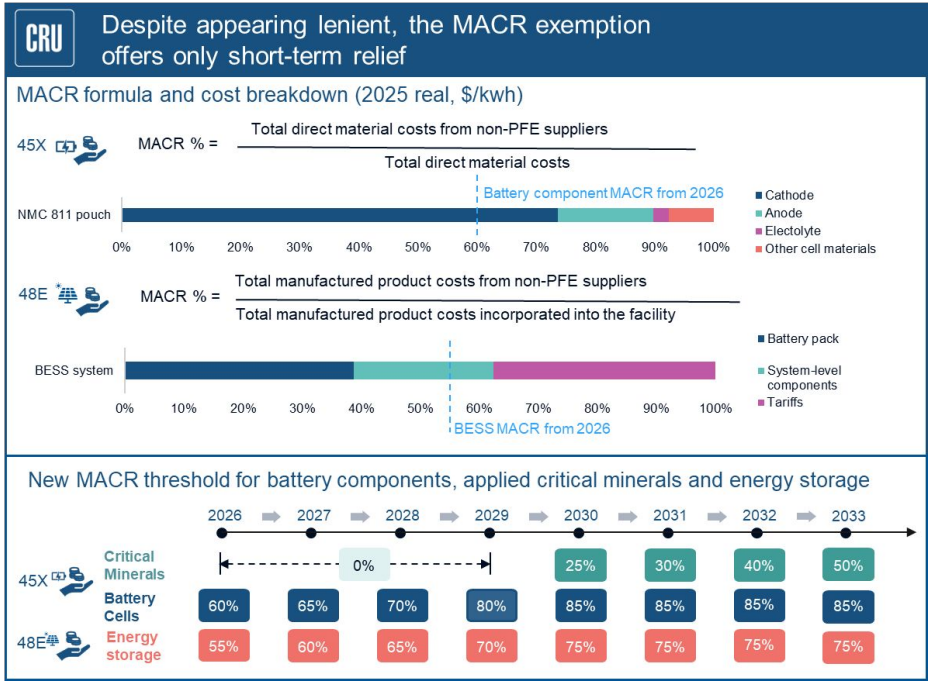
Under the old FEOC rule, any involvement by a FEOC would automatically disqualify a project from receiving the EV tax credit. In contrast, the new PFE framework introduces a more flexible approach: materials or components sourced from a PFE can coexist with compliant sources, as long as the PFE does not exert operational control over the project.

To quantify acceptable levels of PFE involvement, the Material Assistance Cost Ratio (MACR) sets a project-specific cost threshold for PFE-derived content.



CRU Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

Material Assistance Cost Ratio Sets New Sourcing Thresholds



Sourcing rules now apply to 45X and 48E tax credits

The Material Assistance Cost Ratio (MACR) sets a threshold for the proportion of a project's direct material costs or facility cost that must come from non-PFE sources to qualify for tax credits.

One notable relaxation is the 0% MACR requirement for critical minerals through the end of 2029, effectively allowing battery manufacturers to use PFE-linked raw materials without penalty. However, this relief is short-lived as more stringent mineral-by-mineral guidance is expected by 31 December 2027. As a result, manufacturers may only have a two-year window of clarity before compliance tightens again.

For battery components, MACR compliance is generally more manageable. Cathodes, which represent the largest portion of battery material costs, can help meet the threshold as long as they are sourced from non-PFE suppliers - and provided the rules stop at 'tier-1 level' without tracing upstream to pCAM or raw materials.

By contrast, energy storage developers face greater difficulty. LFP battery packs imported from China make up over 60% of total BESS container costs in 2025. This puts the non-PFE share below 40%, well under the 55% MACR threshold coming into effect in 2026. As a result, BESS developers were rushing to meet the "construction start" exemption deadline to avoid MACR-related disqualification altogether.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

US Hikes Tariffs on All Trade Partners

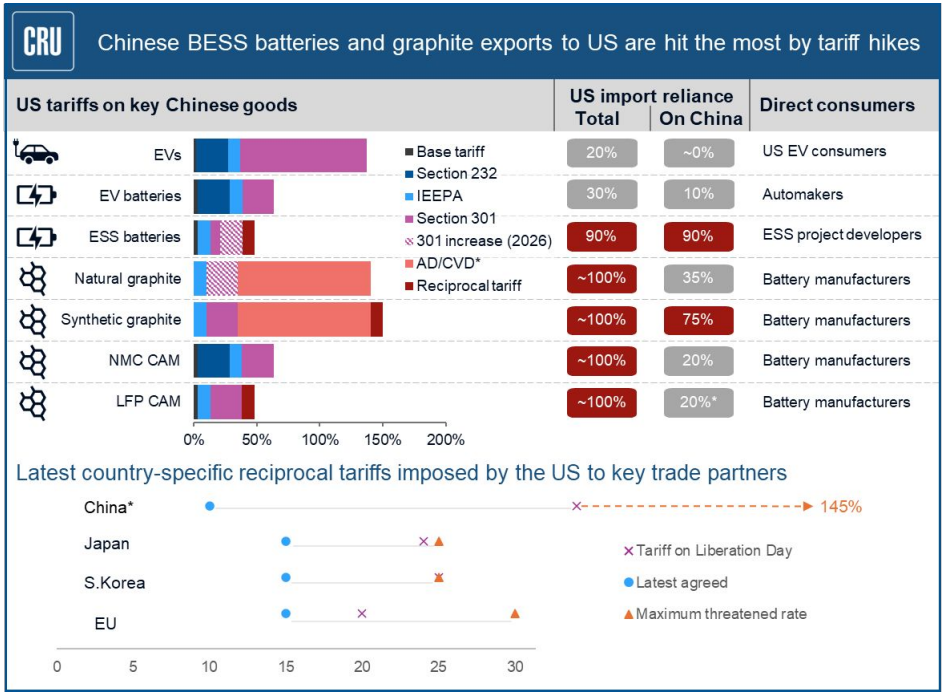
Cost pressures are squeezing profitability

Since returning to office, President Trump has sharply hiked import tariffs.

Key risks:

- While the US is largely self-sufficient in EV and automotive battery assembly, it lacks a domestic supply chain for critical components such as cathode and anode materials.
- The country also lacks LFP battery production, a key technology for energy storage systems and affordable EVs.
- China dominates global supply of LFP cells, CAM, and graphite.
- US-based battery producers remain heavily reliant on cathode imports from South Korea and Japan, both of which are now subject to 15% reciprocal tariffs.

Impacts:
So far, the impact of escalating trade barriers is seen in driving up production costs, squeezing margins, and spurring massive front-loading of procurement ahead of further tariff hikes.



Source: Content & analysis provided by CRU Group (Distinguished Partner).For more information, visit crugroup.com.
*In addition to imports from China, US relies on a Chinese-origin company in Indonesia for LFP CAM.

One-Year US-China Trade Deal Lowers Battery Material Barriers

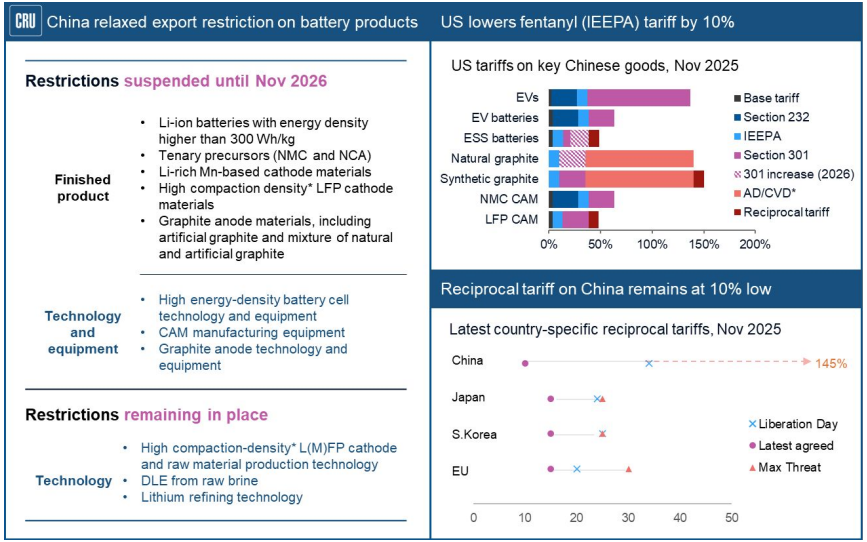
On 1 November, the White House released details on the one-year agreement the US President reached with China. The key updates related to the battery value chain are the **relaxation of US tariffs on Chinese goods and China's export controls**.

US cut the 10% fentanyl tariff for one year. The suspension of heightened reciprocal tariff was also extended. The 10% reciprocal tariff will remain during the suspension. China removed the latest export restrictions on various battery materials announced on 9 October, which required companies to apply for export licenses.

Before the trade deal was released, Korean battery and CAM producers front-loaded export orders for ternary precursor in November because, although Chinese firms were confident that they would obtain the licenses, the approval procedure normally takes 2-4 months and could affect exports in Q4.

Opportunity:
The extension period buys more time for US companies to secure alternative supplies.

Risks:
- China dominates the global supply chain.
- Ramp-up periods for and OEM certification timelines for new supply are longer than this 1-year extension.



Technology export controls that remain in place increase the difficulty for US and other players to build local capability utilising Chinese technology.

Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

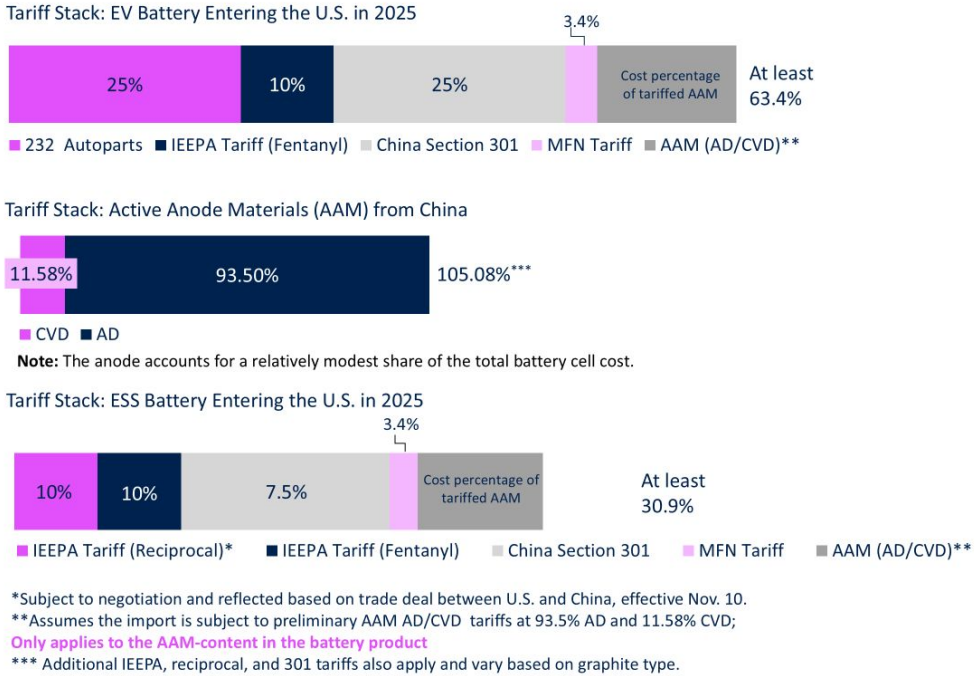
New Tariff Explainer: Tariff Stack for Lithium-ion Batteries from China - December 2025

Imports of batteries and related components are subject to tariffs pursuant to different statutory authorities.

The graphs show tariffs impacting EV and ESS battery supply chains prior to January 1, 2026. (It is worth noting that certain tariffs included in these tariff stacks fluctuated over the course of 2025):

- 25% Section 232 tariff on imports of automobiles & automobile parts
- 10% IEEPA "fentanyl" tariff on imports from Mexico, Canada, and China
- China Section 301 tariffs (25% for EV batteries; 7.5% for ESS batteries)
- 3.4% Most Favored Nation (MFN) tariff
- Anti-Dumping / Countervailing (AD/CVD) Duties on Active Anode Material (AAM) imported from China (Preliminary 93.5% and 11.58% rates *on the value of AAM within a battery only* for country-wide AD and CVD rates, respectively, with higher rates for AAM from certain companies. The U.S. Department of Commerce is expected to issue final rates in 2026.

IMPORTED CHINA LITHIUM-ION BATTERY CELL - TARIFF STACKS



*Subject to negotiation and reflected based on trade deal between U.S. and China, effective Nov. 10.
**Assumes the import is subject to preliminary AAM AD/CVD tariffs at 93.5% AD and 11.58% CVD;
Only applies to the AAM-content in the battery product
*** Additional IEEPA, reciprocal, and 301 tariffs also apply and vary based on graphite type.

Source: Solar Energy Industries Association analysis

New Tariff Explainer: Tariff Stack for Lithium-ion Batteries from China - January 1, 2026

Major changes between 2025 and 2026 tariff stacks include the following:

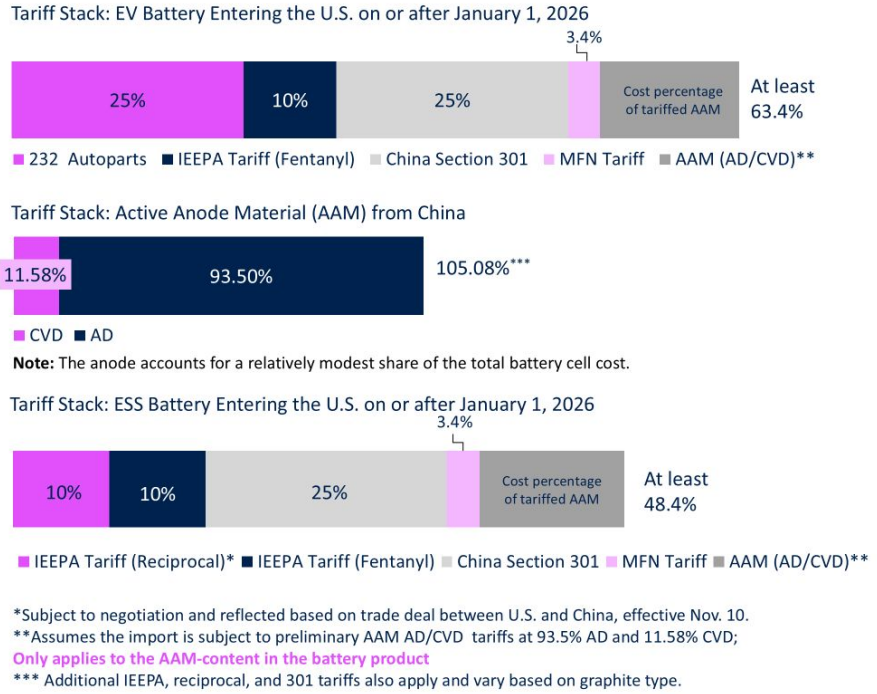
1. China Section 301 tariff increase for ESS batteries from 7.5% to 25% (to match EV battery tariff rate, which remains at 25%)

(Not shown in graph):

2. 25% China Section 301 tariff on natural graphite (up from 0% in 2025)
3. 25% China Section 301 tariff on permanent magnets (used in EVs) (up from 0% in 2025)

As stated in the previous slide, the U.S. Department of Commerce is also expected to issue final AD and CVD rates for AAM imported from China in 2026.

IMPORTED CHINA LITHIUM-ION BATTERY CELL - TARIFF STACKS



*Subject to negotiation and reflected based on trade deal between U.S. and China, effective Nov. 10.
**Assumes the import is subject to preliminary AAM AD/CVD tariffs at 93.5% AD and 11.58% CVD;
Only applies to the AAM-content in the battery product
*** Additional IEEPA, reciprocal, and 301 tariffs also apply and vary based on graphite type.

Source: Solar Energy Industries Association analysis

DOE Battery Priorities

DOE battery priorities under the Trump Administration have been characterized by a pivot toward the upstream, cancellations of financial support for previously-allocated funds for battery and recycling projects, and organizational restructuring.

Jan. 6, 2025

Battery Materials Processing & Battery Manufacturing Grants Program

NOI for ~$725m for grants to support domestic battery materials processing, manufacturing, and recycling

Aug. 13, 2025

$1B NOFO in accordance with "Unleashing American Energy" E.O.

$500m for processing and battery manufacturing, $250m for industrial byproduct recovery, $135m for rare earth supply chain enhancement, and $40 million for ARPA-E RECOVER

Nov 14 2025

2 NOFOs of $355M to expand domestic production of critical minerals and materials

$275m for U.S. industrial facilities to produce critical minerals from existing industrial and coal byproducts, and $80m to establish "Mine-of-the-Future" proving grounds for testing of next-generation mining and mineral-processing technologies

Dec. 1, 2025

DOE CMEI NOFO up to $134M

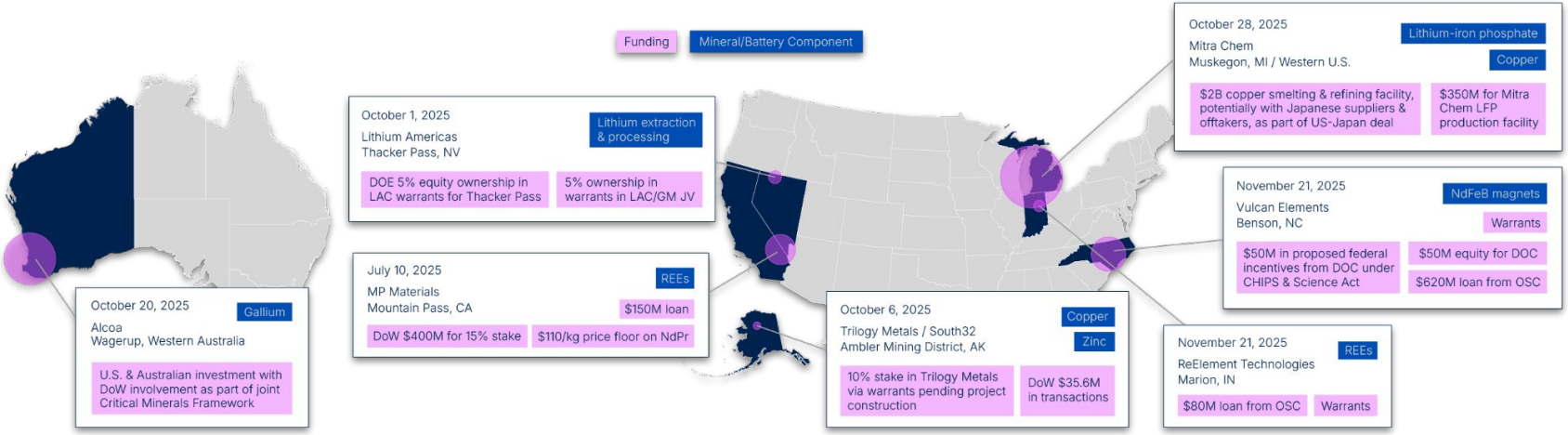
Supports REE recovery and refining from unconventional feedstocks, including mine tailings, e-waste, and other waste materials

Source: Solar Energy Industries Association (SEIA) based on US DOE press releases

Equity Stakes & Trade Deals

The Trump Administration has taken an unconventional approach to funding upstream activities by taking equity stakes in U.S. companies and using trade deals to facilitate upstream investment with foreign partners. The moves have been complemented by an organizational restructuring in November 2025 to align DOE priorities with Trump Administration goals. Key changes include the rebranding of the Loan Programs Office as the Office of Energy Dominance Financing and the absorption of the Office of Manufacturing and Energy Supply Chains into the new Office of Critical Minerals and Energy Innovation.

COMPANIES THAT RECEIVED EQUITY STAKES FROM THE U.S.

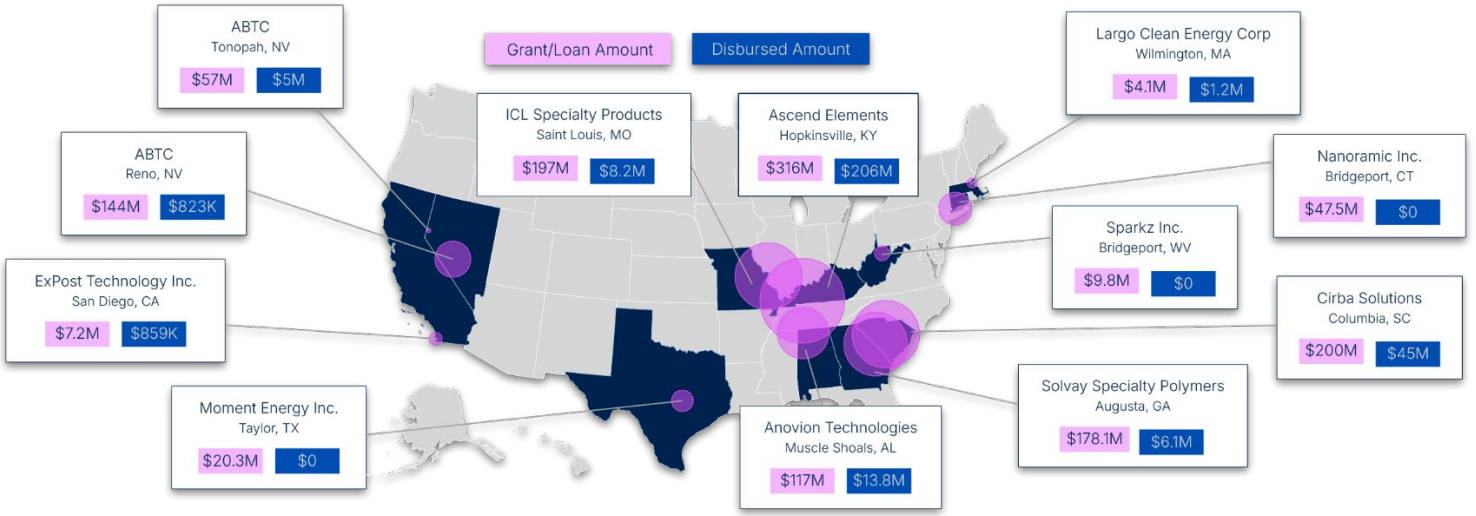


Source: Solar Energy Industries Association (SEIA) based on US agency press releases

DOE Funding Cancellations

Despite recent USG efforts to take equity stake and use trade deals to facilitate investment in U.S. mineral and battery supply chains, the Trump Administration has also canceled financial support for projects with previously-allocated funds. The cancellations impacted companies across the battery supply chain, from battery manufacturing and recycling to the production of electrode active materials, binders and separators, and processed materials for alternative battery chemistries.

U.S. PROJECT FUNDING CANCELLATIONS



Source: Solar Energy Industries Association (SEIA) based on US DOE press releases

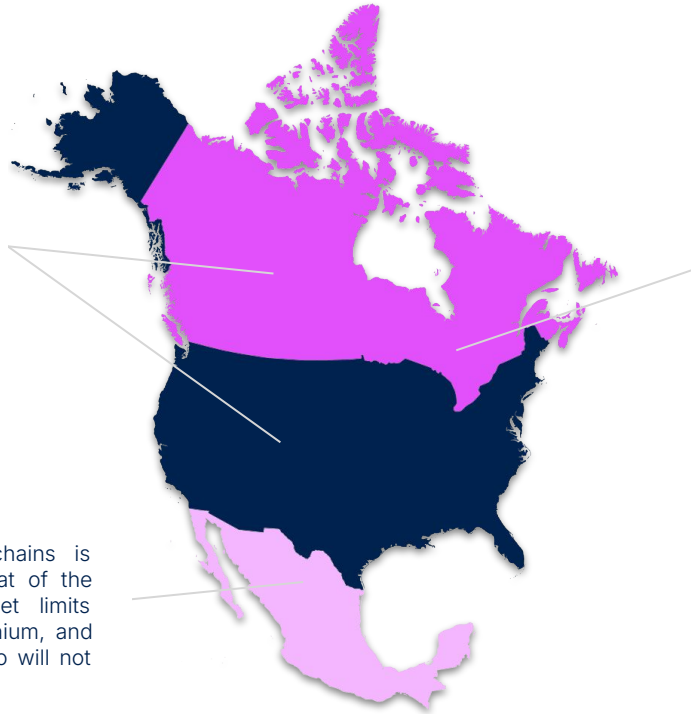
US, Canada and Mexico Critical Mineral and Battery Supply Chain Priorities

U.S. - Canada Cooperation: DPA Title III

The Defense Production Act (DPA) Title III defines "domestic source" as Canada, the UK, and Australia, in addition to the U.S.. Canadian companies are therefore eligible to receive financial support in the form of grants, loan guarantees, subsidies, and offtake agreements. This authority has been used for decades and remains a key tool in building out allied industrial base capacity. In 2023, the U.S. announced $250 million in Defense Production Act (DPA) funding for U.S. and Canadian companies to mine and process critical minerals for batteries. In 2024, DoD invested $20 million into Canadian company Electra Battery Materials to build out and commission North America's only cobalt sulfate refinery in Ontario.

Mexico

Mexico's investment in battery supply chains is comparatively less comprehensive than that of the U.S. and Canada. Mexico's 2026 budget limits investment in critical minerals, including lithium, and President Sheinbaum has stated that Mexico will not grant new mining concessions.



Canada

Canada offers several tools to support upstream and midstream battery supply chains, including the Critical Minerals Infrastructure Fund (CMIF); Critical Minerals Research Development and Demonstration (CMRDD); Critical Minerals Infrastructure Fund (CMIF) – Indigenous Grants; Critical Minerals Geoscience and Data (CMGD); and Canada First and Last Mile Fund.

March 2025: Canada announces 32 projects representing up to $50 million to support Canada's critical mineral value chains, in alignment with the Canadian Critical Minerals Strategy

August 2025: NRCan invests $6,225,000 to support Graphite Nordique's Lac-des-Îles expansion project for natural graphite mining.

October 2025: Canada announces 26 new investments, partnerships and measures to accelerate and unlock $6.4 billion of critical minerals projects.

Source: Solar Energy Industries Association

US-Mexico-Canada Agreement (USMCA) Renegotiation

Why is the USMCA relevant to batteries?

The USMCA governs trade between the US, Mexico, and Canada. It preserves duty-free trade for many products, tightens rules of origin (ROO), and requires compliance with labor and environmental standards. The legislation includes a six-year review and expires after 16 years unless renewed.

The joint 6-year review deadline is July 1, 2026. Industry representatives submitted comments to the US Trade Representative (USTR) in 2025 to inform potential changes.

Industry Recommendations Pertinent to Batteries and Minerals:

- Expanded ROO to include minimum thresholds for critical minerals sourced and processed in North America
- Section 232 tariff relief for USMCA-compliant products subject to Section 232 tariffs on steel and aluminum
- Stronger compliance with auto ROO, regional and labor value content, and steel and aluminum requirements
- Consistent and transparent enforcement of labor and environmental standards



Industry Recommendations Specific to Batteries and Minerals:

- Establishment of a chapter or annex on critical minerals, which includes commitments for guaranteed offtake of critical minerals, rare earths, or related components and coordination on mineral recycling, recovery, and foreign investment in supply chains
- Establishment of a Critical Minerals Initiative under the North American Competitiveness Committee to identify and overcome bottlenecks North American minerals development
- Tariff-free trade of critical minerals across North America
- Adoption of the Electric Vehicle Charging Standard (J3400 – Society of Automotive Engineers) across North America
- Expanded TN visa flexibility to facilitate the flow of technical skills in critical minerals processing across North America

Source: Solar Energy Industries Association

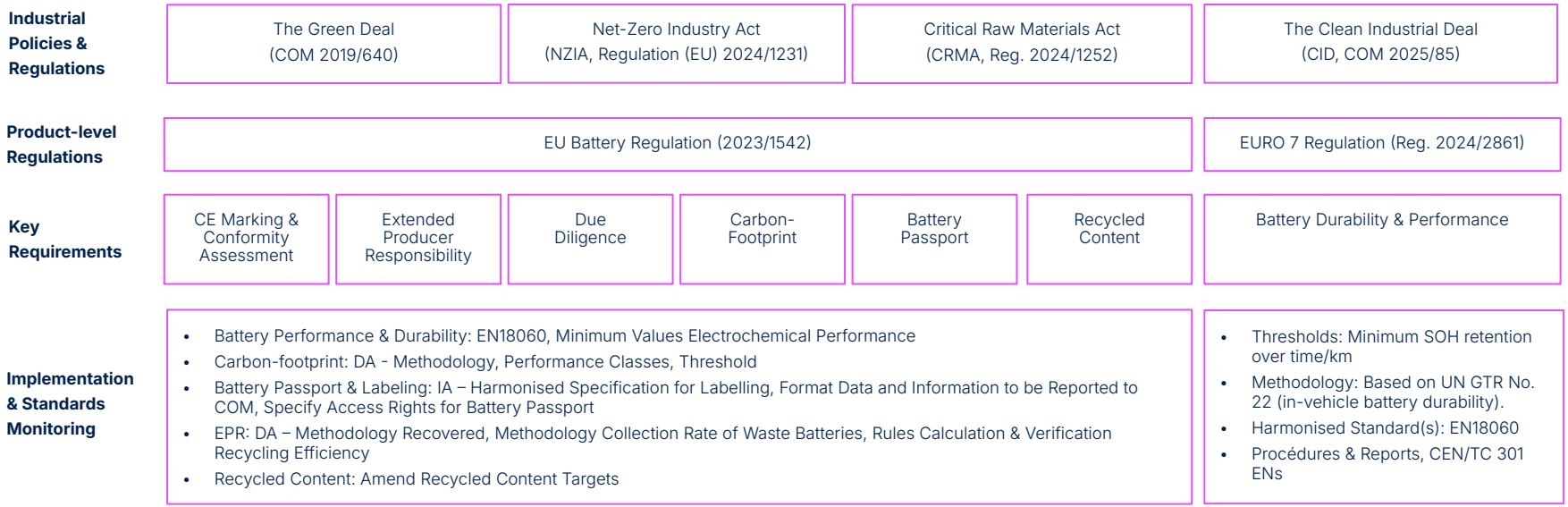
POLICY



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The EU's Integrated Battery Governance Framework

EU policy, industrial strategy, and product regulation now converge under a **single, vertically aligned framework**. The EU Battery Regulation (2023/1542) functions as the core legal backbone, linking CE marking, carbon footprint rules, supply chain due diligence, recycled content, and battery passport obligations to broader net-zero and strategic autonomy goals set by the Green Deal, NZIA, and CRMA. In parallel, vehicle-level regulations, such as emissions targets, introduce durability and performance requirements that further shape battery design, testing, and data obligations for EU market entry.



Source: EU Battery Regulation (EU) 2023/1542; EURO 7 (EU) 2024/1257; NZIA (EU) 2024/1735; CRMA (EU) 2024/1252; European Green Deal;Clean Industrial Deal

EU Battery Regulation: Summary of What the Law Does

Aug. 2023

Regulation enters into force at Union level and begins phased application across categories.

Feb. 2024

Regulation begins to apply with transitional arrangements.

Aug. 2024

August 2024
CE marking and EU Declaration of Conformity duties for batteries start.

2026-2027

Labelling obligations begin in 2026 and QR access to required battery information follows in 2027, subject to the implementing act.

Feb. 18, 2027

Removability and replaceability apply to portable and light means of transport batteries. Battery passport begins for electric vehicle, rechargeable industrial above two kilowatt hours, and light means of transport batteries.

Aug. 18, 2027

Due diligence obligations on critical battery materials begin after the two year postponement.

2027+

Collection and material recovery targets start to bite. Portable collection is sixty three percent by end 2027 and seventy three percent by end 2030. Recovery for cobalt, copper, lead, and nickel is 90% by end 2027 and 95% by end 2031, and lithium is 50% by end 2027 and 80% by end 2031

2031 - 2026

Minimum recycled content starts in 2031 and rises again in 2036 for cobalt, nickel, lithium, and lead.

Scope and who

One rulebook for every battery placed on the Union market. Categories include portable, light means of transport, starter lighting ignition, industrial, and electric vehicle batteries.

Design and repair

A portable battery must be readily removable and replaceable by the end user using commonly available tools and without heat or solvents. If a special tool is truly needed it must be supplied at no cost. Where end user access would compromise safety or essential function, replacement by an independent professional is required and must be feasible.

Information and traceability

Labels and a QR code provide standardised data and link to online information. A digital battery passport begins in 2027 for electric vehicle, light means of transport, and rechargeable industrial batteries above two kilowatt hours and is accessed through a unique identifier and QR.

Circularity and end of life

Producers finance and meet collection targets for portable and light means of transport batteries, and recyclers meet recovery performance for key materials. Recycled content in new batteries begins in 2031 and increases in 2036 to drive a circular value chain

Early designs already reflect the 2027 direction. Pixel Watch 4 is serviceable with a replaceable battery and display. Pixel Buds 2a include a charging case with a user replaceable cell, with guides and service options visible publicly

Source: Wired, DigitalEurope, Consilium-Europa, EU regulation documentation

Emerging EU Battery Policy Signals: Performance Regulation Meets Industrial Strategy

The EU is simultaneously raising battery requirements across both technical performance and supply-chain dimensions. Through EURO 7 and NZIA, battery sustainability is governed across the full lifecycle, performance, durability, data, manufacturing location, and recycling, while industrial localization is leveraged to strengthen EU strategic autonomy, economic resilience, and geopolitical positioning.

EURO 7, Regulation (EU) 2024/2861: Battery Durability as a Regulatory Requirement

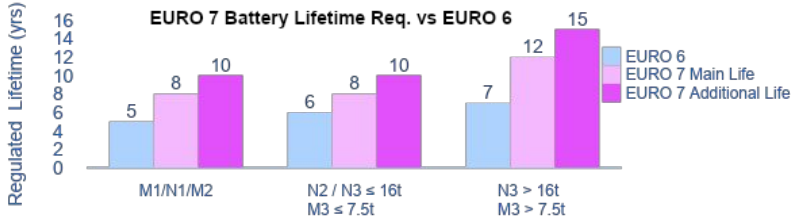
The more than decade-long gap between Euro 6 (2007) and Euro 7 (2024) reflects not regulatory delay, but a fundamental shift in focus, from tailpipe emissions control to governing lifetime performance, durability, and system behavior in an electrified vehicle landscape. Euro 7 elevates battery durability from an engineering objective to a regulatory compliance parameter, reshaping how batteries are designed, validated, and managed across the full vehicle lifetime.

Key Requirements Cover:

- Emission limits (ICE and hybrids)
- Battery Durability & SOH requirements
- On-board monitoring and data availability
- In-use conformity over extended lifetime
- Non-exhaust emissions (brakes, tires)

Impact:

- Increased technical & validation risk
- Higher life cycle testing & compliance cost
- Elevated uncertainty for heavy-duty (N2/N3/M3) battery systems



EURO 7 Minimum SOH Threshold:
For M1 / N1 / M2: 0-5 year: M1 ≥ 80%; N1 ≥ 75%; 5-8 year: M1 ≥ 72%; N1 ≥ 67%
For N2 / N3 / M3: to be specified through implementing acts or harmonized technical standards.

NZIA, Regulation (EU) 2024/1231: Industrial Localization Increasingly Determines Long-term Market Access

The Net-Zero Industry Act (NZIA) marks a strategic shift in EU climate governance. Rather than regulating product performance, NZIA governs where and how net-zero technologies are manufactured, introducing binding industrial capacity, permitting, and financing mechanisms to strengthen EU strategic autonomy.

Strategic Areas & Domestic Capacity Target: **40% EU-based Capacity by 2030***
Materials Processing | Cell Manufacturing | Recycling

Policy Instruments & Incentives:

Accelerated Permitting

Priority Access to EU and National Funding

Access to Public Procurement & Auctions

Impact on EU-based Players:

- Structural advantage via permitting, funding, and procurement
- Faster project execution through streamlined approvals
- Stronger positioning in public tenders and renewable auctions
- Reduced long-term regulatory and investment risk

Impact on Non-EU-based Players:

- Indirect market pressure despite technical compliance
- Localization shifts from optional to strategic
- Increased reliance on EU partnerships or local manufacturing
- Investment decisions increasingly shaped by policy alignment, not cost alone

**Capacity-based benchmark across the value chain; not a product-level requirement*

Source: EURO 7 (EU) 2024/1257; NZIA (EU) 2024/1735

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Battery Passport

Digital battery passport arrives in 2027 for larger rechargeable batteries. The passport will be delivered through delegated and implementing acts. Teams should map data sources now to meet the 2027 start.

Who Needs a Passport

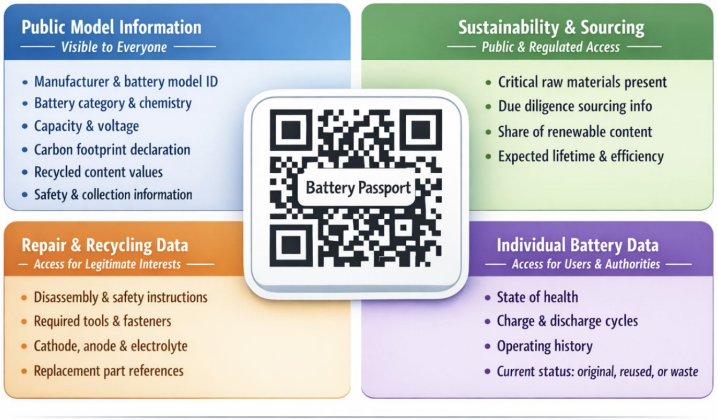
Electric vehicle batteries, Light means of transport batteries such as e-bike and e scooter packs

Rechargeable industrial batteries above two kilowatt hours
Portable batteries used in typical consumer electronics are not in scope for the first wave.

When

From 18 February 2027, each covered battery placed on the market or put into service in the European Union must have a digital passport accessible through a unique identifier and QR.

WHAT DATA IT CARRIES



EU Battery Regulation 2023/1542, Article 77 & Annex XIII

The full list of what the passport needs to contain can be found here.

Source: TWAICE, Power progress news, Circular-Economy-Europa, TheBatteryPass, EU Regulation

EU/UK Rules of Origin Incentivises CAM and Battery Producers to Localise Production

Starting in 2027, automakers must meet stricter Rules of Origin (RoO) under the UK-EU Trade & Cooperation Agreement (TCA) for EVs to qualify as 'originating' and **avoid a 10% cross-border tariff.**

Simply assembling batteries in the UK/EU is not sufficient – key materials, such as CAM, must also meet the originating criteria. If CAM or other key components are sourced from outside the region without substantial processing, the entire battery may be classified as non-originating, triggering tariffs when an EV is exported to the UK or outside EU.

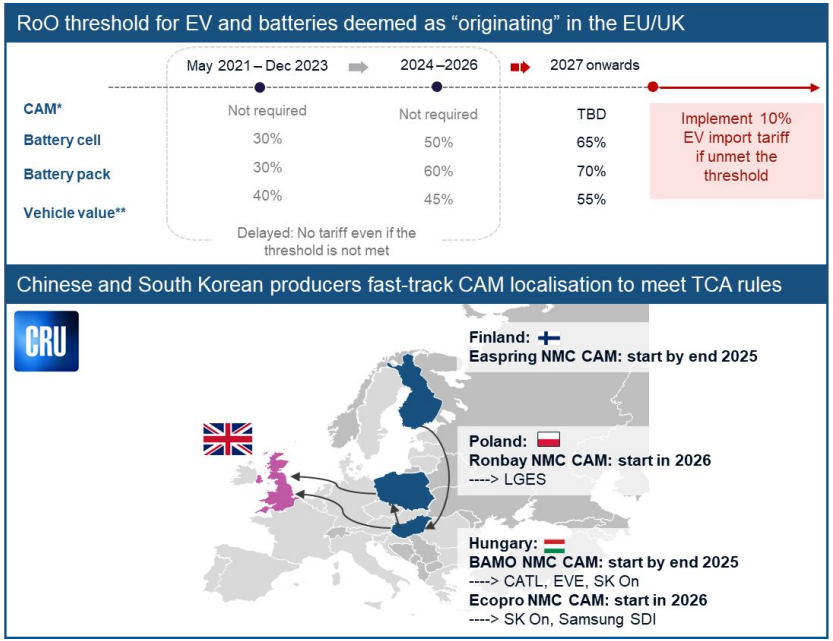
For EV makers and battery suppliers, meeting the compliance before 2027 is critical, as a 10% tariff on the entire EV value, equivalent to ~$65 /kWh based on popular 2025 models, is far more costly than the cost difference between manufacturing batteries in Europe versus Asia.

Currently, regulatory scrutiny of RoO stops at the CAM stage, which accounts for 30-50% of a battery cell's value. Importing pCAM and processing it into CAM within the UK or EU qualifies as originating domestically.

This pathway is preferred by CAM producers, as importing pCAM is far more cost-effective and avoids delays due to environmental permitting issues their pCAM partners are facing in Europe.

Announcements indicate that localisation efforts are accelerating, with Chinese and Korean producers advancing CAM projects in the region.

However, other producers –especially those for LFP– have said that this incentive is outweighed by the higher cost of production, and prefer instead to localize production in Morocco or Indonesia, or even stay in China.



Source: Content & analysis provided by CRU Group (Distinguished Partner). For more information, visit crugroup.com.

The European Commission's "Battery Booster" Program Aims to Bolster a Domestic Supply Chain

Six pillars of the Battery booster strategy, communicated Dec. 16 2025 by the European Commission

Pillar I	**"Supporting The Ramp Up Of EU Manufacturers Through Financial Backing"** Measures include c. **EUR 2.2 billion funds**, a new Battery Booster Facility mobilizing **EUR 1.5 billion in interest-free loans** from 2026, and **production ramp-up support** under a future European Competitiveness Fund
Pillar II	**"Developing A Resilient Upstream Value Chain For Access To Raw Materials And Inputs"** Supports 32 EU and 10 non-EU strategic CRM projects under the Critical Raw Materials Act, a RESourceEU Action Plan with funds of **EUR 3 billion in 2026, EUR 2.9 billion InvestEU guarantee** expected to **unlock about EUR 55 billion investment,** including roughly EUR 6 billion in CRMs by2027
Pillar III	**"Ensuring Value Added Investments And Industrial Level Playing Field In The EU"** Envisages **new conditions on FDI** in strategic battery segments (e.g. limits on foreign ownership, technology transfer, supply-chain integration), combined with competition and trade instruments
Pillar IV	**"Supporting 'Made In EU' Offtakes, Boosting Resilience And Sustainability"** Aims to create "made in EU" lead markets via upcoming **EU content requirements** for batteries and components under an Industrial Accelerator Act and **resilience criteria in EV subsidy schemes** required by the Net-Zero Industry Act from 01/2026
Pillar V	**"Boosting Research, Innovation And Skills For The Eu Battery Value Chain"** Accelerates research, innovation & skills through **R&D funding, investments for next-gen chemistries, start-up funding** etc.
Pillar VI	**"Coordinating Action To Maximize Impact Across Europe"** To **align EU, national and private investments**, and **synchronize demand-side measures** e.g. "made in Europe" requirements

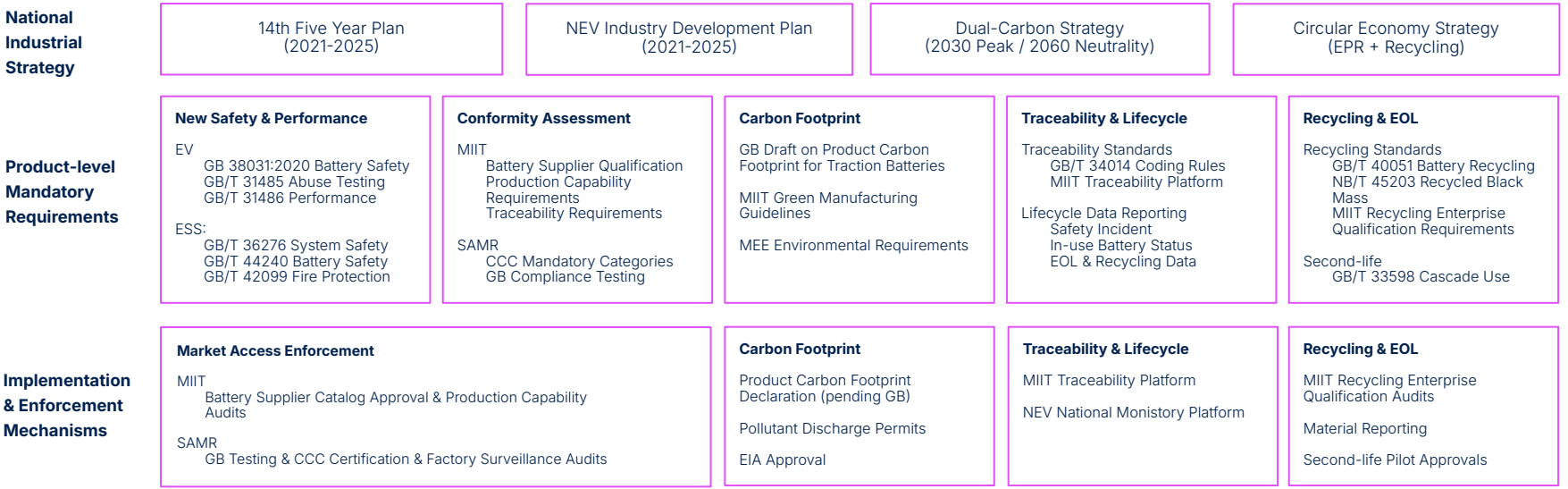
Source: Content & analysis provided by Roland Berger (Distinguished Partner). For more information, visit https://www.rolandberger.com/en/Insights/Global-Topics/Battery.

POLICY



China's Vertically Integrated Battery Governance Framework

China operates the world's most vertically integrated battery governance system, linking national industrial strategies directly to product-level standards and enforcement mechanisms. Through a combination of mandatory GB standards, MIIT qualification systems, traceability platforms, and recycling requirements, China ensures full-lifecycle oversight of EV and ESS batteries.



See the **China section** for wider commentary on China policies and regulations.

Source: State Council of PRC; MIIT; SAMR; MEE; GB / GB-T standards

VF | VOLTA FOUNDATION

Japan's Policy Framework for Batteries

Battery Industry Strategy
(August 2022)

- Act on Economic Security Promotion (May 2022)
- Act on the Promotion of a Smooth Transition to a Decarbonised Growth-Oriented Economic Structure ("GX Promotion Act" enacted May 2023, amended May 2025)
- The 7th Strategic Energy Plan (February 2025)

Targets Toward 2030

- Establish a manufacturing base for liquid LIB
- 150GWh/yr of domestic manufacturing capacity by 2030
- Secure a global presence
- 600GWh/yr of global manufacturing capacity by 2030
- Capture the next-generation battery markets
- Commercialize solid-state batteries around 2030 and maintain Japan's position as a technology leader from 2030 onward.

Key Initiatives

1. Policy package for expanding the domestic foundation
2. Strategic formation of global alliances and global standards
3. Securing upstream resources
4. Development of next-generation technologies
5. Creation of the domestic market
6. Strengthening human resource development and retention
7. Enhancement of the domestic infrastructure and environment

Japan's battery policy is anchored in the 2022 Batteries Industry Strategy, which is reinforced by economic security and carbon-neutral energy policies, and sets out clear 2030 targets supported by a broad, multi-pronged implementation approach.

Source: Battery Industry Strategy (in Japanese)

Korea's Policy Framework for Batteries

2030 K-Battery Development Strategy
(Announced in July 2021)

Vision: Make Korea the world's No. 1 nation in next-generation batteries by 2030.

Strategic Directions

1. Secure unique, top-tier technological capabilities - promote large-scale R&D through public-private cooperation.
2. Build global bases - form an ecosystem through industry-academia collaboration.
3. Expand the battery market - create public- and private-sector demands.

(Secondary) Battery Industry Innovation Strategy
(Announced in November 2022)

Vision: Make Korea the world's strongest battery by 2030.

Strategic Directions

1. Secure a stable supply chain.
2. Establish hubs for advanced technological innovation.
3. Build a robust domestic industrial ecosystem.

Key Initiatives

Form a private-public and cross-industry "Battery Alliance"

- Funded by Korea Trade Insurance Corporation and The Export-Import Bank of Korea (KRW 3T [USD 2.07B]/5 years)
- Critical mineral projects (Chile, Canada, Australia etc.)
- Building battery closed-loop system
- Human resource development

Investment in cutting-edge technologies

- The government invests KRW 1T [USD 690M], and the private sector invests KRW 19.5T [USD 13.5B] by 2030
- Build R&D center and production base (LGES, Samsung SDI, SK On)

Promote investment in domestic facilities

- The government invests KRW 5T [USD 3.45B] in loans and guarantees

Build a domestic industry ecosystem

- Professional development of 16,000 people by 2030
- University courses specializing on batteries

Source: 2030 K-Battery Development Strategy, Battery Industry Innovation Strategy (in Korean), Exchange rate: 1 KRW=0.00069 USD

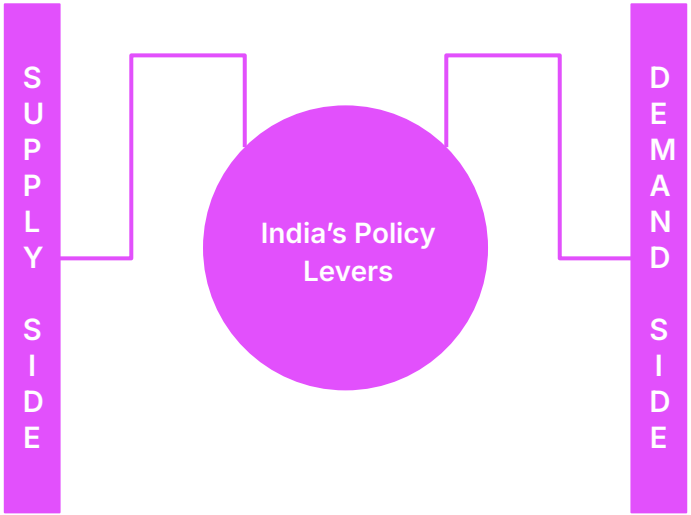
India's Battery Policy and Regulatory Landscape

PLI Scheme: ₹18,100 crore program to boost **50 GWh** of advanced chemistry cell battery production with 10GWh allocated to Grid Scale Stationary Storage.

Battery Recycling Policy: In development to support a **circular energy economy**.

State Incentives: Multiple states offering manufacturing benefits to attract battery plant investments

National Critical Mineral Mission (NCMM), with 1690 million$ incentive to boost recycling capacity for critical minerals.



National Energy Storage Framework: A comprehensive policy vision to streamline storage development.

Advisory on Solar + Storage: Recommends solar projects to include 10% or two hours of storage

Electricity (Amendment) Rules, 2025 - Enable BESS to operate independently or within the power network, and allow ownership and trading of storage capacity by any entity.

Waivers and Incentives:

- Waiver of Inter-State Transmission System (ISTS) charges for BESS upto June'28.
- Viability Gap Funding (VGF): Initially targeted 4 GWh of storage, later increased to 13.5 GWh, with funding up to 30% of project costs.

Energy storage policies have been evolving since 2014, gaining momentum both on the supply and demand side after the Ministry of New and Renewable Energy (MNRE) set a national target of achieving 500 GW of renewable capacity by 2030.

Overview of Key Policies & Investments in the MENA Region

Oil-rich MENA countries are getting on board the energy transition. Some are in locations with high solar (and battery) potential while others are mineral-rich (e.g. lithium, phosphates).

Country	Key Policies	Details
Saudi Arabia	Vision 2030	Economic diversification away from oil and toward critical mineral mining and refining
	Future Minerals Forum	Global platform for Saudi to position itself in the world's critical mineral industry
	EV targets	Targeting domestic production of 500,000 EVs by 2030 and 30% of all Riyadh vehicles to be electric
	MoC with US	Plan to establish a framework for collaboration on critical minerals
UAE	Operation 300bn	Raise industrial sector's contribution to GDP from AED133 billion to AED300 billion
	Net Zero 2050	Roadmap for clean energy development and deployment
	Circular Economy Policy 2021-2031	Strives for sustainable management and efficient utilisation of natural resources
	National Hydrogen Strategy	Targeting 1.4 Mt of clean hydrogen 2031, rising to 15 Mt by 2050
	National Electric Vehicles Policy	Reduce transport sector's energy consumption by 20% by 2050
Morocco	Free Trade Agreements	FTAs with over 50 jurisdictions including the US, UK, and EU
	Belt and Road Initiative	First North African country to sign on to China's BRI
	EV production and export target	Aiming for production of 100,000 EVs per year by 2025 with 60% of vehicle exports to be EV by 2030
Oman	Net Zero 2050	30% renewables by 2030 and net zero by 2050
	Green Hydrogen Strategy	1 Mt of green hydrogen per year by 2030, 8.5 Mt by 2050
Qatar	EV penetration target	Targeting 10% of vehicle sales to be for EVs by 2030
Egypt	Renewables target	Targeting 42% renewables in its energy mix by 2030

Country	Fund	Company	Target country	Notes
Saudi Arabia	PIF	Lucid Motors	US	Majority shareholder via Ayar. In March 2024, PIF invested $1 billion
		Ceer Motors	Saudi Arabia	First Saudi EV-focused brand
		Tasaru Mobility Investments	Saudi Arabia	Setup to invest in domestic automotive supply chain
		Manara Minerals Investment company	Saudi Arabia/ International	JV between PIF and Ma'aden to investin global mining assets
		Saudi Arabian Mining Company	Saudi Arabia	Multi-commodity mining and metals company
		Electric Vehicle Infrastructure Company	Saudi Arabia	JV between PIF and the Saudi Electricity Company to support EV uptake in Saudi Arabia
UAE	ADQ	Orion Abu Dhabi	UAE	JV ($1.2bn) between ADQ and Orion Resoruce Partners to invest in and secure offtakes with metals and mining companies in emerging markets
		Eni	Italy	MoU on critical minerals
	Mubadala	Zenobe	UK	Investment (£270 million ($343 million)) via Infracapital for fleet electrification and BESS
		Masdar	UAE	Shareholder (33%)
		ENGIE	France	MoU to look into EV charging
Qatar	QIA	Glencore	Switzerland	Shareholder (8.6%)
		TechMet	US/Ireland/ International	Investment ($180 million) to support TechMet's investments in critical mineral operations around the world
		QuantumScape	US	6.5% when invested in 2020
		Ascend Elements	US	Investment (Series D)
Oman	OIA	Ascend Elements	US	Investment (Series C)
		Our next Energy	US	Investment
		Group14	US	Investment ($400mn funding round)
		LiChem	US	MoU to explore lithium refinery in Oman
Bahrain	Mumtalakat	Masdar	UAE	MoU to explore renewables in Bahrain

POLICY



Legal Summary

2025 saw intense global patenting (driven overwhelmingly by China and Asian industry leaders), steady but strategically important litigation activity and continued safety-driven recalls across EVs and consumer devices.

Global Patent Landscape: China dominates filings, with rapid growth from emerging domestic applicants and many China-only families; Asian companies remain the core engines of battery innovation. Li-ion keeps its place as the core technology focus worldwide, with strong activity in NMC/LFP cathodes, lithium-metal, silicon anodes and solid-state variants. Na-ion growth has been largely driven by CATL (>20%). Recycling patents remain heavily concentrated in Asian portfolios; Zn-ion activity is emerging, led by Chinese research institutions.

Litigation levels remain steady but high-impact, with more assertive use of enforcement tools. Major actions include between CATL v. CALB, ATL v. CosMx, Tulip (LGES/Panasonic) v. Sunwoda, MU Ionic v. CATL/Opel. There has also been a notable increase in trade secrets and trademark disputes across China, the US and Europe.

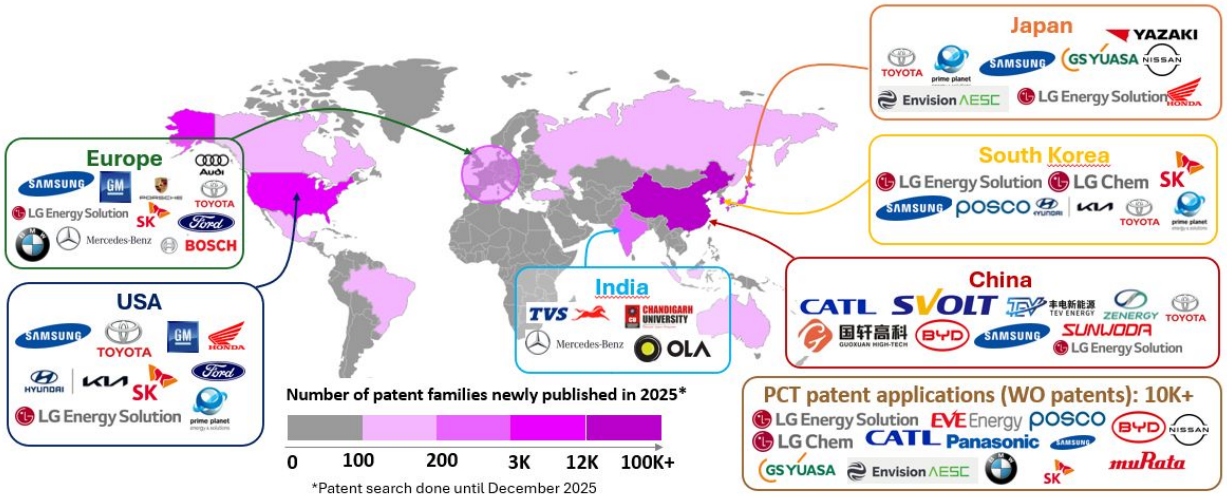
Recall activity highlights ongoing safety vulnerabilities across consumer electronics and EVs. Most recalls (57%) involve consumer products, especially power banks (due to overheating, welding defects, electrolyte leakage). 25–29% EV recalls are linked to HV battery failures (including cell defects, water ingress, BMS mis-detection and structural faults).

IP competition is intensifying, with crowded patent spaces in Li-ion, Na-ion, and solid-state domains increasing freedom-to-operate risk; robust patent landscaping and defensive filings are more critical than ever. Enforcement remains a real strategic level, especially in China, the US, and Germany. Safety and quality vulnerabilities persist, reinforcing the need for stronger traceability, validation and tighter process control across the supply chain.

Worldwide Battery Patent Landscape 2025

Patent activity in 2025 is heavily concentrated in China, with rapid expansion from emerging Chinese entities, mainly having a patenting activity only focused on China. Asian companies continue to shape the competitive IP landscape. Key industry leaders pursue worldwide patent filings to secure global market positions.

2025 GLOBAL PATENTING ACTIVITY IN BATTERY FIELD AND MAIN PATENT APPLICANTS BY PUBLICATION COUNTRIES



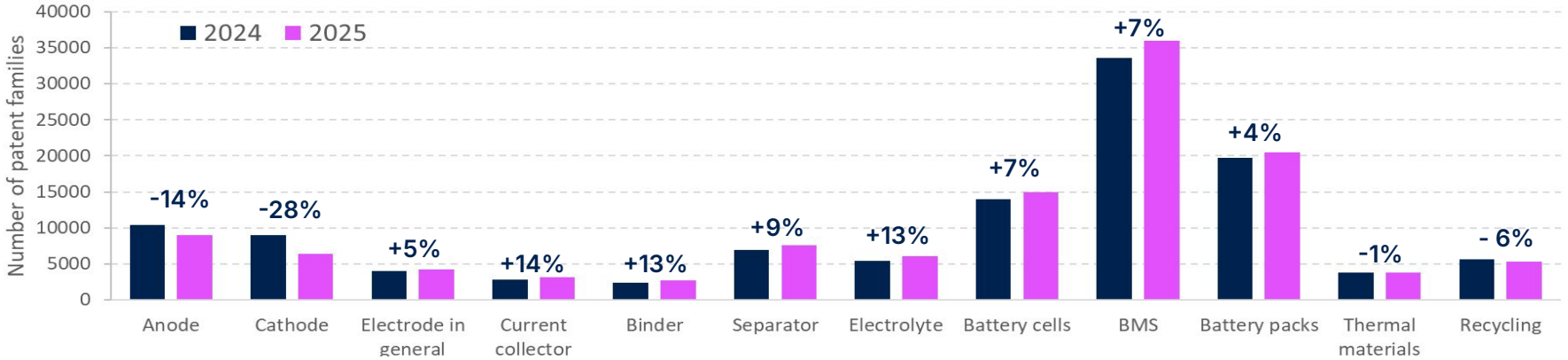
A patent family is a set of patent applications filed in multiple countries to protect a single invention by a common inventor(s). A first patent application is filed in one country – the priority country – and is then extended to other countries. Source: Patent search was done in December 2025 by KnowMade, using keywords and IPC/CPCs (H01M, H02J-007) in Orbit (Questel) which provides 100+ million patent documents from 100 patent offices (USA, Japan, Europe, China, Korea, Taiwan, Hong Kong, Singapore, etc.).

Worldwide Patent Activity by Main Battery Innovation Topics 2025

2025 patent applications highlight accelerating development in current collector, binder, electrolytes, BMS, separator, and cells. Applications relating to electrolyte inventions mainly encompass advanced compositions of liquid electrolytes to reach higher operation voltage and better stability as well as solid-state electrolytes. Battery cell inventions are related to composition, architecture and manufacturing method.

Compared to 2024, anode and recycling applications show a slight decline whereas cathode applications show a significant decline. Thermal materials remains almost stable compared to 2024.

2024-2025 GLOBAL PATENT APPLICATIONS IN BATTERY FIELD SPLIT BY MAIN INNOVATION TOPICS



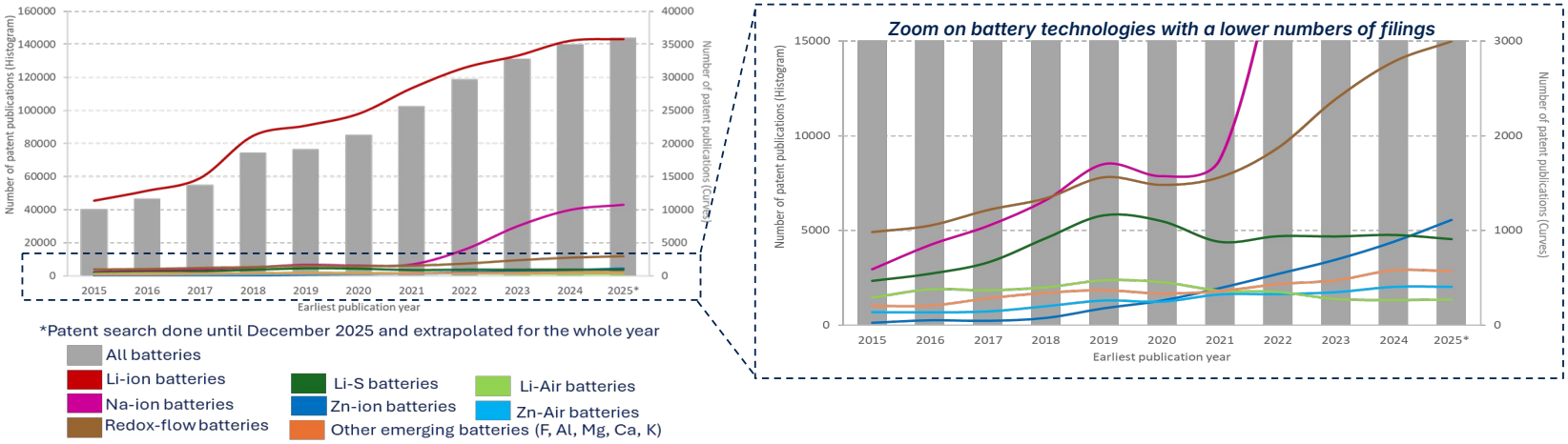
The percentages are the CAGR between 2024 and 2025. CAGR is the Compound Annual Growth Rate calculated with the formula (Value2025-Value2024)-1.

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Evolution of Worldwide Patent Activity by Main Battery Technologies

Li-ion batteries remain the core focus of innovation, whereas Na-ion technologies show rapid growth in patent applications since 2021, whiled Zn-ion technologies gain visibility since 2022, driven by Chinese academic and R&D applicants. Most alternative chemistries exhibit steady filing levels year by year.

IP DYNAMICS BY MAIN BATTERY TECHNOLOGIES



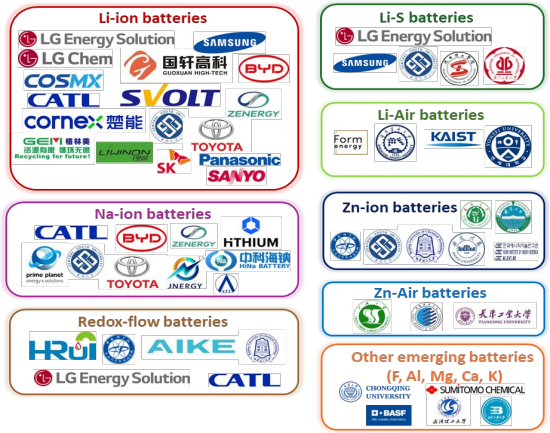
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Worldwide Patent Activity by Main Battery Technologies 2025

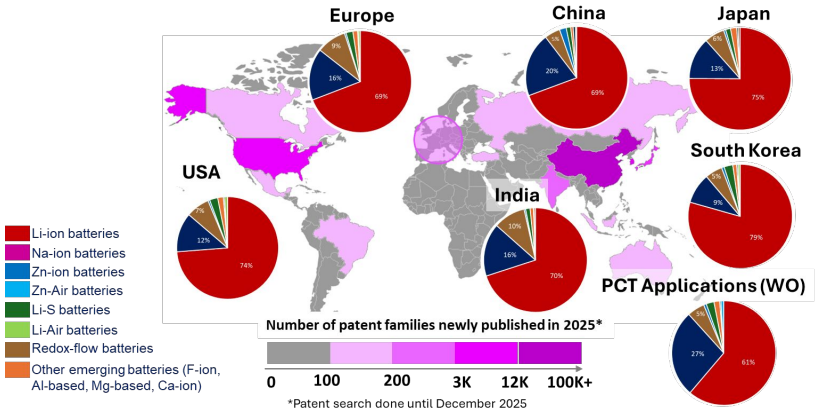
2025 patenting activity in main publication countries is driven by Li-ion, Na-ion and redox-flow battery technologies.

- Li-ion remains the primary focus of patent applications in 2025 for every major publication region.
- Na-ion and redox-flow technologies consistently appear as the leading secondary innovations.
- Patenting on other battery types remains limited compared to these dominant categories.

2025 MAIN PATENT APPLICANTS BY MAIN BATTERY TECHNOLOGIES



2025 PATENT APPLICATIONS BY COUNTRY AND MAIN BATTERY TECHNOLOGIES

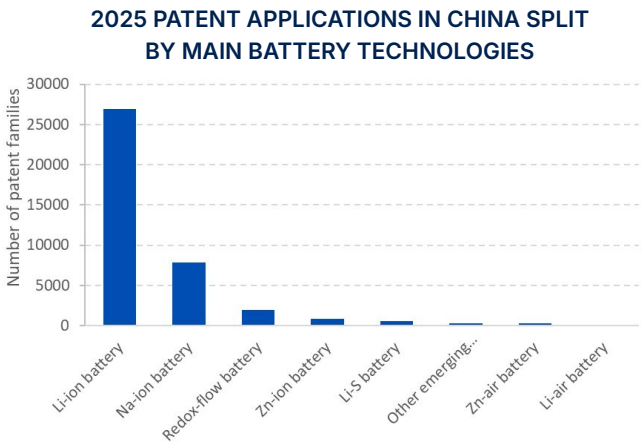


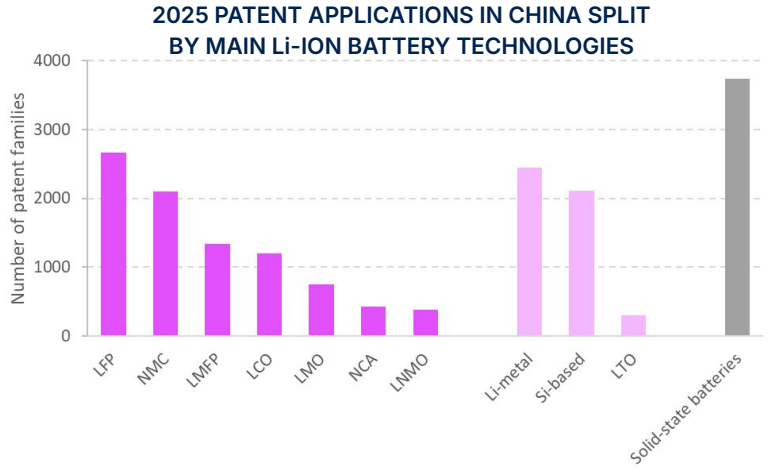
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Patent Landscape in China 2025

China consolidates its position as the global center of battery patenting in 2025, with strong emphasis on Li-ion and Na-ion batteries.

- Patenting activity in 2025 is booming for China, driven by major battery leaders and a fast-growing cohort of domestic entrants focusing their patent applications in China.
- Patent applications mainly focus on Li-ion, Na-ion and redox-flow batteries.
- Li-ion activity is broad, with LFP and NMC prevailing in cathodes, lithium-metal and silicon in anodes and high numbers of applications for solid-state batteries.

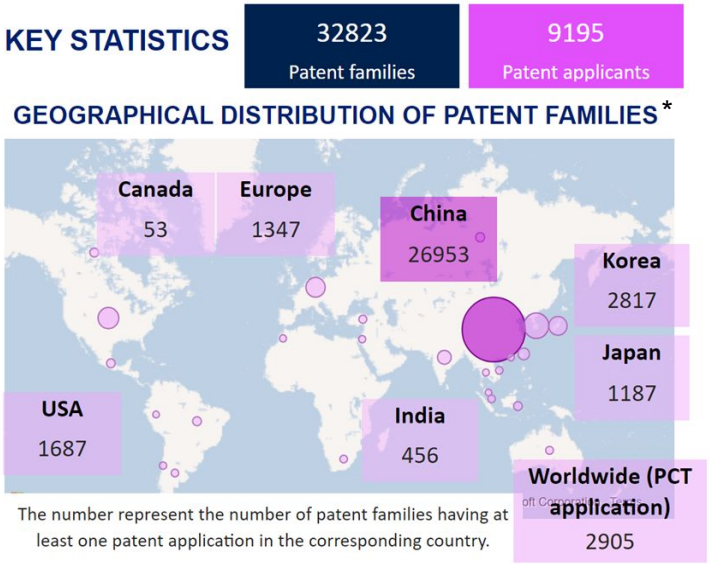


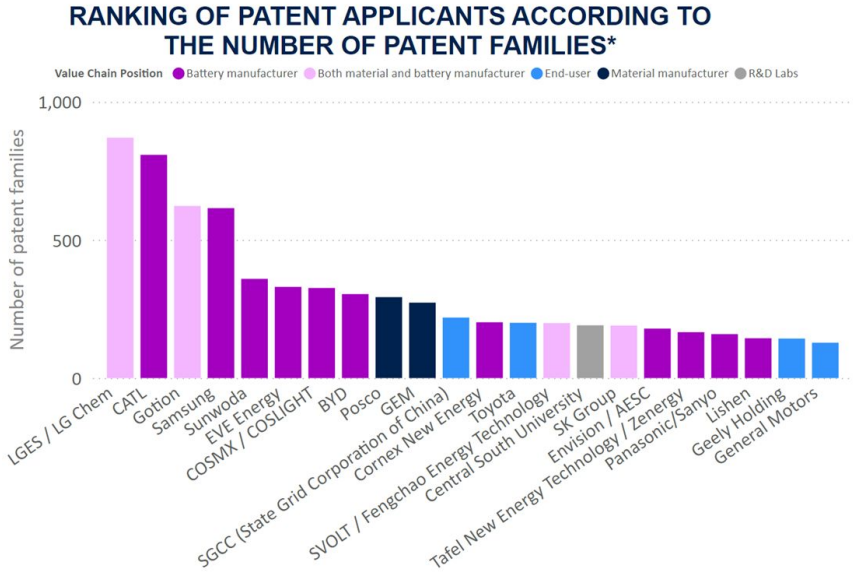


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Overview of 2025 Patent Activity: Li-ion Batteries

- Thriving patenting activity is dominated by applications in China and well-known Asian battery manufacturers.
- Top 4 of 2025 patent applicants (LGES, CATL, Gotion, Samsung) hold about 9% of 2025 patent families.
- General Motors is the sole non-asian company among main 2025 patent applicants.





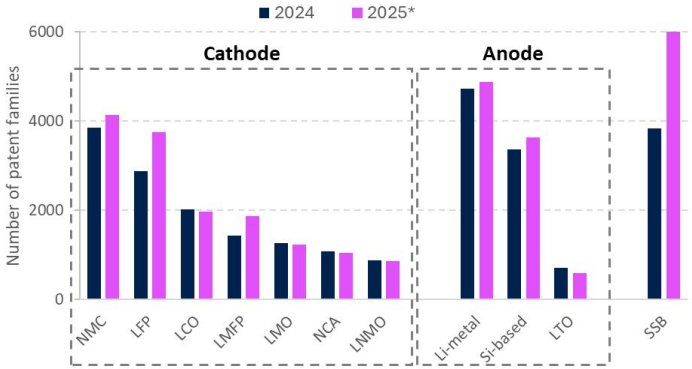
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2025 Patent Trends: Li-ion Batteries

2025 Li-ion patent landscape combines rising interest in advanced materials with clear country-specific technology choices.

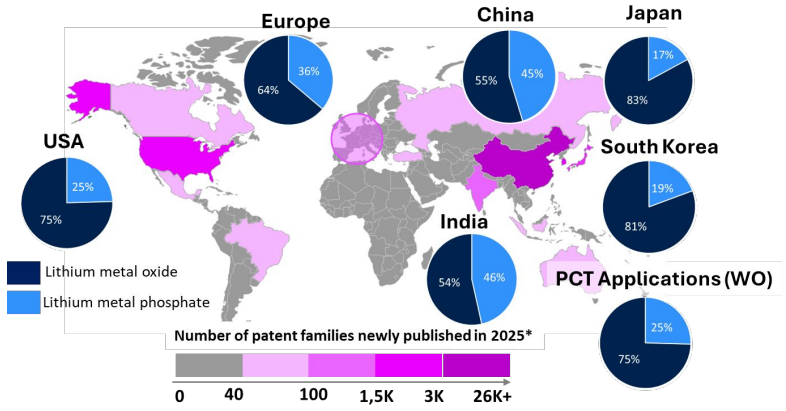
- In 2025, patent applications increased for advanced materials including NMC, LFP, LMFP, lithium-metal, silicon anodes and solid-state batteries, while other materials remain stable.
- Material focus differs by country, especially for lithium metal oxides vs. lithium metal phosphates. China and India show a balanced 50:50 ratio, whereas most other countries exceed 75% oxide-based filings.

2024-2025 PATENT APPLICATIONS BY MAIN Li-ION BATTERY TECHNOLOGIES



*Patent search done until December 2025 and extrapolated for the whole year

2025 PATENT APPLICATIONS RELATED TO Li-ION BATTERIES BY COUNTRY

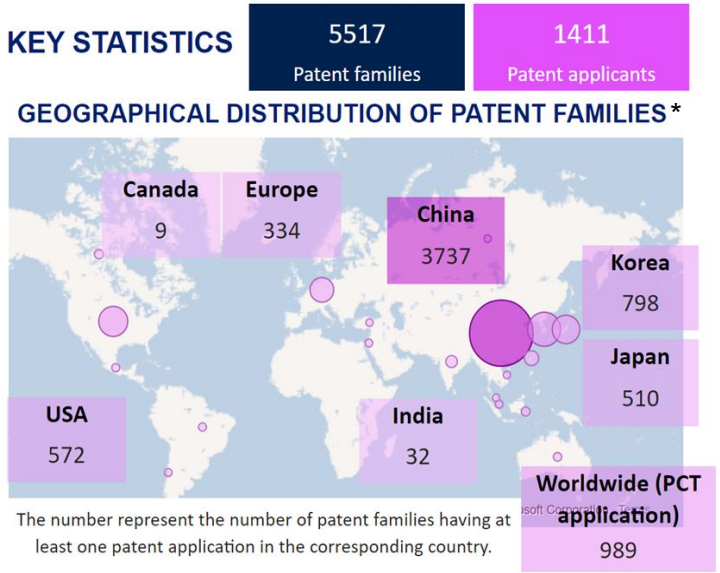


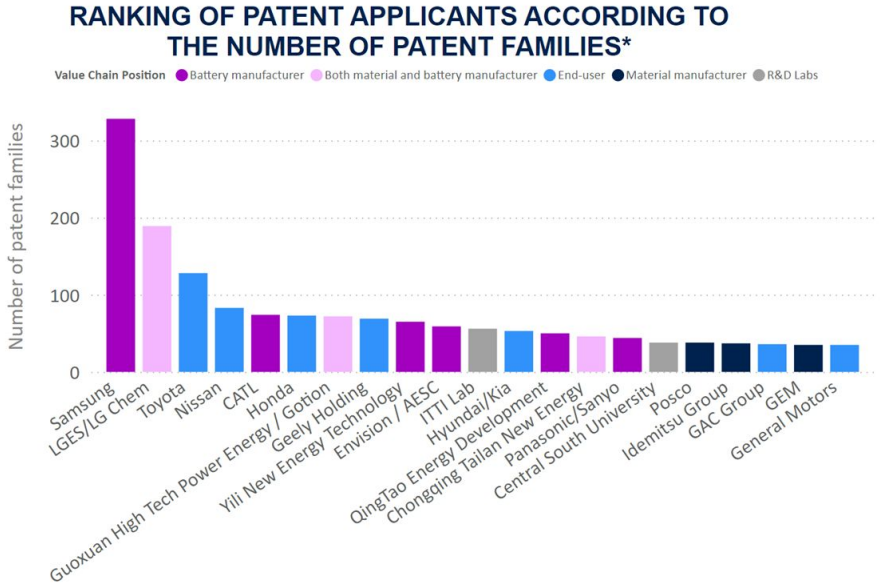
*Patent search done until December 2025

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Overview of 2025 Patent Activity: Solid-state Li-ion Batteries

- Patenting activity is dominated by applications in China and well-known Asian battery and car manufacturers.
- Top 3 of 2025 patent applicants (Samsung, LGES, Toyota) hold about 12% of 2025 patent families.
- General Motors is the sole non-asian company among main 2025 patent applicants.





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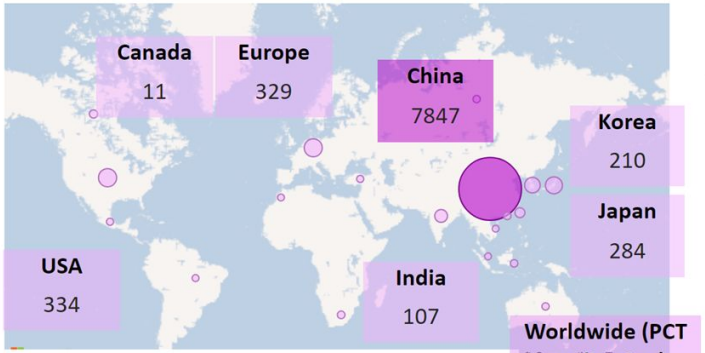
Overview of 2025 Patent Activity: Na-ion Batteries

- Patenting activity is dominated by applications in China and Chinese companies, with key player CATL.
- CATL is the most active patent applicant in 2025 with more than 22% of 2025 patent families.
- PPES and Toyota are the sole non-chinese patent applicants among main 2025 patent applicants.

KEY STATISTICS

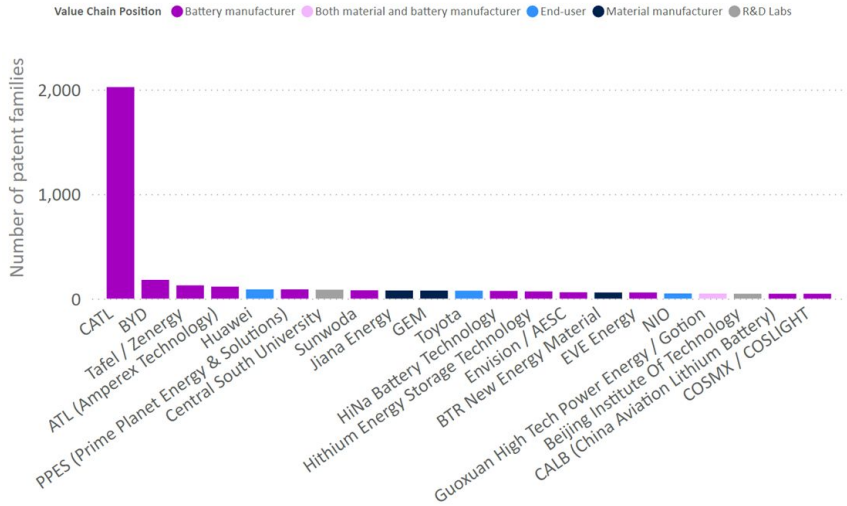
8944	2012
Patent families	Patent applicants

GEOGRAPHICAL DISTRIBUTION OF PATENT FAMILIES*



The number represent the number of patent families having at least one patent application in the corresponding country.

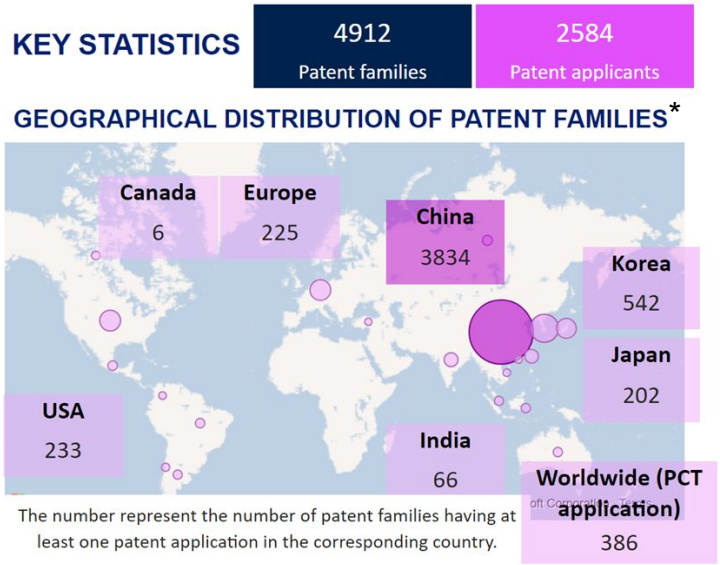
RANKING OF PATENT APPLICANTS ACCORDING TO THE NUMBER OF PATENT FAMILIES*

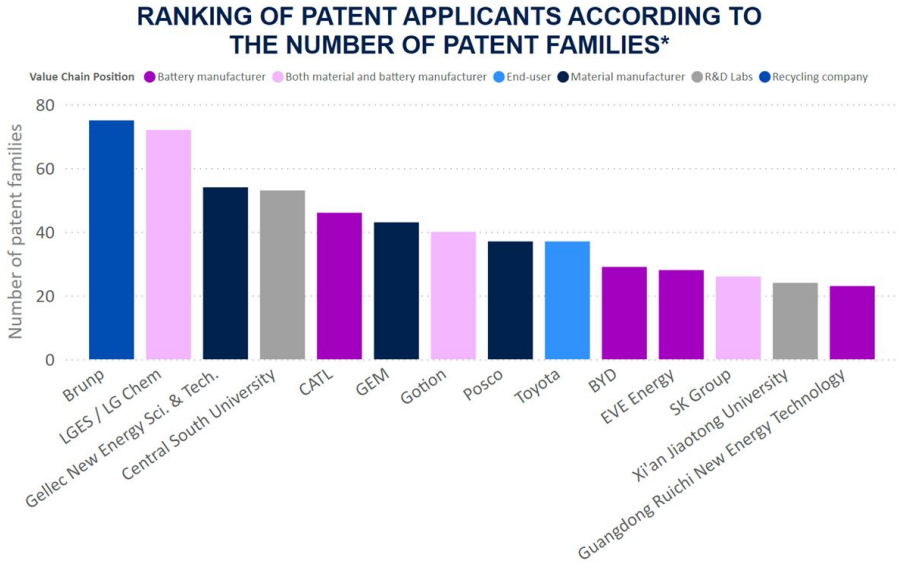


A patent family is a set of patent applications filed in multiple countries to protect a single invention by a common inventor(s). A first patent application is filed in one country – the priority country – and is then extended to other countries. Source: Patent search was done in December 2025 by KnowMade, using keywords and IPC/CPCs (H01M, H02J-007) in Orbit (Questel) which provides 100+ million patent documents from 100 patent offices (USA, Japan, Europe, China, Korea, Taiwan, Hong Kong, Singapore, etc.).

Overview of 2025 Patent Activity: Recycling

- Patenting activity is dominated by applications in China and Asian companies.
- Top 2 of patent applicants (Brunp and LGES) hold 3% of 2025 patent families. Top9 of 2025 patent applicants holds about 9% of 2025 patent families.

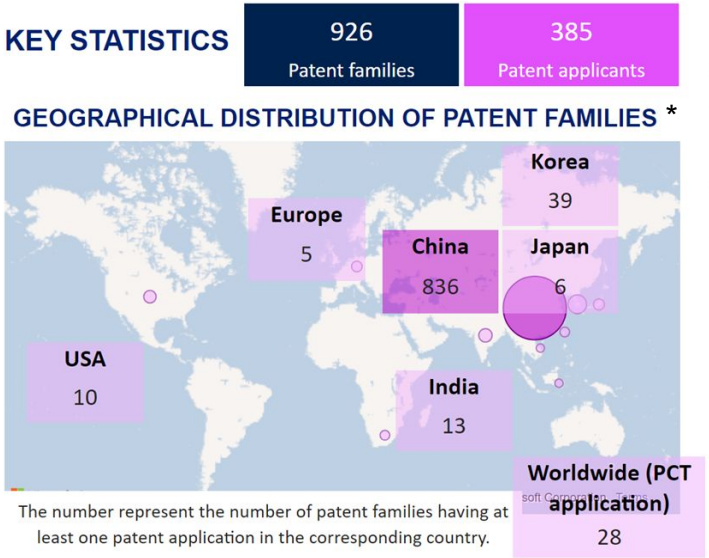


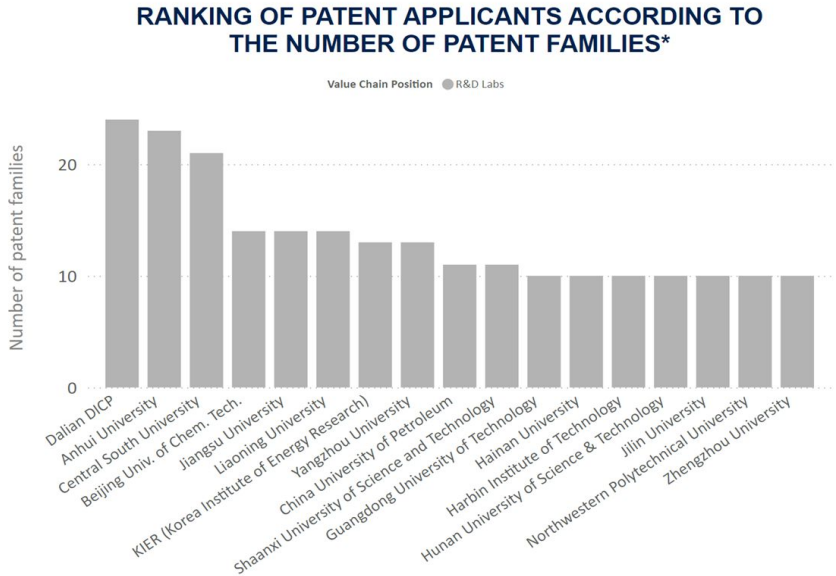


A patent family is a set of patent applications filed in multiple countries to protect a single invention by a common inventor(s). A first patent application is filed in one country – the priority country – and is then extended to other countries. Source: Patent search was done in December 2025 by KnowMade, using keywords and IPC/CPCs (H01M, H02J-007) in Orbit (Questel) which provides 100+ million patent documents from 100 patent offices (USA, Japan, Europe, China, Korea, Taiwan, Hong Kong, Singapore, etc.).

Overview of 2025 Patent Activity: Zn-ion Batteries

- Emerging patenting activity is dominated by applications in China and Chinese R&D labs.
- The top 3 2025 applicants (Dalian Institute of Chemical Physics, Anhui University, Central South University) hold 7% of patent families.
- KIER is the sole non-chinese R&D labs among main patent applicants.





A patent family is a set of patent applications filed in multiple countries to protect a single invention by a common inventor(s). A first patent application is filed in one country – the priority country – and is then extended to other countries. Source: Patent search was done in December 2025 by KnowMade, using keywords and IPC/CPCs (H01M, H02J-007) in Orbit (Questel) which provides 100+ million patent documents from 100 patent offices (USA, Japan, Europe, China, Korea, Taiwan, Hong Kong, Singapore, etc.).

Battery Patent Litigation: Recent Developments

The battery sector has traditionally not seen as much patent litigation as may be expected in a growing market filled with innovative companies and new entrants. However, the past few years have seen a shift, as competition intensifies, and there is a trend to more proactive enforcement of intellectual property rights. Below is a summary of patent litigation actions over the last 5 years:

- LG Energy vs. SK Innovation (2021)[1]: Landmark dispute between two South Korean EV battery companies over **patent infringement** and **misappropriation of trade secrets** in the **US**. Settled in April 2021 with SK paying $1.8 billion and agreeing to a 10-year non-assert agreement, averting an import ban and supply chain crisis for car makers Ford and VW.

- CATL vs. CALB (2021–2025)[2,3]: **Ongoing** "patent war" in **China**, featuring lawsuits, countersuits, and hefty damage claims. CATL first sued CALB in 2021, and by 2023 had won some victories (injunctions and damages) but also saw courts invalidate some patents. CALB counter-sued in late 2023 for ¥1 billion (~$136 million), alleging CATL and even Tesla infringed its patents - though two of CALB's patents were invalidated by the China National Intellectual Property Administration (CNIPA) shortly after. CATL responded with yet another lawsuit in 2024, bringing the battle to at least **7 different patents** and claiming a cumulative ¥700 million (~$95 million) in damages. CATL's vast patent portfolio underpins its aggressive enforcement; the feud highlights rising damages and patent-owner-friendly Chinese courts.

- Umicore enforced patents against Beijing Dangsheng, Ningbo Ronbay and Jiangsu Easpring (2021-2023)[2]: the Belgian company sued for battery cathode material **patent infringement** in **China**; some cases were settled, others were dismissed.

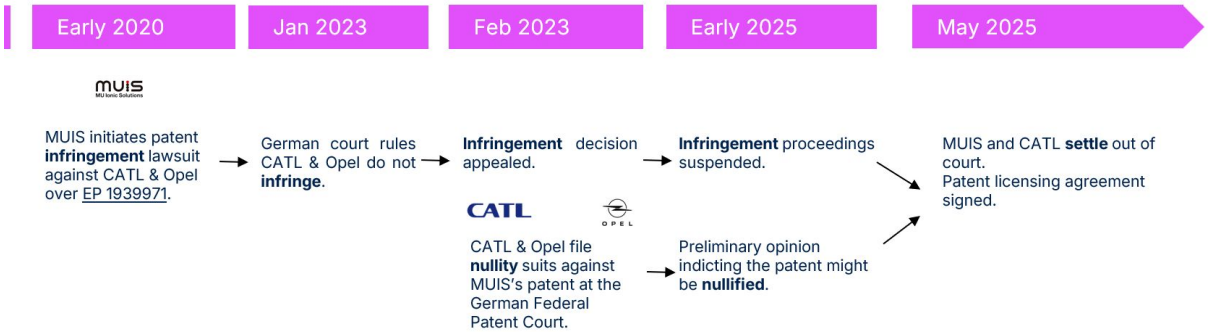
- ATL (TDK) vs. CosMx (2024)[4, 5]: Resulted in injunctions in both the **US** and **Germany** over laptop battery patents. However, the decisions have not all been in ATL's favour, as more recently one of the patents has been revoked in the US.

Source: [1] IP Stars, [2] IP Fray, [3] Grey B, [4] Juve, [5] Best Mag,

Battery Patent Litigation: Recent Developments Cont.

MU Ionic Solutions v CATL and Opel (2023)[6]: In the **bifurcated** proceedings, where infringement and revocation actions are heard separately, it was found that CATL and Opel did not infringe MU Ionic's **German** patent EP1939971. The preliminary opinion of the Federal Patent Court was that the patent might be revoked. The **patent disputes** were **resolved via a licence deal** (covering difluorophosphate-based cathode interface control technology) shortly before the final decision in revocation proceedings.

MU Ionic Solutions (MUIS) v CATL and Opel: bifurcated proceedings in Germany



Tulip Innovation vs. Sunwoda (2025)[7]: Tulip (a consortium of LG Energy Solution and Panasonic) secured landmark injunctions in **Germany** against Sunwoda for infringing three EV battery separator patents. The rulings forced Sunwoda to halt sales and destroy inventory in Germany, and pay damages in principle. Sunwoda has filed nullity actions, where the preliminary opinions are that each of the patents are likely to be upheld. These are the first known final injunctions in Europe on car battery patents. Sunwoda has appealed. Tulip's success shows that licensing pools may enforce rights if voluntary licensing is ignored.

Source: [6] Juve, [7] Juve

Battery IP Litigation: Recent Developments

Beyond patents, battery companies are increasingly embroiled in litigation over trade secrets and trademarks. Trade secret disputes typically concern confidential know-how not covered by patents, such as unique manufacturing processes or formulas, while trademark and trade dress cases centre on brand identity, names, logos, and packaging. These legal battles are shaping the competitive landscape, with courts issuing significant injunctions and damages. Not only is it important to engage with IP to protect innovation and navigate market entry, but it is also key to protecting your brand.

Trade Secrets in the Spotlight:

- Tesla vs. Rivian (2020–2024)[1]: Tesla sued Rivian in the **US** for allegedly poaching employees and stealing battery **trade secrets**, underscoring Tesla's willingness to defend its **proprietary know-how**. The case was settled in 2024 before trial.
- Tesla vs. Matthews International (2024)[2, 3]: **US** Lawsuit over alleged misuse of Tesla's dry coating electrode manufacturing process by a supplier. Matthews was alleged to have used Tesla's **confidential trade secrets** in its patent filings, and by 'selling equipment for dry battery electrode (DBE) manufacturing', which 'embodied Tesla's confidential trade secrets', with Tesla's estimate of damages exceeding $1 billion. The opinion of the District Court confirmed the previous arbitration decision **in Matthews' favour** regarding their right to continue selling DBE technology.
- Zeon Corp. vs. Shenzhen Haodyne (2025) [4]: Japan's Zeon Corp won an injunction and ¥1 million (~£110k) damages for **trade secret theft** in **China** involving battery binder formulas. The decision has been appealed.

Trademark Disputes Emerge:

- Tesla vs. Tesla Power (2024)[5]: **Trademark** dispute over the use of the "Tesla" name by an unrelated **Indian** battery manufacturer. Trademark law generally prevents use of names that cause confusion in related industries, and here "Tesla Power" was deemed close enough to potentially mislead battery buyers for the Indian court to issue an interim injunction barring use of the name.
- Exide vs. Amara Raja (2025)[6]: **Trade dress** (branding design) dispute over Exide's distinctive red and white battery packaging in **India**. Exide is the registered proprietor of the mark EL (used since 1987) and owns copyright over a fragmented 'O' lettering device, which it has been using since 1973. The court sided with Exide, granting an injunction and clarifying the limits of trademark protection for colour schemes in the industry.



Exide's Product (battery-front)



Amara's Product (battery-front)



Exide's Product (box-front)



Amara's Product (box-front)

AMARON
EXIDE
好电科技 HAODYNE
Matthews INTERNATIONAL
TESLA
RIVIAN
ZEON

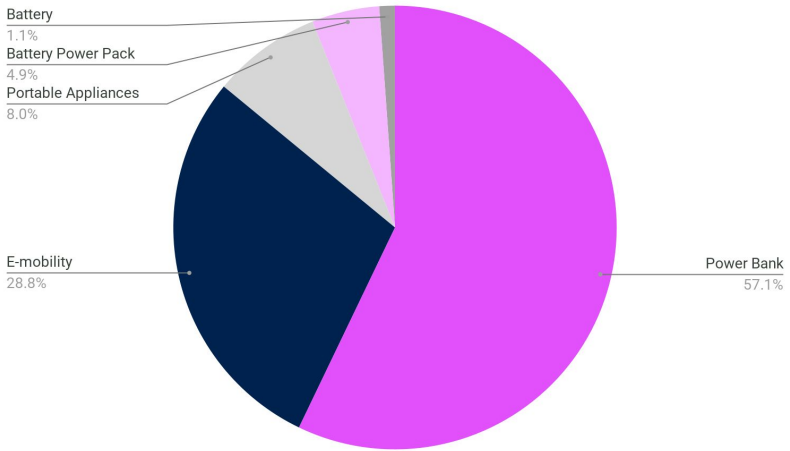
Source: [1] Nat Law review, [2] Matthews, [3] Reddie, [4] Zeon, [5] Legal Online, [6] World Trademark Review

When Batteries Might Fail: A Year in Review

Over the past year, battery recalls have been driven by a broad range of safety issues, most commonly related to overheating, ignition, and fire hazards. Many products were found to overheat during charging or normal use, with some incidents escalating to smoke, flames, or material ejection.

- More than half of the recalls (57%) involve power banks, highlighting the need for additional safety considerations due to their widespread use and close proximity to users.
- A lower number of recalls (29%) are related to electric vehicles (EVs), which largely reflects manufacturers' after-sales strategies focused on preventive and corrective actions.
- Underlying causes of battery recalls included substandard or inappropriate components, poor welding conditions, electrolyte leakage, and defects in raw material quality. In some cases, devices exhibited physical swelling or lacked required safety markings, prompting precautionary recalls. Collectively, these issues highlight ongoing vulnerabilities across the battery supply chain.
- Most battery recalls result from battery-related issues rather than downstream processing, installation or other. There is limited publicly available information regarding recalls initiated directly by battery manufacturers. This emphasizes the importance of proactive safety measures and accountability among battery manufacturers. The battery passport and other measures may assist in accountability.

2025 RECALLS



- E-mobility includes EV, BEV, PHEV, e-scooters, e-bikes, e-buses, e-trucks, and similar electric transportation devices.
- Portable appliances covers everyday devices such as headphones, fans, vacuums, speakers, and other small electronics.

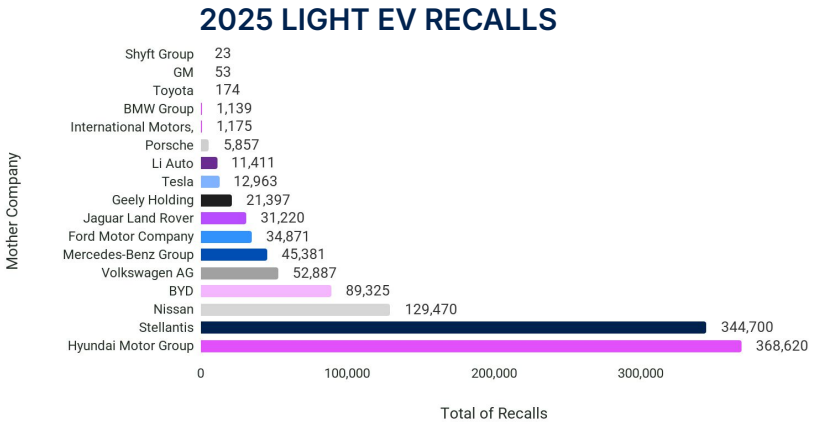
Source: [1] OECD Global Recalls, [2] ASEAN.

Data Collection and Analysis: Recall data aggregated from official international (OECD Global Recalls,ASEAN) and national safety recall databases around the world, including the US (US Consumer Product Safety Commission, National Highway Traffic Safety Administration), UK, China, Japan, South Korea, India, and Canada. Data range Jan 2025 to mid-Nov 2025. Includes formal recalls with disclosed unit volumes only. Data concentration reflects regions with higher reporting transparency (North America, East Asia).

High-voltage Battery Recalls in Light EVs

Electric vehicle recalls in 2025 were predominantly driven by high-voltage battery system failures. Reported issues included internal short circuits, overheating, manufacturing defects, and structural faults. Specific failure modes involved loose or improperly welded components, misaligned or pre-damaged cells, corrosion, water ingress, and battery management system (BMS) detection errors. These issues posed risks of fire, thermal runaway, loss of drive power, and system shutdown during charging or operation, highlighting persistent vulnerabilities in battery design, assembly quality, and system integration.The most critical bottlenecks remain battery supply-chain reliability, battery pack qualification and validation, and installation quality at the vehicle level.

The bar chart illustrates the distribution of EV battery-related recalls by the “mother company”, consolidating recall activity across all subsidiaries and affiliated brands under a single corporate umbrella. This approach provides a view of cumulative recall exposure at the corporate group level.



Data Collection and Analysis

Recall data is based on publicly available announcements from national and international safety authorities.

Limitations:

- Public disclosures typically lack detailed root-cause analysis, relying instead on broad classifications such as thermal runaway, manufacturing defects, or installation issues (cause is difficult to attribute). Recall data alone is not sufficient to assess overall EV quality at the battery brand level.

Source: Data Collection and Analysis: Recall data aggregated from official international (OECD Global Recalls,ASEAN) and national safety recall databases around the world, including the US (US Consumer Product Safety Commission, National Highway Traffic Safety Administration), UK, China, Japan, South Korea, India, and Canada. Data range Jan 2025 to mid-Nov 2025. Includes formal recalls with disclosed unit volumes only. Data concentration reflects regions with higher reporting transparency (North America, East Asia).

COMMUNITY

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2026 Virtual Events Schedule

January

Jan 14
Battery Forum: Startup & Cycle Life

February

Feb 4
Battery Forum: Battery Report Deep Dive

March

March 12
Women in Batteries Interview

April

April 2
Battery Career Fair

April 15
Battery Forum: Manufacturing & Fast Charge

May

May 13
Battery Forum: Electric Mobility & Energy Density

June

June 4
Women in Batteries Interview

June 17
Battery Forum: AI & Safety

July

N/A

August

August 26
Battery Forum: Next Gen Chemistry & Cost Reduction

September

September 9
Women in Batteries Interview

September 17
Battery Career Fair

September 23
Battery Forum: Battery Engineer's Toolkit & Sustainability

October

N/A

November

November 12
Battery Forum: ESS & Yield Improvement

December

N/A

Source: Volta Foundation Events as of February 28, 2026, Events Linked Above.

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2026 Battery Social Networking Events

January

N/A

February

Feb 19
Battery Social @ London

Feb 23
Battery Social @ Berlin

Feb 25-27
Volta 2026

March

March 16
Battery Social @ Berlin

March 19
Battery Social @ San Francisco

March 24
Women in Batteries Meetup @ IBSE

March 25
Battery Social @ International Battery Seminar & Exhibit

March 25
Battery Social @ Munich

April

April 9
Battery Social @ Brussels

May

May 7
Battery Social @ London

May 14
Battery Social @ Ann Arbor, MI

May 28
Battery Social @ San Francisco

June

June 9
Women in Batteries Meetup @ Battery Show Europe

June 9-10
Battery Social @ Battery Show Europe

June 23
Battery Social @ Munich

July

July 9
Battery Social @ Detroit

August

N/A

September

Sept 3
Battery Social @ London

Sept 7
Battery Social @ Barcelona

Sept 21
Battery Social @ Berlin

Sept 24
Battery Social @ NYC Climate Week

October

October 13
Women in Batteries Meetup @ Battery Show NA

Oct 14
Battery Social @ Battery Show NA

November

Nov 23
Battery Social @ Berlin

December

Dec 3
Battery Social @ London

Dec 9
Battery Social @ AABC

Source: Volta Foundation Events as of February 28, 2026, Events Linked Above

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2026 Global Conference & Events Schedule

January

Jan 6-9
CES

Jan 14
Battery Forum: Startup & Cycle Life

Jan 19-23
World Economic Forum

February

February 1-3
Fastmarkets India Battery & Critical Materials

Feb 3
RE+ Northeast

Feb 4
Battery Forum

Feb 9
Benchmark Summit Cape Town 2026

Feb 9-12
NAATBatt Annual Conference

Feb 18-20
InterSolar

Feb 24-26
Project Blue Critical Minerals Conference

Feb 25-27
Volta 2026

March

March 2
Benchmark Summit Toronto 2026

March 10-12
Battery Show Asia

March 11-12
Benchmark Battery Gigafactories Europe

March 11-13
InterBattery

March 18-19
ESS Summit Australia

March 23-26
International Battery Seminar & Exhibit

March 24-26
Fastmarkets Shanghai Battery Raw Materials Conference

March 25-27
ASEE-ASEAN Expo

March 31
RE+ Southeast

April

April 7
ARPA-E Summit

April 7
Middle East Energy Dubai

April 15
Battery Forum: Manufacturing & Fast Charge

April 22-23
Battery Show South

April 27-29
Fastmarkets Asian Battery Materials

May

May 4
ACT Expo

May 5-7
ALTA Australia

May 13
Battery Forum: Electric Mobility & Energy Density

May 13-15
China International Battery Fair

May 18-21
AABC Europe

May 20-21
Renewables Procurement & Revenue Summit

June

June 9-10
Benchmark Battery Giga USA

June 9-11
Battery Show Europe

June 16-18
International Flow Battery Forum

June 16-18
Electric & Hybrid Marine Expo Europe

June 17
Battery Forum: AI & Safety

June 17-18
MOVE Europe

June 22-23
EES Europe

June 22-25
Fastmarkets Lithium Supply & Battery Raw Materials

June 30
Reuters Automotive Europe

Source: Volta Foundation Events as of February 28, 2026, Events Linked Above.

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2026 Global Conference & Events Schedule

July

July 8-9
Battery Cells & Systems Expo

July 14-16
PlugVolt

July 26-29
BATTCon

July 28-30
Volta Foundation Women in Batteries Conference

August

August 11-12
Solid State Battery Summit

August 12-13
Battery Safety Summit

August 17-18
Oslo Battery Days

August 26
Battery Forum: Next Gen Chemistry & Cost Reduction

September

September 9-10
Tokyo Smart Energy Week

September 9-10
K-Battery Show

September 9
RE+ Midwest

September 10-12
International Congress for Battery Recycling

September 16-18
Solar PV & ESWE

September 16-18
WBE Expo

September 20-27
Climate Week NYC

September 23
Battery Forum: Battery Engineer's Toolkit & Sustainability

September 23-24
MOVE America

September 24
Battery Day

September 29-30
Benchmark Giga Africa

October

October 7-9
eCharge Show

October 12-16
Battery Show North America

October 13-15
EVIS & EMG Abu Dhabi

October 22-24
Battery Show India

October 29
Reuters Automotive USA

November

November 3-5
EVIS America

November 5
eVTOL Show USA

November 10-11
Battery Asset Management

November 12
Battery Forum: ESS & Yield Improvement

November 16-19
RE+

November 24-26
Future Battery Forum

December

December 7 - 10
AABC North America

December 8-10
ALTA Americas

Source: Volta Foundation Events as of February 28, 2026, Events Linked Above.

PREDICTIONS

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2026 Predictions

1. **Global EV demand will keep rising** as affordability improves and OEM lineups broaden, including further global adoption of Made-in-China EVs even as incentives normalize in a few markets. **Passenger EV sales to exceed 24M in 2026 (+10% vs 2025).**

2. **BESS demand hyper-growth** will continue, driven by grid congestion, renewable integration, and AI data center load growth. Project pipelines deepen across the U.S., Australia, and Europe. **Global deployments to reach ~120GW / 360GWh in 2026 (+30% vs 2025).**

3. **Battery prices** will decrease as the economy of scale, chemistry mix, and oversupply dynamics outweigh policy headwinds in the US and China. **Average battery pack prices to dip below $100/kWh in 2026.**

4. **LFP batteries** will further consolidate their position as the dominant chemistry for mass-market EVs and BESS (4th gen LFP in China), driven by cost, safety, and supply chain scale. **LFP to represent >55% of global Li-ion demand.**

5. **Na-ion advances from "next" to "shipping"** for specific niches, while staying a small slice of overall demand. Na-ion is unlikely to displace significant Li-ion share near-term, even as commercial deliveries begin. **5 new Na-ion products will become commercially available in 2026.**

6. **The funding gap deepens -** fewer mega-rounds and more distressed M&A as margin pressure, regulatory uncertainty, and higher cost of capital push investors from "scale at any cost" to "prove unit economics + contracted demand." **At least 5 battery startups will pivot** to monetizing patents, process know-how, software, or sell to strategics rather than raising their next big round.

7. **Battery swapping becomes "real" in China** - but remains niche ex-China as China achieves the critical ingredients for mass adoption: standardization, dense urban fleets, aligned OEM ecosystems, and highway-corridor heavy-duty use cases. **China will surpass 3,000 battery swap stations while ex-China fewer than 200 stations will be deployed in 2026.**

8. **Global policy scrutiny** and **China export controls** will not stop international deals, but rather will transform the nature of partnerships (tech licensing, contract manufacturing, and non-equity collaboration). **≥60%** of newly announced cross-border battery manufacturing/technology partnerships involving OCED & Chinese firms will be non-equity, rather than equity JVs or acquisitions.

9. **Batteries become an explicit national security and "energy dominance" priority** as US and European policymakers connect storage to grid resilience, AI tech dominance, defense electrification, and supply chain security. Expect a shift from "cleantech support" framing toward considered industrial strategy. **At least 2 major publications outlining national battery strategies with national security language.**

2025 | BATTERY REPORT

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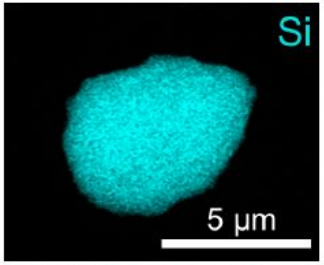
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Using Micro Silicon instead of Nano Silicon

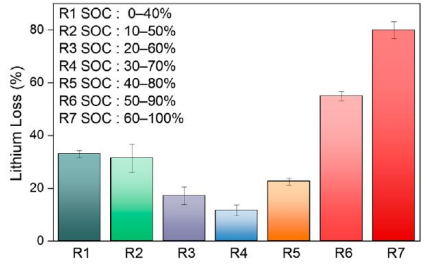
Anode-tailored-full-cell design (ATFD) with **micro silicon particles** (D_{avg} = 4.6 um) and constrained silicon utilization between **30 - 70 % SOC** provides a balance of optimal electrode architecture with good ion transport networks and active area while limiting the volume expansion of silicon.

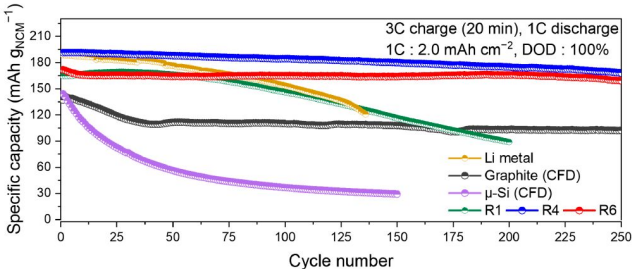
- While nano-silicon is generally preferred to avoid pulverization of silicon, it suffers from high synthesis cost, poor fast charge ability (highly tortuous pore networks) and low initial CEs.
- Microsilicon can circumvent these issues if the large volume fluctuations and subsequent fracture is avoided.
- Si utilization in the **30-70% lithiation window** shows least lithium loss and electrode-level expansion.
- High cycle life of micro silicon anode with NMC cathode at 3C charge, 1C discharge is observed for ATFD design as compared to conventional full-cell-design (CFD) with no lithiation limits.



ANODE MICRO SILICON AND CARBON NETWORK

Li LOSS DURING CONSTRAINED SOC CYCLING OF CELL





FULL CELL MICRO SILICON|NMC CYCLING

Source: T. Lee, M. J. Seong, H. C. Ahn et al.

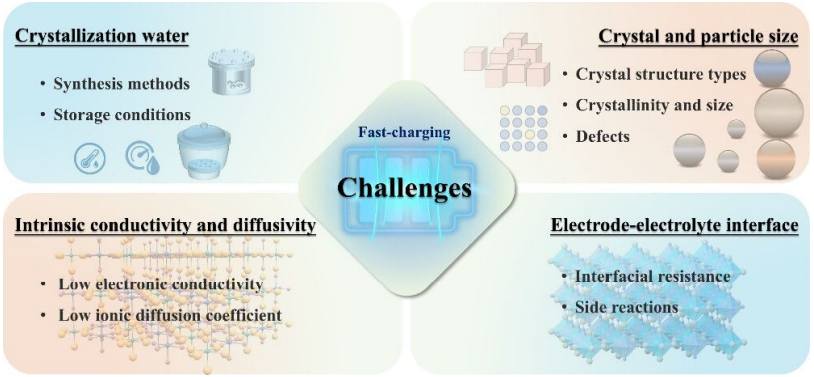
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50%

Differentiating Diffusion in Prussian Blue Analogues

The main challenges for fast-charging PBAs are **unstable crystallization water, low electronic and ionic conductivity,** diffusion limitations from crystal structure and particle size, and high interfacial resistance with side reactions.

Strategies to address these issues include **controlling crystallization water, engineering crystal structure and particle size,** enhancing conductivity and diffusivity through doping and composites, and optimizing the electrode-electrolyte interface with coatings and improved CEI formation.





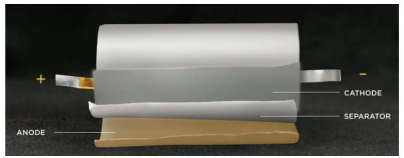
Source: J. Am. Chem. Soc. 2025, 147, 29, 25441–25453

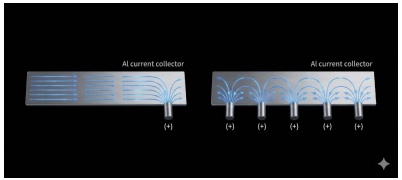
Tabless Cylindrical Cell Technology

Technology Description: All-in-one equipment integra ter), segmented pressure-controlled electrolyte filling, and intelligent temperature-controlled fo

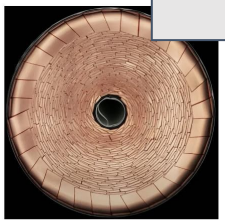
Key Advantages / Features: Enables high precision (> hput (330k cells/hour per line), and consistent mass production.

Writing edits needed before reintegrating





TABLESS CYLI (TESLA -





TABLESS CYLINDRICAL CELL APPLICATION IN CHINA OEM

EVE 亿纬锂能

国轩高科 GUOXUAN HIGH-TECH

CALB 中创新航

RELIANCE EMPOWERING A BETTER LIFE 睿恩新能源

YUNSA

ATL 新能源科技 Amperex Technology Limited

Golden Feather 金羽新能

Source: 国内4家电池厂商推出46系列大圆柱形电池

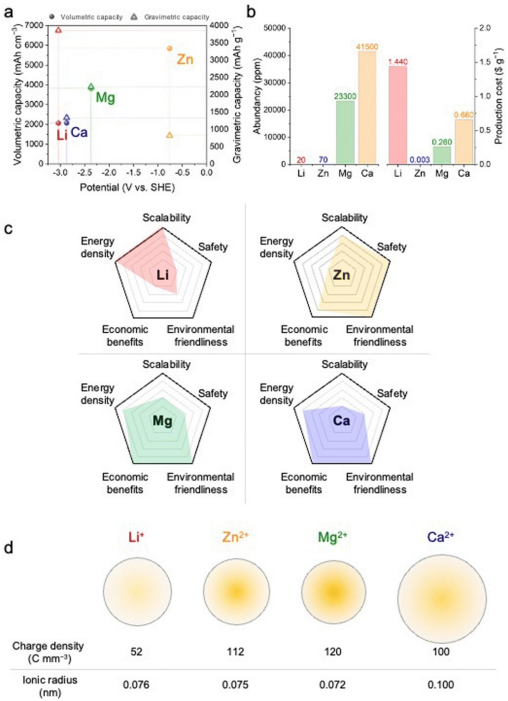
Zn, Mg, and Ca Divalent Metal Batteries: Benefits, Trade-offs, and Key Design Challenges

Li gives the highest energy density, while Zn, Mg, and Ca are cheaper, more abundant, and safer but limited by stronger ion-solvent interactions and slower diffusion.

Each metal requires tailored electrolyte and SEI design - Li needs inorganic SEI, Zn needs water-resistant SEI, and Mg/Ca require strong solvation and compact organic SEI layers.

Table 1 Key notes in designing electrolytes and SEI layers in various metal anode batteries

	Electrolyte design	SEI design
Li	Weak solvation targeted for preferential anion decomposition *via* HCE or LHCE High reactivity of the Li metal needs treatments to form the desired SEI and minimize corrosion.	Inorganic-rich SEI preferred
Zn	Non-flammable Inorganic additives/solvents can be added to enhance the interfacial stability	Increasing effort for forming the SEI and modifying its properties Strategy detail 1: the hydrophobic SEI to prevent water contact Strategy detail 2: the hydrophilic SEI for facile Zn ion transfer
Mg	Strong solvation preferred Anions with large electron distributions preferred for the solubility of salt Need to control contaminants and moisture strictly	Organic-rich and compact SEI preferred Native oxide components preferred to be removed
Ca	Strong solvation preferred Anions with large electron distributions preferred for the solubility of salt Less sensitive to contaminants and moisture	Organic-rich and compact SEI preferred Ion-conducting SEI preferred



Source: Chem. Soc. Rev., 2024,53, 8878-8902

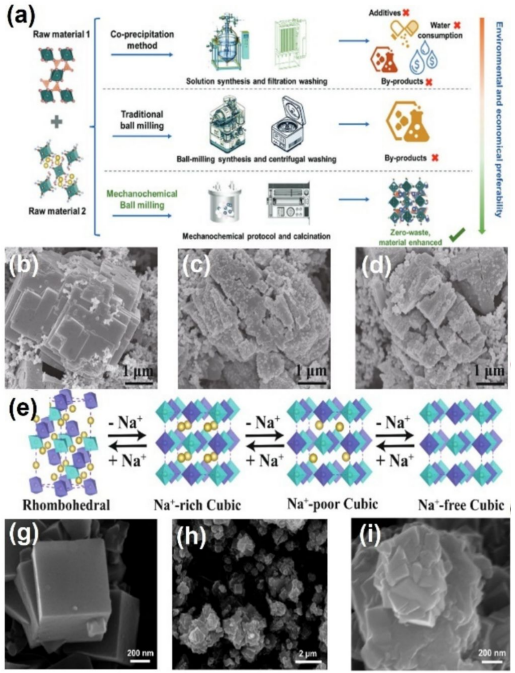
Prussian-Blue Analogues as Cathode Materials

What the paper covers:

- **Prussian Blue Analogues (PBAs)** as promising cathode materials for sodium-ion batteries due to their open frameworks, high theoretical capacity, and low cost.
- Synthesis methods and their impact on **water content**, **vacancies**, and **crystallinity**
- **Degradation mechanisms** (lattice volume changes, phase transitions, and transition metal dissolution) during cycling
- Strategies to enhance stability and kinetics, including **heteroatom doping** (e.g., Zn, Cu) and **vacancy engineering**

Major challenges:

- Traditional co-precipitation introduces interstitial water and vacancies, leading to **framework collapse** and reduced cycling stability.
- **Irreversible phase transitions, iron dissolution**, and **lattice distortions** during electrochemical cycling.
- Significant lattice **volume expansion** and **particle rupture** during cycling



Key progress:

- **Reducing agents** (sodium bisulfite/thiosulfate) to minimize sodium loss during synthesis
- Doping Zn into Mn-based PBAs to mitigate **Jahn-Teller distortions**
- **Vacancy & doping engineering** to facilitate Na ion transport and stabilize redox processes

Future directions:

- Improvement of **long-term cycling stability** and **rate performance** for ESS
- **Solvent-free** or simplified synthesis routes to reduce costs and environmental impact for mass production
- Additional doping R&D beyond **transition metals**

The commercial viability of PBAs in sodium-ion batteries hinges on controlling the **water content and defects during synthesis** and mitigating lattice distortions (via doping) to prevent the structural collapse that currently limits their cycle life.

Source: Coordination Chemistry Reviews 548 (2026) 217215