2024 | BATTERY REPORT

VF | VOLTA FOUNDATION

Revision: 2025030101

> ***“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 2024. 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:

1 **INDUSTRY**	Commercial milestones in battery development and manufacturing
2 **ACADEMIA**	Academic breakthroughs in fundamental battery science
3 **TALENT**	Supply, demand, and insights on talent working in the field
4 **POLICY**	Government targets, incentives, regulations, and their implications
5 **PREDICTIONS**	Trends we believe are likely to happen in the next 12 months

THE BATTERY REPORT IS A PROGRAM BY:

VF | VOLTA FOUNDATION

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1 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 Summary

2024 marked a year of continued growth and adaptation in the global battery industry. Global xEV sales climbed 25% to 17.7M units, with BEV demand up 14% while PHEV demand surged 50%. For the first time, BEVs in China have reached price parity with fossil vehicles. This milestone comes as China continues to lead the world in EV market penetration, with xEVs accounting for 45% of new car sales. Automakers globally are adapting their strategy, with Chinese automakers expanding into Europe and the Global South, while some traditional OEMs cut back on EV targets and investments. The 'BESS Decade' continues to gain momentum with 55% year-on-year growth. Battery Energy Storage Systems (BESS) now account for 15% of total battery deployments, up from 7% in 2020, highlighting its rapid adoption. New BESS installations in 2024 alone contributed over 45% of the current cumulative global capacity of 150 GW / 363 GWh, underscoring BESS's significance as one of the most promising and fast-growing sectors in the battery industry landscape.

Battery prices at the pack level saw the largest drop since 2017, improving 20% from 2023 to a record low of $115/kWh. Global battery manufacturing capacity increased from 1.05 TWh to 1.45 TWh in 2024. Overcapacity across the battery supply chain drove cell prices to the unsustainably low level of $50/kWh for China-made LFP cells, resulting in involutionary competition and investment pullback. New Chinese industrial policy aimed at phasing out low-quality capacity added further pressure. For battery producers navigating this challenging pricing environment, current strategic focus include cost reduction, technological innovation, vertical integration, and diversification into overseas markets in search of higher profit margins. China continues to dominate the supply chain, owning >80% of key cell components and cells.

The battery investment landscape in 2024 slowed, with fewer VC/PE deals due to higher interest rates and geopolitical tensions. While growth was supported by significant debt raises and government funding—such as Northvolt ETT AB's €5 billion green offering and the US DOE's $9.6 billion loan to BlueOval SK—the bankruptcy of Northvolt highlighted risks in the sector, dampening investor confidence. Public market performance was mixed, with established battery OEMs benefiting from new product launches, while shares in EV startups, charging infrastructure, and lithium companies underperformed. The US DOE supported the sector by investing over $3 billion into 25 projects to bolster domestic battery production and supply chains in the United States.

Emerging technology trends in 2024 include the introduction of medium-nickel high-voltage NMC and high-compaction-density LFP cathodes. Significant strides were made in the commercialization of dry electrode processing, LxFP, engineered silicon, and pre-lithiated anodes, all aimed at improving energy density, cost, and safety. Alternative cell chemistries, such as Na-ion, solid-state batteries (SSB), sulfur, and Li-metal, also progressed toward commercialization. Notably, sodium-ion and semi-solid state products, primarily developed by Chinese manufacturers, are now being integrated into commercial EVs and BESS systems.

Novel use cases such as EVTOL, marine, and data centers are achieving higher levels of technical readiness. Notably, artificial intelligence (AI) is quickly being deployed across the entire value chain from materials discovery to fleet data analytics to accelerate the advancement of these technologies and is emerging as a new focus for commercial R&D and entrepreneurial energy in the space.

1 INDUSTRY

Notable Events **January**

BYD breaks ground on $1.4B Na-ion battery plant in Xuzhou, China.

Northvolt raises $5B debt financing to enable expansion of first circular gigafactory in the western world.

Rivian hires Jonas Reinke, ex-Porsche and Apple, to help launch R2 and R3 EV platforms.

CALB announces plan to build a $2.2B Li-ion battery factory in Portugal.

WEEK 1 **WEEK 2** **WEEK 3** **WEEK 4**

Chile forms state-controlled entity with **SQM** to control domestic lithium production.

Norwegian parliament approves legislation that allows companies to apply for permits to prospect for minerals across 280,000 km^2 of Norway's continental shelf in the Arctic.

NASA and **Archer Aviation** partner on advanced battery tech for eVTOLs.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **February**

WEEK 1

UK EV registrations reach 1MM sold, sales for the month rose 21%.

Cirba Solutions and **EcoPro** sign MOU to produce pCAM and CAM in North America.

WEEK 2

Volkswagen to invest $1.8B more in Brazil over the next five years.

China forms Solid State Battery consortium with 200+ members including CATL, BYD, CALB, EVE Energy, Gotion, government agencies, universities, research institutes, and capital partners to drive commercialization of SSBs by 2030.

WEEK 3

LG Chem signs $19B cathode supply agreement with GM.

ACC secures financing for three European factories worth €4.4B.

WEEK 4

BYD launches $15,000 EV with 48 kWh pack, kicking off price war with fossil cars.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **March**

WEEK 1

BYD sales in India are up 314%, launches luxury EV in India's market.

Volvo Cars' European EV sales grew 31% y/o/y.

WEEK 2

SK On announces plans to launch mass production of LFP batteries from 2026.

Rivian postpones $5B EV factory construction in Georgia.

WEEK 3

Nio and CATL partner to co-develop longer life batteries.

Renault to offer remanufactured drives and batteries in after-sales with plans for customers to be able to choose between new original parts and remanufactured components.

WEEK 4

BYD launched ultra low-cost ($9.7k) EV powered by 30 kWh of LFP Blade batteries.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **April**

LGES and General Motors joint venture begins production at 2nd US battery plant in Tennessee.

BYD announces plans to launch next-gen Blade battery this year, improving the specific energy density (SED) from 140 Wh/kg to 190 Wh/kg for LFP.

AM Batteries and Zeon partner to develop dry battery electrode with novel binders.

LGES to license out battery patents to block tech infringement.

WEEK 1 **WEEK 2** **WEEK 3** **WEEK 4**

CATL launches new Tianxing battery with 1 million mile warranty and 15-year service life.

CATL unveils a 'five-year zero degradation' "TENER" stationary storage battery with 430 Wh/L LFP cells and 6 MWh total capacity.

CATL unveils Shengxing PLUS LFP battery at 205 Wh/kg, capable of charging at 4C with "1,000 km range".

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **May**

SES and Hyundai-Kia move forward to B Sample qualification phase.

South Korea plans $7B push to pivot EV battery industry away from China.

Lyten begins shipping lithium-sulfur A sample cells to automotive OEMs, including Stellantis and others.

The Biden administration hikes tariffs on selected Chinese imports, including tariff on EV duties jumping to 102.5% from 27.5%.

WEEK 1

WEEK 2

WEEK 3

WEEK 4

Factorial and LG Chem sign MOU to develop SSBs.

Ion Storage Systems commissions one of the largest SSB manufacturing facilities in the United States.

GM invests $390MM in Kansas for next-gen Chevy Bolt EV production.

Tulip Innovation launched a new licensing program aggregating patents related to lithium-ion battery technology from LG Energy Solution, Ltd. (LG Energy Solution) and Panasonic Energy.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **June**

WEEK 1

China plans $845MM investment to develop SSBs in a government-led project.

Geely presents improved "Short Blade" LFP battery.

WEEK 2

Verkor secures more than $1.4B in green loans to complete its plant in northern France.

BMW cancels $2B battery cells contract with **Northvolt.**

WEEK 3

EnerVenue set to raise $515MM for Ni-H batteries.

Gotion and InoBat to build $1.29B Slovakia EV battery plant.

WEEK 4

EVE Energy launched cylindrical cells with 6C charge rate.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **July**

Volkswagen announces plan to invest up to $5B in Rivian starting with an initial investment of $1B.

BYD to build $1B EV plant in Turkey, which will be able to produce 150,000 electric and hybrid vehicles annually.

Addionics raises $39MM in its Series B round led by GM Ventures.

Turkey announces $5B for the production of electric vehicles and $4.5B for battery production.

WEEK 1

WEEK 2

WEEK 3

WEEK 4

Sila Nanotechnologies raises $375MM in a Series G round led by Sutter Hill Ventures.

Peak Energy raises $55MM Series-A to scale up production of Na-ion batteries.

LGES announces new 4680 line in South Korea, to begin mass production in Q3/Q4 with 8 GWh capacity.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **August**

WEEK 1

Uber partners with BYD, to offer 100,000 drivers lower prices and financing for EVs.

BMW to set up five new assembly sites for high-voltage batteries.

WEEK 2

Natron Energy announces $1.4B gigafactory in North Carolina.

CATL invests in EVTOL developer Autoflight.

WEEK 3

Northvolt closes its subsidiary Cuberg and pulls out of the United States.

Mercedes-Benz Korea reveals issues with batteries supplied by Farasis following EV fire incident.

WEEK 4

Volkswagen scales back plans for battery cell plants in Europe, North America.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **September**

WEEK 1

24M raises $87MM Series E round at $1.3B valuation.

Japan to fund up to $2.4B in new support for domestic EV battery production, bolstering EV plans of Toyota, Nissan, Mazda, and Subaru.

WEEK 2

Mercedes-Benz partners with Factorial to develop SSBs at 450Wh/kg.

US DOE to award $3B to 25 projects for battery manufacturing sector including Group14, South32, Mitra Chem, and Form Energy.

WEEK 3

BMW and Redwood Materials establish partnership to recycle Li-ion batteries in the U.S.A.

GM announces NACS access for its EVs, gaining access to 17,800 Tesla Superchargers.

WEEK 4

CATL shares that R&D spending reached $2.6B in 2023, employing 21,000 engineers.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **October**

Tesla plans 4 new batteries in 2026, including batteries for its robotaxis.

General Motors to retire “Ultium” branding, expands NMC pouch cells to include LFP and prismatic formats.

Rio Tinto to acquire Arcadium Lithium in $6.7B deal.

Indonesia forms a joint venture with CATL to invest $1.2B in battery production.

WEEK 1 **WEEK 2** **WEEK 3** **WEEK 4**

Enovix begins shipping cell samples from its Malaysia fab’s Agility Line.

Form Energy raises $405M Series F round, bringing its total funding raised to more than $1.2B.

Lyten investing more than $1B to build the world’s first Li-S gigafactory in Nevada with up to 10 GWh/yr capacity.

Source: Volta Foundation’s This Week in Batteries Newsletter

Notable Events **November**

WEEK 1

BYD's quarterly sales of BEVs overtake Tesla's for the first time.

Volvo to take ownership of Northvolt battery JV.

WEEK 2

CATL adds 1000 new R&D staff to SSB program, begins trial production of 20-Ah samples.

BYD hits brakes on Canadian expansion plans amid 100% tariffs on Chinese EVs.

WEEK 3

Lyten purchases the manufacturing assets from Cuberg/Northvolt.

CATL announces 2nd-gen sodium-ion EV battery that works down to -40°C.

WEEK 4

Northvolt files for bankruptcy; Scania loans $100MM for bankruptcy process.

Honda opens a demonstration plant for its proprietary solid state battery technology.

Source: Volta Foundation's This Week in Batteries Newsletter

Notable Events **December**

Stellantis CEO Carlos Tavares resigns earlier than expected due to falling U.S. sales without naming a successor.

Stellantis and CATL to invest $4.3B to build an LFP plant in Spain.

GM sells its stake in a battery plant in Lansing, Michigan to its JV partner LGES at the same they extend technology partnership.

Hyundai announces the production of solid state batteries by the end of 2025 and is planning mass production by 2030.

WEEK 1 **WEEK 2** **WEEK 3** **WEEK 4**

BYD launches sodium-ion BESS battery based on the company's Long Blade Battery technology.

Coreshell launched commercial scale 60 Ah battery cells; employs low-cost metallurgical silicon in combination with lithium iron phosphate (LFP) cathodes.

The U.S. DOE announces a $7B conditional commitment to StarPlus Energy, a JV between FCA and Stellantis, to build a battery factory in Indiana.

Source: Volta Foundation's This Week in Batteries Newsletter

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Streamlined, Next-Generation, Chemistry Agnostic Platform to Manufacture Highly Cost-Efficient Batteries at Scale Today.

LFP | NMC | LCO | NCA | Graphite | Silicon | + More

Key Benefits

~10%
Lower Total CO2 Footprint

25%
Less Energy Used During Production

20%+
Smaller Factory Footprint

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Lower Upfront & Long-Term CapEx

Patented Dual-Sided Dry Deposition Process

Raw Material Intake	Powder Feedstock Prep	Electrode Production	Cell Production
Chemistry Agnostic	Spray Drying	Electrostatic Powder Coating	Traditional Processing

Sustainable
0kg of toxic solvent required.

Uniform
Distributes binder materials and carbon conductors with active materials.

Optimized
Enhances mechanical robustness and electrical conductivity.

Less Waste
Reclaims electrode material during the dry coating process.

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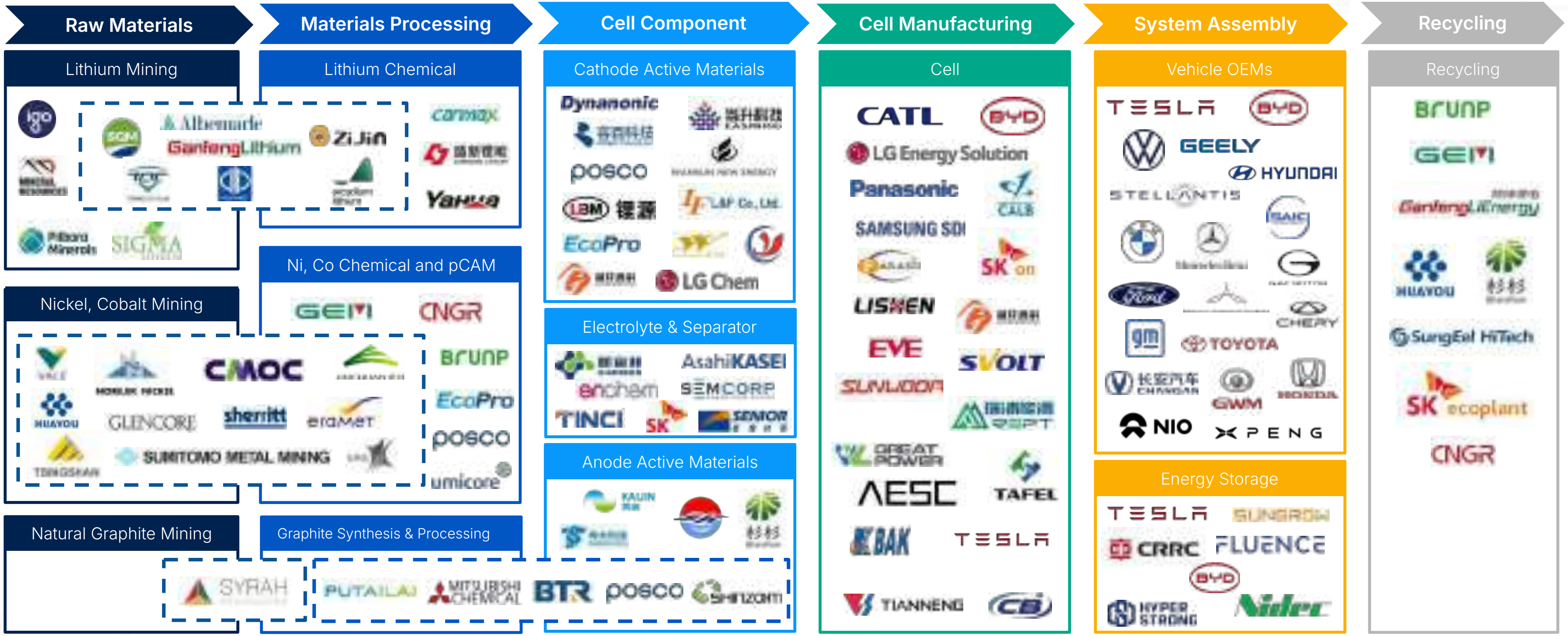
1 INDUSTRY

Incumbents And/Or Public Companies (>$1B Market Cap/Valuation)*



Raw Materials

Lithium Mining

Nickel, Cobalt Mining

Natural Graphite Mining

Materials Processing

Lithium Chemical

Ni, Co Chemical and pCAM

Graphite Synthesis & Processing

Cell Component

Cathode Active Materials

Electrolyte & Separator

Anode Active Materials

Cell Manufacturing

Cell

System Assembly

Vehicle OEMs

Energy Storage

Recycling

Recycling

* estimated as of December 2024

Startup And/Or Small Companies (>$30M Valuation)*

Raw Materials

Lithium Mining

- Controlled Thermal Resources
- ENERGYX
- Lithium Americas
- Summit Nanotech
- Lilac
- Lithios
- CORE Lithium
- Critical Elements
- European Lithium
- Liontown
- Cornish Lithium

Nickel, Cobalt Mining

- Atlas
- Impossible Metals
- Cobalt Blue
- Jervois

Natural Graphite Mining

- Westwater
- talga

Materials Processing

Lithium Chemical

- Novalith
- Adionics
- LiVista
- RockTech Lithium

Ni, Co Chemical

- Jervois
- altilium

pCAM

- nanoOne
- Ascend Elements
- SVX

Graphite

- Anovion
- Novonix
- Vianode

Other Battery Chemicals

- Koura
- pH7
- aepnus

Cell Component

Cathode Active Materials

- 6K
- Mitra Chem
- Novonix
- IBU-tec
- Stratus
- Ascend Elements
- SVX
- Redwood Materials

Anode Active Materials

- Amprius
- Sila
- Anovion
- Group14
- nyobolt
- Echion
- OneD
- E-Magy
- Novonix
- CarbonScape

Electrode

- 24m
- Dynami
- AM Batteries
- Coreshell
- dragonfly
- Addionics
- Anaphite

Li-metal, Electrolyte, Separator

- Sionic
- Sepion
- Soteria
- South 8 Technologies
- Sion Power
- Entek

Cell Manufacturing

Lithium-ion

- Verkor
- Enpower
- Freyr
- PowerCo
- microvast
- Cellforce
- Lyten
- Enovix
- Amprius
- One
- northvolt
- Morrow
- Ateios
- ACC
- dragonfly

Solid-state & Li-metal

- Lyten
- Ampcera
- QuantumScape
- Factorial
- ProLogium
- SES
- Solid Power
- Blue Current

Sodium-ion

- Natron Energy
- Peak Energy
- Unigrid

System Assembly

- Li Auto
- Leapmotor
- Neta
- Aiways
- HiPhi
- VinFast
- Xiaomi
- Rivian
- Lucid
- Ola
- Canoo
- dragonfly
- Rimac
- Volta Trucks
- Mullen
- One
- nyobolt
- gaussion
- Proterra

Recycling

- Ascend Elements
- Redwood Materials
- Li-Cycle
- ENERGYX
- Aqua Metals
- hydrovolt
- RecycLiCo
- green li-ion
- Retriev Technologies
- fortum

* estimated as of December 2024

Startups And/Or University Spin Offs

Materials Processing

Lithium Chemical

LIVISTA
AUSTVOLT

pCAM

CHEMX MATERIALS

Graphite

CONOVATE
granode

(Solid) electrolytes

NATRION
Ampcera
Qkera

Cell Component

Cathode Active Materials

altilium
INTEGRALS POWER

Anode Active Materials

E-MAGY
SILIENERGY
NEBA Lithium Solution
Nanode
ADVANO

Other components

Soteria
Feon

Cell Manufacturing

Li-ion

TYFAST
Molyon
ABF
ATEIOS

Solid-state

Solidion
GQenergy
BTRY
CYMBET
zakuro
Plerisca

Other battery concepts

Battolyser Systems
breathe
GEYSER BATTERIES

Process Technology

8inks
SAKUÚ

System

endurance
VIVITRON
CLEAN ELECTRIC
Rolled-Ribbon
INTECELLS

Recycling

ecomet
Primobius
tozero
altilium
librec
PRINCETON NUEnergy
BATX
ABTC
CYLIB

A Comprehensive Database of Battery Companies: The Battery Business Directory

2000+ COMPANIES MAPPED to 13 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.

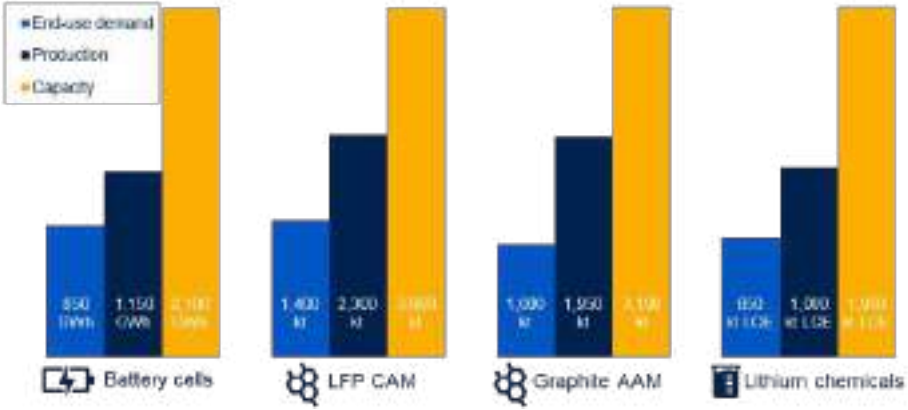
THE BATTERY BUSINESS DIRECTORY

The Battery Business Directory is the largest open-access database for companies operating across the global battery industry. The directory maps over 2,000 organizations spanning 13 key supply-chain segments, providing comprehensive, reliable data that helps battery professionals discover potential partners, suppliers, and customers.

Source: Battery Business Directory

Overcapacity Across The Supply Chain Has Resulted In Intense Competition & Pullback Of Investments

2024 DEMAND, PRODUCTION, AND CAPACITY ACROSS SELECTED SECTORS IN CHINA



OVERCAPACITY POSES EXISTENTIAL CHALLENGE:

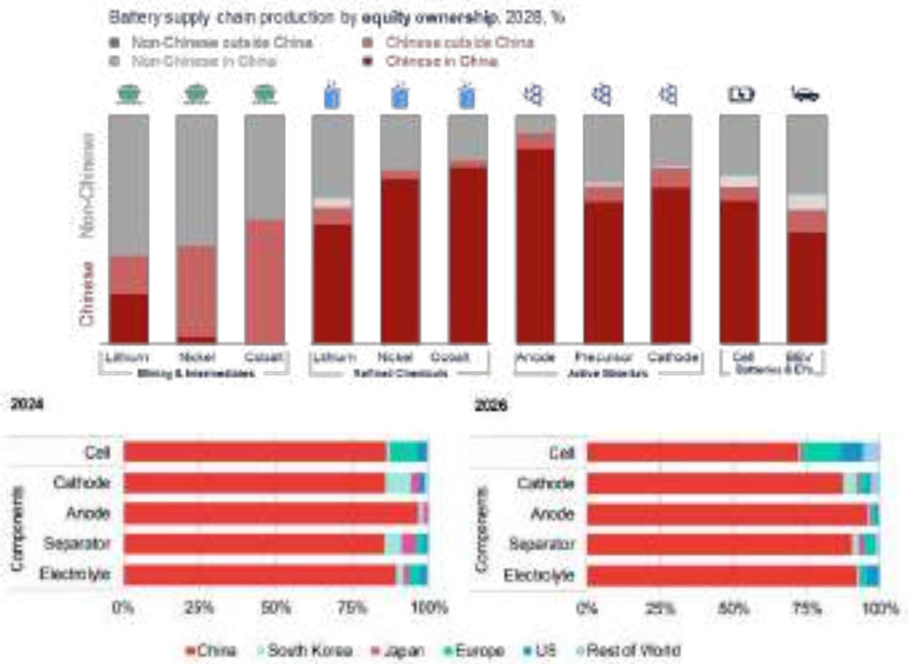
- In China, EV and industrial subsidies have been scaled back, and new industry standards are aimed at **culling low-quality capacity**
- This has led to a crowded market and fierce competition in several stages of the supply chain, with price wars being common and some companies producing despite no orders
- In other industries - such as solar - this story eventually resulted in a wave of consolidation
- In the rest of the world, capacity investments have overshot local demand and many are now being cancelled, cut down, or delayed

CHINESE MANUFACTURERS HAVE 3 STRATEGIC OPTIONS:

1. Embrace cost competition domestically & cut prices to retain market share
2. Focus on technical innovation and supply chain efficiencies to optimize the cost and value of products
3. Expand overseas, where there is less competition, and an opportunity to maximize profits to offset shrinking margins back home

CRU Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. 'Demand' includes exports. There is a time lag from material and cell production to installation into end-use demand. Figures are rounded to the nearest 50. December 2024 data is partially estimated.

China’s Ownership Of The Supply Chain Extends Beyond Its Borders



- China does not have significant geological deposits of battery raw materials, but companies have invested in overseas operations and in processing capacity at home
- This is manifested as dominance in the midstream for chemical intermediates and active materials
- Vertical integration is a strategic benefit as well as a **cost advantage**
- Despite **US FEOC rules** prompting some operations to reduce their Chinese ownership stake, many non-Chinese upstream and midstream projects have been curtailed in 2024, leaving the overall picture unchanged
- China’s supply chain dominance has led to intensely competitive conditions that are squeezing non-Chinese producers

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner), BloombergNEF (Distinguished Partner) ; Top chart shows production by ownership; bottom charts show capacity by location.

Chinese Manufacturers Are Chasing Profits Overseas And Market Potential For LFP

CURRENT STRATEGIC FOCUS OF MAJOR CHINESE BATTERY/P/CAM PRODUCERS

Battery producers

- Minimise scrutiny in US market via technology licensing model
- Strengthen partnerships with OEMs in long-term tech. roadmap

- Develop products for energy storage, PHEV and commercial vehicle market

- Fast-charging technology
- Energy density improvement via chemistry and structural changes
- Financially support suppliers to secure high-tech materials

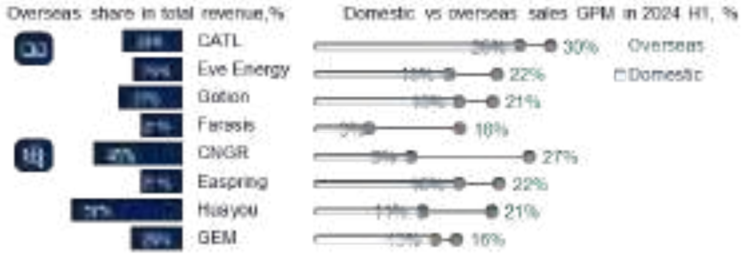
p/CAM producers

- Construct pilot lines overseas to attract OEM and battery customers
- Acquire existing projects and environmental permits from brownfield sites

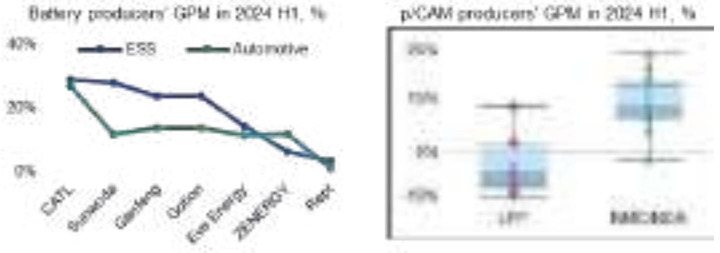
- Traditional NMC producers diversifying into LxFP despite low margins
- Expand metal refining business to consume raw materials

- High compaction density LFP CAM
- Mid-Ni high-voltage CAM for BEV and PHEV
- Ultra high-Ni p/CAM for solid-state batteries
- Continue LMFP development

OVERSEAS SALES ARE SIGNIFICANTLY MORE PROFITABLE FOR CHINESE PRODUCERS



BATTERY MAKERS EARN HIGHER PROFITS FROM ESS, BUT P/CAM BEARS THE LOSS



Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. GPM = gross profit margin. Box plot displays where 50% of the data points fall.

Korean and Japanese Companies' Roles In The Battery Supply Chain

LONG TERM: Korean focus is on vertical integration, expanding into LFP & ESS, balancing relationship with US & China

Accelerating vertical Integration

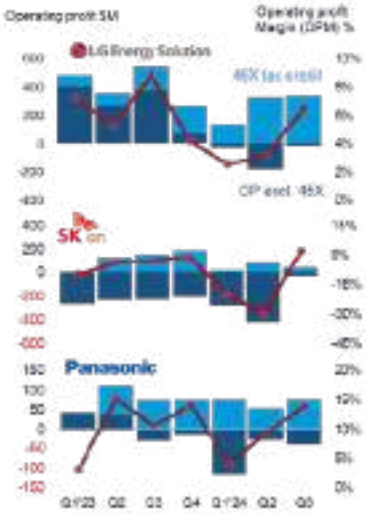
Bringing p/CAM production home

Diversifying technology portfolio

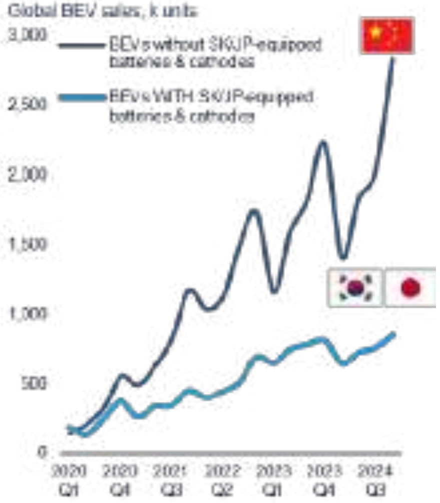
Balancing US requirements & Chinese collaboration

SHORT TERM: lowering growth expectations amid decline in profitability & market share

SK/JP COMPANIES HAVE BEEN RELYING ON US IRA TO PROP UP THEIR PROFITS



SK/JP-SUPPLIED BEVs LAGGING CHINESE COMPETITORS



Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Where Integrated Supply Chain Clusters Are Forming

MAJOR EMERGING SUPPLY CHAIN CLUSTERS OUTSIDE CHINA

Europe and North America mainly downstream-focused

Morocco, South Korea, & Indonesia to be top midstream producers outside China

OPPORTUNITIES	RISKS
North America: • Close to end-use market • IRA production tax credit **US-FTA countries:** • Politically close to the US • Meets requirements for IRA EV tax credit • [Some] close mineral resources	• Policy uncertainties • High labor, material costs + capex • Insufficient skilled labor (North America) • Mining industry less willing to move into midstream
Europe: • Close to end-use market • Saving efforts to trace carbon emissions for Battery Passport • EU Rules of Origin regulations	• Strict environmental permitting • High labor and energy cost in some countries • Bureaucratic delays
Indonesia & Others: • Close to mineral resources • Lower labor and energy costs • More straightforward environmental permitting	• Scrutiny on Chinese ownership by US/EU • Long distance to EU/US markets + tariffs

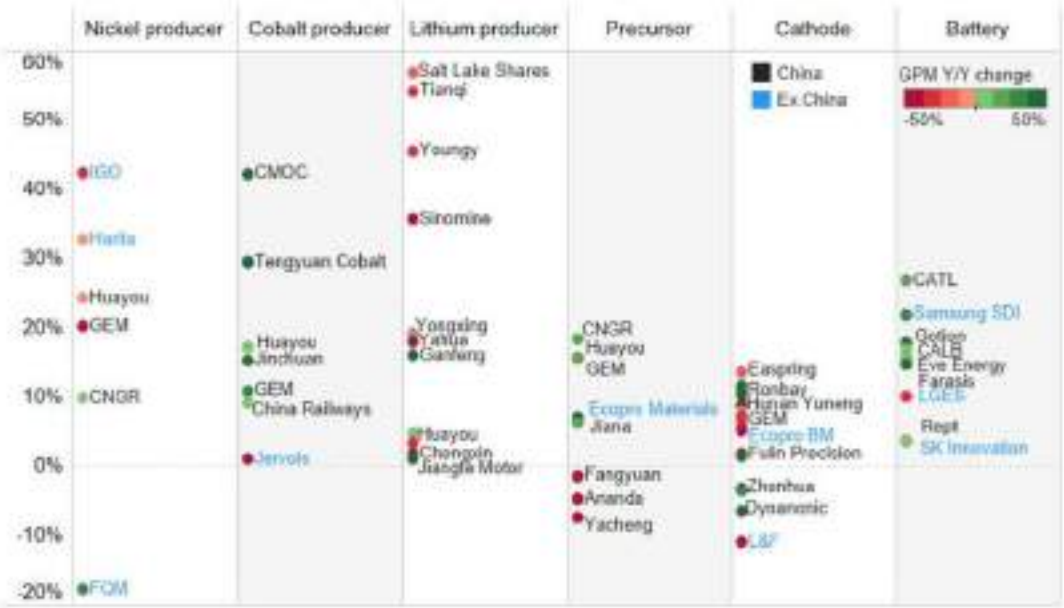
- Asian manufacturers are pivoting their strategies to capture overseas markets, where they can command higher margins
- Europe and North America are working to nurture a domestic supply chain while adopting policies to reduce reliance on China
- The **higher costs** and investment risks are deterring larger overseas investments
- Therefore, supply clusters are converging on what are seen as **low-cost, low-risk countries** like South Korea, Morocco, and Indonesia, to supply the major markets

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Profitability Has Been Redistributed Across The Value Chain

NON-INTEGRATED MIDSTREAM PRODUCERS FACE PROFITABILITY CHALLENGES

Gross profit margin in 2024 Q2 and y/y change, %



Upstream miner and refiners' margins show significant divergence in 2024 as prices hit the cost levels of marginal producers.

Battery producers continue to reap the benefits of falling raw material prices.

While vertically integrated **midstream producers** can leverage profits from mining and refining to reduce p/CAM prices, non-integrated producers are suffering from the slowdown in demand for NMC and export customers, and are losing market share. They are increasingly reduced to a tolling role, with margins set by battery makers.

LFP producers, especially non-integrated ones, are suffering higher losses due to the intense competition and strong bargaining power of battery producers.

Chinese p/CAM and battery producers generally have higher margins than ex. China companies due to their cost competitiveness.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). Profit margin data from CRU's compilation of company reports.

Acquisitions And Consolidation

2024 saw significant **industry** consolidation and acquisition, driven by companies exiting markets, seeking buyers during financial struggles, entering new sectors, expanding supply chains for critical materials, or boosting production capacities.

Volvo Cars to fully acquire Novo Energy by invoking redemption rights from Northvolt

Volvo acquires Proterra's battery unit for battery pack manufacturing/ assembly capacity.

Rio Tinto acquires Arcadium Lithium for $6.7 billion to bring in lithium business

Ultralife acquires Electrochem Solutions to strengthen medical/industrial solutions.

Enerpoly acquires Nilar to boost zinc-ion battery production capabilities with Nilar's line.

Arcadium Lithium acquires Li-Metal's IP and physical assets for $11 million

Pure Lithium acquires Dimien assets focusing on vanadium cathode materials.

EnerSys acquires Brentronics for military and industrial batteries.

Komatsu acquires American Battery Solutions.

LionVolt acquired AMTE Power's battery cell production line in Scotland

Company Bankruptcies

In 2024, the battery industry faced significant financial challenges, leading to several notable bankruptcies and restructurings. Several factors, lowering system prices and performance from China, including a growing difficulty to scale in the West and a challenging investment environment.

northvolt

High production costs, quality issues, access to specialist workforce, and competition in the battery market (see Deep Dive)

redflow

Struggled with scalability and the costs of their **Zn-Br flow battery** technology and competitiveness of Li ion batteries

Ambri

Filed for bankruptcy, blaming a challenging fundraising environment and thwarted plans to expand into manufacturing.

BRITISHVOLT

Filed for bankruptcy in 2023 and dissolved in 2024 due to insufficient funding, poor strategic planning, and lack of experience. Converted to a data center.

VARTA

Decreased demand for some of its battery products and high debt levels = restructuring

Supply chain issues, production delays and recalls of their Ocean vehicle

LORDSTOWN

Production hurdles, lack of demand, and struggles to compete with larger EV makers, rebranded as Nu Ride

MOXION

Financial strains in scaling operations led to shut down operations.

LION ELECTRIC

Received creditor protection in Quebec and expected to file for bankruptcy protection in the US

ITALVOLT

Failed due to **financial instability,** bureaucratic hurdles, lack of technical partnerships and planning.

Note: Non-exhaustive list

northvolt Unpacking The Timeline Of Northvolt's Bankruptcy Proceedings

On November 21st, Northvolt AB filed for chapter 11 bankruptcy protection. The company remains in operation as the stakeholders continue to work through a resolution

JUNE 2024

BMW canceled order for EUR2bn of batteries

JULY

Announced strategic review of business

OCTOBER

- Northvolt's **subsidiary ETT Expansion**(3) files for bankruptcy
- **$300mm** provide by undisclosed investors to Northvolt AB as rescue financing to give more time to stabilize the company

NOVEMBER

- Northvolt **AB files for Chapter 11 bankruptcy**. Liquidity situation becomes dire with just a few weeks of liquid assets
- **Peter Carlsson steps down as CEO**
- **$100mm** in debtor-in-possession financing secured
- Goldman Sachs Asset Management writes off **~$900mm** investment in Northvolt

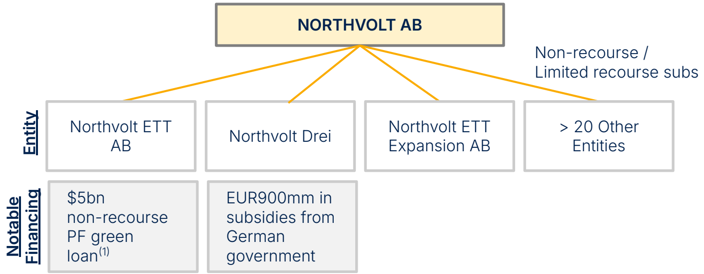
DECEMBER

Appoints Markus Dangelmaier as CEO of Northvolt ETT

JANUARY 2025

- Marketing **medium term financing** to provide runway after restructuring.
- Northvolt owners **vote** to stay operating while seeking financial rescue
- Norsk Hydro to **buy remaining shares in battery recycler** from Northvolt

CORPORATE STRUCTURE

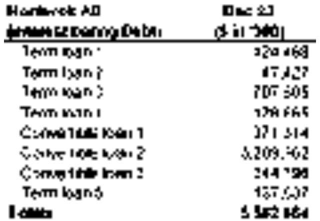


NORTHVOLT AB

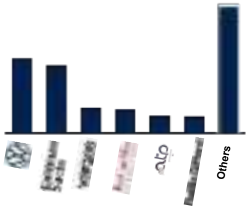
Non-recourse / Limited recourse subs

Entity	Northvolt ETT AB	Northvolt Drei	Northvolt ETT Expansion AB	> 20 Other Entities
Notable Financing	$5bn non-recourse PF green loan(1)	EUR900mm in subsidies from German government		

Debt Structure(2)



Equity Ownership(2)

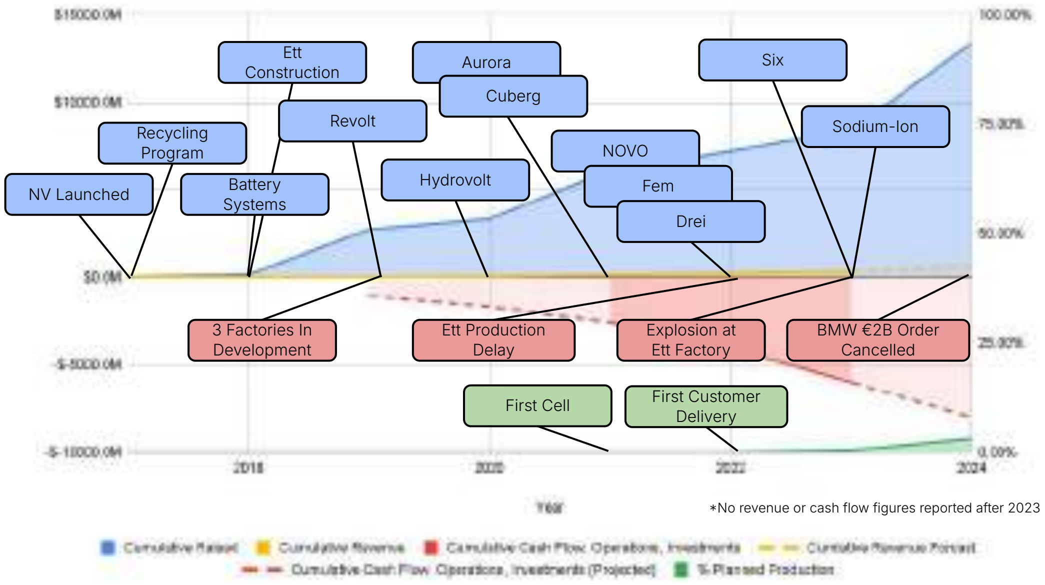


Sources: Bloomberg, company releases, Debtwire

Debt structures estimates per Bloomberg (01/19/2024) and company notices

(1) non-recourse indicates that in the event of default at the entity level, the lender do not have the authority to pursue collateral from the parent company (Northvolt AB) ; (2) Per of the 2023 annual report filing ; (3) Northvolt's flagship battery gigafactory located in Skellefteå, Sweden

Northvolt Financials And Production Execution Issues



*No revenue or cash flow figures reported after 2023

Northvolt's ambitious expansion strategy in a knowledge-constrained and capital-intensive industry revealed critical missteps:

- A lack of focus on core business segments led to overstretched resources and operational inefficiencies.
- Each funding round was paired with a new program or product launch, further diluting focus and straining capacity.
- Severe labor shortages exacerbated challenges, with only 200 staff managing three factories under development.
- Loan structures with rising interest rates starting in 2024 demanded disciplined execution, which was hindered by competing priorities and insufficient workforce support.

Source: Northvolt Sustainability Reports 2022 and 2023, Northvolt Production Numbers

The impact of Northvolt's Cuberg acquisition has been difficult to assess due to lack of purchase price disclosure until now:

- Purchase price ("Cash consideration paid") was USD$11.2 million cash, USD$14.8 million including debt assumption ("Forgiven notes") of USD$3.6 million.
- Equity ("Shares issued, at fair value") and earn-out (Earn-out payment") are non-cash considerations.
- Annualized burn rate of USD$6.9 million for 2021 with a headcount of 56.
- Total cash losses to Northvolt from the Cuberg acquisition estimated to be USD$78 million from 2021 to 2024 when it was shut down months prior to the bankruptcy announcement.
- **Cuberg failed to deliver a viable commercial product** that could have been a category leader; Cuberg failed to deliver on the promise of 'drop-in' li-metal production lines for existing facilities and equipment; Cuberg failed to deliver on its advanced R&D initiative to Northvolt's broader operations

Cuberg could have played a vital role in Northvolt's operational success but was an early casualty leading up to bankruptcy.

Sources: Northvolt sustainability reports 2022, and 2023, and PitchBook. Exchange rate on March 10, 2021 1 SEK = 0.11791 USD

BRITISHVOLT: FAILURE TO MEET MILESTONES = LACK OF INVESTMENT

Founded in 2019, Britishvolt's gigafactory plans were doused when the company underestimated CAPEX and investor appetite. The **original plan** was to build a 30GWh factory in Northumberland, UK and had $2.5 billion in funding promises in hand including a £100 million commitment from the U.K. government.

2021

Founders did not have electric vehicle experience and did not secure the £3.8 billion needed to complete the Northumberland plant when **the company broke ground in 2021.**

2022

Failure to meet milestones and excessive spending led to funding difficulties: Construction was halted in August 2022 and the **U.K. government declined to advance £30 million** in funding in October 2022.

2023

Britishvolt went into administration in January 2023 and was acquired by Australia-based **Recharge Industries** the following month.

2024

In April 2024, plans to restart plant construction failed and the Northumberland site was sold to the Blackstone group, a US private equity firm, for £110 million to be redeveloped into a **data centre.**

Sources: Linked above to various news articles

VARTA

VARTA AG Approved A Financial Restructuring Plan, Secures Investment From Porsche

The 130-year-old German-based company became heavily indebted and **began a financial reorganization** under the German Corporation Stabilization Act (StaRUG) in June 2024

- Varta produces a wide variety of battery technologies that have seen declines in market demand but the company's subsidiary, V4Drive, produces large format lithium-ion batteries used in some Porsche vehicles
- As a result of the reorganization, **the company's shares were delisted** from the Frankfurt stock exchange at zero value and its €485 million debt was reduced to €200 million
- A longtime investor in the company and **Porsche AG invested €60 million** with the latter gaining a 50% stake in Varta AG and a 70% stake in the V4Drive subsidiary

Sources: Linked above to various news articles

1 INDUSTRY

Investment Landscape Overview

Battery investments encompass a wide wide array of sub verticals, including chemistries, production equipment, software, battery facilities, and more. Throughout 2024, certain key trends emerged:

SLOWER FUNDRAISING ENVIRONMENT

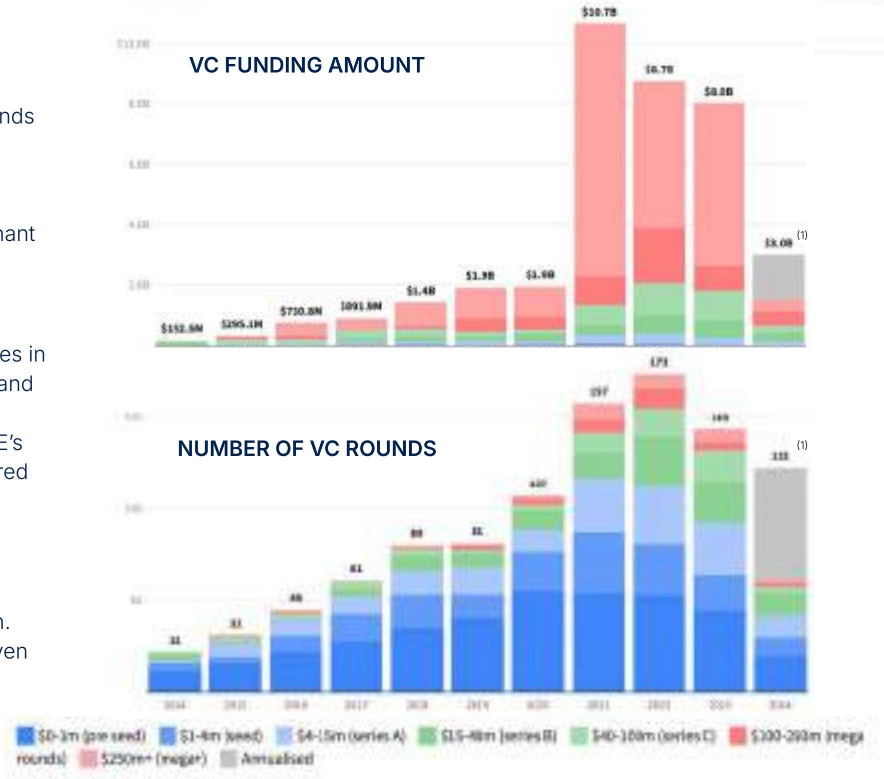
2024 saw a slower pace for VC/PE funding, driven by fewer megarounds, which were a dominant feature from 2020 to 2023.

PUBLIC AND PRIVATE FUNDING SOURCES FOR INFRASTRUCTURE

Large debt and grant funding supported the growth of battery infrastructure. Notable debt raises in 2024 included, Northvolt ETT AB’s €5bn green offering in Jan, Verkor €1.3bn offering in May, and ACC €4.4bn offering in Feb. Additionally, government loans and grant programs continue to provide attractive terms for capital intensive investments. Notable transactions include the DOE’s $9.6bn loan to BlueOval SK, the €1.5bn EU grant to ProLogium, and the €900mm subsidy offered by the german government / EU to Northvolt Drei.

MACROECONOMIC TRENDS AND RECENT DEVELOPMENTS

Across 2024, the battery investment landscape has been shaped by macroeconomic factors including the current interest rate environment, governmental support, and geopolitical tension. Company specific tensions emerged as management teams focus on balance sheet health given slower industry growth lead to weaker P&L.



(1) Annualised as of July 4th

Source: https://dealroom.co/guides/fbc-uk-battery-study-2024

Climate Investors Begin Deploying Dry Powder

$86Bn of Investible Dry Powder for Climate

Dry powder and new Assets Under Management (AUM) by quarter, 2021-2024 YTD ($bn)

The fundraising surge in 2022 allocated a large amount of uninvested capital (aka 'dry powder') to climate focused investments. From 2022 through H1 2024, increasing dry powder indicated that **investors were raising capital more quickly than they were deploying** as climate-focused funds marketed newer vintages. In Q3 2024, dry powder peaked at $93bn. The environment shifted in Q4 as investors start to deploy capital more quickly than it was being raised.

Investors have slowed the pace of deployment, with the **2022 fund vintage deploying just 43% of its capital within two years, compared to 60% for 2020 vintages**. Recent funds benefit from lessons learned through previous investments, resulting in more rigorous due diligence processes and greater selectivity in investment choices.

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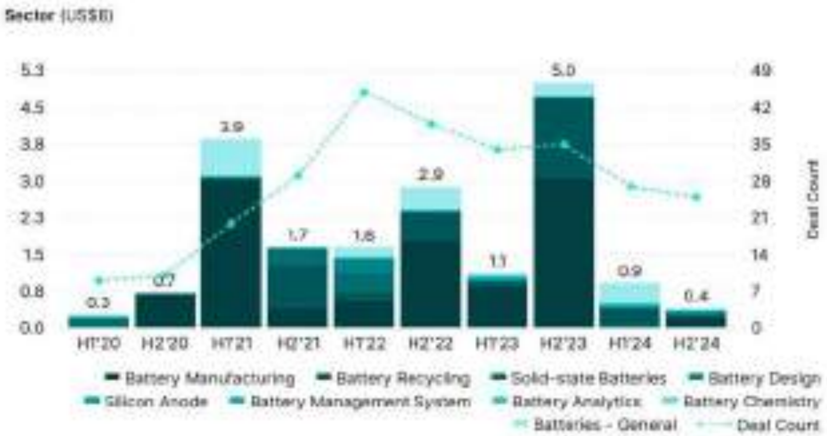
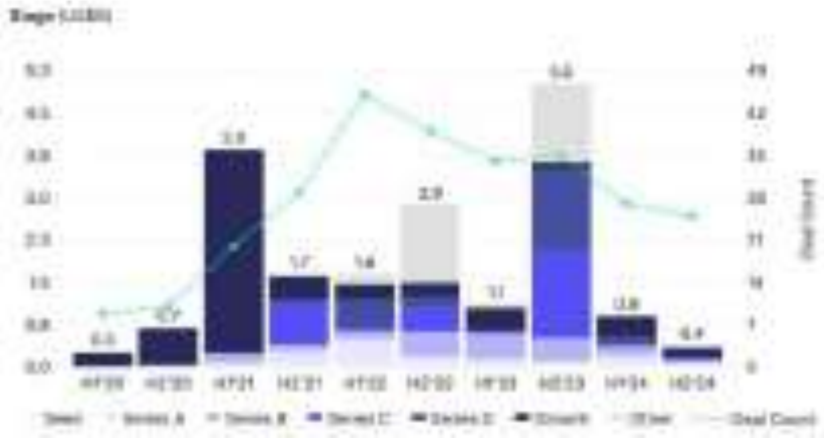
2024 Battery Technology VC Investments

BATTERY TECHNOLOGY INVESTMENTS BY SECTOR



Battery technology investments (excluding energy storage) shrank by 74% YoY, as battery-focused investments within the energy and transportation space were deprioritized in favor of sectors like nuclear and aviation. Macroeconomic and policy uncertainties further dampened investment sentiment, including **delayed U.S. IRA fund rollouts, global political uncertainty, and a higher cost of capital**.

BATTERY TECHNOLOGY INVESTMENTS BY STAGE



Unlike the precedent boom years, 2024's funding environment prioritized **capital efficiency and milestone-driven financing**, with many late-stage rounds blending venture, grants, and debt.

Content & analysis provided courtesy of Sightline Climate (Distinguished Partner). For more information, visit https://www.sightlineclimate.com/

5-Year Cumulative VC Capital Deployment In Battery Technology (By Sector)

With rising geopolitical tensions and trade restrictions on China's battery supply chain, investments are increasingly focused on **localizing manufacturing and supply chains (e.g. U.S. and EU battery gigafactories, anode/cathode production)**, further expanding the largest sector in the battery value chain pictured on the left.

Increased policy support, such as regulations in the **EU Battery Regulation** mandates and extended producer responsibility (EPR) frameworks, attracted additional capital to **closed-loop battery recycling** in addition to solely new cell manufacturing.

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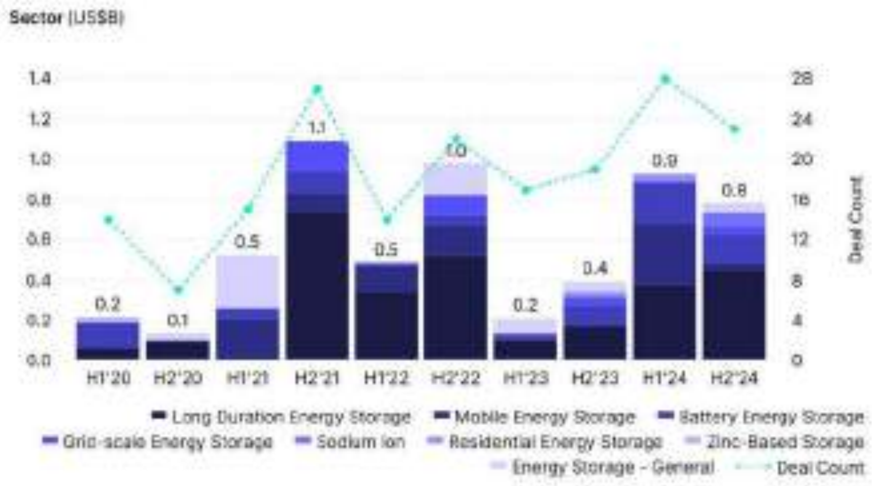
2024 Energy Storage Investments

ENERGY STORAGE INVESTMENTS (BY SECTOR)



Energy storage investments rebounded strongly in 2024, up 184% YoY, This resurgence was driven by growing **need for grid hardening and generous state capacity programs incentivizing installation**.

ENERGY STORAGE INVESTMENTS (BY STAGE)

Venture capital funding in energy storage also saw a **shift toward later-stage investments**, with Series C and growth-stage deals increasing, while early-stage deal sizes remained relatively stable. Investors appear to be prioritizing companies with clear commercial pathways.

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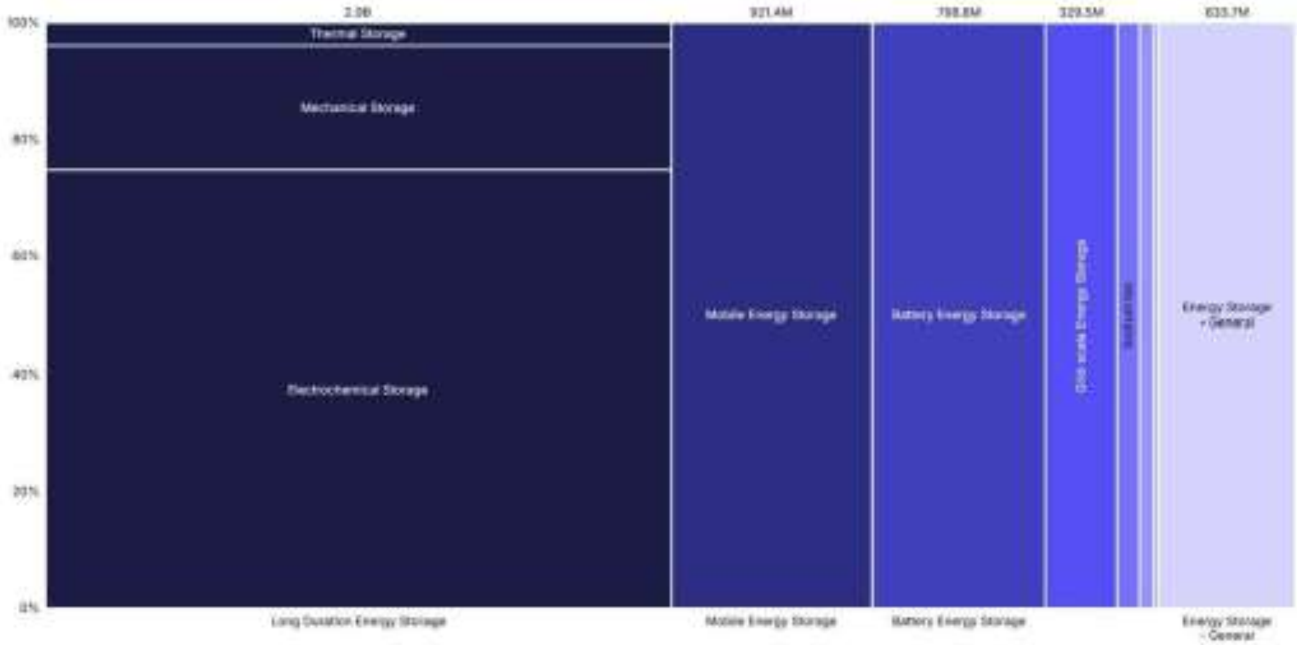
5-Year Cumulative VC Capital Deployment In Energy Storage (By Sector)



Long duration energy storage (LDES), particularly electrochemical storage, has been the primary focus of VC investments, amounting to over $2B in the period of 2020-2024 (>$1.2bn to Form Energy alone).

LDES and non-lithium chemistries (such as flow batteries and sodium-ion) have gained traction alongside investments in manufacturing and supply chain localization. Increased interest in LDES is largely a result of challenges faced by lithium cells in grid hardening applications where battery power may be required for >10 hours.

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Public Market Performance

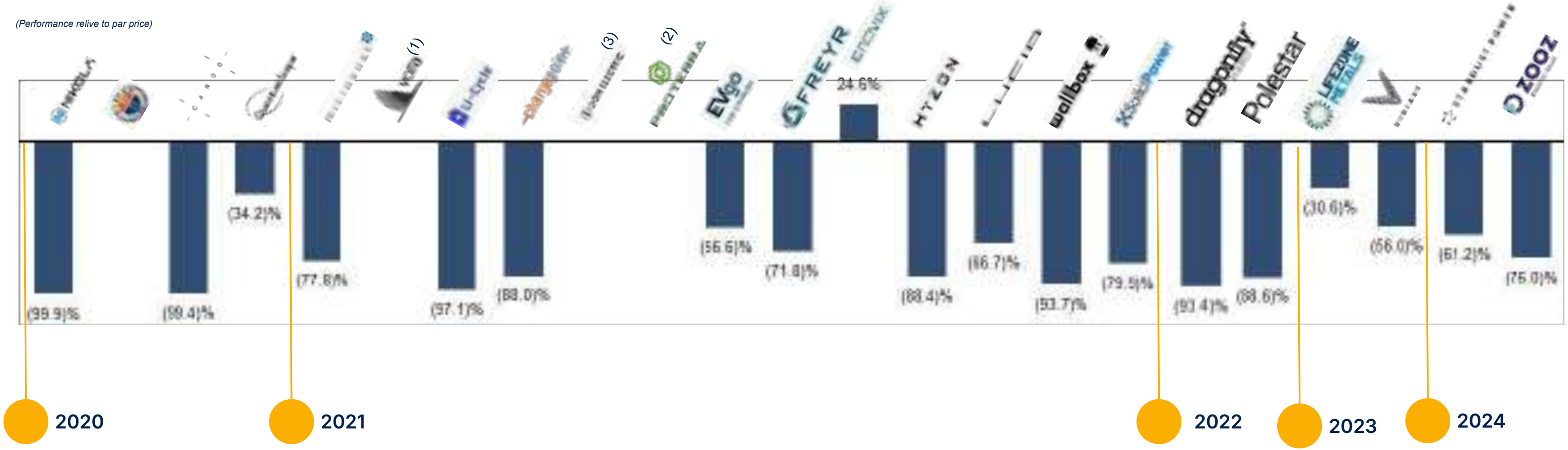
Constrained demand for EVs continues to drag on public market performance of battery companies

Categories	Incumbent Battery	Lithium	Battery Startup	EV Startup[2]	EV Charging[1]
Key Drivers	Slow Demand from EV OEMs in 2024 with preference for Hybrid EVs. Optimism from new battery product launches featuring higher energy density and lower costs	LCE spot price is down ~30% from the beginning of the year. Softening Li demand has led Miners to reduced CapEx plans to right size P&L	High CapEx for battery factories and mixed customer offtake terms	Operating below profitability inflection point while battling lower EV demand	Low utilization, unforeseen maintenance issues, and poor user experience
Constituents	LG Energy Solution BYD CATL SAMSUNG SDI	Albemarle Standard Livent PIEDMONT SIGMA	QuantumScape FREYR [illegible] microvast dragonfly enovix amprius	RIVIAN polestar LUCID V	chargepoint EVgo blink wallbox

Source: CapIQ(1/1/2025) Indexes are market cap weighted. (1) August 2024 Tritium acquired by Exicom ; (2) Fisker was delisted in March 2024

SPAC Performance

Slower growth for EV mobility, underperformance relative to management guidance, and sizable capital expenditures has weighed on battery SPAC performance. All tracked battery stocks except one are trading at a discount to the $10 Par Value. Across the tracked SPAC, companies are down ~33% FY2024 relative to the S&P which is up ~23%



Source: CapIQ(1/01/2025)
(1) Jan 2023, announced that Shell would acquire Volta (2)Nov 2023, Proterra sold to Volvo and Phoenix Motors (3) Dec 2024, Lion ELectric CCAA restructuring process in progress

Select Dilutive And Non-Dilutive Transactions In 2024

Dilutive **Non-Dilutive**

Note: Box sizes made by converting other currency to USD at 1/1/2025
The list is not comprehensive of all transaction in 2024
(1) As of September 2024

DOE Federal Funds In Battery Technology

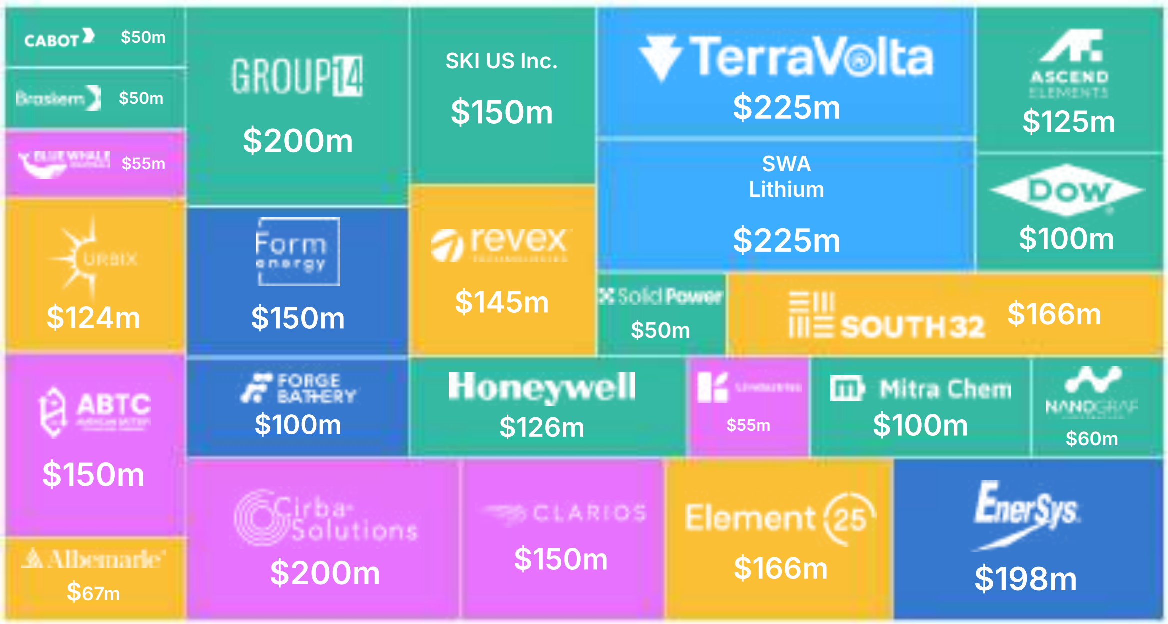
YTD September 2024, the DOE has allocated >$3B to battery technology in the form of grants/loans.

The government grants and loans support the entire battery supply chain, from mineral extraction to recycling.

The largest investment in 2024 by the DOE was issued to BlueOval SK in the amount of $9.6B in late December.(2)

As of January 2025, there are over 160 DOE applicants, across all sectors, seeking over $200B in loan proceeds.

SELECT DOE LOANS IN THE BATTERY VALUE CHAIN(1)



RAW MATERIALS
SEPARATION & PROCESSING
COMPONENT MANUFACTURING
BATTERY MANUFACTURING
RECYCLING

Source: TechCrunch
(1) As of September 2024

Private Capital Market Investors

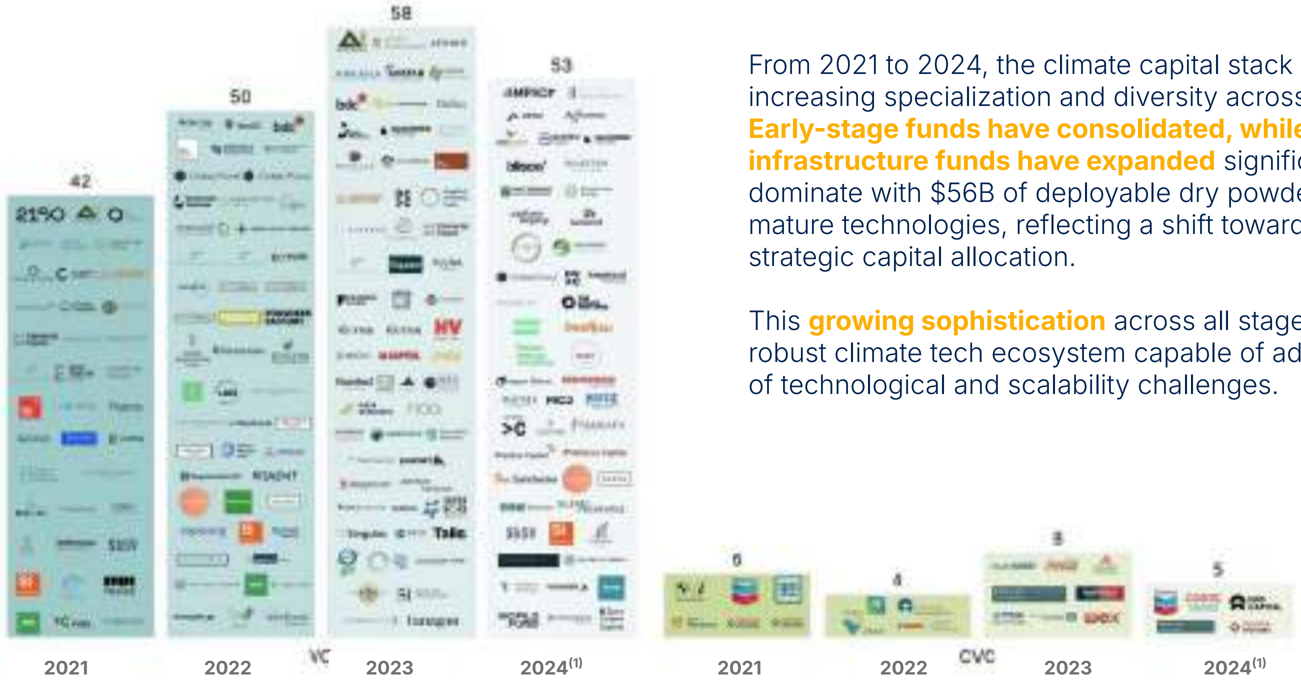
>$150bn of total private climate assets under management (AUM) across 300 Early-stage VCs, Corporate VCs, Growth Equity, Infrastructure , and Private Equity funds since Jan 2021.(1)

INVESTOR TYPE	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	AeraVC AWAANA aiim Baruch Closed Loop Earthshot Keyframe materia impact Riverstone +VOLTA	HITACHI Technology Ventures CRADLE LG Microsoft Climate Innovation Fund Shell Ventures Syensqo Ventures SAMSUNG TDK TOYOTA VENTURES THE CLIMATE PLEDGE VALE Vale Ventures	catalyst FIFTH WALL INVESTCORP KOCH s2gventures TPG RISE +VOLTA T.RowePrice	APOLLO Clean Energy Transition Ara Partners ARCLINE CLEANHILL PARTNERS ECP	CIP EQT GENERATE KKR climate-related investment fund zouk	CPP Investments GIC ADIA TEMASEK QIA

sightline climate

(1) Sightline Climate (Distinguished Partner). For more information, visit https://www.sightlineclimate.com/

Funds Raised In The Last 4 Years - Financial VCs And Corporate VCs



From 2021 to 2024, the climate capital stack has matured, with increasing specialization and diversity across funding stages. **Early-stage funds have consolidated, while growth and infrastructure funds have expanded** significantly and now dominate with $56B of deployable dry powder, focusing on low-risk, mature technologies, reflecting a shift toward disciplined and strategic capital allocation.

This **growing sophistication** across all stages ensures a more robust climate tech ecosystem capable of addressing a wider range of technological and scalability challenges.

sightline climate

Content and analysis provided courtesy of Sightline Climate (Distinguished Partner). For more information, visit https://www.sightlineclimate.com/

(1) As of 7 november 2024

Funds Raised In The Last 4 Years - Growth Equity/PE And Infra

From 2021 to 2024, the climate capital stack has matured, with increasing specialization and diversity across funding stages. **Early-stage funds** have consolidated, while **growth and infrastructure funds** have expanded significantly and now dominate with $56B of deployable dry powder, focusing on low-risk, mature technologies, reflecting a shift toward disciplined and strategic capital allocation.

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Content and analysis provided courtesy of Sightline Climate (Distinguished Partner). For more information, visit https://www.sightlineclimate.com/

(1) As of 7 november 2024

New Funds Raised In 2024

More than $40bn of capital allocated towards climate and energy transitions announced in 2024, with 96 new funds, down 6% from 2023's record.(1)

$1.2BN
JANUARY
Invests in Climate Infrastructure

$335MM
JANUARY
Early growth-stage climate

€350MM
JANUARY
Invests in tech and climate startups

$300MM
FEBRUARY
Climate technologies

$1.5BN
FEBRUARY
Low-carbon infrastructure

$10.0BN
FEBRUARY
Global energy transition fund

€1.1BN
FEBRUARY
Focuses on digitization and decarbonization

€3.0BN
MARCH
Invests in climate and health

$306MM
APRIL
Invest in deep tech and hardware startups

$1.4BN
APRIL
Invests in Climate debut fund

$385MM
APRIL
Climate innovation

$305MM
MAY
decarbonization solutions

€700MM
JULY
Decarbonization and sustainability solutions

$2.7BN
AUGUST
Invest in power and energy infrastructure

$5.0BN
SEPTEMBER
Emerging markets climate fund

$240MM
SEPTEMBER
Sustainable infrastructure

$4.9BN
OCTOBER
Focuses on climate tech verticals

$500MM
OCTOBER
Infrastructure solutions across climate

€700MM
OCTOBER
Invests in decarbonization solutions

$300MM
OCTOBER
Focuses climate tech companies

$1.37BN
NOVEMBER
Renewable energy, grid, and data centers

Note USDEUR converted at 1/1/2025

(1) Sightline Climate (Distinguished Partner). For more information, visit https://www.sightlineclimate.com/

2023 Mega Fund Private Capital Announcements...

Mega-funds ($500M+) account for ~19% of funds in 2023 by count, but constitute ~70% of total AUM

	APOLLO Clean Energy Transition	KKR Global Climate	Brookfield Emerging Markets Transition	TPG RISE CLIMATE	JUST CLIMATE	NGP	Morgan Stanley 1GT climate
Close / Release	**Spring 2023**	**Summer 2023**	**Winter 2023**	**Spring 2022**	**Summer 2023**	**Summer 2023**	**Spring 2023**
2023 Fund Size	**$4bn**	**N/A**	**>$1bn**	**$7.3bn**	**$1.5bn**	**$700mm**	**$1bn**
Mandate	Invest into a diversified global portfolio of yield and hybrid investments Focused on decarbonization as an overarching theme rather than a specific asset class Positioned to address the significant gaps that exist in the capital markets for climate and transition financing	Investment scope includes scaling battery technologies, EV fleet electrification and EV Charging, decarbonizing agriculture and steel The fund's mandate is "climate" which encompass decarbonization of sectors like transportation, food, and industry	Deploy capital exclusively for emerging and developing markets Supporting the four key pillars that underpin COP28's Action Agenda: Energy Transition, Industrial Decarbonization, Sustainable Living and Climate Technologies	Invests in energy transition, green mobility, sustainable fuels and sustainable molecules, and Carbon Solutions Growth-stage investments in innovative climate solutions Fund's performance fee dependent on ability to deliver on greenhouse gas abatement goals	Focused on hard to abate sectors which include energy, mobility, industry and buildings — in order to generate outsized emissions abatement in the next decade	Provide growth capital to companies that drive / enable the growth of renewable energy, the electrification of transport, the efficient use of energy and resources and the management/reduction of carbon emissions Focused on real assets within the energy transition	Focused on investments in growth-stage companies that will seek to collectively avoid or remove one gigaton of carbon dioxide-equivalent (CO2e) emissions from the Earth's atmosphere

Note: funding numbers are as of January 2024

...One Year Later And The Largest Climate Funds Of 2023 Have Begun Cautiously Deploying Capital

All but one of the funds focused on climate investment have acquired an interest in a battery related investment

	APOLLO Clean Energy Transition	KKR Global Climate	Brookfield Emerging Markets Transition	TPG RISE CLIMATE	JUST CLIMATE	NGP	Morgan Stanley 1GT climate
AMOUNT RAISED[1]	$4bn	$3bn	N/A	~$5.0bn[2]	$1.5bn	$700mm	$750mm[3]
FUND INVESTMENTS	PURMO GROUP	Still Fundraising ZENOBĒ AVANTUS	Rebranded as Catalytic Transition Fund. Targeting a $5bn raise	**Fund 2** Intersect Power **Fund 1 2024 investments** BETA Syre	MEVA ENERGY CONTINUUM ABB E-mobility Infinitum ASCEND ELEMENTS VOURITY	INFINIUM CO280 CLOVERLEAF PHYSICS X NOVEON evrealty	Instagrid Huel everstream ANALYTICS

LEGEND
⬚ Battery Related Investment

(2) Represents TPG Rise Climate Fund II
(3) Targeted $1bn, closed at $750mm

sightline climate Sources: Press Releases, Sightline Climate (Distinguished Partner); (1) Some fund sizes adjusted from the previously announced amount

1 INDUSTRY

Section Summary - Cost Reduction Is Now Priority #1 Throughout The Battery Value Chain

The situation for battery manufacturing costs can currently be characterised by three challenges that producers are facing along the value chain:

OVERCAPACITY across the entire supply chain, resulting in pullback of investments.

COST REDUCTION efforts because of shrinking margins and intensifying competition.

DIVERSIFICATION into new markets, driven by rising protectionism and domestic competition.

KEY TAKEAWAYS:

- Battery manufacturers and automakers are prioritising cost reduction as the main survival mechanism in a market with tight margins and intense price competition.
- Battery prices in China are now low enough to drive profound demand, but only the lowest-cost producers will survive.
- New manufacturers in Europe and North America face several barriers in basic manufacturing efficiency and quality. Given this, the Western battery industry continues to consist of the Asian incumbents.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Battery Manufacturing Costs Continue To Fall In 2024

Average cell production costs have fallen steeply since 2022, **driven by plummeting material prices**, especially that of lithium carbonate, CAM, and AAM.

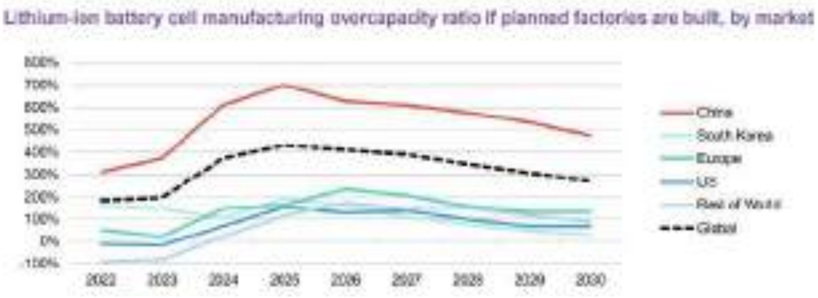
Low material prices have been driven by **overcapacity and oversupply.**

Initially cost reductions were driven by incremental improvements in manufacturing efficiency and cell design, but processes are now so well-optimised that, for example, LFP costs closely follow the price of lithium carbonate.

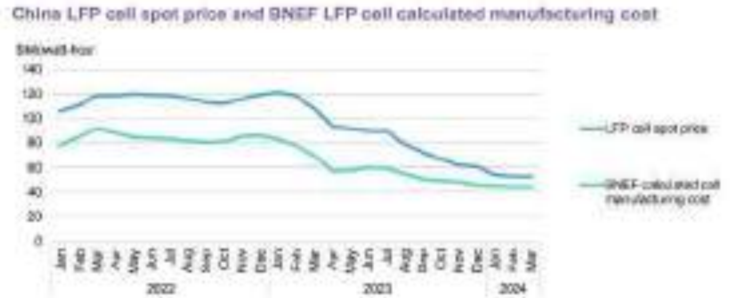
Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. LCE = Lithium Carbonate Equivalent.

Battery Industry Overcapacity Has Led To Low Selling Prices And Shrinking Profit Margins

OVERCAPACITY WAS ONE OF THE BIGGEST DRIVERS BEHIND BATTERY PRICE DECLINES IN 2024


Lithium-ion battery cell manufacturing overcapacity ratio if planned factories are built, by market

BATTERY MARGINS ARE BEING SQUEEZED


China LFP cell spot price and BNEF LFP cell calculated manufacturing cost

- Alongside falling production costs, average selling prices have fallen in 2024 for Chinese made batteries
- The driving factor behind this is the large overcapacity that has emerged, with more cells being produced than can be consumed
- This leads to manufacturers selling at or below production costs to maintain competitiveness and market share, pushing prices to new lows

BloombergNEF

Source: Main content provided by BloombergNEF (Distinguished Partner), ICCSino (LFP cell spot price). Cell cost and price is based on a prismatic cell and excludes taxes.

Battery Pack Prices See Largest Drop Since 2017

VOLUME-WEIGHTED AVERAGE LI-ION BATTERY PACK AND CELL PRICE SPLIT

Average Li-ion battery pack prices dropped 20% from 2023 to a record low of $115 /kWh in 2024.

Factors driving the decline include:

- Cell manufacturing overcapacity
- Economies of scale and reductions in underlying costs from incremental manufacturing improvements such as yield/quality
- Low raw material and component prices
- Adoption of lower-cost LFP batteries
- Slowdown in EV sales growth

Note: Prices vary widely across different countries and application areas.

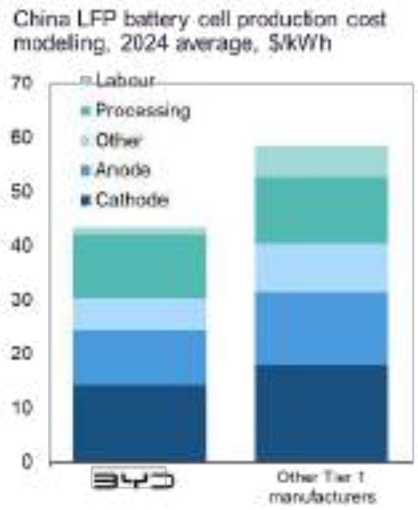
BloombergNEF Source: Content & analysis provided courtesy of BloombergNEF (Distinguished Partner). Note: historical prices have been updated to reflect real 2024 dollars. Weighted average survey value includes 343 data points from passenger cars, buses, commercial vehicles, and energy storage.

How Are Chinese Manufacturers Achieving Super-Low Production Costs?

SUPPLY CHAIN EFFICIENCIES GO HAND-IN-HAND WITH MANUFACTURING EXCELLENCE

Vertical integration	Allows downstream companies to source materials at cost price, ability to pass on any high cost of operations down the value chain, and more control over technical specifications.
Midstream price pressure	Intense competition in the midstream is leading to thinner margins and cell manufacturers are pressuring cathode and anode producers for lower prices.
Upstream cost reduction	Chinese refineries are some of the lowest cost operations globally and have secured low-cost mineral resources. This mitigates the largest cost component for battery cells.
Capex leverage	Economies of scale in the downstream (battery/EV) enables lower unit Capex, cheaper financing in the upstream (mining/refining) and hedges investment risk.
Technical innovation	Chinese companies prioritise scaling up and incrementally optimising proven technologies vs. exploring disruptive tech.
Factory yields & automation	Yields and production processes have been so well optimised that only incremental improvements are now being made. Automation reduces labor costs and enables higher yields.
Industrial ecosystem	Chinese companies tend to operate in integrated industrial parks where there is always a consumer for byproducts or waste from adjacent industries.

TOP MANUFACTURERS ARE IN A LEAGUE OF THEIR OWN



In recent times, battery costs are mitigated in **three main areas**:

1. Manufacturing excellence
2. Supply chain efficiencies
3. Technical innovation

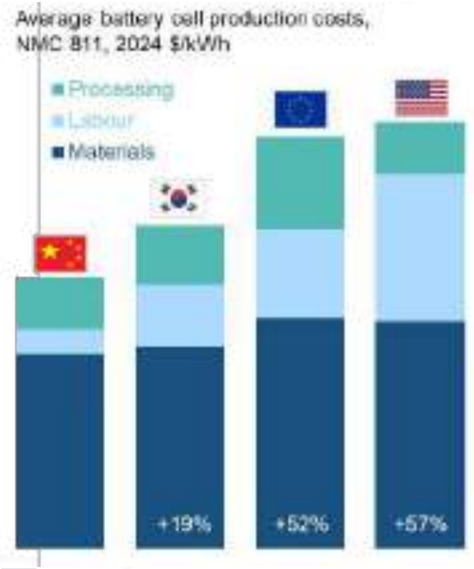
#1 is the foundation for all companies.

#2 and 3 give top manufacturers an additional edge over rest of the industry.

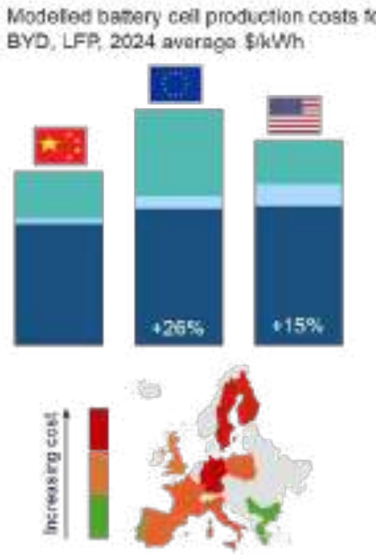
Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Model is showing an EV (power) cell, prismatic, synthetic graphite anode

Costs Are Higher Outside China, Partly Due To Inherent Disadvantages

YIELDS AND AUTOMATION ARE INITIALLY LOWER FOR NEW GIGAFACTORIES



EVEN IF A STATE-OF-THE-ART CHINESE FACTORY WAS TRANSPLANTED INTO EU/US, ENERGY AND LABOR COSTS WILL IMPACT ECONOMICS



Model parameters:

- ➔ Same yields, factory automation, material margins
- ➔ No import tariffs or local premiums on materials
- ➔ Region-average energy prices
- ➔ CAM and AAM made locally

Higher cost of production outside China is influenced by:

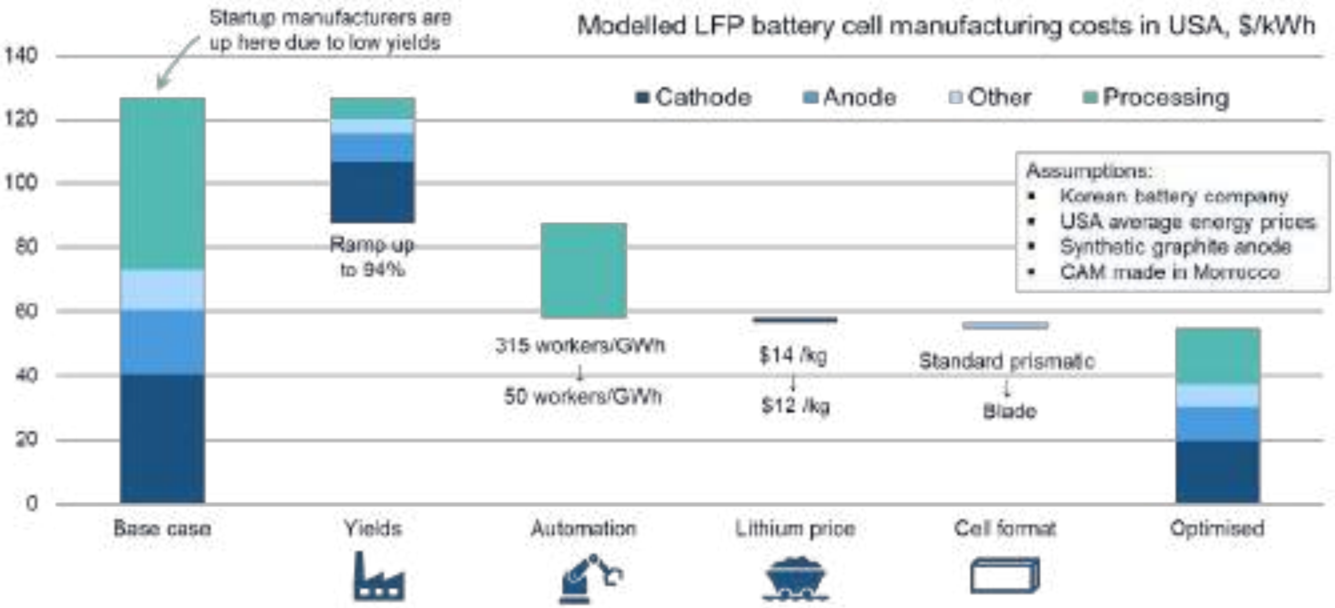
- Initially lower yields and factory automation
- Differences in energy and labour costs
- Higher margins commanded by suppliers
- Import tariffs and local premiums on raw materials

...all of which can be mitigated!

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Automation And Yields Critical For USA Cost-Competitiveness

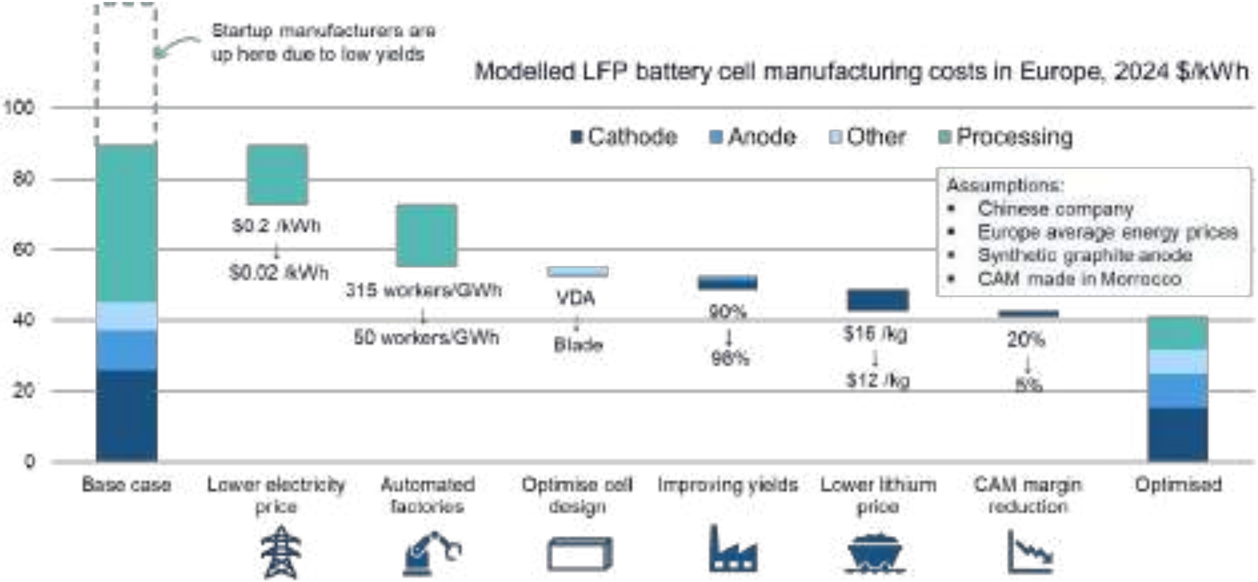
MODELED LFP BATTERY CELL MANUFACTURING COSTS IN USA, 2024 $/kWh



Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Electricity Price And Automation Key For Factories In Europe

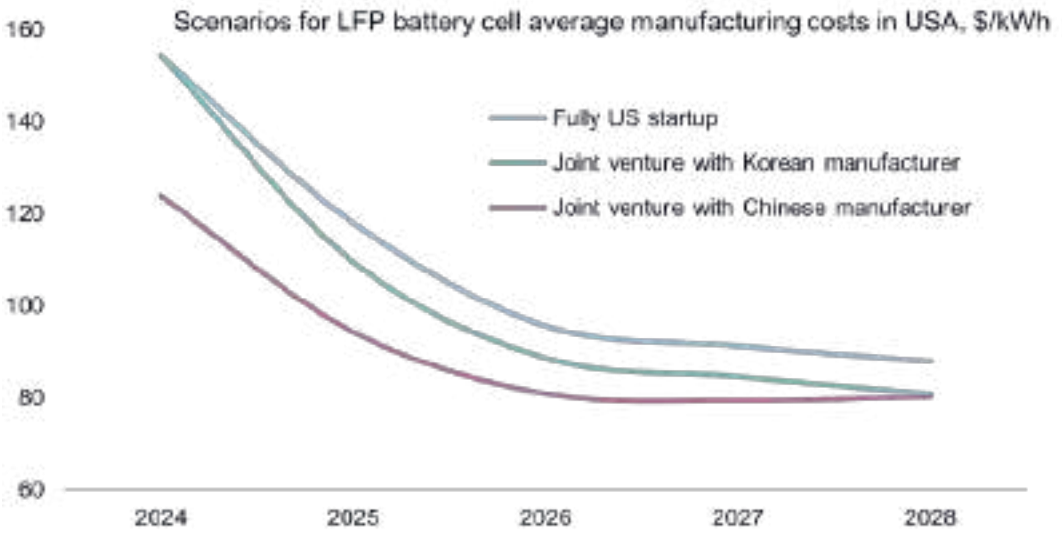
MODELED LFP BATTERY CELL MANUFACTURING COSTS IN EUROPE, 2024 $/kWh



Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

The Battery Conundrum - Joint Venture Or Go It Alone?

JOINT VENTURES CAN DECREASE TIME TO PROFITABILITY



Battery manufacturing is very difficult, with low scrap rates and high throughputs are needed to be profitable.

So far, new manufacturers who chose to go it alone have seldom survived.

Joint ventures with an experienced producer have been the most successful strategy.

This is critical to rapidly **decrease the time to ramp-up** and increase customer confidence in the quality and reliability of supply.

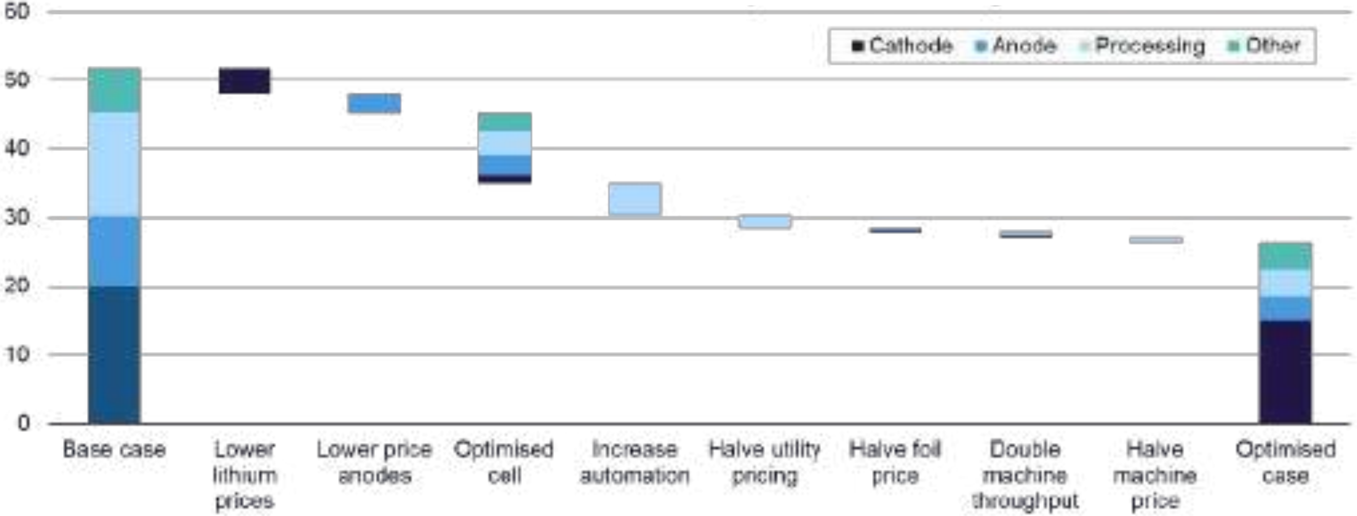
Although Chinese-origin companies are now increasingly willing to work with local partners, they – along with the Chinese government – **are making a concerted effort to avoid the leakage of critical technical know-how.**

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Modeling an EV (power) cell with synthetic graphite anode.

LFP Production Costs Have Further Room To Fall

CHEAPER RAW MATERIALS, OPTIMISING ELECTROCHEMICAL PERFORMANCE, & INCREMENTAL IMPROVEMENTS TO MANUFACTURING PROCESSES:

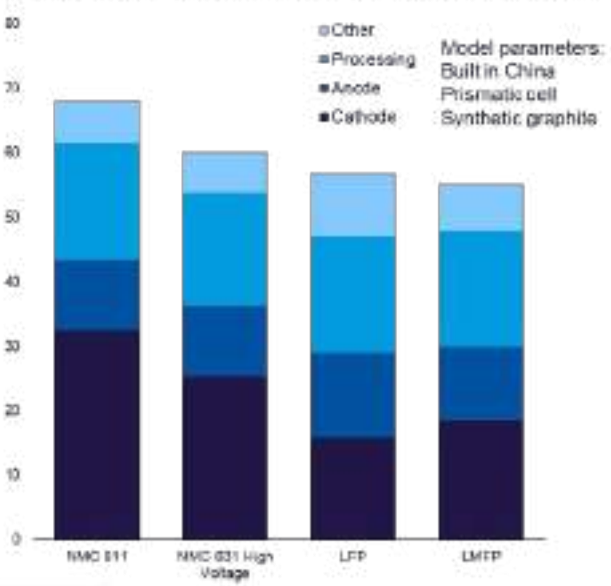
LFP BATTERY CELL MANUFACTURING COSTS IN CHINA, 2024 $/kWh



Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Modeling an EV (power) cell with synthetic graphite anode.

LxFP Retains Cost Advantage Over Nickel-Rich Batteries

AVERAGE BATTERY CELL PRODUCTION COSTS, CHINA, 2024 $/KWH



NMC 811 remains the most expensive chemistry compared to LxFP and emerging NMC based chemistries, despite falling nickel and cobalt prices.

Medium-nickel high-voltage NMC has emerged as a lower-cost alternative to high-nickel NMC while offering comparable energy density.

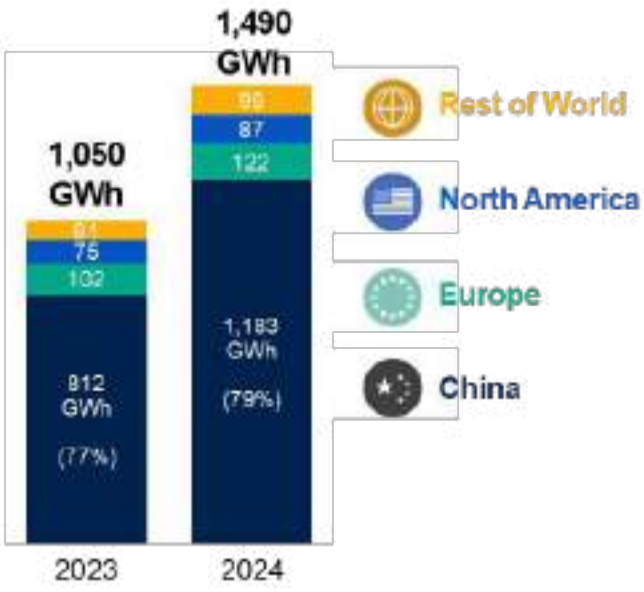
The LxFP family, due to the absence of expensive raw materials and more efficient lithium utilisation, are leading the way for low production costs.

High-compaction-density LFP cathode material may enable cell cost reductions of up to 3%, continuing the trend of incremental improvements to incumbent chemistries.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

1 INDUSTRY

Battery Manufacturing Grows Further Into The Terawatt-Hour-Per-Year Era



IN 2024, GLOBAL LITHIUM-ION BATTERY CELL PRODUCTION REACHED ALMOST

1.5 TWh

59% **were LFP batteries**

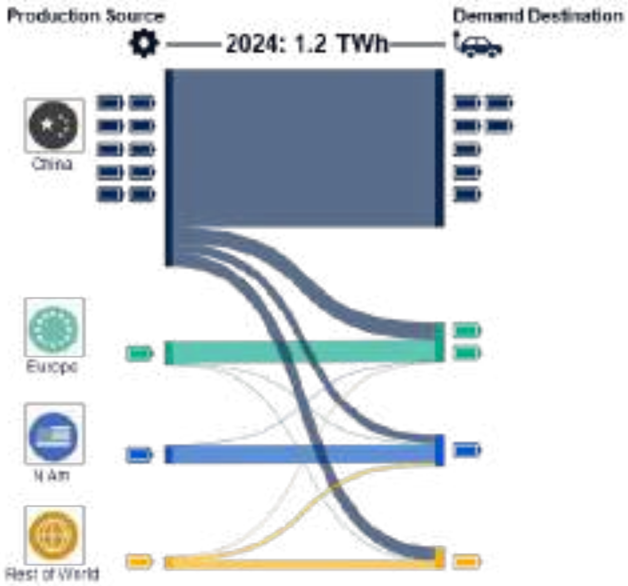
4/5 **were EV batteries**

4/5 **were made in China**

- There is still significant **overcapacity** and –in the case of China– overproduction compared to demand
- This is the reason for LFP's share being higher than in end-use demand
- Much of the battery requirements are imported from Asia as most gigafactories in the pipeline outside China are still ramping up
- The industry remains an oligopoly with the top **3 manufacturers making up 2/3 of output**

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Battery production data from CRU's primary data collection, national industry associations, and manufacturer reports. December 2024 data is partially estimated.

China Is The Battery Export Hub But Production Is Localizing



- Much of Europe and North America's battery supply are currently **imported from Asia.**
- But **trade flows** of batteries between regions **are dampening** over time. There will be increasing localisation of battery production to where they are used, due to:
  - **Trade policy** – tariffs are increasing over time
  - **Supply security** – automotive industry aiming to avoid a repeat of supply disruptions
  - **Cost and ESG** – transporting bulky batteries across regions is expensive and emissions-intensive
- Although other regions are ramping up their production bases, China will remain the largest battery producer.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Trade flows less than 1 GWh are not shown. 'Demand Destination' refers to where the battery is installed. Total GWh represents end-use demand and does not show overproduction of battery cells.

Gigafactory Tracker - 1,372* GWh Of Capacity

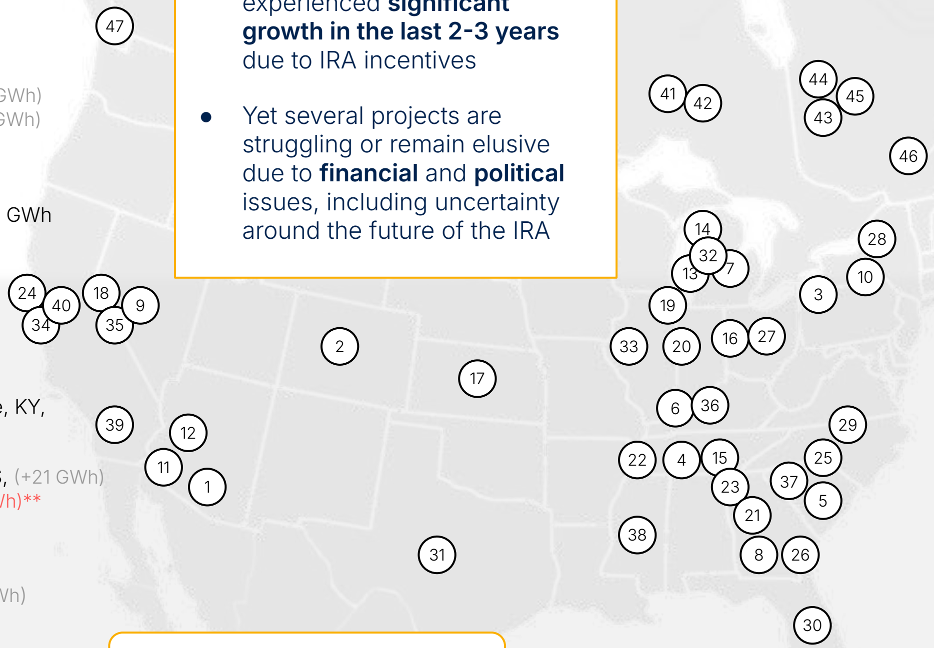
USA

1 ABF, Tucson, AZ, (+15 GWh)
2 Amprius Tech, Brighton, CO, (+5 GWh)
3 Electrovaya, Jamestown, NY, (+1 GWh)
4 AESC, Smyrna, TN, 3 GWh
5 AESC/BMW, KY, (+30 GWh)
6 AESC/Mercedes, Florence County, SC, (+30 GWh)
7 Ford/CATL, Marshall, MI, (+20 GWh)*
9 Nanotech Energy, tbd, NV, (+6 GWh)
8 FREYR, Newnan, GA, (+34 GWh)
10 IM3NY, Endicott, NY, 1 GWh, (+37 GWh)*
11 KORE Power, Buckeye, AZ, (+12 GWh)
12 LGES, Queen Creek, AZ, (+53 GWh)
13 LGES, Holland, MI, 5 GWh, (+20 GWh)
14 Ultium Cells, LGES/GM, Lansing, MI, (+50 GWh)
15 Ultium Cells, LGES/GM, Spring Hill, TN, 35 GWh
16 LGES/Honda, Jeffersonville, OH, (+40 GWh)
17 Panasonic, DeSoto, Kansas, (+30 GWh)
18 Panasonic/Tesla, NV, 37 GWh, (+73 GWh)
19 Samsung SDI/GM, New Carlisle, IN, (+27-36 GWh)
20 *(2 plants)* StarPlus Energy (Samsung SDI/Stellantis), Kokomo, IN, (+33 GWh & +34 GWh)
21 SK, Commerce, GA, 22 GWh
22 BlueOval (SK/Ford), Stanton, TN, (+45 GWh)
23 SK/Hyundai, Bartow County, GA, (+35 GWh)
24 Tesla, Fremont, CA, 10 GWh
25 Toyota, Greensboro, NC, (+30 GWh)
26 LGES/Hyundai, USA, (+30 GWh)
27 Ultium Cells, LGES/GM, Warren, OH, 41 GWh
29 Forge Battery, Raleigh, NC, (1-3 GWh)
30 SAFT, Jacksonville, FL, (+5 GWh)
31 Tesla, Austin, TX, 6 GWh (+94 GWh)
32 ONE, Belleville, MI, 10 MWh (+20 GWh)
33 Gotion, Manteno, IL, (+40 GWh)
34 Lyten, San Jose, CA, (+0.2 GWh)
35 Lyten, Reno, NV, (+10 GWh)
36 *(2 plants)* BlueOval (SK/Ford), Glendale, KY, (+40 GWh & +40 GWh)
37 Pomega, Waterboro, SC, (+6 GWh)
38 Amplify Cell Tech, Marshall county, MS, (+21 GWh)
39 Statevolt, near Salton Sea, CA, (+54 GWh)**
40 Lyten, San Leandro, CA, (+6-10 GWh)

CANADA

41 LGES/Stellantis, Windsor, ON, (+49.5 GWh)
42 PowerCo, St. Thomas, ON, (+90 GWh)
43 Lion Electric, Joliet, QC, (+5 GWh)*
44 StromVolt, tbd, QC, (+10 GWh)
45 Northvolt Six, Montreal, QC, (+60 GWh)
46 BlueSolutions, Montreal, QC, 0.5 GWh
47 Molicel, Maple Ridge, BC, (+2.8 GWh)**

- North America has experienced **significant growth in the last 2-3 years** due to IRA incentives
- Yet several projects are struggling or remain elusive due to **financial** and **political** issues, including uncertainty around the future of the IRA



How to read this map
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*

Gigafactory Tracker - 1,504* GWh Of Capacity

FRANCE
1 ACC, 13 GWh, (+27 GWh)
2 AESC, (+30 GWh)
3 Verkor/Renault, (+50 GWh)
4 Prologium, (+48 GWh)
5 Tiamat, (+5 GWh)

GERMANY
6 ACC, (+40 GWh)**
7 CATL, 14 GWh, (+10 GWh)
8 Leclanche, 4.5 GWh
9 Northvolt Drei, (+60 GWh)
10 SVOLT, (+24 GWh)**
11 SVOLT, (+16 GWh)**
12 Tesla, 50 GWh, (+50 GWh)
13 PowerCo, (+20 GWh)
14 Cellforce Group, (+20 GWh)
15 Customcells, (+unknown GWh)
16 EAS, 0.5 GWh

ITALY
17 ACC, (+40 GWh)**
18 ITALVOLT, (+45 GWh)**
19 FAAM, 0.35 GWh, (+8 GWh)

PORTUGAL
20 CALB, (+45 GWh)

NETHERLANDS
21 Eurocell, (+1 GWh)**

SWEDEN
22 Northvolt, 16 GWh, (+44 GWh)*
23 NOVO (Volvo), (+50 GWh)*

HUNGARY
24 CATL, 100 GWh
25 EVE Energy, (+28 GWh)
26 Samsung SDI, 40 GWh, (+10 GWh)
27 SK, 18 GWh, (+29.3 GWh)
28 Sunwoda, (+unknown GWh)

NORWAY
29 Elinor, (+40 GWh)
30 FREYR, (+29 GWh)**
31 Morrow, unknown GWh (+42 GWh)
32 Beyonder, (+10 GWh)

FINLAND
33 Finnish Minerals, (+60 GWh)

SPAIN
34 AESC, (+50 GWh)
35 PowerCo, (+60 GWh)
36 Basquevolt, unknown GWh (+10 GWh)
37 CATL/Stellantis, (+50 GWh)

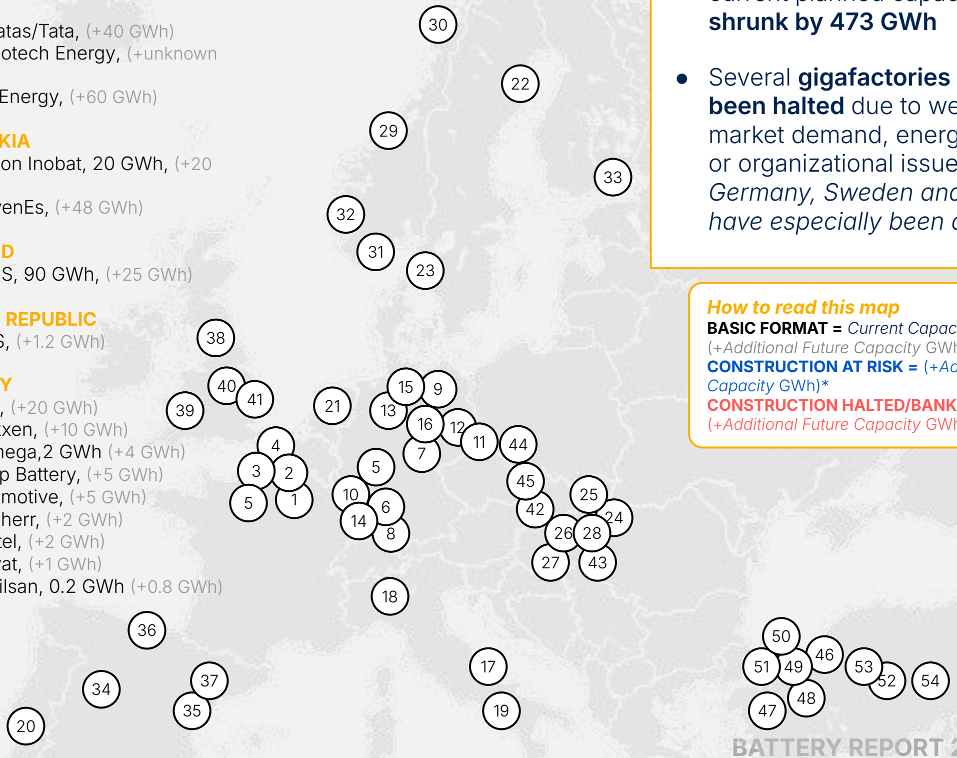
U.K.
38 AESC, 2 GWh, (+33 GWh)
39 Agratas/Tata, (+40 GWh)
40 Nanotech Energy, (+unknown GWh)
41 Eve Energy, (+60 GWh)

SLOVAKIA
42 Gotion Inobat, 20 GWh, (+20 GWh)
43 ElevenEs, (+48 GWh)

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

CZECH REPUBLIC
45 MES, (+1.2 GWh)

TURKEY
46 Siro, (+20 GWh)
47 Maxxen, (+10 GWh)
48 Pomega,2 GWh (+4 GWh)
49 Reap Battery, (+5 GWh)
50 Ottomotive, (+5 GWh)
51 Ampherr, (+2 GWh)
52 Vestel, (+2 GWh)
53 Inovat, (+1 GWh)
54 Aspilsan, 0.2 GWh (+0.8 GWh)



- According to the Battery Atlas, current planned capacity **shrunk by 473 GWh**
- Several **gigafactories have been halted** due to weakened market demand, energy costs, or organizational issues. *Germany, Sweden and Italy have especially been affected*

How to read this map
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

Gigafactory Tracker - 437* GWh (+5,796 from China) of Capacity

INDIA
1 Reliance, Gujarat, (+50 GWh)
2 Amara Raja, Telangana, (+16 GWh)
3 Exide, Karnataka, (+12 GWh)
4 Godi, Hyderabad, (+12 GWh)
5 OLA, Tamil Nadu, (+100 GWh)
6 TATA, Gujarat, (+10 GWh)
7 Lucas TVS / 24M, Thervoy Kandigai, (+10 GWh)
8 Cyngi, Telangana, (+1.2 GWh)
9 JSW/LGES, India, (+10 GWh)
10 Mahanagar / IBC Inc., Bengaluru, (+unknown GWh)

VIETNAM
11 Gotion, Vung Ang, (+5 GWh)

THAILAND
12 GPSC, Map Ta Phut, (+10 GWh)
13 Amita Technology / Eve, Bang Pakong, (+4 GWh)
14 NV Gotion, Rayong, (+8 GWh)
15 24M / Novo+, Rayong, (+0.1 GWh)

INDONESIA
16 CATL, Karawang, (+15 GWh)
17 Hyundai/LGES, Karawang, 10 GWh (+10 GWh)

MALAYSIA
18 EVE Energy, Kedah, (+unknown GWh)
19 Samsung SDI, Seremban, unknown GWh, (+16 GWh)
20 Enovix, Seremban, (+unknown GWh)
21 Zhuhai CosMX Battery, Seremban, (+unknown GWh)

SOUTH KOREA
22 Samsung SDI, Cheonan, unknown GWh, (+12 GWh)
23 LGES, Ochang, 21 GWh (+12 GWh)
24 SK, Seosan, 5 GWh
25 Kumyang, Gijang, (+unknown GWh)

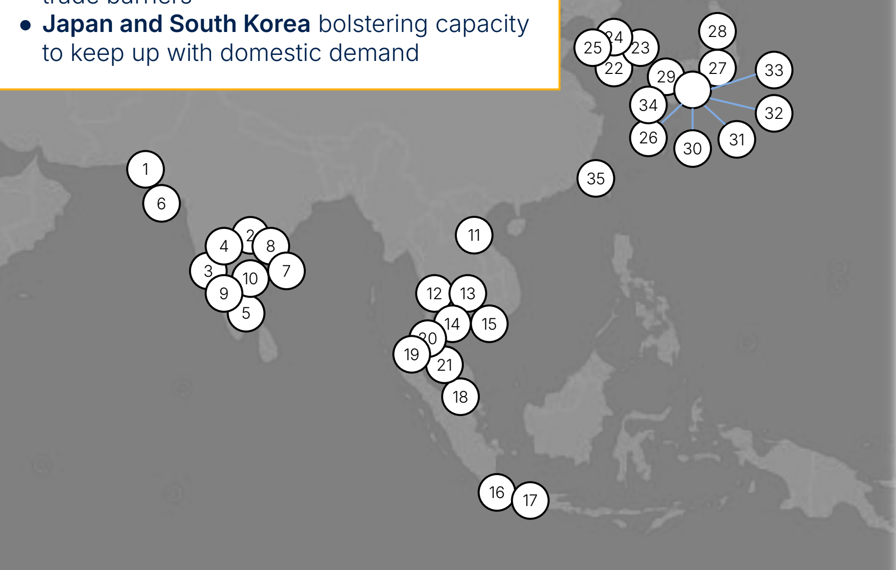
JAPAN
26 Prime Planet, Himeji, Japan, unknown GWh, (+30 GWh)
27 AESC, Kanagawa, 2.6 GWh
28 AESC, Ibaraki, (+18 GWh)
29 Panasonic, Osaka, 4 GWh
30 Panasonic, Uchida, 10 GWh
31 Panasonic, Asonaka, (+unknown GWh)
32 Panasonic, Gunma, (+16 GWh)
33 Electrovaya Tech, Japan, (+unknown GWh)
34 Nissan, Japan, (+5 GWh)

TAIWAN
35 ProLogium, Taoyuan, (+2 GWh)

CHINA
See "Chinese Gigafactory Plants" on the following page.

How to read this map
BASIC FORMAT = *Current Capacity* GWh, (+*Additional Future Capacity* GWh)

Greater Asia is experiencing growth from:
- An emerging **Indian market**
- **Chinese manufacturers** localizing in low-risk ASEAN countries to circumvent trade barriers
- **Japan and South Korea** bolstering capacity to keep up with domestic demand



Source: All uncited factories are from Batterieproduktion, India 1, India 2, Thailand

*total includes future & current capacities
**note: sodium-ion excluded

Gigafactory Tracker - 5,796* GWh Of Capacity | Part 1 Of 3

CATL

1 Ningde, 253 GWh, (+27 GWh)
2 Yibin, 126 GWh, (+144 GWh)
3 Jining, (+180 GWh)
4 Luoyang, 30 GWh, (+90 GWh)
5 Changzhou, 118 GWh
6 Xiamen, (+60 GWh)
7 Guiyang, 30 GWh, (+30 GWh)
8 Yichun, 50 GWh
9 Zhaoqing, 25 GWh
10 Guangzhou, 12 GWh, (+6 GWh)
11 Beijing, (+15 GWh)
12 Xining, 11 GWh

CALB

13 Xiamen, 20 GWh, (+40 GWh)
14 Changzhou, 32 GWh, (+25 GWh)
15 Hefei, 20 GWh, (+30 GWh)
16 Wuhan, 20 GWh, (+30 GWh)
17 Chengdu, 20 GWh, (+30 GWh)
18 Jiangmen, 35 GWh, (+15 GWh)
19 Meishan, 20 GWh

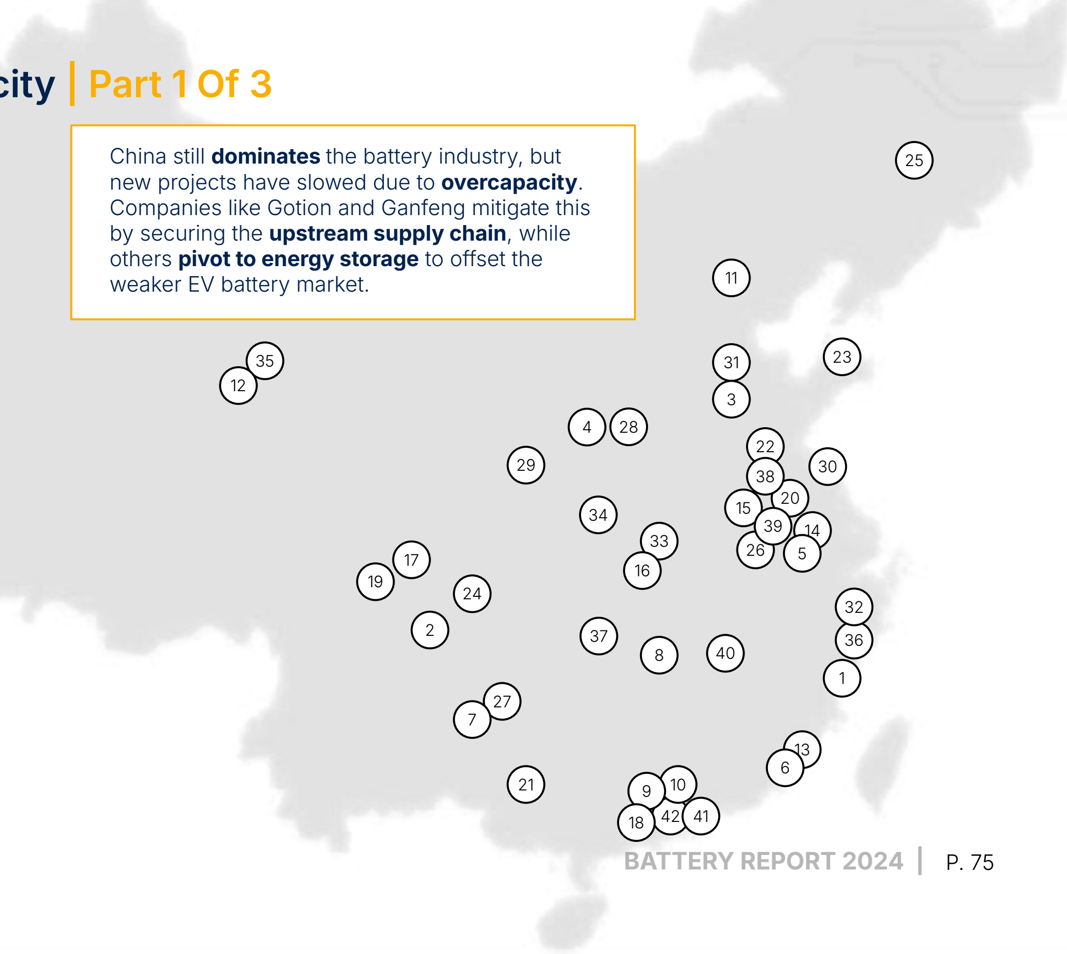
LGES

20 Nanjing, 139 GWh, (+6 GWh)

BYD / FINDREAMS

21 Nanning, 70 GWh
22 Xuzhou, 15 GWh, (+45 GWh)
23 Yantai, (+50 GWh)
24 Chongqing, 35 GWh, (+10 GWh)
25 Changchun, 15 GWh, (+30 GWh)
26 Wuhu, 40 GWh
27 Guiyang, 25 GWh, (+15 GWh)
28 Zhengzhou, (+40 GWh)
29 Xi'an, 32 GWh
30 Yancheng, 30 GWh
31 Jinan, 30 GWh
32 Shaoxing, 15 GWh, (+15 GWh)
33 Wuhan, 12 GWh, (+18 GWh)
34 Xiangyang, 10 GWh, (+20 GWh)
35 Xining, 24 GWh
36 Taizhou, 22 GWh
37 Changsha, 10 GWh, (+10 GWh)
38 Bengbu, 10 GWh, (+10 GWh)
39 Chuzhou, 5 GWh, (+15 GWh)
40 Fuzhou, 15 GWh
41 Shenzhen, 14 GWh
42 Huizhou, 2 GWh

China still **dominates** the battery industry, but new projects have slowed due to **overcapacity**. Companies like Gotion and Ganfeng mitigate this by securing the **upstream supply chain**, while others **pivot to energy storage** to offset the weaker EV battery market.



How to read this map
BASIC FORMAT = *Current Capacity* GWh, *(+Additional Future Capacity* GWh)

Source: New Energy Terminal

*total includes future & current capacities
**note: sodium-ion excluded

Gigafactory Tracker - 5,796* GWh Of Capacity | Part 2 Of 3

China still **dominates** the battery industry, but new projects have slowed due to **overcapacity**. Companies like Gotion and Ganfeng mitigate this by securing the **upstream supply chain**, while others **pivot to energy storage** to offset the weaker EV battery market.

GOTION HIGH TECH
43 Hefei, 14 GWh, (+44 GWh)
44 Anqing, 30 GWh, (+10 GWh)
45 Liuzhou, 15 GWh, (+15 GWh)
46 Yichun, 10 GWh, (+20 GWh)
47 Nanjing, 28 GWh
48 Lu'an, 15 GWh, (+10 GWh)
49 Tangshan, 10 GWh, (+10 GWh)
50 Chuzhou, 10 GWh, (+10 GWh)
51 Qingdao, 3 GWh

SVOLT
52 Changzhou, 18 GWh, (+47 GWh)
53 Chengdu, 31.5 GWh, (+28.5 GWh)
54 Huzhou, 15 GWh, (+15 GWh)
55 Dazhou, (+30 GWh)
56 Suining, 20 GWh, (+9 GWh)
57 Ma'anshan, 28 GWh
58 Shangrao, 24 GWh
59 Yancheng, 22 GWh
60 Nanjing, 15 GWh

SUNWODA
61 Jinhua, 50 GWh
62 Nanchang, 36 GWh, (+14 GWh)
63 Zaozhuang, 24 GWh, (+26 GWh)
64 Yichang, 20 GWh, (+10 GWh)
65 Nanjing, 18 GWh, (+12 GWh)
66 Deyang, 20 GWh

EVE ENERGY, SK ON
67 Jingmen, 146 GWh, (+43 GWh)
68 Chengdu, 20 GWh, (+50 GWh)
69 Yancheng, 10 GWh, (+30 GWh)
70 Shenyang, (+40 GWh)
71 Huizhou, 24 GWh
72 Qujing, 23 GWh
73 Nantong, 10 GWh
74 Yuxi, (+10 GWh)
75 Changzhou, 7.5 GWh

REPT
76 Jiaxing, 12 GWh, (+61 GWh)
77 Wenzhou, 26 GWh, (+24 GWh)
78 Foshan, 15 GWh, (+17 GWh)
79 Chongqing, (+30 GWh)
80 Liuzhou, 10 GWh, (+10 GWh)

HITHIUM
81 Chongqing, 28 GWh, (+33 GWh)
82 Xiamen, 45 GWh
83 Heze, (+30 GWh)

AESC
84 Shiyan, 20 GWh, (+20 GWh)
85 Ordos, 10.5 GWh, (+20 GWh)
86 Cangzhou, 10 GWh, (+20 GWh)
87 Wuxi, 5 GWh, (+15 GWh)

CORNEX
88 Xiaogan, 60 GWh, (+90 GWh)
89 Yichang, 40 GWh, (+110 GWh)
90 Wuhan, 10 GWh, (+40 GWh)

GREAT POWER
91 Quzhou, 11 GWh, (+36 GWh)
92 Qingdao, (+36 GWh)
93 Ulanqab, (+11 GWh)
94 Liuzhou, 10.5 GWh
95 Xuancheng, (+10 GWh)
96 Changzhou, 3 GWh, (+4 GWh)
97 Zhuhai, unknown GWh
98 Zhumadian, unknown GWh

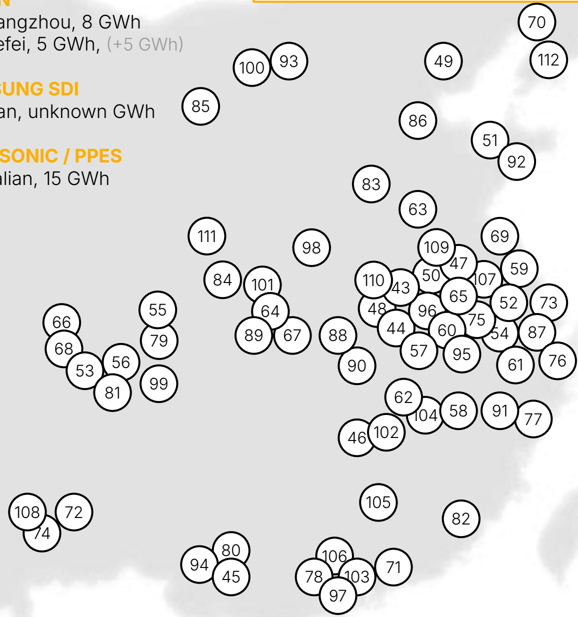
GANFENG
99 Chongqing, (+44 GWh)
100 Hohhot, (+20 GWh)
101 Xiangyang, (+20 GWh)
102 Xinyu, 13 GWh, (+6 GWh)
103 Dongguan, (+10 GWh)
104 Nanchang, (+10 GWh)

FARASIS
105 Ganzhou, 37 GWh, (+12 GWh)
106 Guangzhou, 15 GWh, (+15 GWh)
107 Zhenjiang, 24 GWh
108 Kunming, (+24 GWh)

PYLON
109 Yangzhou, 8 GWh
110 Hefei, 5 GWh, (+5 GWh)

SAMSUNG SDI
111 Xi'an, unknown GWh

PANASONIC / PPES
112 Dalian, 15 GWh



Source: New Energy Terminal

How to read this map
BASIC FORMAT = *Current Capacity* GWh,
(+Additional Future Capacity GWh)

**total includes future & current capacities*
***note: sodium-ion excluded*

Gigafactory Tracker - 5,796* GWh Of Capacity | Part 3 Of 3

DFD
113 Nanning, 5 GWh, (+20 GWh)
114 Jiaozuo, 11.5 GWh

GEELY, YAONING
115 Ganzhou, 12 GWh, (+30 GWh)
116 Quzhou, 24 GWh
117 Tangshan, (+24 GWh)
118 Yingtan, 5 GWh, (+15 GWh)
119 Xuancheng, 15 GWh
120 Yancheng, 6 GWh, (+6 GWh)
121 Yueyang, (+12 GWh)
122 Hangzhou, (+12 GWh)
123 Chongqing, (+12 GWh)
124 Zhenjiang, 3 GWh, (+6 GWh)
125 Shangrao, 3 GWh, (+3 GWh)

CHERY
126 Wuhu, 6.25 GWh, (+20.75 GWh)

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

LISHEN
128 Chuzhou, 22 GWh, (+20 GWh)
129 Tianjin, 4 GWh, (+26 GWh)
130 Wuxi, (+24 GWh)
131 Qingdao, 4 GWh, (+10 GWh)

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

TIANNENG
133 Huzhou, 9 GWh, (+17 GWh)
134 Ma'anshan, 3 GWh, (+17 GWh)

SHUANGDENG
135 Xiangyang, 2.8 GWh, (+7.2 GWh)
136 Taizhou, 2 GWh, (+4 GWh)

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

COSPOWERS
138 Chuzhou, (+20 GWh)
139 Nantong, (+12 GWh)
140 Changde, 4.5 GWh, (+5.5 GWh)
141 Dongying, 2 GWh, (+4 GWh)
142 Dali, 3 GWh, (+3 GWh)

HIGHSTAR
143 Changsha, (+30 GWh)
144 Nantong, 5.7 GWh, (+4 GWh)
145 Zhuhai, (+6 GWh)

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

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

EVPS
148 Chuzhou, 4 GWh, (+6 GWh)

PHYLION
149 Chuzhou, 5.6 GWh, (+4 GWh)
150 Suzhou, 2.2 GWh

CBAK
151 Nanjing, 2 GWh, (+18 GWh)
152 Dalian, 1 GWh, (+1 GWh)
153 Shangqiu, 0.5 GWh

BAK
154 Zhengzhou, 4.5 GWh, (+30 GWh)
155 Fuzhou, 2 GWh, (+11.5 GWh)
156 Shenzhen, 3.5 GWh

COSMX
157 Deyang, (+25 GWh)
158 Chongqing, (+15 GWh)
159 Jiaxing, 2.5 GWh, (+10 GWh)

EXENCELL
160 Mianyang, 6 GWh, (+12 GWh)
161 Yancheng, (+18 GWh)
162 Zhuhai, (+18 GWh)
163 Dali, (+18 GWh)

RISESUN MGL
164 Nanjing, (+30 GWh)
165 Tianjin, 6.3 GWh, (+9.2 GWh)
166 Beijing, 0.5 GWh

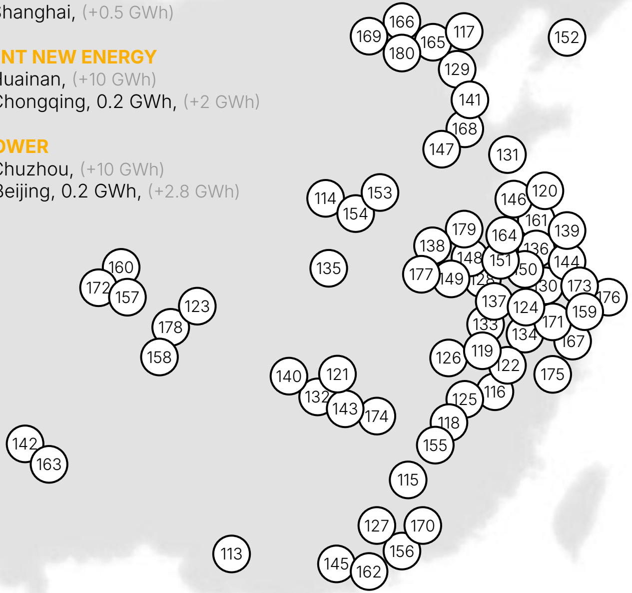
WELION
167 Huzhou, 2 GWh, (+20 GWh)
168 Zibo, 6 GWh, (+14 GWh)
169 Beijing, (+8 GWh)
170 Shenzhen, (+0.6 GWh)
171 Changzhou, 0.2 GWh

QINGTAO
172 Chengdu, (+15 GWh)
173 Suzhou, 0.7 GWh, (+10 GWh)
174 Yichun, 1 GWh
175 Taizhou, (+0.5 GWh)
176 Shanghai, (+0.5 GWh)

TALENT NEW ENERGY
177 Huainan, (+10 GWh)
178 Chongqing, 0.2 GWh, (+2 GWh)

ENPOWER
179 Chuzhou, (+10 GWh)
180 Beijing, 0.2 GWh, (+2.8 GWh)

China still **dominates** the battery industry, but new projects have slowed due to **overcapacity**. Companies like Gotion and Ganfeng mitigate this by securing the **upstream supply chain**, while others **pivot to energy storage** to offset the weaker EV battery market.



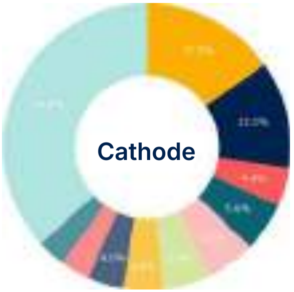
How to read this map
BASIC FORMAT = *Current Capacity GWh, (+Additional Future Capacity GWh)*

Source: [New Energy Terminal]

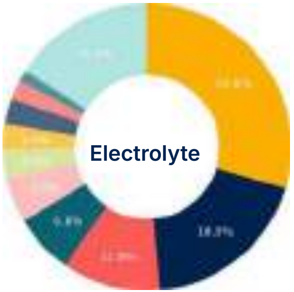
*total includes future & current capacities
**note: sodium-ion excluded

Material Suppliers - Market Share Breakdown

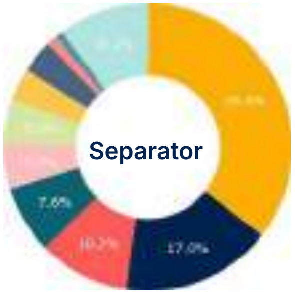
2024 Data



- ● Hunan Yuneng (LFP)
- ● Dynanonic (NCM)
- ● Hubei Wanrun
- ● ECOPRO
- ● Ronbay
- ● LOPAL
- ● Xiamen Tungsten
- ● Ronbay
- ● BYD
- ● Tianjin B&M
- ● Other

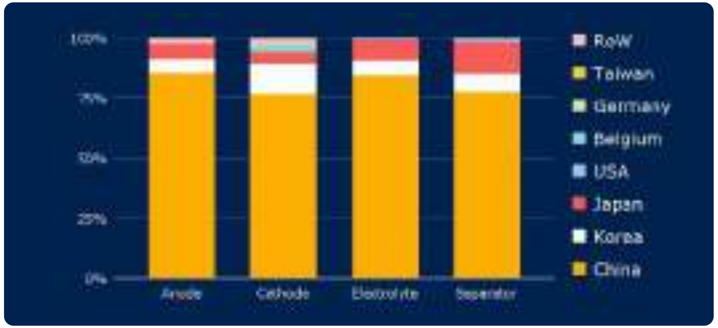


- ● Tinci
- ● Shenzhen Capchem
- ● Guotai-Huarong
- ● BYD Cell
- ● MU Ionic Solutions
- ● Enchem
- ● Central Glass
- ● Dongguan Shanshan
- ● Soulbrain
- ● Dongwha Etec
- ● Other



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

- ● BTR New Energy
- ● Kaijin
- ● Zichen
- ● Shanshan Group
- ● XFH
- ● Shinzoom
- ● Posco
- ● Resonac
- ● Mitsubishi Chemical
- ● Sinuo
- ● 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.

Source: Fraunhofer ISI - Tim Wicke, Researcher

Major Equipment Manufacturers - USA

PROCESS AREA	Ross	Delta ModTech	Owens	DURR*	Wirtz	BW	Digatron*	Coesia*	Comau*	Mpac*	Convergix	GROB*	Mühlbauer	PEC
Mixing	✔			✔	✔									
Coating		✔	✔	✔	✔	✔								
Calendaring		✔	✔	✔	✔	✔								
Slitting		✔	✔	✔	✔	✔								
Stack		✔	✔		✔	✔	✔	✔	✔	✔	✔	✔	✔	
Wind						✔	✔	✔		✔		✔		
Packaging		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	
Filling				✔	✔	✔	✔	✔		✔	✔		✔	✔
Formation							✔	✔	✔					✔
Degassing							✔		✔				✔	✔
Aging							✔	✔	✔					✔
Test / Grade							✔		✔	✔	✔	✔		✔

Sources: Ross, Wirtz Manufacturing, DURR, barryWehmiller, Delta ModTech, Owens Design, Convergix, Comau, Mpac, GROB, Coesia, PEC Corp, Digatron Systems - Non exhaustive list

*US Subsidiary - Manufacturing Within USA

Major Equipment Manufacturers - South Korea

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

Sources: TSI, CIS, KGA, PNT, mPlus, ETS, Cowin Tech Top Material, Hanwha Momentum, Hana Technology, WonikPNE, DA Technology, MOT, SNF - Non exhaustive list

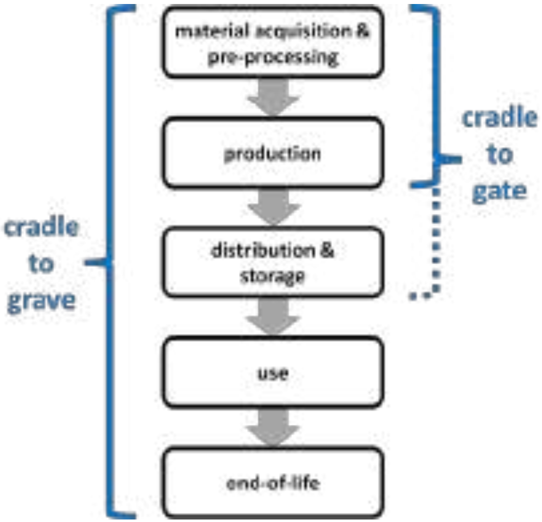
Major Equipment Manufacturers - China

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

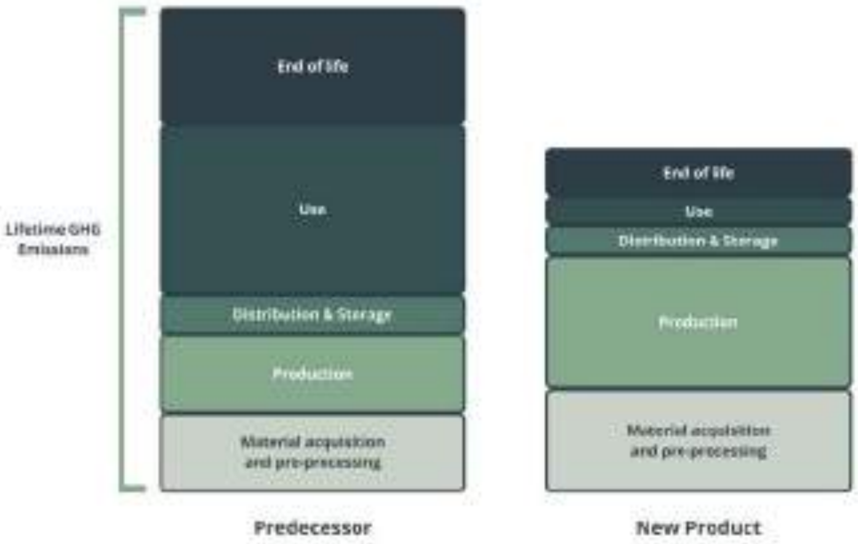
Sources: AutoRich, Ongoal Technology, Mesnac, GMK, Shangshui, Yinghe Technology, Lyric, LEAD, KATOP, Hymson, Bozhon, Hangke Tech, HYNN - Non exhaustive list

The Entire Battery Value Chain Must Now Be Knowledgeable Of Their Carbon Footprint (GWP)

Even small, private companies will have to know their GWP to be able to **respond to a customer request for information**



SCOPE 1-3 (FORMAL, ISO 14040)



SCOPE 4 - AVOIDED EMISSIONS (INFORMAL)

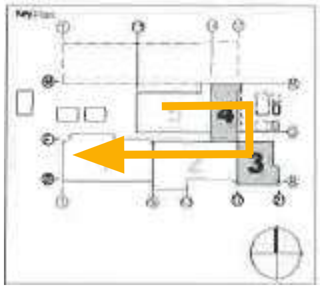
Source: GHG Institute (Scope 1-3, Scope 4)

Evolution Of The Manufacturing Footprint

LGES in Holland, Michigan Case Study

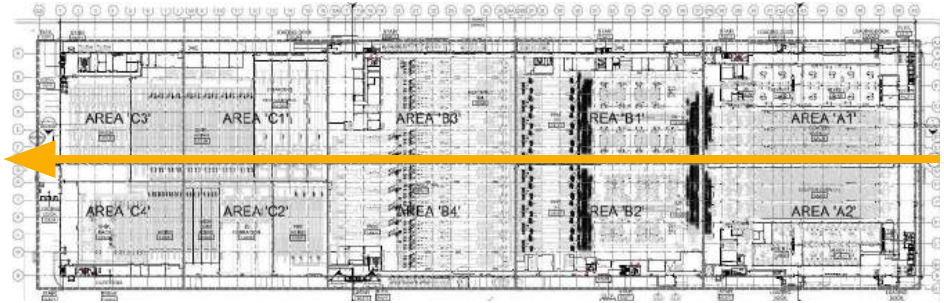
With early gigafactories, an angular factory design was often used to save space, but in the current production environment a linear design is used to improve efficiency and scalability

START (<10 GWh)



AD HOC DESIGN - ANGULAR MATERIAL FLOW
Commissioned: **2011**
5 GWh

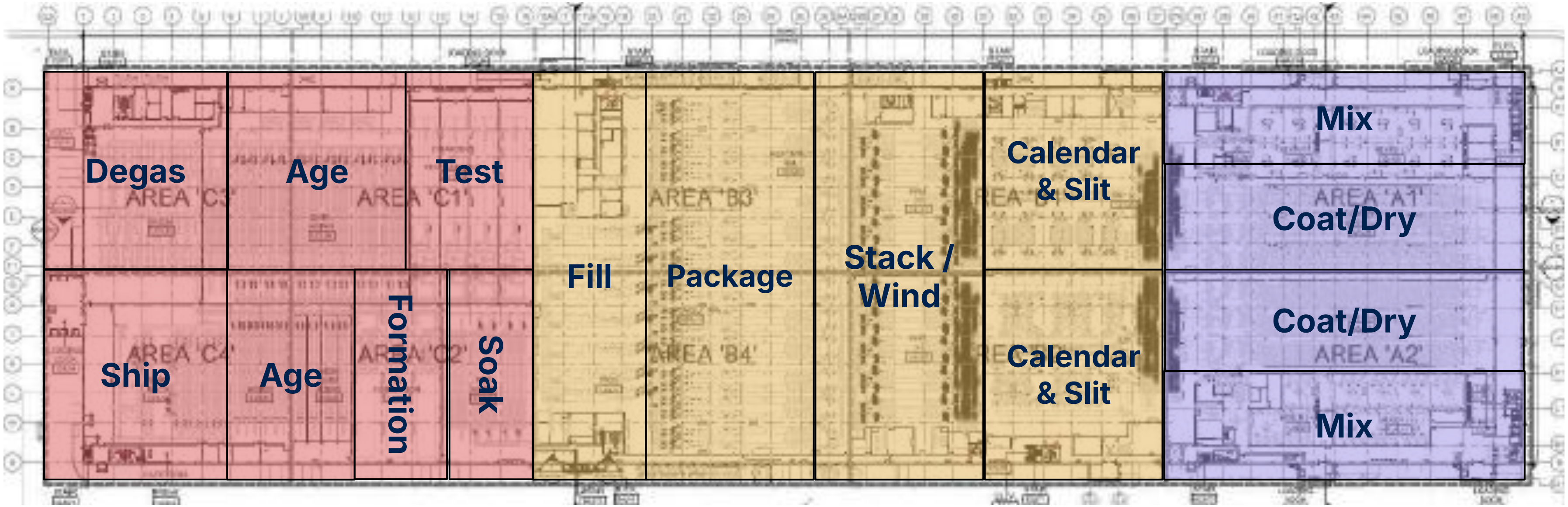
SCALE (>10 GWh)



MODULAR DESIGN - SIMPLIFIED MATERIAL FLOW
Commissioned: **2024**
20 GWh

Source: City of Holland, Michigan, USA

Manufacturing Process Groups - Leading Edge 20 GWh Pouch Line



- Many models and manufacturing metrics currently in use are based on early ‘GWh-scale’ factories using outdated estimates
- Current generation (leading edge) facility metrics are now available based on LGES facility

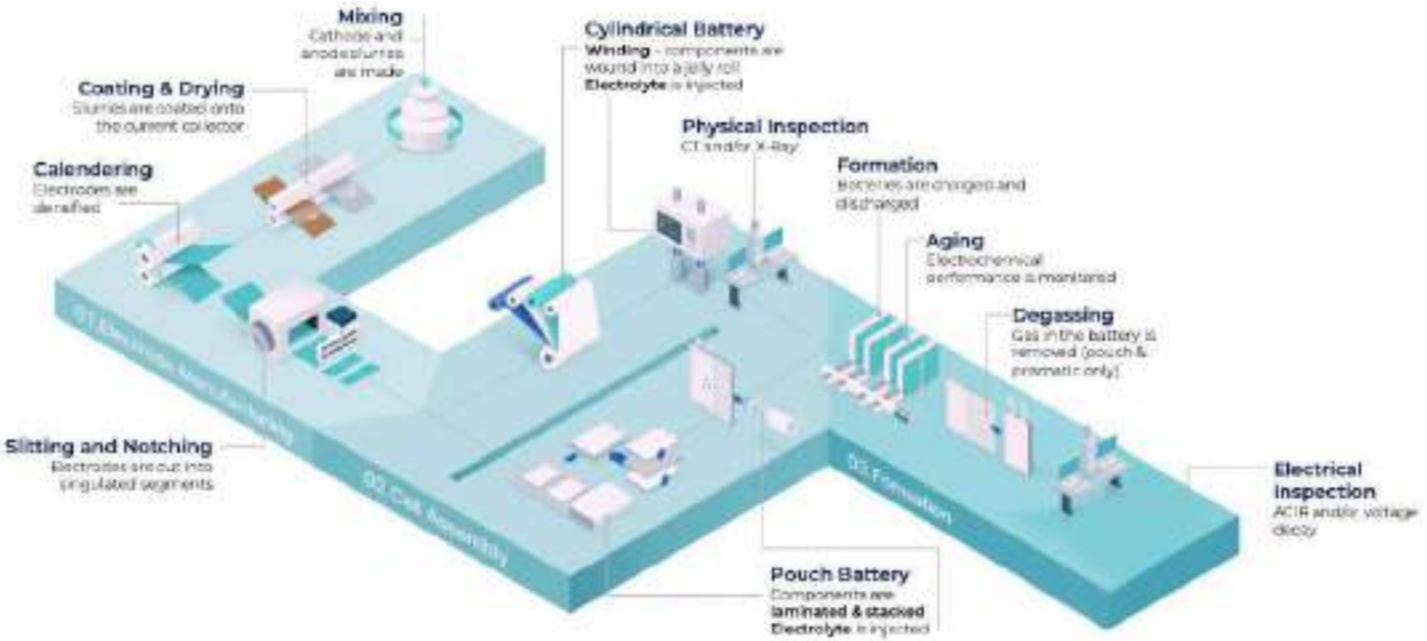
Source: City of Holland, Michigan, USA

Facility Metrics - 20 GWh Pouch, USA - 1,919′ X 502′ = 963,338 Square Feet

PROCESS AREA	Area (Sq Ft)	Area/GWh (Sq Ft)	Area %	Temperature	Dew Point	Clean Room Class
Mixing	96334	4817	10%	22 +/- 2°C	/	ISO 8
Coating	134867	6743	14%	22 +/- 2°C	Semi-dry 5 to -5°C	ISO 7
Calendaring	48167	2408	5%	22 +/- 2°C	Semi-dry 5 to -5°C	ISO 7 - ISO 8
Slitting	48167	2408	5%	22 +/- 2°C	Semi-dry 5 to -5°C	ISO 7 - ISO 8
Stack/Wind	115601	5780	12%	22 +/- 2°C	Dry -40 to -50°C	Minimum ISO 7
Packaging	115601	5780	12%	22 +/- 2°C	Dry -40 to -50°C	Minimum ISO 7
Filling	96334	4817	10%	22 +/- 2°C	Extra dry -50 to -70°C	Minimum ISO 7
Formation	38534	1927	4%	22 +/- 3°C	/	/
Degassing	48167	2408	5%	22 +/- 3°C	/	/
Aging	125234	6262	13%	22 +/- 3 (HT 30-50)°C	/	/
Test / Grade / Ship	96334	4817	10%	22 +/- 3°C	/	/

Source: VDMA , City of Holland (LGES)

Manufacturing Process Map - Overview



CELL CAPACITY

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

CAPEX

$55-127 million/GWh

HUMANS/GWH

175 jobs created per GWh

SCRAP (RAMP UP)

15-30%

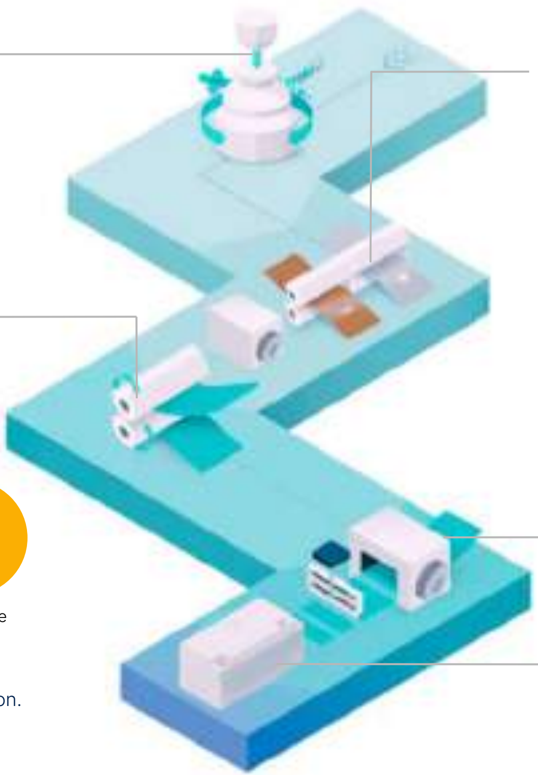
Scrap remains one of the **key issues,** primarily due to electrode production & lack of training

For solutions to improve yield and reduce scarp, see **software solutions** and **QA/QC hardware solutions**

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

Sources: LG Energy; VDMA; Faraday Institution; Mastering Ramp-up of Battery Production, Fraunhofer

Manufacturing Process Map - 1. Electrode Production



CHALLENGES
slurry quality (uneven dispersion)

MIXING

Slurries are made by mixing active material, binder, and solvent
The different combinations between those three highly affect coating & drying

CHALLENGES
electrode waste; physical damage to material

CALENDARING

Electrodes are densified to a target value

Here it's important to determine **electrode quality** and density

COATING & DRYING

Electrode slurries are coated onto the current collector 54% cost of electrode production
All other process steps depend on the quality of this step.

CHALLENGES
processing time; utilization loss; difficult to measure quality & get quality metrics

SLITTING & NOTCHING

Electrodes are cut into singulated segments

Uncoated areas are **cut out** leaving the parts where tabs will be grounded

CHALLENGES
edge quality (burr defects often occur - dangerous), difficult to inspect at speed; tool wear; **lowest OEE of any process because it's difficult to automate**

VACUUM DRYING

Removes leftover solvent

CHALLENGES
processing time; footprint; takes 12-24 hours

39% of total manufacturing cost

50-80 m/min pouch film speed

20-30 m/min cylindrical film speed

5% scrap rate

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

Sources: LG Energy; BCG

Dry Electrode Technologies - Timeline of Manufacturing Deployments & Partnerships

In 2024, **momentum behind dry electrode technology surged**, as both established industry giants and ambitious newcomers pushed the boundaries of next-generation battery innovations. From large-scale pilot lines to bold investments, new partnerships, and breakthrough product launches, the year was anything but quiet—setting the stage for a **fiercely competitive race to redefine the future of lithium-ion production.**

APRIL 2024
Dragonfly Energy announced its dry electrode process was validated through a third-party assessment.

JULY 2024
LG Energy Solution plans to complete a pilot line for its dry electrode process at the Ochang plant by the end of this year and to achieve series production by 2028.

AUGUST 2024
Tesla produced a Cybertruck with in-house dry cathode and dry anode 4680 cells – making it an all dry electrode vehicle.

SEPTEMBER 2024
Samsung SDI completed the "Dry EV Line", a pilot line for dry electrode technology at the Cheonan plant, and started pilot production.

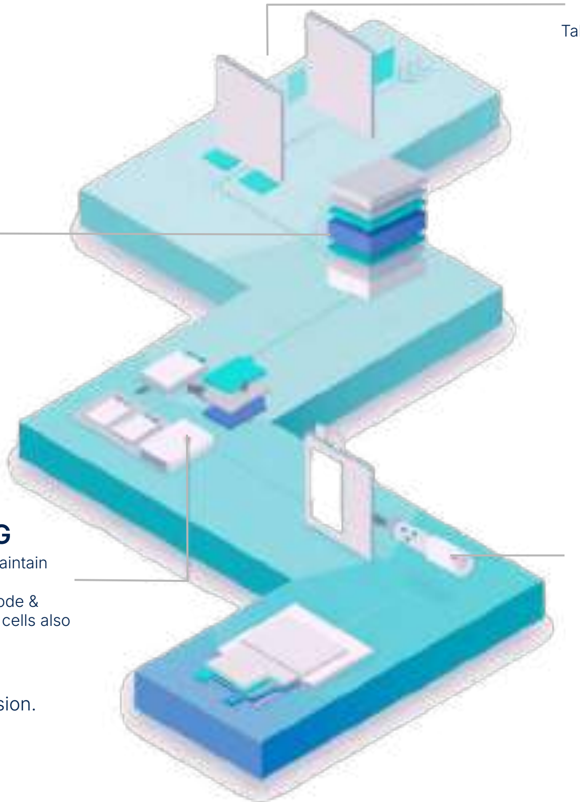
OCTOBER 2024
Anaphite raised $13.7M in Series A to commercialize their dry battery electrode material preparation process.

DECEMBER 2024
AM Batteries Inc. receives investment from Shibaura Machine Co., Ltd. (fka Toshiba Machine) to scale up dry spray process for electrode production.

Note: non-exhaustive

Sources: Dragonfly Energy, Korea Herald, Autoevolution, Samsung SDI, Anaphite, AM Batteries

Manufacturing Process Map - 2. Cell Assembly - Pouch



TAB WELDING
Tabs are ultrasonically welded to the jelly roll

CHALLENGES
foil damage; coating adhesion

POUCH FORMING
Making a case by pressing a film

CHALLENGES
corner cracking

20% of total manufacturing cost

2-20 parts/min speed

5% scrap rate

LAMINATION & STACKING/WINDING
Lamination: laminating layers to maintain positional integrity
Stacking: stacking layers of electrode & separator. Note that **wound** pouch cells also exist.

CHALLENGES
positioning accuracy of anode & cathode sheets (alignment); speed (affects positioning)

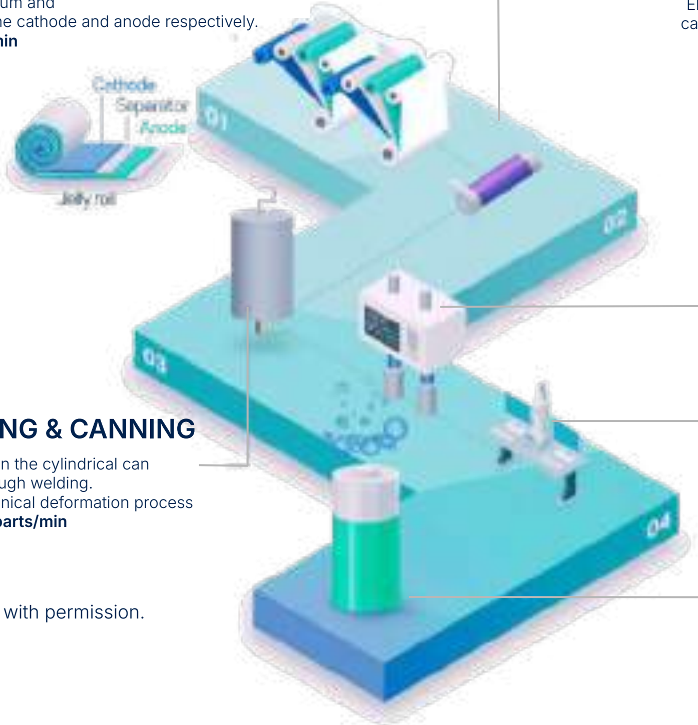
ELECTROLYTE INJECTION
Filling the electrode pocket with electrolyte through metered dispensing

CHALLENGES
dosing and distribution accuracy of the electrolyte in the cell; No electrolyte residues in the sealing seam; seal integrity

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

Sources: LG Energy; BCG; RWTH PEM

Manufacturing Process Map - 2. Cell Assembly - Cylindrical



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

WINDING & TAB WELDING

Winding the cathode, anode, and two separator rolls. Welding the aluminum and copper tabs onto the cathode and anode respectively.
SPEED: 30 parts/min

20%
of total manufacturing cost

5%
scrap rate

CHALLENGES
metal contamination

TAB SHAPING & CANNING

The jelly roll is put in the cylindrical can and then fixed through welding.
High-speed mechanical deformation process
SPEED: 300-600 parts/min

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

PHYSICAL INSPECTION

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

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

DEGASSING/ PRE-CHARGE

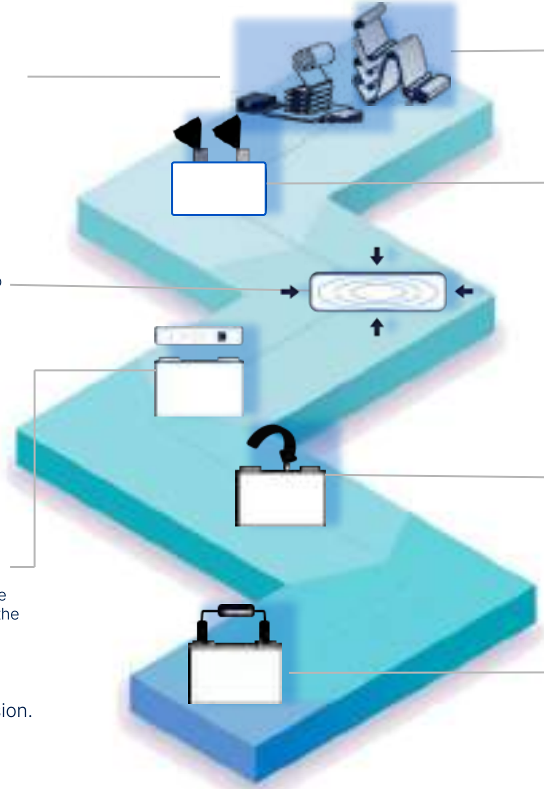
Optional process to remove gas

CHALLENGES
exhaust gas treatment
Avoiding residual gas during sealing and folding steps

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

Sources: LG Energy; BCG; RWTH PEM

Manufacturing Process Map - 2. Cell Assembly - Prismatic



CHALLENGES
anode, cathode, separator alignment

Z-STACKING

Winding the cathode, anode, and two separator rolls. Welding the aluminum and copper tabs onto the cathode and anode respectively.
SPEED: 30 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

20% of total manufacturing cost

5% scrap rate

CHALLENGES
cap to can alignment, missed laser welding spot

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

Roll the slitted cathode, anode, and separator together by controlling speed, tension, etc.
SPEED: 30 parts/min

CHALLENGES
uneven stress, burr issues, and powder loss

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

CHALLENGES
throughput and quality

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

Sources: CATL, RWTH PEM

Stacking Versus Winding

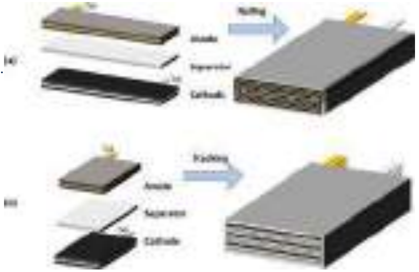
HOW ARE THE TWO TECHNIQUES DIFFERENT?

Stacking involves stacking electrodes and separators into precise layers that are atop one another to form a flat cell. These can be separate cut layers or one continuous electrode as well. This process enables **high energy density and precise structural stability**, making it ideal for applications requiring compact, **high-performance batteries,** such as electric vehicles (EVs) and aerospace systems.

Winding, or the jelly-roll process, involves rolling electrodes and separators into a cylindrical or prismatic structure. It is widely adopted due to its **speed and scalability**, making it suitable for **mass production** in consumer electronics and power tools.

Recent innovations include **hybrid techniques** like laminated winding and Z stacking, which combines stacking and winding to optimize energy density while maintaining manufacturing efficiency.

Automation in stacking processes has also improved production speeds, closing the gap with winding techniques.



a) Winding; b) Stacking

	Strength	Weakness	Opportunity	Threat	Applications
Stacking	Higher **energy density and thermal management** due to lower internal resistance. Less prone to **swelling & core collapse.** **Customizable** for unique form factors, like EVs & aerospace. Improved **packing efficiency** for rectangular modules, maximizing volume utilization in packs.	**Slower production speed** due to precision layer alignment & index motion. **Higher costs** due to complex manufacturing equipment. **Limited scalability** in high-volume production. **Potential failure** (burrs, delamination, etc.) due to additional cutting required.	**Rising demand for EVs and stationary energy storage systems** highlights stacking's high-density benefits. **Advances in automation and robotics** are making stacking more cost-competitive.	**Competing technologies** like hybrid stacking-winding techniques may reduce its exclusivity in precision. **Limited scalability** compared to winding could deter adoption in mass markets.	**Fastest growing solution** with companies like BYD (Blade battery) and Apple adopting it for high C-rate applications (due to lower internal resistance)
Winding	**Mature, well-established** technology with **lower production costs.** High **production speed and scalability**, ideal for mass production.	Slightly **lower energy density** due to voids at edges of rolled layers. **Packing efficiency is lower** for rectangular or prismatic packs due to cylindrical shapes. Prone to **localized hotspots** during high discharge rates.	**Popularity** in passenger & commercial EVs and consumer electronics at low cost supports growth. **Innovations in thermal management solutions** such as shutdown separators could address limitations in heat dissipation.	**Emerging battery formats,** such as solid-state cells, could demand new manufacturing paradigms.	**Most stable technology** with companies like CATL & Tesla and commercial high volume manufacturers are widely utilizing this technique due to its scalability and lower cost.

Sources: Tycorun, Bonnen Batteries, Evaluating the Manufacturing Quality of Lithium Ion Pouch Batteries

Manufacturing Process Map - 3. Formation

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

CHARGING & DISCHARGING

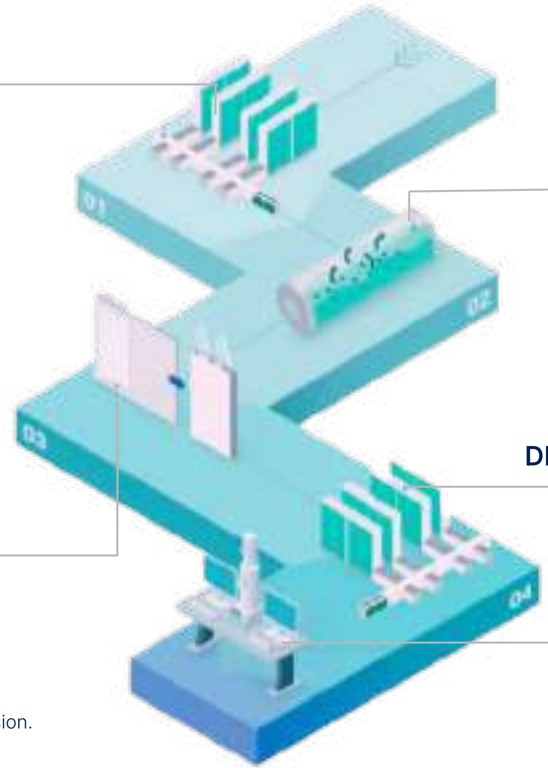
Electrochemical activation.
SEI is formed on the anode

41%	5-25 days	9%
of total manufacturing cost	time	scrap rate

CHALLENGES
residual gas inside the cell; seal quality; throughput (a lot of additional CAPEX)

DEGASSING

Pouch only.
Gases formed during aging are cut off inside of a vacuum chamber (sacrificial gas bag).



AGING

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

CHALLENGES
Process time, throughput; factory footprint

CHARGING, DISCHARGING, & AGING

The previous processes are repeated

CHALLENGES
throughput

QUALITY CONTROL

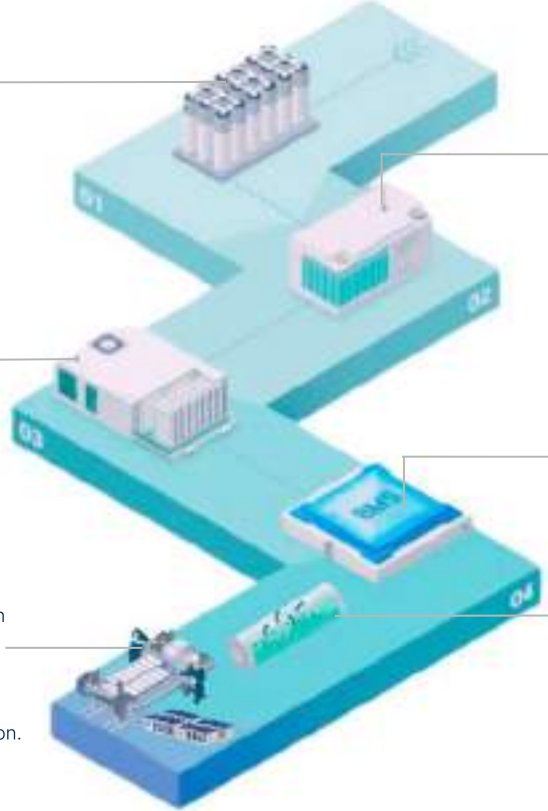
End of line check - capacity, resistance, voltage, etc., and cosmetic

CHALLENGES
cosmetic & variation in capacity; yield

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

Sources: LG Energy; BCG; RWTH PEM

Manufacturing Process Map - 4. Pack Assembly



CHALLENGES
surface cleaning; weld quality; cell to cell matching

CONNECTING BATTERY CELLS

Battery cells are connected after surface is cleaned

MODULARIZATION

The cells are attached to the module case

CHALLENGES
ensuring cable flexibility, Battery cells handling

CHALLENGES
damage due to placement (primarily pouch); large machinery required due to module mass & dimensions, safety at high voltages

PACK ASSEMBLY

The modules are put in the battery pack and connected

APPLYING BMS

A Battery Management System is applied to battery pack

CHALLENGES
correct wiring and integration of the BMS

CHALLENGES
battery pack integration with other components in EV or BESS

FINAL INTEGRATION

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

FINAL TEST

A series of electrical test including charge and discharge cycle are performed to ensure the highest quality

CHALLENGES
testing sequence, results and accepted limits vary between manufacturers, resulting in lack of standardization

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

Sources: LG Energy; RWTH PEM

High Yield Production Is Challenging - Reducing Scrap Is Necessary To Compete With China

SCRAP RATES OVER YEARS OF OPERATION

COST OF SCRAP

All battery manufacturers will have to **master operational excellence** to match industry leader CATL. The available and developing technology sets of **manufacturing data collection and analysis** should be the primary solution.

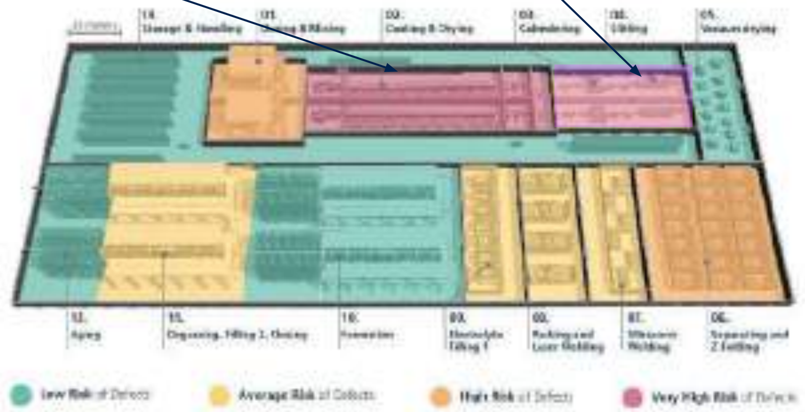
Source: Mastering Ramp-up of Battery Production, Fraunhofer (Both Figures)

Cell Manufacturing Issues - Electrode Manufacturing Is Difficult

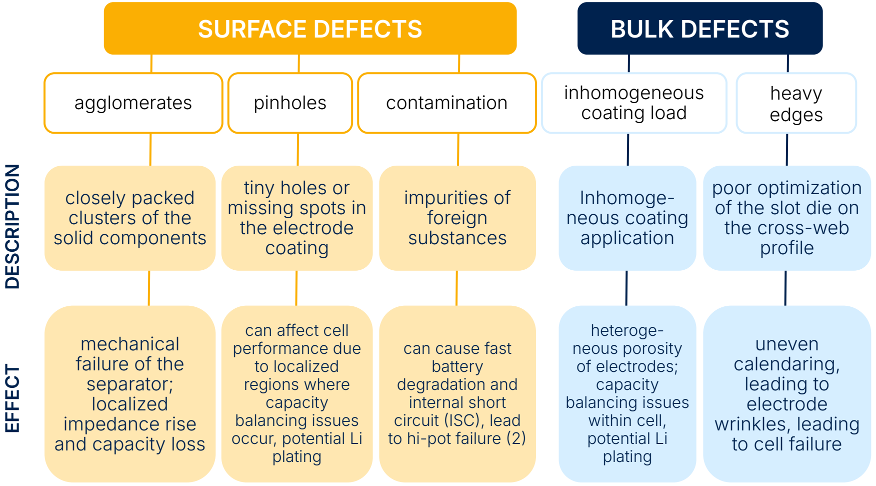
Every step in battery production presents challenges, but some, like **coating, drying, and slitting** carry a significantly higher risk of defects. The **heat map** illustrates these critical areas, highlighting their **likelihood of defects.**

Produces most **scrap** during **ramp-up**

Contamination occurs leading to **cell failure** (most relevant for **mass production**)



MAJOR DEFECTS THAT CAN OCCUR DURING COATING AND DRYING OF ELECTRODES



	SURFACE DEFECTS			BULK DEFECTS	
	agglomerates	pinholes	contamination	inhomogeneous coating load	heavy edges
DESCRIPTION	closely packed clusters of the solid components	tiny holes or missing spots in the electrode coating	impurities of foreign substances	Inhomogeneous coating application	poor optimization of the slot die on the cross-web profile
EFFECT	mechanical failure of the separator; localized impedance rise and capacity loss	can affect cell performance due to localized regions where capacity balancing issues occur, potential Li plating	can cause fast battery degradation and internal short circuit (ISC), lead to hi-pot failure (2)	heterogeneous porosity of electrodes; capacity balancing issues within cell, potential Li plating	uneven calendaring, leading to electrode wrinkles, leading to cell failure

Sources: Mastering Ramp-up of Battery Production, Fraunhofer (Both Figures but with internal edits*); (2) High-Potential Failure Analysis, Sotto; Detecting the foreign matter defect in lithium-ion batteries[...], Pan et al.

Investing In QA/QC: - Hardware & Software In The Era Of Industry 4.0 To Improve Ramp Up & Yield

Industry 4.0 is the **"next phase in the digitization of the manufacturing sector"**, driven by advancements in technology, data, and connectivity. Its transformative potential lies in **integrating cutting-edge tools and systems** to create smarter, more efficient production environments.

HERE ARE SOME KEY MANUFACTURING QA/QC AREAS IMPACTED BY INDUSTRY 4.0 THAT EVERY MANUFACTURER SHOULD CONSIDER:

ADVANCED TECHNOLOGY AND HARDWARE:

Sensors and hardware are now designed to be more compact, accurate, and reliable, enabling **broader, quicker data collection** with **greater precision.**

INTELLIGENT AND CONNECTED EQUIPMENT:

IoT (Internet of Things) has enabled **real-time data collection, integration, and monitoring.** It has also allowed for **adaptability** (re-calibration for example).

MACHINE LEARNING AND AUTONOMOUS DECISION-MAKING:

AI/ML are driving the **development of incredible inspection equipment & software** that leverages **predictive analytics** to **automate decision making**, improving throughput and quality.

TRACEABILITY:

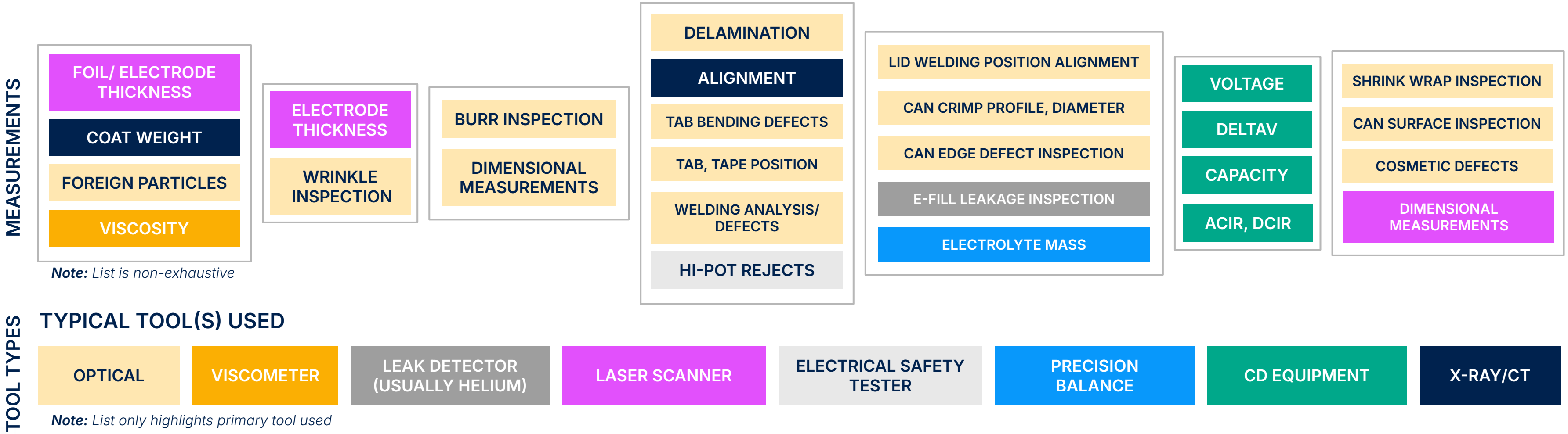
Advanced equipment and software enable **traceability across the production line**, key to **accelerating ramp up** and **reducing scrap** by identifying defects & yield issues early.

IT'S ALL CONNECTED. EVERY PROCESS STEP AFFECTS THE NEXT. INTEGRATION AND TRACEABILITY IS KEY.

Other advanced industries like **semiconductor** have embraced this shift, investing **billions into QA/QC & advanced analytics**

Sources: The Rise of Industry 4.0 and its Impact on Metrology, What are Industry 4.0, the Fourth Industrial Revolution, and 4IR?

Some Core In-Line Measurements To Track Quality - Color Coded By Tool



MEASUREMENTS

- FOIL/ ELECTRODE THICKNESS
- COAT WEIGHT
- FOREIGN PARTICLES
- VISCOSITY

- ELECTRODE THICKNESS
- WRINKLE INSPECTION

- BURR INSPECTION
- DIMENSIONAL MEASUREMENTS

- DELAMINATION
- ALIGNMENT
- TAB BENDING DEFECTS
- TAB, TAPE POSITION
- WELDING ANALYSIS/ DEFECTS
- HI-POT REJECTS

- LID WELDING POSITION ALIGNMENT
- CAN CRIMP PROFILE, DIAMETER
- CAN EDGE DEFECT INSPECTION
- E-FILL LEAKAGE INSPECTION
- ELECTROLYTE MASS

- VOLTAGE
- DELTAV
- CAPACITY
- ACIR, DCIR

- SHRINK WRAP INSPECTION
- CAN SURFACE INSPECTION
- COSMETIC DEFECTS
- DIMENSIONAL MEASUREMENTS

Note: *List is non-exhaustive*

TOOL TYPES

TYPICAL TOOL(S) USED

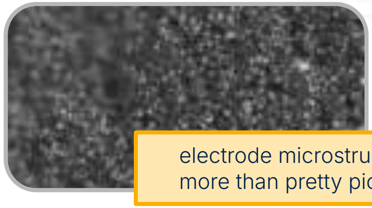
- OPTICAL
- VISCOMETER
- LEAK DETECTOR (USUALLY HELIUM)
- LASER SCANNER
- ELECTRICAL SAFETY TESTER
- PRECISION BALANCE
- CD EQUIPMENT
- X-RAY/CT

Note: *List only highlights primary tool used*

Source: research done on multiple tool providers and insights from manufacturing experts

QA/QC Technologies - High Resolution Electrode Inspection In-Line

In the past, electrode morphology has been key in R&D. But, not in manufacturing, largely due to **micron level in-line inspection** being nearly impossible. Now, manufacturers are **recognizing the importance of in-line electrode inspection**, due to its impact on cell quality, and **exciting solutions are entering the market**. Let's dive into why this is important and how it's done.



electrode microstructure, more than pretty pictures

WHAT ARE THE FEATURES?

- **Agglomerations** and **contamination**
- **Grain** size, arrangement and **uniformity**
- **Surface roughness**
- **Voids** in electrode structure
- **Defect progression** (cracks, fractures)

WHY IS IT IMPORTANT TO CAPTURE THEM?

Contamination: Causes fast **battery degradation** and internal short circuit (**ISC**), leads to **battery failure**.

Agglomerations: Causes **defects in coating**, leads to **scrap.**

Larger Grains: Enables uniform lithium deposition, reduces dendrite formation → **Improves safety**.

Grain Arrangements: Helps **ionic and electronic pathways,** improves **tortuosity.**

Uniform Grain Size: Boosts energy/power density; non-uniformity causes stress, cracks, and degradation.

Defects & Voids: Increases resistance, weakens structure → **Reduce efficiency and long-term performance.**

Read the papers linked below to find out more

HOW IS IT DONE? - EXAMPLE METHOD

Optical Hardware

- 1-3 micron resolution
- Can operate at film speed
- Takes 50+ images/sec
- Lighting system to enable 3 directional observations

+

AI/ML Engine

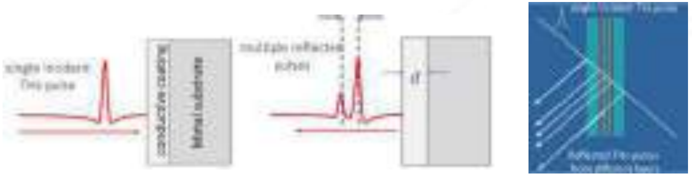
- Instant image processing
- Identifies and measures each image feature

Provider example: PDF/SOLUTIONS

Sources: PDF Solutions, High-Potential Failure Analysis, Sotto; Detecting the foreign matter defect in lithium-ion batteries[...], Pan et al.; The Impact of Li Grain Size on Coulombic Efficiency in Li Batteries, Mehdi et al.; Particle size and zeta potential of electrode materials: better characterization, better performance, Anton Paar; Balancing particle properties for practical lithium-ion batteries, Zhang et al.; Effect of the grain arrangements on the thermal stability of polycrystalline nickel-rich lithium-based battery cathodes, Hou; Identifying the Origins of Microstructural Defects Such as Cracking within Ni-Rich NMC811 Cathode Particles for Lithium-Ion Batteries, Heenan et al.; The influence of void space on ion transport in a composite cathode for all-solid-state batteries, Hlushkou et al.; Probing the particle size dependence of nonhomogeneous degradation in nickel-rich cathodes for high-energy lithium-ion batteries, Song et al.

QA/QC Technologies - Terahertz

To date no sensor technology was capable of measuring coating density, coating thickness and conductivity simultaneously, accurately and rapidly during the in-line coating process. Terahertz sensors offer a solution that provide density, thickness and conductivity in one measurement, allowing for real-time feedback and control.



WHAT ARE THE FEATURES?

- Density of the coating
- Thickness of the coating
- Conductivity of the coating
- Electromagnetic Wavelength 1 mm to 100 µm
- Currently deployed at US battery manufacturer

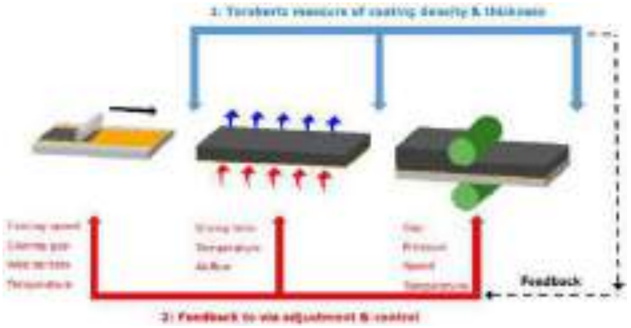
WHY IS IT IMPORTANT TO CAPTURE THEM?

Density of the coating: The mass of active material per unit area dictates the final capacity of the electrode and while higher coat weights are desirable to increase energy density, they typically also lower the power density.

Thickness of the coating: Ensuring the homogeneity of coating thickness in the production process is one of the biggest challenges in high volume manufacturing. Thicker electrodes contain a greater amount of active materials, increasing energy density, but also have greater diffusion distances, lowering power output, as well as potentially causing uneven response across the electrode and leading to quicker degradation.

Conductivity of the coating: High conductivity improves the capacity at higher discharge rates, with more energy extracted from the battery at a given time.

HOW IS IT DONE? - EXAMPLE METHODS



Provider examples: LUNA

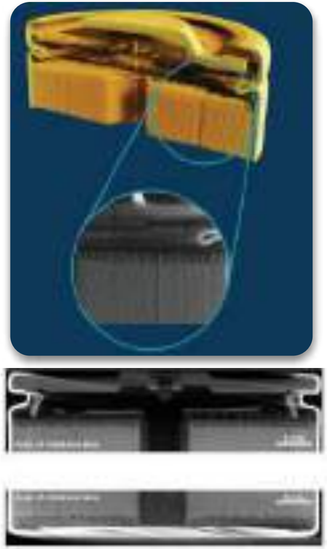
Sources: Teraview

QA/QC Technologies - CT-Scanning Is Transforming Battery Manufacturing

A Computed Tomography (CT) Scan uses X-rays to create detailed 3D images of battery components. The sample rotates while X-rays pass through it, capturing multiple 2D projections. These projections are reconstructed into a full 3D model for internal analysis.

Unlike traditional 2D inspection, CT provides complete volumetric data over the battery cell.

	Non-destructive	Scalable to ≥1k/cell	Full cell inspection	Spatially resolved	Resolution of ≤50 µm
Cycling & Storage	✗	✗	✓	✗	
Ultra High Precision Coulometry (UHPC)	✗	✗	✓	✗	
Electrochemical Impedance Spectroscopy (EIS)	✓	✗	✓	✗	
OCV decay during formation	✓	✗	✓	✗	
High Potential testing (HiPot)	✓	✓	✓	✗	
Dissection	✗	✗	✓	✓	✓
Cross section	✗	✗	✗	✓	✓
In-line vision	✓	✓	✗	✓	✓
Acoustics	✓	✓	✓	✓	✗
2D X-ray imaging	✓	✓	✗	✓	✓
3D X-ray imaging/CT scanning	✓	✓	✓	✓	✓



EMERGING CT TECHNOLOGIES:

Faster Scanning

CT inspection for batteries must match the high throughput of battery production. In 2024, new techniques have emerged, using **AI-supported reconstruction algorithms**, **fast detectors**, or **high-brightness X-ray sources**.

Full cell scanning in-line

As an effect of the increased scanning speed, **CT scanning of full cylindrical cells at high speed has been developed** - with throughputs approaching full cell in-line CT.

Data Management

With increasing scan speed, and in-line CT, extreme data volumes will be generated (~50 GB/cell). To manage this effectively, robust data management tools are required for easy data access, storage, and sharing. In response, **new cloud based tools have been developed** to address these challenges.

SELECTION OF COMPANIES OFFERING BATTERY CT:

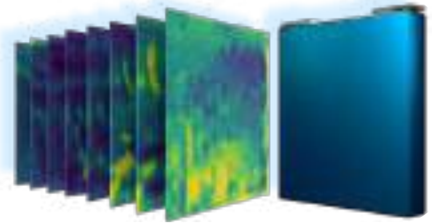
excillum
GLIMPSE
ROYMA
Innometry
Waygate Technologies
ZEISS
Nikon
UNICOMP
EXACOM
VCbattery
lumafield
TECHVALLEY

Sources: Table from "Battery Quality Control via High throughput CT Scanning"

MIXING
COATING
CALENDARING
SLITTING/NOTCHING
WINDING/STACKING
FILLING
FORMATION/AGING
EOL

QA/QC Technologies - High Resolution-High Throughput Ultrasound

Ultrasound has emerged as a promising non-destructive testing approach for battery inspection. Factors such as material properties, density, and porosity influence the interaction of ultrasonic waves with battery materials. In lithium-ion batteries, wave propagation can be described using theories like Biot's theory for fluid-saturated porous media or the slurry model for electrode coatings.



WHAT ARE THE FEATURES?

- In-line, high voxel count imaging
- Software enabled metrology
- Software enabled electrical test (SoC)
- Typically operates on frequencies between 1-10 MHz
- Currently deployed at US and EU battery manufacturers

WHY IS IT IMPORTANT TO CAPTURE THEM?

Thickness & Density Measurement: Measures electrode thickness and uniformity to maintain consistent performance.

Electrolyte Distribution Analysis: Evaluates the uniform distribution of the electrolyte, critical for battery efficiency.

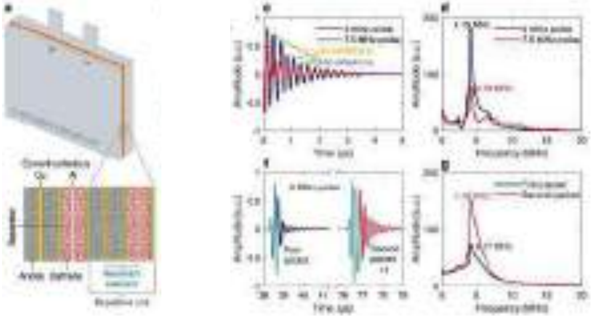
Adaptability to Various Battery Chemistries: Compatible with lithium-ion, solid-state, and other emerging battery technologies.

Quality Control: Ensures proper alignment of components and verifies manufacturing precision.

Data Integration: Provides data for process optimization and feedback into manufacturing systems.

Defects & Voids: Increases resistance, weakens structure → **Reduce efficiency and long-term performance.**

HOW IS IT DONE? - EXAMPLE METHODS



Provider examples:

TITAN

liminal

Sources: Imperial College London, Liminal Insights, Titan Advanced Energy Solutions

1 INDUSTRY

Applications Overview

ELECTRIC VEHICLES

Global EV demand remains intact. The growth rate has slowed down, but this is not affecting all markets and companies.

To adapt to this unprecedented change in the automotive industry, automakers are prioritising affordable and competitive vehicles.

BEV batteries are trending towards larger form-factor cells, primarily prismatic formats.

Automakers are accelerating plans for module-less pack architecture.

BESS

The market for battery energy storage systems (BESS) is booming, with installations starting to take more % of battery adoption in recent years.

Rapidly falling costs, coupled with policy and technical innovations, have led to increasing BESS adoption, led by grid-scale installation.

Grid-scale Li-ion systems have led the sector, but rapid innovation abounds in other ESS sectors such as Residential, C&I, VPP, V2G and LDES.

The industry has made improvements on safety but continues to face challenges as codes, standards, and public perceptions of BESS evolve.

OTHER EMERGING MARKETS

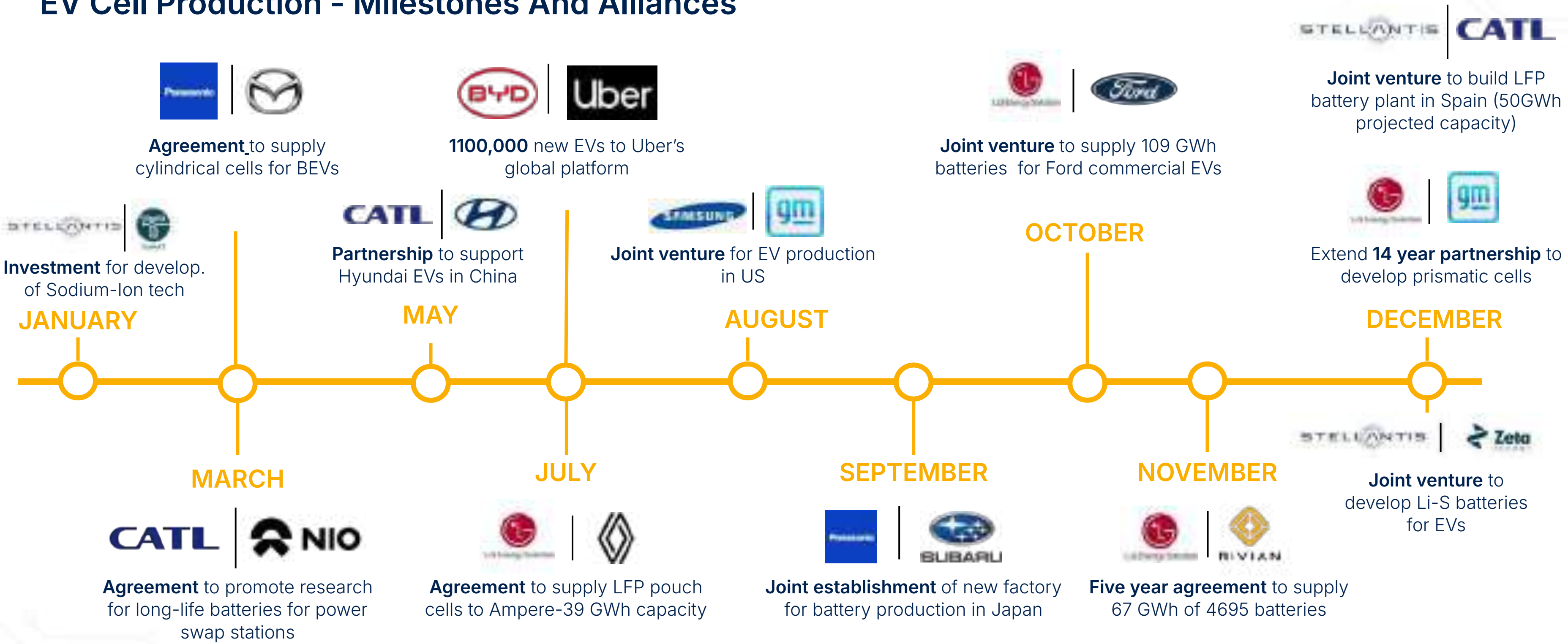
Aviation companies are near market readiness by using high-end Li-ion batteries.

New markets showing in off-highway EVs, light-EVs, trucking, maritime battery market.

While e-bike sales dominate the micro-mobility market, addressing fire risks and safety standards is a priority.

AI data centers are consuming more batteries to enable renewables integration, UPS, load leveling, power quality, and other services.

EV Cell Production - Milestones And Alliances



JANUARY

Investment for develop. of Sodium-Ion tech

MARCH

Agreement to supply cylindrical cells for BEVs

Agreement to promote research for long-life batteries for power swap stations

MAY

Partnership to support Hyundai EVs in China

JULY

1100,000 new EVs to Uber's global platform

Agreement to supply LFP pouch cells to Ampere-39 GWh capacity

AUGUST

Joint venture for EV production in US

SEPTEMBER

Joint establishment of new factory for battery production in Japan

OCTOBER

Joint venture to supply 109 GWh batteries for Ford commercial EVs

NOVEMBER

Five year agreement to supply 67 GWh of 4695 batteries

DECEMBER

Joint venture to build LFP battery plant in Spain (50GWh projected capacity)

Extend **14 year partnership** to develop prismatic cells

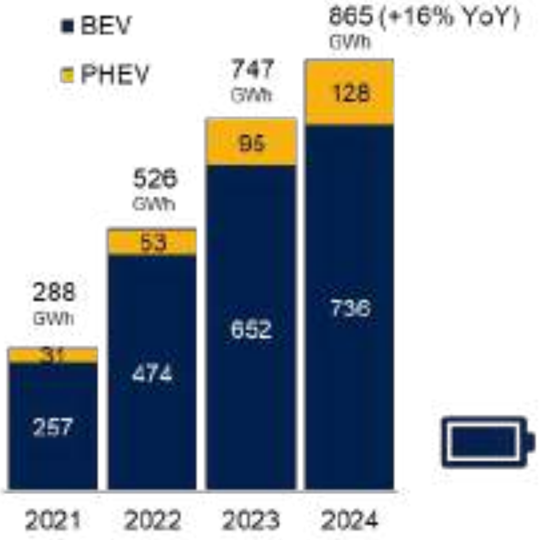
Joint venture to develop Li-S batteries for EVs

Source: News Articles Linked Above

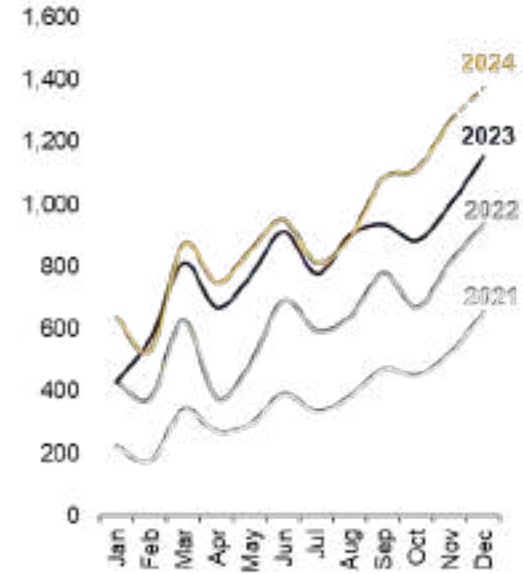
Global EV Demand Remains Positive But Battery Usage Slows Down

GLOBAL LIGHT DUTY EV* SALES, MILLION VEHICLES

GLOBAL LIGHT DUTY EV* BATTERY DEPLOYMENT, GWh



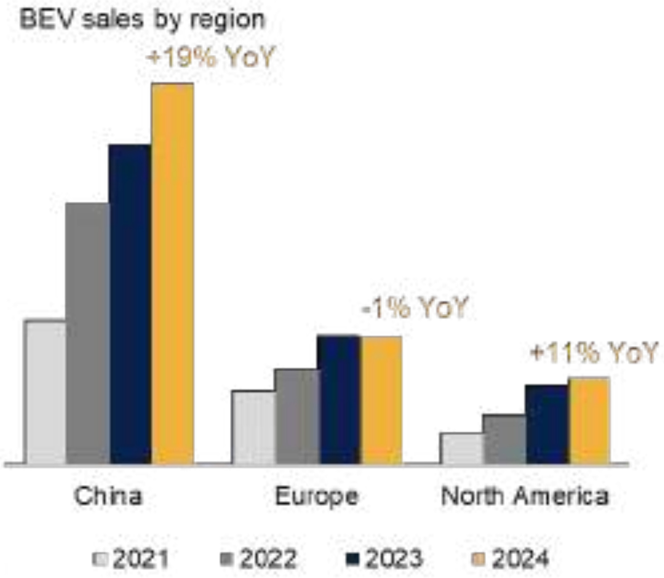
GLOBAL BEV SALES, 2024, THOUSAND VEHICLES



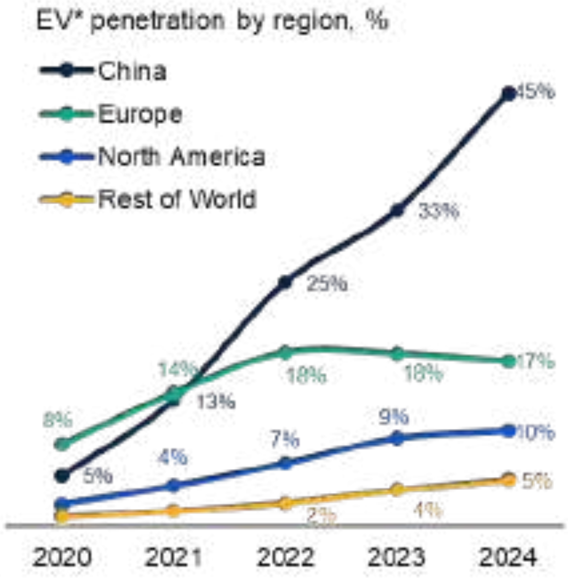
Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.
*EV includes BEV, PHEV, EREV. Showing passenger cars and light commercial vehicles.

EV Slowdown Is Not Uniform Across All Markets And Companies

CHINA IS PROPPING UP GLOBAL DEMAND



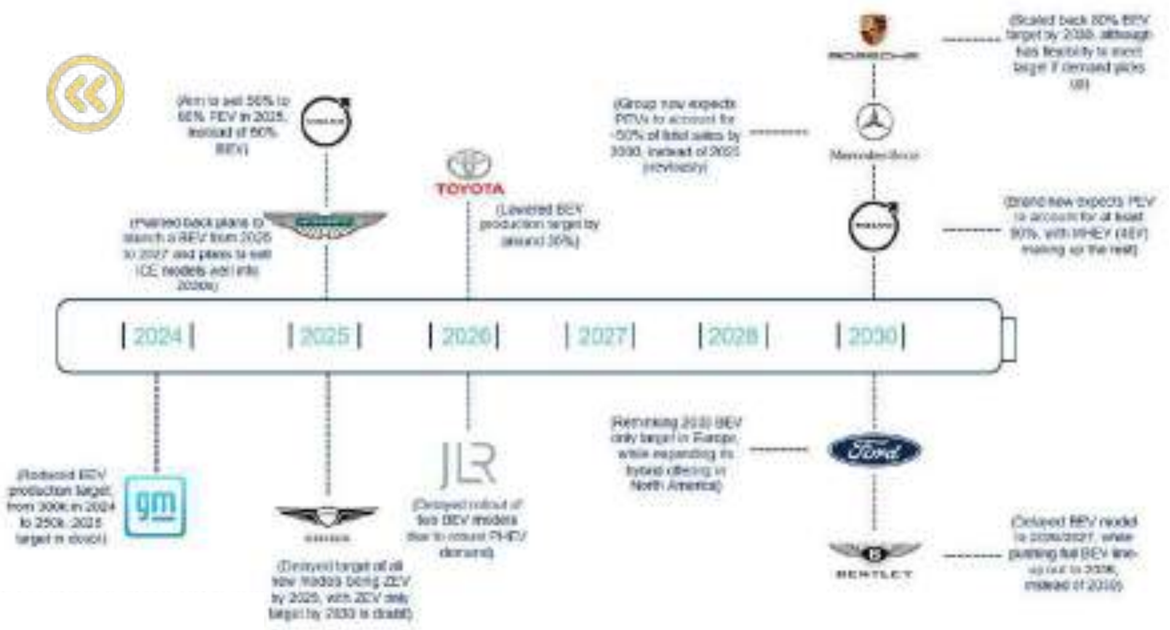
MAJOR REGIONS ON DIFFERENT TRAJECTORIES, AND GROWTH VARIES BY INDIVIDUAL MARKETS



PURE-PLAY MANUFACTURERS CONSOLIDATING THEIR LEAD

Source: GlobalData Auto, CRU Group. *EV includes BEV, PHEV, EREV. Showing passenger cars and light commercial vehicles.

Some OEMs Cut Back Ambitious EV Targets & Investments, While Others Reaffirm Commitments



The slowdown in demand for some legacy automakers has prompted them to reassess their aggressive BEV targets and cut back on investment plans, while other companies have reaffirmed their commitments.

Some have pulled back on their hybrid lineups, and others are lobbying policy makers to relax regulations.

The slowdown is seen as a relief providing them more time to enhance their BEV capabilities and competitiveness.

Held firm on its 2030 target for EVs to be 70% of EU and 50% of U.S. and China sales

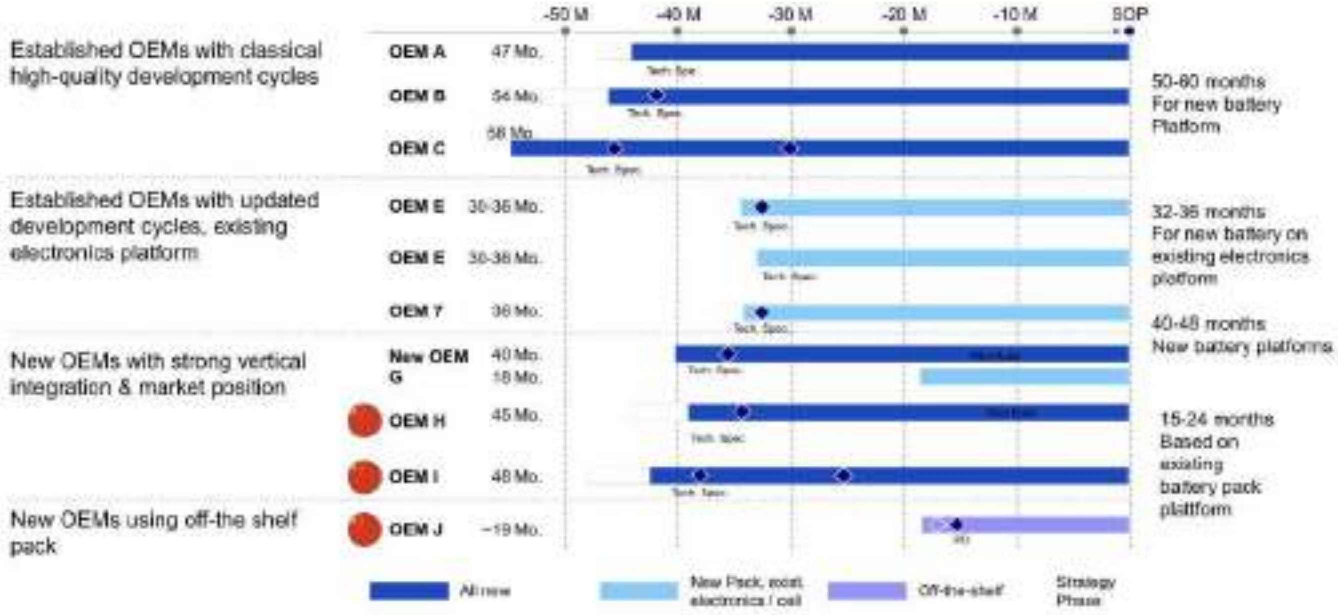
Targeting 5.55 million annual global sales by 2030, a 30% increase from 2023

Raised its 2024 sales target to 4 million, up from the previous estimate of about 3.6 million

Source: CRU Group, company announcements. PEV = BEV, PHEV, EREV

Automakers Pushing To Shorten EV Development Times

DEVELOPMENT TIMES VARY BY STRATEGY ARCHETYPE



Shorter vehicle development times provide many advantages: Battery and BEV technology is changing rapidly and OEMs need to be able to make rapid changes, e.g. switch to a new battery in the middle of a program life cycle.

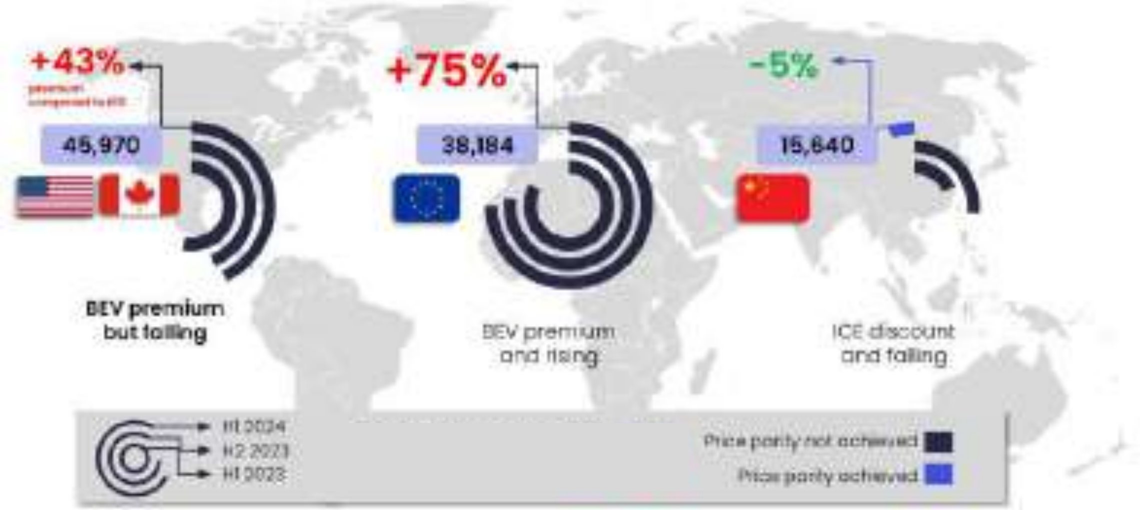
Chinese and new EV players set the benchmark for development times: typically one year shorter, and less than half if using an off-the-shelf (OTS) pack solution.

Roland Berger

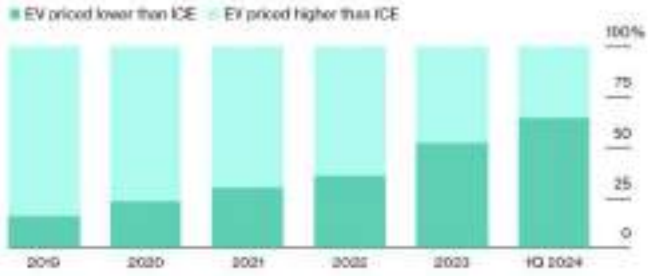
Source: Content & analysis provided courtesy of Roland Berger (Distinguished Partner). For more information, visit https://www.rolandberger.com/en/Insights/Global-Topics/Battery/.

BEV-ICE Price Parity Achieved In China, While The Rest Of World Catches Up

BEV PREMIUM BY REGION FROM A SALES WEIGHTED AVERAGE OF BEV AND ICE BASE PRICES[1]



CHINA SHARE OF EV MODELS PRICED ABOVE OR BELOW ICEs[1]

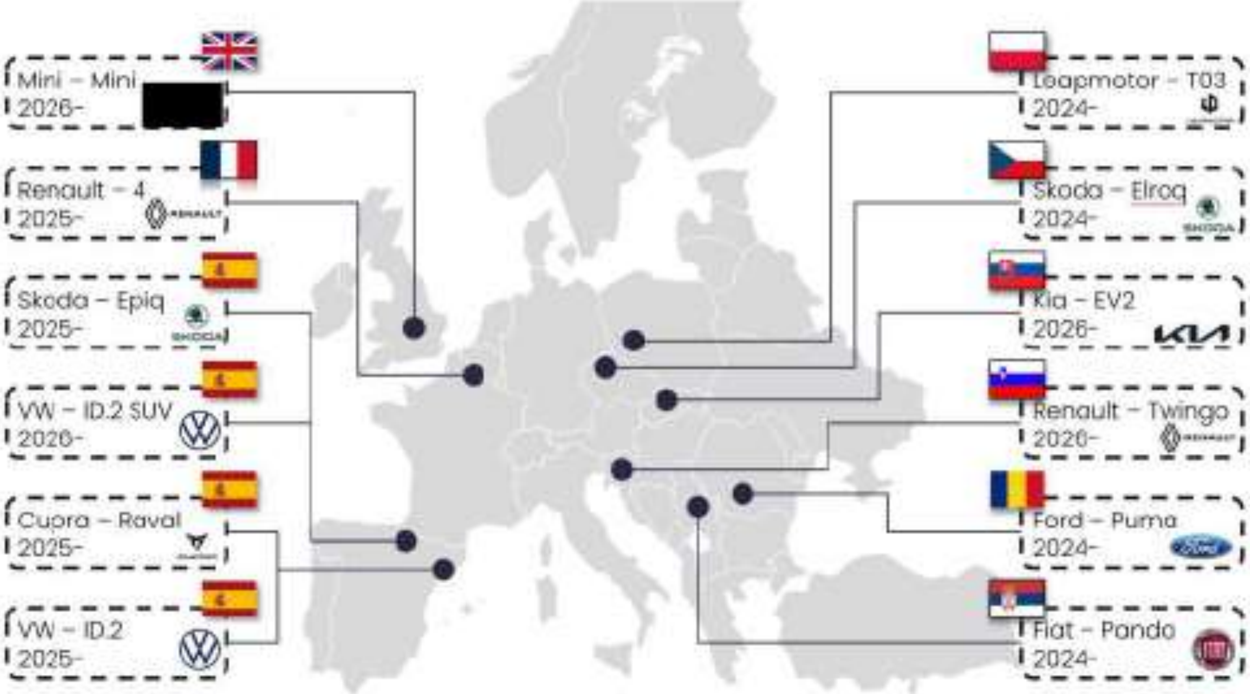


Chinese OEMs have achieved price parity by a combination of:

- Underlying cost reductions
- Intense price competition
- Economies of scale
- Local and national incentives for consumers

Source: Main content provided by [1] Rho Motion, [2] BloombergNEF (Distinguished Partners)

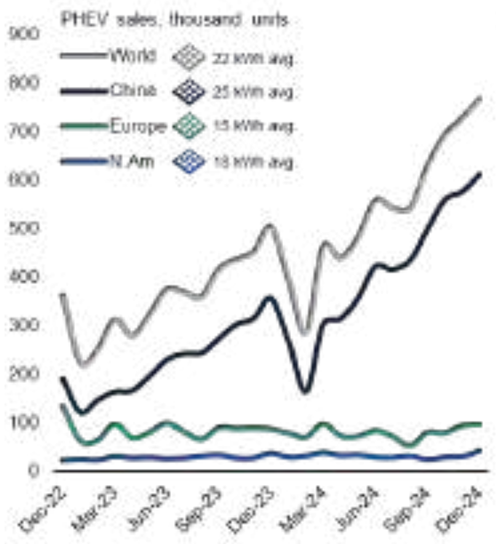
There Is An Upcoming Wave Of Small, More Affordable, BEVs In Europe



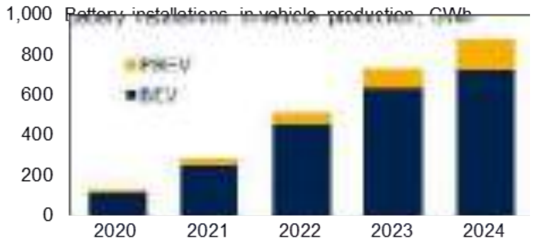
Although not shown here, there are also affordable Chinese imported models on sale or planned.
Content & analysis provided courtesy of Rho Motion (Distinguished Partner). For more information, visit https://rhomotion.com/research/ev-production-quarterly-outlook/.

Many OEMs Shifting Toward Plug-in Hybrids

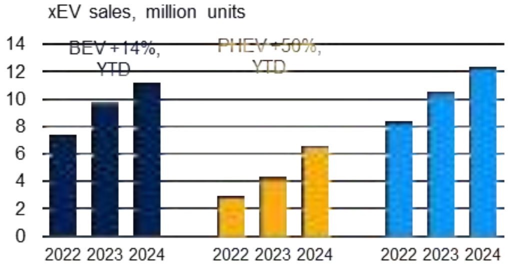
CHINA IS DRIVING A PHEV RESURGENCE, AND WITH BIGGER BATTERY PACKS THAN ELSEWHERE



PHEVS PROVIDE MODEST CONTRIBUTION TO BATTERY DEMAND IN SHORT-TERM



PHEVS FASTEST GROWING xEV TYPE THIS YEAR



- PHEVs are benefiting from more favorable pricing, similar incentives to BEVs (China only), vehicle variety, and increased driving range with bigger packs
- **Series range-extender EVs** are in a revival, starting with Chinese and now US automakers. EREVs constitute almost one third of PHEV battery demand
- EU regulations are encouraging OEMs to increase pack capacities, but the 2035 ZEV-only mandate restricts PHEVs
- US OEMs have been leaning on their hybrid vehicles offerings, and latest EPA emissions standards allow them greater flexibility in meeting average emissions targets using different powertrains
- PHEVs are propping up the battery demand growth rate in the short term, but on balance the pivot to hybrids constitutes a net downgrade to battery demand as pack capacities are much smaller than BEVs

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Range extender EVs (EREV) included in the PHEV category.

Revival Of Range Extender EVs (EREV)

EREVs are series plug-in hybrids - essentially a BEV carrying a small ICE engine to charge the battery when needed. Both pure-play Chinese BEV markers and legacy automakers adjusting their powertrain strategy to include EREVs.

HYUNDAI	08/24 - Announcing new EREV models with 900 km total range, adjusting prior brand strategy **Planned SOP before 2030**
NIO	11/24 - Announcing new EREV models under their Firefly brand for Middle east, North Africa and Europe **Planned SOP 2026**
PENG	11/24 - Announcing new EREV model with 1,400 km total range & 430 km pure electric and 5C charging rate **Planned SOP H2/2025**
ZEEKR	08/24 - Announcing new EREV models featuring a new electric-hybrid powertrain technology **Planned SOP H2/2025**
xiaomi	09/24 - A leaked document of Bosch showing an EREV model - SUV with codename N3 **Planned SOP 2026**
AVATR	05/24 - Announcing new EREV models with CATL battery (39 kWh) - total range 1,150 km & 245 km pure electric **Planned SOP 2026**
STELLANTIS	11/24 - **Launching large models** under the STLA Frame platform with 1,100 km range

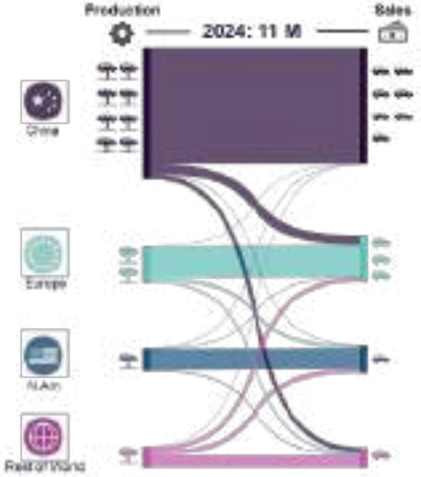
Source: Hyundai, Nio, Peng, Zeekr, Xiaomi, Avatr, Stellantis

EU Hikes Tariffs On Chinese-made BEVs

New tariffs are impacting Chinese EV exports to the EU, encouraging localisation in the long term but hindering EV adoption in the short term, although some manufacturers are absorbing the cost increase.

SOME MANUFACTURERS HIT WITH ALMOST 45% TARIFFS[1]

35% of DOMESTIC BEVS ARE IMPORTED, AND EUROPE IS THE TOP DESTINATION FOR CHINESE BEV EXPORTS[2]



Source: [1] Content & analysis provided courtesy of Rho Motion (Distinguished Partner), [2] CRU Group (Distinguished Partner)

Chinese OEMs’ Responses To Additional EU BEV Tariffs

BYD – Szeged, Hungary

Production to start H2 2025

SAIC – Galicia, Spain

Said to be considering establishing a plant in Spain, which aims to start production in 2027. The OEM is also said to be considering Hungary and Czechia.

Chery – Barcelona, Spain

Chery will begin production in Spain before the end of 2024. The capacity of 150,000 does not meet Chery’s long-term ambition, the OEM is looking for a second European site.

Geely

Will utilise Volvo, LEVC, and Lotus factories to appropriately arrange production capacity for EU region.

Leapmotor – Tychy, Poland

Started assembly of the T03 at a Stellantis facility.

Kia – Žilina, Slovakia

The EV5 is currently produced in China; however, production is set to begin in Slovakia from 2025

Xiaopeng Motor

Currently looking for a production site in Europe.

NIO

Will consider a European plant if annual sales in the region reach 100,000.

Potential opportunities to circumvent the tariffs

SAIC is considering importing BEVs from Thailand, where is currently produces the MG-4.

Issues with this strategy

For the vehicle to count as Thai, 40% of its components must be local to meet the product origin requirements. The exact tariff on Thai made vehicles entering Europe is unknown given the lack of precedent and trade agreement, although SAIC said it expects a tariff of 10-20%.

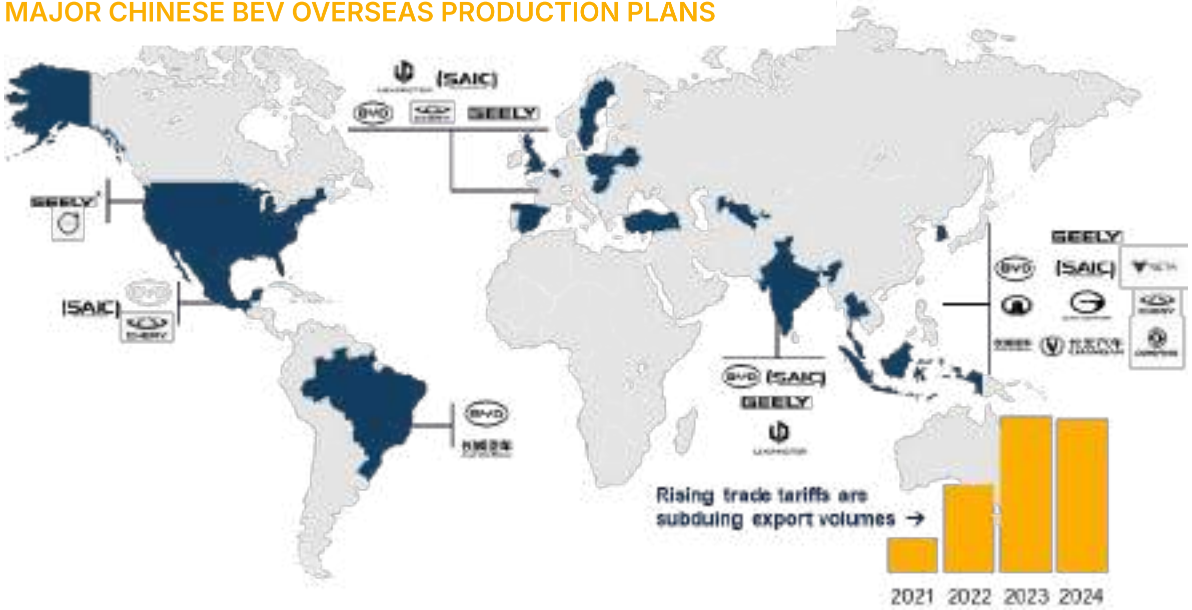
Other OEMs that could pursue a similar strategy

TESLA HONDA Great Wall

Content & analysis provided courtesy of Rho Motion (Distinguished Partner). For more information, visit https://rhomotion.com/research/ev-production-quarterly-outlook/.

Chinese Automakers Expand Into Europe And The Global South

MAJOR CHINESE BEV OVERSEAS PRODUCTION PLANS

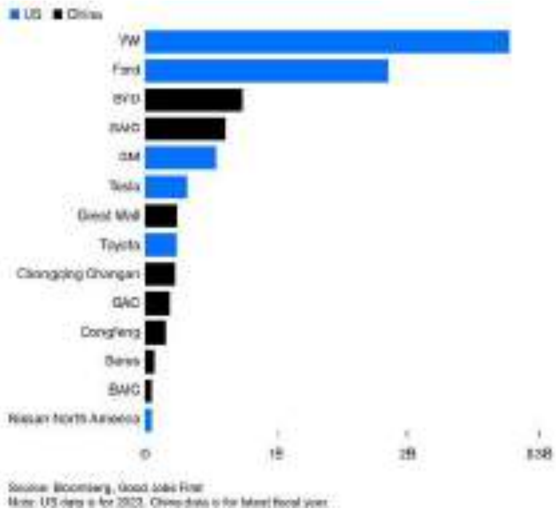


- Chinese companies are expediting global expansion and leveraging their cost advantages
- Domestic competition and foreign trade policies are prompting them to **build overseas**, despite the higher costs of production and supply chain procurement
- Europe has welcomed localization but US has, generally speaking, been against Chinese entry
- Chinese OEMs are therefore focusing on 'Global South' and third countries, such as Hungary, Mexico, Brazil, South East Asia

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). Not an exhaustive list. Includes kit production. *Geely's presence in the US is through its ownership of the Volvo brand, owned by Geely Group. BYD postponed plans its plans in Mexico in September 2024.

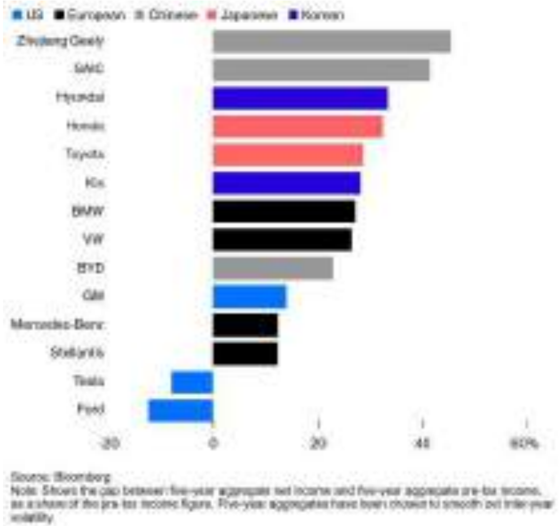
China’s Subsidies For EV Companies Have Been Scaled Back

DECLARED SUBSIDIES TO CHINESE AUTOMAKERS ARE DWARFED BY SOME OF THOSE ELSEWHERE



Source: Bloomberg, Good Jobs First
Note: US data is for 2023. China data is for latest fiscal year.

CHINESE AUTOMAKERS PAY RELATIVELY STANDARD TAX RATES



Source: Bloomberg
Note: Shows the gap between five-year aggregate net income and five-year aggregate pre-tax income, as a share of the pre-tax income figure. Five-year aggregates have been chosen to smooth out inter-year volatility.

MAJOR CHINESE AUTOMAKERS DON’T HAVE THE PRIVILEGE OF UNIQUELY CHEAP FUNDS

Data	WACC	Weight of debt	Cost of debt	Cost of equity
Kia	15.7%	4.6%	2.85%	20.9
Tesla	12.8	1.5	4.76	12.9
BYD	**10.9**	**6.6**	**1.99**	**11.6**
Hyundai	9.3	69.7	3.13	21.7
Toyota	9.1	45.9	6.57	14.8
Ford	7.3	79.2	6.26	11.4
GM	7.3	72.2	5.38	11.2
Geely	**6.8**	**45.9**	**1.99**	**10.9**
Honda	5.5	57.1	5.67	12.0
BMW	5.3	64.8	2.32	10.8
Mercedes	5.2	66.0	3.06	10.9
SAIC	**5.1**	**61.4**	**1.82**	**10.3**
VW	4.1	79.7	2.63	12.4

Source: Bloomberg
Note: WACC=weighted average cost of capital

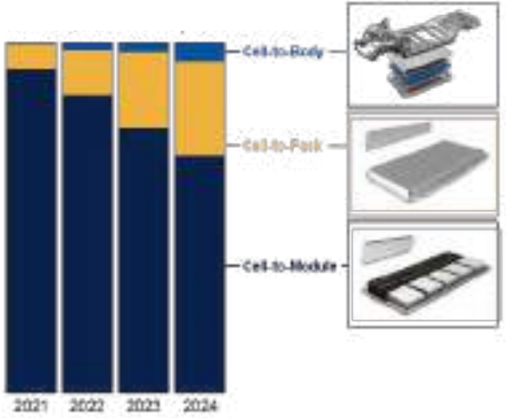
For more on policy, see Policy Section.
Source: Bloomberg News

Automakers Accelerate Plans For Module-Less Pack Architecture

- Cell-to-Pack and Cell-to-Body configurations offer benefits of increased energy density, less weight, and less component cost
- They are often in combination with large-format cells
- The improved pack-level energy density has enabled LFP's suitability in the largest vehicles
- There are technical and end-of-life challenges to be managed, but cost reduction reduction has taken priority

CELL-TO-PACK DESIGNS ARE TAILORED TO SPECIFIC VEHICLE PLATFORMS[1]

SHARE OF CELL INTEGRATION ARCHITECTURE IN BEVs, % VEHICLES PRODUCED BASIS [2]



Source: Main content provided by [1] Roland Berger (Distinguished Partner), [2] CRU Group (Distinguished Partner)

Innovations In EV Battery Pack Architecture

SOLID STATE BATTERIES

NIO ET7 rolls out with **semi-solid state** battery.

Mercedes & Factorial form a partnership to develop SSBs.

QuantumScape starts **B sample production** of SSBs.

Honda unveils SSB **production line readiness**.

THERMAL MANAGEMENT

Aspen PyroThin - an **insulating material** designed to prevent heat & fire spread in packs. Used in GM Ultium platform & contracts with Toyota, Scania & Audi.

"Safety Reinforced Layer" a thin material between the cathode and current collector, increases electrical resistivity at elevated temperatures, preventing shorts and potential fires.

MANUFACTURING INNOVATIONS

Revolutionizes **cell manufacturing with 3D printing**, producing custom-shaped, high-performance SSBs while eliminating wet processes for speed and scale.

Powder-to-electrode - directly applies dry electrode powder to current collectors using advanced spray technology.

Electrode-to-pack - integrating electrodes directly into the battery pack, bypassing conventional cell and module assembly.

MODULARITY & MATERIAL INNOVATIONS

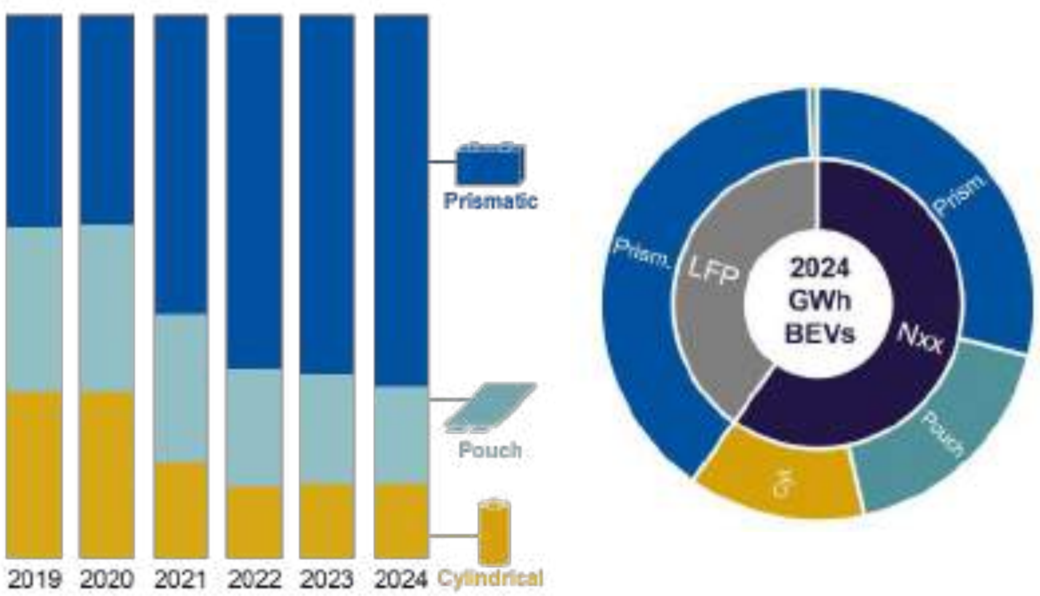
Xerotech Hibernium - Scalable modules made with 21700 cells. **678 different packs** made with identical modules that come in only **6 different sizes.**

Impervio separator prevents dendrite formation inside the cell further enhancing safety.

Woven composites are advancing enclosures, with companies like Asahi Kasei & SABIC working on materials that enhance thermal runaway protection & integrating built-in cooling channels.

Cell Formats - BEV Market Trending Towards Large-Format Cells, Primarily Prismatic

SHARE OF CELL FORMATS IN BEVs, % GWh BASIS



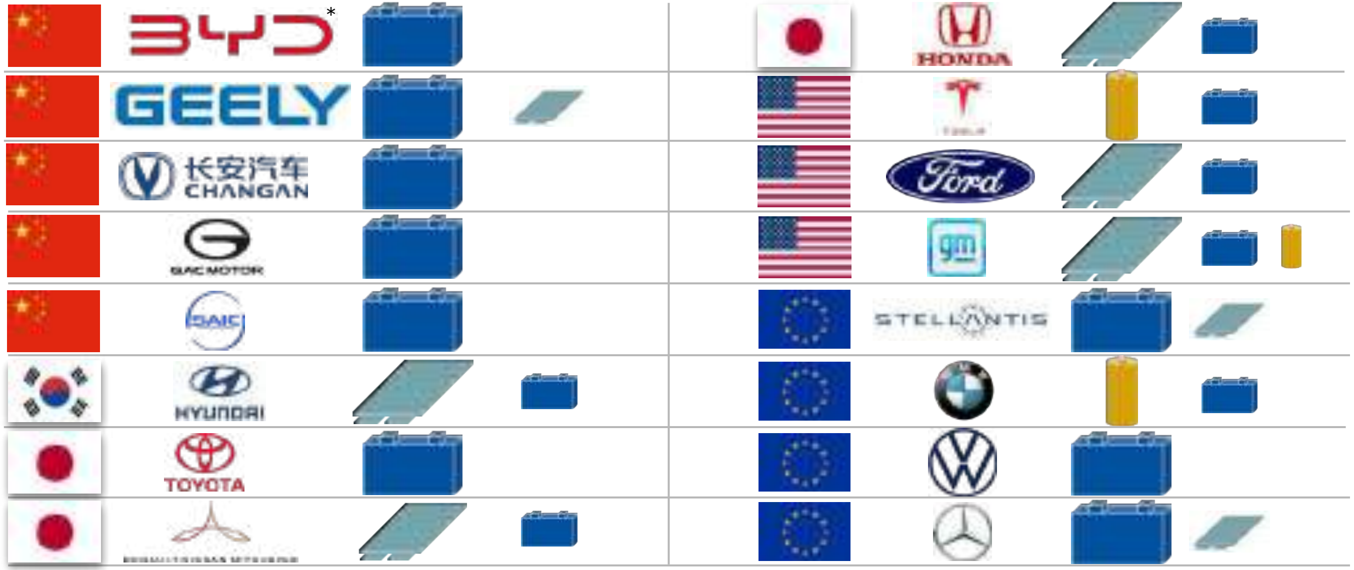
- Cell format is influenced by chemistry and vice versa - LFP is driving trend towards prismatic
- Prismatic is virtually the only format shared between both chemistries today
- Chinese manufacturers are the market leaders and they prefer prismatic - middle-of-the-road solution between the energy density of pouch vs. mechanical robustness of cylindrical

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Note: 'Nxx' includes NMC and derivatives

Cell Formats By Battery Manufacturers Trending Towards Prismatic And Primary Contributors From Asia

Sources for primary form factors: Added to company icons
Sources for secondary form factors:: CATL, CALB, Sunwoda, LGES, Toshiba, Gotion High Tech, Envision
Large and small icons denote primary and secondary cell preference respectively.
*Prismatic cell icon used as best fit for blade battery representation

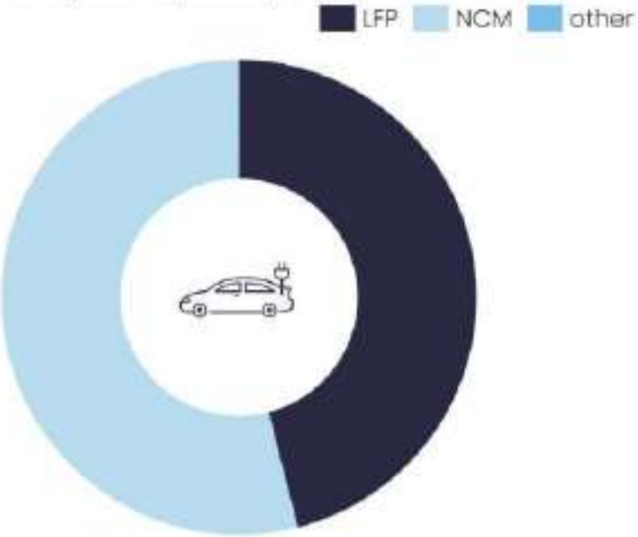
Cell Formats By Vehicle Manufacturers Similar Trend As Battery Makers With More Distributed Market



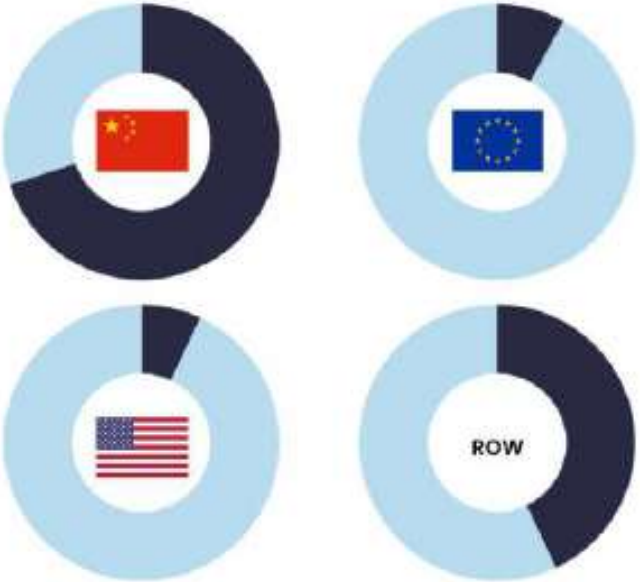
Sources for primary form factors: Added to company icons
Sources for secondary form factors: Geely, Hyundai, Renault Nissan Mitsubishi, Honda, Tesla, Ford, GM, Stellantis, BMW, Mercedes-Benz
Large and small icons denote primary and secondary cell preference respectively.
∗Prismatic cell icon used as best fit for blade battery representation

Chemistry Varies Significantly By Application And Region

2024 CHEMISTRY SHARE BY MARKET, EV



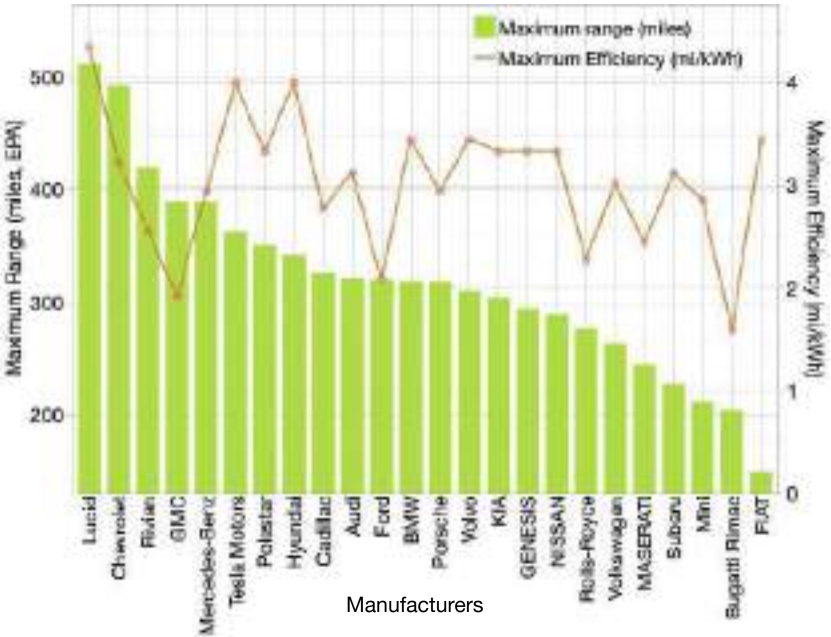
2024 CHEMISTRY SHARE BY REGION



Content & analysis provided courtesy of Rho Motion (Distinguished Partner). For more information, visit https://rhomotion.com/research/ev-production-quarterly-outlook/. Showing chemistry share on a sales basis in end-use demand.

Range And Efficiency Trends In US Market

EV MY2025 Max EPA Range and Efficiency by OEM in US



RANGE

- The longest EPA-certified range for an EV is the Lucid Air sedan, rated at 516 miles per charge.
- For the 2025 model year, the median range of all-electric vehicles (EVs) hit a record 283 miles per charge, an increase of 13 miles from the previous year and over four times the median range of 2011 models.

EFFICIENCY

- For the 2025 model year, EPA-rated combined city/highway consumption ranged from 1.49 to 4.17 miles per kilowatt-hour (mi/kWh).
- Miles per kilowatt-hour (mi/kWh) are based on the EPA combined city/highway rating.

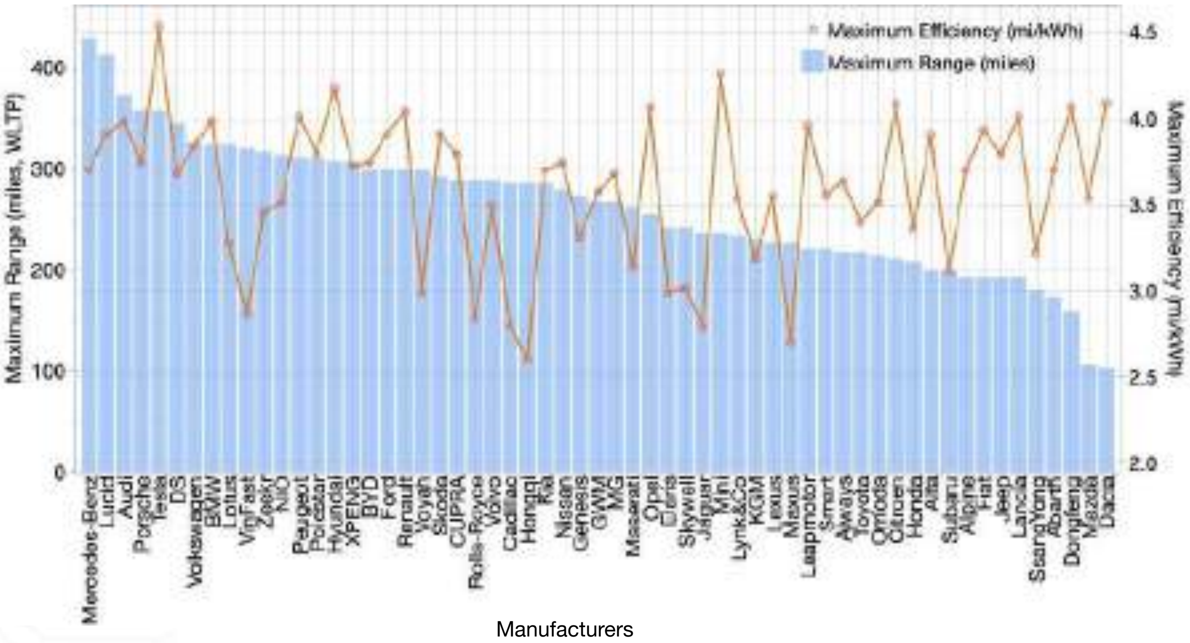
NOTE

This page's range and efficiency values are estimated by **the US Environmental Protection Agency (EPA) method** and cannot be directly compared with the WLTP and CLTC values in the following pages.

Source: EPA

Range And Efficiency Trends In EU Market

EV MY2025 Max WLTP Range and Efficiency by OEM in Europe



Source: EV database

RANGE

- The longest range for an EV is the Mercedes Benz EQS 450+ SUV, claimed at 690 kilometers (equivalent to 429 miles) per charge

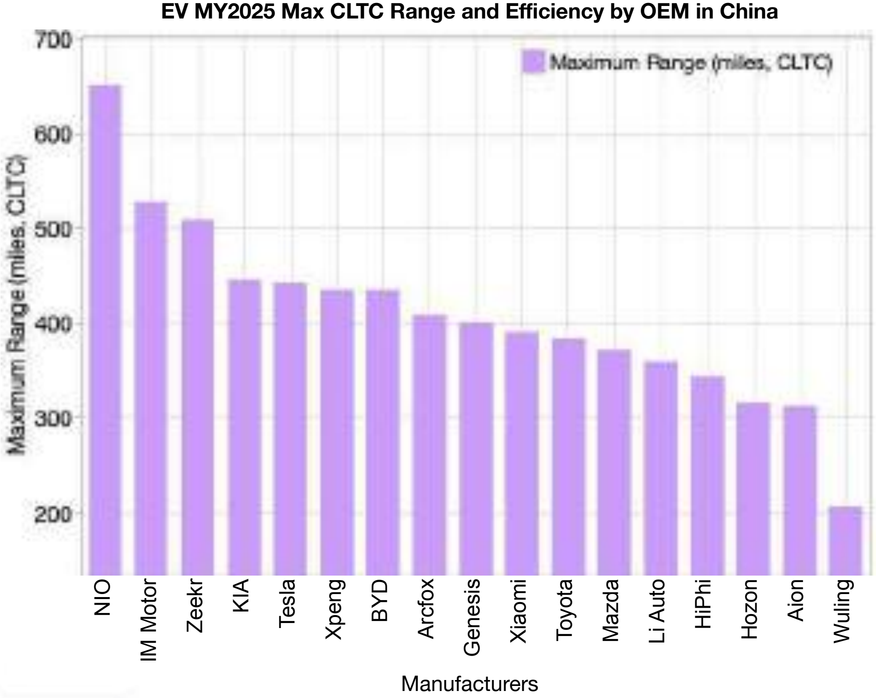
EFFICIENCY

- OEMs in EU market claimed for efficiencies between 1.93 to 4.54 miles per kilowatt-hour (mi/kWh)
- Tesla's Model 3 showed the highest efficiency of 4.54 mi/kWh

NOTE

Displayed range and efficiency values are based on **Worldwide Harmonised Light Vehicle Test Procedure (WLTP)** and not intended for direct comparison with US EPA-certified and CLTC range and efficiency values. However, the original values are converted from kilometers (km) to miles (mi) for consistency.

Range Trends In China Market



Source: Manufacturer's websites and media (data compilation)

RANGE

- NIO ET7 has CLTC-certified range of 1050 kilometers (equivalent to 652 miles) per charge for the model year 2025 and ranked as the longest range.
- ET7's 150kW battery introduces semi-solid-state to the market
- EREVs (Extended Range EVs) are rapidly growing powertrain technology in China. This hybrid system is operated by electric power as regular BEVs with a small ICE present to recharge the battery. Such system often greatly boosts the single-charge driving range with smaller battery size **(Electrek)**

NOTE

- OEM coverage: This page focused on introducing Chinese OEMs and does not cover all electric vehicles available in the Chinese market
- Displayed range and efficiency values are based on **CLTC (China Light-Duty Vehicle Test Cycle)** and not intended for direct comparison with US EPA and WLTP range and efficiency values. However, the original values are converted from kilometers (km) to miles (mi) for consistency

Fast Charging Trends - North America

The metric used to assess fast charging performance is range added in 10 and 20 min of fast charging. The number of vehicles that can add >200 mi in 20 min is lower than their competitors from EU and especially China (see next slide).

EPA Range added after 10 min and 20 min of DC Fast Charging

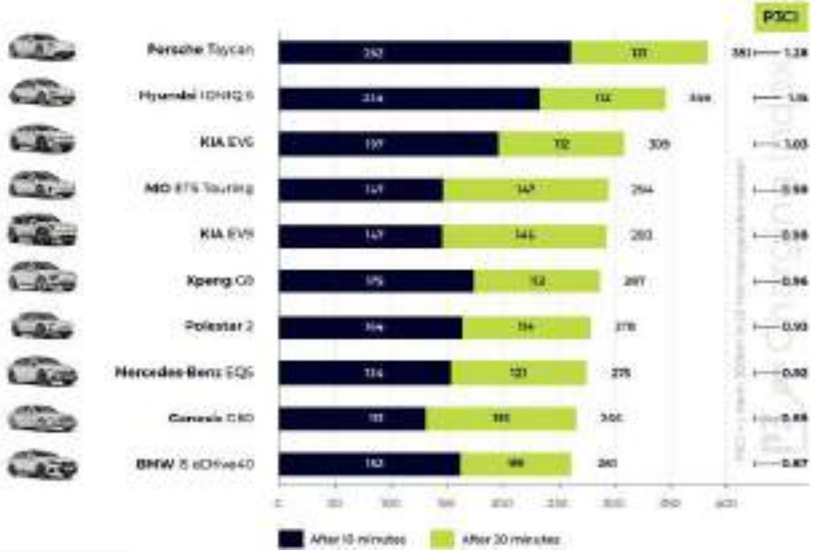
Definitions: P3CI - US = Real recharged range within 20 minutes/ 200 mi

Source: P3 Charging Index, June 2023

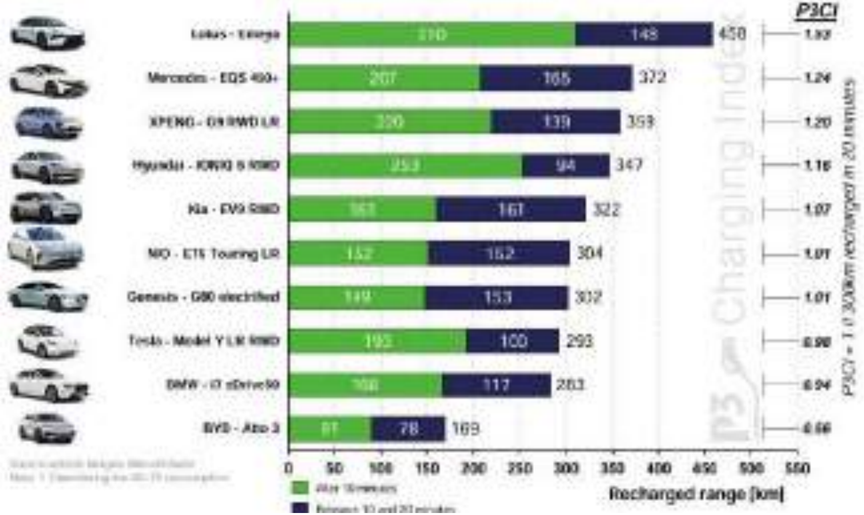
Fast Charging Trends - Europe And Asia

The metric used to assess fast charging performance is range added in 10 and 20 min of fast charging. The number of vehicles that can add >300 km in 20 min is higher in China than in Europe.

EUROPE



CHINA

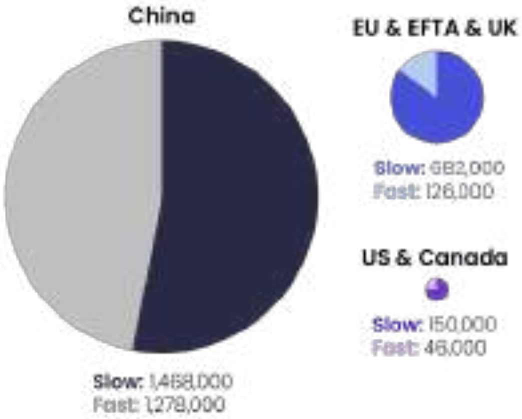


Source: P3 Charging Index 2024, P3 Charging Index - Asia 2024

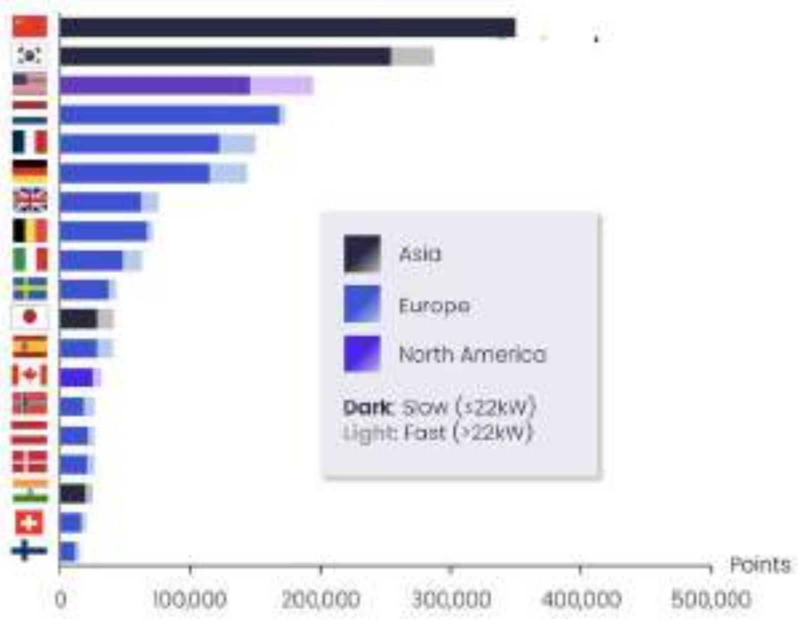
More Fast DC Chargers Installed, With China Leading Installations

China continues to roll out public charging infrastructure at a fast rate, with over 3.26 million charge points installed by November 2024. Approximately 47% of these are fast DC chargers

There is an overall trend across countries to faster DC speeds. This shift is primarily driven by falling costs, higher demand for high-speed charging, and increased profit potential.



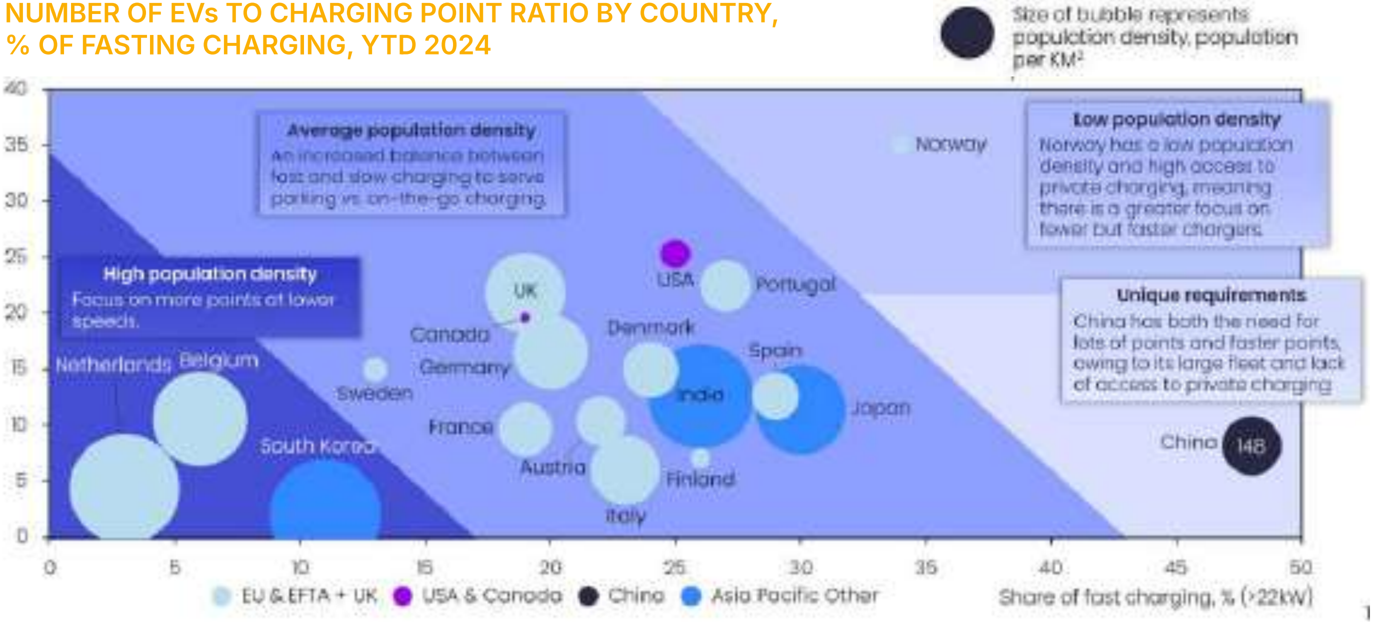
ACCUMULATED PUBLIC CHARGE POINTS BY COUNTRY - NOVEMBER 2024



Content & analysis provided courtesy of Rho Motion (Distinguished Partner). For more information, visit https://rhomotion.com/research/ev-production-quarterly-outlook/.

Balance Of Fast And Slow Charging Infrastructure Vary By Country

NUMBER OF EVs TO CHARGING POINT RATIO BY COUNTRY,
% OF FASTING CHARGING, YTD 2024



Size of bubble represents population density, population per KM²

Average population density
An increased balance between fast and slow charging to serve parking vs. on-the-go charging

High population density
Focus on more points at lower speeds.

Low population density
Norway has a low population density and high access to private charging, meaning there is a greater focus on fewer but faster chargers

Unique requirements
China has both the need for lots of points and faster points, owing to its large fleet and lack of access to private charging

Source: Content & analysis provided courtesy of Rho Motion (Distinguished Partner). For more information, visit https://rhomotion.com/research/ev-charging-quarterly-outlook/.

Penetration Of Artificial Intelligence In EV Value Chain

A notable trend in 2024 has been the penetration of AI across the entire value chain of a Lithium ion Battery

CELL MATERIALS DISCOVERY	**AI models** screen thousands of potential combinations & helps predict material properties at the atomic scale, thereby aiding discovery of **novel materials** for electrolytes, electrodes and separators
ACCELERATED TESTING	AI accelerates testing protocols by **simulating electrochemical reactions** in different material compositions, reducing reliance on time intensive physical experiments
MANUFACTURING PROCESS OPTIMIZATION	AI used to optimize electrode **coating & drying process**, which may reduce time taken for cell 'formation' exponentially
BATTERY LIFETIME PREDICTION	AI models used to predict battery aging. A **study** by Stanford Energy demonstrates a 9.1% error in life prediction using the first 100 cycles; applied on a set of 124 LFP cells with life range of 150-2300 cycles
FLEET DATA ANALYSIS	AI has been used for **fleet analytics** to optimize performance and to help uncover key stress factors affecting battery health. AI can also detect anomalies in battery packs thus preventing untimely aging

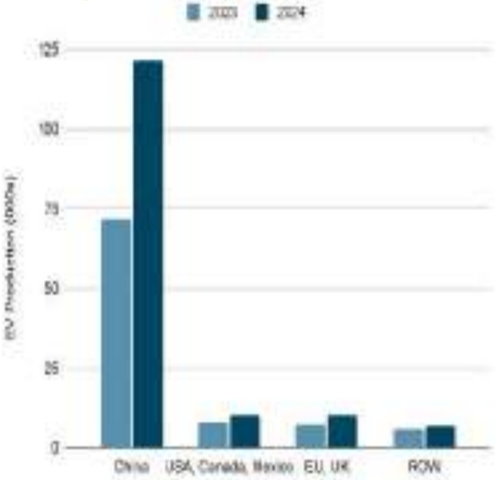
CHEMIX
Microsoft Azure Quantum Elements
DeepMind
QuantumScape
JCESR
camLine
CATL
Panasonic
Microsoft
Stanford ENERGY
TESLA
MONOLITH
Coulomb AI
AIONICS
ELECTRA

Source: Company Announcements

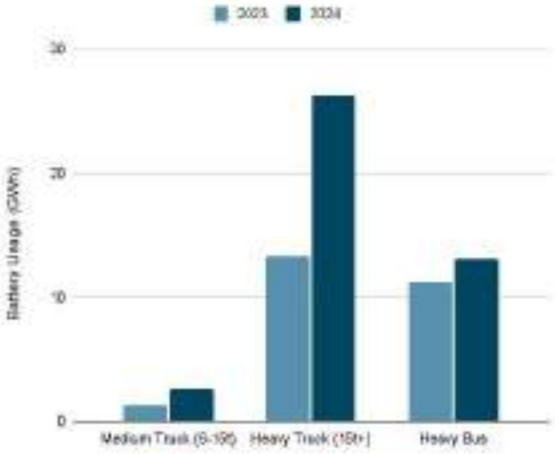
Heavy Mobility Market Developments - Market Size & Demand Growth

- Global electric truck and bus production (>6t GVW) increased 56,000 units in 2024, from 94,000 units in 2023. The 60% increase was despite total vehicle production falling 167,000 units
- China accounted for the majority of volume and growth, increasing by 49,700 units, 69% in 2024
- Stringent CO^2 and GHG legislation in Europe, US and China, alongside falling TCO for heavy EVs, will see over 767,000 units produced in 2030
- Total battery demand in 2024 is estimated at 42 GWh, up from 26 GWh in 2023, excluding spares for swappable batteries swapping in China

HEAVY VEHICLE EV PRODUCTION 2023/2024



HEAVY VEHICLE GWH BATTERY USAGE 2023/2024

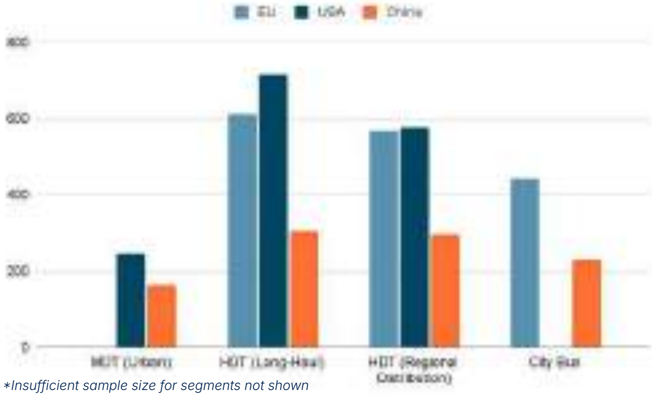


Source: KGP-GlobalData Global Commercial Vehicle Powertrain Forecast Q4 2024. EV Includes Battery Electric and Fuel Cell vehicles >6t GVW

Heavy Mobility Key Players - Battery Solutions & Partnerships

- In 2024, Heavy Truck EV batteries averaged 297 kWh, Medium Trucks averaged 222 kWh, and Heavy Bus averaged 254kWh
- LFP is the dominant chemistry as OEMs prioritise cycle life and cost
- Technology development will see battery life extending to over 1.6M miles
- CATL, which dominates the global market, announced its new TECTRANS LFP battery in 2024
- Other significant suppliers including Samsung SDI, Gotion and EVE. Notably in 2027 the new JV between Daimler Truck, Paccar, Accelera and EVE, Amplify Cell Technologies, will start production at its new 21 GWh plant in Mississippi, USA

AVERAGE BATTERY SIZES BY END USE 2024



**Insufficient sample size for segments not shown*

CATL TECTRANS

- Durability up to 2.8m km (1.9m miles)
- Charging up to 4C (70% SOC in 15 mins)
- Range up to 500km

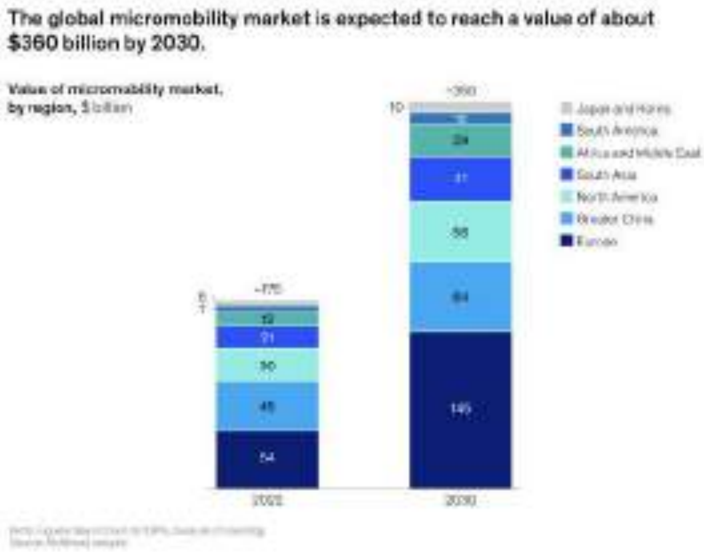
AMPLIFY CELL TECHNOLOGIES

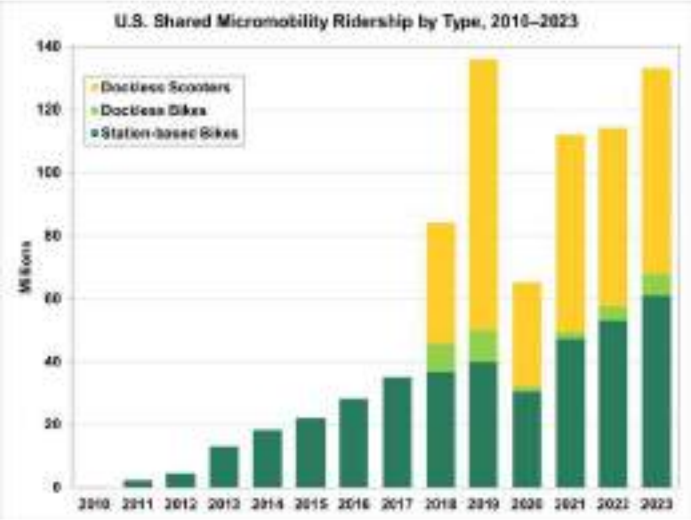
- Joint-venture between Daimler Truck (30%), PACCAR (30%), Accelera (30%) and EVE (10%)
- 21GWh capacity plant to start production in 2027

Source: KGP xEV Model Database November 2024

Micro-Mobility Market Size & Demand Growth

The micro-mobility market growth is mostly **driven by e-bike sales**. **McKinsey**[1] estimates that the global micro-mobility market will reach about $360 billion by 2030, up from about $175 billion in 2022, with Europe sharing most of that value. The US has also seen record high demand, driven by ample incentive programs [2]. Safety issues continue to be grappled with, spurring regulation [3,4].

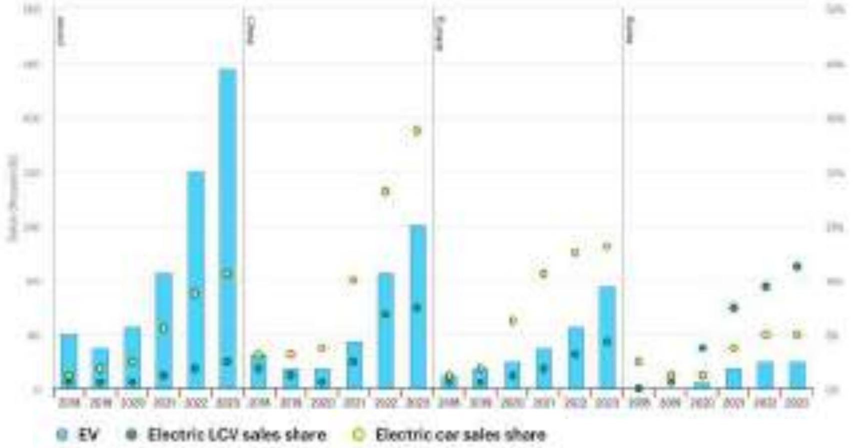




Source: [1] McKinsey, [2] US DOE, [3] NYFD, [4] Safety Bulletin

Light Commercial Vehicles Market Size

ELECTRIC LIGHT COMMERCIAL VEHICLE SALES AND SALES SHARES, 2018-2023*



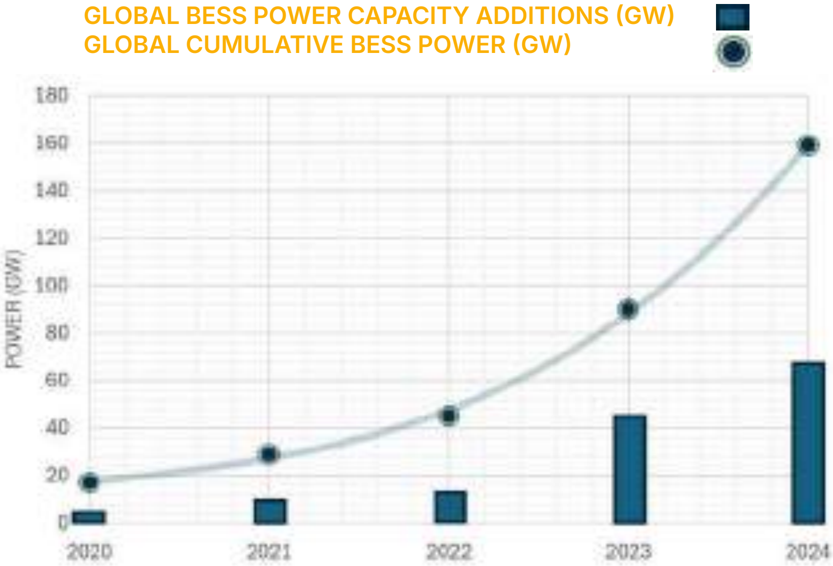
*EV = electric vehicle; LCV = light commercial vehicle where weight is less than 3.5 tonnes.
In China, LCVs include small-sized buses, some light-duty trucks and mini trucks.
Latest available dataset until 2023

Source: IEA

1 INDUSTRY

Global BESS Deployments Soar

The "[Decade of Energy Storage](#)" continues to exceed expectations, with **69 GW / 169 GWh** of new Battery Energy Storage Systems (BESS) installed in 2024. This brought cumulative global BESS capacity to **150 GW / 363 GWh**, led by Li-ion batteries which represented over **98%** of battery installations in 2024.



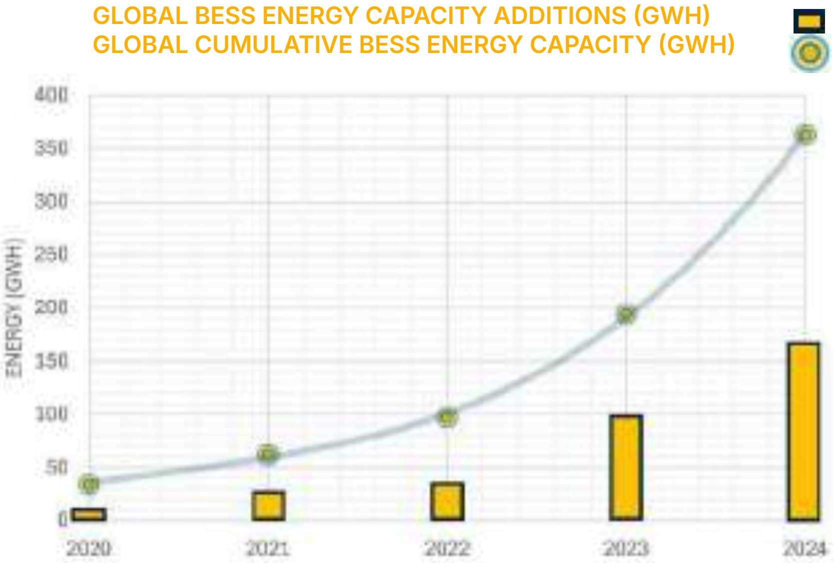
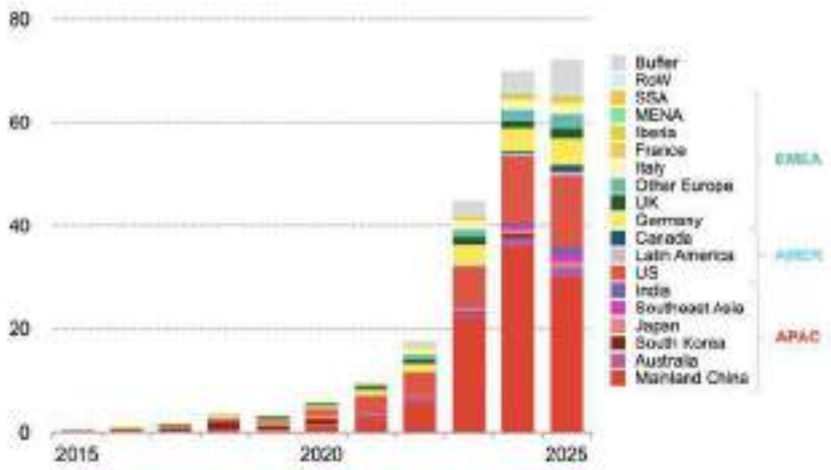


Chart sources: Compiled by PowerSwitch, based on publicly available data from BNEF and Woodmac: 2020 (Cumulative), 2020, 2021, 2022, 2023, 2024
Li-ion fraction: Rho Motion (via Energy Storage News)

Growth In BESS Power Additions Last Year Exceeded 55% YoY

GLOBAL ADDITIONS BESS POWER (GW)



- 2024 global BESS deployments of 69GW represent a **55% increase** from 2023 deployments on a power basis
- Battery projects are surging around the globe, but dominated by a few key countries / regions: China (36GW), US(13GW), Europe(10GW) and Australia (2GW)
- The Economist called grid-scale storage the "**fastest-growing energy technology**" in 2024
- The 2020s have continued to meet expectations that this will be the **decade of energy storage**

BloombergNEF Source: Main content provided by BloombergNEF (Distinguished Partner).

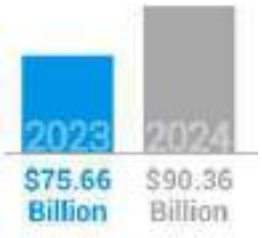
BESS Share Of Battery Demand Has Doubled Since 2020

A GROWING BATTERY SEGMENT

SHARE OF BESS OF OVERALL BATTERY MARKET

- BESS deployments have grown more quickly than the battery industry as a whole
- BESS now make up 15% of total battery deployments, up from 7% in 2020
- Primary drivers in the surge are **falling battery costs**, **government policy incentives**, and **a massive uptick in investments** in BESS technology and projects

VALUE OF BESS MARKET



- In 2024 the value of the BESS market grew by over 20% year-over-year to **$90B**
- The utility-scale market comprises over 85% of this market, with the remainder divided between residential and commercial and industrial (C&I) installations
- Li-ion is the market leader with **over 98% of grid-scale BESS deployments** in 2024
- Li-ion **expected to overtake** pumped hydro in terms of power capacity in 2025
- Utility markets drive approximately 87% of the demand

Source: Main content provided by Rho Motion (Distinguished Partner)

China And US Markets Lead In BESS Deployments

The US and China are the clear leaders when it comes to BESS deployment:

- Collectively these two markets account for approximately **70%** of all BESS projects in 2024, on a power basis
- Mainland China's BESS installations were the clear market leader in 2024. They added **36 GW / 84 GWh** for full-year 2024, up **64% on a GW-basis from 2023**
- U.S. energy storage deployments across all segments are **expected to reach** 13 GW / 41 GWh for full-year 2024, up 72% on a GW-basis from 2023

BloombergNEF Source: Data provided by BloombergNEF (Distinguished Partner).

Leaderboard - BESS Installations In The World by Interconnection Power

- Individual BESS installations are growing ever larger - as of November 2024, the largest operational BESS is the Edwards & Sanborn BESS in California, at 821 MW / 3,280 MWh
- Many systems are built in several phases, adjacent to one another, under separate interconnection applications
- While China leads the US in deployed BESS capacity, the US leads in construction of large individual projects, with 9 of the world's 11 operational projects greater than 300MW
- Currently there are multiple projects in development that expect to break the 1 GW barrier, but no system of this size has yet become operational

OPERATIONAL BESS PROJECTS (MW / MWH) AS OF NOVEMBER 2024

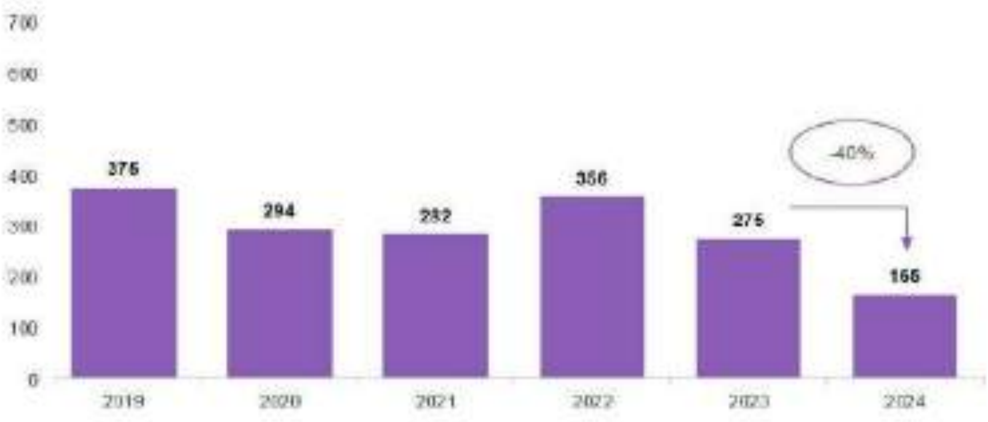
Source: PowerSwitch, based on publicly available data from project developers..

Storage Costs Fell Significantly In 2024

- One of the biggest drivers in today's storage market are the rapidly falling costs of batteries
- Costs have fallen dramatically - according to BNEF cost per kWh fell on average to **$165/kWh** in 2024, **down 40% YoY from 2023,** and less than half of the 2019 value
- In China, costs are falling even farther - a **December 2024 bid for 16 GWh** of battery enclosures + PCS in China had an average price of **$66/kWh**
- An uptick in prices in 2022 was driven by constrained supply, high Lithium prices and lingering pandemic supply chain issues

COST OF BATTERY ENCLOSURE + PCS[1]

$/kWh in 2024 Real Dollars



BloombergNEF

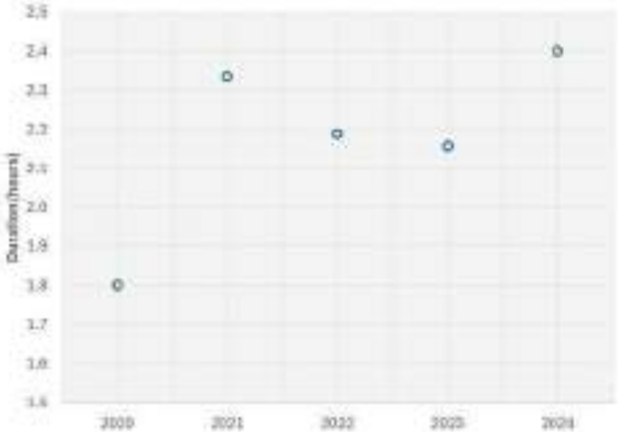
Source: Includes content from BloombergNEF (Distinguished Partner).

[1] This pricing is based on unit of usable energy capacity, including DC-block battery enclosures and power conversion system (PCS), but exclusive of EPC and grid connection costs.

Average Project Duration Continues To Rise

AVERAGE BESS DURATION (HOURS) BY REGION[1]

GLOBAL AVERAGE PROJECT DURATION (HOURS)[2]



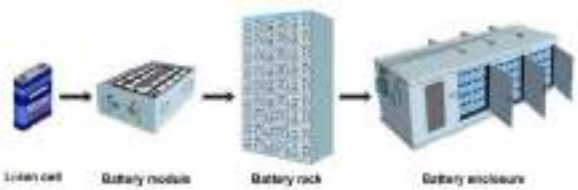
- Storage **duration** is defined as the time to discharge a battery's rated energy at its rated power - **C-Rate** is the inverse of duration
- Average duration of BESS Projects has increased **33%** from **1.8 hours in 2020** to **2.4 hours in 2024**
- This is driven primarily by the shift from **NMC** to **LFP chemistry**, as well the declining cost of energy storage on per-kWh-basis, as based on growing use cases and markets that favor longer duration with derating factors

rho motion
A BENCHMARK COMPANY

Sources: [1] Rho Motion as discussed in Energy Storage News ; [2] Compiled by PowerSwitch, based on publicly available data from BNEF and Wood Mackenzie: 2020 (Cumulative), 2020, 2021, 2022, 2023, 2024

Key Players In BESS Cell And Integrated System

BESS projects are built up from cell to module to rack to integrated enclosure. A major trend in 2024 was cell manufacturers moving up the value chain to offer integrated systems, often competing with the integrators who use the same cells. This slide shows the leading cell manufacturers and integrators. Some companies that are both cell manufacturers and system integrators use both their own cells as well as those from other cell manufacturers.



PLAYERS THAT ARE BOTH BESS CELL MANUFACTURERS AND SYSTEM INTEGRATORS

- AESC
- eos
- CATL
- saft
- Narada
- BYD
- HTHIUM
- ESS INC
- Form energy
- Gotion
- EVE Energy
- INVINITY ENERGY SYSTEMS
- REPT
- TrinaStorage
- CALB
- SAMSUNG SDI
- LG Energy Solution
- GREAT POWER

BESS SYSTEM INTEGRATORS

- AESI
- CLOU
- 中国中车 CRRC
- ENERGY VAULT
- e-STORAGE
- EVLO
- FLEXGEN
- FLUENCE
- HUAWEI
- HYOSUNG
- HYPER STRONG
- KEHUA TECH
- NHOA ENERGY
- POWIN
- PREVALON
- RelyEZ
- risenstorage
- WÄRTSILÄ
- TESLA
- SERMATEC
- SUNGROW

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

acciona
aes
AREVIA POWER
AVANTUS
AXIUM
aypa
Brookfield
Clēnera
EDF renewables
enel
GRIDSTOR
Hecate Energy
Invenergy
akaysha
Intersect Power
KEY CAPTURE ENERGY
NEXTera ENERGY
NRSTOR
Ørsted
PINEGATE
PLUS POWER
RECURRENT ENERGY
REV
RWE
SB Energy
spearmint energy
STELLAR
STRATA CLEAN ENERGY
VISTRA ENERGY

DEVELOPERS IN EUROPE AND LATIN AMERICA

Alcemi
AURA POWER
ENGIE
BW ESS
Grenergy
GIGA Storage
STATERA
frv
S4 ENERGY
HARMONY ENERGY
Zelestra
tagenergy
ZENOBĒ

DEVELOPERS IN ASIA AND AFRICA

ACWA POWER
中国南方电网
JSW Energy
中国三峡
GLOBELEQ
INFINITY POWER
Reliance
Scatec
MASDAR
Terra Solar
TATA POWER

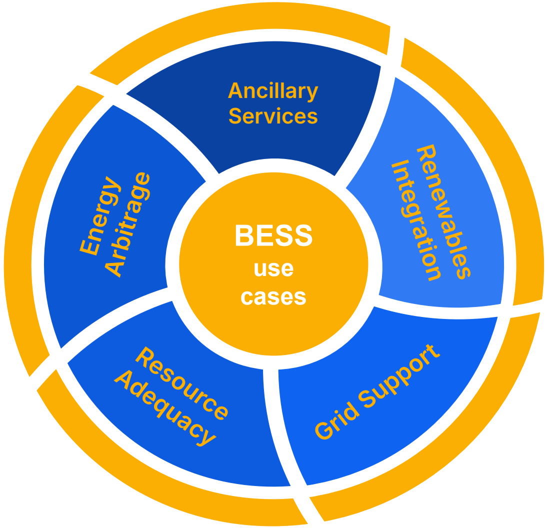
DEVELOPERS IN AUSTRALIA

akaysha
amp
EQUIS
enel
lightsource bp
NEOEN
res

Summary Of BESS Use Cases

BESS projects are versatile assets that can provide a vast array of uses to any power grid ("grid-following"), or by generating their own grid ("grid-forming") either to off-grid locations or to grid-connected locations choosing to island from the main grid. While BESS projects enable deeper penetration of renewable energy on a grid, there are five leading use-cases that account for most of the revenue earned by a project:

- **Ancillary Services:** A range of services used to help maintain grid stability, such as frequency response.
- **Renewables Integration:** Helps ensure an efficient use of energy produced from renewables
- **Grid Support:** Managing transmission and distribution network constraints
- **Resource Adequacy:** Providing power capacity that can be deployed in peak demand periods to ease strain on grids
- **Energy Arbitrage:** Storing energy when prices are low and selling it when prices are high, maximizing profits



0-10 hours ① **Short duration:** Durations up to 10 hours

10-36 hours ② **Inter-day LDES:** Sometimes called "diurnal"

36-160 hours[1] ③ **Multi-day / week LDES:** Commonly called "seasonal"

160+ hours ④ **Seasonal shifting:** Generally included in "seasonal", but distinct in that this does function as a conventional, storable fuel

Source: Includes content from Roland Berger (Distinguished Partner).

Navigating Revenue Models - Contract vs. Merchant

BESS revenue models can be categorized as either contract-driven or merchant-driven, based on the operating strategy and risk tolerance. The choice is influenced by the energy market where the BESS operates, as well as market conditions, financial goals, and the investor's risk appetite. Regardless of the model, BESS systems offer the flexibility to provide multiple applications simultaneously, enabling operators to stack revenues from diverse sources and align revenue strategies with evolving market opportunities. Most systems built in 2024 used some combination of contract and merchant-driven revenue.

MECHANISM	CONTRACT-DRIVEN	MERCHANT-DRIVEN
Revenue Stability	Predictable income: long-term agreements with fixed rates	Variable income: earning fluctuate based on markets
Market Exposure	Limited exposure to price volatility	Fully exposed to market dynamics
Risk Level	Lower risk with guaranteed payments	Higher risk due to market fluctuations
Profit Potential	Consistent but lower returns	Potentially higher profits during favorable conditions
Key Revenue Streams	Tolling (fixed payments), Capacity, Energy Hedge	Energy Markets, Capacity Auctions, Ancillary Services
Investor Profile	Risk-averse investors prioritizing stability	Investors with higher risk tolerance, seeking higher returns

BESS Deployment Pathways

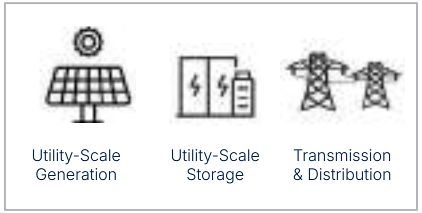
Based on their location **relative to the electrical meter** and their **role in the energy system**, BESS systems can be deployed in two ways:

- **Front-of-the-Meter (FTM):** connected to the transmission or distribution networks on the grid, or co-located with renewable energy generation
- **Behind-the-Meter (BTM):** installed behind the utility meter, typically owned/managed by and delivers energy to commercial, industrial, or residential consumers directly

BESS systems can also be deployed differently by **connection type**:

- **On-Grid:** connected to the main grid, support peak shaving and renewable integration, with growing demand driven by renewable energy expansion and grid resilience needs
- **Off-Grid:** independent of the main power grid, provide power in remote areas or as power backups, with trends toward increased adoption for rural electrification and sustainable energy solutions

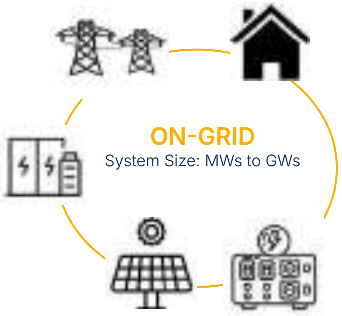
Note: Hybrid systems, capable of switching between on-grid and off-grid modes, are gaining traction in intermittent grid and renewable energy scenarios.



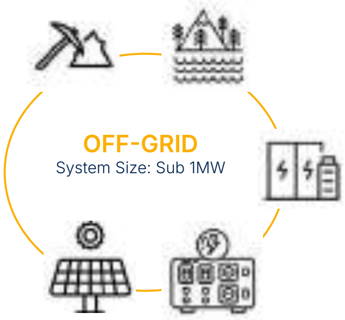
FRONT OF THE METER (FTM)
Market Share: 80%
System Size: MWs to GWs

VS.

BEHIND THE METER (BTM)
Market Share: 20%
System Size: 5kW to 10MW



VS.



Source: NREL, Symtech Solar and Cervicorn Consulting

ESS Technology Bankability - Degradation, Cycle-life And Product Warranties / Guarantees

- **Workmanship Warranties:** Most BESS Manufacturers, together with EPC contractors, offer a 'workmanship warranty' that covers a period following the system's reaching Commercial Operations Date (COD). Most commonly this warranty is valid for 1-3 years, covering initial defects and component failures (short-term).

- **Performance Guarantees:** Beyond COD, manufacturers typically offer **performance guarantees** for their systems under a separate **Long Term Service Agreement** (LTSA). These guarantees allow for a certain level of guaranteed degradation, verified by a capacity test, conducted annually. The most common terms for an LTSA are warranties:
  - 7,200 cycles over 20 years (equivalent to 1 cycle per day), although some manufacturers are offering warranties up to 10,000 cycles over 25 years
  - Typical degradation from 100% at COD to approximately 70% in year-20
  - Typical round-trip efficiencies
  - Guaranteed Availability of 97% or more, outside of the system's scheduled maintenance hours

- **Corrective Maintenance:** Most LTSAs do not cover corrective maintenance, which is the result of an unexpected event in the system's operations, although some contracts offer a higher-priced 'Extended Warranty' which does include a larger payment to account for corrective maintenance work.

- **Insurance Requirements:** Insurance is typical at several tiers of the project: manufacturers insure their expected degradation levels, EPC contractors hold insurance policies to cover for unforeseeable issues in construction, and projects transition to operational project insurance once the project has reached COD.

- **Bankability:** All of the above policies, warranties, and guarantees have become more standardized in the industry, resulting in greater confidence for finance of utility-scale energy storage projects; collectively this is a sign of the industry maturing and becoming more bankable.

Source: PowerSwitch, Norton Rose Fulbright, ACCURE, DNV, Energy Storage News

Utility-Scale BESS Products Converge Towards 20ft Enclosures With >5 MWh Capacity

BRAND	PRODUCT	DC CAPACITY (MWh)*	PRODUCT PIC
CATL	TENER	6.25	
FLUENCE	Gridstack Pro	5.6	
BYD	MC Cube T	6.4	
e-STORAGE	SolBank 3.0	5.0	
POWIN	Pod	5.0	
SUNGROW	PowerTitan 2.0	5.0	
WÄRTSILÄ	Quantum 3	5.0	
HYPER STRONG	HyperBlock III	5.0	

Standard Size, Ever-growing Capacity

- Early on the ESS industry had 40-foot containers; later this evolved to ‘cube’ products in 10-foot sizes, but the industry has now coalesced around a single size: the 20-foot shipping container

20ft (6m) Long x 8ft (2.4m) Wide x 8.5 ft (2.6m) High

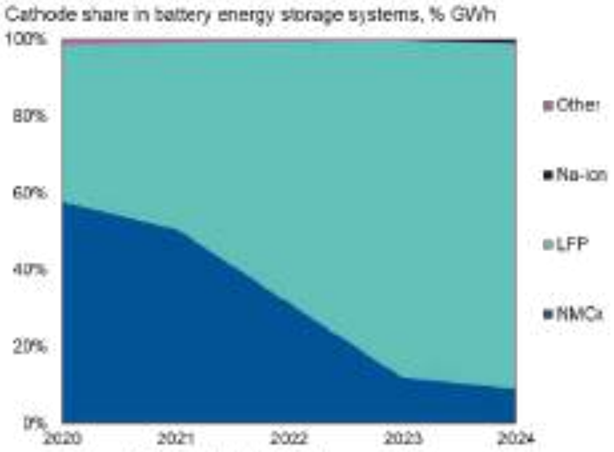
- Driven by safety concerns and ease of shipping, each container has gradually added more and more energy. Increasing energy density of the cells, larger format cells, and more efficient design have all contributed to this convergence. While some designs use traditional corrugated shipping containers, others have opted for proprietary enclosures.
- Nearly all enclosures feature integral liquid cooling, although some offer air-cooling as an alternative.
- The industry is still divided among products that feature integral PCS units in the enclosure (AC Block product) or those that require an external PCS (DC Block products). Notable leaders in AC Block are Tesla, Sungrow, and Wartsila.

*** DC rated capacity for each project is as reported by manufacturer. Products enclosures are based on 20-foot containers. All products are DC block, with the exception of the PowerTitan 2.0 and Quantum3.**

BESS Is Predominantly LFP-based, But Faces Limitations For Long Duration Applications

LEADING BESS CHEMISTRY

LFP has overtaken **NMC** as the dominant stationary storage chemistry, accounting for over 80% of ESS **today**



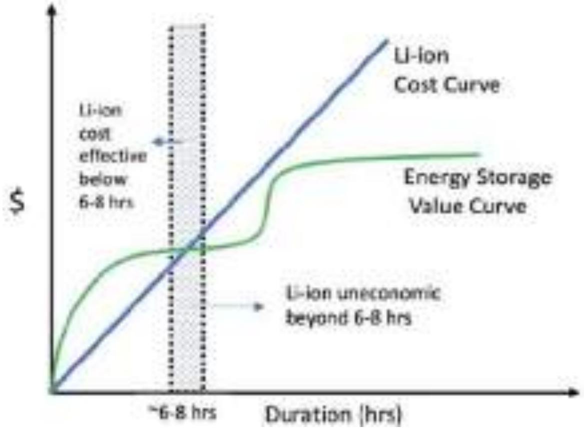
LIMITATIONS OF LI-BASED ESS FOR LONGER DURATIONS

Li-ion ESS is cost-effective for short durations in 2 use cases:

(1) Demand-supply matching from few seconds to 1 hr

(2) Energy arbitrage (i.e. buy energy/charge when it's cheap, sell/discharge during higher-price hours)

Li-ion is not cost effective past **8 hours** at current prices for either use case scenario, driving the investigation of alternative chemistries
*(see **LDES**)*



Source: Cathode chemistry chart from CRU Group (Distinguished Partner). cost effectiveness graphic from MCJ Newsletter.

Alternative Chemistries - Sodium-Ion, Iron Air And Flow Batteries

Although Li-ion occupies approximately 98% of the BESS market, there are several competing chemistries vying to become leaders based on improvements in cost, safety performance and duration. See more on these technologies in the **Non-lithium Chemistries** section.

SODIUM-ION (NA-ION)

Intended for 2-10 hour grid storage, residential storage, and lead-acid replacement

KEY 2024 DEVELOPMENTS:

- BYD launched a BESS long **blade Na-ion cell** (90 Wh/kg) for large-scale grid applications
- Hithium launched a **sodium-ion cell** specifically for utility-scale storage
- CATL announced a **combined Li-ion/ Na-ion battery cell**
- DOE **announced a $50m grant** to advance research in Na-ion battery cell technology

FLOW BATTERIES

Intended for ~6-24hr energy storage to stabilize grid & provide peak shifting/load shifting capability

KEY 2024 DEVELOPMENTS:

Total global flow battery capacity increased to >40 GWh

- **Vanadium (VFRB):** Large capacity additions were made in Asia, including a **700 MWh project** in China.
- **Iron Flow:** 2 GWh in iron flow deployment was **announced in California** and >3 GWh in Australia.

METAL AIR

Intended for use cases up to 100hr to provide dispatchable capacity for seasonal storage

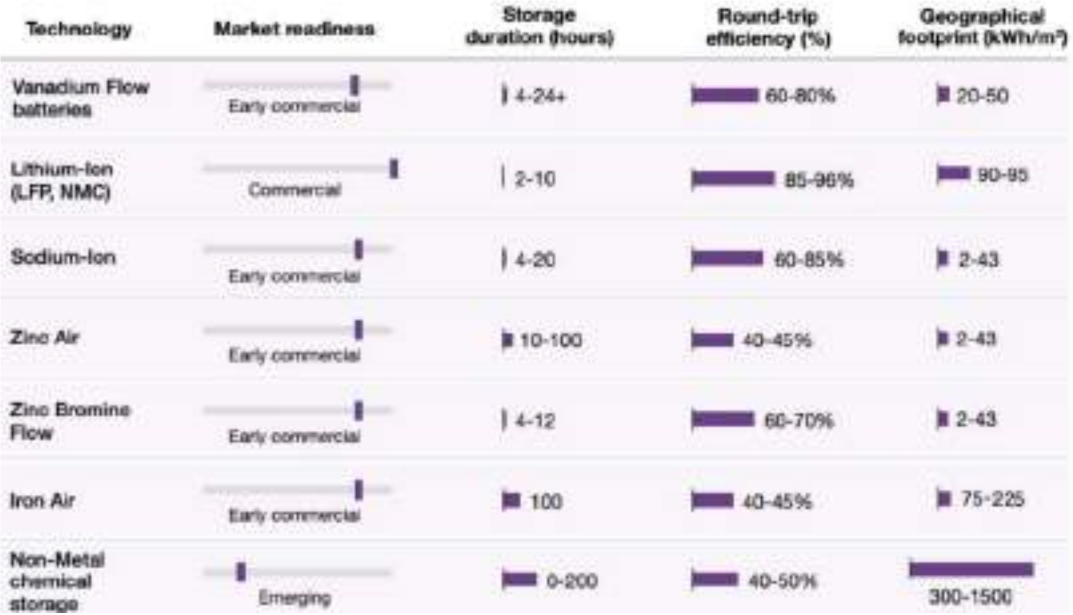
KEY 2024 DEVELOPMENTS:

- **Iron-Air:** Form Energy raised $405M in its Series F round. Upcoming 1.5 MW/150 MWh project with Minnesota utility Great River Energy (GRE) in 2025.
- **Nickel/Hydrogen:** EnerVenue raised $515M and announced pilot project in Milwaukee for its 2-12hr duration batteries

Sources: https://vanitec.org/latest-from-vanitec/article/china-sees-surge-in-100mwh-vanadium-flow-battery-energy-storage-projects

Long-Duration Energy Storage (LDES) Technologies

- Definitions of LDES vary, but are typically considered within a range of 8 hours (0.125C) to 100 hours (0.01C).
- LDES encompasses a wide range of technologies including chemical, thermal, and mechanical, in addition to electrochemical (batteries)
- Battery LDES deployed as of 2024 is approximately 2GW, or 1% of total global deployed BESS capacity.
- Long Duration Storage Shot™, one of DOE's Energy Earthshots™ that aims to reduce storage costs by 90% for systems that deliver 10+ hours of continuous power
- Although LDES has significant investment and promise, Li-ion accounts for over 98% of storage installed today, with a dominant position in bankability, RTE, and product offerings



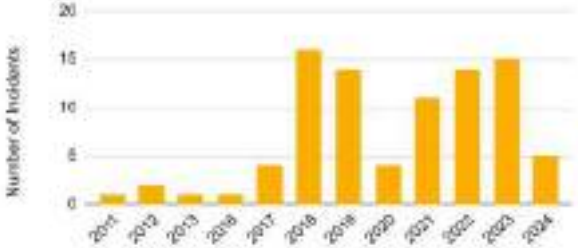
Technology	Market readiness	Storage duration (hours)	Round-trip efficiency (%)	Geographical footprint (kWh/m²)
Vanadium Flow batteries	Early commercial	4-24+	60-80%	20-50
Lithium-Ion (LFP, NMC)	Commercial	2-10	85-96%	90-95
Sodium-Ion	Early commercial	4-20	60-85%	2-43
Zinc Air	Early commercial	10-100	40-45%	2-43
Zinc Bromine Flow	Early commercial	4-12	60-70%	2-43
Iron Air	Early commercial	100	40-45%	75-225
Non-Metal chemical storage	Emerging	0-200	40-50%	300-1500

rho motion A BENCHMARK COMPANY

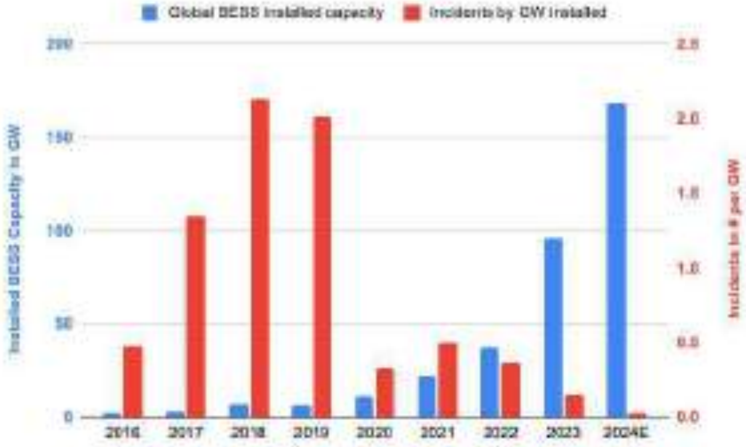
Source: Rho Motion ; LDES Council

Major Declines In Rate Of BESS Safety Incidents

NUMBER OF INCIDENTS BY YEAR



- A **May 2024 report** from Electric Power Research Institute (EPRI) performed the most comprehensive analysis of operational incidents in operational BESS projects
- An incident was defined as: *"An occurrence caused by a BESS system or component failure which resulted in increased safety risk. For lithium ion BESS, this is typically a thermal risk such as fire or explosion."*
- **5 registered events** occurred in 2024 (3 in US, 1 JPN, 1 SGP)
- The incidents highlight the **importance of effective fire suppression systems** designed
- Effective emergency response plans are crucial to mitigate the risks associated with BESS incidents, these include:
    - Evacuation procedures
    - Air quality monitoring
    - Public safety measures



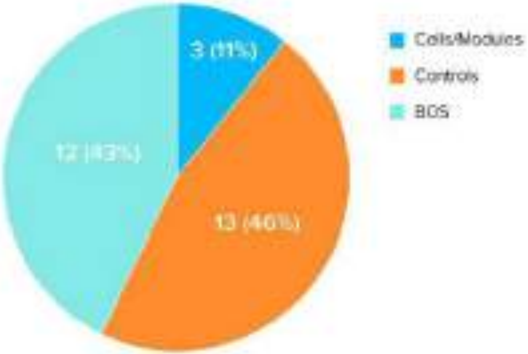
GW installed grows, incidents decrease: As the total installed BESS capacity has grown exponentially, the number of incidents remain constant or drop

Incidents by GW at its lowest: A rate of is reflected in the incident by installed GW ration which is at its lowest since 2016 (0.03 incidents/GW installed)

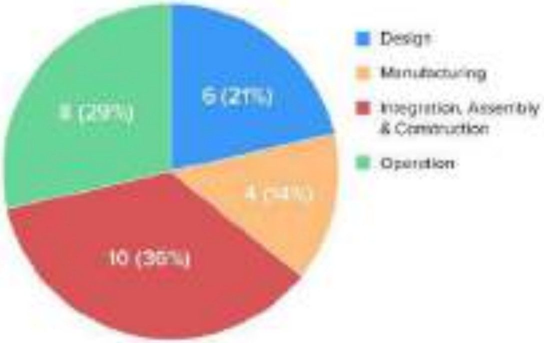
Source: BNEF, EPRI, EPRI Wiki, Data for installed BESS capacity: 2016 to 2023 KEARNY, Electricity storage A booming sector of technology September 2024; 2024:Energy Storage News

Control Issues And Integration Challenges Dominate Safety Incidents Rather than Direct Cell Failures

INCIDENTS BY TRIGGERING COMPONENT



ROOT CAUSES OF INCIDENTS



BOS = Balance of System

- **Control issues are triggering many incidents:** While **only 11% of incidents were directly attributed to cell failures**, many more were indirectly caused by cell failures triggered through operation conditions outside of predefined safety windows due to control issues
- **Issues happen early in the project lifecycle:** In about **3 out of 4 cases, events happen during construction**, commissioning or within the first 2 years of operation
- **Integration remains challenging:** **Integration related issues are the most common root cause** of incidents including wiring, coolant systems or safety systems

Source: EPRI

ESS Safety - Large Scale Burn Testing a New Addition to Existing Fire Testing Standards

- **UL9540A:** This standard, developed by the private US-based accreditation agency UL Solutions, is the leading standard for fire testing and nearly every major manufacturer has performed tests using this standard. It involves measuring the results of a lab-controlled burn of various components of the system, starting with simplest and working up to the most complex:
  - **Cell-level**: Combustion of a single battery cell, measuring the gases produced
  - **Module-level**: Combustion of a collection of battery cells connected together
  - **Unit-level**: A collection of battery modules connected together and installed inside a rack and/or an enclosure
  - **Installation-level**: same setup as the unit test with additional fire suppression systems used

- **Large scale tests on entire BESS units:** These tests involved intentionally triggering thermal runaway events within entire BESS enclosures to assess their ability to contain the fire and prevent propagation to adjacent enclosures.

- **The benefits of large scale fire testing:**
  - These tests often exceed the current standard industry requirements outlined in **NFPA 855** and **UL 9540A**
  - Preparations for the the upcoming **CSA C800** standard, which will establish new safety benchmarks for large-scale testing of energy storage systems in 2026
  - The **CSA C800** simulates real life incidents and provides insights into the worst-case fire performance which supports the proper risk assessment

Source: Utilitydive, BatteryStandardsTable

ESS Safety - Codes And Standards

The US DOE provides a template for authorities which aim to procure BESS and highlights the relevant codes and standards. The **following standards have been added in the 2024** template:

NFPA 68: This standard deals with **explosion protection through deflagration venting.** In the context of BESS, this involves designing ventilation systems to safely release pressure in the event of an explosion, preventing catastrophic failure.
NFPA 69: This standard focuses on **explosion prevention systems,** such as those that detect and suppress explosions before they can cause significant damage. For BESS, this involves installing fire suppression systems, gas detection systems, and other measures to prevent fires and explosions within the battery modules.
NFPA 72: This standard covers **fire alarm and signaling systems.** For BESS, this involves installing fire alarms, smoke detectors, and other early warning systems to detect fires and initiate appropriate responses, such as activating fire suppression systems or alerting personnel.

Other relevant codes and standards:

CODE/STANDARD	DESCRIPTION
NFPA 70	National Electrical Code
NFPA 855	Standard for the Installation of Stationary Energy Storage Systems
UL 1642	Standard for Lithium Batteries
UL 1973	Batteries for Use in Light Electric Rail Applications and Stationary Applications
UL 9540	Energy Storage Systems and Equipment

CODE/STANDARD	DESCRIPTION
UL 9540A	Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
IEEE 1547	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electrical 1 Power System Interfaces
UL 1741	Standard for Static Inverters and Charge, Converters, Controllers and Interconnection System Equipment
UL 62109-1	Safety of power converters for use in photovoltaic power systems – Part 1: General requirements

As part of effort to reduce fire and improve safety, **AHJ's and fire marshals are requiring these two documents** for ESS system installations: (1) Emergency response plan and (2) Decommissioning plan/guide.

Source: Energy.gov, Energy.gov

Regulatory Map For BESS Projects In Major Markets

RFP / AWARD

For **regulated markets** where there are specific MW or MWh targets, competitive RFPs are held for projects, which are then awarded via negotiated offtake agreements.

In **deregulated markets**, developers perform interconnection studies and must support the cost of network upgrades incurred as a result of the project. Offtake may be regulated through government incentives or contracts, or may be done on the private market.

INTERCONNECTION

Whether from a competitive award, or built to capture revenues in a certain market, the **grid must allow for interconnection** based on the specific charge and discharge requirements of the BESS. Typically allowed based on application / study by a utility, grid operator, or regulator. Depending on the arrangement the developer may be required to fund some or all of the upgrades required to the grid to support the project.

FEDERAL / STATE / PROVINCIAL / REGIONAL PERMITS

Most projects have some national, state, provincial, or regional approval that must be granted - this includes whatever planning or siting committees must be consulted, environmental approvals, and any additional studies such as noise or community approval. Electrical and construction codes must be followed.

Local Authorities Having Jurisdiction (AHJs) enforce compliance with national, state, and local codes.

PRODUCT-SPECIFIC REGULATIONS

Based on the AHJ's interpretation of the code, the project, and **its key components** such as the BESS, PCS, and controls system, **must meet certain requirements**. At the product level this may include UL 9540, UL 9540A, corresponding IEC standards, and the projects must meet project-level standards such as NFPA 855.

Global Investments Surge In Battery Storage

A fivefold growth since 2018: Investments in battery storage have soared to meet the demands of electrification and renewable integration.

Record Investment Growth in Battery Storage

- Global investment in battery storage is expected to exceed $50 billion in 2024, with a 70% increase in 2023, led by the US and Europe
- Total investment: $150 billion, with $115 billion in EV batteries and $40 billion in energy storage
- Dominant regions: 90% of funding concentrated in China, Europe, and the US

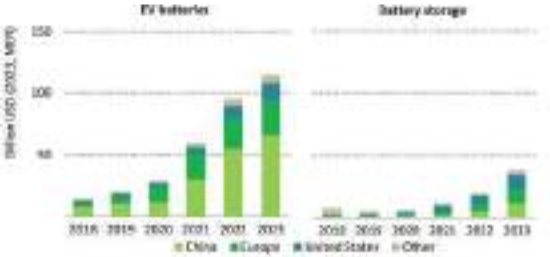
Venture Capital Focus

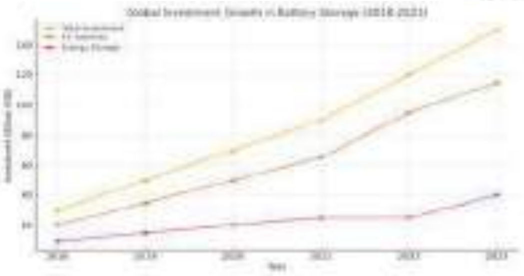
- $6 billion funding for innovations like new chemistries and battery recycling- **Technology investment**
- 15% of funds directed to recycling and alternatives to lithium- **Technology investment**

Top Developers Leading the Charge

- China Energy Investment: 11.8 GW capacity-**Deployment**
- NextEra Energy: 10.9 GW in the US.- **Deployment**
- Engie: Expanding across EU, US, and Latin America with 6.3 GW planned- **Deployment**

GLOBAL INVESTMENT IN EV BATTERIES AND BATTERY STORAGE, 2018-2023



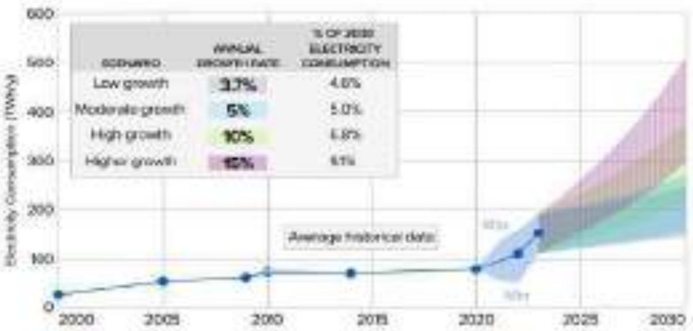


Technology investments are driving innovation and sustainability, deployment investments are focusing on scaling and integration into existing energy systems.

Source: Batteries and Secure Energy Transitions World Energy Outlook Special Report, RechargeNews

AI And Data Centers Are A Major Driver Of Power Demand And BESS Deployments

PROJECTIONS OF POTENTIAL ELECTRICITY CONSUMPTION BY U.S. DATA CENTERS: 2023–2030



"Gen AI has accelerated the pace and scale of power demand more than any other technology in the past two decades." McKinsey Report, 2024

- Power needs of data centers are expected to grow three times by the end of the decade, going from between 3% of total U.S. power demand in 2024 to 9% in 2030
- In the 15% growth scenario, electricity demand for data centers in the US is expected to increase to over 400 TWh/year, including significant BESS installs

GEOGRAPHIC DISTRIBUTION AND PROJECTED POWER DEMAND BY U.S. DATA CENTERS: 2023-2030

"Geographic distribution of data centers is notably uneven, creating localized grid stress." EPRI White Paper, 2024

- As of 2024, there were approximately 10,655 data centers globally, of which half (5,381) were in the United States.
- Limited grid capacity has resulted in data centers considering self generation, mostly solar PV and battery storage
- In the US, 15 states account for 80% of the national data center load with data centers in VA consuming over 25% the total electricity available in the state.

Source: McKinsey, EPRI, S&P Global

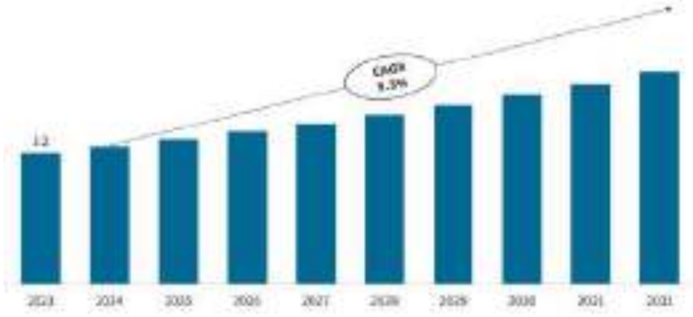
Generative AI And Data Centers - Battery Market Size, Trends, and Competitive Landscape

Given the massive electricity consumption of data centers, there is a growing push to ensure their operations are sustainable. As a result, major hyperscalers like **Google, Apple, and Meta have committed to using only carbon-free energy by 2030,** driving a significant shift away from diesel generators. Increasingly, operators are turning to battery energy storage systems (BESS) to reduce carbon footprints of data centers and AI applications.

DATA CENTER BATTERY MARKET TRENDS:

- **Evolving Battery Chemistries**: From legacy lead-acid to nickel-zinc and lithium-ion, data center operators are exploring multiple options to ensure high reliability.
- **Uninterrupted Operations**: Any downtime can be extremely costly, pushing demand for robust energy storage solutions.
- **Space Constraints**: Facilities have limited footprints, making energy density and efficiency critical in maximizing power capacity.
- **Balancing Cost and Longevity**: Operators carefully weigh factors like durability, total cost of ownership, and ease of maintenance to determine the best fit.

GLOBAL DATA CENTER BATTERY MARKET SIZE 2023 - 2032 (USD BILLION):



GLOBAL DATA CENTER BATTERY MARKET SHARE BY COMPANY, %

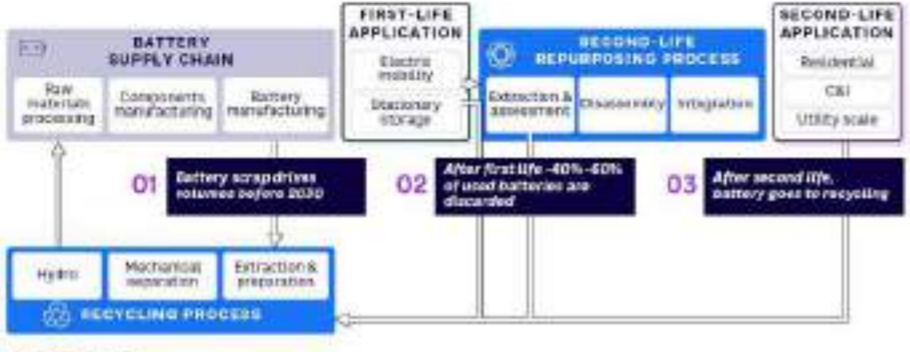
Source: McKinsey, EPRI, S&P Global, Global Market Insights

Second Life Batteries - Repurposing EV Batteries For BESS

Second life batteries are those that are used in applications after being removed from EVs. They are either placed back into EVs, or converted into stationary BESS products.

Second life use cases are challenging because while they have reduced cost, the cells must be removed from the EV, tested, incorporated into the new product, and re-sold. UL 1974 and IEC 6330 are standards for Evaluation for Repurposing Batteries

The second-life EV batteries market is estimated at approximately $2B in 2024, but is expected to grow quickly as EV market penetration increases. Many automakers have started efforts to commercialize second-life BESS applications from their vehicles.



Source: Arthur D. Little

NOTABLE 2024 SECOND LIFE CORPORATE ACTIVITIES:

- **Kia Europe**'s collaboration with **Deutsche Bahn**'s startup encore to repurpose EV batteries into energy storage systems
- **Audi AG** and **RWE**'s energy storage project in Germany utilises batteries from electric cars.
- **Nissan** and **ecobat** partnered to recycle, repair, and repurpose Nissan's EV batteries

Source: AD Little Second Life: Maximizing Life Cycle of EV Batteries

Commercial & Industrial (C&I) ESS - Market Trends

The C&I energy storage sector was estimated at $3B in 2023, with newly installed capacity reaching 2.4 GW / 4.9 GWh, or approximately 3% of the overall market by power capacity. C&I is rising due to falling BESS costs, supportive government policies, rising costs for demands, and a trend of industrial facilities building co-generation (and storage) on site together with new facilities (particularly among **data centers**).

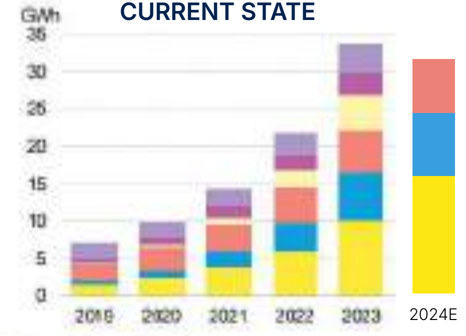
TOP 5-TRENDS IN 2024 SHAPING FUTURE OF C&I ENERGY STORAGE

1. **Tighter standards for products:** Due to influx of many player entering the niche market for the C&I space, certifications bodies are increasing their grips on code & compliance such UL 9540A(edition 4) and 9540 (edition 3), UL 1741 and 1741 SB, UL 5500 for remote software updates to counter cyber security threats for PCS,BMS and EMS.
2. **20-year equipment lifespan has been adopted as industry standard:** As in the utility-scale space, products with higher lifespan provide higher edge on competition.
3. **Storage-as-a-Service**: Unlike utility-scale deployments, C&I requires greater customer engagement to explain its value proposition and demonstrated return on investment to the offtaker, as the BESS it typically located on the C&I customer's property. Rather than being funded directly by the offtaker, many C&I installations have instead signed offtake agreements guaranteeing utility tariff savings, making the prospect less capital-intensive and more attractive to potential customer.
4. **Virtual power plants (VPP) capabilities:** As an added value stream, many C&I installations have used VPPs to add increase the ROI of C&I BESS installations. Depending on the market, C&I BESS installations are able to aggregate and optimize the BESS assets, allowing them to derive significantly greater revenue than if they were serving the local offtaker only. See the **VPP Slide** later in this deck for more detail.
5. **Intelligent Operation and Maintenance (IO&M).** Effective C&I BESS must work closely with other energy components like existing SCADA controls, PV controls (if applicable), and in conjunction with the grid and its tariffs. Optimizing internal load versus external price curves to maximize profitability is key. Hence there is the need to automate operation and maintenance to realize full system operation.

Source:https://energybase.com

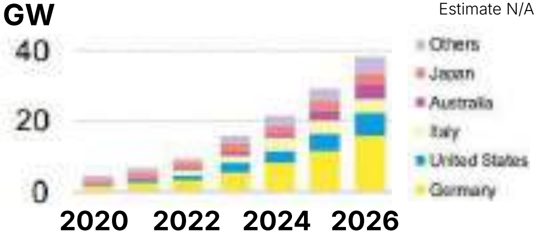
Residential ESS - Markets And Motivations

CURRENT STATE



Source: BloombergNEF

OUTLOOK



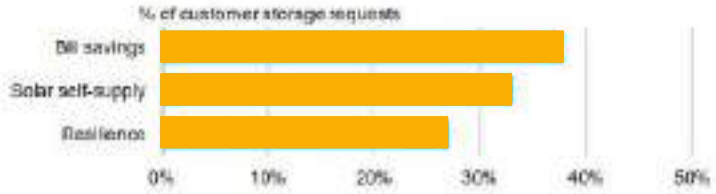
Growth: All the leading markets have introduced incentives to promote the installation of storages

Incentives: Subsidies, self-consumption incentives, and time-varying tariffs create economic benefits for battery storage

PV market: The mature residential PV market supported the storage growth - especially in Italy and Germany with an PV+storage rate of 77% and 75%, respectively. Contrary to the US and Australia with PV+storage rates of only 9% to 15%

KEY MOTIVATIONS FOR INSTALLING RESIDENTIAL STORAGES:

1. **Economic Benefits and Bill savings:** The main reason is to reduce costs and save on electricity bills
2. **Solar self-supply and Sustainability:** Homeowners want to increase solar self-supply
3. **Resilience and Back-up Power:** In regions with unreliable grids or frequent power outages, batteries provide a valuable backup power source, ensuring continued energy supply during disruptions



Source: EnergySage, BloombergNEF

BloombergNEF Sources: BloombergNEF (Distinguished Partner), Estimate 2024, USA: WoodMac, WoodMac, ESS-News and assuming similar growth in WoodMac; Battery-Charts: GER; Review-energy: ITA

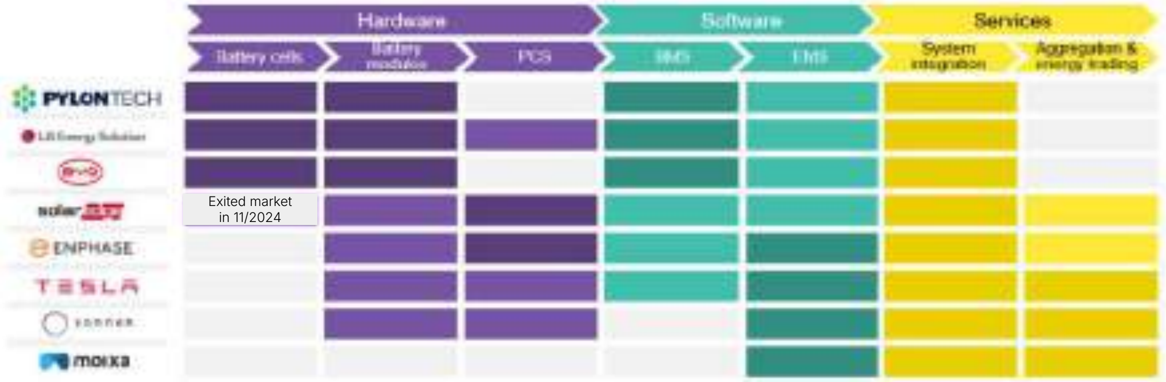
Residential ESS - Selected Residential Storage Companies

Intensifying Competition: Established battery and solar manufacturers are entering the residential energy storage market.

Downstream Focus: Storage system providers are focusing on downstream activities like developing strong local installer networks, system integration and advanced energy and battery management software.

Strategic Partnerships: Battery manufacturers often rely on white-label partnerships with local integrators to gain market access.

Market-Specific Solutions: As energy markets become more complex, there is a growing need for residential storage systems tailored to specific market regulations and tariffs.



	Hardware			Software		Services	
	Battery cells	Battery modules	PCS	BMS	EMS	System integration	Aggregation & energy trading
PYLONTECH	■	■		■	▨	■	
LG Energy Solution	■	■	▨	■	▨	■	
BYD	■	■		■	▨	■	
solaredge	Exited market in 11/2024	▨	■	▨	▨	■	▨
ENPHASE		▨	■	▨	■	■	▨
TESLA		▨	▨	▨	■	■	■
sonnen		▨	▨		■	■	■
moixa					■	■	■

Darker shading represents core business

BloombergNEF Source: PV-Magazine, BloombergNEF (Distinguished Partner)

Virtual Power Plants (VPPs) can help reduce load on the grid, but its participation is largely dependent on regional policies

OVERALL

A Virtual Power Plant (VPP, also known as a Distributed Power Plant) is the coordinated charge or discharge of stationary energy storage assets to act as a larger BESS asset on the grid. VPPs are typically deployed using large numbers of residential- or C&I-scale battery products. These systems are often owned by third parties and participate in programs where the coordinator compensates the battery owners. In return, the coordinator manages the fleet of assets to participate in large-scale markets, such as utility capacity markets, which individual assets cannot access.

BENEFITS

VPPs can provide grid services, ensure market participation by consumers, reduce grid congestion and provide additional revenue streams for consumers who want to participate in the energy transition. Since they are distributed assets, they do not rely on time-consuming interconnection issues, and are desirable to utilities since they are **reducing demand across the grid without introducing additional stresses at specific points.**

CHALLENGES

The success of VPP is dependent on the regulatory, policy and market rules. A positive example is the program which was launched by Tesla and PG&E. The formed VPP delivered 100 MW of power in July 2024 which limited the need to deploy fossil-fuel peaker plants. However, many utilities do not have markets or market rules that allow for VPPs to participate in these locations.

ENTIRE MARKET INCL. ALL FLEXIBLE LOADS:

Up to 2024, the NA market contains already **more than 33 GW of flexible loads managed via VPP** (incl. not only batteries). Some of the top VPP aggregators operating in this space are:

CPower Energy: 7 GW

Voltus: 7 GW

Enel NA: 5 GW

FOCUS ON RESIDENTIAL STORAGE

Certain manufacturers of residential BESS products have offered VPP participation as a voluntary, compensated program for their users.

Some notable publicized examples of the larger VPP deployments are shown here:

sonnen	**40 MW** / September 2024 / Texas, US
TESLA	~100 MW / July 2024 / California, US
sunrun	32 MW / July 2024 / California, US

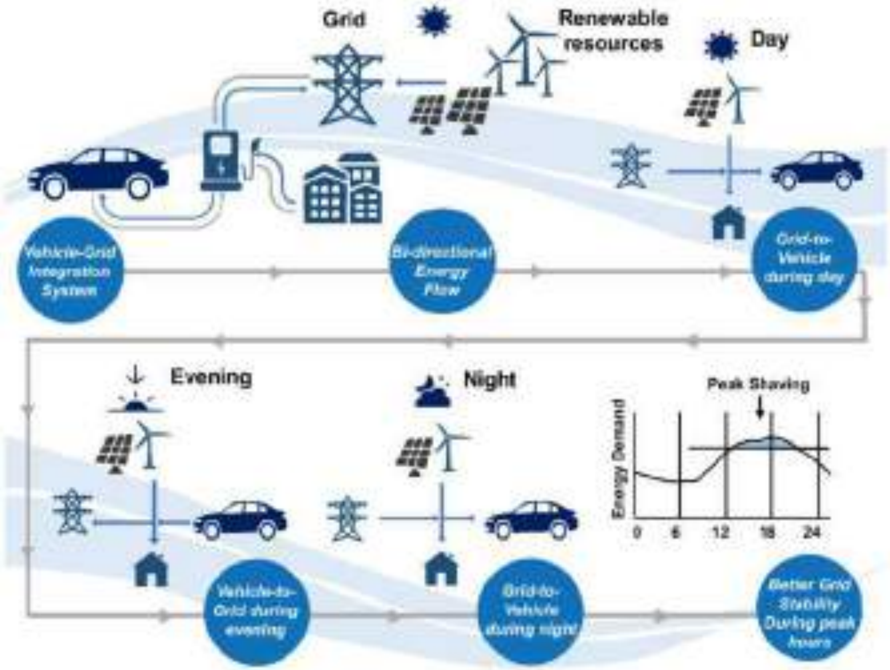
Source: IEA, Guidehouse Insights

Vehicle-To-Grid (V2g) Tested In Pilot Programs, Faces Challenges To Scale

Vehicle to Grid ("V2G") is the **use of electric vehicles' bi-directional charging capabilities to provide services to the grid**. There are currently ~40m EVs on the road globally (including PHEVs and BEVs), totalling over 1,300 GWh of energy storage (relative to approximately 340 GWh of stationary energy storage through end of 2024). As both markets continue to grow, V2G technology continues to evolve to allow EV owners to monetize their vehicles by connecting them to the grid. As with VPPs, V2G is deployed by having thousands of distributed storage batteries charging or discharging simultaneously.

V2G has been deployed extensively in pilot programs, it has yet to be adopted widely at scale. There are many **technical and economic challenges** to deployment:

- V2G requires charging and discharging, while some vehicles do not physically allow for bi-directional power flow
- There is no standard across vehicle manufacturers, or communication profiles, so most V2G programs must be run by a specific manufacturer
- The technology requires a high number of vehicles participating to result in significant economies of scale



Source: MDPI

Overview Of Global Policy Support for BESS

Accelerating Deployment Through Global Initiatives: Governments globally are supporting battery storage through subsidies, targets, and regulatory reforms to accelerate renewable energy integration. More on this topic can be found in the Policy Section of the report.

Standardizing warranty practices reduces complexity, mitigates risks, and promotes BESS deployment build investor and consumer confidence.

UNITED STATES

- Inflation Reduction Act: Up to 50% federal tax credits for battery storage
- State-Level Targets: 50 GW of storage additions projected in 9 states over 20 years, including LDES targets in California and Massachusetts

CHINA

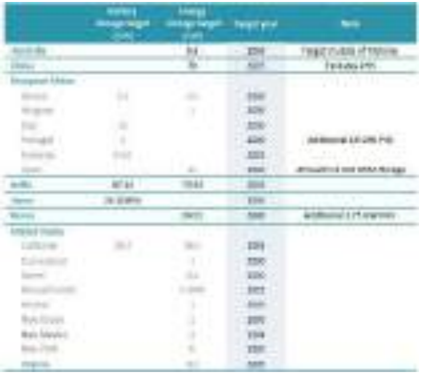
- Surpassed the 2020 national target of 30 GW by 2025; new regional plans target 80 GW by 2025
- Mandates storage pairing (10–30%) with wind and solar projects; financial incentives like feed-in tariffs and waived grid tariff

INDIA

- National Framework for Energy Storage Systems: Requires 5% storage for new renewable projects
- Waived inter-state transmission charges for 12 years; Viability Gap Funding covers 40% of project costs

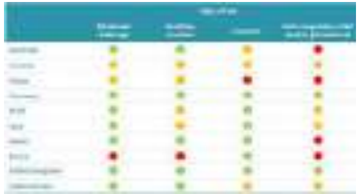
EUROPEAN UNION

- Targeting 45 GW by 2030 through National Energy and Climate Plans
- Reforms to eliminate double taxation; mechanisms like Contracts for Difference (e.g., Greece, Italy)
- EU Innovation Fund and Recovery Facilities offer financial support



BEHIND-THE-METER POLICY MEASURES IN SELECTED COUNTRIES

ELIGIBILITY OF BATTERY STORAGE BY TYPE OF USE BY COUNTRY



Source: Batteries and Secure Energy Transitions World Energy Outlook Special Report, DNV, ESMAP

IRA Investment Tax Credit Guidelines

In the U.S., the Inflation Reduction Act has been a huge boost to the renewables industry through the Investment Tax Credit, which offers incentives for construction of solar, wind, and storage projects by offering federal tax credits to offset a portion of the project's cost.

The original law had several vague provisions, which have been clarified by guidance that has gradually been issued by the Internal Revenue Service (IRS). The table below shows the tax credits described in the IRA, which gradually decline from 2022 to 2036. Although there is concern that the incoming Trump Administration would rescind these credits, this would require an Act of Congress, which is possible but difficult given the slim majorities held by the Republican Party in the U.S. Senate and House of Representatives.

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Base for All Projects															
Base ITC*	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%	4.50%	3%	0%
Bonus for Meeting Dcms**		2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	1.50%	1%	0%
Bonus for Siting in "EC"		2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	1.50%	1%	0%
Adders for Projects that Meet Labor Requirements															
Base ITC*	24%	24%	24%	24%	24%	24%	24%	24%	24%	24%	24%	24%	18%	12%	0%
Bonus for Meeting Dcms**		8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	6%	4%	0%
Bonus for Siting in "EC"		8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	6%	4%	0%
Allocated Low-Income Bonus for Projects Under 5 MWac* **															
Base ITC*		10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	7.50%	5%	0%
Bonus for Meeting Dcms**		20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	15%	10%	0%
Bonus for Siting in "EC"															

* Actual phased down is based on the later of the dates shown or the year after electric sector CO2 emissions drop 75% below 2022 levels.
** Must include 100% domestic iron/steel and an increasing percent of manufactured goods over time.
*** Allocated credits will be based on an application and award process that will have to be developed by the Secretary. Maximum of 1.8 GWdc/year.
DCMS = Domestic Content Minimums; EC = Energy Community;

Source: IRA, HR5376

IRA Domestic Content Bonus vs. Requirements

The IRA has provisions to provide additional tax credits for projects that can prove that a certain portion of the hardware used on the project were manufactured in the U.S. The purpose of this is to incentivize US manufacturing of Li-ion batteries, in order to combat China's dominance in this field. This section summarizes the terms of these incentives, including recent IRS guidance.

DOMESTIC CONTENT BONUS (ADDS 2%, 10% ABSOLUTE TO ITC, ADDS 10% RELATIVE TO PTC)

- Applies to project placed in service 2023 or later
- The values 40% of the total cost of the manufactured product used at the site must be from products mined, produced or manufactured in the US for projects that start construction through 2024
    - For projects that start construction in 2025, 45%,in 2026 50%, 2027 and thereafter 55% *
- To qualify, all iron and steel used in the project must be sourced from the US
- There is no exceptions waiver available to private BESS installations pursuing the domestic content bonus

DOMESTIC CONTENT REQUIREMENT FOR DIRECT PAY

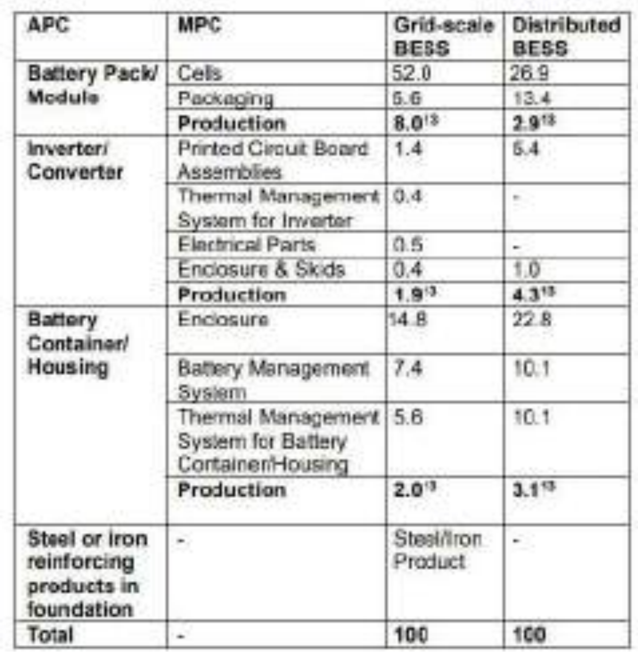
- Applies to projects that begin construction in 2024 or later
- Eligibility is similar to Domestic Content Bonus
- If the Domestic Content requirements are not met, the portion of the credit available is reduced per the following schedule
    - 90% if project construction starts in 2024
    - 85% if projects starts in 2025
    - 0% if projects starts after 2025
- Treasury is required to provide exceptions under the following circumstances:
    - If the inclusion of steel, iron or manufactured products which are produced in the US increases the overall cost of construction by more than 25%
    - If relevant steel, iron or manufactured products are not produced in the US in sufficient and reasonably available quantities of satisfactory quality

Source: Federal Solar Tax, HR5376

BESS Safe Harbor Table

Another provision of the ITC is a new ‘safe harbor’ table. This guidance from the IRS allows taxpayers to determine a project’s domestic content percentage by relying on additive fixed percentages for specifically identified U.S. manufactured components or subcomponents, rather than relying on the manufacturer disclosing its actual direct cost to manufacture products.

Projects also can qualify for the domestic content bonus under earlier IRS guidance in Notice 2023-38 by determining an energy project’s total percentage of its manufacturer’s U.S. direct costs of products over all manufacturer’s direct costs of U.S. and non-U.S. products. However, the new safe harbor will make it unnecessary to track down all manufacturer’s costs for many developers and sponsors of energy projects.



APC	**MPC**	**Grid-scale BESS**	**Distributed BESS**
Battery Pack/ Module	Cells	52.0	26.9
	Packaging	5.6	13.4
	Production	**8.0**[13]	**2.9**[13]
Inverter/ Converter	Printed Circuit Board Assemblies	1.4	5.4
	Thermal Management System for Inverter	0.4	-
	Electrical Parts	0.5	-
	Enclosure & Skids	0.4	1.0
	Production	**1.9**[13]	**4.3**[13]
Battery Container/ Housing	Enclosure	14.8	22.8
	Battery Management System	7.4	10.1
	Thermal Management System for Battery Container/Housing	5.6	10.1
	Production	**2.0**[13]	**3.1**[13]
Steel or iron reinforcing products in foundation	-	Steel/Iron Product	-
Total	-	**100**	**100**

Source: Notice 2025-08 Domestic Content guidance

ESS Industry Pain Points - Focusing On Commissioning And Project Planning

1. **Tight timelines:** Often caused by construction and equipment delivery delays due to supply chain issues, it takes in average more than 1,000 days to bring a BESS online in competitive markets, like ERCOT in the US
2. **Supply chain:** Components from various regions lead to complex logistics, especially transformers are low in stock with leads times of up to 120 weeks in 2024
3. **Battery Management System (BMS) failures:** Unreliable BMS can lead to unexpected shutdowns, dangerous situations, and issues like overcharging or deep discharging.
4. **Battery cell quality:** Faulty cells can negatively impact rack performance and increase the risk of warranty claims and safety incidents.
5. **State of Charge (SOC) estimation errors:** Particularly challenging with LFP batteries, inaccurate SOC estimates can lead to system imbalances.
6. **Integration complexities:** Underperforming auxiliary components and faulty container design define temperature and moisture levels which can lead to component damages and incidents
7. **Permitting and grid interconnection approvals:** Securing necessary permits and approvals can significantly delay project timelines. In the ERCOT market, the average delay time is larger than 6 months.
8. **Knowledge and capability gaps:** The rapid growth of the BESS market highlights expertise shortages among developers and storage providers

Sources: Fluence, Accure, TWAICE, IHI terrasun

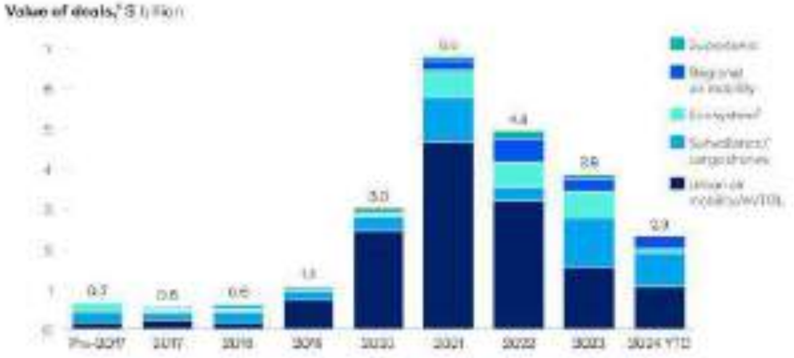
1 INDUSTRY

Electric Aviation Leaders Approach Market Readiness Amid Funding Decline

Future Air Mobility (FAM) or Advanced Air Mobility (AAM) is an umbrella term encompassing various advanced air transportation modes, including **Urban Air Mobility (UAM)** with eVTOL aircraft, **Regional Air Mobility (RAM)** with eVTOL, eCTOL, and eSTOL aircraft, as well as **surveillance and cargo drones**, and supersonic flights.

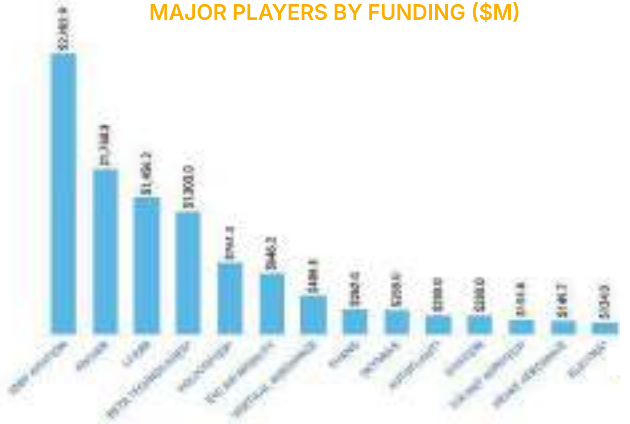
A **McKinsey report** shows that as of August 2024, funding in the sector had reached $2.3 billion, with nearly 80% directed toward UAM and drones. While this indicates a potential to match 2023's total of $3.9 billion by year-end, it also reflects a continued decline in investments since the peak levels seen in 2021.

TOTAL DISCLOSED FUNDING FOR FUTURE AIR MOBILITY HAS DECLINED



Source: AAM Reality Index

MAJOR PLAYERS BY FUNDING ($M)



This **funding decline** comes at a particularly challenging time for the industry, as **major companies in the sector are nearing market readiness**. This critical phase demands substantial financial resources to ensure the safety, reliability, and regulatory compliance. The lack of funding has been especially severe for a few European companies that filed for insolvency in 2024.

Three **key factors** will determine the success or failure of a company: establishing a clear **path to certification**, achieving **full-scale production**, and demonstrating strong **market demand**.

Notable Battery-Electrified Aviation Events In 2024

2024 was marked by contrasting fortunes in funding, new strategic partnerships, and moderate progress toward certifications.

JANUARY

NASA and Archer partner on next-gen battery tech for electric aircraft

FEBRUARY

Heart Aerospace raises $107M in Series B

Joby Aviation completes third stage of FAA certification process

PROPEL-1K Program. The DOE announces $15M to advance next-generation energy storage for aviation

JUNE

CATL announces a battery that is expected to power electric plane with 1,800-mile by 2028

Archer Receives FAA Certification to Begin Operating Commercial Airline

The **FAA and EASA** release an updated and harmonized guidance on certification criteria for eVTOL

JULY

Archer receives an additional $55M investment from automotive giant Stellantis

AUGUST

AutoFlight and CATL sign a strategic investment and cooperation agreement worth hundreds of millions of dollars

OCTOBER

Toyota to Invest $500 Million in Joby Aviation

Lilium officially files for insolvency

BETA Technologies raises more than $300M in additional equity

DECEMBER

Archer teams up with Anduril to build defense aircraft and raises $430 million

New investor consortium to save **Lilium** with €200 million

Volocopter files for insolvency while seeking investors

Vertical Aerospace finalises $50m investment agreement

Major Battery-Electrified Aviation Players

AMERICAS

- Joby
- ARCHER
- wisk
- EVE
- supernal
- overair
- PIVOTAL
- BETA
- SURFAIR
- REGENT
- COSMIC
- ELROY AIR
- Whisper Aero
- ELECTRA

EMEA

- VOLOCOPTER
- LILIUM
- VERTICAL
- AUTOFLIGHT
- ascendance
- PIPISTREL
- AURA AERO
- Heart Aerospace
- DRONAMICS
- MAEVE
- VÆRIDION

ASIA - PACIFIC

- EHANG 216
- SKYDRIVE
- VOLANT
- 亿维特航空
- TCab Tech
- VERTAXI
- VOLAR

DEVELOPMENT FOCUS

eVTOL

eSTOL/eCTOL

Focusing solely on eVTOLs, the **World eVTOL Aircraft Directory** includes over 1,000 concepts from more than 400 designers. This slide presents a list of AAM major players, divided between eVTOL and eSTOL/eCTOL. Automotive OEMs like Volkswagen and Honda, as well as airplane OEMs like Airbus, are also developing their own models. Technical details of selected designs, which are more likely to reach production, as assessed by the **Advanced Air Mobility Reality Index**, are discussed in the following slides.

Source: EVTOL News, AAM Reality Index

eVTOL (Electric Vertical Take-Off And Landing)

eVTOLs are primarily developed for UAM (Urban Air Mobility), though some also target RAM (Regional Air Mobility). Most battery specifications remain undisclosed. Market-ready models rely on high-end lithium-ion batteries, while designs in development feature innovative chemistries like solid-state, lithium-sulfur, or metal-air. Under investments pressure, the choice of chemistry is driven by the aircraft launch and certification timeline.

							
AIRCRAFT	VoloCity - **Volocopter**	EH216-S - **EHang**	S4 - **Joby Aviation**	Midnight - **Archer**	Prosperity 1 - **Autoflight**	AE200 X01 - **Aerofugia**	VX4 - **Vertical Aerospace**
MAX TAKE-OFF MASS **# PASSENGERS** **RANGE**	1000 kg 1+1 pilot 20 km	620 kg 2 (autonomous) 35 km	2400 kg 4+1 pilot 161 km	3175 kg 4 +1 pilot 32-80 km	1500 kg 4 (autonomous) 250 km	- 4+1 pilot -	- 4 + 1 pilot 161 km
POWER SUPPLY **CHARGING SYSTEM**	Battery Electric Battery Swap	Battery Electric -	Battery Electric -	Battery Electric Fast Charge	Battery Electric -	Battery Electric -	Battery Electric Fast Charge
BATTERY	Lithium-ion	17 kWh	Lithium-ion 235 Wh/kg (pack level)	Lithium-ion (**Molicel**) 142 kWh	160 kWh	-	Lithium-ion (**Molicel**)
FIRST FLIGHT **ENTRY INTO SERVICE** ***(ANNOUNCED)***	2021 2025	2018 2023	2018 2025	2023 2025	2022 2026	2023 2026	2023 2027

Source: Multiple, Company websites and announcements; Data compilation

eSTOL (Electric Short Take-Off & Landing), eCTOL (Electric Conventional Take-Off & Landing)

eSTOLs and eCTOLs are less discussed than eVTOLs, as they resemble conventional airplanes, but are key to RAM (Regional Air Mobility). Like eVTOLs, they currently rely on proven battery technologies and await further advancements in battery chemistries. As a result, some market-ready models are reporting lower ranges than initially promised, and hybrid power systems are more common. Additionally, companies like ZeroAvia are working on hydrogen fuel cell alternatives.

						
AIRCRAFT	ALIA CX300 - **Beta Technologies**	Alice - **Eviation**	Viceroy - **Regent**	EL - **Electra Aero**	ES-30 - **Heart Aerospace**	Velis Electro - **Pipistrel**
MAX TAKE-OFF MASS **#PASSENGERS** **RANGE**	3175 kg 5+1 pilot 621 km	8400 kg 9 + 2 pilot 463 km	7000 kg 12 + 2 pilots 290 km	1400 kg 9 + 2 pilots 800 km	- 30 + pilots 200 km (full el.) - 800 km (hy.)	600 kg 1 + 1 pilot 86 km
POWER SUPPLY **CHARGING SYSTEM**	Battery Electric Fast Charge (1 h)	Battery Electric Fast Charge	Battery Electric	Hybrid	Hybrid Fast Charge (0.5 h)	Battery Electric Fast Charge (1 h)
BATTERY INFO	Lithium-ion	Lithium-ion 820 kWh 260 Wh/kg (cell level)	-	Lithium-ion	-	-
FIRST FLIGHT **ENTRY INTO SERVICE** ***(ANNOUNCED)***	2020 2025	2018 2023	2018 2025	2023 2029	2022 2026	2023 2026

Sources: Multiple, Company websites and announcements; Data Compilation

Cargo Drones

Cargo drones are the most diverse category within advanced air mobility, with payloads ranging from a few kilograms to several hundred kilograms. The service range also varies significantly, with models achieving the highest ranges typically using hybrid power systems. Many eVTOL and eSTOL designers are active in this market, introducing new models or repurposing passenger designs for cargo transport. In some models, the cargo is stored within the drone's fuselage, while in others, it is carried externally.

					
AIRCRAFT	CarryAll - **AutoFlight**	Nuuva V300 - **Pipistrel**	Chaparral C1 - **Elroy Air**	EH216-L - **Ehang**	Zipline **Platforms 1, 2**
MAX PAYLOAD **RANGE**	400 kg 250 km	460 kg 2500 km	136 kg 483 km	220 kg 35 km	1.8 - 3.6 kg 38 km (**2**) - 190 km (**1**)
POWER SUPPLY	Battery Electric	Hybrid	Hybrid	Battery Electric	Battery Electric
BATTERY INFO	160 kWh	-	-	-	-
FIRST FLIGHT **ENTRY INTO SERVICE** ***(ANNOUNCED)***	2023 2024	2024 2025	2023 2024	2020 2021	2016 (**Platform 1**) -

Sources: Multiple, Company websites and announcements; Data Compilation

Marine Batteries - Overview

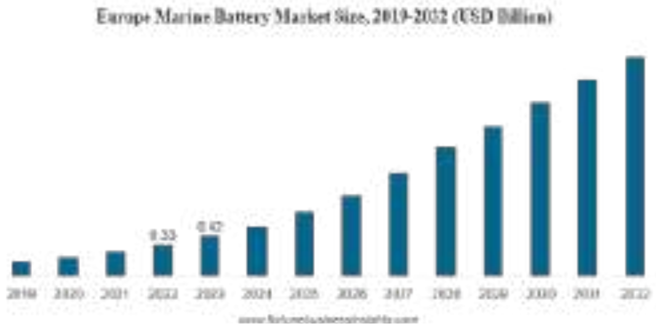
The marine battery market in EU is projected to grow from USD $0.42 billion in 2023 to more than USD $1.7 billion by 2032, with the global demand reaching more than USD $5 billion.

Lithium ion batteries account for ~35% of all deployed marine storage, followed closely by lead acid and fuel cells.

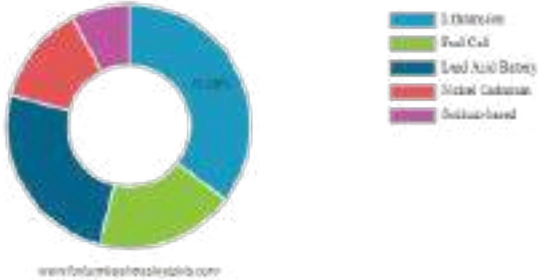
Applications include energy supply for auxiliary loads and/or propulsion, in a range of vessels from ferries to recreational craft. They are implemented in three main types of systems:

- **Semi-hybrid:** The battery is installed as part of the ships auxiliary system to provide a hybrid or full-electric grid.
- **Full-hybrid:** The battery is installed alongside a ship's main engines, providing support or allowing the vessel to be operated under electric power for short periods of time.
- **Full-electric:** The battery is the sole power source on the vessel, providing. In recreational boats, Some full-electric vessels use hydrofoils to lift the boat out of the water, improving energy efficiency by ~80% compared to displacement vessels.

EUROPE MARINE BATTERY MARKET SIZE, 2019-2032 (USD BILLION)



GLOBAL MARINE BATTERY MARKET SHARE, BY BATTERY, 2023



Source: Fortune Business Insights

Marine Battery - Applications

							
Vessel Name (Company)	MF Ampere (Norled)	Elektra (FinFerries)	Bastø Electric (Bastø Fosen)	Candela P-12 (Candela)	N30 (Navier)	Saint-Malo (Brittany Ferries)	Artemis EF-24 (Artemis)
In operation	2015	2017	2021	2024	2024	2025	TBD
Vessel Type	Full-electric	Hybrid-electric	Full-electric	Foiling Full-electric	Foiling Full-electric	Hybrid-electric	Foiling Full-electric
Battery Capacity	1.04 MWh	1.0 MWh	4.3 MWh	0.25 MWh	0.11 MWh	11.5 MWh	2.8 MWh
Typical Route	6 km crossing	1.6 km crossing	10 km crossing	Up to 74 km	Up to 140 km	260 km crossing	Up to 130 km
Vessel Capacity	360 passengers 120 cars	375 passengers 90 cars	600 passengers 200 cars	30 passengers	4 to 6 passengers	1,300 passengers 470 cars	150 passengers

Source: Multiple, Company websites and announcements

Space Applications

SpaceX Starship rocket is expected to continue to reduce cost to orbit and enable larger battery applications to support expanded mission capacity.

APPLICATIONS	AMBIENT PRESSURE	MISSION EXAMPLE	CELL CHEMISTRY EXAMPLE	AVG. MISSION DURATION	RADIATION	AVG. TEMPERATURE	DESIGN CHALLENGES
EARTH	101.3 kPa	Electric vehicle	Graphite + NCM	8-12 years	H-3, Be-7, C-14,Na-22 0.21mSv/year	-30°C to +40°C	Corrosion
UPPER ATMOSPHERE	200 Pa	Stratostats	Graphite + LCO	<100 days	He, Li- through Fe ions Neutrons 1-10 MeV 1.2 Neutrons/cm^2/s,	-20°C to -60°C	Low temperatures, icing, pressure variations
LOW EARTH ORBIT (LEO)	10^{-6} - 10^{-9} Pa	ISP satellites	Graphite + NCA or LFP	<30 days (humans) 4 - 26 years (constellations)	1000-10 M Protons and Electrons/cm^2/s	-65°C to +125°C	Sealing under frequent temperature variation
GEOSYNCHRONOUS ORBIT (GEO)	10^{-12} Pa	Media broadcasting	Graphite + NCA or Nickel Hydrogen	>7 years (many operating past EOL)	400-500 km/s Protons & Electrons 30/cm^2/s	-196°C to +128°C	Calendar life, high cycle-life
LUNAR	3 × 10^{-9} Pa	Lunar rover	Pu-238 RTG (radioisotope thermal generator)	3 months design, 31 months life (Jade Rabbit rover)	Protons, Electrons 10-10000 MeV, 1-10 Protons/cm^2/s	-130°C to +120°C	Extended duration of hot and cold/dark periods
MARS	560 Pa	Martian rover	Graphite + NCA	90 days NASA design (Opportunity lasted ~15 years)	Protons, Electrons 1-1000 MeV, 100-1000/s	-153°C to +20°C	Sealing under temperature variation, RTG radiation
DEEP SPACE	10^{-14} - 10^{-18} Pa	Deep space probes	Pu-238 RTG (radioisotope thermal generator)	45+ years (Voyager)	Protons, Electrons 1-10,000 MeV 100-10,000/s	-270°C	Calendar life, RTG radiation and decreasing heating

Source: (1) NASA (2) Virtue Market Research (3) E3S (4) Zhang, J., et al. (5) ESA (6) Singh, L., et al. (7) NASA (8) IDA Org (9) Naito, M., et al. (10) Guo, J., et al. (11) NASA (12) Phys Org (13) NASA (14) NASA (15) Space Flight

Space Missions

Missions completed in 2024 required batteries to operate in a variety of different space conditions. Planned space missions for the future are expected to increase demand for space battery development and application-specific testing for the challenging environments.

	COMMUNICATION SATELLITE	MOON MISSION	LEO HUMAN HABITATS	SCIENTIFIC CAPSULES	HOBBYISTS	MARS MISSION
COMPANY	SpaceX	NASA	Vast	Varda	Crunchlabs	JAXA
MISSION(S)	As of January 2025, there are 6,912 Starlink satellites in orbit, of which 6,874 are working. Larger V2 satellite is expected to launch in 2025.	Artemis	Haven-1	Pharmaceutical trial in 2024	Selfie camera in space; launched January 2025	MMX mission to Mars moon Phobos to collect and return sample
LIFE EXPECTANCY	~5 years	~30 days	3 year orbital with 40 days crewed	~8 months (previous W-1 test mission)	~0.1 to 1 year	5 year return mission
IMPLICATIONS FOR BATTERY DESIGN	Station containing fuel is the system life-limiting factor. Critical to prevent thermal runaway in constellation orbit to avoid Kessler syndrome.	-130°C surface temperatures over 14 day lunar night and 120°C lunar day requires specialized thermal design.	90-minute temperature swings. Battery's ability to vent toxic gases from micro-meteor impacts must be isolated from crew.	90-minute temperature swings on the surface. Continuous Power consumption to maintain process temperatures for scientific capsules.	120Wh cubesat battery. Cell phone batteries must survive LEO operating conditions.	Long duration mission with QSO orbit. Cell longevity over wide temperature change.
BATTERY CHALLENGES	Cell longevity, temperature cycling	Large long-duration temperature variance, radiation	Human life safety, micrometeors	Thermal management in LEO and re-entry capsule	Mass-sensitive design that requires basic operational thermal stability	Surface temperatures range from -4°C to -112° C, reduced solar radiance

Source: Starlink, JAXA 1, CrunchLabs 1, CrunchLabs 2, Jaxa 2, Artemis

Medical Device Batteries

The global medical batteries market has been experiencing steady growth, driven by the increasing adoption of **portable and implantable devices**. It is expected to reach ~USD 2.64 billion by 2033, exhibiting a CAGR of 5.32% during the forecast period.[3]

The regulatory landscape for medical device batteries is rigorous. Manufacturers must adhere to both general **battery standards and medical-specific regulations** to ensure safety, reliability, and compliance across global markets. Key standards include IEC 62133-2, UL 2054, ISO 13485, ISO 14971, IEC 60601-1, and IEC 60601-1-11.[1]

APPLICATIONS	USE CASE EXAMPLE	KEY COMPANIES & DEVELOPMENTS	COMMONLY USED CHEMISTRY	EXPECTED CALENDAR LIFE	EXPECTED CYCLE LIFE	CHALLENGES
INTERNAL BODY BATTERY	Pacemakers, new sensors for orthopaedic implants	Ilika is testing a medical solid-state battery for sensing implant effectiveness.[5] Brain implants, such as Neuralink, needs advancements such as wireless battery technology.[9]	Rechargeable has been tried but were short-lived in pacemakers ~10 years ago[8]. Li-ion primary cells are more common in pacemakers today.[4]	Up to 10 years[7]	Li-ion is single use New micro solid-state aiming for 1000+ cycles[5]	Surgical need for replacement of battery in pacemakers. Wireless rechargeable batteries for sensing technologies are under development and will require FDA approval.
EXTERNAL BODY BATTERY	Disposable patches with needles for blood glucose monitoring	Abbott Laboratories reported 21% increased sales in CGM glucose-monitoring products.[2]	MnO_2, Ag_2O_6	~3 days (disposable)	Single use	The absence of efficient recycling pathways for disposable medical devices means that these materials are seldom reclaimed and can result in soil and water contamination.

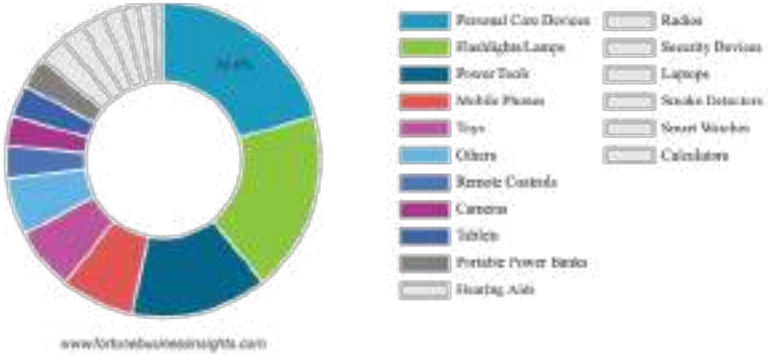
Source: Regulations Summary[1], Abbot Labs[2], Market Size[3], Li-I[4], Micro Solid-State Batteries[5], External Body Chemistries[6], Calendar Life[7], Rechargeable Issues[8], Neuralink[9]

Consumer Electronics

Batteries in consumer electronics include alkaline, zinc carbon, lithium-ion, nickel metal hydride, and other chemistries.

There is an increasing demand for portable and household electronic devices like power tools, increasing the need for easy access to recycling options for consumers.

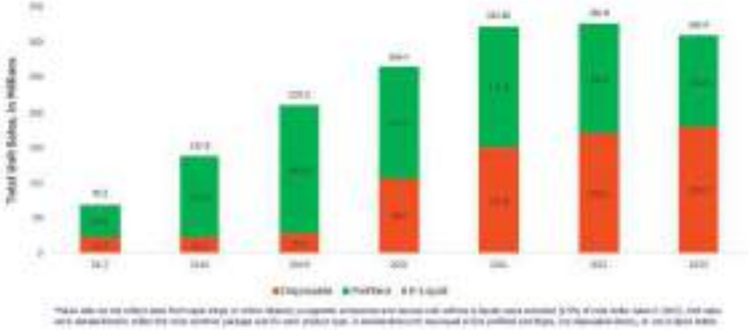
GLOBAL CONSUMER BATTERY MARKET SHARE, BY APPLICATION, 2023



E-Cigarette (Vape) Batteries

From 2020 to 2023, the total e-cigarette unit sales in the U.S. increased by 42.8%, of which 94% were disposable.[1] In the UK, around 1.3M **single-use** e-cigarettes are disposed each week, equivalent to 10 tonnes of batteries each year.[2]

US NATIONAL E-CIGARETTE UNIT SALES BY PRODUCT TYPE, ANNUAL ESTIMATES, 2017-2023*



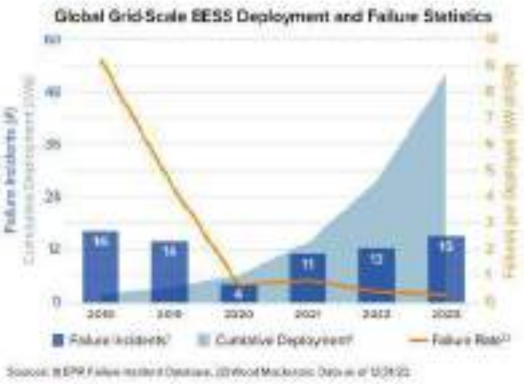
Source: Fortune Business Insights, CDC Foundation Report, Joule

1 INDUSTRY

Fire Events & Response

Fire events underscore the importance of multi-front approaches in lowering the failure incidence rate of battery products. These include validating propagation-resilient designs, proactive measures in quality, working standards, handling, storage, emergency response, and safe disposal of EOL lithium-ion batteries to mitigate fire risks.

PUBLIC EVENT EXAMPLES & RESPONSES
Otay Mesa, California, USA: A fire erupted at the Gateway Energy Storage facility. The fire persisted over several days, with batteries reigniting multiple times. Firefighters implemented evacuation orders and worked to contain the blaze.
Fuzhou, Fujian, China: A fire burned down in a BYD dealership, marking the tenth BYD incident since 2021. BYD conducted an inspection, stating no abnormalities were found in the vehicle batteries and denying that the fire originated from its vehicles.
Hwaseong, Gyeonggi, South Korea: A series of explosions at a lithium battery factory owned by Aricell resulted in a massive fire, killing 23 workers and injuring eight. Approximately 145 personnel and 50 units of firefighting equipment were deployed, extinguishing the fire after about five hours. Subsequently, three company officials were investigated for violating industrial safety laws, and the CEO was arrested.
San Pedro, California, USA: A big rig carrying lithium-ion batteries overturned near the Port of Los Angeles, causing a fire that burned for days. Firefighters allowed the fire to deplete its combustible material and burn out. The incident led to the closure of the Vincent Thomas Bridge and several port terminals, disrupting operations.
Florida, USA: 16 lithium-ion battery fires, including six EVs, caused by exposure to saltwater storm surge during Hurricane Helene. Residents were advised to unplug and relocate damaged devices to open spaces, and agencies coordinated safe disposal measures. EV manufacturers were urged to provide guidance for storm-prone areas.
Fredericktown, Missouri, USA: A massive fire erupted at the Critical Mineral Recovery facility, a lithium-ion battery recycling plant, releasing thick, toxic smoke. Authorities ordered evacuations and shelter in place orders for residents. The Missouri Department of Natural Resources assessed potential environmental impacts.

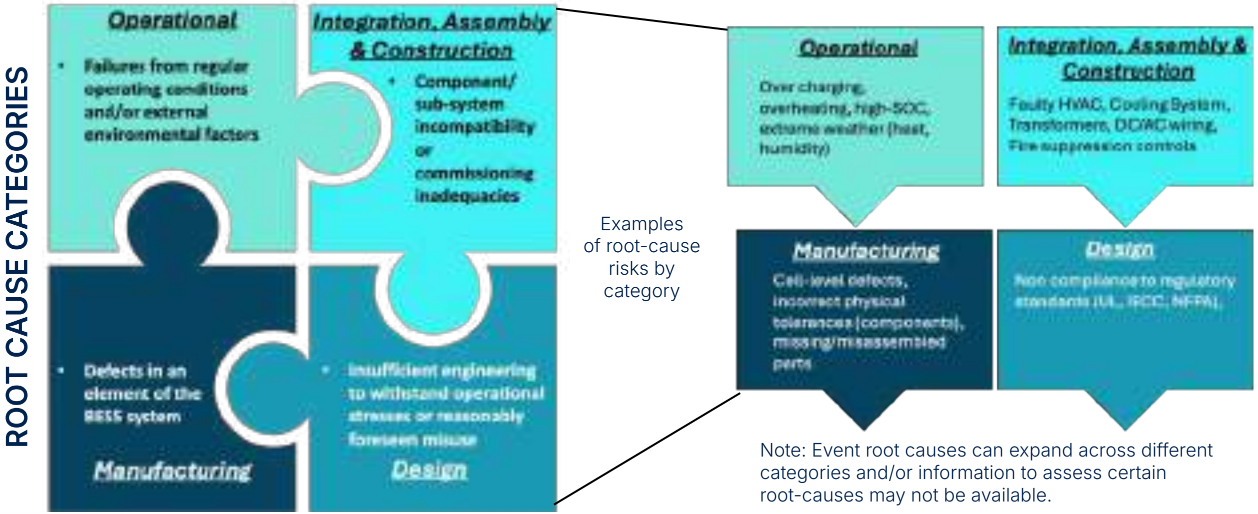


Data from EPRI suggests failure rates of BESS **have decreased** as more battery systems have been deployed.

Root Cause Of BESS Failures

Publicly accessible records of BESS thermal events categorized by root-cause failure mode(s) can be limited and/or incomplete.

While specific enumeration of root-cause failure modes of BESS thermal events is limited and can be highly nuanced, they can be broadly grouped in the following **categories:**



Examples of root-cause risks by category

Note: Event root causes can expand across different categories and/or information to assess certain root-causes may not be available.

THERMAL EVENT DATABASES:

- **UL**- 171 thermal events
- **EPRI**-26 with root-cause

REASONS FOR LIMITED DATABASES WITH ROOT CAUSES:

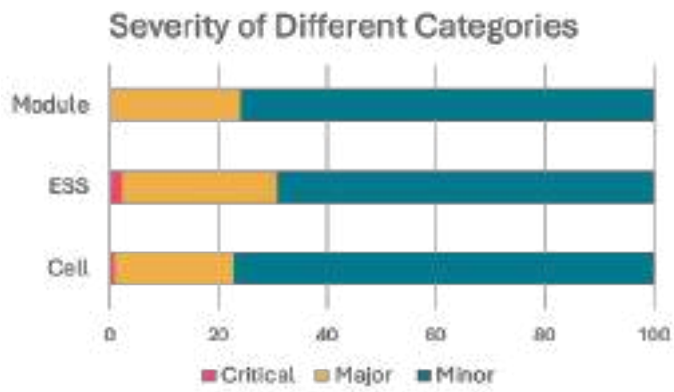
1. Difficulty assessing **damaged** components
2. Significant **cost and time** needed to investigate,
3. hesitancy to provide root-case for specific **event** due to litigation concerns

For most common BESS fire root-causes see **BESS section**

Quality Assessments Of BESS Systems

A meta-analysis of quality audits of 320+ BESS units in five countries reveals that when compared to cell- or module-level defects, **system-level defects are the most likely to lead to high-severity failures** and are the most common type of quality risks in BESS systems **accounting 72% of quality issues.**

Outer rings in the diagram indicate individual categories of the main risks. System defects from improper integration procedures account for the **majority of system-level quality issues.**



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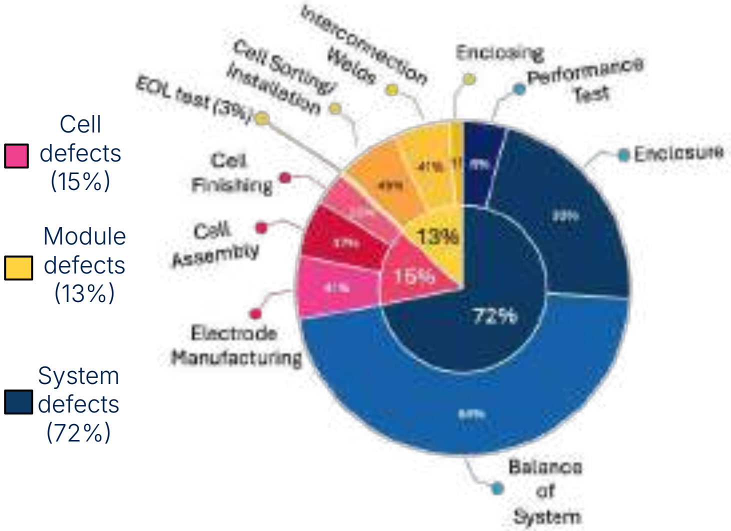
Granular Categorization of Quality Risks



Source: Clean Energy Report [Note: Report used data up to December 2023 Figures shown in slide were reproduced using data provided by authors, which takes into account compiled quality audit data until November 2024.]

Case Study - New York State Interagency Fire Safety Working Group (WG)

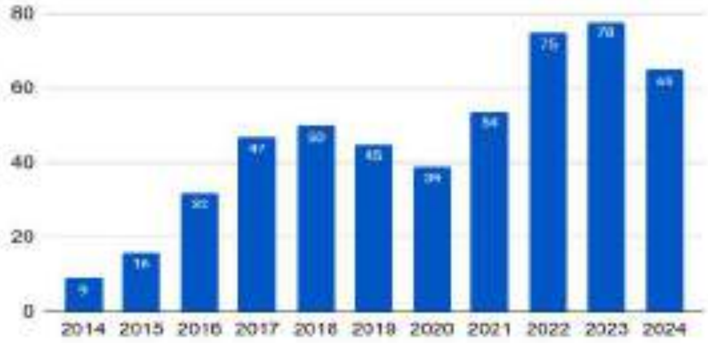
A number of BESS fires occurred in NYC during early and mid 2023, prompting the creation of an inter-agency working group (WP) aimed at investigating three high-profile fire events and creating a review of relevant Codes, Standards, and Regulations. The **goal** was to recommend changes to the fire regulation and safety landscape.

After **feedback** from public and industry safety leaders, a **Notice of Rule in Development** was made public in July 2024. The full list of recommendations and changes can be found **here**. Some **key recommendations** for BESS systems (>600 kWh) were:

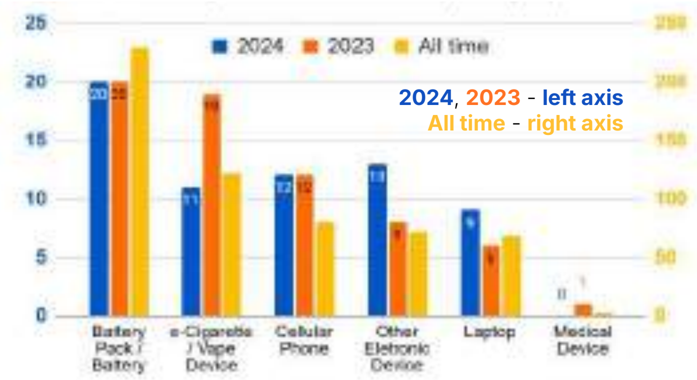
CODE	CHANGES
FCNYS 1206.8	Requirement of industry-funded independent peer reviews for all BESS projects.
FCNYS 1206.7.1	On-call personnel with knowledge of installation must be available for dispatch within 15 minutes and able to arrive on-scene within 4 hrs in case of a BESS Fire.
FCNYS 1206.11.8	Extending safety signage requirements beyond the BESS unit.
FCNYS 1206.2	No more BESS project fire code exemptions for utility-owned BESS projects.
FCNYS 12.07.05.4	Centralization of station service alarm for monitoring of fire detection systems for all BESS installations.

Aviation Safety Incidents

NUMBER OF BATTERY RELATED INCIDENTS IN THE US



NUMBER OF BATTERY RELATED INCIDENTS IN THE US BY CATEGORY



Number of incidents remain stable: Until December 2nd, 2024, there were a total of 65 incidents reported by the US FAA. This is about the same number of incidents were reported in 2023 at the same time of the year (63).

E-cigarettes continue causing incidents: Compared to 2023, e-cigarettes and similar devices created almost twice as many incidents.

Safety procedures are in place: Response to such incidents involve the cabin crew placing the faulty device(s) into thermal containment bags, with the flight continuing to its destination.

Source: FAA

Root Cause Of EV Thermal Failures

Battery and charging malfunctions continue to be a concerning root-cause of EV battery fires.

While different datasets report variances in categorization of root-cause factors, **vehicle faults and battery-management related factors remain the major known root cause** of EV thermal events.

ROOT CAUSE CATEGORIES

Human Factors

- Crashes
- Negligence
- Arson
- Other Accidents

Vehicle Faults

- Battery faults
- Internal Electrical Faults
- Component Faults

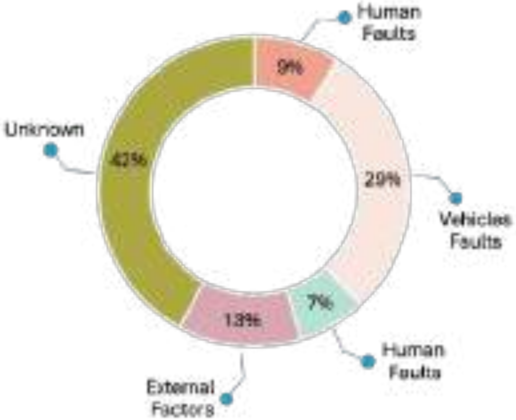
Management Factors

- Charger/charging failure
- Operation out of spec
- Poor system-integration (balancing)

External Factors

- Weather
- External Water Intrusion
- External Fire
- Wildlife

ATTRIBUTED ROOT-CAUSES FOR EVENTS



Images adapted from [1]

Sources: [1] Tohir, M.Z.M., Martin-Gomez, C., Open. Res. Eur, [2] Zhang,Z., Dong, H., Wang, L., Wang, Y., He, X., Energ. Technol., [3] EV Fire Safe

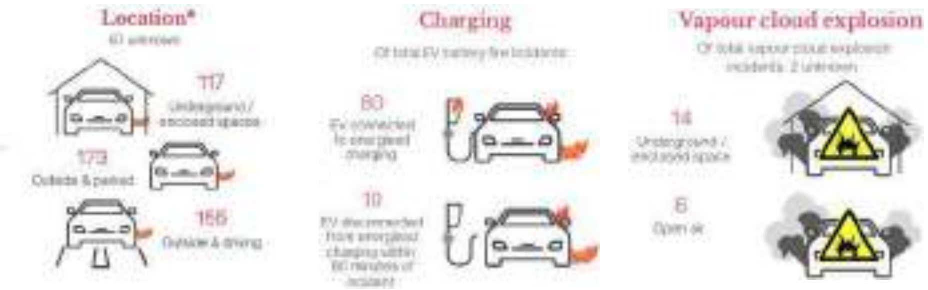
EV Thermal Failures During Charging

Of the 511 fire incidents analyzed by **EV Firesafe** since 2010, 90 incidents occurred when the vehicle was charging. The cause of nearly half the incidents is unknown post incident.

A fraction of incidents end in explosions, with a majority of those involving cars parked in enclosed spaces.

FREQUENCY OF EVENTS WHILE CHARGING

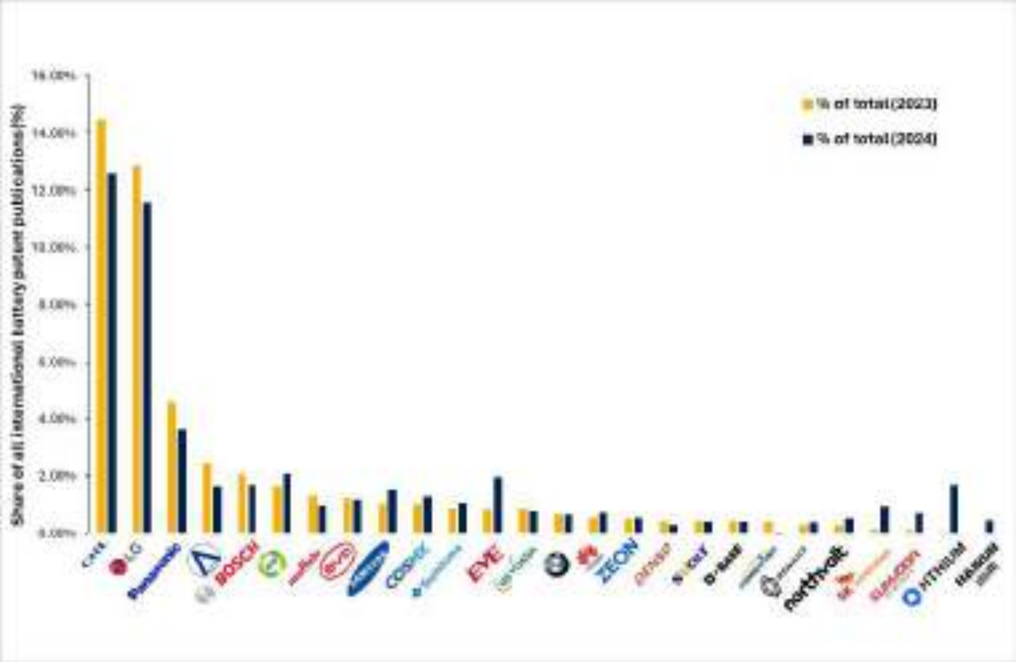
Images taken from [3]



1 INDUSTRY

Changes To The Battery Patent Landscape Between 2023 And 2024*

- The total number of international (PCT) **patent applications increased by 4.19%** (From 10,578 applications in 2023 to 11,021 in 2024)
- **CATL and LG continue their dominance** of PCT publications in 2024, with 12.6% and 11.6% share of total, respectively
- Notable increases in publications for EVE and Hithium in 2024. Hithium particularly notable due to their remarkable growth from a negligible number in 2023 to a significant share in 2024. Hithium now ranks just outside the top 5 battery applicants.
- Bosch is the only non-Asian company in the top 10 applicants for both years



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*Due to 18-month lag between patent application submission and publication, data for 2024 publications reflects applications submitted between mid-2022 and mid-2023

Source: Espacenet search for PCT publications in 2023 and 2024 within CPC classification H01M (batteries), filtered by applicant name and limited to the "top" applicants from both years

Technical Areas Driving Innovation - Patent Data In 2023 And 2024*

- The technical field with the biggest increase in 2024 was "*intercalation of metals other than lithium, e.g. Mg or Al*" (CPC classification H01M 10/054)
- General electrode innovations (H01M 4/02) and battery recycling methods (H01M 10/54) also experienced notable increases
- Methods of coating collectors for electrode manufacture (H01M 4/0404) experienced the largest reduction
- In general, innovation seems to have shifted downstream from the cell component level to the macro scale, e.g. maintenance, recycling, thermal management and pack mounting

*Due to 18-month lag between patent application submission and publication, data for 2024 publications reflects applications submitted between mid-2022 and mid-2023

Source: Espacenet search for PCT publications in 2023 and 2024 within CPC classification H01M (batteries), filtered by CPC sub-classes and limited to most popular sub-classes and the biggest "movers" within those most popular sub-classes

1 Industry

Cell Chemistry Overview

The performance of a lithium-ion battery is determined by the properties and interactions of its key components: the anode, cathode, electrolyte, and separator.

ANODE

The **anode**, typically made from graphite or silicon, affects energy density, cycle life, and charge rate by hosting lithium ions in the charged state.

CATHODE

The **cathode**, composed of materials, such as lithium cobalt oxide or nickel-manganese-cobalt (NMC), determines the battery's capacity, voltage, and thermal stability.

ELECTROLYTE & SEPARATOR

The **electrolyte**, often a liquid or gel containing lithium salts in organic solvents, facilitates ion transport between the electrodes while maintaining electrochemical stability.

The **separator,** a porous membrane, prevents physical contact between the anode and cathode, thereby avoiding short circuits, while allowing ion flow.

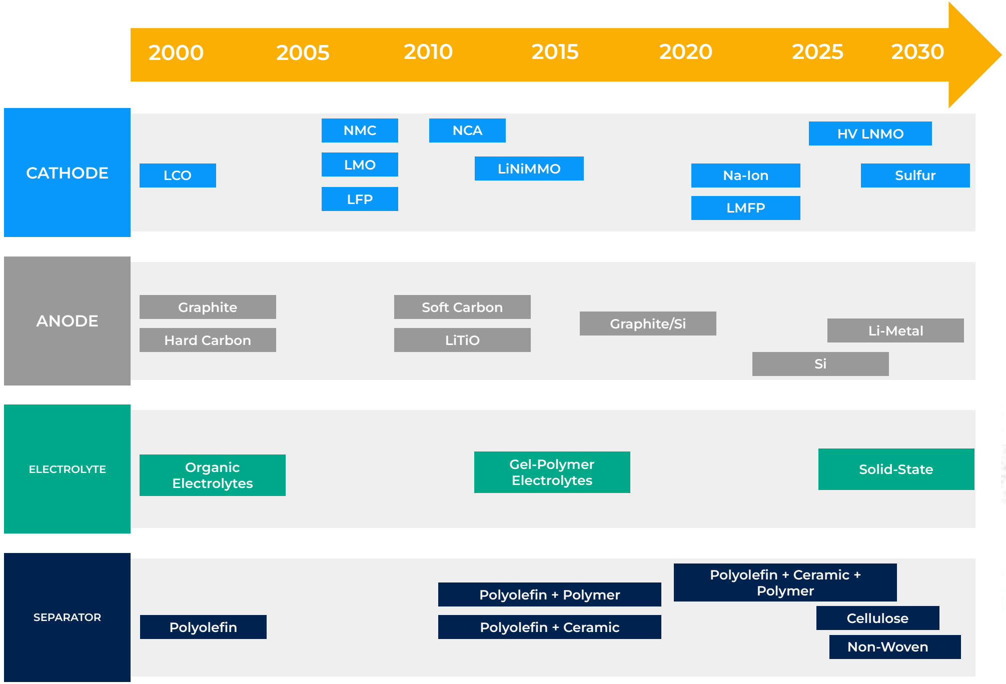
CELL DESIGN

In addition to materials, battery design plays a crucial role in performance. Factors like *electrode thickness*, *packing density*, *cell geometry*, and *thermal management systems* impact energy output, heat dissipation, and overall efficiency.

An optimized cell design must balance performance needs, such as energy capacity, power delivery, and overall safety and reliability, with the the cost of the system.

Source: Battery Report 2023 Cell Chemistry, Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

Timeline Of Battery Cell Chemistry Development



2000 2005 2010 2015 2020 2025 2030

CATHODE
LCO
NMC
LMO
LFP
NCA
LiNiMMO
Na-Ion
LMFP
HV LNMO
Sulfur

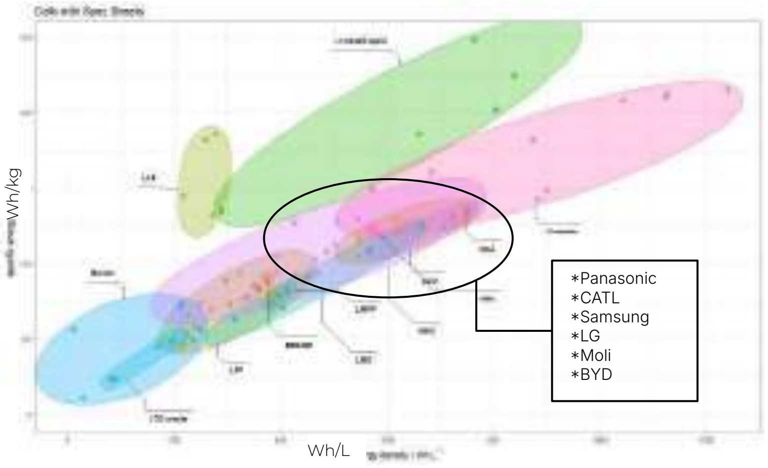
ANODE
Graphite
Hard Carbon
Soft Carbon
LiTiO
Graphite/Si
Si
Li-Metal

ELECTROLYTE
Organic Electrolytes
Gel-Polymer Electrolytes
Solid-State

SEPARATOR
Polyolefin
Polyolefin + Polymer
Polyolefin + Ceramic
Polyolefin + Ceramic + Polymer
Cellulose
Non-Woven

ACHIEVING 500 WH/KG: A KEY GOAL FOR GOVERNMENT AGENCIES IN THE US, EU, AND JAPAN

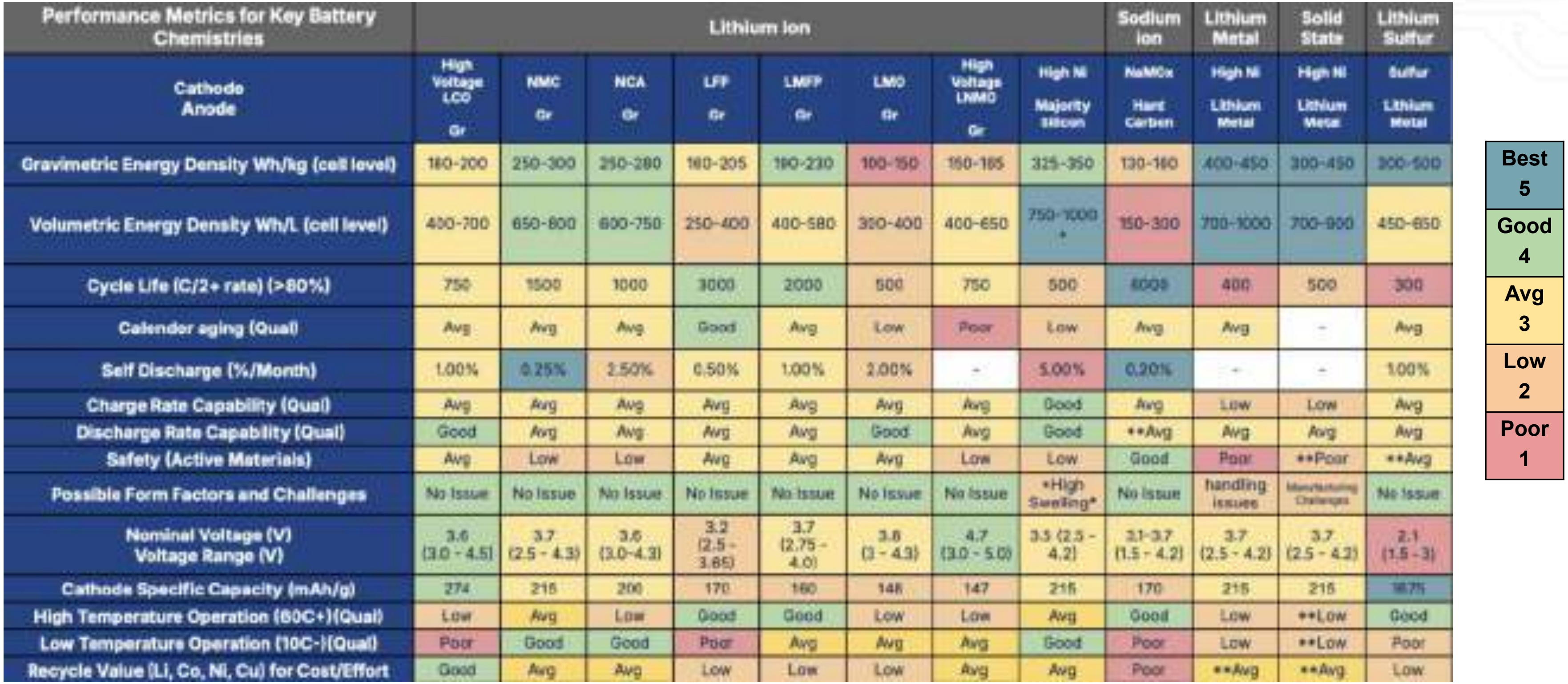
- USA Battery 500
- USCAR
- Japan Rising II (now Rising III)
- Battery 2030 EU



*Panasonic
*CATL
*Samsung
*LG
*Moli
*BYD

Source: Battery Report 2023 (pg 117), Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

1 **INDUSTRY** | **CHEMISTRY** | TRADE OFF MAP (1/2)



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	180-205	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 Challenges	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	Good	Avg	Avg	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 1/01/2025 (Version 3.0)

1 INDUSTRY | CHEMISTRY | TRADE OFF MAP (1/2)

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	428.42	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	12.30	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	17.74	Cycle Life	Wh/kg	Reliability	Safety	Avg	Avg	Avg	Avg	Low	Poor	Poor	Low	Avg	Poor	++Avg	++Avg
Automotive	Moped	88.04	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	69.15	Wh/kg	Wh/L	Power	Cycle Life	Avg	Good	Good	Avg	Avg	Poor	Poor	Good	Poor	Low	++Good	Poor
	Sedan	231.8	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	215.34	Wh/L	Wh/kg	Cycle Life	Cost	Poor	Low	Low	Low	Low	Poor	Poor	Avg	Poor	++Avg	++Low	++Avg
	Industrial Trucks	34.72	Wh/kg	Cycle Life	Cost	Self Discharge	Poor	Avg	Low	Low	Low	Poor	Poor	Avg	Poor	++Avg	++Low	++Good
Consumer Electronics	Computers & Tablets	486.76	Wh/L	Safety	Reliability	Cost	Good	Avg	Low	Avg	Avg	Low	Good	Low	Low	Poor	++Poor	++Poor
	Smart Phones & Watches	568.12	Wh/L	Safety	Reliability	Cost	Good	Avg	Low	Avg	Avg	Low	Good	Low	Low	Poor	++Poor	++Poor
	Power Tools & Gardening	26.5	Power	Cost	Safety	Reliability	Good	Poor	Low	Avg	Avg	Low	Good	Low	Low	Poor	++Poor	++Poor
	E-Bikes	49.7	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	11.68	Safety	Reliability	Power	Self Discharge	Avg	Low	Low	Avg	Low	Avg	Low	Good	Poor	Low	++Avg	++Poor
	Surgical Tools	16.38	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	300.77	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 1/01/2025 (Version 3.0

1 Industry

Cathode Introduction

In lithium-ion batteries, the cathode chemistry refers to the composition of the positive electrode, typically made from transition metal oxides like lithium cobalt oxide (LiCoO2), lithium manganese oxide (LiMn2O4), lithium nickel manganese cobalt oxide (NMC), or lithium iron phosphate (LFP), each offering different balances of energy density, cycle life, cost, and thermal stability depending on the specific metal combination used; the choice of cathode material significantly impacts the battery's overall performance characteristics like voltage, energy density, and power capability.

Function of the cathode:
During charging, lithium ions move from the cathode to the anode, storing energy; during discharge, the process reverses with lithium ions moving back into the cathode.

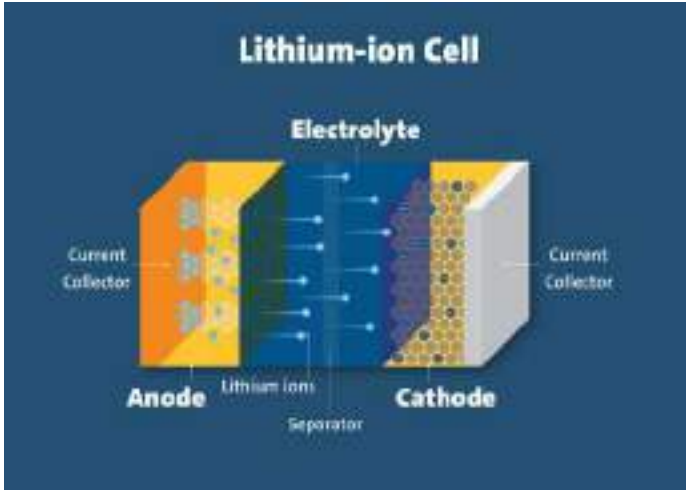
Factors influencing cathode choice:

- **Energy density:** How much energy a battery can store per unit weight.
- **Power density:** How quickly a battery can deliver power.
- **Cycle life:** How many charge-discharge cycles a battery can withstand before significant degradation.
- **Cost:** The price of the cathode material.

Recent trends:
Research is focused on improving performance and reducing costs:

∗High-nickel NMC compositions with reduced cobalt content to achieve higher energy densities while maintaining safety and cost-effectiveness.

∗The development of LMFP, adding manganese to LFP, to increase voltage and energy density.



Sources: Redwood, ANL, Nature-lithium-ion battery cathode chemistry, Battery Report 2023 Cell Chemistry, Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

Major pCAM And CAM Producers

AMERICAS

2030 capacity plan*:
750 kt CAM
175 kt pCAM

- LG Chem
- posco
- EcoPro
- BASF
- TESLA
- ASCEND ELEMENTS
- REDWOOD MATERIALS

EMEA

2030 capacity plan*:
1,000 kt CAM
300 kt pCAM

- umicore
- BASF
- 当升科技
- HUAYOU
- CNGR
- LG Chem
- EcoPro
- Hunan yuneng
- BTR
- 容百科技

ASIA - PACIFIC

2030 capacity plan*:
9,000 kt CAM
4,700 kt pCAM

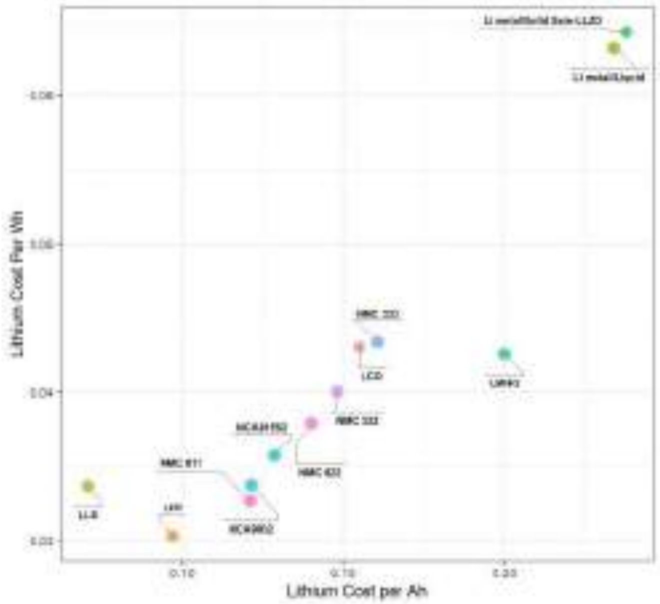
- 当升科技
- CNGR
- Dynanonic
- GEM
- HUAYOU
- 容百科技
- EcoPro
- LG Chem
- posco
- Sumitomo
- L&F Co.,Ltd
- Lopal 龙蟠科技
- 富临精工 FULIN P.M.
- Hunan Yuneng New Energy
- BASF
- umicore

OPERATING

PLANNED

*announced plans as of Q1 2025. Not risk-adjusted

Chemistry Lithium Wh & Ah Cost Map - Drive Towards Cheaper Batteries

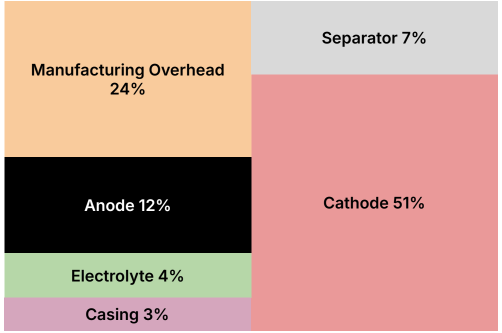


For more details, please visit: Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0)

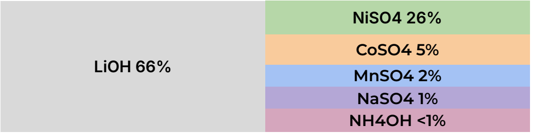
Current market conditions are demanding cheaper batteries for EV's at the same performance of modern day NMC811 batteries.

- **Cost Drivers**
  - 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 cost reductions while improving performance

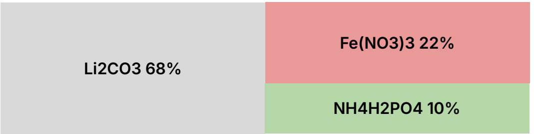
CELL COST BREAKDOWN



NMC811 COST BREAKDOWN



LFP COST BREAKDOWN



Source: Battery Official,Battery Report 2023 (pg 131),Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

Impact Of Nickel Content On The Performance And Applications Of NCM And NCA Cathodes

	NCM 5-series*		NCM 6-series		NCM8-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) 01/02/25	11,386 (consumables)	13,588 (NEV, new energy vehicles)	13,119 (consumables)	14,489 (NEV)	15,237 (consumables) 16,980 (NEV)	n/a	n/a		19,503
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		EV		EV		Heavy duty EV Long range EV		EV, Powertools, two-wheelers.

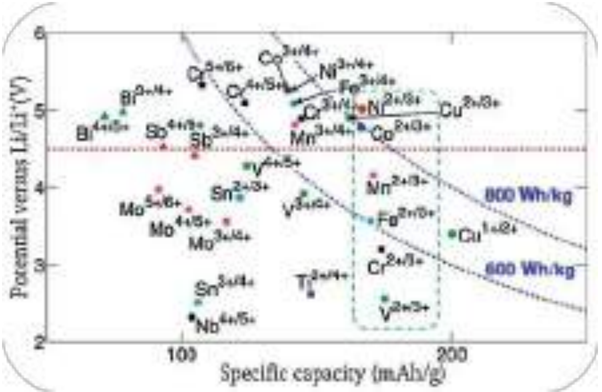
*5-series means there are ~50% Ni in the composition

Source: MTI, MSE, Fangzheng Report, SMM

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, adjusting element ratios, and applying doping or coating**.



[1] Specific Capacity of Cathode Material Only

- **The high-voltage battery market is growing rapidly**, driven by demand for long-range EVs, advanced 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 **LMFP**.
  - High-voltage LCO is ideal for high-energy applications in consumer electronics, drones, and power supplies for AI centers and supercomputers.
  - Single-crystal mid-Ni NCM uses high voltage to offset mid-Ni's lower capacity while offering enhanced safety.
  - LMFP boosts LFP's voltage while maintaining thermal stability, making it suitable for blending with high-voltage mid-Ni NCM.

- However, high voltage brings challenges like gas evolution, electrolyte compatibility, and heat generation, requiring advanced thermal management techniques and cell-to-pack (CTP) designs.

Source: Liu et al. Mater. Today 2016

Nickel Manganese Cobalt (NMC) Basic Information

	Strength	Weakness	Opportunity	Threat
NMC	• **Properties and performance:** ○ High energy density ○ Low temperature performance ○ High voltage • Strong battery supply chain • High recycle value	• **Safety** ○ High thermal release ○ Dangerous side reactions during cycling ○ Off-gassing, cell swelling ○ Ni, Co hazardous to human and environmental health • High cost of metals and processing	• **Broad range of use cases** ○ Long range/high-end EVs ○ Buses, boats, heavy-duty equipment, power tools • Broad market for recycling supply chain • Scalable process • Continuing advances in safety and performance	• Advances in lower cost and safer alternatives ○ LFP, LNMO, sodium-ion • Nickel and cobalt supply chain ○ **Ni and Co make NMC expensive** despite metal prices at all-time lows ○ Ni Mining practices can be environmentally damaging

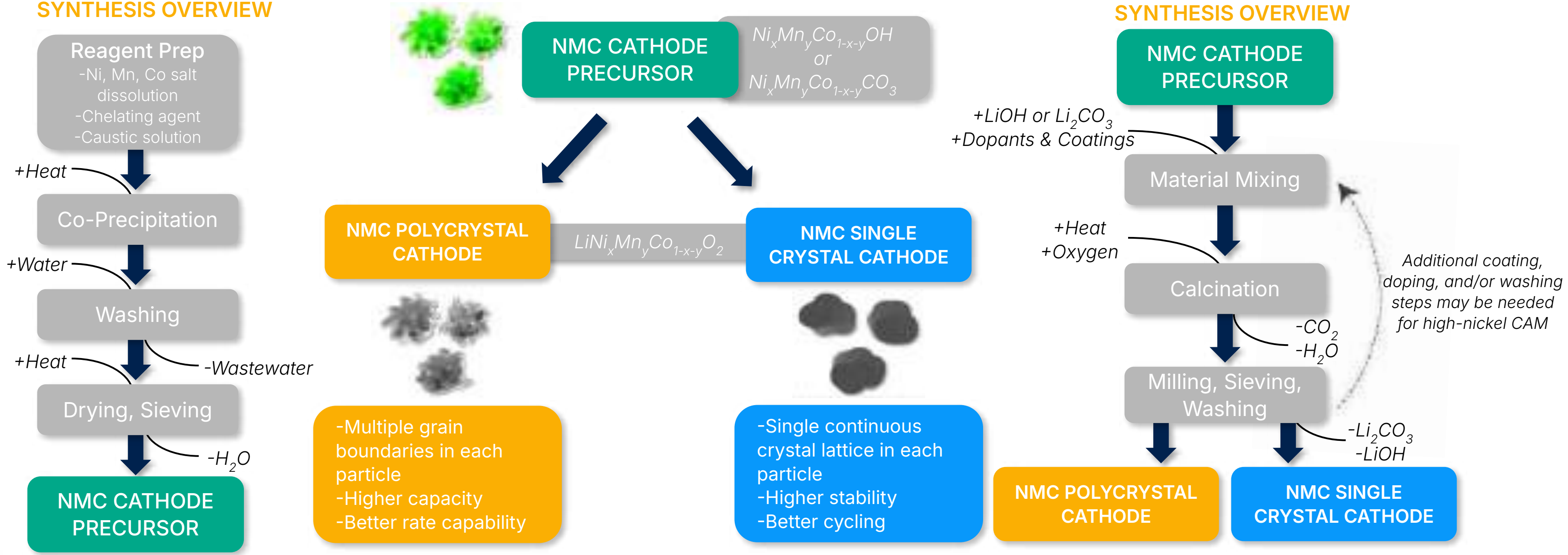
Lithium Nickel Manganese Cobalt Oxide (NMC): One of the most common cathode chemistries in modern EVs, especially outside of China.

Significant research progress: Improvements to NMC safety and performance continue to be researched, including variations such as high-voltage medium-nickel chemistries as well as new dopant and coating formulations.

Current industry leaders: Mostly located in China, South Korea, Japan, and Europe, but North American capacity is in the pipeline.

Source: F I Saaid et al. Heliyon Cell Press. 2024

NMC Cathode Active Material Synthesis Process



NMC CATHODE PRECURSOR SYNTHESIS OVERVIEW

Reagent Prep
-Ni, Mn, Co salt dissolution
-Chelating agent
-Caustic solution

+Heat

Co-Precipitation

+Water

Washing

+Heat
-Wastewater

Drying, Sieving

-H_2O

NMC CATHODE PRECURSOR

NMC CATHODE PRECURSOR

$Ni_xMn_yCo_{1-x-y}OH$
or
$Ni_xMn_yCo_{1-x-y}CO_3$

NMC POLYCRYSTAL CATHODE

$LiNi_xMn_yCo_{1-x-y}O_2$

NMC SINGLE CRYSTAL CATHODE

-Multiple grain boundaries in each particle
-Higher capacity
-Better rate capability

-Single continuous crystal lattice in each particle
-Higher stability
-Better cycling

NMC CATHODE SYNTHESIS OVERVIEW

NMC CATHODE PRECURSOR

+LiOH or Li_2CO_3
+Dopants & Coatings

Material Mixing

+Heat
+Oxygen

Calcination

-CO_2
-H_2O

Milling, Sieving, Washing

Additional coating, doping, and/or washing steps may be needed for high-nickel CAM

-Li_2CO_3
-LiOH

NMC POLYCRYSTAL CATHODE

NMC SINGLE CRYSTAL CATHODE

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

JANUARY

Ascend Elements targets 90% reduction of carbon footprint of NMC622 CAM using its Hydro-to-Cathode® process by 2030

FEBRUARY

LG Energy Solution Wroclaw (Poland) plans to deliver around 200k NMC battery modules for e-buses by 2027

MARCH

Cobalt Blue plans cobalt-nickel refinery in Kwinana, Australia, with production estimated by 2026 to meet U.S. IRA & EU CRMA

APRIL

Green Li-ion launches first US battery grade pCAM-producing recycling facility, capable of processing 3 kt of black mass from NMC batteries

MAY

Orano and **XTC New Energy** sign agreement for to build two plants for CAM and pCAM in Dunkirk, France

JUNE

LOHUM producer of NMC CAM (India) is set to expand second-life battery recycling capacity from 5 to 30 GWh by 2027 with $100M CAPEX

JULY

Huayou Cobalt announces construction progress on NMC CAM factory in Ács, Hungary

AUGUST

NOVONIX and **CBMM** sign joint development agreement focused on Nb addition to improve cycle life of NMC CAM

SEPTEMBER

Altilium delivers first EcoCathode™ NMC to UKBIC for production and qualification of NMC811 cells

OCTOBER

Earspring Finland receives environmental permit for NMC battery plant project in Kotka, Finland

NOVEMBER

Axens aims to acquire land in Saint-Saulve, France for NMC CAM joint plant with **Hunan Changyan Lico**

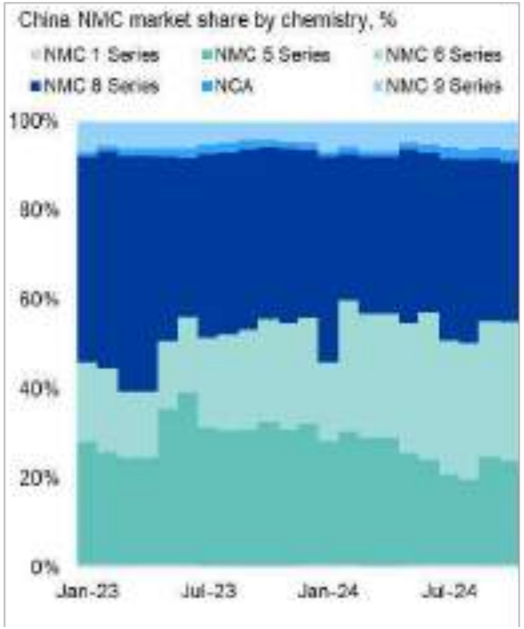
DECEMBER

Ascend Elements aims to produce up to 3 kt of battery grade lithium carbonate in Covington, Georgia, starting in 2025

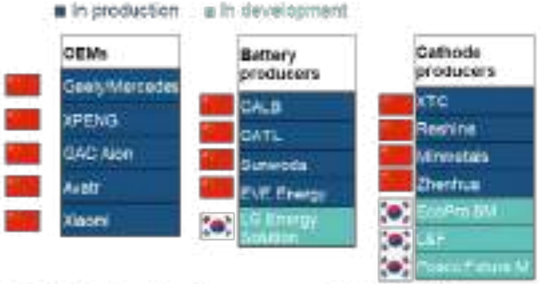
Source: Various news articles linked above

Medium-Nickel High-Voltage Technology Is Aimed At Enhancing Competitiveness of NMC

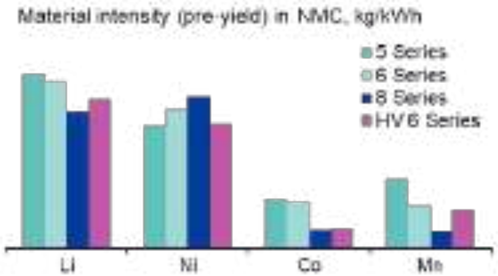
MID-Ni NOW MOST OF CHINA Ni-CATHODE MARKET



MANUFACTURER PLANS FOR MID-Ni HV CATHODE



MATERIAL INTENSITY IS ON PAR WITH NMC 811



- MNHV cathode offers the energy density of NMC 811 with the low cost of NMC 5/6 Series
- Enabled by single-crystal material
- There is a higher risk of battery degradation, but this is being mitigated
- Developed at a time of high Ni/Co prices and now increasingly adopted in best-selling BEVs
- High-voltage chemistries dampen the demand for expensive raw materials
- Several automakers are now moving back away from high-nickel chemistries

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Modelled intensity for MNHV is based on NMC 631 variant

Nickel Cobalt Aluminum (NCA) Basic Information

	Strength	Weakness	Opportunity	Threat
NCA	• **High energy density with excellent rate capability** • Long calendar life and structural stability • No manganese leaching or structure deformation issues • Mature production techniques • Strong recycling value • Washing step could be omitted during process	• High cost due to higher Ni content and Al price as well as the manufacturing process • Thermal stability concerns, particularly at high temperatures • **Complex manufacturing process in that it is difficult to evenly incorporate aluminum into CAM particles**	• High power applications like power tools, forklift, e-trucks • Application in electric race cars • **Fast charging capabilities for consumer electronics and EVs** • High-end electric vehicles with extended range • ESS	• **Competition from NCM and NCMA chemistries** • Emergence of high voltage cathode materials • NCA technology and products are not as widely accessible or cost effective as NCM

Nickel Cobalt Aluminum (NCA): Continues to be a prominent technology in electric vehicles and portable electronics.

Development progress: Optimizing 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 and EcoPro have made significant investments in NCA development in the past year.

Primary use: EV applications, with power tools, e-bikes, and portable electronics making up the rest.

Source: Battery Report 2023, GEM Co., Ltd, ZHNANO

JANUARY

EcoPro BM & **Samsung SDI** sign $33.5B NCA CAM supply deal for EV batteries between 2024-2028

FEBRUARY

Cirba Solutions and **EcoPro** cooperate on recycled materials for pCAM and CAM production.

MARCH

Stellantis presents Dodge Charger Daytona, the first model based on STLA Large architecture with a 100.5 kWh NCA battery

APRIL

EcoPro BM obtains non-exclusive license on GEMX® platform for high-Ni CAM production (such as gNMC®, gNCA®) from **CAMX Power**

MAY

Volvo Trucks uses high-nickel NCA battery packs, but continues to explore other battery chemistries

JUNE

Samsung SDI obtains a GEMX® platform non-exclusive license for gLNO®, gNMC®, gNCA® from **CAMX Power**

JULY

Samsung SDI clinches $724M deal with **NextEra Energy** for Samsung Battery Box 1.5 with a total capacity of 6.3 GWh

AUGUST

Samsung SDI agrees with **General Motors** to establish a joint venture with $3.5B capital to produce of 27 GWh EV batteries in New Carlisle, Indiana

SEPTEMBER

Next-Gen Energy Technology and **Siemens** sign MoU to support Next-Gen's efforts to build NCA CAM plant in Australia

OCTOBER

Posco Future M begins NCA cathode production at plant with 30 kt/year capacity in Pohang, South Korea

NOVEMBER

BloombergNEF report shows that **Redwood Materials** NCA CAM production method requires 60% less water and 80% less energy than mining and refining of virgin materials

DECEMBER

M2i Global partners with **Next-Gen Energy Technology** on setting up a pilot plant of NCA CAM with a capacity of 2-10 kt/year in Australia

Source: Various news articles linked above

Nickel Cobalt Manganese Aluminum (NCMA) Basic Information

	Strength	Weakness	Opportunity	Threat
NCMA	- Combines the strengths of NCM and NCA - **Reduces Co content, lowering costs and addressing supply chain concerns** - High energy density - Suitable for various cell formats, providing flexibility in design and application	- **Requires precise control in synthesis to maintain quality** - Structural instability due to high Ni content - High nickel content drives up costs in raw materials, CAM production, and manufacturing processes like CTP. - Thermal instability	- **High-end EVs with long range and fast charging capabilities** - Power tools requiring high output and fast energy delivery - Drones - Strong recycling potential for valuable materials	- Competition from NMC, NCA, and LFP - **Growing safety concerns over high nickel content** - High sensitivity to nickel prices

Lithium Nickel Cobalt Manganese Aluminum Oxide (NCMA): Represent the 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, and reduced reliance on cobalt. The ongoing research 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

JANUARY

LG Chem breaks ground for NCMA CAM production plant in Clarksville, Tennessee, that will supply 60 kt/year starting in 2026

FEBRUARY

LG Chem signs $17B contract with **GM** to supply 500 kt of NCMA CAM from 2026 through 2035

MARCH

LG Energy Solution R&D investment exceeds $760M in 2023,with plans to increase spending on development of NCMA and LFP batteries

APRIL

L&F wins $6.8B contract to supply 176 kt of NCMA cathodes to the European battery cell producer from 2025 to 2030

MAY

Kia unveils latest EV3 model with 600 km range, equipped NCMA battery cell produced by **HLI Green Power**

MAY

Cadillac introduces OPTIQ model with 300 mile driving range based on Ultium Platform with 85 kWh NCMA battery pack

JULY

HLI Green Power opens $1.2B battery plant in Karawang, Indonesia with annual capacity of 10 GWt/h of NMCA cells to power 150k BEVs

AUGUST

LG Energy Solutions plans to complete pilot line for dry coating in Ochang, South Korea by the end of the year, aiming for mass production in 2028

OCTOBER

LG Energy Solutions and **Toyota** sign supply agreement for 20 GWh/year of NCMA modules for BEV starting in 2025

OCTOBER

LG Energy Solutions signs two agreements, worth $9.5B together, to supply **Ford Motor** with a total of 109 GWh of cells from 2026 through 2032

NOVEMBER

LG Energy Solutions signs 5-year, $6.7B deal to supply 67 GWh of NCMA EV batteries for **Rivian** R2 SUV, set to debut in 2026

DECEMBER

Ultium Cells celebrates production of their 100 millionth NMCA battery cell in their Warren, Ohio facility

Source: Various news articles linked above

Lithium Cobalt Oxide (LCO) Basic Information

	Strength	Weakness	Opportunity	Threat
LCO	• High energy density: Ideal for portable electronics • Extensive real world data availability; perfect for medical applications • Higher voltage capability: Supports voltages up to 4.5V • **Mature technology: Longer track record of use compared to other cathode chemistries** • Highest recycling value	• Lower thermal stability • Limited to lower C rates due to overheating • Higher cost • Reduced cyclability under high power demand • **Cobalt price volatility and supply instability** • Gas evolution • Environmental impact during manufacture and mining	• **Portable and consumer electronics** • Industries requiring 10+ years of reliability data • High recycling value in domestic industry • Energy supply for AI and supercomputers needing high capacity and energy density • Blended with NCM in lower-profit portable devices	• **High energy NCM and NCA for high performance applications** • High voltage NCM for energy intensive use cases • Ethical concerns and supply instability of cobalt due to geopolitical factors

Lithium Cobalt Oxide ($LiCoO_2$): Still a widely used cathode material, especially in consumer electronics like smartphones, laptops, and medical devices, due to its high energy density and stable voltage.

Research focus: Increasing its practical capacity, enhancing thermal stability, improving cycle life, and reducing its environmental impact, particularly through recycling initiatives.

Current industry leaders: production primarily based in China, Japan, and South Korea.

Source: LCO Overview, LFP Pros and Cons, LCO vs LFP, LCO Life Cycle, Congo's Cobalt Controversy,

JANUARY

Nanotech Energy 18650 2Ah LCO Safe Cell along with their NMC (2.1Ah) and LFP (1.5Ah) versions are ready for production at Chico 2 plant in Chico, California

FEBRUARY

SiAT and **CPDC** show that adding 5% of LCO to 2nd gen LMFP paste prevents catastrophic failure at 4.5V in nail penetration test

MARCH

EaglePicher awarded **GS Yuasa** contract to supply Generation 4 LSE112 (112 Ah, 3.75V) LCO/Graphite cells for space

APRIL

Cobalt Blue Holdings plans Cobalt-Nickel Refinery Project near Perth, Australia, the country's first large-scale cobalt and nickel refinery

APRIL

Apple announces use of 100% certified recycled cobalt in all Apple-designed batteries by 2025

JUNE

TMC and **SGS** produce the world's first cobalt sulfate from deep-seafloor polymetallic nodules, demonstrate the viability of this resource

JULY

Ateios Systems announces release of first PFA-free RaiCore™ High-Voltage Lithium Cobalt Oxide electrodes

SEPTEMBER

Electra Battery Materials Corporation announces $20M strategic investment from DoD for first battery grade cobalt refinery in North America

NOVEMBER

Nippon Foundation and the **University of Tokyo** discover 200 mt of rare materials, including 610 kt of cobalt, around Minami-Tori-shima island harbors

DECEMBER

Ateios Systems secures $350k NSF Engines grant for development of RaiCore™ LCO cathodes

DECEMBER

Cobalt Blue and **Ecobatt** announce strategic partnership to establish a domestic supply chain of critical minerals by processing black mass from recycled batteries

DECEMBER

Ateios Systems signs strategic partnership with several battery manufacturers for its RaiCore™ High Voltage Lithium Cobalt Oxide electrodes

Source: Various news articles linked above

Lithium Cobalt Oxide (LCO) Basic Information

Lithium cobalt oxide remains the leading cathode material for lithium-ion batteries in portable electronics due to its high specific capacity and stable discharge platform. As the demand for higher energy density and longer cycle life increases, raising the working voltage has emerged as the most effective solution. By increasing the charge cut-off voltage above 4.4V, more lithium is extracted, enabling additional Li+ ions to contribute to the de-intercalation process and significantly boosting practical capacity. **High-voltage LCO is increasingly in demand for advanced consumer electronics, drones, and energy supply solutions for AI centers and supercomputers.**

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%

In mid-2023, Shanghai Metals Market (SMM) began publishing prices for high-voltage LCO to enhance market transparency and help upstream and downstream industries manage price fluctuations and risks. **This move reflects the maturation of high-voltage LCO technology and the increasing demand for higher energy density in advanced electronic applications.**

Voltage (V)	Price (USD/mt) 01/03/25
4.2	16,182.32
4.4	16,617.55
4.45	17,161.6
4.48	17,639.15
4.5	18,062.3
4.53	20,888.55

Source: Wu et al. J. Energy Chem. 2022, SMM1, SMM2

Lithium Iron Phosphate (LFP) Basic Information

	Strength	Weakness	Opportunity	Threat
LFP	- **Cost-Effectiveness:** uses abundant and relatively inexpensive materials, avoiding cobalt and nickel - **Safety:** high thermal and chemical stability, reducing the risk of overheating and fires - **Long Cycle Life:** These batteries can endure more charge-discharge cycles than other chemistries, making them ideal for applications requiring durability over a long lifetime	- **Lower Energy Density compared to NMC or NCA cathodes, limiting the range in EVs or capacity in portable devices** - Volumetric Limitations: The lower energy density requires larger and heavier battery packs for the same capacity - A significant portion of LFP production is concentrated in China - Lower incentive to recycle LFP batteries	- **EV Market Growth:** The demand for affordable and safe batteries aligns well with LFP technology for entry-level and commercial EVs - **Stationary Energy Storage:** long cycle life and safety make LFP ideal for renewable energy storage systems, a rapidly growing market - **Cell to Pack technology:** Helps offset energy density concerns and reduces pack costs due to lower complexity	- Higher energy density alternatives like NMC chemistries surpass LFP in performance-critical applications - Market Saturation: Rapid adoption could lead to oversupply and declining profit margins, impacting producers heavily reliant on LFP cathodes - **Minimal recycling value of LFP batteries could be problematic with recycling mandates**

Lithium iron phosphate (LFP): Solidified their dominance in the global battery industry in 2024, capturing 56% of the lithium ion cathode market share [1].

Recent surge: Primarily driven by extensive adoption in China, with LFP batteries supplying over 70% of the country's electric vehicle (EV) demand.

The appeal of LFP technology: Lies in its cost-effectiveness, safety, and environmental benefits, as it avoids the use of scarce and expensive materials like nickel and cobalt.

Global expansion: International manufacturers, including those in Europe and the United States, have begun exploring LFP solutions to enhance EV affordability and sustainability.

Source: Battery Report 2023 (pg125), Nature-lithium-ion battery cathode chemistry, Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

JANUARY

First Phosphate Corp. enter agreement with **American Battery Factory Inc.** & **Integrals Power Ltd.** to produce 40 kt LFP CAM annually

FEBRUARY

LG Energy Solutions signs agreement to purchase 160 kt of LFP CAM from China-based **Changzhou Liyuan** by 2029

MARCH

SK announces mass production of LFP batteries in 2026, dependent on demand

APRIL

Jiangsu Lopal Tech launches LFP production plant with initial output of 30 kt at Kendal Industrial Park in Indonesia

MAY

Hunan Yuneng announces $135.5M investment in 50 ktpa LFP battery production plant in Extremadura, Spain

JUNE

Gotion High Tech plans $1.3B plant for LFP cells in Kenitra, Morocco, aiming to start production in Q3 2026 with initial capacity of 20 GWh

JULY

AESC Spain begins construction of LFP gigafactory with annual capacity of 30 GWh in Cáceres, Spain

AUGUST

Morrow Batteries opens first GWh LFP battery cell factory Arendal, Norway, with plans to deliver product by the end of the year

SEPTEMBER

First Phosphate selects Saguenay-Lac-St-Jean, Québec, Canada for 10 kt LFP CAM plant, transforming phosphate from mines located 80-120 km away

OCTOBER

StB Giga Factory Inc. an Australian-Chinese joint venture, opens $124.6M plant for LFP batteries in New Clark City, Philippines with 300 MWh capacity

NOVEMBER

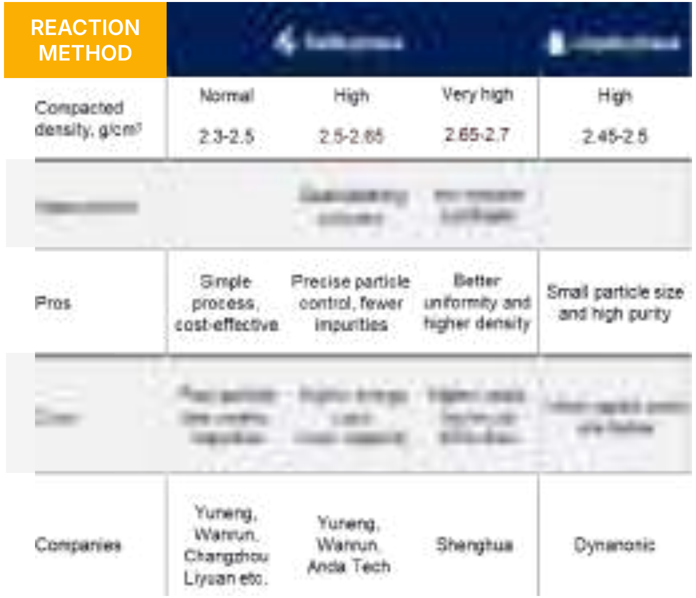
Ford plans 20 GWh LFP battery plant in Marshall, Michigan in 2026 to be run by subsidiary **BlueOval Battery Park Michigan**

DECEMBER

Stellantis and **CATL** announce plans to invest up to €4.1B in joint venture for large-scale LFP CAM plant in Zaragoza, Spain

Source: Various news articles linked above

High-Compaction-Density Cathode Is The Next Evolution In LFP Technology



REACTION METHOD	[illegible]			[illegible]
Compacted density, g/cm³	Normal 2.3-2.5	High 2.5-2.65	Very high 2.65-2.7	High 2.45-2.5
[illegible]		[illegible]	[illegible]	
Pros	Simple process, cost-effective	Precise particle control, fewer impurities	Better uniformity and higher density	Small particle size and high purity
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Companies	Yuneng, Wanrun, Changzhou Liyuan etc.	Yuneng, Wanrun, Anda Tech	Shenghua	Dynanonic

- Enables fast-charging in LFP batteries
- Higher energy density
- Requires new tooling & processes
- Commands a premium
- Already in several BEVs in China

High compaction density (HCD) LFP cathode material - improves **energy density and fast-charging capabilities** by addressing the trade-off between electrode thickness and performance.

In China, it may **accelerate the phase-out of old LFP capacity**, as manufacturers must upgrade equipment and modify processes. HCD LFP involves a shift from single-sintering to a double-sintering process that ensures precise particle control, fewer impurities, and uniform carbon coating.

Although the new process increases production time and costs, **battery manufacturers have been willing to pay a premium** for high-quality materials and **help struggling LFP producers** to invest in new-generation production lines.

Also referred to as '4th Gen LFP', HCD is specifically carved out in China's recent proposal to **restrict technology exports for high-end LFP.**

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Lithium Manganese Iron Phosphate (LMFP) Basic Information

	Strength	Weakness	Opportunity	Threat
LMFP	• **Higher energy density than LFP** • Lower cost per kWh than NMC • **Abundance and low cost of Mn** • Higher voltage • Better low temperature performance than LFP • Thermal stability • High voltage platform • Leverage existing LFP manufacturing processes and infrastructure	• Reduced cycle life compared to LFP, due to the Jahn-Teller distortion of Mn and metal dissolution into electrolyte. • **Poor electrical conductivity lithium-ion diffusion** • Like LFP, SOC estimation is challenging • Dual voltage plateau worsens cell consistency, causing mileage data fluctuations in BMS	• **Mid-to-Long Range EVs** • Heavy-duty vehicles (trucks and buses) • Blend cathode with NCM for high-voltage batteries • Potential to replace LFP in EV applications	• Lack of industry standardization causes product inconsistencies • Scaling challenges • Advanced modifications required for LMFP increase process complexity • **Underdeveloped supply chain**

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 and lithium-ion diffusion through coating, doping, and size reduction

LMFP development: Led by major Chinese battery manufacturers, with new North American companies also advancing LMFP technology for EV and ESS applications

Source: Battery Report 2023 (pg125),Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

LMFP v. LFP

STRUCTURE

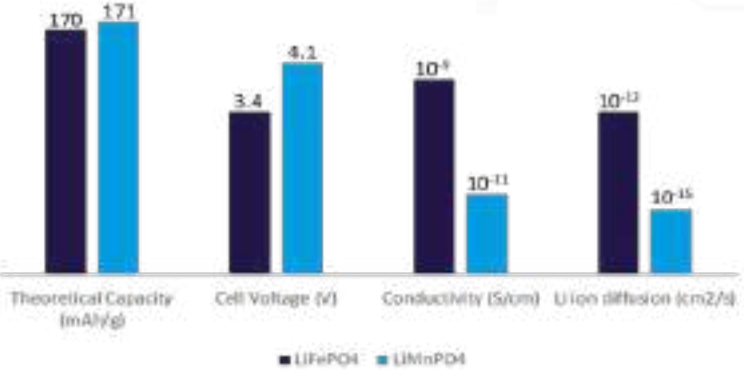
- LMFP partially replaces Fe in LFP with Mn.
- Incorporating Mn into the system raises the redox voltage, resulting in increased overall energy density.

PERFORMANCE

- LMFP's capacity at low-temperature performance is more stable compared to LFP.
- Both chemistries exhibit similar safety profiles.

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	161.7 mAh/g	157.4 mAh/g	142.4 mAh/g	126.3 mAh/g	63.0 mAh/g
534.9 Wh/kg	553.5 Wh/kg	557.0 Wh/kg	515.8 Wh/kg	459.9 Wh/kg	230.6 Wh/kg

*20% Mn: $LiMn_{0.2}Fe_{0.8}PO_4$

Source : Guoyuan Securities, Battery Report 2023 (pg125)

FEBRUARY

SiAT announces strategic partnership with **CPDC** to launch 2nd gen LMFP paste with phosphazene to enhance safety

FEBRUARY

Tesla validates LMFP battery cells (M3P) from **CATL**, which are already being used in EV's from Chery and Huawei

MARCH

Mitra Chem and **Saint-Gobain Ceramics** enter strategic partnership to commercialize IRA-compliant LMFP cathodes in 2026

APRIL

BYD announces launch of 2nd gen of Blade Battery based on LFMP with 220 Wh/kg cell level density and 190 Wh/kg pack level gravimetric density

MAY

Jitendra EV launches high performance Primo S and Primo Plus scooters with LMFP and NMC batteries

JUNE

Gotion InoBat Batteries receives €214M from Slovakia for construction of L(M)FP battery plant in Slurany, Slovakia

JULY

LOHUM plans to develop LMFP as part of a new recycling and CAM production facility with capacity 20 GWh by 2027, supported by $136M investment

JULY

Wildcat Discovery Technologies and **Austin Elements** set up collaboration to recycle LMFP batteries and battery scrap

SEPTEMBER

Firebird Metals receives permits to operate battery grade manganese sulphate and tetroxide plant in Jinshi, Hunan, China targeting initial production in late 2025

OCTOBER

REPT BATTERO exhibits 430-520 Wh/L LMFP cell with Wending® technology for enhanced fast-charging performance and safety at 90th Paris Motor Show

NOVEMBER

Integrals Power begins distributing samples of LFP and LFMP battery cathode materials customers in Europe and the U.S.

DECEMBER

Ronbay Technology completes construction of 10 gt LMFP Solid-State Capacity Project

Source: Various news articles linked above

Lithium Manganese Oxide (LMO) Basic Information

	Strength	Weakness	Opportunity	Threat
LMO	• LMO has better thermal stability compared to NMC and NCA • LMO-based batteries have longer cycle life • Good power density for EVs and power tools • Cost-efficient in production due to low manganese cost • **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 has lower energy density compared to NMC and NCA • Lower charge cutoff voltage at 4.2V • LMO batteries may have a higher rate of self-discharge • LMO may suffer from capacity fade and and poor efficiency at high power • Relatively poor performance at low temperatures • **Over long cycles, capacity fade occurs due to structural degradation**	• **LMO batteries balance cost and performance, potentially leading to more affordable EVs** • LMO is more sustainable and requires no cobalt • LMO stability could be interesting for solid-state batteries • Partnerships with OEM could increase LMO adoption • The rise of electric two wheelers, light vehicles, and drones presents an opportunity for LMO technology	• **Rapid advances in more mature chemistries, such as NCA, NMC and L(M)FP** • With consumer demand for long-range EVs, higher energy CAM, such as NMC or NCA might outpace LMO • L(M)FP has lower costs and better thermostability and performance • Since manganese is more abundant, its extraction might lead to greater environmental impact and pollution

Lithium manganese oxide (LMO): Originating from John B. Goodenough's group, LMO emerged into the market in early 1990s and was used in earlier generations of the Nissan Leaf.

Advantage: LMO's advantages lie in its cost-effectiveness, safety, and environmental benefits, as well as the fact that it avoids the use of scarce and expensive materials, such as cobalt or nickel.

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: Battery Report 2023 (pg130).

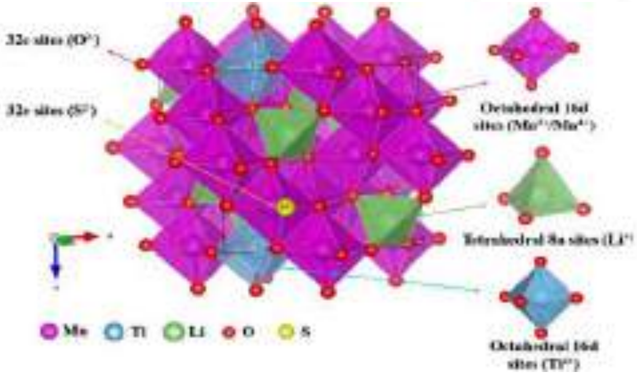
Stabilization Of The LMO ($LiMn_2O_4$) Spinel Structure

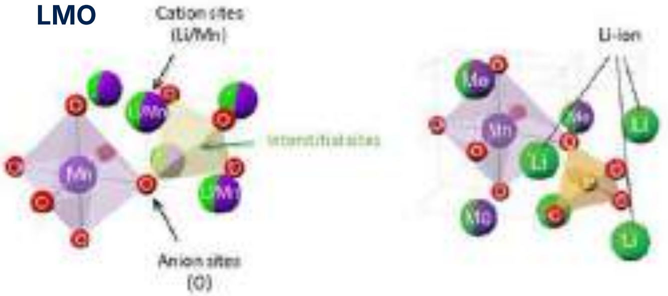
Cation and anion substitution may enhance LMO CAM performance:

- **Researchers from Gyeongsang National University** introduced a novel multi-substituted spinel by partially replacing manganese (Mn^{4+}) with titanium (Ti^{4+}) and oxygen (O^{2-}) with sulfur (S^{2-}) at specific sites. This approach stabilized the structure by mitigating Jahn–Teller distortion and maintained capacity integrity throughout the spinel's operational lifespan [1].

- **Tesla** issued a patent proposing substitution of lithium (Li^+) with an alkaline or alkaline-earth cation M^{n+} (e.g. n = 1: Na^+ or K^+ or n = 2: Mg^{2+} or Sr^{2+}), (Mn^{4+}) with a group 13 element M'^{m+} (such as B^{3+} or Al^{3+}) and oxygen (O^{2-}) with an anion dopant X^{k-}(such as F^- or Cl^- or SO_4^{2-}) in $Li_{(1+a)}M_bMn_{(2-c)}M'_cO_{(4-d)}X_e$ to improve cycle life by stabilizing the spinel structure and reducing Mn dissolution [2].

- **Toyota Central R&D Labs, Inc.** improved cycle life and increased the capacity of LMO CAM by introducing non-metallic elements, such as boron (B^{3+}) and phosphorus (P^{5+}), into interstitial sites. Boron doping stabilizes the crystal structure, leading to a longer battery life. Phosphorus increasing battery capacity by allowing more Li^+ storage, which leads to higher energy density [3].





Source: [1] O. Nyamaa et. al. Mater. Adv., 2024,5, 2872-2887; [2] WO patent 2024147993A1; [3] Toyota Central R&D Labs

JANUARY

Jupiter Mines extracts and sells manganese ore from South African Tshipi Borwa mine and exploring techniques for refining it into battery-grade Mn material

FEBRUARY

Manganese X Energy plans to become first mining company in North America for sustainable high-purity Mn for EV batteries

MARCH

Ghana Manganese Company Ningxia and **Tianyuan Manganese Industry Group** form $450M joint venture for Mn refinery

APRIL

Calix Ltd. produces a novel LMO CAM using Calix flash calcination. CXL LMO/Li metal shows reversible capacity of 110mAh/g with 86% capacity retention over 500 cycles

APRIL

Talent New Energy claims to set a new record in energy density, offering >1300 mile range with a new all-solid-state battery using a lithium-rich manganese based cathode

JUNE

Stratus Materials announces a key performance milestone for LXMO™ pouch cells, surpassing 1k full DoD cycles with >80% of initial capacity

JULY

Tesla patents new "doped manganese-rich cathode active materials" with better cycle life and reduced Mn dissolution

SEPTEMBER

Giyani Metals receives 15-year mining license to Kgwakwe Hill, Botswana for battery-grade manganese

SEPTEMBER

South32 receives $166M U.S. DoE grant for Hermosa Clark project in Arizona to support development of commercial-scale manganese production

SEPTEMBER

Firebird Metals receives permission to operate its battery grade manganese sulphate and tetroxide plant in Jinshi, Hunan, China, targeting late 2025 for production

NOVEMBER

Mn Battery Minerals Pty Ltd plans to become a global producer of High Purity Manganese Sulphate Monohydrate

NOVEMBER

Giyani Metals reports progress on commissioning demo plant of battery grade manganese ore in Johannesburg, South Africa

Source: Various news articles linked above

Lithium Manganese Nickel Oxide (LMNO) Basic Information

	Strength	Weakness	Opportunity	Threat
LMNO	• LMNO has higher energy density than LMO, approaching that of NMC and NCA • Could be used in long-range EVs and high performance consumer electronics • **LMNO offers better thermostability than other high-energy CAM** • Higher charge voltage cutoff at 4.7 V • LMNO-based batteries exhibit good cycle life, with minimal capacity fade over many charge/discharge cycles	• Lower capacity than NMC-based cathodes • Voltage instability at high charge rates • Higher production cost than for LFP or LMO • **Difficult manufacturing process requires precise control of material composition** • Poor performance at low temperatures compared to L(M)FP • LMNO can suffer from Mn dissolution and structural degradation during cycling • Lack of low cost electrolytes stable at LMNO's charge voltage	• Growing demand for mid/long range EVs • Thermostability and long cycle life are advantages for BESS • Ideal candidate for next generation of solid-state batteries • **Good choice for electric aviation, drones and lightweight mobile applications** • Mitigate supply chain risk from cobalt	• NMC has higher energy density and L(M)FP has lower production cost • Alternative Cobalt-free chemistries such as L(M)FP could offer superior performance at lower costs • Due to advances in solid-state batteries, other CAM may become more competitive • **Increasing demand for nickel in battery manufacturing could reduce cost-effectiveness of LMNO**

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),

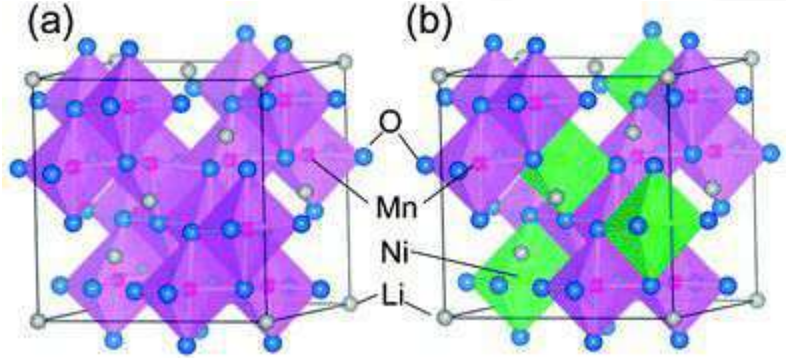
Development of LNMO technology: Began in the mid-2000s, but still exists primarily in cell prototypes and not currently used in EVs. However, growing concerns about the sustainability of cobalt mining and supply chain risks may speed up its adoption.

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: Battery Report 2023 (pg130),Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

LMNO vs. LMO

- In LMNO compared to LMO, Mn is partially replaced by Ni
- 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



LMO **LMNO**

Ni/Mn ratio in LMO (cell voltage, practical capacity, energy density)

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	170.0 mAh/g	200.0 mAh/g	220.0 mAh/g	230.0 mAh/g	250.0 mAh/g
180.0 Wh/kg	230.0 Wh/kg	300.0 Wh/kg	330.0 Wh/kg	360.0 Wh/kg	380.0 Wh/kg

Source: K. Mukai et al. RSC Adv., 2013, 3, 11634-11639

FEBRUARY

Topsoe inaugurates LNMO CAM pilot in Frederikssund, Denmark with designed capacity of 200 t/year

FEBRUARY

South 8 Technologies develops LiGas® liquefied gas electrolyte and demonstrates full compatibility with 4.6V LNMO batteries

FEBRUARY

Echion Technologies and **Topsoe** published a white paper on high performance 3V LNMO-XNO™ cell system

MAY

Echion Technologies and **Morrow Batteries** sign multi-year supply agreement for XNO™ anodes to be used in Morrow's LNMO-X technology

JUNE

Morrow Batteries opens Norway's largest battery research center in Grimstadt, Norway

JUNE

3beLiEVe Project demonstrates recycling process for LNMO cells

JULY

COBRA project concludes by producing a prototype featuring an LNMO cathode and Si/C anode

SEPTEMBER

IREC and **Topsoe** collaborate on developing aqueous processable LNMO materials and electrodes

OCTOBER

South 8 Technologies's LiGas® liquefied gas electrolyte named to TIME's Best Inventions of 2024 for improving safety, cost, and performance of LiB cells

NOVEMBER

HyList project receives funding from Horizon Europe to develop Generation 4b all-solid-state LiB based on LNMO CAM

DECEMBER

Morrow Batteries receives $131M loan for scale-up and development of LFP and LNMO chemistries

DECEMBER

Nano One secures 11 new patents in 2024, including on One-Pot synthesis of LNMO CAM

Source: Various news articles linked above

SpectraPower: Silicon Valley's Battery Lab

Located in Livermore, CA, SpectraPower offers comprehensive battery services tailored for the energy storage industry with a focus on companies developing new materials and testing batteries. Partner with SpectraPower to accelerate your battery innovation from concept to commercialization.

- **Facility: Complete pouch cell fabrication and test line including:**
  - Powder and Slurry processing and preparation
  - Electrode coating (single and double sided)
  - Electrode preparation: calendaring, punching, and tabbing
  - Cell assembly: automated stacking, sealing and electrolyte fill
  - Cell Testing: >700 channels, from 1 mA to 1000A
  - Environmental chambers: -70°C to 200°C
  - Biologic Electrochemical Impedance Spectroscopy, 4-point probe
- **Services offered:**
  - Prototype Cell Fabrication and Comprehensive Cell Testing
  - Custom Electrode Fabrication incorporating advanced materials
  - Cell Disassembly, Analytical Services, and Reporting
  - Third Party Evaluation and Due Diligence
  - Expert Reports, Testimony, and Independent Testing for litigation, safety incidents, and intellectual property cases.

Why go to the trouble, risks, delays, and costs of building and staffing your own prototype line when the SpectraPower Team can build your cells today!

Why Choose SpectraPower?

- **Experienced Team:** Our team has a proven track record, including building America's first Li-ion manufacturing plant.
- **State-of-the-Art Facilities:** Equipped to handle a wide range of battery technologies and testing requirements.
- **Fast Project Initiation:** With a large inventory of battery materials, we can initiate projects quickly without sourcing delays.

SpectraPower can provide fixed price services or support time and materials projects.

Contact us for a quote today!

Email: info@spectrapowerllc.com
Website: www.spectrapowerllc.com

1 INDUSTRY

Anode Summary And Key Points 2024

In 2024, graphite remains the primary anode material due to its affordability, reliability, and dominance in the global supply chain. However, research is heavily focused on developing silicon-based anodes for higher energy density, either for blending with or replacing graphite anodes. While silicon offers a much higher capacity, its large volume expansion during lithium insertion poses challenges like cracking and pulverization. This requiring solutions such as nanostructuring, advanced binders, and optimized electrode designs to enable practical application in commercial cells.

Key points about lithium-ion battery anodes in 2024:

Dominant material: Graphite is still the most commonly used anode material due to its affordability and reliable performance. Global supply is heavily dependent on China which represents 70% of natural graphite production and 90% of processing capacity.

Emerging technology: Silicon-based anodes have gained significant attention due to their potential for much higher energy density compared to graphite, but without the safety concerns of lithium metal or the cost and manufacturing complexities of solid-state lithium metal.

Research focus: Companies are actively developing and patenting silicon-based anode technologies to address the challenges of silicon anodes, including volume expansion during charging, with nano-structuring, incorporating binders and conductive additives, and optimizing electrode and cell design.

Market trends: Graphite supply and availability concerns have sparked initiatives to expand graphite production outside of China and brought focus on building out the supply chain for alternatives anode materials (e.g., silicon, lithium metal, LTO, and hard carbons).

BENCHMARK Source: Ufine, Benchmark Minerals, Battery Report 2023 (pg133-42), Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

Anode Key Performance Metrics

The choice of anode material in lithium-ion batteries is a critical decision that depends on the specific requirements of the application and significantly influences the overall performance, safety, and cost-effectiveness of the battery. Graphite is a reliable and cost-effective option, while silicon and lithium metal offer higher energy density but face challenges related to stability and safety. LTO, while lower in energy density, excels in terms of safety and cycle life. Several factors are considered when selecting an anode material:

ENERGY DENSITY

Anode materials with higher energy density can store more lithium ions, resulting in batteries with greater overall energy storage capacity. Different materials, such as graphite, silicon, and lithium metal, offer varying energy densities, and the choice depends on the specific application requirements.

CYCLE LIFE

The number of charge-discharge cycles a battery can undergo without significant degradation is crucial for long-lasting and reliable energy storage. Anode materials must exhibit stability and durability over multiple cycles to ensure the battery's longevity.

COST

The cost of materials plays a crucial role in determining the overall cost-effectiveness of the battery. Anode materials should be economically viable for large-scale production while maintaining acceptable performance levels.

SAFETY

Safety is a paramount concern in battery design. Anode materials should minimize the risk of dendrite formation, which can lead to internal shorts, overheating, and potential safety hazards. Stable anode materials contribute to the overall safety of lithium-ion batteries.

RATE

Fast charging involves high charge and discharge rates, and the anode material must efficiently facilitate the rapid movement of lithium ions to and from the anode, which is an important metric in applications such as electric vehicles and consumer electronics.

CATHODE COMPATIBILITY

Both the anode and cathode materials must be compatible to ensure efficient lithium-ion transport and maximize battery performance. The overall electrochemical compatibility of the materials contributes to the efficiency and reliability of the battery.

MANUFACTURABILITY

The chosen anode material should be suitable for cost-effective and scalable manufacturing processes. Ease of processing and integration into battery production lines is a practical consideration for commercial viability.

ENVIRONMENTAL IMPACT

There is increasing emphasis on choosing anode materials that are environmentally friendly and sustainable. The industry is exploring materials that minimize environmental impact during production, use, and disposal of lithium-ion batteries.

Source: Battery Report 2023 (pg133), Battery Talk: Battery Application Break Down 1/01/2025 (Version 3.0

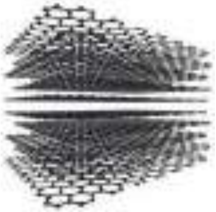
Commonly Used Anode Materials & Performance Tradeoffs

	GRAPHITE	SILICON	LTO	LI METAL
Description	Graphite has been the traditional choice due to its stability, cost-effectiveness, and well-established manufacturing processes.	Silicon offers higher energy density than graphite but comes with challenges related to volume expansion.	LTO offers lower energy density but longer cycle life.	Lithium metal offers the highest energy density but comes with challenges related to safety and cycle life, often due to dendrite formation.
Pro	Widely used in lithium-ion batteries, stable, low cost, and exhibits good cycling performance.	High theoretical capacity, leading to higher energy density compared to graphite.	Exceptional cycle life, high rate capability, and excellent safety characteristics.	Highest theoretical capacity, potentially leading to significantly increased energy density.
Con	Limited energy storage capacity, can hinder the development of high-energy-density batteries.	Higher cost than graphite (per kg) and significant volume expansion during charge/discharge cycles leads to mechanical degradation and reduced cycle life.	Lower energy density compared to graphite and silicon.	Prone to dendrite formation during cycling, posing safety risks and reducing cycle life. Ongoing research focuses on addressing these challenges.

Source: Ufine, Battery Report 2023 (pg134)

Graphite Basic Technology And Information

Graphite is the industry standard anode active material (AAM) for Li-ion batteries (LIBs)



Graphite, an allotrope of carbon, occurs naturally but can also be synthesized. Lithium ions intercalate into its layered structure. Fully lithiated graphite (LiC6) offers a theoretical maximum capacity of 372 mAh/g. Fully processed natural graphite for AAM is called uncoated spherical purified graphite (USPG). Carbon coating, applied to both natural and synthetic graphite, enhances electrical conductivity, minimizes surface reactions, and boosts coulombic efficiency during cycling.

NATURAL GRAPHITE

Production process: Mining of flake graphite, grinding, beneficiation (e.g. flotation), purification and spheroidization to produce USPG.

+ Capacity and rate capability can be slightly better than synthetic graphite.

− Mining can cause environmental degradation. Chemical purification (e.g. HF) can be hazardous.

SYNTHETIC GRAPHITE

Production process: Carbonaceous precursors (e.g. petroleum coke and coal tar) are processed at high temperatures and refined.

+ Cycle life and thermal stability can be slightly better than USPG.

− Energy-intensive production process. Precursors are byproducts of the petrochemical industry.

SUPPLIERS

Leading suppliers of both natural and synthetic graphite include BTR, Shanshan and Putailai (China), Posco (Korea), and Resonac (Japan).

ALTERNATIVES

Blending natural graphite and synthetic graphite, and sometimes incorporating a small amount of silicon monoxide (SiOx), is common. Other forms of silicon, blended with graphite or as a replacement, are in limited use but under extensive development.

Sources: 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.

Major Graphite AAM Producers

AMERICAS

- 🟧 SYRAH
- ⬛ ANOVION
- ⬛ NOVONIX
- ⬛ epsilon
- ⬛ WESTWATER
- ⬛ Vianode

EMEA

- 🟧 talga
- 🟧 Vianode
- ⬛ PUTAILAI
- ⬛ BTR

ASIA - PACIFIC

- 🟧 BTR
- 🟧 SHINZOOM
- 🟧 KAIJIN
- 🟧 PUTAILAI
- 🟧 posco
- 🟧 MITSUBISHI CHEMICAL
- 🟧 RESONAC
- ⬛ epsilon

🟧 OPERATING

⬛ PLANNED

Source: Company announcements

VOLTA FOUNDATION

FEBRUARY

Panasonic Energy signs agreement for synthetic graphite for EV batteries

NMG to supply **GM** with graphite anode material for EV battery production

MARCH

POSCO diversifies graphite supply for battery anodes

MAY

Automakers win extension on use of **Chinese graphite** in EV tax credits

JULY

Graphite One links Alaska to EV industry

AUGUST

UP Catalyst secures additional €2.3 Million to accelerate scale-up of battery raw material production from CO_2 emissions

SEPTEMBER

Aurubis and **Talga** to develop battery-grade recycled graphite

Urbix graphite processing facility selected by US DoE for $125 million funding negotiation under Bipartisan Infrastructure Law

OCTOBER

Northern Graphite and Rain Carbon announce agreement to jointly develop natural graphite battery anode material

NOVEMBER

NOVONIX and **PowerCo SE** sign binding offtake agreement

NOVONIX and **Stellantis** sign binding offtake agreement

DECEMBER

UP Catalyst sets a new industry standard for low-emission, high purity carbon nanotubes and battery-grade graphite

Source: Company announcements (each linked in source)

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 an **extremely high theoretical capacity** (3,862 mAh/g) and low electrochemical potential, making them attractive **for high-energy applications**. Early research in the 1970s and 1980s focused on their potential in lithium-based batteries, but these efforts were hindered by **safety issues**, primarily the growth of dendrites—needle-like lithium deposits that form during repeated charge-discharge cycles. These dendrites can pierce the separator, leading to short circuits and thermal runaway, posing significant risks. As a result, the development of lithium-ion batteries (Li-ion), 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**. Advances in materials science and battery design have led to innovations aimed at mitigating the safety and stability challenges of lithium metal. Techniques such as solid-state electrolytes, protective coatings, and advanced separators are being developed to suppress dendrite formation and enhance cycle life. The lithium metal anode's **potential to dramatically outperform graphite and silicon anodes** makes it a key focus for next-generation battery research. Its successful integration into solid-state batteries and lithium-sulfur systems would represent a major step forward, signaling a shift in the lithium-ion industry toward higher-performance solutions while addressing long-standing challenges like safety and scalability.

Source: Lithium Metal Anodes in Solid-State Batteries, high safety Li-metal anodes, safer lithium metal batteries

Lithium Metal Anode Basic Technology And Information

	Strength	Weakness	Opportunity	Threat
LI METAL	• High energy density • Lightweight • Enables other advanced battery chemistries, such as solid-state and lithium-sulfur	• Limited cycle life • Cost (higher) • Low Coulombic efficiency • Manufacturability of lithium metal • Safety (dendrite formation and high reactivity)	• Demand for high energy density batteries • Aerospace • High-end automotive • Defense-related applications (drones) • Advancements in solid-state technology	• Competition from other technologies (NMC/silicon batteries) and next gen chemistries such as metal-air or lithium sulfur • Safety regulations • Increasing lithium costs and supply chain concerns

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. Lithium metal anodes are prone to dendrite formation during charging, which can cause short circuits, thermal runaway, and fires. Additionally, their reactivity with electrolytes can reduce cycle life and efficiency.

Compared to traditional graphite anodes used in lithium-ion batteries, lithium metal anodes can theoretically delivery much higher capacity but are significantly less stable and more challenging to commercialize. When 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, these batteries share similar safety concerns but can provide lower production costs and weight advantages. Many companies are working or have worked to mitigate the safety challenges inherent to lithium metal anodes, using techniques such as solid state materials, electrolyte design, protective coatings, and dendrite suppression.

Source: Lithium Metal Anodes in Solid-State Batteries, high safety Li-metal anodes, safer lithium metal batteries, Battery Report 2023 (pg 140-142)

Manufacturers Who Have Announced Or Plan To Work With Lithium Metal

LITHIUM METAL PRODUCERS

- ALBEMARLE
- Li METAL
- TCC
- GanfengLithium
- CEL
- SQM
- arcadium lithium
- MINERAL RESOURCES
- Pilbara Minerals
- APPLIED MATERIALS

BATTERY MANUFACTURERS

- LYTEN
- QuantumScape
- SES
- Sion Power
- Factorial
- NexTech
- Solid Power
- Blue Solutions
- one
- Zeta
- [illegible]
- SEPION TECHNOLOGIES

AUTOMOTIVE MANUFACTURERS INTERESTED

- gm
- BOLLORE
- STELLANTIS
- HYUNDAI MOTOR GROUP

JANUARY

Sion Power raises $75M in early stage funding round, led by LG Energy Solutions.

FEBRUARY

24M announces Eternaltye, an electrolyte formulated for lithium-metal, with improved cycle life and rate capability.

MARCH

SLAC publishes a study on atomic-scale calender aging mechanisms for lithium-metal anodes, highlighting the electrolyte design as a key factor.

APRIL

SES AI to begin developing B-samples in accordance with Hyundai Motors and Kia JDA. The B-sample line will build cells for Urban Air Mobility.

MAY

Adden Energy demonstrates <10 min fast charge of lithium-metal battery at room temperature in a lab-scale cell..

JUNE

SK On announces a gel polymer electrolyte that can facilitate lithium metal performance at room temperature, with good fast charging and cell safety.

JULY

SES AI's 100Ah cell passes GB38031-2020, China's EV battery safety standard.

Cuberg, a Northvolt subsidiary, shuts its doors as tech is transferred to Sweden.

PowerCo & Quantumscape announce joint venture to manufacture solid-state lithium metal batteries.

AUGUST

Lyten announces plan for world's first lithium-sulfur gigafactory near Reno, Nevada, commercial in 2027, using a lithium-metal anode.

SEPTEMBER

Li-Metal announces proposal to delist from the Canadian Stock Exchange, amidst "challenging market conditions."

OCTOBER

Techno-economic analysis of lithium-metal anodes suggests that thermal evaporation, compared to extrusion and atomic layer deposition, is a more economically-viable method for producing lithium metal anodes at scale.

NOVEMBER

Lyten announces acquisition of Cuberg production facilities in San Leandro, CA to build a 200 MWh lithium-sulfur production facility, commercial in 2025.

DECEMBER

Source: Various news articles linked above

Silicon Basic Technology And Information

Engineered silicon increases anode specific capacity as a blend with or replacement for graphite in Li-ion batteries (LIBs)

Lithium is a metal that forms an alloy with silicon. Fully lithiated silicon (Li15Si4) has a theoretical maximum capacity of 3,572 mAh/g—9.6 times that of graphite. However, silicon undergoes up to 400% volume expansion when lithium is inserted. Volume expansion and contraction during cycling can cause mechanical degradation and capacity fade. Materials engineering strategies aim to curb these issues, though often with a compromise in capacity compared to silicon's theoretical maximum.

Silicon Monoxide (SiOx)

Production process: Vaporizing Si and SiO2 then condensing; and ball milling Si and SiO2 powders.

+ Established production methods and in widespread use for several years.

− Limited to < 10% in the anode for reasonable cycle life.

Silicon in Carbon (Si-C)

Production process: CVD of silane to form nano-silicon particles in engineered carbon structures.

+ Structures are designed to restrain volume expansion and degradation.

− Energy cost of thermal process required to produce the carbon micro-structures.

Elemental Silicon (Si)

Production process: Grinding MGS (for µ Si); and CVD of silane on current collector or in graphite (for n Si).

+ No inactive anode material means higher specific capacity.

− Potential for volume changes and degradation.

SUPPLIERS

Leading suppliers of SiOx include Daejoo Electronic Materials (Korea), BTR (China), and Shin-Etsu Chemical (Japan).

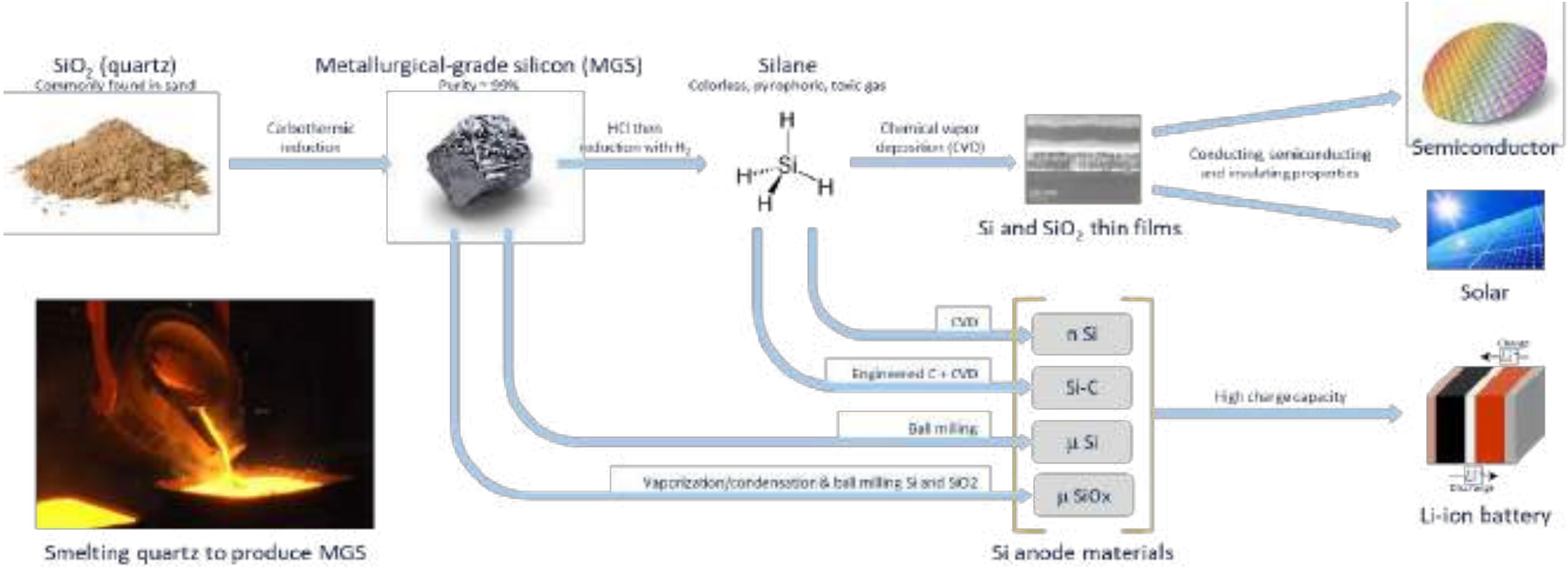
ALTERNATIVES

Silicon is considered to be the most promising anode material for LIBs due to its very high theoretical capacity. R&D to mitigate the capacity fade problem continues, e.g. with composites, micro-structures, nano-structuring, and coatings.

Sources: 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.

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



Sources: 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 Anode Players Continue Development, Qualification, Scale-Up, And Production (1 of 2)

The top 10 include anode active material (AAM) manufacturers and battery manufacturers with proprietary silicon

	Group14	Enovix	Sila	StoreDot	Enevate
AAM or Battery	AAM	Battery	AAM	Battery	Battery
HQ	Woodenville, WA	Fremont, CA	Alameda, CA	Herzliya, Israel	Irvine, CA
Year Founded	2015	2007	2011	2012	2005
Employees	350	561	409	140	76
Type	Startup	Public NAS:ENVX	Startup	Startup	Startup
Total $ Raised	$683M	$616M	$1,310M	$191M	$202M
Funding Stage, Date	PE Growth, Sep 2023	PIPE, Jul 2021	Series G, Jun 2024	Series E, not listed	Series E, 2021
Valuation / Market Cap	$3,000M	$2,100M	$1,970M	$1,270M	$501M
Technology Approach	Silicon encapsulated in hard carbon matrices	Thick silicon, stacked and constrained	Nano-composite silicon	Silicon-based anode, layered structure	Silicon-dominant anode, porous
Application(s) Targeted	EV, consumer electronics	EV, energy storage	Consumer electronics, EV	EV	EV

Sources: Top 20 by post-money valuation found in Pitchbook (Jan 2025). Crunchbase, DealRoom and company websites. Excluding large, established AAM and battery manufacturers with an interest in Si.

Silicon Anode Players Continue Development, Qualification, Scale-Up, And Production (2 of 2)

7 of the top 10 are headquartered in the western US

	OneD	Amprius	Nexeon	Zhide	GruEnergy
AAM or Battery	AAM	Battery	AAM	AAM	AAM
HQ	Palo Alto, CA	Fremont, CA	Abingdon, UK	Jinhua, China	San Jose, CA
Year Founded	2013	2008	2006	2018	2017
Employees	45	84	108	Not listed	43
Type	Startup	Public NYSE:AMPX	Startup	Startup	Startup
Total $ Raised	$99M	$305M	$99M	$197M	$20M
Funding Stage, Date	Series C, Jun 2023	IPO, Jun 2022	PE Growth, Aug 2022	Series D1, Aug 2024	Series A3, Mar 2023
Valuation / Market Cap	$366M	$360M	$352M	$197M	$120M
Technology Approach	Silicon nanowires in graphite particles	Silicon nanowires on current collector	Silicon-based powders, porous	Silicon nano-particles in carbon matrices	Silicon-carbon composite, coating
Application(s) Targeted	EV	Aviation	EV, wearable, medical	Consumer electronics, EV	Consumer electronics, EV

Others in Top 20

SICONA NANOGRAF NEO BATTERY IONBLOX ECELLIX Coreshell enwires GDI gelion

Sources: Top 20 by post-money valuation found in Pitchbook (Jan 2025). Crunchbase, DealRoom and company websites. Excluding large, established AAM and battery manufacturers with an interest in Si. Others in top 20 are in order of valuation found in Pitchbook (Jan 2025).

Prelithiation Of Silicon Anodes

Prelithiation is a process that adds lithium directly to silicon anodes in lithium-ion batteries to compensate for lithium loss during first cycle loss. This process can improve the battery's energy density, cycle life, and rate performance.

Silicon anodes offer much higher energy density than traditional graphite, but their high capacity leads to extensive lithium consumption during the formation of the solid electrolyte interphase (SEI) and structural instability due to volumetric expansion. Prelithiation compensates for this loss by introducing lithium to the anode before the first charge, ensuring the cathode retains more of its potential capacity. Techniques for prelithiation include chemical methods, electrochemical deposition, and the use of lithium-rich additives. While effective in improving energy density and cycle life, challenges remain in scaling the process, such as high costs, ensuring safety, and managing the reactivity of lithium during production.

BENEFITS OF PRELITHIATION

Increases energy density: Prelithiation can improve the energy density of the battery.

Improves cycling stability: Prelithiation can improve the battery's cycling stability.

Reduces side reactions: Prelithiation can reduce side reactions between the anode and electrolyte.

Prevents fracture: Prelithiation can prevent the silicon-based particles from breaking and pulverizing.

Sources: Prelithiation Effects, Pre-Lithiation of Silicon Anodes, Prelithiation strategies

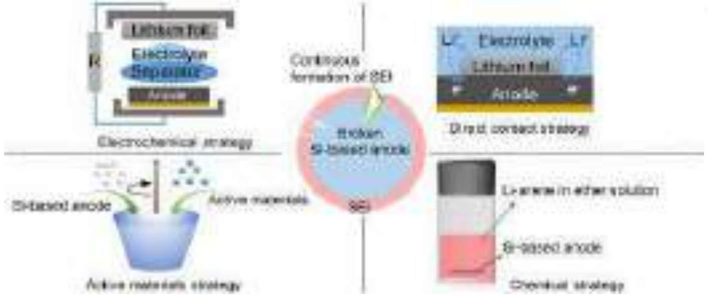
Prelithiation Of Silicon Anodes - Methods

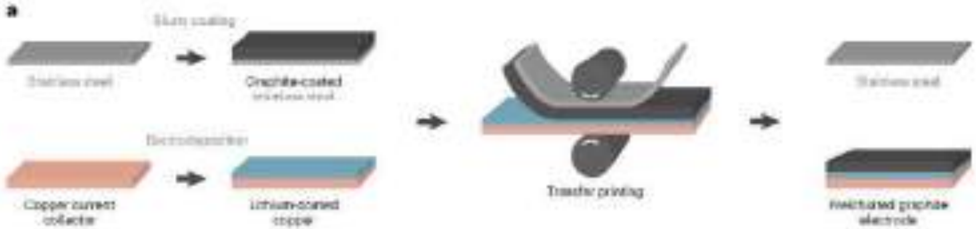
In-situ prelithiation: This method places an ultra-thin layer of lithium foil on the bottom of the anode during battery fabrication.

Direct contact prelithiation: This method involves adding lithium directly to the anode.

Thermal evaporation: This method uses thermal evaporation of lithium metal to prelithiate the anode.

Transfer printing: This method uses electrodeposition equipment to produce prelithiated anodes.





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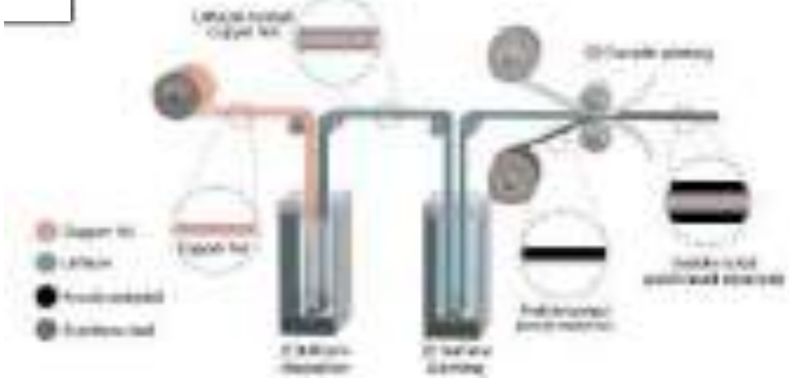


Sources: Prelithiation Effects, Pre-Lithiation of Silicon Anodes, Prelithiation strategies

1 INDUSTRY

Electrolyte - The Adaptable Battery Material Unlocking Cost, Performance, and Safety Potential

Liquid electrolytes in lithium-ion batteries facilitate the transport of lithium ions between the cathode and anode. Electrolytes are optimized for ionic conductivity, thermal/voltage stability, and compatibility with electrode materials. Well-designed electrolytes form a stabilizing SEI on the electrodes that protect the electrodes while allowing ions to pass freely through both the SEI and electrolyte.

Class	Purpose	Considerations	Examples
Salts	Add conductivity to allow for ion transport. Decomposition products can participate in SEI formation.	Higher conductivity and solubility increase rate capability, a key aspect for high power or fast charge. Thermal and electrochemical stability can decrease Li^+ inventory and affect lifetime. Lithium salts are a major cost component of most conventional electrolytes.	$LiPF_6$: most common due to its solubility, stability, and cost. Highly moisture sensitive, releasing deleterious fluoride. Degrades >60 °C and >4.3-4.5V. LiFSI, LiTFSI are favored for greater stability (thermal and electrochemical) and higher conductivity but cost prohibitive. Less common: $LiBF_4$(lower conductivity). $LiClO_4$ (good conductivity, oxidizer), $LiAsF_6$ (high conductivity and stable, toxic and expensive), $LiNO_3$ (Li metal stabilizer, safety concerns). Good SEI formers, stable, expensive: LiBOB, LiDFOB, $LiPF_2O_2$. Salts are used in low concentrations as additives to offset downsides.
Solvents	Medium for ion conduction, wets separator and electrodes. Participates in SEI formation.	Viscosity and freezing point: Higher viscosity slows ion conduction, which worsens with lower temperature, decreasing rate capability. Solvation: Solvents are chosen to increase ionic conductivity and solubility. Solvent blends must also efficiently de-solvate ions at the electrode surface. Compatibility with electrode materials.	Carbonates: most common for cost, compatibility with common active materials, and ability to solvate salts. Solvent blends include: *Cyclic*: EC (high freezing point, graphite stabilizer), FEC (adds F^- to SEI, enables Si anodes).) *Linear*: DMC (improves viscosity and conductivity), DEC (enhances low temperature performance), EMC (similar to previous with lower volatility), fluorinated (emerging, more expensive but enables high voltage). Esters (MP, EA, etc.) and Ethers (DME, DOL, glymes) have good compatibility with Li metal but high flammability. Nitriles (acetonitrile, succinonitrile, etc.) have improved high temperature performance as well and a broader voltage window with some concerns related to toxicity and reactivity with other components.
Additives (<~10% by weight)	Tune performance. Modify SEI, enable greater stability, suppress gas formation, etc.	Compatibility: Careful balancing of cell chemistry with the needs of the application. Additives often enhance one aspect of performance while negatively affecting another. Concentration: additives are often help form the SEI, but overly thick SEI layers can deplete Li inventory and decrease rate performance.	Additives span a wide range of chemistries and often contain multiple functional groups: Unsaturated additives are the prototypical (VC, VEC) and undergo electroreduction to form SEI at the anode and it is generally accepted that they play a role at the cathode as well. FEC is often used as an additive to add LiF to SEI.. Fluorination of molecules containing other functional groups is also common. Sulfur-containing additives such as PS or DTD can form an advanced SEI and improve the stability of the system. Toxicity and regulatory concerns sometimes limit use. Phosphorous compounds mitigate flammability at high concentrations but can form too thick SEIs. Nitriles and isocyanates form films often applicable to high voltage.

Source: 1. Electrolytes and Interphases in Li-Ion Batteries and Beyond, Kang Xu, Chemical Reviews. 2014. Link

FEBRUARY

24M (US) unveils Eternalyte designed for improved cycle life and rate capability in Li metal batteries.

India's **GFCL** announces $LiPF_6$ plant intended to be operational by end of year.

South8's LiGas (US) demonstrates LMNO electrolyte that improves the historical challenge with high voltage breakdown.

Sepion Technologies publishes video of its new electrolyte with a self-extinguishing time "25x better than commercial electrolytes".

SEPTEMBER

German **E-lyte** announces opening of first electrolyte plant in Germany capable of producing 20 kT per year.

NOVEMBER

The South Korean material company, **EnChem** will be supplying 70% of the electrolyte spent at AESC's factory in Orda City.

US-based **Koura** announces expansion of custom electrolyte business with low lead time after beta testing.

China's **Do-Fluoride** forms joint venture with Soulbrain to deliver $LiPF_6$ salt.

MARCH

AI start-up **Chemix** in the U.S. announces $20M Series A toward data-driven electrolyte development.

APRIL

Asahi Kasei (Japan) announces acetnitrile-based electrolyte promising excellent "ultrawide temperature" performance.

U.S. startup **Feon** announces $6.1 seed funding for advanced electrolyte discovery and UN 38.3 certification of their Li metal batteries.

JUNE

Mitsubishi announces recycling pilot with partner T2M that includes electrolyte recovery from EV batteries.

DECEMBER

Source: Various news articles linked above

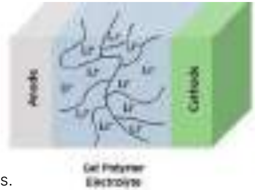
Electrolyte Types And Research Areas

In the electrolyte industry, technological advancements look toward overcoming key battery challenges: liquid electrolyte reactivity, temperature performance and lifetime of Li-ion; enabling emerging anodes (Si, Li metal, "anode free").

Borrowing from non-liquid technologies:
All solid-state batteries are a significant industry thrust and are covered elsewhere, but semi-solid gels (polymer + liquid electrolyte) and liquified gases are being commercialized.

Liquified gas: South8's LiGas, named Times' best invention of 2025, non-toxic gases have a reduced fire risk and high rate capability (low viscosity + high conductivity).

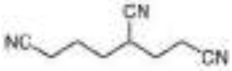
Semi-solid and gel electrolytes: A step toward solid polymer electrolytes, a polymer matrix is saturated with liquid (solvent + salt). They are less flammable and often have higher temperature stability. Like solid electrolytes, ionic conductivity is lower compared to traditional liquids and advancements often seek to increase conductivity In Li metal cells, they exhibit less dendrite formation. Source



24M, Anthro Energy, QuantumScape, and others use gel polymers.

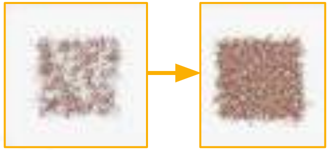
Expanding molecular library:
Following the existing model for liquid electrolyte, advancements focus on discovery of new molecules to add to the blend.

AI Discovery: Companies such as Chemix or Sepion use AI and machine learning to discover new battery materials.



Nitrile chemistry: Recently several companies have announced nitrile solvents and additives. Asahi Kasei announced acetonitrile as a solvent to widen the optimal temperature range for electrolytes. Tesla publishes nitrile sulfites in a 2019 patent with Prof. Jeff Dahn while Sila publishes a 2023 patent. Ascend Performance materials manufactures Trinohex Ultra (shown on the left), a tritrile additive after winning a challenge with Samsung in 2021.

Advancing salt chemistry:
$LiPF_6$ is the most commonly used electrolyte salt, but modifying concentration or chemistry to enhance performance.



High salt concentrations: SES advertises "salt in solvent" electrolytes (shown left) with high salt concentrations, promising higher Coloumbic efficiency and enabling lithium metal cells with a liquid electrolyte. PNNL popularized localized high concentration electrolytes (LHCEs) which use a second solvent (diluent) where the salt is poorly soluble to achieve a similar effect. This concept is moving to industry, such as Giner Inc's advertised development work.

Dual salt electrolytes: While $LiPF_6$ is cost effective, adding secondary salts in the electrolyte improves performance while mitigating the the cost or solubility challenges with more appealing options. Several publications and patents[1,2] mention the concept and several industrial electrolyte suppliers offer dual salt options.

Ionic liquids (ILs) show promise for their stability and non-flammability, but cost and viscosity limit their utility. Recently, IL have been used as additives or cosolvents to balances to advantages against these challenges. Source

Key Players In Li-Ion Battery Electrolytes

AMERICAS

Koura

TINCI 天赐

新宙邦 CAPCHEM

enchem

Dongwha

soulbrain

3M

BASF We create chemistry

MITSUBISHI CHEMICAL

UBE

EMEA

ELYTE

TINCI 天赐

enchem

ASIA - PACIFIC

TINCI 天赐

新宙邦 CAPCHEM

[illegible]

HSC HSC CORPORATION *

[illegible]

enchem

冠城大通 Guancheng Datong*

Ruitai

AsahiKASEI

MITSUBISHI CHEMICAL

soulbrain

GTIG

[illegible]

OPERATING

ANNOUNCED

*Primarily focused on component manufacture

Battery Separator Types And Technologies

Lithium-ion battery separators physically separate the positive and negative electrodes while allowing the transport of lithium ions. The most commonly used lithium-ion battery separators are typically made of polyolefin materials (typically PE or PP) coated with ceramic. There are many other different types of separators used in lithium-ion batteries with different performance traits and trade offs., and are broadly categorized below.

Separator Type	Material	Characteristics
Polyolefin	Polyethylene (PE) and/or polypropylene (PP)	Polyolefin separators are widely used due to their cost-effectiveness, chemical stability, and ease of manufacturing. They are commonly found in commercial lithium-ion batteries
Ceramic-Coated	Polyethylene or polypropylene separators with a ceramic coating	Ceramic-coated separators provide enhanced thermal stability and safety. The ceramic layer helps prevent thermal runaway by inhibiting the growth of internal shorts and dendrites
Composite	Combination of different polymers, ceramics, or other materials	Composite separators leverage the strengths of multiple materials to achieve a balance of properties, mainly to add electrochemical stability, prevent shorts, and inhibit growth of lithium dendrites.
Microporous	Often composed of polyethylene or polypropylene with added fillers or ceramic coatings	Microporous separators have a porous structure, allowing for efficient ion transport while maintaining good mechanical strength. The addition of fillers or ceramic coatings can enhance thermal stability and reduce the risk of thermal runaway
Glass Fiber	Glass fibers combined with a polymer matrix	Glass fiber separators offer good mechanical strength and can be used in high-temperature applications. They are known for their resistance to puncture and excellent thermal stability
Nonwoven Fabric	Nonwoven materials made of synthetic fibers	Nonwoven fabric separators provide good mechanical strength and are often used in flexible and lightweight battery designs. They can offer flexibility and conformability to different battery shapes
Composite Membrane	Combination of polymer and ceramic materials	Composite membrane separators aim to provide a balance between mechanical strength, thermal stability, and ion conductivity. They are designed to enhance safety and performance in lithium-ion batteries

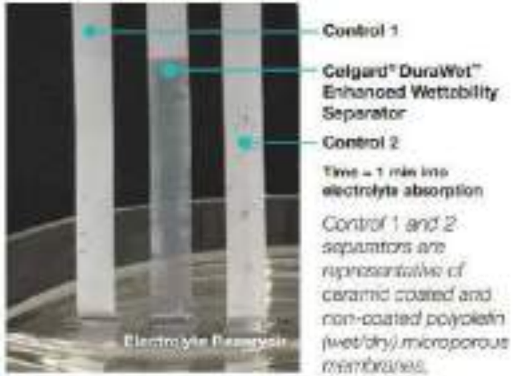
Sources: Celgard, Sepion, Review on Lithium-Ion Battery Separators, 24M, Battery Report 2023 (pg 132)

Development Focuses In Separators

The separator is a thin membrane that electronically isolates the positive and negative electrodes while providing a porous medium for ion transport via the electrolyte. It can also serve safety functions like slowing dendrite penetration to the opposing electrode and, in the event of a short, slowing thermal runaway.

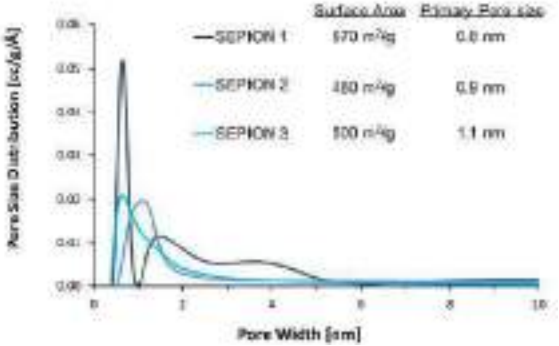
Areas of technology development in 2024 included wettability, ion selectivity, and safety.

Celgard demonstrates a separator with improved wettability vs typical controls, potentially decreasing required cell soak time.



Control 1 and 2 separators are representative of ceramic coated and non-coated polyolefin (wet/dry) microporous membranes.

Sepion's ion-selective coating prevents transition-metal crossover to the anode via sub-nanometer primary pore size.



Cell built with **24M's Impervio** separator suppresses thermal runaway vs a control in an overcharge abuse condition.

Sources: Celgard, Sepion, 24M

Key Players In Li-Ion Battery Separators

AMERICAS

- ENTEK
- CELGARD
- SEPION
- 24M
- META
- Magnera
- Soteria
- QuantumScape
- GNEM

EMEA

- FREUDENBERG
- SENIOR
- AHLSTROM
- GESSNER
- MICROPOROUS

ASIA-PACIFIC

- Asahi KASEI
- TORAY
- SUMITOMO CHEMICAL
- SK innovation
- SEMCORP
- 恒力石化
- [illegible]
- [illegible]
- UBE
- GELLEC 金力股份
- [illegible]
- [illegible]
- [illegible]
- [illegible]
- [illegible]
- [illegible]
- ProLogium

JANUARY

SK ie technology explores Canada for battery separator manufacturing plant. Ontario and Quebec are under consideration.

FEBRUARY

Trent Capital Partners acquires full control of battery separator company **Microporous**.

MARCH

noco-noco and **Neogen Chemicals Ltd** signs 3-year marketing and distribution license for X-SEPA™ battery separators in India

APRIL

Honda had reached a basic agreement with **Asahi Kasei Corporation** on collaboration for the battery separators production in Canada

MAY

Green New Energy Materials to build a first U.S. $140M battery separator manufacturing facility in Denver, North Carolina

JUNE

Prologium delivers 8k samples of Li-ion ceramic solid state battery of Logithium™ technology with innovative ceramic separator.

JULY

ENTEK receives a conditional $1.2B loan for EV battery separator manufacturing plant in Terre Haute, Indiana, U.S.

AUGUST

Semcorp completes the first construction phase of wet Li battery separator production plant in Debrecen, Hungary.

SEPTEMBER

24M unveils new tested data for the transformative battery separator Impervio™ that could significantly improve battery safety during overcharge

OCTOBER

Sepion Technologies secures $17.5M to build battery separator manufacturing plant in Western Sacramento, California, U.S.

NOVEMBER

Asahi Kasei Corporation breaks ground on $1.6B Li-ion battery separator manufacturing plant in Port Colborne, Ontario, Canada

DECEMBER

QuantumScape releases Cobra, new-generation equipment for ceramic solid-state battery separator production

Source: Various news articles linked above

1 INDUSTRY

Key Trends Of The Current State Of The Solid-State Battery Industry

OEM RACE

Almost all the automotive OEMs are actively participating in the solid-state battery race with varying strategies:

- In-house research in SSB (e.g. Toyota)
- Strategic partnerships with SSB companies (e.g. Nio with WeLion)
- Direct investments in one (e.g. BMW, Ford, Stellantis) or multiple SSB companies (e.g. Mercedes, Hyundai, Kia)
- Publicly disclosed mixed strategy, combining in-house development with investments in other companies (e.g. Honda)

TECHNOLOGY

- There is no consensus on the electrolyte to be used, although polymers have achieved the highest level of maturity. Significantly, there is a growing trend towards employing semi-solid polymer electrolytes to enhance workability with the cathode
- Notably, there is a substantial focus on Sulfide SSBs in the Asia-Pacific region

TIMELINES

- The majority of startups in this sector were founded between 2010 and 2016 and are now either public or in the late stages of investments
- Several companies have recently announced pilot scale lines opening in January 2025 (e.g. Hyundai/SES-AI, Honda)
- The Start of Production (SOP) for most players is forecasted or announced to be between 2025 and 2030

Source: Company Announcements and News Reports, Battery Report 2023 (pg 158-165)

Types of Solid Electrolytes

Solid-state batteries differ from classical lithium-ion batteries due to their use of a solid electrolyte. However, a consensus on the preferred chemistry for the solid electrolyte has not been reached, as each type comes with distinct pros and cons.

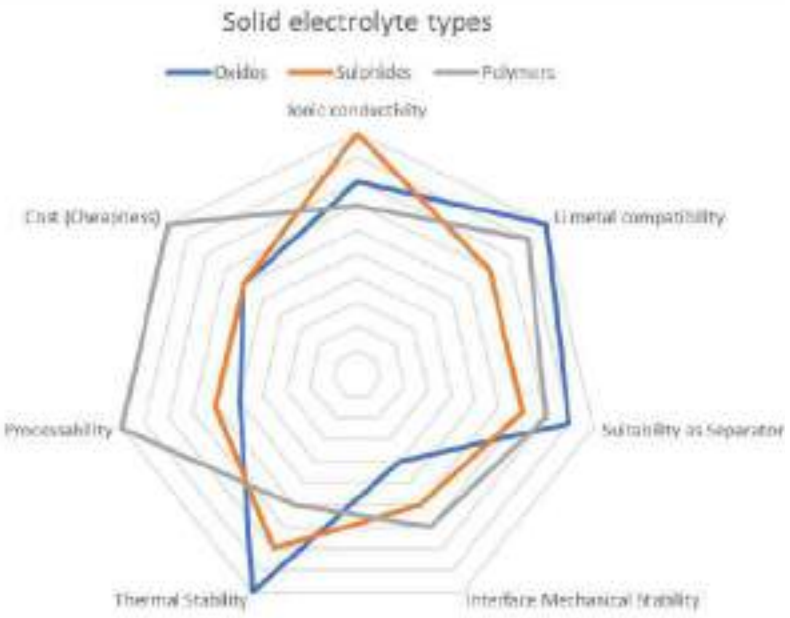
The two most common families of electrolyte used are:

- **Ceramic** (including Oxides and Sulphides)
- **Polymers** (solid, composite, or gel; the latter often referred to as a semi-solid electrolyte)

Key properties of a good solid-state electrolyte include high ionic conductivity, a robust electrode-electrolyte interface, high thermal and electrochemical stability, the ability to suppress dendrites, high processability, and low manufacturing cost.

Ceramic electrolytes exhibit high ionic conductivity and mechanical strength but suffer from poor interfacial properties. Their rigid nature also In contrast, organic polymers boast good interfacial properties but struggle with low ionic conductivity and mechanical strength.

So far, polymers have achieved a higher level of technology readiness owing to their superior processability.



Source: BatteryBits,Battery Report 2023 (pg 158-165)

Manufacturing Differences With Respect To Traditional Li-Ion With Liquid Electrolyte

CHEMISTRY	ANODE PRODUCTION	CATHODE PRODUCTION	SEPARATOR PRODUCTION	CELL ASSEMBLY
Li-ion with Liquid Electrolyte	Anode slurry mixing and coating, drying, calendering	Cathode slurry mixing and coating, drying, calendering	Extrusion process, can be both dry and wet	Stacking, packaging, electrolyte filling and degassing, aging
Oxide Solid State Battery	Lithium foil extrusion, calendaring, lamination	Cathode slurry mixing and coating, drying, LT sintering	Slurry mixing and coating, HT sintering, lamination, LT sintering	Stack pressing, aging
Sulfide Solid State Battery	Lithium foil extrusion, calendaring, lamination	Cathode slurry mixing and coating, drying, calendering	Slurry mixing and coating, drying, calendering	Stack pressing, aging
Polymer Solid State Battery	Lithium foil extrusion, calendaring, lamination	Extrusion, calendaring	Extrusion, calendering	Stack pressing, aging

Key Manufacturing Differences	Remarkable difference in comparison to Li-ion, primarily attributed to the extrusion process of the lithium metal foil. Notably, the process for Si-based anodes is more akin to traditional Li-ion methods.	For Oxide and Sulfide, the cathode undergoes a process similar to traditional Li-ion, but solid electrolyte particles are mixed in the slurry. Additionally, Oxide SSBs need the expensive sintering step. On the other hand, Polymer SSBs necessitate extrusion.	In Oxide and Sulfide SSBs, the wet processing of the separator markedly differs from the traditional extrusion process employed in Li-ion batteries.	Unlike Li-ion batteries, SSBs do not require electrolyte filling and degassing, marking one of the distinctive advantages of SSBs.

Source: Fraunhofer ISI

Manufacturing Differences With Respect To Traditional Li-Ion With Liquid Electrolyte

Solid-state batteries share common components with liquid electrolyte-based ones but differ in resource demand due to the choice of solid electrolyte and anode materials. There are two main distinctions: the inclusion of new metals in the electrolyte and the increased lithium content.

INCLUSION OF NEW METALS

The inclusion of new metals like lanthanum, germanium, or zirconium in solid-state batteries sets them apart from traditional lithium-ion batteries:

- Zirconium is common and poses no significant supply chain issues. (present in oxide solid electrolyte)
- Lanthanum, while abundant among rare earth metals, could face increased demand with growing SSB adoption. (present in oxide solid electrolyte)
- Germanium, being relatively scarce and costly, may not be suitable for widespread use in batteries. (present in oxide and sulfide solid electrolyte)

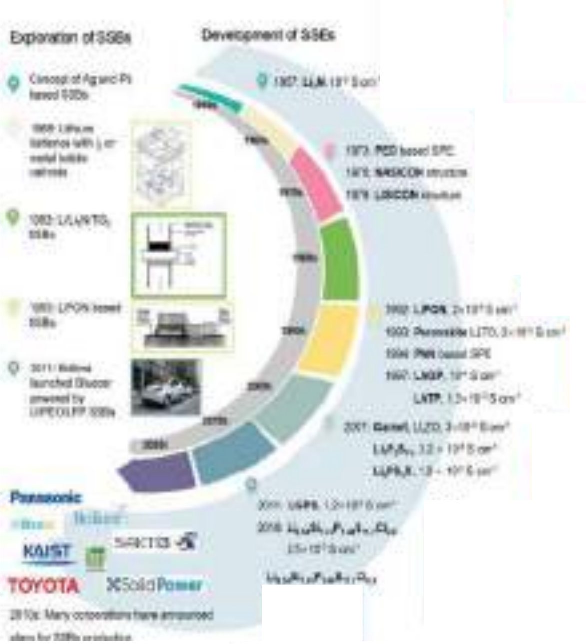
LITHIUM CONTENT

Regarding lithium demand:

- Cathode materials show no major changes compared to those in conventional lithium-ion batteries
- Noteworthy changes occur in the electrolyte, with a solid electrolyte resulting in an average additional demand for lithium ranging from 10 to 20 g/kWh compared to liquid organic electrolytes
- Lithium metal in the anode demands an additional lithium content, roughly equivalent to the transition from a liquid to solid electrolyte. The additional amount varies depending on the anode thickness and the excess lithium added to the cell to improve its performance

Source: Fraunhofer ISI

Solid State Batteries - Latest Developments



2024 was dominated by news of announced solid state battery production facilities beginning to ramp up production of A and B sample cells.

Q1 2024

JANUARY

Prologium inaugurates the world's first GWh-level solid state lithium ceramic battery factory, with mass production planned for 2027

MARCH

Quantumscape ships six-layer Alpha-2-sample cells to their OEM partners with larger cathode loadings as compared to their A0 cells

Q2 2024

APRIL

Hyundai announces a new B-sample factory in South Korea to begin SSB production in 2024 (now Jan. 2025)

JUNE

Factorial delivers B- sample cells to Mercedes-Benz, less than 1 year after delivering their A-Sample cells

JUNE

Boston-based **Ionic Materials** declares bankruptcy after 12 years in business

Q4 2024

OCTOBER

Stellantis announces a demo fleet of Dodge Chargers on the road by 2026

NOVEMBER

Honda announces a pilot scale SSB factory / demonstration line opening in January 2025.

Source: Company Announcements and News Reports, Battery Report 2023 (pg 158-165)

Main Solid State Players

AMERICAS

EMEA

ASIA-PACIFIC

ELECTROLYTE CHOICE

OXIDE
UNDISCLOSED
POLYMER
SULPHIDE
SEMI-SOLID

Source: Pitchbook, Crunchbase, Company Announcements, and News Reports
Note: $10M in funding has been chosen as the threshold for the map

Main Solid State Players And OEM Investments

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	FUND, STAGE	NOTABLE OEM INVESTORS
Blue Solutions	Polymer Solid Electrolyte	1998	$496M - Public	BOLLORE
Ilika	Oxide Solid Electrolyte	2004	$30M - Public	-
Ensurge	Oxide Solid Electrolyte	2005	$180M - Public	[illegible]
Prologium	Oxide Solid Electrolyte	2006	$538M - Series E	[illegible] V
QuantumScape	Oxide Solid Electrolyte	2010	$1.5B - Public	VW
24m	Semi-Solid Electrolyte	2010	$185M - Series H	VW
Solid Power	Sulfide Solid Electrolyte	2011	$387M - Public	BMW Ford SOLVAY SAMSUNG
Iten	Oxide Solid Electrolyte	2011	$110M - Series C	-

Source: Dealroom, Crunchbase, Pitchbook
Note: $10M in funding has been chosen as the threshold for the table

Main Solid State Players And OEM Investments Cont.

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	FUND, STAGE	NOTABLE OEM INVESTORS
SES	Semi-Solid Electrolyte	2012	$600M - Public	HYUNDAI KIA HONDA gm LG SK GEELY
StoreDot	Semi-Solid Electrolyte	2012	$190M - Series D	Mercedes-Benz SAMSUNG VINFAST VOLVO OLA ELECTRIC
Factorial Energy	Polymer Solid Electrolyte	2014	$240M - Series D	HYUNDAI KIA Mercedes-Benz STELLANTIS
Blue Current	Polymer Solid Electrolyte*	2014	$46M - Series Unknown	-
Ion Storage Systems	Oxide Solid Electrolyte	2015	$85M - Debt Financing	TOYOTA
Sakuu	Undisclosed	2016	$84M - Series C	-
Svolt	Sulfide Solid Electrolyte	2016	$2.9B - Series B	xiaomi
Welion	Semi-Solid Electrolyte	2016	$287M - Series D	xiaomi HUAWEI
Tailan New Energy	Oxide Solid State Electrolyte*	2018	$55M - Series B	CHANGAN

*Composite Electrolyte

Source: Dealroom, Crunchbase, Pitchbook
Note: $10M in funding has been chosen as the threshold for the table

Main Solid State Players And OEM Investments Cont.

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	FUND, STAGE	NOTABLE OEM INVESTORS
LionVolt	Oxide Solid Electrolyte	2020	$20M - Series A	-
Solivis	Sulfide Solid Electrolyte	2020	$19M - Series B	-
Solithor	Oxide Solid Electrolyte	2021	$10M - Seed	-
Soelect	Polymer Solid Electrolyte	2021	$13M - Series A	gm VENTURES
Adden Energy	Undisclosed	2021	$20M - Series A	-
BasqueVolt	Polymer Solid Electrolyte	2022	$30M - Seed	-

Source: Dealroom, Crunchbase, Pitchbook
Note: $10M in funding has been chosen as the threshold for the table

1 INDUSTRY

Lithium-Sulfur Battery - Basic Information

	Strength	Weakness	Opportunity	Threat
Lithium Sulfur (LiS)	• Cost • Safety • Specific energy • Abundance of sulfur	• Cycle life • Energy density • Battery supply chain • Power • Difficult to read state of charg	• Low/ mid-range /entry-level EV's • e-Bus • e-Trucking • Cost sensitive applications	• NMC/high-voltage LNMO • Na-ion battery • Regulations on energy density and pack cycle life • Increasing material cost

In 2024, lithium-sulfur (Li-S) batteries remained a promising technology for next-generation energy storage, with advancements addressing key challenges such as the "shuttle effect" and limited cycle life. Efforts included improved cathode designs, advanced electrolytes, and nanostructured sulfur materials to enhance stability and energy density.

Li-S batteries offer significant advantages, including higher theoretical energy density, reduced weight, and cost-effectiveness due to the abundance of sulfur. They are particularly attractive for applications requiring lightweight energy storage, such as drones, aviation, and long-range electric vehicles.

However, Li-S batteries face competition from established lithium-ion chemistries, such as lithium iron phosphate (LFP), which offer better cycle life, safety, and proven scalability, albeit with lower energy densities. Additionally, lithium-metal batteries present another competitive technology, boasting comparable energy densities but facing challenges related to dendrite formation and safety. Despite these competitors, ongoing research and industry partnerships signal that Li-S batteries could become a key player in the future of sustainable energy storage.

Source: Reuters, ,Argonne, UFine ,Battery Official,Battery Report 2023 (pg 143-146)

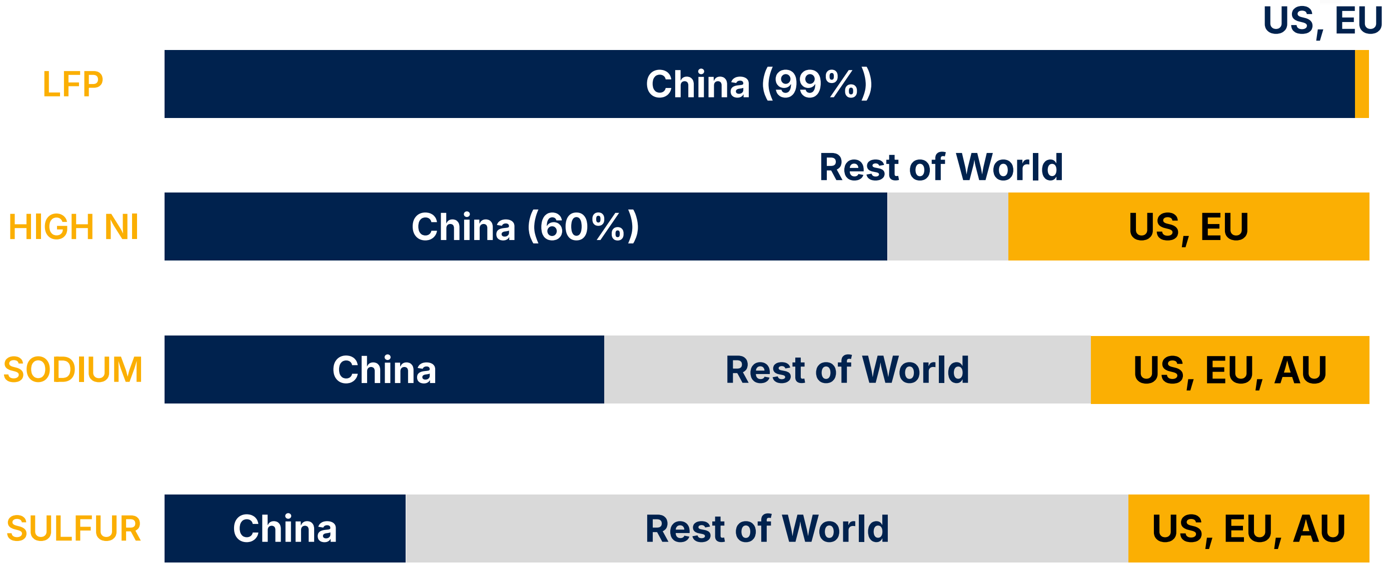
Lithium-Sulfur Battery Bill Of Materials

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

Sources: 1. Yao, A. Benson, S.M., Chueh, W.C. How quickly can sodium-ion learn? Assessing scenarios for technoeconomic 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.

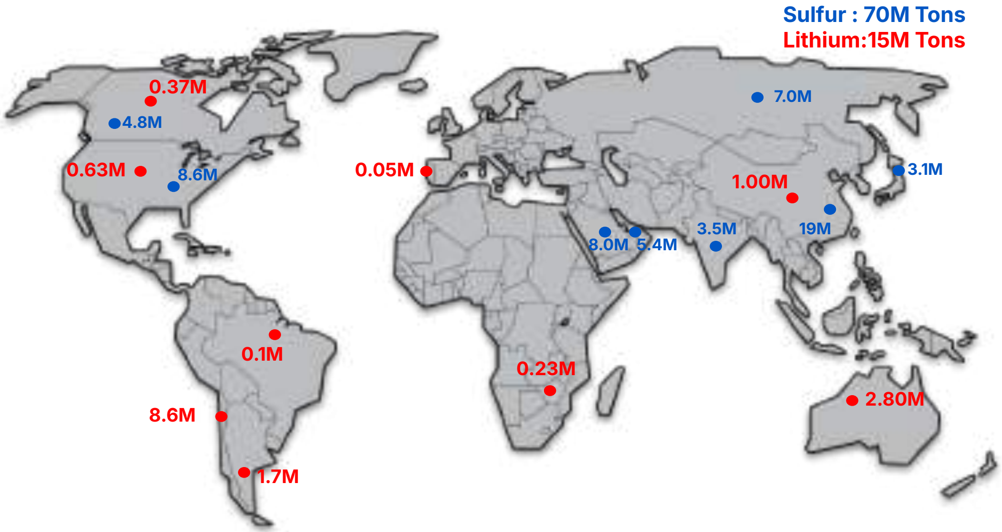
Lithium-Sulfur - A Geographically Agnostic Battery Chemistry



*** 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 (pg 143-146)

Vast Abundance Of Sulfur Is Key To Addressing Long Term Battery Supply Chain Challenges



SOURCES OF ECONOMICALLY RECOVERABLE SULFUR / LITHIUM. [1]

- Sulfur & Lithium or 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 (pg 143-146)

Lithium-Sulfur Battery Players By Region

AMERICAS

- LYTEN
- Zeta
- conamix

EMEA

- theion

ASIA-PACIFIC

- Li-S Energy
- gelion
- Gotion
- OXLiD
- GS YUASA
- LG

FEBRUARY

Zeta Energy awarded US Department of Energy grant for $4 million project to advance higher-performing, domestic Lithium-Sulfur batteries for greater range in EVs

MARCH

Australia's Federal Minister for Industry and Science opens Li-S Energy Battery Plant and announces $AUD1.7M industry growth program grant

SEPTEMBER

Lyten's Lithium-Sulfur battery technology chosen to be demonstrated on the International Space Station.

OCTOBER

US startup **Lyten** to invest over $1 bln in Nevada lithium-sulfur battery factory

OCTOBER

China's **GNE** develops lithium-sulfur battery with energy density of 700Wh/kg.

NOVEMBER

Lyten acquires Cuberg's facility to boost US Lithium-Sulfur battery production for drone and defense applications

NOVEMBER

Ultra-fast charging lithium-sulfur battery is capable of powering long-haul EVs and commercial drones

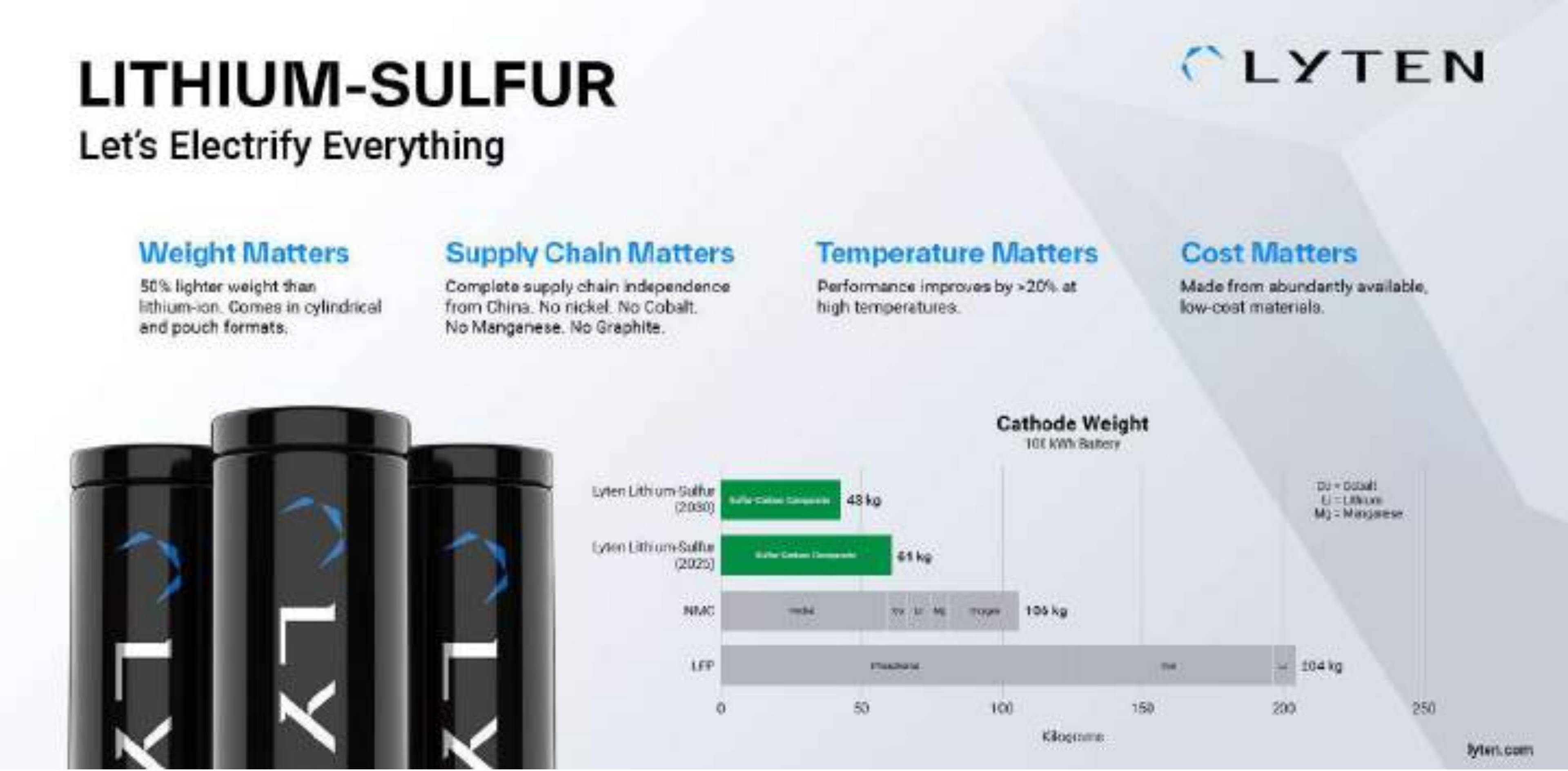
DECEMBER

Lyten secures $650M LOI from the Export-Import Bank of the United States in support of expanding Lithium-Sulfur battery manufacturing in the U.S.

DECEMBER

Stellantis, Zeta Energy agree to jointly develop lithium-sulfur EV batteries

Source: Various news articles linked above



LITHIUM-SULFUR

Let's Electrify Everything

LYTEN

Weight Matters

50% lighter weight than lithium-ion. Comes in cylindrical and pouch formats.

Supply Chain Matters

Complete supply chain independence from China. No nickel. No Cobalt. No Manganese. No Graphite.

Temperature Matters

Performance improves by >20% at high temperatures.

Cost Matters

Made from abundantly available, low-cost materials.

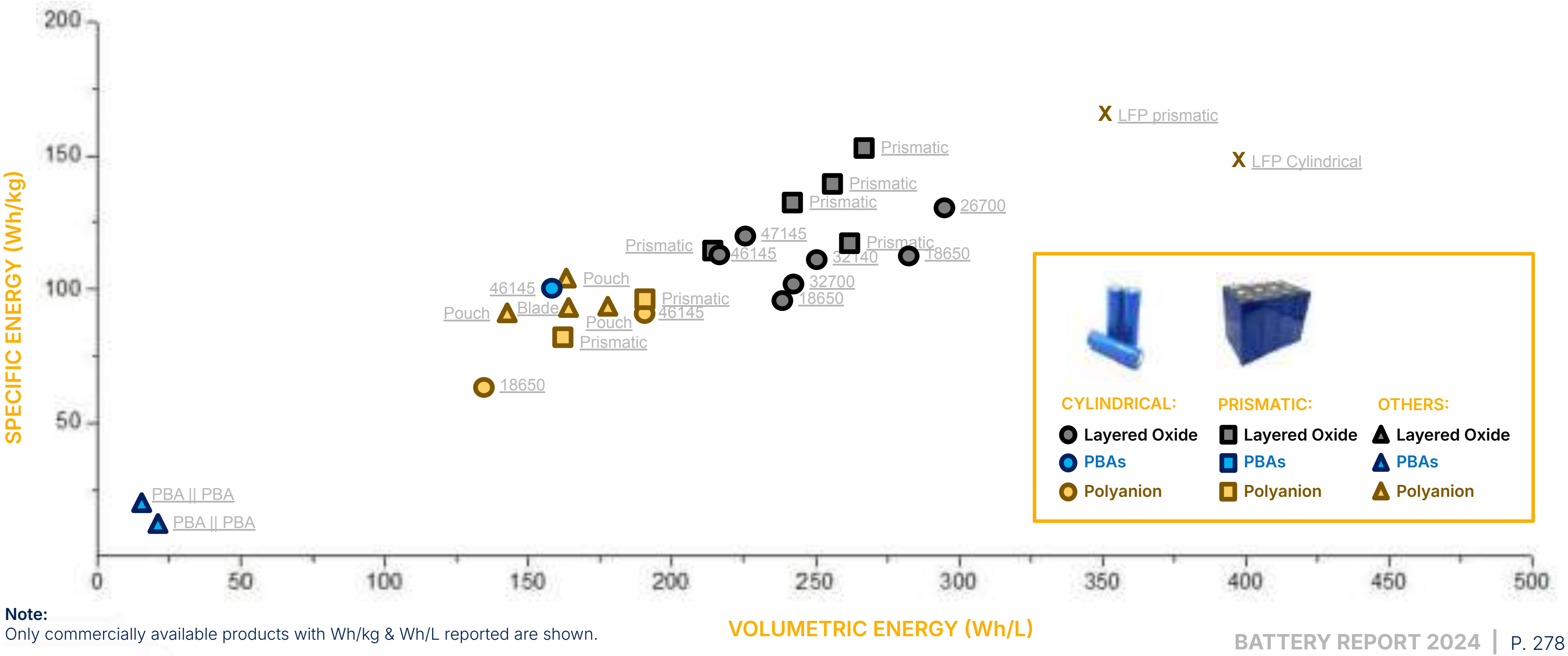
Cathode Weight

100 kWh Battery

lyten.com

1 INDUSTRY

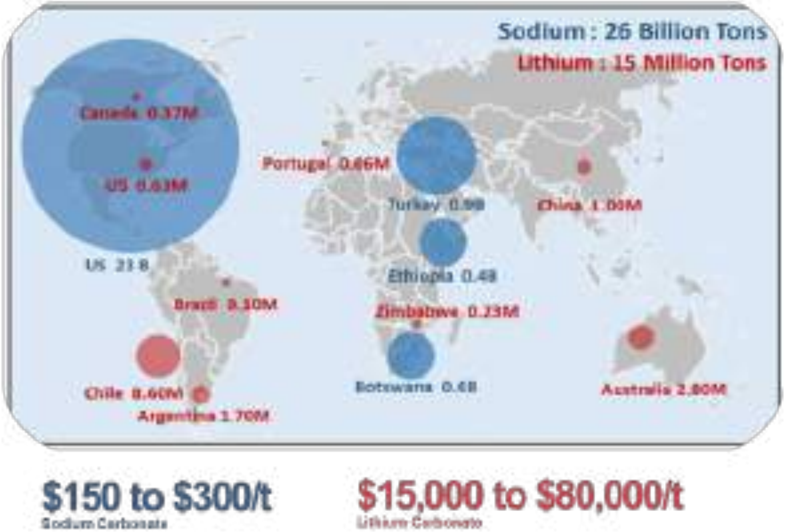
Na-ion Form Factors & Reported Energy Densities



Note:
Only commercially available products with Wh/kg & Wh/L reported are shown.

Vast Abundance Of Sodium Is Key To Addressing Long Term Battery Supply Chain Challenges

SOURCES OF ECONOMICALLY RECOVERABLE SODIUM / LITHIUM. [1]



- United States holds >90% of world's sodium material reserves.[2]
- Sodium naturally exists in Soda ash (Na_2CO_3) form, and is already an established raw material commodity, reducing processing requirements.
- Massive abundance & ease of processing translate into 100x lower raw material prices vs equivalent Li_2CO_3. Potentially achieving <$40/kWh at scale.[3]
- Sodium ion batteries adopt manufacturing methods identical to lithium ion, allowing immediate scalability compared to other emerging next generation technologies.[4]
- Common advantages: Low temperature operation, potential for 0V or 0% SOC storage/transport, high power / rate, long cycle/calendar life.
- Common disadvantages: Lower energy density vs lithium ion, higher near-term costs, wider voltage ranges, uncertainty around safety claims.

Sources: See references above

JANUARY

BYD breaks ground on 30 GWh sodium battery plant in cooperation with Huaihai, making world largest sodium ion plant.

JANUARY

Stellantis Invests in Sodium-Ion: announced plans to fund Tiamat, aiming to diversify its EV battery portfolio.

FEBRUARY

Farasis Energy rolls iut Sodium-Ion powered EV: the JMEV EV3, offering 250km range for urban commute.

MARCH

JAC Motors launches Sodium-Ion EV exports under its YiWei brand, ships 10,000 vehicles to Latin America.

APRIL

CATL announced that Chery Auto would be the first EV company to use their mass-produced sodium-ion batteries.

JUNE

South Korean material giant **Ecopro BM** to produce sodium ion cathodes for a South Korean carmaker.

JULY

World's Largest Sodium-Ion battery operational in China: The Datang Group announced a 100 MWh sodium-ion battery system in Hubei province.

AUGUST

Natron Energy announces plans for $1.4 Billion, 1.2 million sq. ft. Giga-Scale Sodium-Ion battery manufacturing facility in North Carolina.

OCTOBER

Reliance acquires 100% of UK-based Faradion, proposed gigafactory as part of its Dhirubhai Ambani Green Energy Giga Complex.

OCTOBER

CATL launched Freevoy Super Hybrid Battery, hybrid vehicle battery to contain both LFP and Na-ion chemistry.

NOVEMBER

U.S. Department of Energy awards $50 million to establish Na-ion Storage (LENS) consortium. Led by DOE’s Argonne National Laboratory.

DECEMBER

Chinese EV giant **BYD** has launched sodium-ion grid-scale BESS product, using its Long Blade Battery cell.

Sodium Ion Battery Bill of Materials

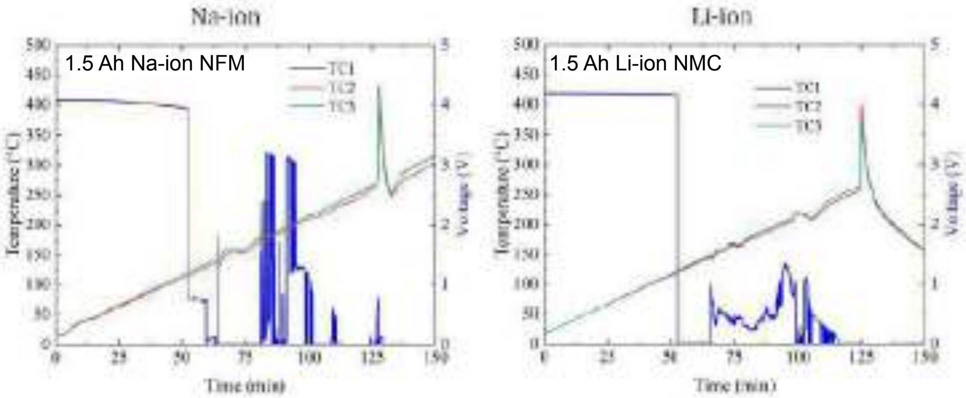
ACTIVE	MATERIAL	$/KG	EXAMPLE CHEMICAL FORMULAS	PROSPECTS & CHALLENGES
Cathodes	Layered Oxide	9 – 13 [1] 4.3 – 8 [2,3]	O3 – $NaNi_xFe_yMn_zO_2$, O3 - $NaCu_xFe_yMn_zO_2$ P2 - $Na_aFe_xMn_yO_2$, P2 - $Na_aNi_xMn_yO_2$	Material stability at high voltage may limit useable capacity and require nickel, but relatively high energy and high tap density
	Polyanion	4 – 6 [1,2]	$Na_3V_2(PO_4)_3$, $Na_3V_2(PO_4)_2F$, $Na_4Fe_3(PO_4)_2(P_2O_7)$, $Na_2Fe_2(SO_4)_3$	Volumetric & Specific energy density is poor, but improved safety could yield cost-downs at pack level
	Prussian White/Blue	2.5 – 3.5 [4] (projected)	$Na_2Fe[Fe(CN)_6]$ $Na_2Mn[Fe(CN)_6]$	Moisture sensitivity may increase costs in material and cell manufacturing
Anodes	Hard Carbon	4 – 11 (realistic) [1,2] 4 – 32 [1,2,3]	C	Growing supply chain is driving lower costs, but many feedstock choices could limit cost and volume.
	Alloys	8 – 20 [1,2]	P, Sn, Sb, Pb, Sn_xP_3	High theoretical volumetric energy density, but expansion must be managed and could limit practical energy density
	Anodeless	n/a	Na *(Note: No commercial Na foil available)*	High energy density with minimal processing, but expansion must be managed and could limit practical energy density

INACTIVE	MATERIAL	$/KG	EXAMPLE CHEMICAL FORMULAS	PROSPECTS & CHALLENGES
Electrolyte	$NaPF_6$ Carbonate-Based	7 - 11 [1,3]	$NaPF_6$ in EC/PC/DEC/DMC/EMC	Good oxidative stability, but generates volatile/toxic gas at high voltage/during thermal runaway. $NaPF_6$ forms soluble SEI species.
	$NaPF_6$ Ether-based	Unknown, but glymes are 2-3x cost of PC	$NaPF_6$ in DEE/DME/DEG/TEG/THF	Superior SEI stability and lower Na plating risk/ compatibility with Na metal, but limited oxidative stability. $NaPF_6$ forms soluble SEI species.

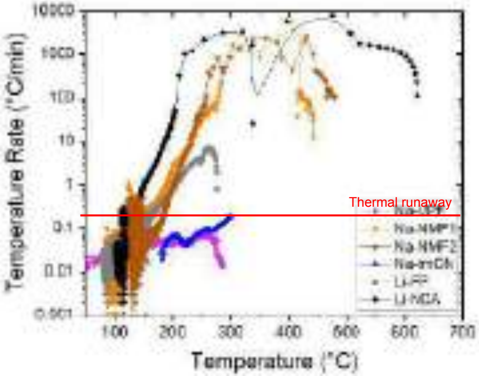
Sources: 1. Yao, A. Benson, S.M., Chueh, W.C. How quickly can sodium-ion learn? Assessing scenarios for technoeconomic competitiveness against lithium-ion batteries. arXiv::2403.13759v3 (2024). ; 2. Shanghai Metals Market (SMM). Metals.com. ; 3. Omenya, A. Sodium-Ion Battery Development. DOE-OE Peer 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.

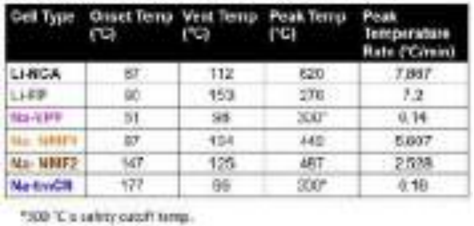
Key Findings From Na-ion vs Li-ion – ARC / Thermal Ramp Testing

- Na-ion layered oxide (NFM) show similar thermal runaway properties (>1˚C / min) to Li-ion NMC/NCA.
- Na-ion polyanion (NVPF) and Prussian blue avoids thermal runaway (<1˚C / min).
- Na-ion Prussian blue generates hydrogen cyanide during cell abuse.
- Thermal runaway risk is correlated to energy density / cell capacity.



Source: Alex M. Bates and Loraine Torres-Castro, Sandia National Laboratories





Cell Type	Onset Temp (°C)	Vent Temp (°C)	Peak Temp (°C)	Peak Temperature Rate (°C/min)
Li-NCA	87	112	620	7,887
Li-FP	90	153	276	7.2
Na-VPF	51	98	300*	0.14
Na- NMF1	87	104	440	5,607
Na- NMF2	147	125	487	2,528
Na-tmCN	177	96	300*	0.18

*300 °C is safety cutoff temp.

Source: Rachel Carter, Gordon Waller, Connor Jacob, Dillon Hayman and Corey Love, US Naval Research Laboratory

Na-ion's New Capabilities Reported

0V OR 0% STORAGE & TRANSPORT

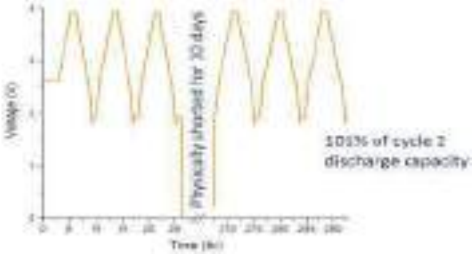
Reports found the potential for no detrimental effects during over discharge to 0% or 0V, this is mainly due to absence of Cu Foil.

LOW TEMPERATURE OPERATION

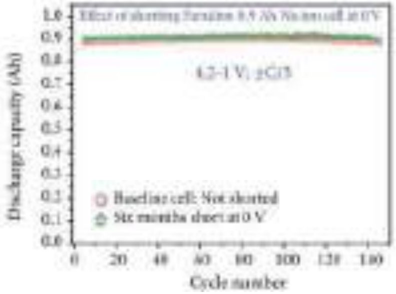
Na-ion can operate up to -40˚C or lower. This is mainly due to the electrolytes used that avoid sluggish effects seen in Li-ion.

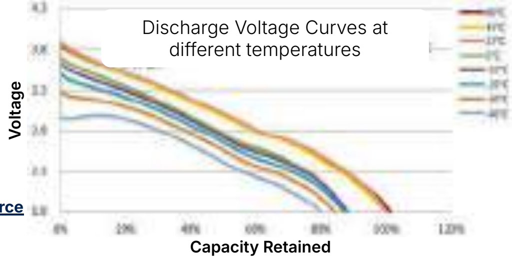
HIGH POWER / FAST CHARGE EXCEEDING LI-ION

Discharge rates >10C, and charge rates >4C commonly reported, this is mainly due to the rate capabilities of Hard carbon (vs graphite).



Source

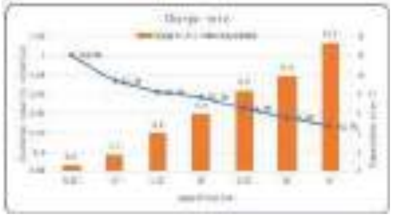




Discharge Voltage Curves at different temperatures

Source

0.3C charge at 25°C, cut-off 0.05C		-40°C	-30°C	-20°C
Discharge C-rate	0.33		82.4%	89.0%
	0.5	73.9%	83.6%	89.8%
	1		83.8%	88.8%
	2		84.6%	88.0%
	4			



Source

Source: Rachel Carter, Gordon Waller, Connor Jacob, Dillon Hayman and Corey Love, US Naval Research Laboratory

Sodium-Ion Batteries Hold Promise For Adoption In Two-Wheelers & Hybrid Integration With Li-Ion In EVs

China-based TAILG has revealed its new sodium-ion battery technology in its luxury e-bikes, capable of reaching 115 kilometers in temperatures below 0 C, while maintaining a speed of 25 km/h, with a lifecycle exceeding 2,000 cycles.

Komatsu has developed and unveiled a concept machine for a 1.5-ton electric forklift powered by sodium-ion batteries, which is ready to start proof of concept tests at job sites beginning in March 2024.

TWO WHEELERS

EV

INDUSTRIAL EQUIPMENT

JMEV rolled out the world's first sodium-ion-powered EV, JMEV EV3 (Youth Edition). Equipped with Farasis Energy's 140-160 Wh/kg sodium-ion batteries, this A00-class EV offers a range of 251 km.

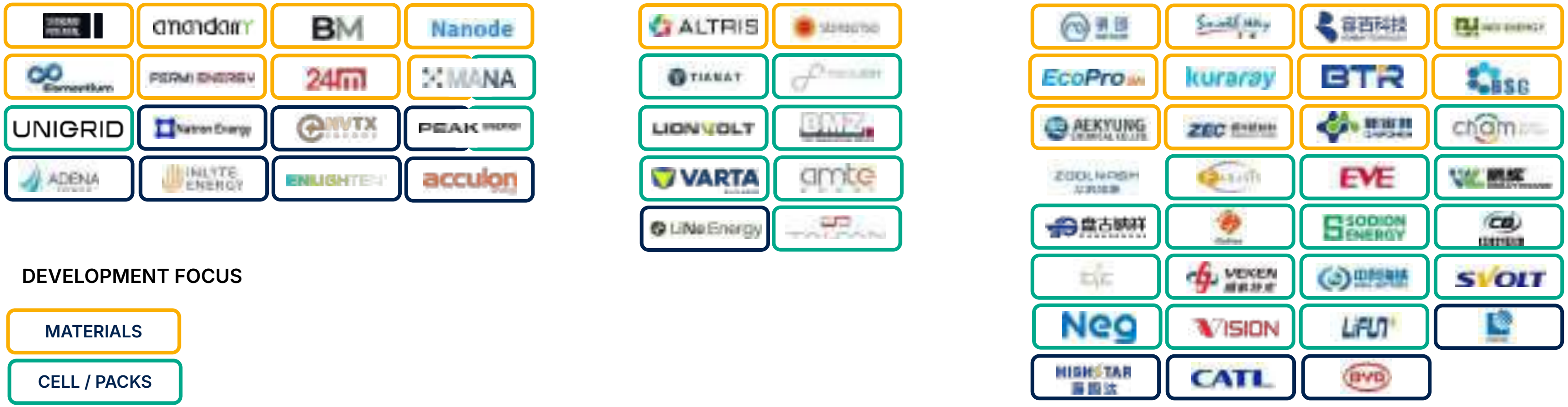
CATL's Freevoy battery pack for hybrid vehicles. Integrated with sodium-ion batteries and lithium-ion batteries, it can deliver more than 280 kilometers on a 10-minute charge and normal operations at <-20C low-temperatures.

Sodium Ion Battery Players By Region / Areas Of Focus

AMERICAS

EMEA

ASIA-PACIFIC



DEVELOPMENT FOCUS

- MATERIALS
- CELL / PACKS
- FULL SYSTEMS

Sodium-Ion Batteries Demonstrate Strong Progress In Various Energy Storage Applications And Serve As Potential Lead-Acid Replacements Across Diverse Scenario

GRID-SCALE ENERGY STORAGE

BYD's recently-launched sodium-ion BESS product, using its proprietary form factor Long Blade Battery cell, which has an energy storage capacity of 2.3MWh a voltage range from 800V-1400V.

RESIDENTIAL ENERGY STORAGE

Australian company **PowerCap** has recently unveiled an innovative sodium-ion battery system tailored for home energy storage, options ranging from 3.4 kWh to 20.4 Wh.

BACKUP POWER SUPPLY

Natron scales up production capacity of sodium-ion batteries to 600 megawatts annually, addressing the energy storage needs of data centers powering the surge in Artificial Intelligence.

OTHERS AS LEAD-ACID REPLACEMENTS

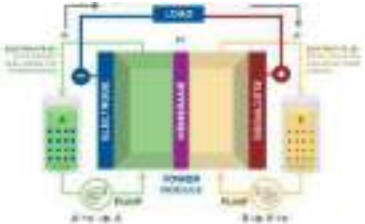
Biwatt scaled the commercial deployment of its residential sodium-ion storage systems in 2024. Beyond that, Biwatt is introducing tool-oriented sodium-ion products, including the lead-acid replacement P1 (12V 100Ah), the starter battery P2 (12V 70Ah), and the jump starter.

Redox Flow Batteries

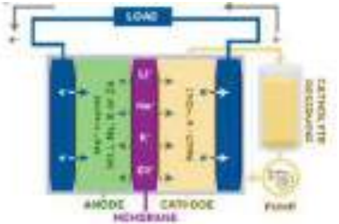
Redox flow batteries (RFBs) come in variations in form factor and chemistry giving a wide range of performance leading in long lifetime and safety and opportunity for advancement.

TRADITIONAL RFBS

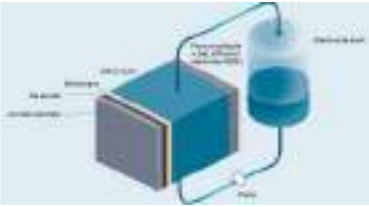
REDOX TARGETING RFBS



HYBRID RFBS



METAL AIR



VALUES AS OF 2023[1]	TRADITIONAL RFB	METAL AIR
Cell-level energy density	22-30 Wh/kg	20 Wh/kg (Fe-air) 150-300Wh/kg (Zn-air)
Volumetric energy density	30-40 Wh/L	28 Wh/L (Fe-air) 100-200 Wh/L (Zn-air)
Cycle life	>10,000	500
Calendar life	20 years	25 years
Efficiency	60-90%	59-64%
Other Features	Non-flammable	Non-flammable, high sustainability

Sources: DOE Flow Battery Technology Assessment; Fraunhofer Institute Alternative Battery Technologies Roadmap 2030+

Flow Battery Companies Are Rapidly Emerging In The Americas And Emea

AMERICAS

noon energy
ESS Inc
Form Energy
ENERVENUE
cmblu
STRYTEN ENERGY
LARGO
VRB ENERGY
THE SUN COMPANY
e-zinc
ABOUND

EMEA

voltstorage
REDOX
KEMIWATT
pinflow energy storage
redoxblox
cellcube
INVINITY ENERGY SYSTEMS
elestor
SINERGY FLOW
RIVUS

ASIA - PACIFIC

allegro
RKP
[illegible]

METAL AIR
VANADIUM
ORGANIC
IRON
OTHER

Looking to establish themselves as leaders of long duration grid storage technologies.
These technologies are widely varied and at a range of development from R&D to commercial deployment.

$1 Billion Has Been Invested Into Metal Air/Flow Batteries In 2024

Led by government funding signaling a growth in the energy storage market and the need for safer, longer duration options

COMPANY NAME	FUNDING AMOUNT ($M)	FUNDING SOURCE (LEAD INVESTOR)	INVESTMENT TYPE
Allegro Energy	$11.1	The Grantham Foundation	Series A
CleanTech Strategies LLC	$5.0	US Department of Energy	Project Grant
CMBlu Energy	$31.5	Greece Ministry of Environment and Energy	Manufacturing Grant
e-Zinc	$31.0	Evok Innovations	Series A2
ESS, Inc	$115.0	EXIM MMIA, Queensland Gov't and Private	Manufacturing Grants
Form Energy	$475.0	US Department of Energy, T Rowe Price	Project Grant, Series F
Invinity Energy Systems	$29.7	US Department of Energy	Project Grant
NextEra Energy Resources Development	$49.1	US Department of Energy	Project Grant
Noon Energy	$8.8	California Energy Commission	Project Grant
Redflow	$39.0	California Energy Commission, US Department of Energy	Project Grants
Redox One	$40.0	Tharisa	Series A
RedoxBlox	$74.5	Khosla Ventures, California Energy Commission, Prelude Ventures	Project Grants, Series A
Stryten Energy	$5.0	US Department of Energy	Manufacturing Grant
VRB Energy	$55.0	Shaxi Red Sun Co. Ltd.	Strategic Investment

Partnerships To Deploy And Further Develop Commercial Flow Battery Technology Drove The Headlines

JANUARY

Stolthaven and XL Batteries announce partnership

JANUARY

ACWA Power and VoltStorage collaborate on Iron Salt Battery

MARCH

Mercedes-Benz orders First sustainable SolidFlow energy storage system by CMBlu Energy

MAY

Octet Scientific forms key Partnership with e-Zinc to boost energy storage innovation

JUNE

4MWh Sale to PowerFlex for California PV+Storage project

JUNE

California Agency awards $26.7M for LDES projects

JULY

Invinity official opens new UK manufacturing facility

AUGUST

EnerVenue accelerates Australian expansion with AVID Group master supply agreement

OCTOBER

CellCube receives $19M for MW Scale Vanadium Redox flow battery system

DECEMBER

EnerVenue provides RWE with LDES vessels for pilot project

DECEMBER

Stryten Energy and Largo launch LDES company Storion Energy

DECEMBER

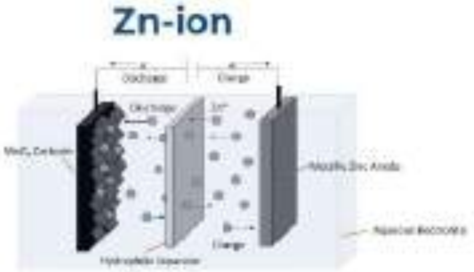
Argonne and Idaho National Labs partner with CMBlu Energy for LDES Project

Zinc-ion Batteries

Advancing the design of primary household batteries, Zinc Manganese Dioxide batteries have had significant development as cheap, safe and sustainable rechargeable batteries.

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. The manufacturing process emits **70% less CO_2** during manufacturing and is fully recyclable. 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.



USE CASE: BACKUP POWER AND GRID STORAGE

LDES: NYSERDA Awards Nearly $15M to Four Demonstration Projections

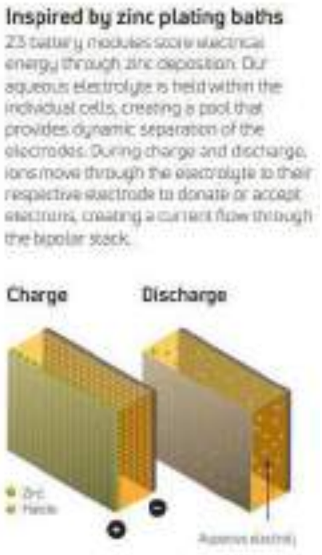
DHS Announces First Winners, Awards $835k "Clean Power for Hours Challenge" in Celebration of Earth Day 2024

OCED Awards LDES STORED project, led by UEP in Collaboration with the NYPA and EPRI

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

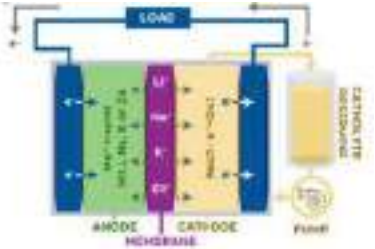
NON FLOW CHEMISTRY



Inspired by zinc plating baths

Z3 battery modules store electrical energy through zinc deposition. Our aqueous electrolyte is held within the individual cells, creating a pool that provides dynamic separation of the electrodes. During charge and discharge, ions move through the electrolyte to their respective electrode to donate or accept electrons, creating a current flow through the bipolar stack.

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 CASE: GRID STORAGE

Eos Energy and Pine Gate Renewables Sign Agreement to Expand Existing Relationship

Eos Energy Announces Expansion of Existing Project with Indian Energy and the California Energy Commission

Eos Energy Signs Agreement with City Utilities of Sprinfield, Missouri to Provide 216 MWh of Energy Storage

Eos Energy and FlexGen Partner to Accelerate a Fully Integrated American Made Stationary Storage Solution for LDES Applications

Features:

Non-flammable, no HVAC/fire suppression needed

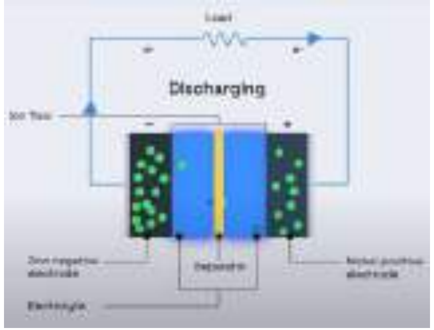
Domestically manufactured and sourced **(Eos claims >85% from USA)**

Duration times: 3-12 hours today

Nickel Zinc Batteries

Nickel Zinc batteries are growing as alternatives to lead acid batteries for critical infrastructure providing higher power densities, indoor fire safety, and lower total cost of ownership.

BASIC CHEMISTRY



$Zn + 2NiOOH + 2H_2O \rightarrow Zn(OH)_2 + Ni(OH)_2$

Features:
3x power density to lead acid, ½ size, ⅓ weight

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 manufacturers.

USE CASE: BACKUP POWER

Vertiv and ZincFive Collaborate to Deliver Safe and Reliable Nickel-Zinc Battery Energy Storage for Data Center UPS in North America and EMEA

ZincFive Announces 1GW of Mission Critical Data Center Power Solutions Delivered and Contracted

Kohler Uninterruptible Power and ZincFive Team Up to Deliver Safe, Sustainable Nickel-Zinc Energy STorage Solutions for Data Centers

EnZinc Opens Critical Battery Component Manufacturing Center to Meet Growing Customer Demand

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[1]	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

The Americas And EMEA Have The Opportunity To Lead Zinc Battery Manufacturing With Not Only Many Battery Manufacturers Present, But Also Much Of The Supply Chain

AMERICAS

BATTERY MANUFACTURERS

ZincFive
eos
URBAN ELECTRIC POWER
e-zinc
ENZINC
SALIENT
IMPRINT ENERGY
ZELOS
THE SUN COMPANY
ABOUND

SUPPLY CHAIN

Zochem
Octet Scientific
CELGARD
سابك sabic
TETRA

EMEA

enerpoly
[illegible]
SunErgy

everZINC
Brüggemann
GRILLO
IMR Metal Powder Technologies
EasyI Zinc

ASIA - PACIFIC

gelion
PMB DEFENCE

JG Chemicals
bdj
NIPPON SHOKUBAI
Silox
Diamondchem
Hindustan Zinc
vedanta

ZINC ION
ZINC NICKEL
ZINC HALIDE
ZINC AIR

ZINC SALTS
ELECTROLYTE
ELECTRODE MATERIALS
SEPARATORS

Major Players In The Zinc Battery Market Have Announced More Commercial Deployments In The Grid Storage And Data Center Market

APRIL

LDES: NYSERDA Awards Nearly $15M to Four Demonstration Projections

Eos Energy and Pine Gate Renewables Sign Agreement to Expand Existing Relationship

MAY

ABB Introduces Innovative Nickel-Zinc Battery for Leading Data UPS Solution

DHS Announces First Winners, Awards $835k "Clean Power for Hours Challenge" in Celebration of Earth Day 2024

JULY

Eos Energy Successfully Launches Commercial Production on First State-of-the-Art Manufacturing Line

Eos Energy Announces Expansion of Existing Project with Indian Energy and the California Energy Commission

Vertiv and ZincFive Collaborate to Deliver Safe and Reliable Nickel-Zinc Battery Energy Storage for Data Center UPS in North America and EMEA

OCED Awards the LDES STORED project, led by UEP in Collaboration wtih the NYPA and EPRI

AUGUST

Kohler Uninterruptible Power and ZincFive Team Up to Deliver Safe, Sustainable NIckel-Zinc Energy Storage Solutions for Data Centers

NOVEMBER

Eos Energy Signs Agreement with City Utilities of Springfield, Missouri to Provide 216 MWh of Energy Storage

DECEMBER

Eos Energy and FlexGen Partner to Accelerate a Fully Integrated American Made Stationary Storage Solution for LDES Applications

Eos Energy Secures 400MWh Order with International Electric Power to Deliver Critical Resilience in California

Zinc Battery Manufacturers Face The Challenging Transition From R&D

Pilot projects to commercial production, striving to scale up by enhancing manufacturing processes, strengthening supply chain partnerships, and securing funding to advance their operations.

	MANUFACTURING/SUPPLY CHAIN PARTNERSHIP ANNOUNCEMENTS
	Celgard and AEsir Technologies Form Strategic Alliance
	Hindustan Zinc and US-based AEsir Technologies join hands for developing Zinc Batteries
	Vedanta NIco and AEsir Technologies Partner to Revolutionize EV Battery Technology with NIckel-Zinc Batteries
e-zinc	e-Zinc Raises $31 Million for Manufacturing Facility
enerpoly	Zinc-Ion Battery Innovator Enerpoly Acquires Full Cell Production and Pack Assembly Lines to Boost European Energy Resilience
	Sweden's Enerpoly Opens World's First Zinc-Ion Battery Megafactory
ENZINC	EnZinc Opens Critical Battery Component Manufacturing Center to Meet Growing Customer Demand
eos	Eos Energy Enterprises and TETRA Technologies, Inc. Extend Partnership, Expanding Electrolyte PRoduction Capacity
	Eos Energy Successfully Launches Commercial Production on First State-of-the-Art Manufacturing Line
	Eos Energy Signs MOU with Wabash to Dramatically Accelerate the Supply Chain Ecosystem for American Made Energy Storage Solutions
	Eos Energy Enterprises Join Forces with SABIC Specialties to Produce Specialty Current Collectors
	DOE Awards $15M to Prize Winners for Domestic Clean Energy Manufacturing Facilities
ZincFive	ZincFive Accelerates Investment in U.S. Manufacturing

A Total Of $805M Was Invested In Zinc Battery Technologies Led By The US Government Largely For Deployments And Scale Up Of Leading Manufacturers

COMPANY NAME	FUNDING AMOUNT ($M)	FUNDING SOURCE (LEAD INVESTOR)	INVESTMENT TYPE
New Lab LLC	$5.0	US Department of Energy	Project Grant
Urban Electric Power	$0.4	US Department of Homeland Security	Project Grant
Redflow	$9.0	California Energy Commission	Project Grant
Eos Energy Enterprises	$315.5	Cerberus Capital Management	Strategic Investment
e-Zinc	$31.0	Evok Innovations	Series A2
Urban Electric Power	$6.5	US Department of Energy	Project Grant
NextEra Energy Resources Development	$49.1	US Department of Energy	Project Grant
Redflow	$30.0	US Department of Energy	Project Grant
Urban Electric Power	$5.0	US Department of Energy	Project Grant
Eos Energy Enterprises	$303.5	US Department of Energy Loan Programs Office	Loan Commitment
EnZinc	$8.0	TO VC	Series A
Eos Energy Enterprises	$42.0	California Energy Commission	Project Grant

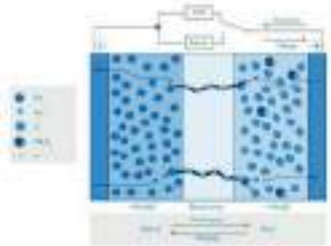
High Temperature Batteries

High temperature batteries use molten electrodes separated by a solid ceramic electrolyte separator. They were developed for stationary storage applications for discharge durations of up to 8 hours.

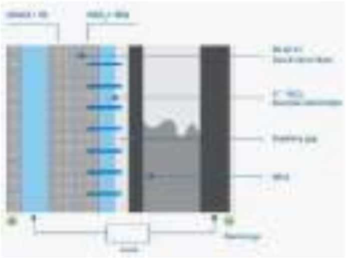
SYSTEM OVERVIEW

High temperature batteries operate at temperatures over 250°C to ensure that the electrodes remain in a molten state and are electrochemically active. The electrolyte is typically sodium beta-alumina. There are two high temperature battery chemistries which have been successfully commercialised as of 2024:

Sodium-sulfur [1] batteries, where molten sulfur and molten sodium are separated from a beta-alumina electrolyte layer.



Sodium nickel chloride [2] batteries, sometimes called ZEBRA batteries, which use nickel chloride and molten sodium electrodes.



USE CASE: GRID STORAGE

High temperature batteries typically have cell energy densities of 100 to 200 Wh/kg, and operate at round-trip efficiencies of around 70 to 80% when operating at temperature. They have been widely deployed in energy storage applications for discharge durations of up to 8 hours, making them suitable for pairing with solar PV installations.

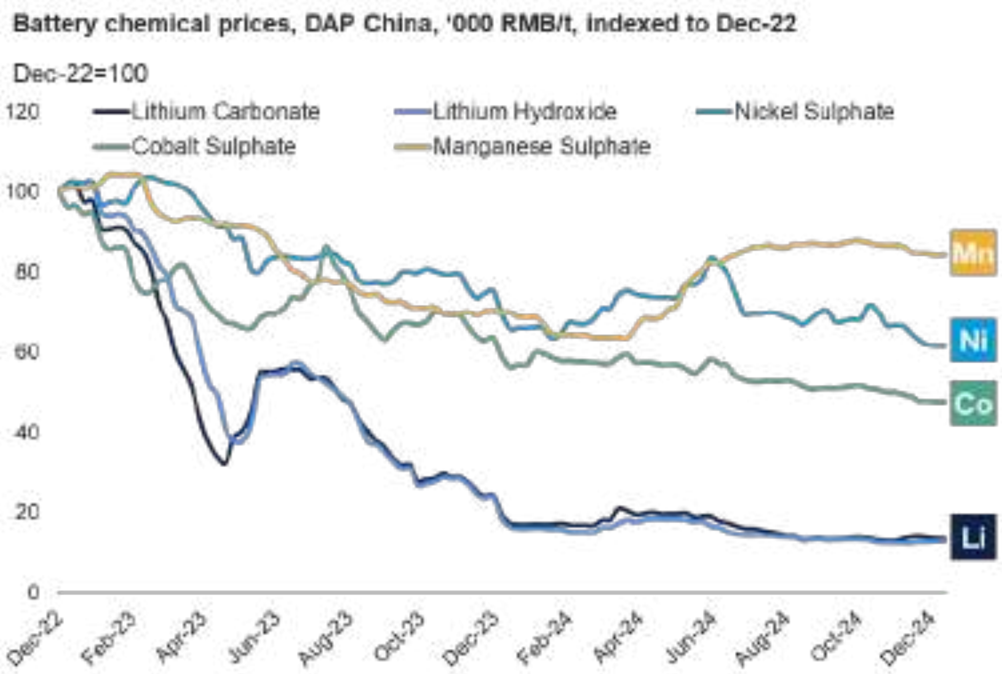
Source: [1] NGK Insulators - Product, [2] EASE - Technologies

1 INDUSTRY

Section Summary - Overview

- 2024 has been a challenging year for raw material producers and the midstream, but a boon for anyone buying materials.
- Supply growth has continued to overshoot demand, pushing prices down further.
- Now many mining and refining operations – especially higher-cost ones – are curtailing supply, and adjusting CapEx to realign with demand growth.
- However, investment continues to drive supply growth at a global level, with stakeholders keen to secure their positions in a bright future for battery raw materials.
- Major downstream manufacturers are accelerating vertical integration strategies and directly investing in raw materials
- China is the only major market to see raw material import growth in 2024.
- Lithium demand from batteries is a long-term certainty, but the speed and scale at which it grows outside China is now at more risk than ever due to policy changes and industry pullbacks.
- All battery raw materials are being thrifted over time, and – in the case of nickel and cobalt – being substituted out.

Battery Raw Material Prices Stay Low In 2024



- Mining investments have increased supply of battery materials
- Rate of growth supply has outpaced EV and battery demand
- Companies have struggled to draw down on inventories
- Continued shift to LFP in EVs has softened demand for nickel and cobalt

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Lithium - Low Prices Are Great For Battery Costs, But Risks Long-Term Supply

Supply outpacing demand has pushed lithium prices to their lowest level in 38 months. While low prices enable cheaper batteries, this also means (generally speaking, as there are exceptions):

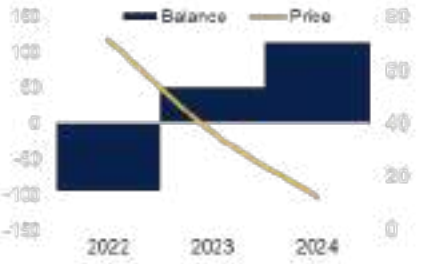
- Further demand feedback from EVs and BESS
- Operating mines are curtailed in the short-term
- Project investment in the short-to-medium term is dampened

...all of which increases the risk of supply not keeping up with demand.

This means continuing cycles of volatility, albeit not as severe as in the past.

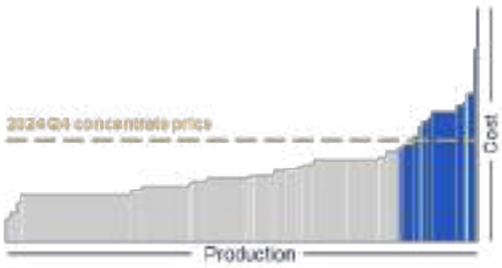
Surplus supply continues to weigh on prices...

Lithium market balance and price, kt LCE & $/t LCE



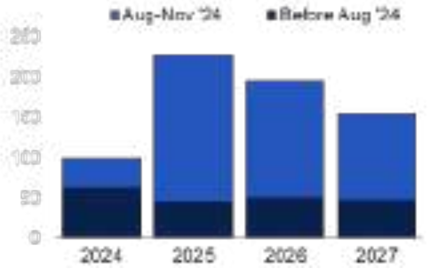
...which pressures margins for the highest-cost mines

Value-adjusted cash mining costs*, $ /dmt conc.



...which results in curtailments to mining supply

Realised mine curtailments, kt LCE, as of Dec-24



Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. *Cost curve shows only pegmatite operations.

Latest Trends In The Lithium Industry

Many producers keep operations going, despite curtailments elsewhere, and mine permits continue to be granted

Supply is emerging from new sources, such as Argentina, Africa, and China's Sichuan province

The average lithium ore grade is decreasing over time, which increases the cost of producing lithium chemicals

High-cost miners and non-integrated refiners are struggling to be profitable

Chinese lithium refineries are the lowest-cost but also underutilized

Individual mining operations of all sizes are optimizing processes and **scaling up production to bring costs down**

Lithium intensity in batteries is decreasing, requiring less material per kWh over time

Much more lithium is being consumed in CAM than end-use due to overproduction, especially for LFP

China leads imports & refining, but CAM is expanding overseas, precipitating a **shift in regional lithium chemical consumption**

Leading battery manufacturers gain influence over lithium prices **as they accelerate vertical integration**

Price discovery is gaining momentum on the physically settled Guangzhou Futures Exchange

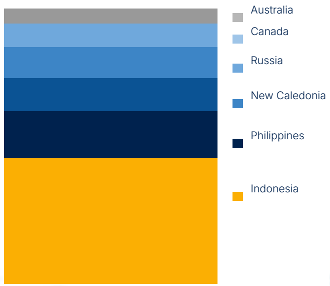
Mergers & acquisitions are heating up, but supply is still diversifying by region and resources

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Indonesia Is Consolidating Its Dominance In The Nickel Industry

Indonesia Ni exports have increased from $4B to $35B

TOP NICKEL PRODUCERS 2024



NICKEL RESERVES (Millions mt)

Source: S&P Global, SMM

NICKEL CURTAILMENT POLICY

44 smelters are currently in operation and 26 are still under construction. This condition pushes down Nickel prices in 2024 as low-cost supply floods the market.
To mitigate the oversupply condition and risks that could undermine investments and the country's lead in the market, Indonesia has:

- Imposed a moratorium on RKEF Nickel Pig Iron smelters
- Considered removing the tax holiday for RKEF smelters
- Considered a future policy that favors higher-grade nickel smelters (HPAL, which is relevant for the battery industry)

Nickel ore production in 2024 also had bureaucratic delays, resulting in massive imports from the Philippines.

ESG COMPLIANCE

Indonesia is working to design ESG frameworks tailored to its local conditions, balancing sustainable nickel production with global market demands, and environmental responsibilities.

Latest Trends In The Nickel Industry

Investments in Indonesian supply continue, but Western-backed projects in the country are being cancelled

Indonesia is enacting curtailment policies to mitigate oversupply and protect higher-grade operations

Project curtailments, especially in Australia, have brought ex.Indonesia supply to its lowest level in years

Leading battery manufacturers gain influence over nickel & cobalt payables as they **accelerate vertical integration**

Sluggish nickel demand in batteries has pushed pCAM and NiS producers to **move into (non-battery) metal refining**

Non-integrated nickel sulphate and pCAM producers are struggling to be profitable

Nickel consumption in pCAM has been stagnant for 3 years

Stainless steel remains by far the largest demand driver for nickel

Battery- and auto-makers now moving away from high-nickel chemistries towards **high-voltage medium-nickel**

Nickel intensity in batteries is decreasing, requiring less material per kWh over time

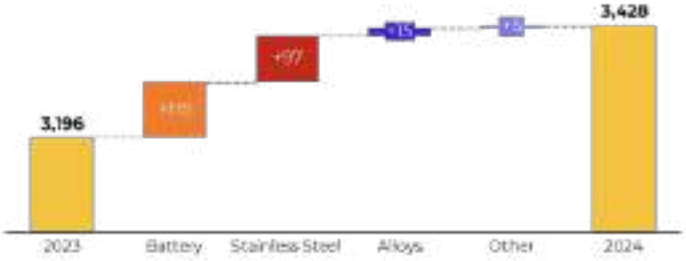
China leads refining, but pCAM is expanding overseas, precipitating a **shift in regional nickel demand**

Nickel sulphate capacity expansions are slowing in China but accelerating in Indonesia and South Korea

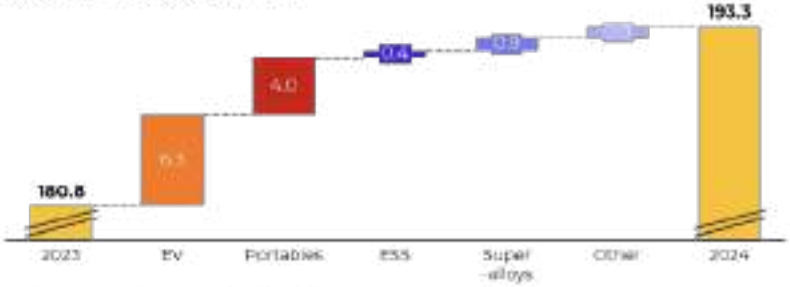
Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Cobalt Demand Relies On Batteries, While Stainless Steel Drives Nickel Demand

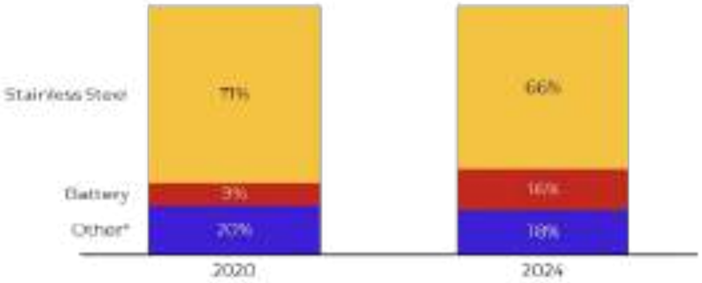
Nickel Demand (2023 vs. 2024), Unit: kt Ni contained



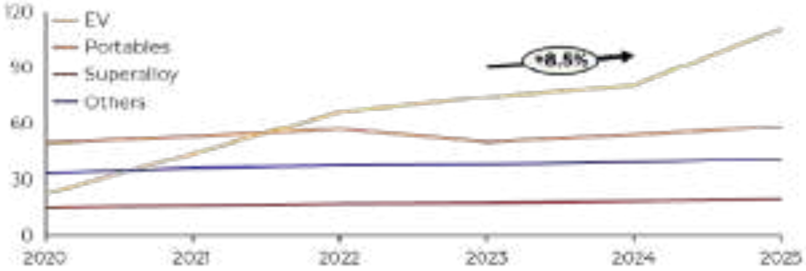
Cobalt Demand (2023-25), Unit: kt



Nickel Demand by Application, Unit: kt Ni contained



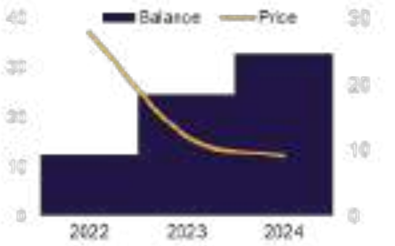
Cobalt Demand by subsegment, Unit: kt



Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/cobalt.

Cobalt Is In A Severe Oversupply Situation

Refined cobalt market balance & price, kt and $/lb Co



KEY TRENDS:

DRC, Indonesia, and China driving oversupply and overcapacity

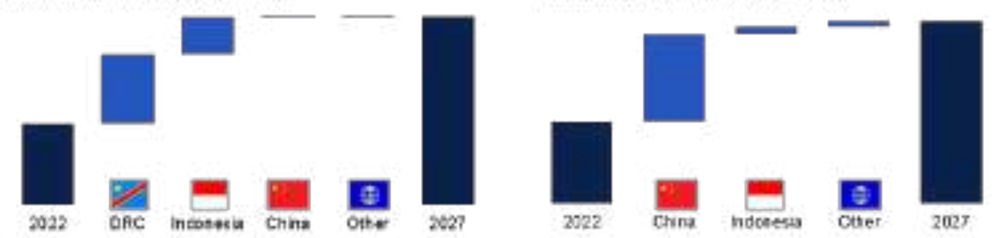
Supply is becoming even more concentrated - several Australian and US projects curtailed

Cobalt demand diversifying beyond China with new pCAM projects, but mainly in low-risk and low-cost countries like Indonesia

Very little supply outside the Chinese-controlled DRC-Indo-China triumvirate

Additional mine supply, kt Co

Additional refined supply, kt Co



LARGE SURPLUS DRIVEN BY SUPPLY GROWTH:

Almost all cobalt is mined as a byproduct of nickel or copper. As such, miners are not deterred by low Co prices and will continue production as long as Ni and Cu markets incentivize it. Curtailments are far from being enough to balance the market.

COBALT IS BEING THRIFTED AND SUBSTITUTED:

Shift to Co-free LFP and improvements to NMC cathode materials are heavily dampening demand for Co in batteries - average Co intensity has dropped by two thirds in five years.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Manganese Due For Great Influx Of Demand In Batteries

CHINA DOMINATES HIGH PURITY MANGANESE PROCESSING AND PRODUCES THE CHEAPEST PRODUCT[1]

Mn chemicals used to make Li-ion and Na-ion CAM[2]:

MANGANESE SULPHATE

- for NMC, NMCA, LMFP, future LNMO and LMR

MANGANESE CARBONATE

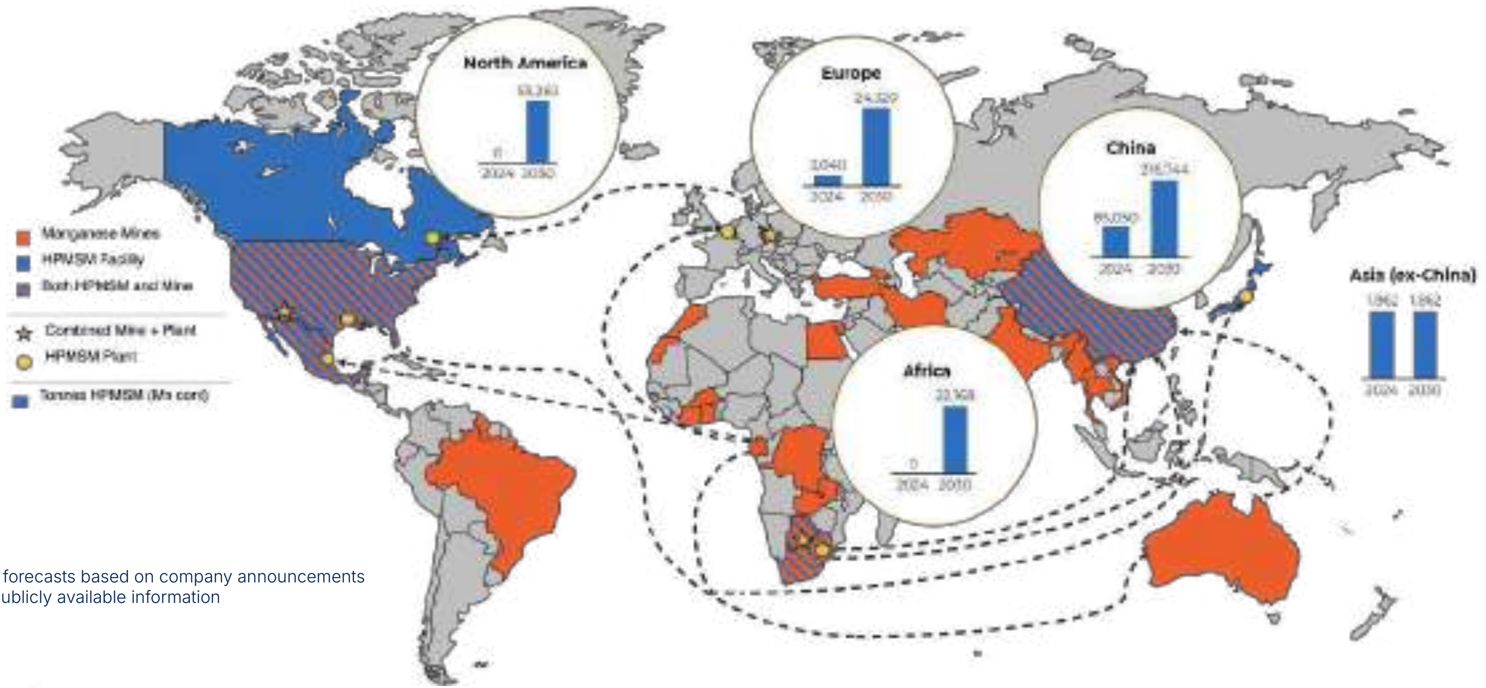
- for LMFP and layered-oxide Na-ion

MANGANESE TETROXIDE

- for LMFP and layered-oxide Na-ion

Source: [1] Manganese Metals Company, [2] CRU Group (Distinguished Partner)

Manganese Mines Are Concentrated In Asia (China & Ex-China) In 2024

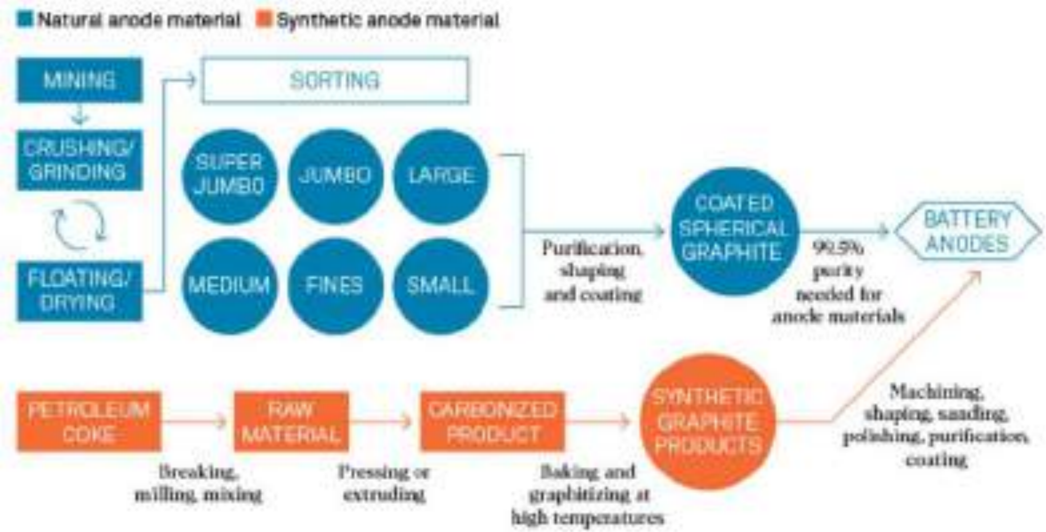


2030 forecasts based on company announcements and publicly available information

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/manganese.

Graphite 101

NATURAL GRAPHITE IS MINED FROM THE EARTH
SYNTHETIC GRAPHITE IS DERIVED FROM PETROLEUM COKE



Source: S&P/Battery Materials Review

OVER 85% OF BATTERIES USE SYNTHETIC GRAPHITE

Natural graphite has (historically) been cheaper and much less carbon-intensive to produce.

Synthetic graphite is favored for its high purity and predictable performance, with benefits of fast charging and long cycle life.

Lead time on a synthetic graphite plant is much shorter than natural graphite mine.

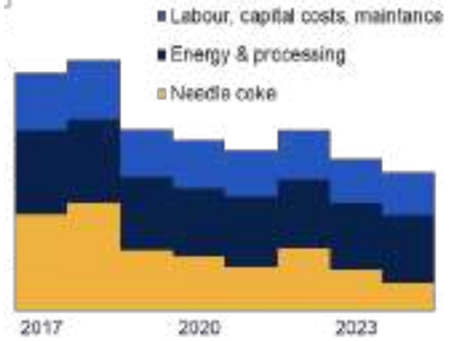
Synthetic graphite has consolidated its market share, but it is sometimes blended with small amounts of natural graphite.

China controls 85-96% of production depending on the product in question.

Synthetic Graphite Costs Have Fallen Significantly

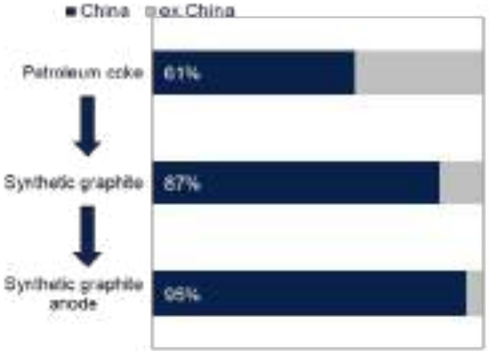
Abundant feedstock and low energy prices keep Chinese costs low

Average synthetic graphite AAM production cost, China, nominal, $/kg



...but geopolitics and higher costs ex.China pose a risk to supply & prices

Production share in SG anode supply chain, 2024



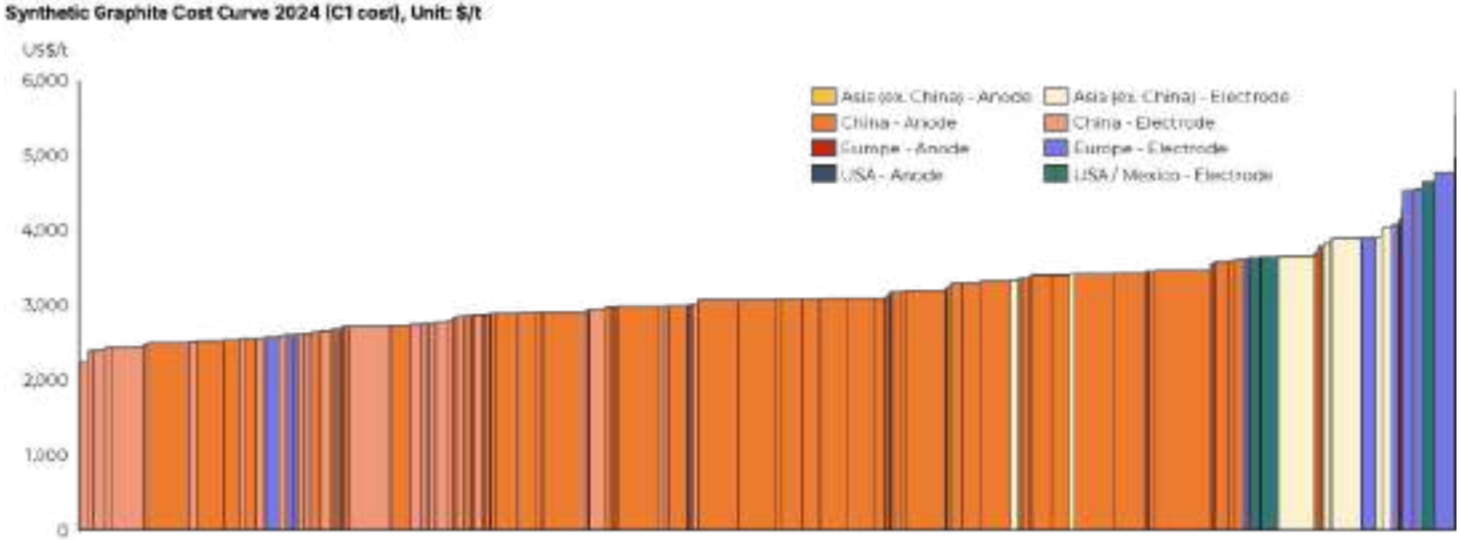
PRODUCTION AND PROCUREMENT COSTS FOR SYNTHETIC GRAPHITE ANODE MATERIAL HAVE FALLEN SIGNIFICANTLY IN RECENT TIMES

- Underlying costs are driven by **electricity and needle coke prices**, as SG production is an energy- and oil-intensive process.
- There has long-been a massive abundance of capacity for petroleum coke and graphite anode in China.
- Similar to the CAM market, AAM in China is in a state of **overcapacity and intense price competition**, while producers are currently commanding higher prices outside China.
- The main upside risk to ex.China prices is if China bans exports outright or if punitive tariffs are applied elsewhere.
- ex.China production is converging on **Indonesia, Morocco,** and limited parts of the US and Europe, for which underlying costs can reach similar levels to that of China.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). AAM = Anode Active Material. Price margin not shown.

High Costs Are The Main Hindrance To Synthetic Graphite Production Outside China

Production costs in China are lower than the rest of the world, mainly due to cheap energy and abundant feedstock materials.



Synthetic Graphite Cost Curve 2024 (C1 cost), Unit: $/t

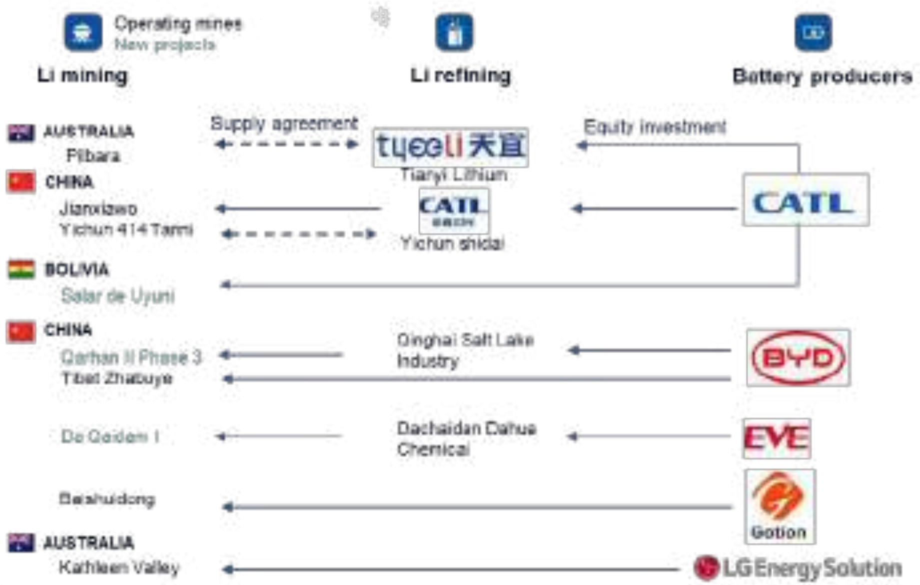
Notes:

- C1 cost includes feedstock, processing cost, G&A cost, power cost, labor cost, logistics cost and other cost (if any)
- Different operations on the cost curve produce material with different types of anode materials and electrodes in terms of quality and carbon content, thus will not receive the same prices for all material sold

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/synthetic-graphite.

Leading Battery Manufacturers Gain Influence Over Material Prices

Example: Battery manufacturers involvement in lithium upstream supply



BATTERY MANUFACTURERS VERTICALLY INTEGRATING WHILE THE MIDSTREAM IS RELEGATED TO MIDDLE MEN

To reduce the impact of price volatility on costs, and to gain an **additional competitive edge**, battery producers have sped up their vertical integration strategies by acquiring equity stakes in lithium, nickel, and cobalt resources and refineries.

This trend has several implications:

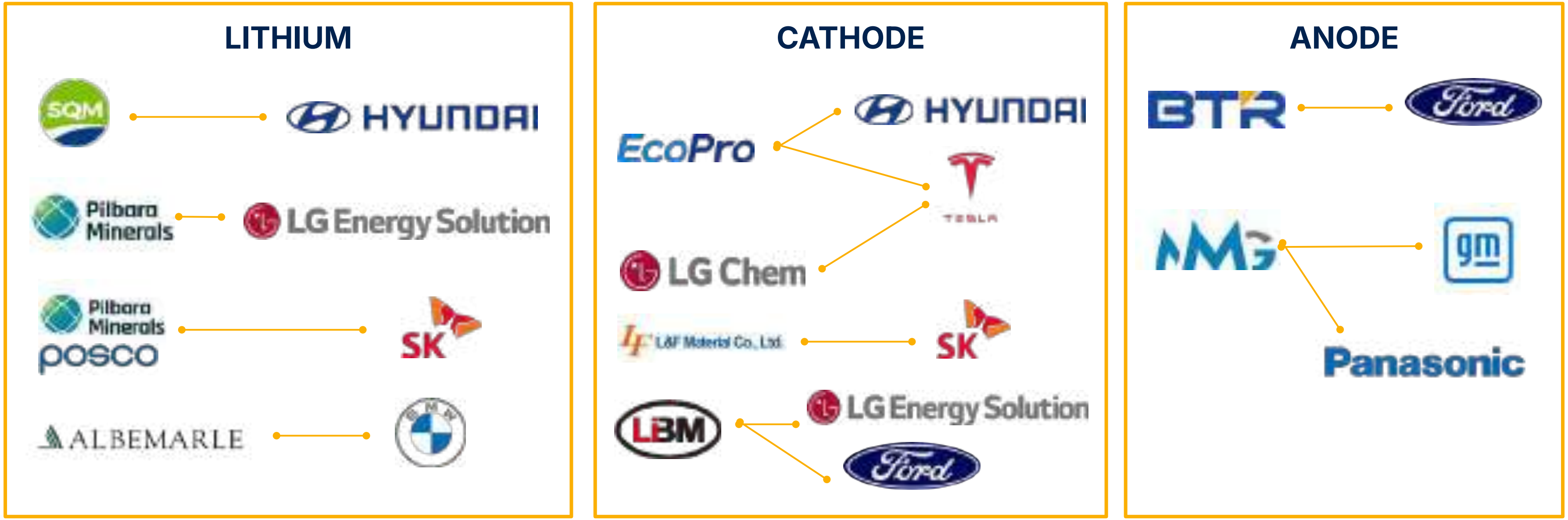
- More mined feedstock is removed from the open market and moved in-house, allowing battery manufacturers to control costs and secure supply.
- Manufacturers have less reliance on the spot market, making spot prices less representative.
- Cathode producers are increasingly relegated to a tolling role, with margins set by battery makers.

Influencing power in the supply chain can shift throughout time, depending on where supply availability is tight compared to demand.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

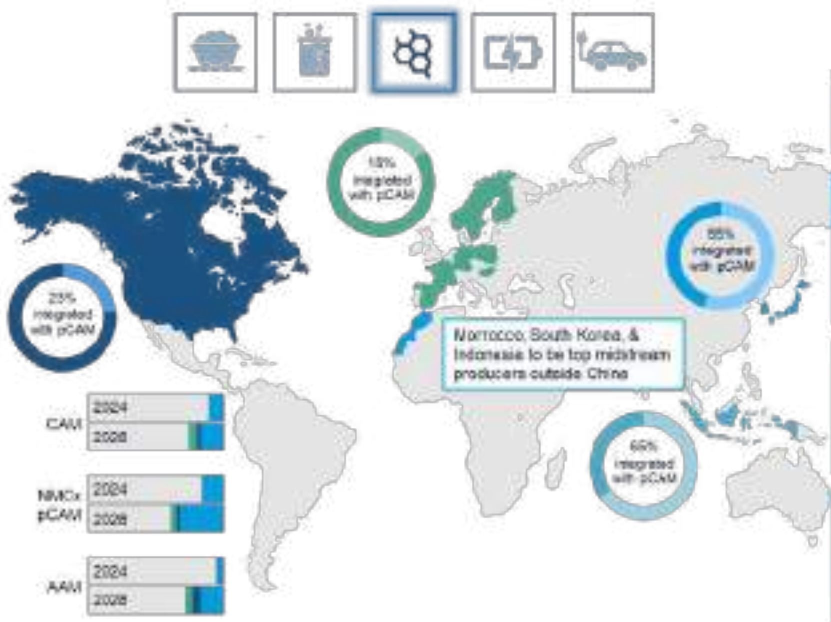
Downstream Manufacturers Continue Direct Supply Sourcing Efforts In 2024

MAJOR SUPPLY AGREEMENTS MADE IN 2024



Source: Company announcements

Diversification Of p/CAM Supply Is Gradually Shifting Regional Battery Material Consumption



OPPORTUNITIES

North America:
- Close to end-use market
- IRA production tax credit

US FTA countries:
- Politically close to the US
- Meets requirements for IRA EV tax credit
- Morocco is close to phosphate resources

Europe:
- Close to end-use market
- Saving efforts to trace carbon emissions for Battery Passport
- EU Rules of Origin regulations

Indonesia & Others:
- Close to mineral resources
- Lower labor and energy costs
- More straightforward environmental permitting

RISKS

- Policy uncertainties
- High labor, material costs + capex
- Insufficient skilled labor (North America)
- Mining industry less willing to move into midstream

- Strict environmental permitting
- High labor and energy cost in some countries
- Bureaucratic delays

- Scrutiny on Chinese ownership by US/EU
- Long distance to EU/US markets + tariffs

- Precursor and cathode material production - the first point of consumption for refined battery chemicals - is gradually expanding outside China
- Asian producers are pivoting their strategies to **capture overseas markets,** where they can command higher margins
- European and North American trade policies are also aimed at incentivising ex.China supply
- **The higher costs and investment risks** outside China are deterring more profound overseas investments
- Therefore, supply clusters are forming in what are seen as **low-cost, low-risk countries** like South Korea, Morocco, and Indonesia to supply major markets

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). Showing only major planned pCAM/CAM/AAM bases. 'Integrated pCAM' includes precursor iron phosphate and ternary precursor.

1 INDUSTRY

Recyclers Consider Their Business Models Carefully To Withstand Long-Term Challenges

CURRENT NA & EU RECYCLING MARKETS USING “BUY AND SELL” MODELS - CHINESE MARKET CHARACTERIZED BY MORE CLOSED LOOP PARTNERSHIPS

Open – "Buy & sell"

- **Recyclers buy batteries** or get even get paid to take batteries (esp. for LFP) from OEM networks and/or independent collectors
- Some recyclers buy additional black mass from independent shredders
- Recyclers **sell recycled materials/metals** in open market (e.g., to refiners or P-CAM/CAM producers)
- Exposure of recyclers to fluctuating raw materials prices

🟦 Recyclers ⬜ 3rd parties

Closed – "Recycling-as-a-Service (RaaS)"

- **Recyclers become service providers** and charge cell manufacturers or OEMs a **fee to recycle the material**
  - Cell manufacturers or OEMs own the inputs (scrap, EoL batteries) and outputs (recycled materials) of the recycling process
  - RaaS is usually applied in closed loop partnerships
- While RaaS has already been introduced in China, it is not yet widely adopted in EU and NA as it requires:
  - Large capacity installations (esp. for hydrometallurgy)
  - Steady stream of sufficient volumes to ensure asset utilization
  - Established closed loop partnerships & reverse logistic networks

"The service business model works in China, but it has not been widely introduced into Europe & North America – Likely to be adopted more by the end of the decade"

In short-term, the profit margins of pure-play recyclers are under pressure from low raw material prices.

Those that operate in a **closed loop/tolling arrangement** are more protected from current market dynamics.

In the long-term, as end-of-life batteries become more abundant than manufacturing scrap, companies will want to seize the opportunities of the **‘open buy & sell’ model.**

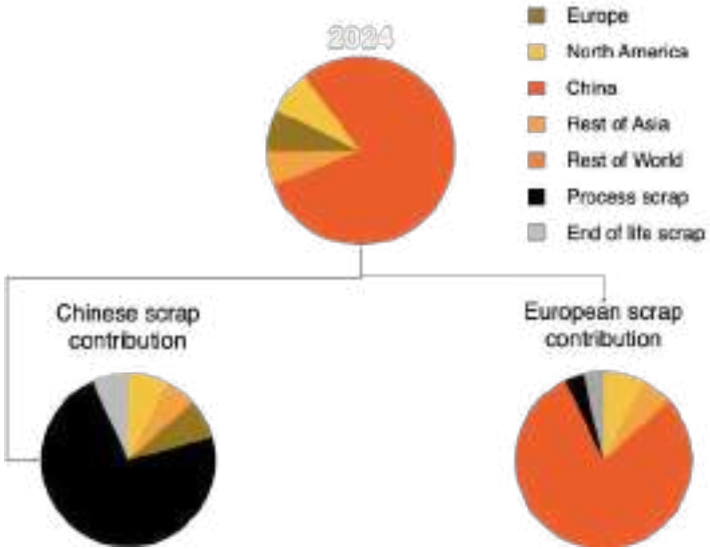
To increase value add and improve margins, black mass refiners are **vertically integrating** in both directions - into collection, shredding/black mass production, and precursor cathode production (pCAM).

Roland Berger

Source: Content & analysis provided courtesy of Roland Berger (Distinguished Partner). For more information, visit https://www.rolandberger.com/en/Insights/Global-Topics/Battery/.

Process Scrap Availability Currently Exceeds End-Of-Life Scrap

BREAKDOWN OF CHINESE AND EUROPEAN COMBINED SCRAP POOL COMPARED TO TOTAL 2024 REGIONAL SCRAP DISTRIBUTION



Chinese scrap accounts for more than 80% of global recycling scrap in 2024. The large majority of this is **process (manufacturing) scrap.**

China has scaled its battery manufacturing capacity to keep pace with global battery demand, resulting in process scrap being the dominant contributor to its regional scrap pool.

As the rest of the world has accelerated electrification, but is still establishing regional manufacturing capacity, end-of-life scrap - even if relatively small - dominates over process scrap.

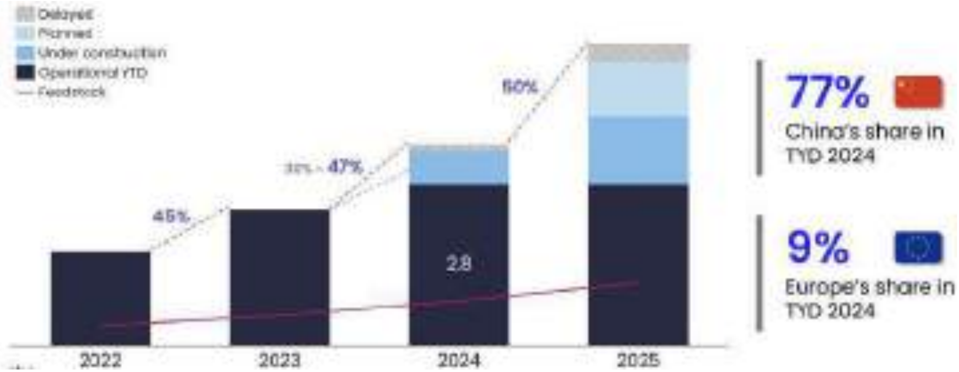
BENCHMARK

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/recycling.

Recycling Pre-Treatment Capacity Growth Slows In 2024

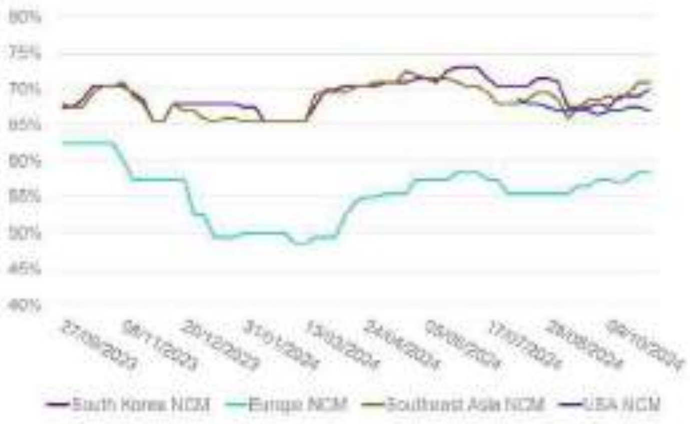
PRE-TREATMENT EXCEEDS BLACK MASS REFINING CAPACITY

Global annual pre-treatment capacity by plant status, million tonnes



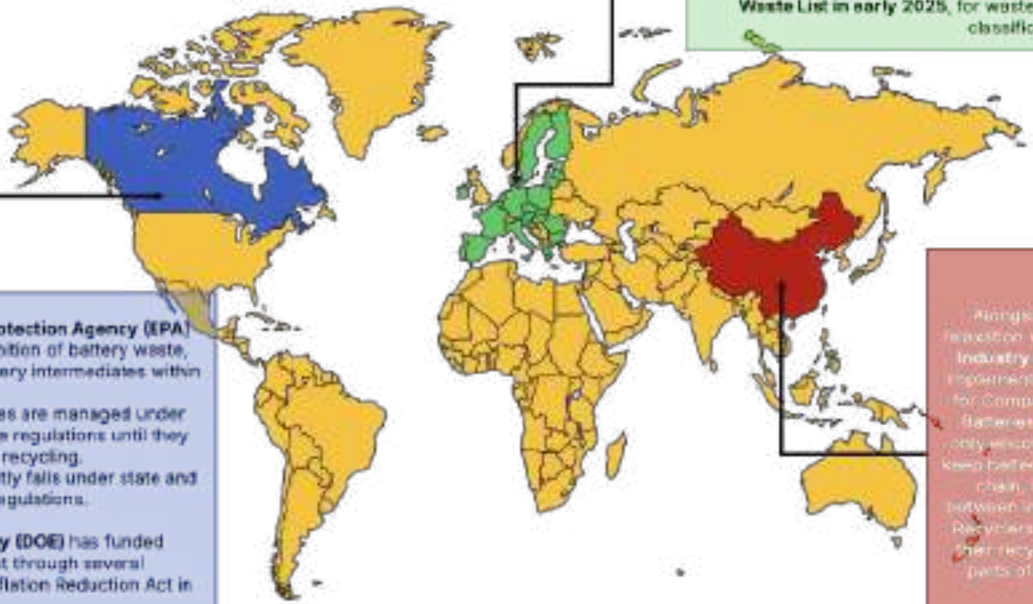
TWO GLOBAL MARKETS FOR BLACK MASS EXIST: EUROPE AND EVERYONE ELSE

NCM payables price across different regions, payable %



Source: Rho Motion (Distinguished Partner), Fastmarkets

Recycling Legislation Across The Globe



Within the EU, the **critical raw materials act (CRMA)** and the **EU battery regulation** have been implemented, outlining critical mineral recycling rates, recovery targets in the near- to mid-term.

The European Union (EU) is expected to **disclose its updated European Waste List in early 2025**, for waste battery and battery intermediate classification.

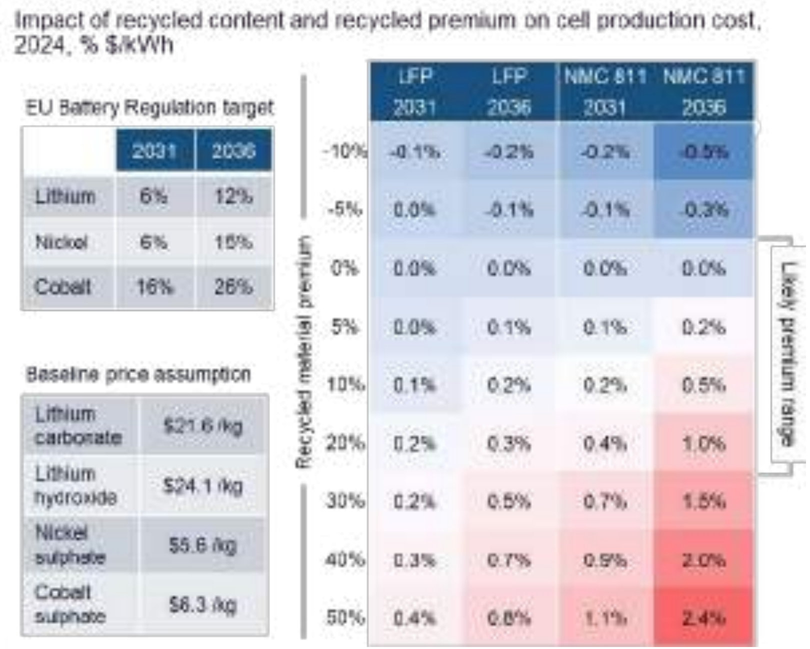
- The **US Environmental Protection Agency (EPA)** is responsible for the definition of battery waste, black mass and other battery intermediates within the US. Currently:
  - Lithium ion batteries are managed under the universal waste regulations until they reach a facility for recycling.
  - Black mass currently falls under state and local solid waste regulations.
- The **Department of Energy (DOE)** has funded recycling capacity buildout through several initiatives as part of the Inflation Reduction Act in recent years.

Alongside the planned black mass import relaxation within China, **The Chinese Ministry of Industry and Information Technology (MIIT)** implemented the "Industry Standard Conditions for Comprehensive Utilization of Waste Power Batteries for New Energy Vehicles". This not only encourages reliable recycling practices to keep battery materials within the Chinese supply chain, but also encourages collaboration between industries to meet these requirements. Recyclers are expected to continually develop their recycling technologies/equipment for all parts of the battery and enhance recycling efficiency.

BENCHMARK

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/recycling.

EU Recycled Content Mandates Likely To Have Minimal Impact On Battery Costs



Impact of recycled content and recycled premium on cell production cost, 2024, % $/kWh

EU Battery Regulation target

	2031	2036
Lithium	6%	12%
Nickel	6%	15%
Cobalt	16%	26%

Baseline price assumption

Lithium carbonate	$21.6 /kg
Lithium hydroxide	$24.1 /kg
Nickel sulphate	$5.6 /kg
Cobalt sulphate	$6.3 /kg

Recycled material premium	LFP 2031	LFP 2036	NMC 811 2031	NMC 811 2036
-10%	-0.1%	-0.2%	-0.2%	-0.5%
-5%	0.0%	-0.1%	-0.1%	-0.3%
0%	0.0%	0.0%	0.0%	0.0%
5%	0.0%	0.1%	0.1%	0.2%
10%	0.1%	0.2%	0.2%	0.5%
20%	0.2%	0.3%	0.4%	1.0%
30%	0.2%	0.5%	0.7%	1.5%
40%	0.3%	0.7%	0.9%	2.0%
50%	0.4%	0.8%	1.1%	2.4%

The EU Battery Regulation mandates a minimum recycled content in batteries used in the EU in the future.

Automakers and battery makers will **scramble for recycled material**, and if this is combined with a lack of available feedstock, it is possible that secondary material commands a premium.

However, the impact on overall battery cell production costs is likely to be minimal, and is less for LFP than that of NMC, as only lithium carbonate is affected.

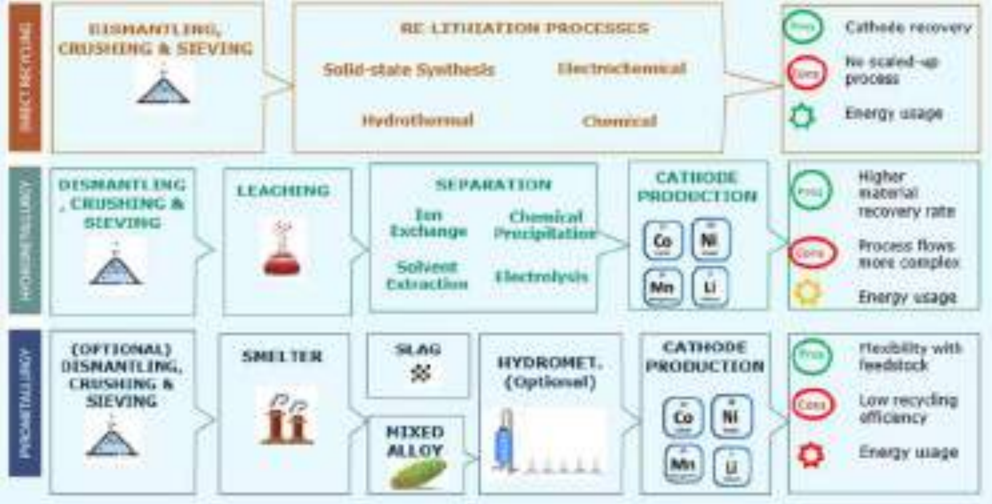
European manufacturers are particularly concerned about the economics of recycling LFP. Given the comparatively lower value of constituent materials, it may deter black mass refiners in the region from establishing LFP recycling capacity and producing lithium carbonate.

The most likely scenario is that regulations force LFP recycling to take place and the burden placed on the downstream manufacturer. However, even under a 'tolling fee', **the overall lifetime cost of using LFP is significantly less than that of NMC.**

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

Recycling Processes - 95% Of Global Capacity Uses Hydromet Or Variants Thereof

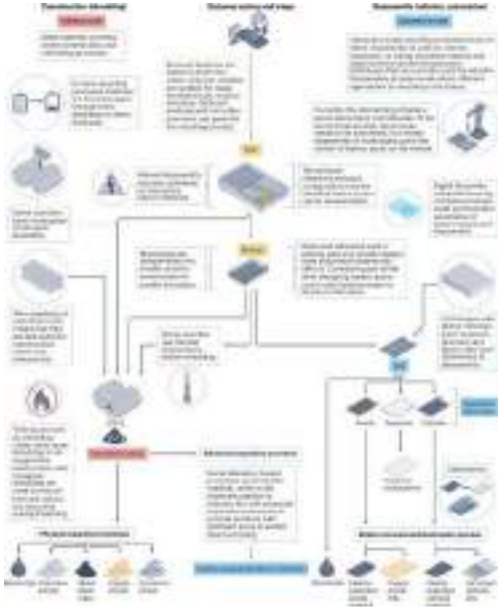
Pyromet: more established and more flexible with feedstock, but emissions-intensive
Hydromet: higher material recovery rate, but more complex process flows
Both pyro- and hydromet have environmental concerns, and the requirements for treatment can be costly



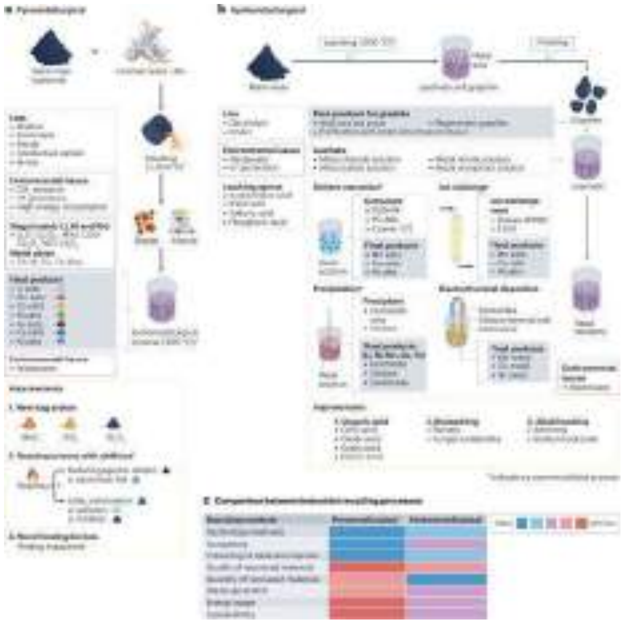
Source: IEA, Malene Fumany

Recycling Processes Are Evolving To Improve Recovery Rates And Minimize Costs

PRE-TREATMENT PROCESSES



INDUSTRIAL RECYCLING PROCESSES



DEVELOPING RECYCLING PROCESSES

Source: Ma, X., Meng, Z., Bellonia, M.V. et al. The evolution of lithium-ion battery recycling. Nature Journal

Second-Life Batteries - An Overview

- **Second-life batteries** consist of cells, modules, and packs that are repurposed into less power-intensive applications when they approach their end of life
- The end of life of a battery is typically taken at 70-80% state of health (SoH). Beyond this value, performance degradation is accelerated and such batteries can only be used effectively at a lower C-rate, for instance in residential storage systems
- Some second-life batteries make their way back into EVs, if a similarly aged battery pack needs one of their cells/modules being replaced. This operation is named **remanufacturing**

Source: IDTechEx

Second-Life Batteries - Current Applications

- Generally speaking, any product where a new battery is used is also suitable for a second-life battery.
- Most common applications are where a new Li-ion battery may be too expensive, or where low volumes exclude interested buyers from purchasing batteries from traditional vendors
- Second-life batteries are also appealing for projects with ESG requirements
- So far, used batteries have found their way into **niche applications** such as off-grid power banks and wheeled energy storage systems, all the way up to more **conventional products like utility-scale BESS arrays.**

1 – 5 kWh

10 – 30 kWh

>1000 kWh

Source: E-Energy, Reefilla, B2U

Battery Repurposing - A Budding Industry Facing Fierce Competition

Upstream competition from ever cheaper new batteries coming out of China

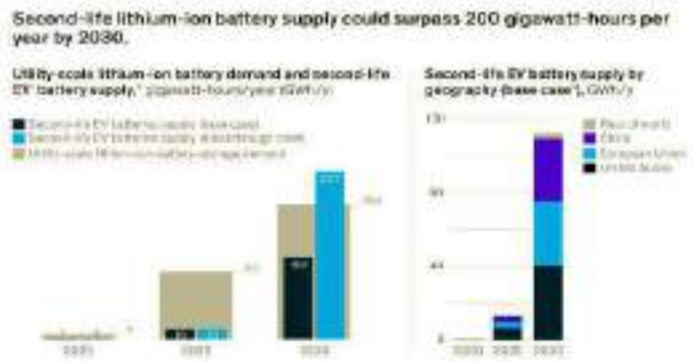
Downstream competition from battery recycling companies scrambling for feedstock for their plants

The industry is mostly developed in Europe, where the Battery Regulation enables lawful battery repurposing through the provisions listed in **Article 73**

Source: IDTechEx

Reuse And Recycling Results In Significant CO_2 Emissions Reduction And Cost Savings

- Today's battery recycling technologies can recover 80%-95% of the critical minerals.
- Manufacturing costs for a vehicle battery can be 5-30% lower when using recycled cathode material.
- Reusing end-of-life EV batteries as BESS can lower production costs by ~40% and reduce its emissions footprint by ~50% compared to all-new BESS.
- A reused EV battery can last 5+ years, depending on its SOH and second-life application.
- Second-life BESS avoided emissions are realized in the manufacturing process, however round-trip efficiency is lower.
- The second-life EV battery market is **expected to reach $28.17B by 2031, growing at a CAGR of 43.9% from base year 2024.**



Sources: U.S. Dept. of Energy (graphic), The World Economic Forum, McKinsey & Co (graphic), Chen et. al., EV Magazine, Systemiq, The Battery Pass Consortium, ReCell Center, International Energy Agency

Lack Of Standardization Leads To Complexity In Battery Dismantling

- Wide distribution of very different EV pack architectures leads to complexity in terms of uniform battery dismantling strategies
- More complex or tedious dismantling processes constitute additional costs
- Even within similar battery architectures, differences may exist in terms of how to safely handle battery packs that have aged differently
- The low volumes of dismantled batteries have led this to be a mostly manual process to date
- However, several European projects have been started to look into automated battery disassembly, such as **CarE-Service**, **DemoRec**, and **DemoBat**
- The use of image recognition software, ML, and AI are deemed as quintessential to maximize the capabilities of automated battery disassembly systems

Source: RWTH Aachen

Consolidation Is Happening On Where To Source Second-Life Batteries

- Used batteries can originate from a number of sources: used EVs, test vehicle batteries, scrap yards, overproduction stocks, struggling OEMs
- The complexity in managing such a disparate number of sources, as well as different battery architectures, can only be solved through meticulous product documentation, performance testing and validation, and logistics know-how
- A number of companies have stepped up to deal with this complexity and smooth out the whole purchasing experience, and many of them have not made it to 2025
- The BatteReverse project keeps track of all second-life battery stakeholders within wider EU, and only four marketplaces are listed, namely Circunomics (Germany), Cling Systems (Sweden), GBD (Norway), and Second Life EV Batteries (UK)
- Some repurposers source their batteries directly from OEMs, although this creates a vendor lock-in problem

Source: BatteReverse

1 INDUSTRY

Software Player Overview

BATTERY CYCLING AND MATERIAL R&D DATA SOLUTIONS

VOLTAIQ
Byterat
Polaron
MONOLITH
BATTALYSE
MATERA
astrolabe
N
AIONICS
CITRINE

MULTISCALE CELL MODELLING

COMSOL
GT-AutoLion
ABOUT:ENERGY
Ansys
Chemix
BATEMO
PyBaMM
HEXAGON
SIEMENS
ionworks

MANUFACTURING PROCESS CONTROL

BECKHOFF
Rockwell Automation
comLine
Honeywell
ABB
Palantir
INFICON
Ignition
LEAD
SIEMENS
PDF/SOLUTIONS
SICK
Schneider Electric

MANUFACTURING ANALYTICS

PDF/SOLUTIONS
VOLTAIQ
AmpLabs
HEXAGON
SIEMENS
APPLIED MATERIALS
E7
eyelit
ACCURE

CELL QUALITY AND INSPECTION

PDF/SOLUTIONS
KEYENCE
Nikon
lumafield
EXACOM
TITAN
excillum
liminal
GLIMPSE

BMS SOFTWARE

Brill Power
BattGenie.
elysia
eatron
BREATHE
ELECTRA

ENERGY MANAGEMENT SYSTEMS

INDIE
FRACTAL EMS
FLEXGEN
POWIN
FLUENCE

BATTERY INTELLIGENCE/FIELD ANALYTICS

TWAICE
Qnovo
Coulomb AI
zitara
eatron
elysia
ACCURE
Brill Power
ELECTRA
PowerUp

ESS DATA, OPTIMISATION, AND DEPLOYMENT

TYBA
Gridmatic
Equilibrium Energy
enspired
Entrix
arenko
enertel.ai
Powerline
HABITAT
keeling labs
AURORA
Ascend Analytics
AmpLabs
modo
infyos
terralayr
Storlytics
Cellect

Organizing, Cleaning, And Prepping Battery Data For Analysis Takes Significant Time And Effort

Medium

Search

Battery researchers have a problem...

Predicting battery failure

Source:

Executives from Electra Vehicles, Ionworks, Form Energy

"**Lack of access to data** is the #1 problem."

"Without [good data], you can't make good models. It's very hard and costly to get [good data] yourself."

"We absolutely do want to model this, but you can't validate your model without ... collecting all that data."

FORRESTER

AI For EV Battery Validation

FORRESTER OPPORTUNITY SNAPSHOT | MAY 2024

Scope:

165 decision makers in the automotive industry responsible for EV battery testing, validation, and development in the US and Europe

57% of respondents cite deciphering complex relationships in vast, multiparameter datasets as a significant barrier [to battery validation].

61% estimated months to years of time savings from AI-powered cell characterization testing that leverages standardized data sets.

STATE OF DATA SCIENCE 2023

ANACONDA

SURVEY: Data Prep and Cleaning reported as the **most time-consuming activities** for data practitioners.

Scope = 1,071 respondents

BIGDATAWIRE

Data Prep Still Dominates Data Scientists' Time, Survey Finds

Alex Woodie

Data scientists spend about 45% of their time on data preparation tasks, including loading and cleaning data, according to a survey of data scientists conducted by Anaconda.

Sources: Medium: Battery Researchers have a problem... , Forrester: AI for Battery Validation / Doc, Anaconda: State of Data Report 2023 / Doc, Big Data Wire: Data Prep Still Dominates Data Scientists' Time, Survey Finds

Standards - Battery Laboratories Aim To Establish Industry Standards For Battery Data, Facilitating Use Of Open-Source Physics-Based And AI Models In Battery Science

2021

BATTERY ARCHIVE
Launch of the first public data repository to visualize, analyze and benchmark battery data in a standard way across battery labs

2022

BATTERY DATA ONTOLOGY
BattInfo established an ontology for attributes of batteries and battery materials, facilitating standardization of metadata

2023

BATTERY DATA GENOME
Argonne National Lab publishes Call to Action to establish uniform data acquisition and sharing practices across battery science community

BATTERY PARAMETER EXCHANGE
The Faraday Institution launches **BPX standard**, to standardise the reporting and measurement of physics based model parameters.

2024+

BATTERY DATA FORMAT (BDF)
Battery Data Alliance**, a Linux Foundation Project, launches the Battery Data Format - a new standard for formatting battery cycling data

* FORRESTER **AI For EV Battery Validation**
Industry Study - May 2024

Base: 165 decision makers in the automotive industry responsible for EV battery testing, validation, and development in the US and Europe

"Over half (57%) of respondents cite deciphering complex relationships in vast, multiparameter **datasets as a significant barrier** [to AI-powered battery validation]." The majority (61%) estimated **months to years of time savings** from AI-powered cell characterization testing that leverages **standardized data sets.**

Sources: Forrester: AI for Battery Validation / Doc , ** Battery Data Alliance/Linux Foundation

Importance Of Software In Cell Manufacturing - Digitalization Is Key For Ramp Up & Quality

Ramping up cell manufacturing is very complicated, often resulting in high scrap rates, delays, and quality issues. Early scrap rates can reach **15–30%**, costing up to **€900,000 daily** for a **40 GWh factory**, while delays in production readiness average seven months, with daily losses of **€1.1 million**.

These challenges are due to the complexity battery production, which involves up to 140 interconnected steps, strict quality demands, and limited industry standardization. Addressing these hurdles requires advanced **digital tools and data-driven strategies** to optimize processes, reduce waste, and accelerate production stabilization.

AREAS DIGITALIZATION IS KEY FOR CELL PRODUCTION

Digital Traceability (Electrode to Cell)
The ability to trace the electrode and cell across production allows for effective monitoring, defect identification, root cause analysis, and process optimization. This area is one of the biggest pitfalls of cell manufacturers to date.

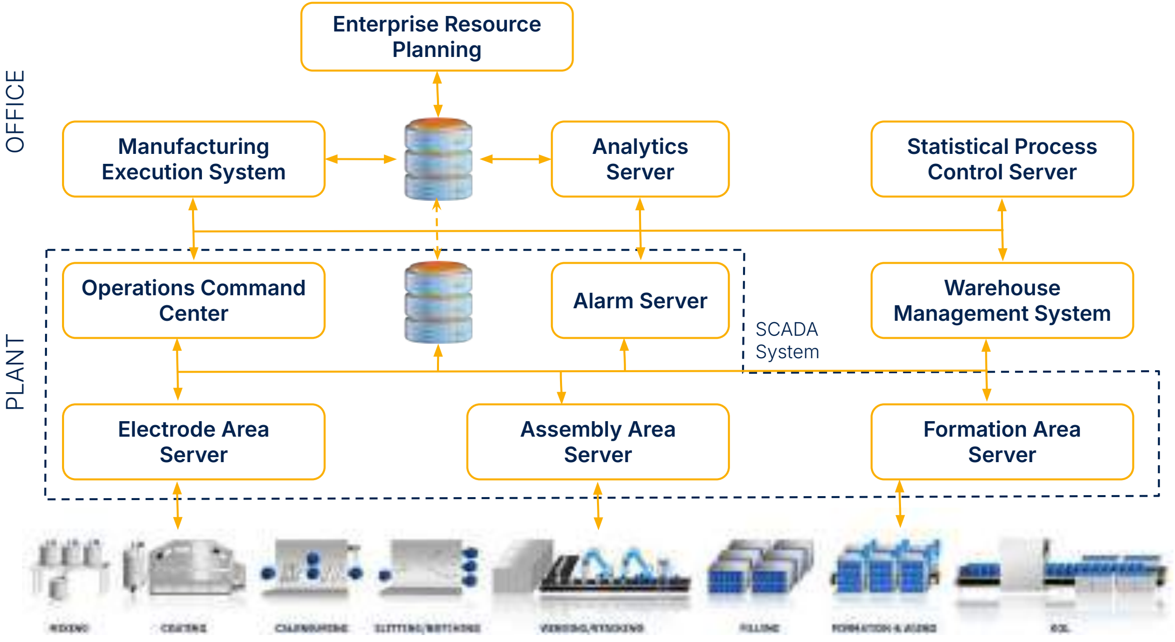
Root Cause Analysis and Optimization
A robust data collection, storage, and analysis infrastructure allows for systematic root cause analysis (RCA). This will help manufacturers understand interdependencies between process parameters, catch errors early in production, and optimize cell quality.

Efficiency and Learning Rates
Software helps accelerate the production learning curve by offering insights into processes through advanced data analytics and machine learning by integrating & analyzing image, sensor, and other data.

Integration and Standardization
Modular IT architectures and standardized data models streamline machine integration, enabling seamless communication across various production systems, tools, and lines.

Sources: Mastering Ramp-up of Battery Production, Fraunhofer; Internal Expertise

Typical Manufacturing Data Infrastructure



TYPES OF MANUFACTURING DATA

Some Core Examples:

IoT/FDC
Equipment sensor data collection

Process
Metrology, run card, materials, MES, etc.

Image
X-ray, CCD image, Optical, etc.

Testing
End-of-line: formation, aging, QC and beyond

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 have **all the correct sensors, inspection, and test systems** installed on the production line to enable sufficient data **traceability** and **analysis**

Sources: PDF Solutions; Graph from Internal Experts

Data Storage Options - Cloud, On-Prem, Or Hybrid Solutions

Battery manufacturing generates enormous volumes of data (up to **2-7TB per day per production line**), with a significant portion coming from critical image data used for cell and electrode inspection. In addition, automotive customers often require **10 years of data storage** from their suppliers.

Managing & storing such vast amounts of data is crucial for ensuring efficient and scalable operations.

Advanced industries like semiconductors have **recognized the importance of Cloud**, with many embracing the **hybrid** approach for a balance between **security, scalability, and cost**.

FEATURE	ON-PREMISE	CLOUD
Scalability	Limited by infrastructure	Highly scalable
Cost	High upfront and maintenance costs	Pay-as-you-go, cost-effective
Data Sharing	Restricted to local access	Centralized and accessible globally
Security	High physical control	Often has superior encryption and protocols
Flexibility	Limited	High flexibility
Adoption	Mature but less agile	Gaining traction
Complex Analytics	Harder to scale	Supports AI/ML for advanced insights

TIERED DATA STORAGE APPROACH

to manage large amounts of data

To manage & store large data volumes, many companies use **tiered data storage** systems. This moves less critical data from high-speed Tier 1 storage to more cost-effective Tier 2 or cloud-based storage over time.

This approach **reduces costs, allows for efficient long-term data archiving**, and ensures seamless access and re-archiving when needed for analytics or other purposes.

Sources: "Cloud Vs. On-Premise Analytics", "What is tiered storage?", "Automotive Optocouplers—Beyond Meeting the Electrical Performance at High Temperature"

Advanced Analytics

"A proliferation of sensors everywhere [...] is generating an **enormous amount of data**. Much of that data is useless, but within that data also are **patterns**, or pieces of patterns, that are not always obvious.[...] It can be used as a **guide for [...] identifying weaknesses in manufacturing** that previously had gone unnoticed." (***Semiengineering, 2024***)

In big data, the focus used to be data mining, but the **next evolution is advanced data analytics**, applying AI to data to detect patterns. Let's explore how this can be applied in cell manufacturing.

PIPELINE TO ADVANCED DATA ANALYTICS

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, CCD image, 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

Analytics Applications

Many cell problems are found **at end of line** or during **formation/aging**. Insights generated via **AI/ML data analytics** enable manufacturers to **identify problems earlier, saving time.**

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

Bridging The Skills Gap With Large Language Models

CURRENT CHALLENGE: SKILLS GAP

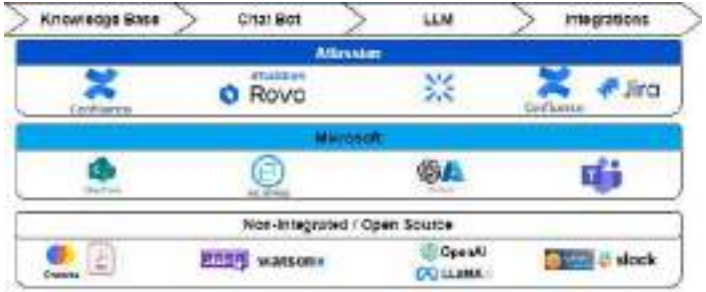
A shortage of skilled engineers, technicians, and tool operators has created bottlenecks, with a small number of experts overwhelmed by demands.

AI AS A SOLUTION:

Implementing LLM based intermediate agents can scale up expertise, addressing user queries with efficiency.

KNOWLEDGE BASE ENRICHMENT:

Experts can shift focus from handling inquiries to advancing the company technology and enriching the knowledge base for continuous improvements.



Sources: "How LLMs Are Transforming The Customer Support Industry", "How Large Language models (LLM) help enterprises enhance customer experiences Alekya Jonnala Software Development Manager in Amazon"

Building Industrial AI Pipelines For Reliability, Scalability And Cost Efficiency

Advanced AI enables deep insights for battery manufacturing, by discarding the paradigm of single modal, single task, and training on limited data to a **pattern of multimodal, multitask, and pre-training on massive data** [1]. But **high cost of hardware** and staff training hinders adoption [2].

GOAL: FACTORY FOUNDATION MODEL

- Real time micro-defect image analysis
- Real time macro-defect image analysis
- LLM enabled Out of Control Action Plan (OCAP)
- LLM enhanced PM (Preventative Maintenance)
- Root cause analysis

WHAT DO WE NEED FOR FACTORY DEPLOYMENT?

Reliability: Ensures AI systems consistently perform as expected in factory operations, even under varying conditions or workloads.

Scalability/Availability: Enables AI systems handle increasing data volumes or compute demands and guarantees that AI systems are operational and accessible whenever required for critical factory processes. [3]

Heterogeneous Computing: Leverages diverse hardware (e.g., CPUs, GPUs, FPGAs) to optimize the performance of different types and sizes of models.

Model Lifecycle Management: Forces model and data traceability to ensure continued relevance in the face of rapid product and process innovation.

HOW IS IT DONE?- Example Method

AI SUITE

kafka

ModelOps

kubernetes

✚

EDGE INFERENCE

AI Training

Model Pruning

Model Quantization

Edgebox Configuration

Sources: [1] Zhang, Large Scale Foundation Models for Intelligent Manufacturing Applications: A Survey, Zhang et al.; [2] "High Cost Hinders AI Adoption Among IT Clients", Consultia; [3] Edge AI: A Taxonomy, Systematic Review and Future Directions, Jill et al.

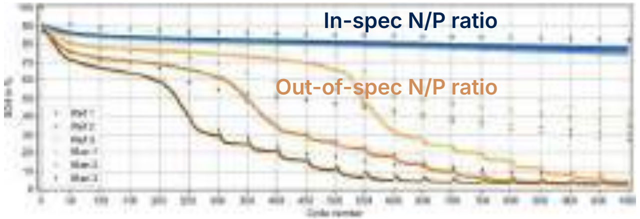
Electrode To Cell Traceability - Challenges & Methods

Upstream variations, such as mass loading inconsistencies, can impact cell cycling stability. However, variations in batch slurry mixing and roll-to-roll electrode manufacturing are difficult to trace during downstream unit cell assembly.

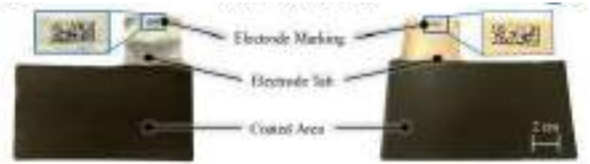
Current Method: Batch-level (ex. total slurry viscosity, composition) and roll-to-roll level (ex. mean mass loading, thickness) aggregate quality metrics are tied to child cells; localized traceability is lost.

Being Developed: Periodic data matrix codes (DMCs) that are laser-marked on electrode rolls encode localized quality metrics that can be parsed during cell assembly. This improves the resolution of loading & N/P traceability from roll-basis to individual cells.

CYCLING INSTABILITY CAN BE CAUSED BY LOCALLY OUT-OF-SPEC LOADING & N/P RATIO



DMC ON EACH UNIT ELECTRODE CARRIES LOCALIZED MASS LOADING DATA



SLURRY MIXING BATCH PROCESS

ELECTRODE MANUFACTURING ROLL-TO-ROLL PROCESSES

CELL ASSEMBLY UNIT PROCESSES

Sources: Chemistry Europe, Advanced Science News, *Mastering Ramp-up of Battery Production*

Quality Control Solutions

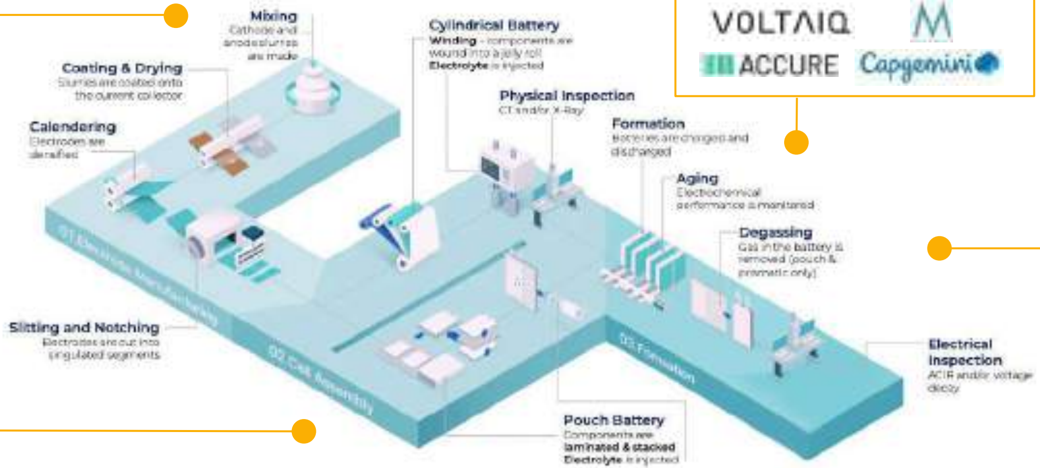
Quality control is crucial in battery manufacturing, as companies like CATL aim for ambitious standards like **1 Part Per Billion (PPB)** defect rates. Achieving this is challenging due to the unpredictability of batteries, making it essential to **catch issues across every stage of production** to avoid costly recalls and warranties.

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

ThermoFisher Scientific, PDF/SOLUTIONS, KEYENCE, TESCAN, ZEISS, SirenOpt, METTLER TOLEDO

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



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

VOLTAIQ, ACCURE, Capgemini

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

KEYSIGHT, NOVONIX, NEWARE, Arbin, HIOKI

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.

Waygate Technologies, GLIMPSE, EXACOM, lumafield, TITAN, ISRA VISION, Nikon, excillum, liminal

Sources: LG Energy, different providers listed above

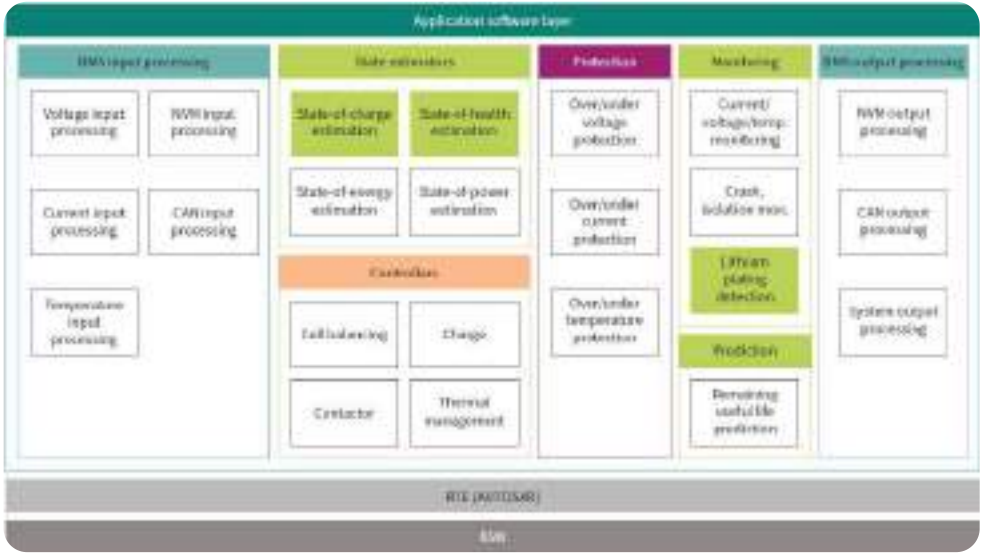
BMS - Overview

MODERN BATTERY MANAGEMENT SYSTEMS (BMS) MUST MEET FAR GREATER DEMANDS THAN IN THE PAST.

They now handle **advanced functions** such as Remaining Useful Life (RUL) prediction, diagnostics, and faster charging, while also being **robust and accurate**—even for LFP chemistries. BMS must support emerging battery chemistries, enhance safety, and comply with new regulations like the Battery Passport.

Key challenges include **enabling wireless solutions** (requiring sophisticated networking software), ensuring **cybersecurity** (such as tamper-proof battery history and secure data for Battery Passport compliance), and supporting **over-the-air (OTA) updates**. BMS must also adapt to **battery swapping scenarios**, where it interfaces with diverse vehicles and drivers, integrate new measurement technologies like in-operando EIS, and align with domain and zonal architectures (e.g., x-in-1 systems with software running outside the battery). **Cloud** analytics integration further adds to this complexity.

Finally, **AI** is revolutionizing BMS by enabling solutions to previously unattainable challenges in safety, functionality, and time-to-market, driving a new era of innovation.



OVERVIEW OF A MODERN BMS SW STACK (1)

Sources: (1) Exploring next-generation AI battery management systems with Infineon and Eatron technologies, In the New Era of Wireless Battery Management Systems (wBMS), Security Takes the Spotlight | Analog Devices, Driving the future: A comprehensive review of automotive battery management system technologies, and future trends - ScienceDirect, Software can unlock hidden potential in EV batteries

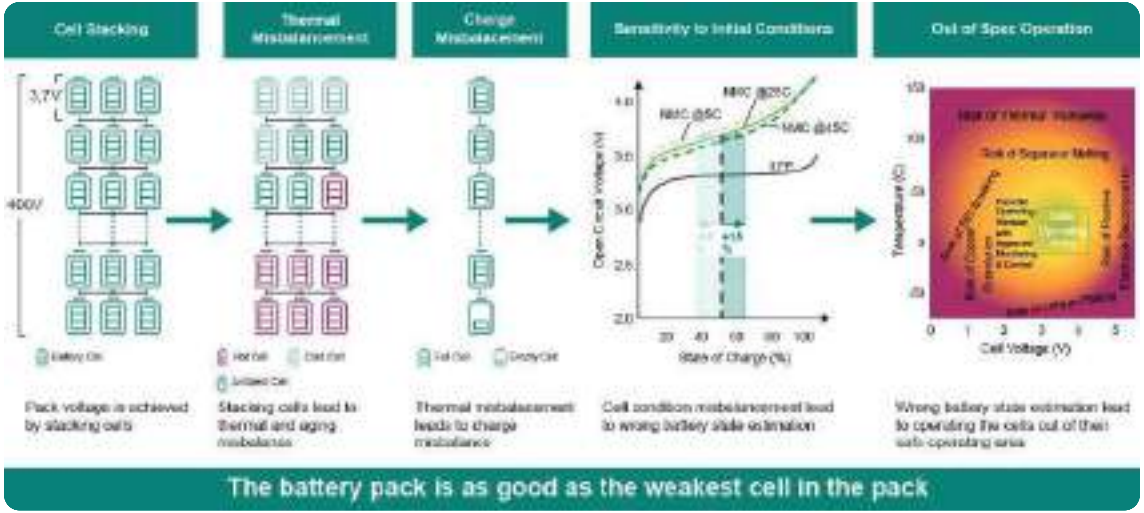
BMS - Estimation

ESTIMATING BATTERY STATES AND LIFETIME AT THE EDGE IS A CHALLENGING TASK, PARTICULARLY WITH CHEMISTRIES LIKE LFP.

Accurate estimation is critical for each cell, as the **overall performance of the pack depends on its weakest cell.**

Historically, state estimation requirements for automotive, mobility, and energy storage applications have been around **3% for NMC** and **5% for LFP** for State of Charge (SoC), and **under 5%** for State of Health (SoH). However, recent expectations demand accuracy **better than 2%** for both SoC and SoH across chemistries like NMC and LFP.

Meeting these stringent requirements has driven the adoption of **advanced physical models** and data-driven approaches, leveraging the latest developments in **AI** to achieve unprecedented precision.



Graphic sourced from (1)

Sources: (1) Accelerating eMobility with Automotive Grade AI for Batteries - EE Times, Exploring next-generation AI battery management systems with Infineon and Eatron technologies

BMS - Diagnostics

Machine learning has transformed diagnostics by enabling real-time detection and prediction capabilities that were previously unattainable with conventional algorithms, leveraging increased compute capabilities onboard and in the cloud.

It is now possible to detect **li-plating**, **torn cell tabs**, and **predict risk of thermal runaway** with real-time capable machine learning models in a BMS.

MODERN HARDWARE ENABLING DEPLOYMENT ACROSS APPLICATIONS

Infineon Aurix TC4 with PPU Accelerator

- Achieves **>95% speedup** for ML features like lithium plating detection and remaining useful life (RUL) prediction.

Syntiant Edge AI Accelerator

- Supports a wide range of applications: Consumer electronics; E-bikes; Micro light commercial vehicles (LCVs); Forklifts with low power ML acceleration capability.

LINKED CLOUD AND EMBEDDED SOLUTIONS

Edge and Cloud Compute to increase accuracy

- Linked ecosystem approach to **diagnostics, prognostics, SOH, and RUL**
- Adaptive BMS
- Leverages online and offline compute capacity for batch analytics and increased accuracy, reduced false positives and negatives

REAL WORLD IMPACT

Software Updates Over Replacements

Safety recalls are increasingly handled by diagnostic software updates rather than full battery replacements.

Example: **The Porsche Taycan recall**

INNOVATIVE PARTNERSHIPS

LG Energy Solution (LG ES) & Qualcomm

- LG ES diagnostics software deployed on Qualcomm automotive SoCs.
- Leverages high compute capacity for improved diagnostics and performance.

BMS - Auxiliary Controls

THERMAL MANAGEMENT HAS EVOLVED TO ENABLE FASTER CHARGING, AND PREDICTIVE THERMAL MANAGEMENT IS GETTING MORE WIDESPREAD

Historically, thermal management focused on maintaining the battery within its optimal temperature range. However, with the increasing demand for faster DC charging, modern thermal management systems must now anticipate and manage the heat generated during a DC charging session.

Automakers like **Tesla**, **Porsche**, **Audi** and **Hyundai** have implemented **predictive thermal management** to enable fast charging. These systems precondition the battery, either by cooling or heating, ensuring the battery is at an optimal temperature upon arrival at the station. Typically the system either starts preconditioning when a driver selects a DC charging station on the navigation system(1), or based on factors such as navigation routes, departure timers, and the driver's usage behavior(2).

Preconditioning can cut down charging time by up to 50%, as shown by a Tesla Model 3 example on the right(3).

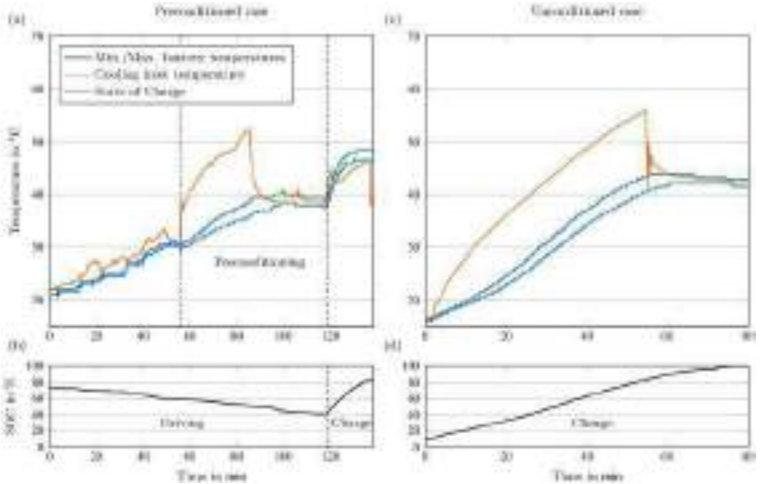


Figure 11 from (3): A Preconditioned Tesla Model 3 on the left, and an unconditioned case on the right.

Sources: (1) Hyundai Ioniq 5 battery preconditioning, (2) High-performance, compact, and intelligent: the high-voltage battery for the Premium Platform Electric | Audi MediaCenter (3) Quantifying the State of the Art of Electric Powertrains in Battery Electric Vehicles: Comprehensive Analysis of the Tesla Model 3 on the Vehicle Level, Porsche reveals predictive thermal management system - electrive.com

Battery Fleet Management Software Consolidates Into Five Key Areas

ASSET MANAGEMENT

Platforms for overall operational management of battery fleets, combining technical and commercial performance.

Origami
Cellect
arenko
stem

PERFORMANCE ANALYTICS

ACCURE
TWAICE
volytica diagnostics
elysia
zitara
Brill Power
AVILOO
BiB
BAMOMAS
Coulomb.AI
ELECTRA
eatron

MARKET OPTIMIZATION

Software for battery revenue optimization through algorithmic trading, aggregation

suena
enspired
volue
modo
Entrix

END-OF-LIFE MANAGEMENT

circunomics
cling
Recurrent
CURRENTS

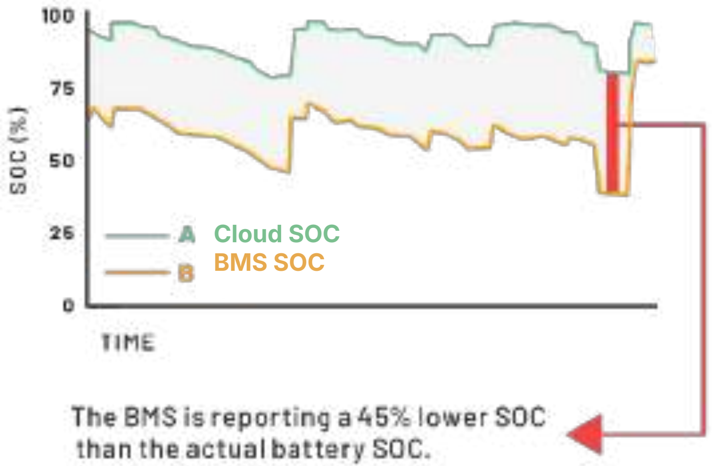
DISPATCH (CHARGE/DISCHARGE) & REVENUE OPTIMIZATION

TYBA
Gridmatic
Equilibrium
Ascend Analytics
enspired
HABITAT
arenko
enertel.ai
Powerline
Entrix
terralayr
geniess
keeling labs
AURORA
Starlytics

Source: Energize Capital: Battery Software Deep Dive

SOC Estimation - Performance Analytics Can Reduce BMS SOC Estimation Errors In LFP Battery Systems

EXAMPLE OF STATE OF CHARGE (SOC) ESTIMATION ERRORS IN A **50+ MWh LFP BESS**



The BMS is reporting a 45% lower SOC than the actual battery SOC.

Flat OCV curve of LFP systems results in BMS SOC estimation errors

- The BMS uses coulomb counting (integrated current) to estimate SOC, but sensor errors accumulate over time
- Resting periods are used to re-calibrate coulomb counting
- Recalibration in LFP systems difficult, due to flat OCV curve of LFP systems

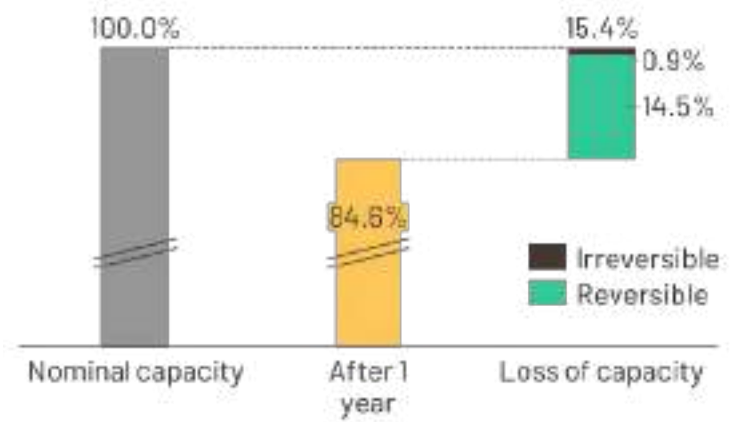
Cloud-based SOC estimator can reduce SOC estimation errors

- SOC error detection system identifies errors, allowing for recalibration during low-value time slots
- Continuous cloud-based SoC correction can minimize SOC estimation errors to +/- 3%

Sources: "Overcoming SOC Inaccuracies in LFP Batteries: How to Increase Revenue and Simplify Operations", "How State of Charge Estimations Can Make or Break Your BESS Project"

Imbalances - Predictive Maintenance Can Reduce Imbalances In Bess And Recover Reversible Capacity Losses

EXAMPLE: CAPACITY LOSS OF A 80 MWh+ LFP BESS



- Irreversible capacity losses due to aging
- Reversible capacity loss due Imbalances and SOC estimation errors

Mitigation strategies for irreversible capacity losses

- Exchange of battery modules
- Battery energy storage system augmentation

Mitigation strategies for reversible capacity losses

- Internal BMS balancing
- Forced balancing (e.g. balancing cycle)
- Recalibration of SOC estimator
- External balancing with balancer unit

Predictive battery analytics enables predictive maintenance to recover reversible capacity losses

Source: "Reclaiming Lost Capacity: Understanding Reversible Battery Degradation"

Cybersecurity Vulnerabilities

BMS VULNERABILITIES

Compromised Sensors: Attackers can tamper with temperature sensors (e.g., adding resistors) to cause overcharge or over-discharge, damaging cells.

Software Modifications: Malicious actors may alter BMS software or use underpowered chips to disrupt operations.

Hardware Trojans: Circuit modifications during design/fabrication (e.g., in microprocessors) can be triggered externally or internally.

State Estimation Attacks: Targeting calculations by manipulating methods or locations within the system.

Firmware Alterations: Firmware can be tampered with to compromise functionality.

COMMUNICATION NETWORK VULNERABILITIES

Wireless Communication: Susceptible to EMI and cyberattacks that disrupt CMU-PMU data.

CAN Bus: Older versions lack authentication and encryption, making it vulnerable to manipulation.

IoT Platforms: Protocols like MQTT can be exploited via fake routers or unauthorized nodes, compromising the network.

External Communications: BESS portals, cloud services, and HMIs are potential entry points for attackers.

V2X Communications: Emerging technologies (e.g., V2C, V2G) are vulnerable to reliability and security risks.

EVSE: Attacks can bypass credentials, send malware, or deactivate chargers.

EXTERNAL INTERFACE VULNERABILITIES

OBD Ports and USBs: Serve as attack entry points through connected devices.

Supply Chain: Malware or hardware trojans introduced during manufacturing can compromise systems.

Sources: Cybersecurity of Battery Management Systems, In the New Era of Wireless Battery Management Systems (wBMS), Security Takes the Spotlight | Analog Devices, Cyber-Physical Cloud Battery Management Systems: Review of Security Aspects, Cybersecurity of Battery Energy Storage Systems, Cybersecurity of Battery Energy Storage Systems

Cybersecurity Attack Types, Impacts And Countermeasures

TYPES OF ATTACKS

Confidentiality Attacks: Unauthorized access to sensitive data via spyware, malware, brute-forcing, or cloning.

Integrity Attacks: Malicious data modification, including false data injection, random delays, and replay attacks.

Availability Attacks: Disruption of system functions, such as denial-of-service (DoS) attacks.

IMPACTS OF ATTACKS

Functional Impacts: Malfunctions, such as "denial-of-charging" attacks.

Financial Loss: Premature maintenance or battery replacement due to degradation.

Safety Risks: Overcharging, over-discharging, or compromised cooling systems causing thermal runaway or fires.

Side Impacts: Corrupted data affecting future battery models and algorithms.

Grid Instability: V2G attacks disrupting frequency and voltage in the power grid.

COUNTERMEASURES

Encryption: Use TLS and database encryption to secure sensitive data.

Resilient Software Design: Implement secure algorithms, robust state estimators, and secure coding practices.

Hardware Security Modules (HSMs): Ensure software authenticity, integrity, and secure communication.

User Authentication: Require multifactor authentication for sensitive data access.

Cross-Verification: Compare onboard and cloud BMS computations to detect anomalies.

Physical Protection: Secure housing, remove unnecessary ports, and hardwire components.

Data Transparency: Involve human oversight in data and algorithmic decisions.

Wireless BMS Security: Secure keys, Authenticate and Encrypt wireless communication and secure debug ports.

Anomaly Detection: Combine battery modeling, state estimation, and statistical methods to detect false data injection attacks.

Defense-in-Depth: Layer physical, network, and device security with a zero-trust approach.

Sources: Cybersecurity of Battery Management Systems, In the New Era of Wireless Battery Management Systems (wBMS), Security Takes the Spotlight | Analog Devices, Cyber-Physical Cloud Battery Management Systems: Review of Security Aspects, Cybersecurity of Battery Energy Storage Systems, Cybersecurity of Battery Energy Storage Systems

Cybersecurity Standards And Regulations

BESS

NERC CIP: Standards protecting cyber assets of the electrical grid, potentially including energy storage systems.

NIST Cybersecurity Framework: Voluntary framework for improving cybersecurity, covering identification, protection, detection, response, and recovery.

IEEE Standards:

2030-2011 & 2030.2-2015: Smart grid interoperability framework, referencing security standards like ISO/IEC 27000 and NISTIR 7628.

1547-2018: Addresses interconnection and interoperability of distributed energy resources (DER), including cybersecurity for communication mandating protocols like IEEE 2030.5 (SEP2), IEEE 1815 (DNP3), and Sunspec Modbus.

P2686 (Draft): Recommended practice for Battery Management Systems in Energy Storage Applications, covering physical and software interfaces.

ISA/IEC 62443 (ISA-99): BESS relevant standard for industrial automation and control system security, covering requirements for operators, service providers, and manufacturers.

DHS NCCIC and ICS-CERT: Resources providing guidance on improving industrial control system cybersecurity with defense-in-depth strategies.

CIS Critical Security Controls: Prioritized cybersecurity actions for organizations.

AUTOMOTIVE

ISO/SAE 21434:2021: "Road Vehicles - Cybersecurity Engineering" Defines requirements for managing cybersecurity risks throughout the lifecycle of vehicle electrical and electronic systems, from development to end-of-life. Introduces Automotive Cybersecurity Integration Levels (ACILs) to quantify cybersecurity requirements.

UN Regulation No. 155: Mandates cybersecurity management systems in vehicles in many countries.

ISO 15118-20:2022: "Road Vehicles - Vehicle to Grid Communication Interface" Specifies secure communication between electric vehicles and the charging grid, including digital certificates and TLS-based encryption.

Graphic sourced from (1)

Sources: Cybersecurity of Battery Management Systems, (1) In the New Era of Wireless Battery Management Systems (wBMS), Security Takes the Spotlight | Analog Devices, Cyber-Physical Cloud Battery Management Systems: Review of Security Aspects, Cybersecurity of Battery Energy Storage Systems, Cybersecurity of Battery Energy Storage Systems

Right To Repair Act

The right to repair movement is **gaining global momentum**, with **important consequences on battery software.**

POLICY AND LEGISLATION ACROSS THE WORLD

US: Multiple states, including California, Colorado, Minnesota, and New York, are introducing "Right to Repair" legislation, granting independent repair shops access to tools and documentation.
European Union: The EU is actively actively promoting repairability and circularity with regulations like:

- **a.** **Battery Regulation:** Includes provisions on recycled content, carbon footprint, battery passport (containing information on repair, disassembly and carbon footprint), performance and durability, the state of health, and recycling efficiency.
- **b.** **EU Right to Repair Directive (2024/1799):** Requires manufacturers to offer repairs, incentivizes repair during the liability period, and extends warranties by 12 months post-repair.

France: A repairability index has been adopted, scoring products from 0-10.
South Africa: The government has signed a "Right to Repair" position statement.
Germany: A draft repair act would require manufacturers to stock spare parts for 10 years and make them available within 14 days at reasonable prices.

IMPLICATIONS ON BATTERY RELATED SOFTWARE

Independent Repair Enabled: The EU bans software and other practices that restrict independent repair, ensuring access to compatible and reused spare parts.
Information and Tools Accessible: Repairers and consumers will have improved access to repair information and tools, including software and diagnostics.
Online Repair Platform: A European platform will connect consumers with local repair services, potentially including software information.
Mandatory Repairs: Manufacturers must repair technically repairable goods beyond the warranty period, possibly including software updates and patches necessary for proper battery function after replacement.
Replaceable Batteries: New portable devices and light transport must have replaceable batteries, designed without software locks.
Battery Passport: From February 2027, EV batteries require a digital passport with repair and disassembly details.
State of Health (SoH) Data: Battery management systems must provide accessible, up-to-date SoH information. Harmonized SoH determination standards are expected by June 2027.

2 ACADEMIA

2 ACADEMIA

Lithium-ion Batteries/Solid-state

- Research on lithium-ion cathodes uncovers how atomic structure, microstructure, doping, coatings, and electrolytes stabilize nickel-rich and lithium-rich phases.
- Anode material research is revisiting the roots of lithium batteries, focusing on stable lithium metal stripping and plating.
- Solid-state battery reproducibility is a challenge—proposed standards and methodologies aim to push the field forward.

Sodium-ion Batteries

- Na-ion batteries are moving from academia to commercialization. While hard carbon seems to be the preferred anode, the best cathode—Prussian whites/blues, NASICONs, layered oxides—remains uncertain.
- The next few years will reveal key challenges and innovations, including progress in sodium-ion solid-state cells.

Novel Materials

- Academia is fueling the discovery of new crystal structures, materials, and breakthroughs.
- Turning lab innovations into commercial products takes time—but past discoveries like LCO, NMC, and LFP have paved the way.
- Deep learning is ramping up to uncover next-gen cathode and electrolyte compositions.
- Molecular electrolytes are prime candidates for high-speed research methods.

Call to Action

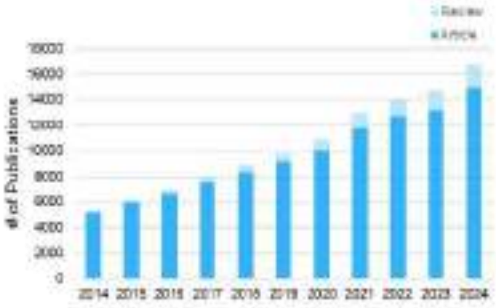
- Academic research complements industrial activities. Academia has more freedom to explore unproven ideas and materials, and to do in-depth studies of battery mechanisms. Academia can share best practices and produce open-source tools.
- Academic research should be a place for discovery and understanding. The creation is knowledge *in posterum*, not a product for immediate sale.

2 ACADEMIA

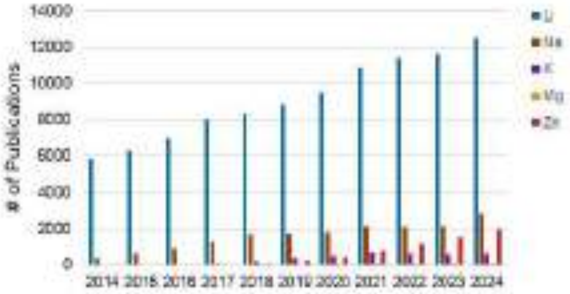
Growth In Publications Driven By China And India; Sodium And Zinc Gain Popularity

- The number of publications continues to increase in 2024, including a larger number of review articles
- There is growing interest in alternative chemistries such as Na, K and Zn
- China publishes more papers than the US, India, South Korea, and Germany combined

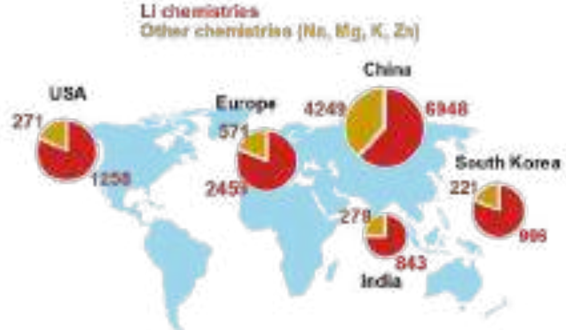
ANNUAL PUBLICATION VOLUMES



BATTERY CHEMISTRY FOCUS



RESEARCH VOLUME BY COUNTRY

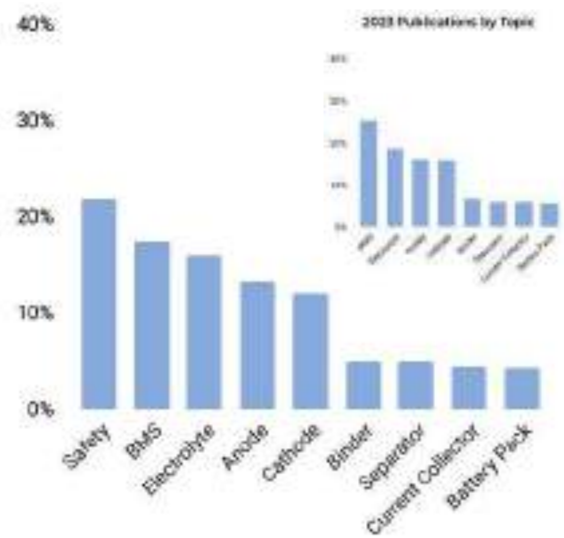


Source : Queried from https://www.webofscience.com/, accessed 2025-01-09
Queries: (TS=("lithium-ion batter* " OR "Lithium ion batter*" OR "Li ion batter*" OR "Li-ion batter*" OR "lithium-ion cell* " OR "Lithium ion cell*" OR "Li ion cell*" OR "Li-ion cell*" OR "sodium-ion batter* " OR "Sodium ion batter*" OR "Na ion batter*" OR "Na-ion batter*" OR "sodium-ion cell* " OR "Sodium ion cell*" OR "Na ion cell*" OR "Na-ion cell*" OR "potassium-ion batter* " OR "Potassium ion batter*" OR "K ion batter*" OR "K-ion batter*" OR "potassium-ion cell* " OR "K ion cell*" OR "K ion cell*" OR "K-ion cell*" OR "magnesium-ion batter* " OR "Magnesium ion batter*" OR "Mg ion batter*" OR "Mg-ion batter*" OR "magnesium-ion cell* " OR "Mg ion cell*" OR "Mg ion cell*" OR "Mg-ion cell*" OR "zinc-ion batter* " OR "Zinc ion batter*" OR "Zn ion batter*" OR "Zn-ion batter*" OR "zinc-ion cell* " OR "Zn ion cell*" OR "Zn ion cell*" OR "Zn-ion cell*"))

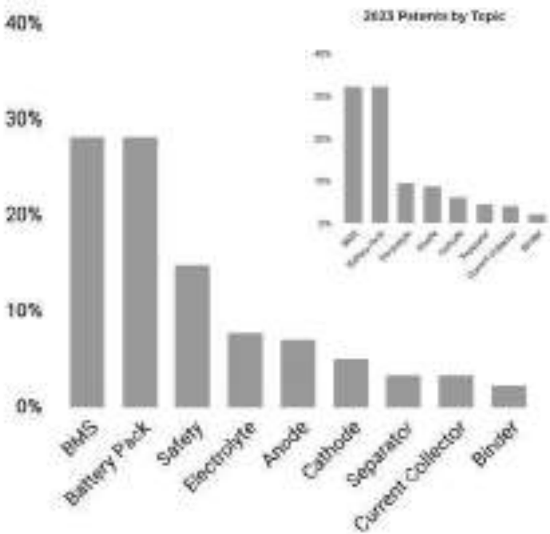
Safety Is The Most Published Topic, System-Level Design The Most Patented

- Safety surpasses BMS and electrolyte as the most published research topics in 2024.
- Materials-level research topics maintain their order ranking from the previous year.
- BMS and battery pack innovations, both system-level topics, remain the most patented areas.

2024 PUBLICATIONS BY TOPIC



2024 PATENTS BY TOPIC



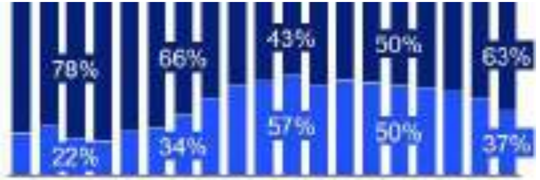
For more details on patent breakdown, visit Legal Section

Source: Queried from https://scholar.google.com, accessed 2025-01-05
Queries: (battery X) after:priority:20240101, where X = topic of interest

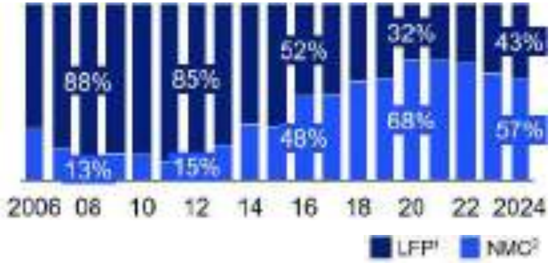
Research Pivoting From NMC To L(M)FP Batteries

- The percentage of patents filed for NMC has been decreasing since 2016, with LFP taking a majority from 2020
- The percentage of publications on LFP compared to NMC **follows the same trend as patents but roughly 5 years later**
- The trend is far stronger in China compared to the rest of the world: in 2022, **62% of battery patents filed in China** were LFP, compared to **41% in the rest of the world**

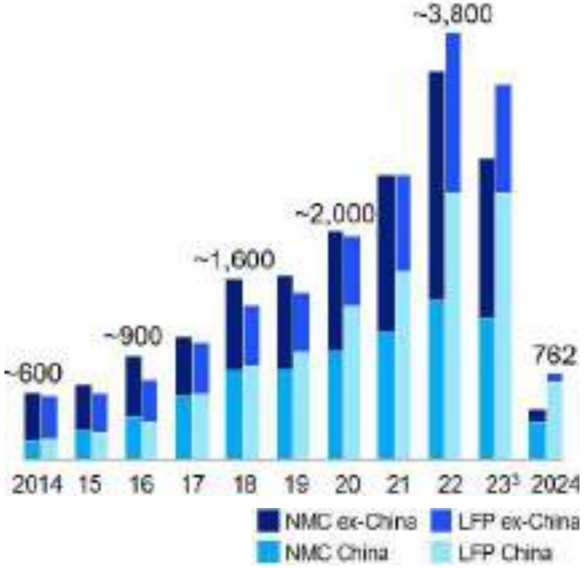
SHARE OF FILED PATENTS OF NMC AND LFP



SHARE OF PUBLICATIONS OF NMC AND LFP



TOTAL NUMBER OF PATENTS PER PATENT OFFICE



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1. Search terms: battery AND cathode AND ("LFP" OR "LMFP" OR "iron phosphate" OR "FePO4")
2. Search terms: battery AND cathode AND ("NMC" OR "NCM" OR "NCA" OR "nickel manganese cobalt" OR "LiNiMnCoO2")
3. Not all filed patents are already published

Source: McKinsey, Patents queried from Google Scholar and Publications queried from Web of Science, accessed 2024-09-01. Queries: for LFP: battery AND cathode AND ("LFP" OR "LMFP" OR "iron phosphate" OR "FePO4"); for NMC: battery AND cathode AND ("NMC" OR "NCM" OR "NCA" OR "nickel manganese cobalt" OR "LiNiMnCoO2")

2 ACADEMIA

Milestones In The Invention Of Rechargeable Lithium-Ion Batteries

Stanley Whittingham demonstrates the first cathodes capable of intercalating lithium using TiS_2 and other dichalcogenides [1],[2]. [1970s].

[1] Whittingham. Science. 1976
[2] Whittingham, Prog. Solid St. Chem 1978

1970s

Michel Armand introduces the concept of a "rocking-chair" battery, which stores energy by shuttling ions between different anode and cathode intercalating materials[3]. [1970s]

[3] Mauger et al. J. Electrochem. Soc. 2020

John Goodenough employs the use of cathode materials ($LiCoO_2$) capable of reversibly intercalating Li^+ at high voltages [4]. [1980].

[4] Mizushima et al. Mater. Res. Bull. 1980

Rachid Yazami shows successful intercalation of lithium into graphite using polymer electrolytes [5] [1983].

[5] Yazami, J. Pow. Source. 1983

1980s

Akira Yoshino demonstrates a rechargeable Li-ion battery using a carbonaceous material as the anode while working for Asahi Kasei Corporation[6]. [1985 patent].

[6] Profile of Akira Yoshino

Sony releases the first successful commercial Li-ion battery [1991].

Picture taken from Sony Archives

1990s

Advances in lithium-ion materials, now ubiquitous, continue with new cathode chemistries, such as **LTO** [7], **NMC** [8], and **LFP**[9].

[7] Ferg et al. J. Electrochem. Soc. 1994
[8] Delmas et al. Solid State Ion. 1992
[9] Padhi et al J. Electrochem. Soc. 1997

2019 Nobel prize in Chemistry awarded "for the development of lithium-ion batteries".

CURRENT

Continued development of fundamentals, materials, and applications of Li-ion batteries

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, TiS_2//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, TiS_2//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.

In 2019, Whittingham was awarded the Nobel Prize in Chemistry "for the development of lithium-ion batteries".

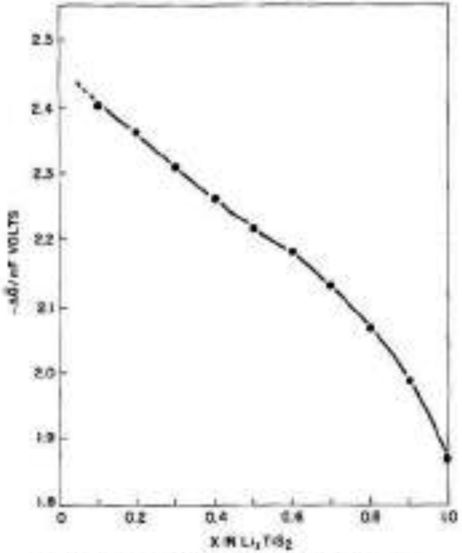


Fig. 1. Partial molar free energy of formation of Li_xTiS_2

Those familiar with the Nernst equation will recognize that the y-axis is simply the familiar E(V)

Source : Whittingham, Chalcogenide battery. US patent 4,009,052, 1973. Whittingham *Science* 1976. Whittingham *J. Electrochem. Soc.* 1976. Whittingham *Nat. Energy* 2021.;
Image - Binghamton University

$LiCoO_2$ (LCO) - The First High-Voltage Intercalation Cathode

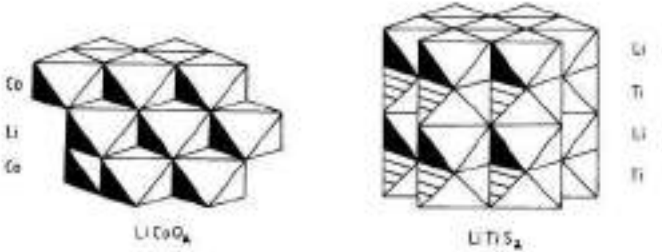


FIG. 1
Idealised structures of $LiCoO_2$ and $LiTiS_2$

In 1980, John Goodenough's team at Oxford unveiled the oxide cathode $LiCoO_2$ 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 $LiCoO_2$.

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.

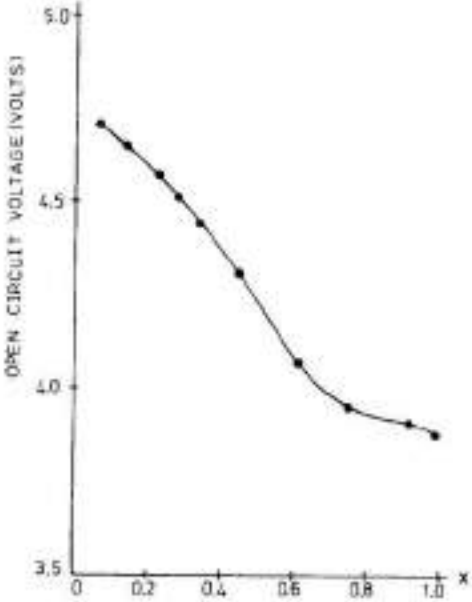


FIG. 3
Open circuit voltage versus composition x for $Li_xCo_{1.01}O_2/Li$

Source : Mizushima, Jones, Wiseman, Goodenough *Mat. Res. Bull.* 1980. Manthiram, Goodenough *Nat. Energy* 2021.; Image - UChicago

$LiFePO_4$ (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.

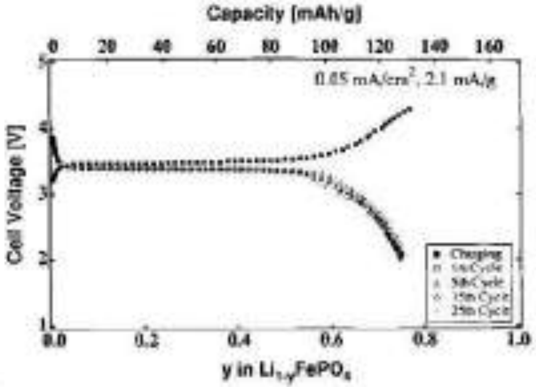
Li atoms in LFP can be reversibly extracted at **3.4 V vs. Li^+/Li**

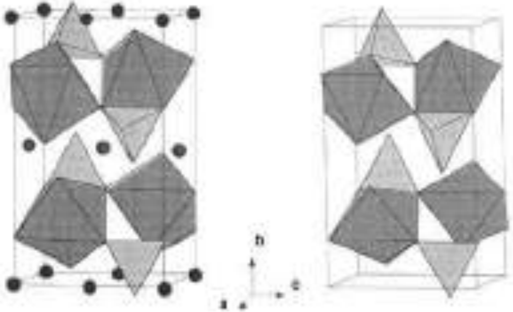
Insertion voltage is independent of state-of-charge

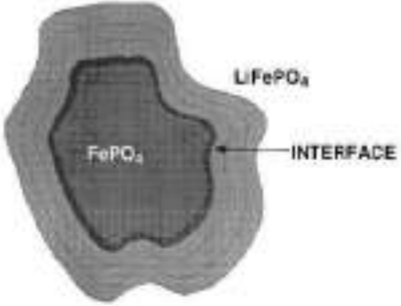
Similar **olivine crystal structure** between $LiFePO_4$ and $FePO_4$

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 : Padhi, Nanjundaswamy, Goodenough *J. Electrochem. Soc.* 1997, 4, 1188. Padhi, Nanjundaswamy, Masquelier, Okada, Goodenough *J. Electrochem. Soc.* 1997, 5, 1609. 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**

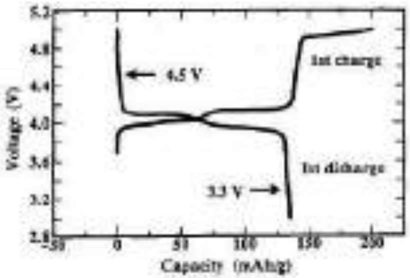
Mn_2O_4 spinel provides tetrahedral sites for Li insertion at 4.1 V and 3.9 V

Cubic structure allows for isotropic expansion and contraction

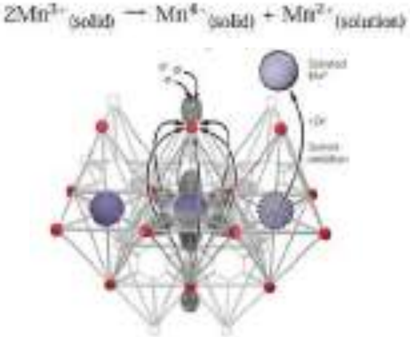
When Li stoichiometry is > 1, cubic symmetry reduces to tetragonal

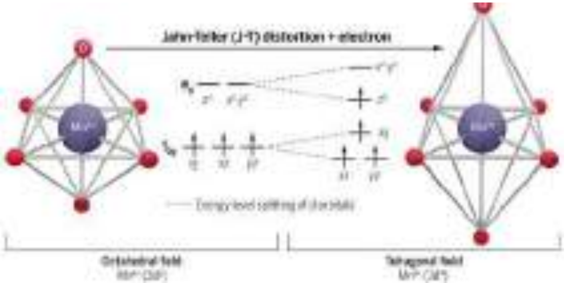
$LiMn_2O_4$ has **poor stability with electrolyte due to Mn dissolution**

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 operated between 3.0 V and 5.0 V [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**

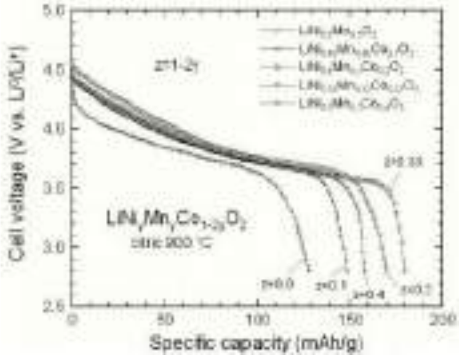
Specific capacities of up **~220 mAh/g** have been reported

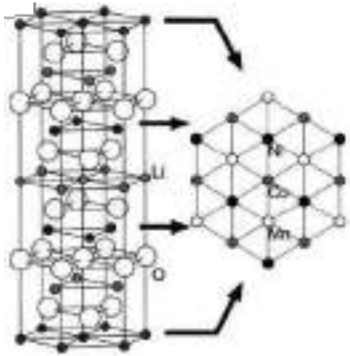
Layered crystal structure similar to LCO

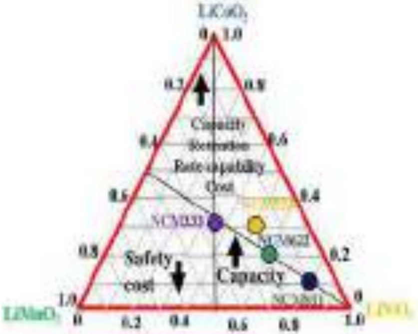
Li intercalates between the layers, not all Li can be removed or the structure would collapse

Compositional versatility allows **tuning performance and stability**

Ni improves capacity, Co improves conductivity, and inactive Mn stabilizes the structure





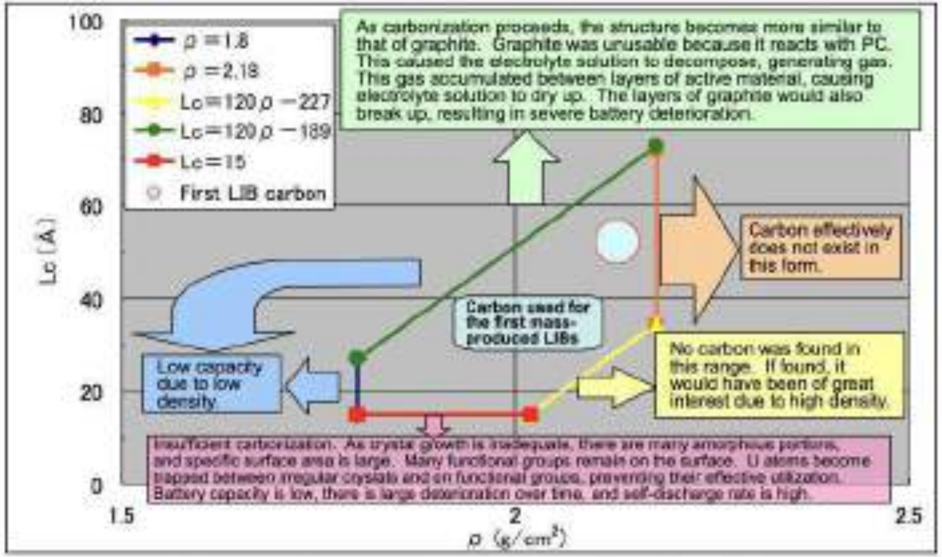


Source : [1] J. Power Sources 1999, 81-82, 416-419; [2] Nat. Commun. 2020, 11, 1550; [3] Adv. Energy Mater. 2020, 10, 1903864; [4] J. Power Sources 2003, 119, 644; [5] Materials 2016, 9, 595

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 ~0.5V v. Li^+/Li without structural degradation.

Its amorphous carbon regions acts 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.



As carbonization proceeds, the structure becomes more similar to that of graphite. Graphite was unusable because it reacts with PC. This caused the electrolyte solution to decompose, generating gas. This gas accumulated between layers of active material, causing electrolyte solution to dry up. The layers of graphite would also break up, resulting in severe battery deterioration.

No carbon was found in this range. If found, it would have been of great interest due to high density.

Insufficient carbonization. As crystal growth is inadequate, there are many amorphous portions, and specific surface area is large. Many functional groups remain on the surface. Li atoms become trapped between irregular crystals and on functional groups, preventing their effective utilization. Battery capacity is low, there is large deterioration over time, and self-discharge rate is high.

Figure 4. Carbonaceous material suitable for LIB discovered by Dr. Yoshino In 1985

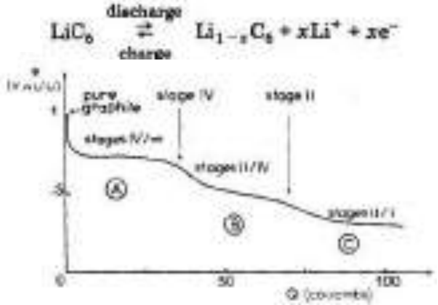
Source : Yoshino, A. Nat Energy 6, 449 (2021), Xie, A retrospective on lithium-ion batteries. Nat Commun 11, 2499 (2020); [1] Nobel Prize, [2] Asahi Kasei

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

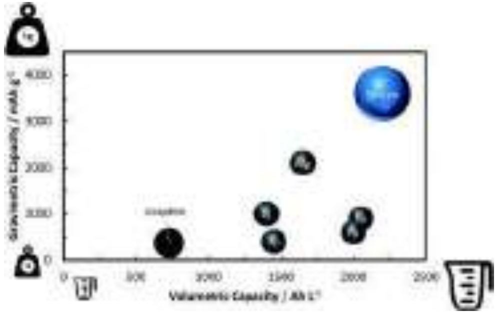
CHALLENGES

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, better thermal stability, and independence from natural resources [2].

Embedding silicon/silicon oxide for increased energy densities. Silicon has a theoretical energy density of 3578 mAh g^{-1} [2].



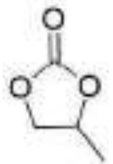
Source: [1] Yazami, R., and Ph Touzain. "A reversible graphite-lithium negative electrode for electrochemical generators." *Journal of Power Sources* 9.3 (1983): 365-371.
[2] Asenbauer, Jakob, et al. "The success story of graphite as a lithium-ion anode material–fundamentals, remaining challenges, and 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)

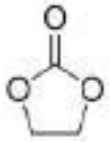
Between 1950s and 1990s, typical electrolytes consisted of various lithium salts dissolved in PC [1]. PC demonstrates strong solvating ability and has a high oxidative stability above 4.0 V_{Li}. Unfortunately **PC can cointercalate with lithium into graphite, leading to exfoliation,** which limits its practical application.



propylene carbonate (PC)

Ethylene carbonate (EC)

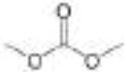
Initially, PC was preferred over EC because EC has a melting point of 37 C. To overcome this high melting point, EC is often mixed with linear carbonate esters such as dimethyl carbonate and diethyl carbonate [1]. Dahn et al.'s discovery that **EC's forms a stable solid electrolyte interphase (SEI)** was key to enabling the graphite anode [2]. EC based electrolytes combined with graphite anodes increased energy density of LIBs by 30–50%.



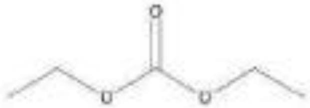
ethylene carbonate (EC)

LINEAR CARBONATES

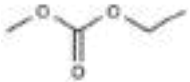
Linear carbonates are typically used as co-solvents with their cyclic counterparts. In 1994, Tarascon and Guyomard first added DMC as a cosolvent to EC [3] [4]. Linear carbonates have relatively low boiling points, viscosities, and dielectric constants. Therefore, **they are often used to improve ionic transport** in the electrolyte. Surprisingly, when combined with cyclic carbonates, the stability window of the resulting mixture is increased to 5.0 V [5]. In the present, cyclic and linear carbonate mixtures are commonly used. Other popular linear carbonates include DEC, EMC, and PMC.



dimethyl carbonate (DMC)



diethyl carbonate (DEC)



ethyl methyl carbonate (EMC)

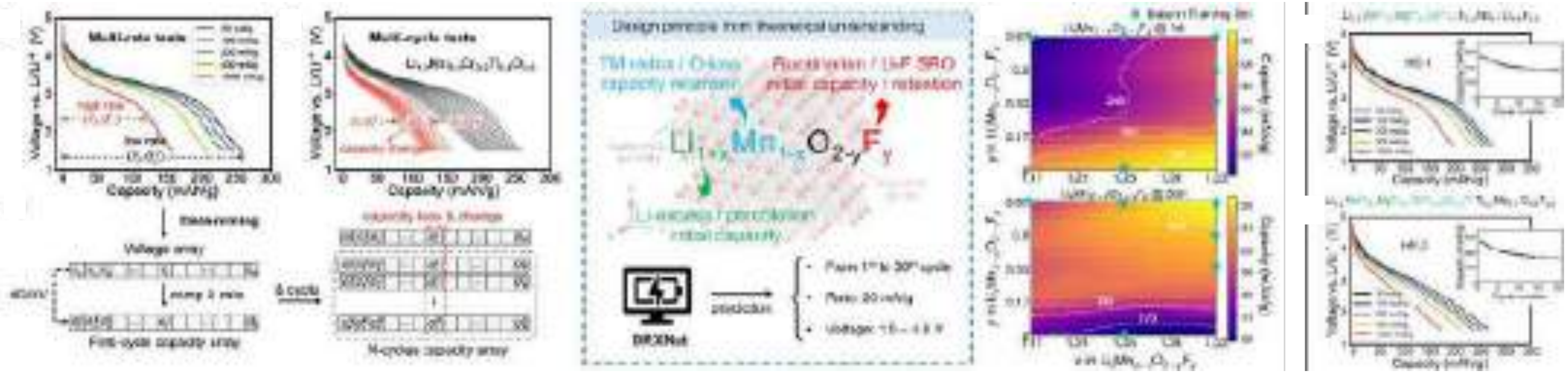
> "Within the various brands of lithium ion cells, ... the formulas remain proprietary information; however, the overwhelming majority of these are apparently based on two indispensable components: EC as the solvent and $LiPF_6$ as the solute. In most cases, one or more linear carbonates, selected from 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. Li-ion battery electrolytes. *Nat Energy* 6, 763 (2021). https://doi.org/10.1038/s41560-021-00841-6
[2] Rosamaría Fong et al 1990 J. Electrochem. Soc. 137 2009, DOI 10.1149/1.2086855
[3] Guyomard, D.; Tarascon, J. M. *J. Electrochem. Soc.* 1993, *140*, 3071, DOI: 10.1149/1.2220987
[4] Tarascon, J. M.; Guyomard, D. *Solid State Ionics* 1994, *69*, 293, DOI: 10.1016/0167-2738(94)90418-9
[5] Xu, Kang. "Nonaqueous liquid electrolytes for lithium-based rechargeable batteries." *Chemical reviews* 104.10 (2004): 4303-4418.

2 ACADEMIA

Deep Learning Of Experimental Electrochemistry For Battery Cathodes Across Diverse Compositions

The rapid expansion of machine learning in battery research is revolutionizing materials discovery, performance prediction, and process optimization, but its transformative potential hinges on addressing the need for high-throughput experimental validation. Zhong *et al.* present a machine learning framework, DRXNet, for optimizing battery cathodes with disordered rocksalt (DRX) materials. Leveraging a dataset of over 19,000 discharge voltage profiles covering 14 metal species, the model predicts electrochemical properties and guides the discovery of novel compositions for DRX cathode materials, such as Li-Mn-O-F and high-entropy systems.

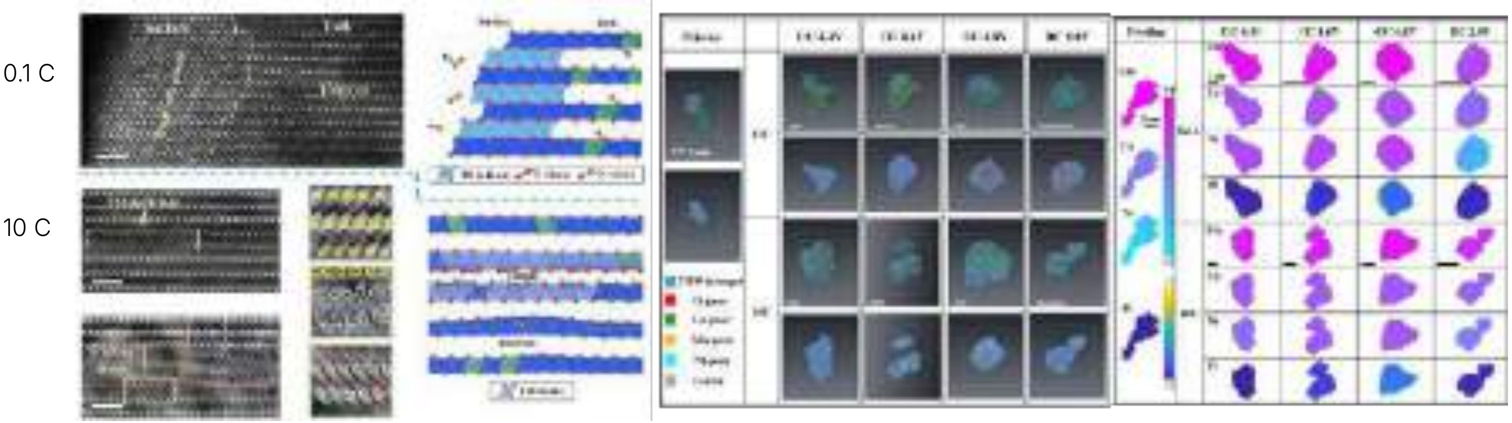


DRXNet enables rapid identification of promising materials for high-performance and sustainable lithium-ion batteries, addressing challenges like data scarcity and complex optimization.

Source : Zhong et al. *Joule* 2024

Revealing The Degradation Pathways Of Layered Li-Rich Oxide Cathodes

Liu et al. investigate the degradation pathways of layered lithium-rich transition metal oxides (LRTMO) as high-energy-density cathodes for lithium-ion batteries. LRTMO suffers from structural instability and irreversible changes during cycling, leading to capacity fading and voltage decay. Using multi-dimensional analytical tools such as X-ray tomography and STEM, the study reveals two distinct degradation mechanisms at different cycling rates.



The degradation of LRTMO follows distinct pathways driven by cycling rate: oxygen defects dominate at low rates, while lattice distortions and ion diffusion constraints take precedence at high rates. Homogenizing reaction kinetics and enhancing structural stability are key to improving performance.

Source : Liu et al. Nat. Nanotechnol. 2024

Towards A Better Understanding Of The Cathode Electrolyte Interphase (CEI) For Enhanced Stability

MODEL CATHODE MATERIALS

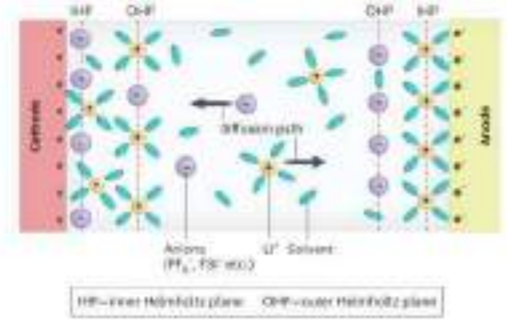
Model cathode materials are needed to establish a convincing baseline and isolate effects on the cathode. Suitable candidates include single crystal Ni-rich NMC and commercial polycrystalline NMC811.

Single crystal NMC76

Single crystal NMC811 with irregular morphology

ELECTROLYTES & ADDITIVES TO STABILIZE CEI

Electrolyte components and their oxidative stability determine the composition of CEI. When the cathode is polarized, the inner Helmholtz plane is dominated by anions, suggesting that salt engineering may be helpful. Other solutions involve additives or more stable solvents.



SIMULATING THE CEI

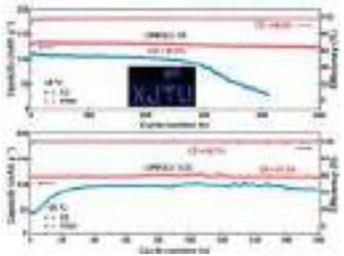
Combining ab initio simulation techniques with machine learning will aid the understanding of complex results from advanced characterization techniques. A caveat of applying atomistic simulations is that the results and predictive power depend heavily on the accuracy and complexity of the underlying models.

> "Full understanding of CEI formation and evolution at varied length and time scales, especially at high voltages, is still lacking in the battery community. Progress is urgently needed to better tune CEI properties at the atomic scale to further stabilize the electrochemical energy storage system."

Source: Xiao, J., Adelstein, N., Bi, Y. et al. Assessing cathode–electrolyte interphases in batteries. Nat Energy 9, 1463–1473 (2024).

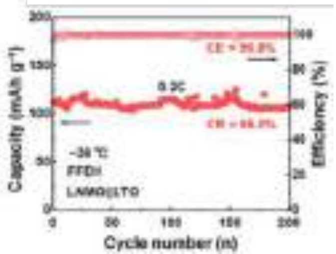
Reconstructing Inorganic-Rich Interphases By Nonflammable Electrolytes For High-Voltage And Low-Temperature $LiNi_{0.5}Mn_{1.5}O_4$ Cathodes

HALF CELL

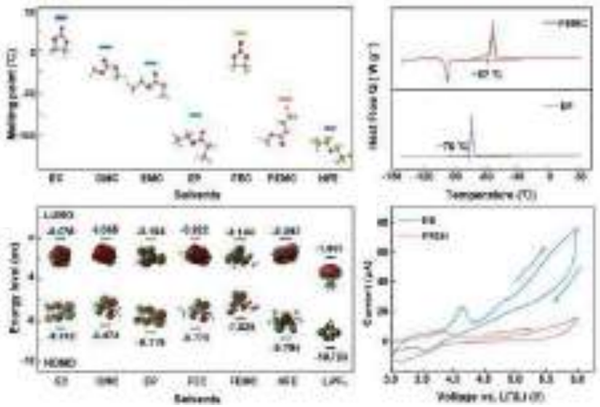


- **25 °C cycling:** The capacity retention during long-term cycling is up to 95.8% after 500 cycles at 2 C
- **−20 °C cycling:** When cycled at −20 °C, LNMO exhibits a reversible capacity of 114 mAh g^{-1} at 0.2 C with a capacity retention of 97.5% even after 180 cycles

FULL CELL



- $Li_4Ti_5O_{12}$ (LTO) is known as a “zero-strain material”, which is suitable for pairing with LNMO for high-power applications
- LNMO||LTO coin cells were fabricated over the voltage range of 2.0–3.5 V. Even at −30 °C, ≈96.0% capacity retention is achieved after 200 cycles



STRUCTURE-PERFORMANCE CORRELATION:

A Li_2CO_3/LiF-rich heterostructured CEI layer, which possesses the electron blocking capability of LiF, the fast Li+ transport kinetics of Li_2CO_3 and good mechanical stability, is generated by the synergistic decomposition of hybrid solvents.

The robust, homogeneous, and well-balanced CEI layers subsequently prevent catalyzed parasitic side reactions, prohibit transition-metal dissolution, and ensure fast interfacial reaction kinetics crossover to the LNMO cathode, thus improving cycling stability of the cell.

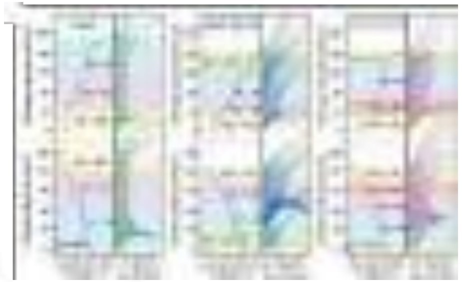
Source: Adv. Funct. Mater. 2024, 34, 2400996

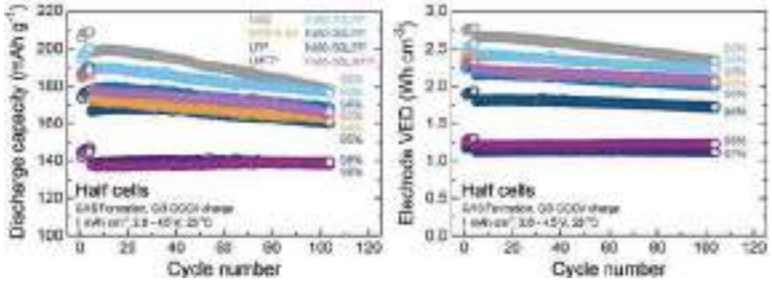
Layered/Olivine (NMA/LMFP) Blended Cathodes For Cost And Performance

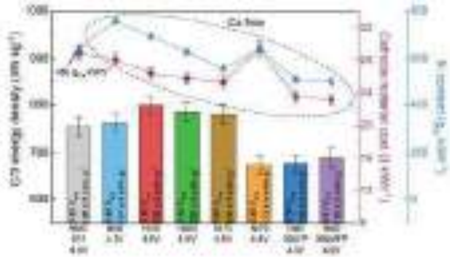
Blending layered oxide with olivine is an effective alternative for delivering energy density and cycling stability comparable to lower-Ni cathodes with moderate charging voltages. Blending with 30 wt% olivine $LiMn_{0.5}Fe_{0.5}PO_4$ (LMFP) virtually eliminates the diffusion limitation of layered oxides at low state-of-charge, with enhanced pulse power characteristics rivaling high-Ni systems.

Kinetics The impedance decreases once the discharge voltage becomes low enough for the LFP or LMFP to be electrochemically active. Due to its higher average voltage and flatter voltage profile, LMFP will become electrochemically active at a higher discharge voltage (≈3.6 V) than for LFP (≈3.4 V)

Performance & Cost Blending olivine cathodes with high-Ni cathodes allows the cathode Ni content and materials cost to be reduced below 80% while maintaining energy density and cycling stability. Comparable volumetric energy densities suggest that the optimal blend of Ni80/LMFP contains at most 30% LMFP.





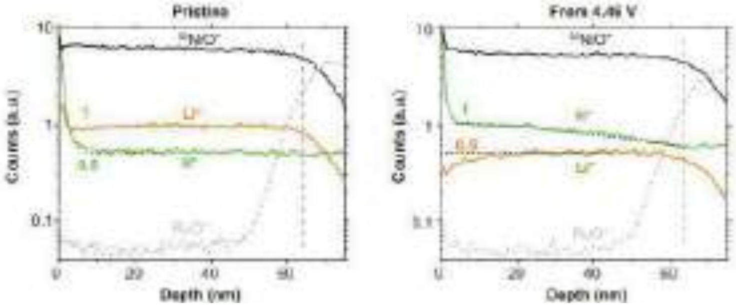


Source: Adv. Energy Mater. 2024, 2403002)

Degradation Of NMC Cathodes Via Hydrogenation From Carbonate Solvents

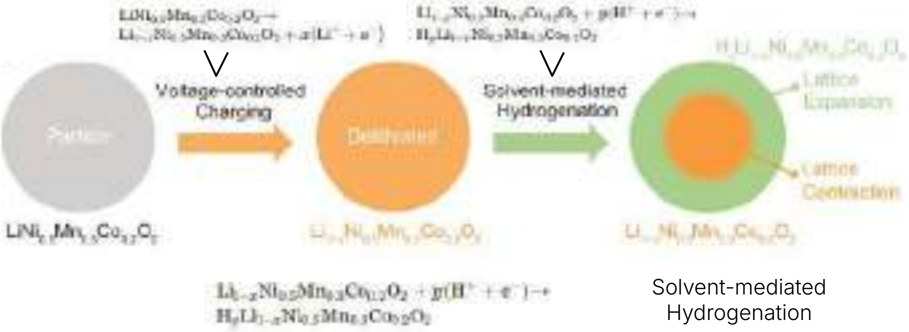
The prevailing theory of cathode degradation self-discharge in carbonate-containing electrolytes centers around the diffusion of lithium from the electrolyte into the cathode. However, using computational techniques such as Density Functional Theory (DFT), and spectroscopy techniques such as DFT, XANES, NEXAFS, XRD and XAS, Wan et al. discovered that insertion of protons into a charged cathode can occur via decomposition of -CH_2 containing species in the electrolyte. This hydrogen transfer from the the carbonate solvent to the delithiated cathode accelerates at higher cut-off voltages (>4.3V).

TOF-SIMS DEPTH PROFILES



A) Pristine NMC-532 film in LP57
B) NMC-532 filmcycled to 4.46V in LP57

***Note the change in H- concentration as a function of film depth for the charged electrode (Figure B)**



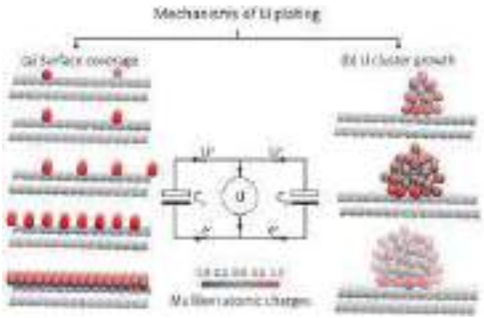
Solvent-mediated Hydrogenation

Wan et al. present a new mechanism of cathode degradation and self-discharge for NMC cathodes via solvent-mediated hydrogenation of the cathode.

Source: Wan et al. Science 2024

2 ACADEMIA

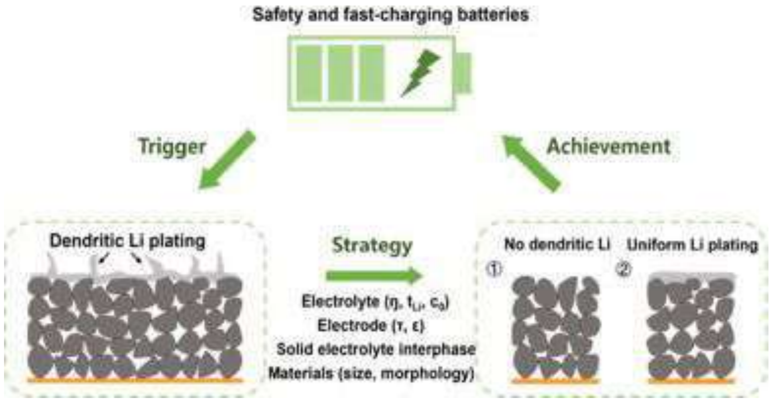
How To Avoid Plating And Dendrites While Fast Charging Graphite Anodes



Using *ab initio* simulations, Bhandari et al. predict that Li deposition occurs in the following stages: at positive voltages vs. Li, surface deposition of Li^+ ions is the dominant process; below a critical cross-over voltage (−12 mV on the basal plane of unlithiated graphite and −29 mV on lithiated graphite), the reduction of aggregated Li^+ ions and the formation of metallic Li clusters takes over.

The authors encourage experimentalists to verify these results.

On the same subject, Liu et al., wrote a review of the fundamentals of dendritic metallic Li formation and strategies for suppressing metallic Li plating. They describe the entire Li^+ transport pathway at the anode including effects from the electrolyte, pore structure of electrode, and surface and bulk of the materials.



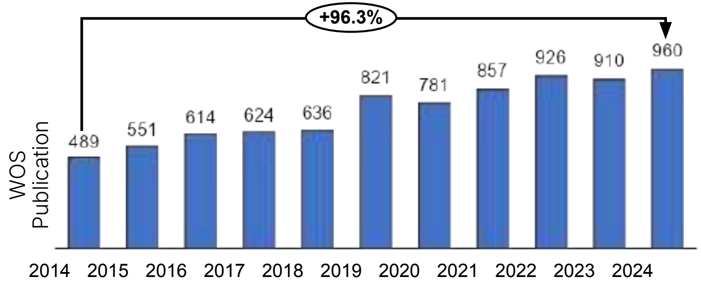
KEY TAKEAWAYS:

SEI on graphite is still not fully understood.
Reversible, uniform lithium plating might be the best strategy for fast charging graphite.

Source: Bhandari et al. J Mat Chem A, 2024 ; Liu et al. J. En Chem. 2024

Continued Increase In Publications On Si Anode. Mechanism Disclosed For Si Anode In Ssb As One Of The 2024 Highlights

GENERAL TREND



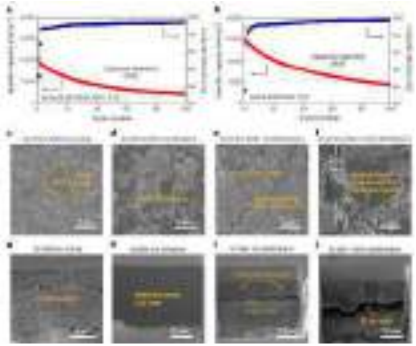
In the past 10 years, the number of research publications with “Si anode, lithium-ion battery” as key words has increased by 96.3% (from 489 to 960), suggesting continued interested in the area

PROS AND CONS:

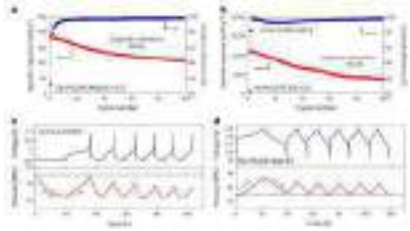
- High theoretical specific capacity (3590 mAh/g, $Li_{3.75}Si$ at RT), low lithiation potential and low lithium dendrite risk (only 0.3 V vs. Li^+/Li)
- Severe volume expansion during lithiation leads to Si particle pulverization and continuous SEI formation

Source: *Web of Science, Nat. Mater. 23, 543-551 (2024))*

PROGRESS HIGHLIGHT



2D AND 3D SI|LPSCL INTERFACES



SI|LPSCL|NCM@LBO FULL CELLS

Rapid growth of the solid electrolyte interphase (SEI) at the Si|Li_6PS_5Cl interface causes large increases in resistance of the composite anodes, leading to rapid capacity decay.

Pure silicon anodes without intermixed solid electrolyte demonstrate sufficient ionic and electronic conductivities, enabling high specific capacity.

Microscale void formation during delithiation causes larger mechanical stress at the 2D interfaces of these pure silicon anodes compared to the interconnected 3D interfaces of the silicon anode/ solid electrolyte composite.

Unlocking The Use Of Silicon-Containing Anodes Via Different Techniques

Particle coating mitigation strategies are aimed at accommodating the extensive volume expansion of silicon (~320%) and thereby minimizing particle cracking/ pulverization, which can lead to loss of electrical contact and/or low active material utilization and therefore low capacity retention. The following articles highlight recent publications that employ three of the most commonly-used particle coating mitigation strategies:

Image taken from [4]

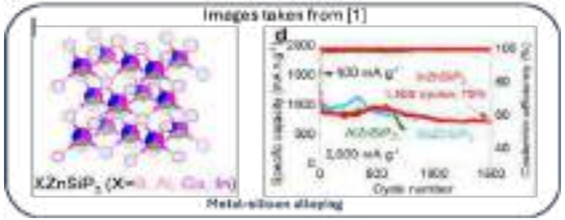
Volume expansion in the silicon anode leads to severe degradation of cycling performance during lithiation/ delithiation, so various techniques are under consideration for improving the performance of silicon-containing anodes.

DIFFERENT TECHNIQUES

Li et al. [1] employed a ball-mill method to systematically create various **high-entropy silicon-metal particles** from SiP spherulites and thus generating various lithium-storing active materials from the silicon base. Of these, InZnSiP₃ achieved a capacity of ~720 mAh g^{-1} after 1500 cycles (2 Ag^{-1}) and maintained a similar capacity at a high C-rate (10 A g^{-1}).

Sun et al. [2] created a **biomimetic 3-D interwoven conductive binder** employing PAA as a backbone and PEG/PEI as connections that mitigated Li^+ resistance and relieved volumetric lithiation stress. A rate capability of ~1900 mAh g^{-1} was achieved at 8.0 A g^{-1} and a capacity retention of 85%+ for 150 cycles at a high areal capacity loading (3 mAh cm^{-1}).

Wu et al. [3] synthesized a **yolk-shell architecture** from microsized silicon particles using an alkali etch step that creates a void on the surface of the silicon between a double-walled "shell" layer to better accommodate the volume expansions. This strategy allowed for a high capacity-retention of 95% after 100 cycles in a full cell.


Images taken from [1]

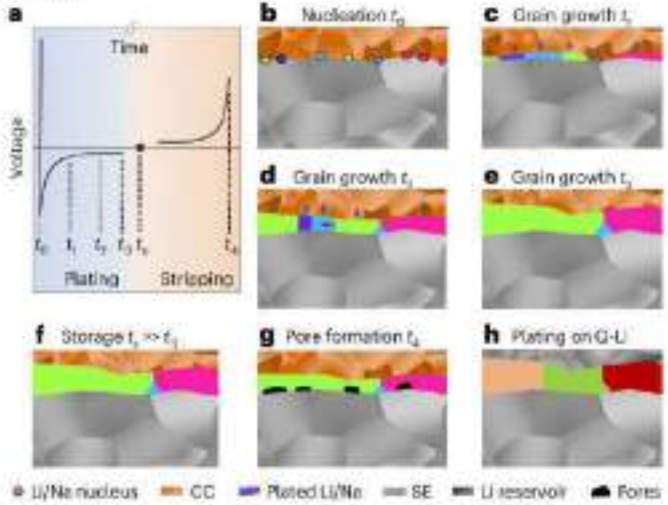

Images taken from [2]


Images taken from [3]

Sources: [1] Li et al. J. Am. Chem. Soc. 2024; [2] Sun et al, Nano Lett, 2024 ; [3] Wu et al. Small. 2024 ; [4] Choi and Aurbach. Nat. Rev. Matter. 2016

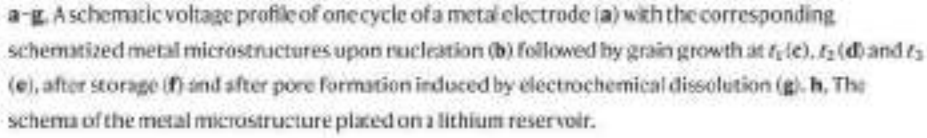
Imaging The Microstructure Of Lithium And Sodium Metal In Anode-Free Solid-State Batteries Using Electron Backscatter Diffraction

Fig. 5: Schematic evolution and the origin of the observed columnar microstructure of deposited alkali metal films in RFCs during electrochemical deposition and dissolution.



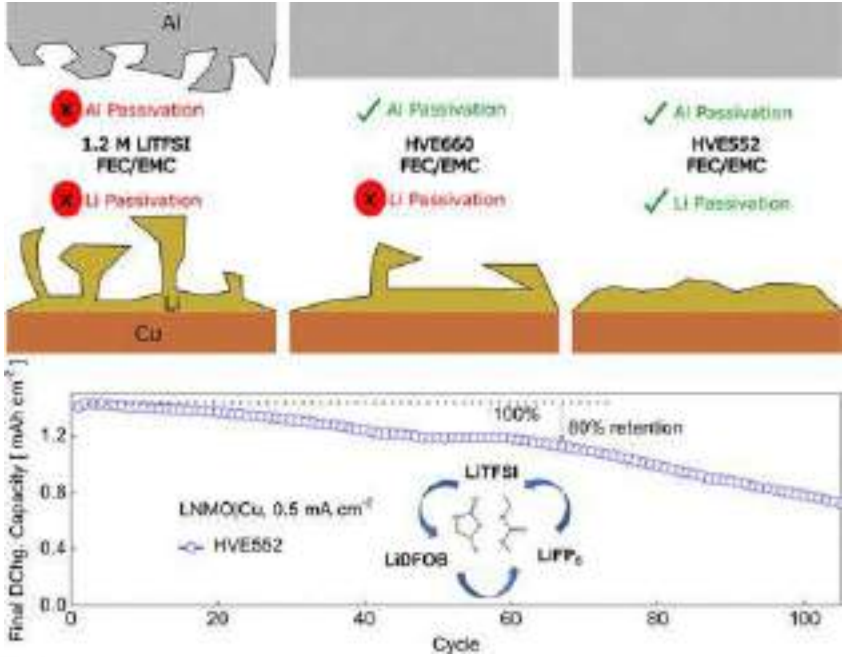
In this research, metal growth and dissolution were investigated using in situ electron backscatter diffraction, yielding new insights:

- It is possible to tune the electrochemical properties, such as available stripping capacity, by controlling the deposited microstructure, **with a preference for small grains in the microstructure**
- Controlling the microstructure of the current collector or solid electrolyte may not be a successful path to influencing the deposited metal microstructure. **Lithium plated on the lithium foil matches the microstructure of neither the solid electrolyte nor the foil**
- The merging of grains in electrodeposited alkali metals is driven by grain boundary movement. **Tailored impurities, such as seed layers or particles, can influence this mobility and be used to modify the microstructure.**


a–g, A schematic voltage profile of one cycle of a metal electrode (**a**) with the corresponding schematized metal microstructures upon nucleation (**b**) followed by grain growth at t_1 (**c**), t_2 (**d**) and t_3 (**e**), after storage (**f**) and after pore formation induced by electrochemical dissolution (**g**). **h**, The schema of the metal microstructure plated on a lithium reservoir.

Source: Fuchs et al. Nature Mat., 2024

Ternary Salt–Solvent Electrolytes For 5 V-Class Anode-Less Li-Metal Batteries



- A three-salt combination of LiTFSI, LiDFOB, and $LiPF_6$ in carbonate solvent (FEC/EMC) was developed for high-energy-density Li-metal batteries.
- LiTFSI is highly corrosive to aluminum surfaces, which can be mitigated by passivating the Al current collector with the addition LiDFOB salt. However, the dual-salt combination of LiTFSI and LiDFOB does not deliver long-term cycling due to the rapid consumption of LiDFOB.
- Adding $LiPF_6$ improves cycling stability and long-term performance by creating a LiF-dense layer, enhancing ionic conduction.
- The electrolyte was tested in a cobalt-free $LiNi_{0.5}Mn_{1.5}O_4$–Li anode-less cell, **which completed 65 cycles with less than 20% capacity loss.**

Source: Shubhadeep Pal et al. , ACS Energy Letters 2024

2 ACADEMIA

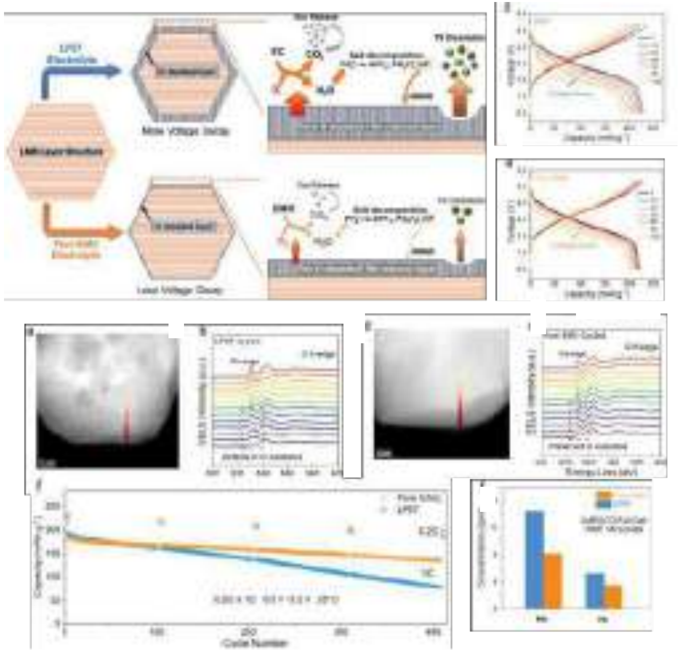
Electrolyte Development For Li-Rich High-Voltage Batteries

Wang et al. proposed a novel approach to suppress both voltage decay and capacity fade in $Li_{1.2}Mn_{0.6}Ni_{0.2}O_2$ (LMR) cathodes by examining how different electrolyte solvents affect oxygen loss from the cathode surface.

The study focused on the effect of EC on surface oxygen loss from the cathode. While EC solvent does not affect bulk oxygen (SXRD and GITT), there is an increase in surface oxygen loss (XAS, EELS, and Raman), which they further found to correlate with increased Ni and Mn dissolution (leakage current analysis and OEMS).

Galvanostatic cycling test of LMR versus LTO cells showed that an electrolyte composed of only EMC solvent has 75% better capacity retention after 400 cycles when compared to an electrolyte containing both EC and EMC.

Using EC-free electrolytes (e.g. pure EMC) reduces surface oxygen loss and transition metal dissolution from the cathode, while minimizing capacity degradation and voltage fade for Li-rich high voltage batteries

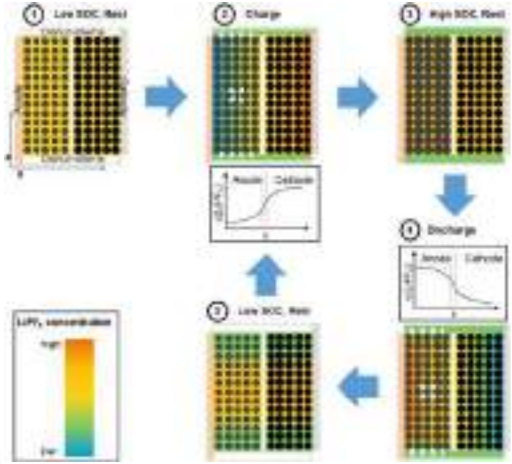


Source: Wang, Rui, et al. "Influence of Carbonate Electrolyte Solvents on Voltage and Capacity Degradation in Li-Rich Cathodes for Li-ion Batteries." Advanced Energy Materials (2024): 2401097.

Salt Inhomogeneity Induced By Electrolyte Motion – A Novel Aging Mechanism In Large-Format Lithium-Ion Cells

Researchers at BWM, Solchenbach et al., propose an underexplored mechanism for degradation in cells - electrolyte motion induced salt inhomogeneity (EMSI).

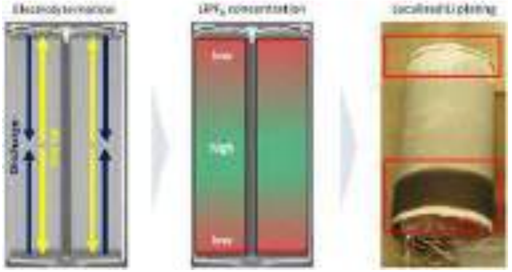
In the proposed mechanism, the electrolyte expelled from the jellyroll upon charge is at a lower than average salt concentration.



HYPOTHESIS SUPPORTED BY:

- X-ray CT
- Moment of inertia
- Cell dissection
- IC & LC-MS of salt and solvent amount sampled along jellyroll height (z-axis)
- Capacity, DCIR, DCh end slippage over cycles
- P2D simulation

Over cycles, a polarization in salt concentration builds because it takes weeks to months for the salt concentration to re-equilibrate along the height of the jellyroll (~95mm).



The **polarized salt distribution** leads to localized degradation and Li-plating, accelerating capacity fade and internal resistance growth. This is exacerbated in cells with larger dimensions, subject to higher C-rates.

The effects are not as pronounced in cells with lower electrolyte loading (no net electrolyte expelled out of the jellyroll even at 100% SOC)

Source: Solchenbach et al. Energy Environ. Sci. 2024.

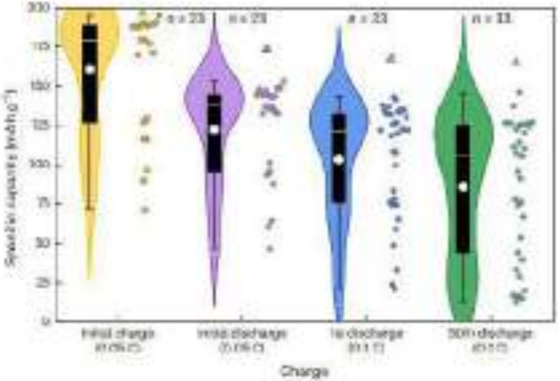
Reproducibility Of All-Solid-State Battery Cell Performance

In this study, the interlaboratory comparability of all-solid-state battery cycling data was investigated. Commercial NMC 622, Li6PS5Cl and indium foil were sent to 21 different groups. The groups were asked to assemble and cycle ASSB cells under defined conditions but using their individual cell set-ups and preparation procedures.

The initial discharge capacities at 0.1 C after pretreatment range from 23.7 mAh/g to 143.1 mAh/g. Thus, the comparability of ASSB cell data originating from different groups and cell set-ups is limited.

To improve the comparability, we recommend reporting all processing and cell parameters in Table 1.

Moreover, with a cell failure rate of 43%, this study shows that the assembly of ASSB cells is challenging. Therefore, we recommend reporting the number of failed cells to better assess the reproducibility and robustness of the assembly protocol.



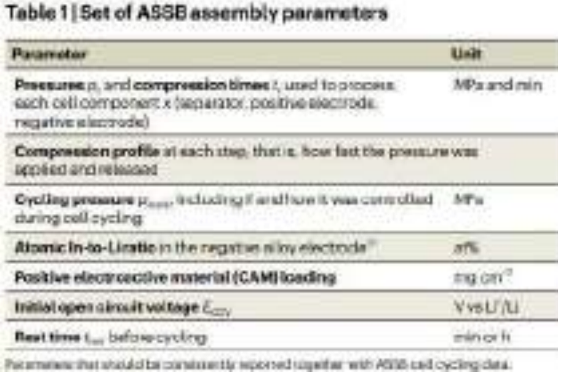


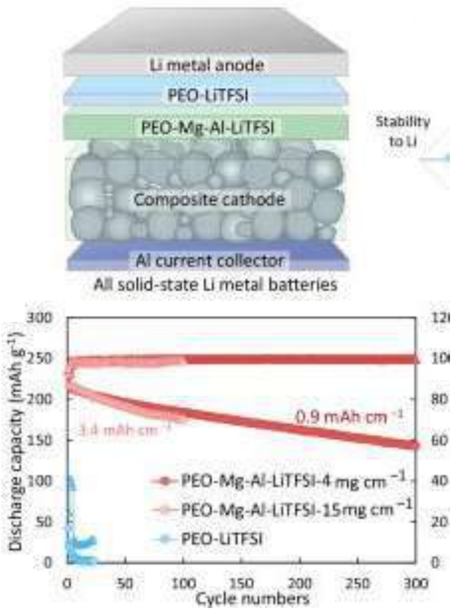
Table 1 | Set of ASSB assembly parameters

Parameter	Unit
Pressures p_x and **compression times** t_x used to process each cell component x (separator, positive electrode, negative electrode)	MPa and min
Compression profile at each step, that is, how fast the pressure was applied and released	
Cycling pressure p_{cycl}, including if and how it was controlled during cell cycling	MPa
Atomic In-to-Li ratio in the negative alloy electrode[*]	at%
Positive electroactive material (CAM) loading	mg cm⁻²
Initial open circuit voltage E_{OCV}	V vs Li⁺/Li
Rest time t_{rest} before cycling	min or h

Parameters that should be consistently reported together with ASSB cell cycling data.

Source: Puls et al. Nat Energy, 2024

Strong Lewis-Acid Coordinated PEO Electrolyte Achieves Over 580 Wh/kg In 4.8 V-Class All-Solid-State Batteries



Polyethylene oxide (PEO)-based electrolytes are one of the go-to materials for solid-state batteries, but typically have poor oxidation resistance at high voltages, limiting energy density.

The introduction of Mg^{2+} and Al^{3+} ions improves cyclic stability by weakening electron density in ether oxygen chains, reducing undesirable interactions with cathodes.

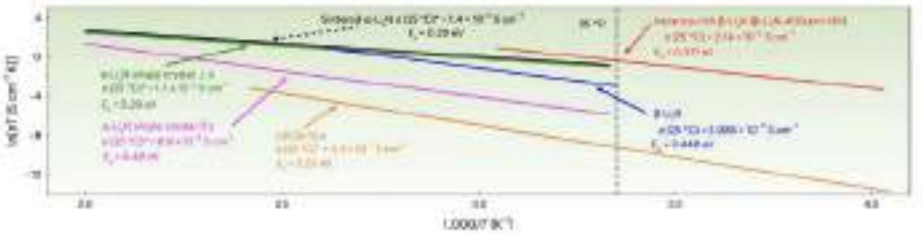
The authors used Lewis-acid coordinated electrolytes and Ni-rich cathodes to achieve high-voltage stability at 4.8 V over 300 cycles. Further, the demonstration of industrial-scale electrolyte membrane, and Ah-level pouch cells over 586 Wh kg, including one with good cycling stability, suggests the potential for practical applications in all-solid-state batteries.

Source: An et al. Nature Comm., 2024

Superionic Conducting Vacancy-Rich B-Li3n Electrolyte For Stable Cycling Of All-Solid-State Lithium Metal Batteries

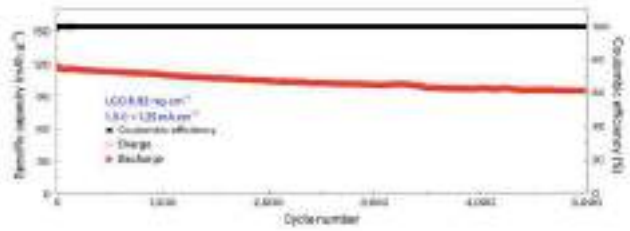
Li et al. utilize a vacancy-mediated superionic diffusion mechanism to achieve room temperature ionic conductivity of 2.14 × 10^{-3} S cm^{-1} in β-Li_3N along with extremely stable cycling performance, surpassing almost all reported nitride-based solid state electrolytes.

Ionic Conductivity of Vacancy-Rich
β-Li_3N Compared to Other
Nitride-Based Solid-State Electrolytes



FULL-CELL APPLICATION:

LCO Cathode: capacity retention of 82.05% at 95.2 mAh g^{-1} over 5,000 cycles at 1.0 C



NCM83 Cathode: capacity retention of 92.5% at 153.6 mAh g^{-1} over 3,500 cycles at 1.0 C

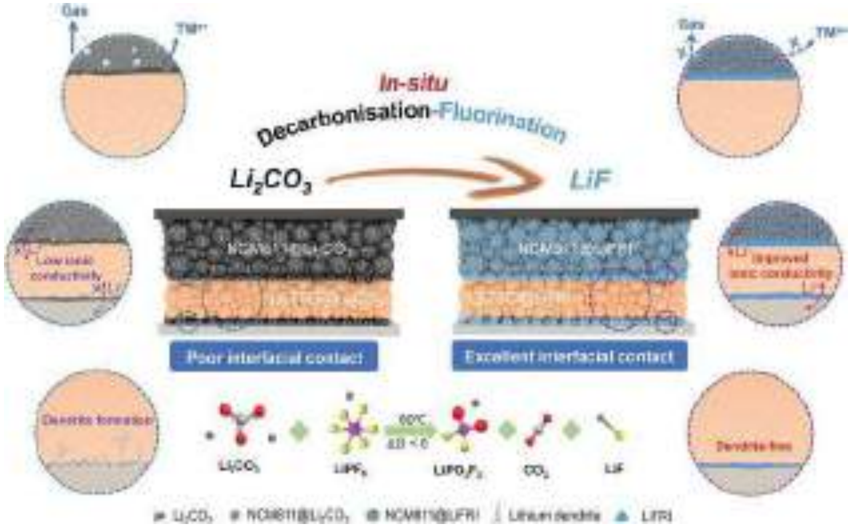
Source: Li et al, Nature Nanotech, 2024

In Situ Li_2CO_3 Conversion in Solid State Batteries For Improved Interfacial Contact

Li-intercalated ceramics, such as LLZTO, often spontaneously form a layer of inactive Li_2CO_3 upon contact with moisture or CO_2, hindering kinetics in cycling. Conventional Li_2CO_3 removal methods usually involve high temperature or acid-based treatments, which can often damage the underlying ceramic LLZTO electrolyte.

Researchers at Tianjin University have developed a low-temperature decarbonization–fluorination strategy to address this issue. By reacting in situ Li_2CO_3 with $LiPF_6$ at 60°C, they successfully construct ultrastable, LiF-rich interphases throughout the cell.

Notably, this fluorination strategy is capable of removing a significant fraction of Li_2CO_3 across all interfaces, even within grain boundaries. The fluorination of all interfaces also suppresses parasitic reactions while reducing the interface resistance, eliminating gas evolution within the cycling window of up to 4.5V, and demonstrating a cycling stability of up to 7,000 h.



Li_2CO_3 is a common Li-battery degradation product that inhibits cell cycling. The *in-situ* conversion of Li_2CO_3 to LiF-rich regions creates a protective interphase with stable electrochemical cycling.

Source: Guo, Pan, Yi, Chi, Yin, Geng, Yin, Zhan, Zhao, Jin, Fang, He, Kang, Wu, Yang

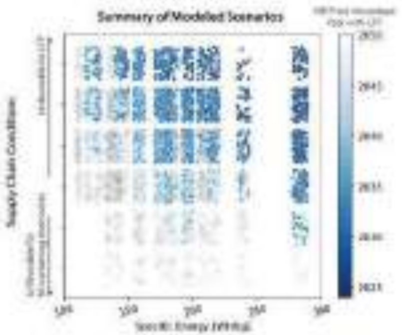
2 ACADEMIA

Sodium-Ion Batteries - An Emerging Alternative To Lithium-Ion

COST PROJECTIONS OF NA-ION BATTERIES

Research by Yao et al. [1] indicates that Na-ion batteries could achieve **cost parity** with low-cost Li-ion variants by the **early 2030s**. The study explored **over 6,000 scenarios** to assess various development roadmaps and market conditions, highlighting that substantial R&D progress is crucial for enabling this transition.

The research highlights a significant manufacturing pipeline for Na-ion cells, with over **240 GWh announced through 2030**, indicating strong industry interest and investment in this technology as a response to lithium price volatility.



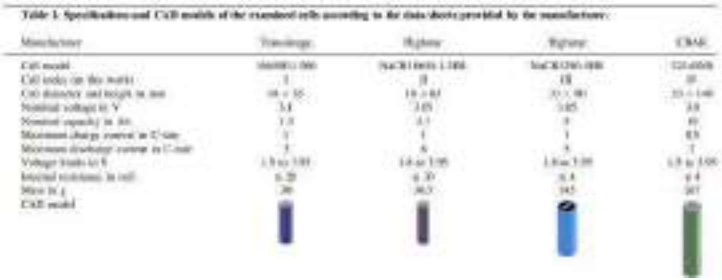
Na-ion batteries are no longer confined solely to the academic domain and have started making their way into the commercial world.

TEARDOWN OF FOUR COMMERCIAL NA-ION CELLS

Dorau et.al [2] provide a comprehensive **analysis of four commercially available cylindrical sodium-ion batteries**, revealing key insights into their structural and electrochemical performance.

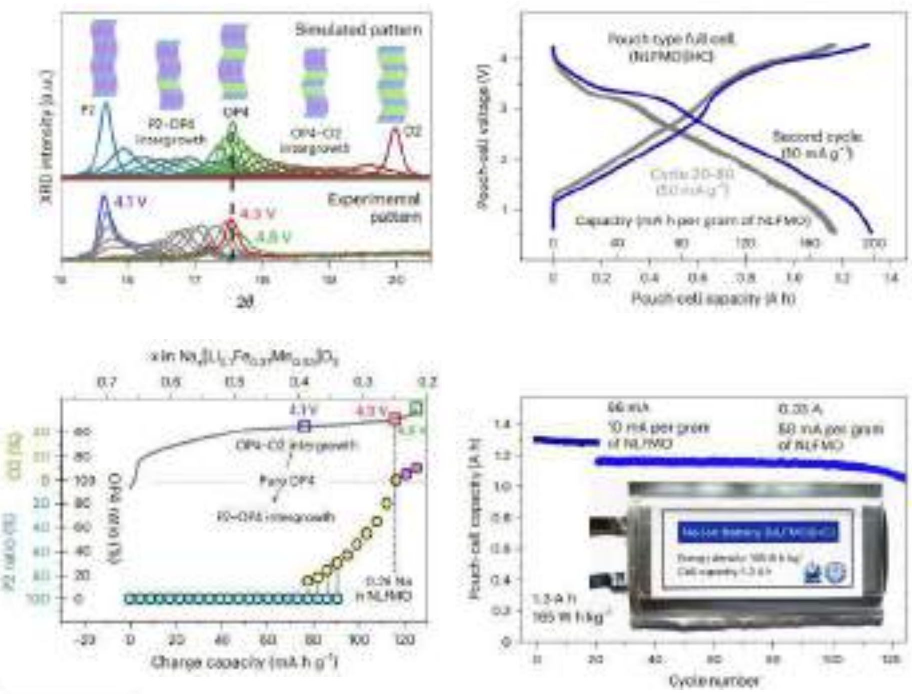
The batteries, with capacities ranging from 1.3 Ah to 10 Ah and voltages between **3.0 V and 3.1 V**, utilized **nickel-manganese-iron layered oxides** as cathodes and hard carbon anodes with particle sizes of 2–12 µm.

Separator materials included polyethylene with protective α-Al2O3 coatings. Doping the cathodes with zirconium or copper improved ion diffusion and structural stability, mitigating degradation. Specific area capacities ranged from 1.29 to 1.98 mAh/cm². At 0°C, all cells showed **sodium plating risks**, potentially compromising safety during high-rate charging.



Source :
[1] Yao, A., Benson, S.M. & Chueh, W.C. Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. Nat Energy (2025) ; [2] Comprehensive Analysis of Commercial Sodium-Ion Batteries: Structural and Electrochemical Insights, Filip Adam Dorau et al 2024 J. Electrochem. Soc. 171 09052

Control Of OP4 Phase Transition Ensures High Cycle Stability



Wang et al. [1] demonstrated the successful control of **P2–OP4–O2** intergrowth structures, stabilizing structural transitions during high states of charge. **The OP4** phase was identified as a boundary phase that **prevents irreversible distortions**, ensuring reversible transitions with a specific capacity of **198 mAh/g**, maintained over **100 cycles** with **92% retention**. The study quantified the reversible migration of lithium ions, which are part of the cathode sublattice, between transition metal (TM) and alkali metal (AM) layers, with **migration remaining reversible up to a cut-off voltage of 4.3 V**.

The critical OP4 phase transition was locked at 4.3 V, preventing structural distortions caused by neighboring **O-type stacking faults**. The study also optimized both cationic (Fe/Mn) and anionic (Oxygen) redox activities, delivering a charge capacity of 125.5 mAh/g during the first charge and 165.8 mAh/g during discharge.

A sodium-ion pouch cell was developed, achieving an energy density of **165 Wh/kg, setting a high-performance benchmark for SIBs.** Extending the cathode voltage window from 1.5 V to 4.3 V resulted in a 15% increase in specific energy density, from 480 Wh/kg to 550 Wh/kg at the cathode level, marking a significant advancement in sodium-ion battery technology.

Controlling P2–OP4–O2 phase transitions stabilizes the performance of layered oxides, preventing structural distortions, boosting energy density, and maintaining high capacity retention with improved redox reversibility

Source: [1] Wang, X., Zhang, Q., Zhao, C. et al. Achieving a high-performance sodium-ion pouch cell by regulating intergrowth structures in a layered oxide cathode with anionic redox. Nat Energy 9, 184–196 (2024)

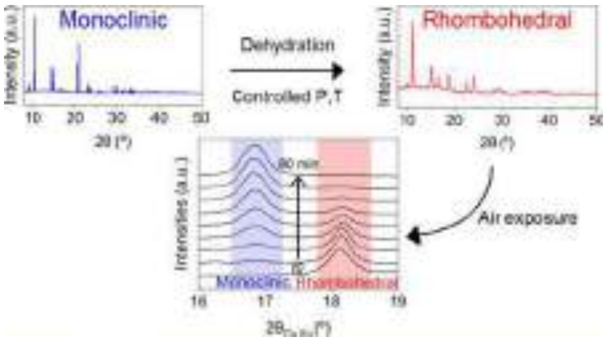
Water Content Matters - Key To Stability And Performance In Prussian White Systems

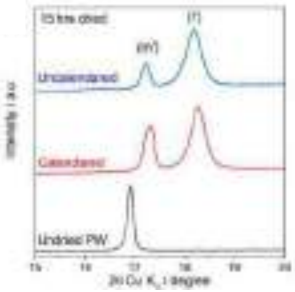
Dreyer et. al. [1] quantified gas evolution in Prussian White (PW) cathodes, showing that $NaClO_4$ electrolyte caused significantly **higher $(CN)_2$ emissions** than $NaPF_6$ during cycling. **Undried PW** released up to 6.44 wt% water during overcharge, **driving H_2 evolution**, while $NaPF_6$ suppressed toxic cyanogen, underscoring the impact of water content and electrolyte on battery safety.

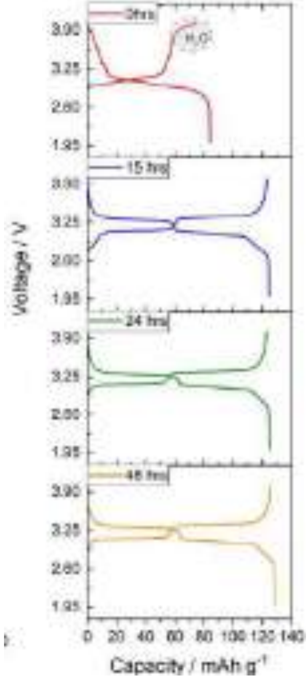
Maddar et. al [2] showed that optimized **dehydration** of PW at 170°C under vacuum (10^{-2} mbar) for 48 hours achieved **~10 wt% water loss**, transitioning to a rhombohedral structure and **increasing capacity to ~160 mAh g^{-1}.** Longer drying times and lower pressures further enhanced electrochemical performance. Rehydration studies revealed **up to 10% water uptake** under standard conditions, reversing these improvements and highlighting critical thresholds for stability.

Clavelin et al. [3] examined dehydration and rehydration in PW cathodes, showing that the **monoclinic-to-rhombohedral phase transition** occurs at 120°C under 10^{-2} mbar (vs. 135°C at 20 mbar). The rhombohedral phase achieved 90% of theoretical capacity (~154 mAh g^{-1}) compared to 81% (~126 mAh g^{-1}) for the monoclinic phase. **Ultrafast rehydration** reverted the rhombohedral phase to monoclinic within **80 minutes of air exposure.**

Effective control of water content and dehydration processes in Prussian White (PW) cathodes is crucial for optimizing electrochemical performance and ensuring battery safety. Aqueous electrode processing is feasible if effective drying strategies are implemented.







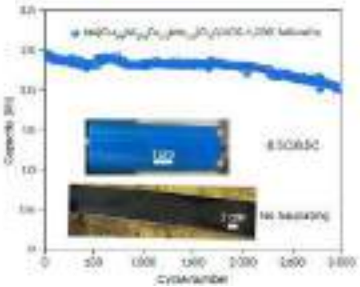
Source:
[1] Dreyer SL, Maddar FM, Kondrakov A, Janek J, Hasa I, Brezesinski T. Elucidating Gas Evolution of Prussian White Cathodes for Sodium-ion Battery Application: The Effect of Electrolyte and Moisture. Batter Supercaps 2024:202300595.
[2] Maddar FM, Walker D, Chamberlain TW, Compton J, Menon AS, Copley M, et al. Understanding dehydration of Prussian white: from material to aqueous processed composite electrodes for sodium-ion battery application. J Mater Chem A 2023;11:15778–91.
[3] Clavelin A, Thanh D Le, Bobrikov I, Fehse M, Drewett NE, López GA, et al. Dehydration Conditions and Ultrafast Rehydration of Prussian White: Phase Transition Dynamics and Implications for Sodium-Ion Batteries. ACS Mater Lett 2024:5208–14.

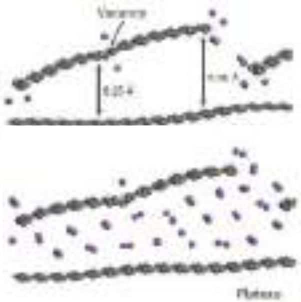
New Discoveries In Sodium-Ion Storage Mechanisms In Hard Carbons

FAST CHARGING IN HARD CARBON ANODES

Li et. al. [1] unveiled a unified **storage mechanism** for Li and Na in hard carbon anodes, introducing an **underpotential deposition** (UPD)-like process for Na^+ storage in wedge-shaped nanopores.

This mechanism facilitates quasi-metallic Na clustering at a slightly higher plateau potential due to interface energy differences between Na and graphene walls. These insights enabled the development of 26700-type cells with **3 Ah capacity**, achieving **83% retention** after 3,000 cycles at an **ultra-fast 6.5C rate** with no Na plating. The study also highlighted the **optimal pore size (~1 nm)** for balancing storage capacity and fast kinetics, providing a fundamental understanding of how nanopore geometry drives performance.

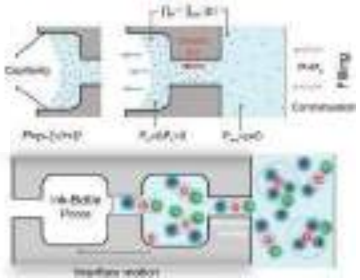


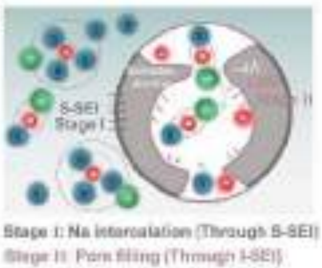


SEI-INDEPENDENT PRE-DESOLVATION

Lu et. al. [2] redefined the sodium-ion storage mechanism in hard carbons by identifying a novel **SEI-independent pre-desolvation** process within nanopores, driven by **capillary effects** and **osmotic pressure.** Unlike traditional SEI models, this mechanism alters the electrolyte solvation structure, achieving a **record-high initial Coulombic efficiency** (ICE) of 99.09% after 10 days of aging.

The insights led to the development of a **dual-SEI model**, distinguishing between a surface SEI (S-SEI) and an internal nanopore SEI (I-SEI). The I-SEI's thinner, inorganic-rich composition facilitates Na+ transport with reduced resistance, enabling a negative-to-positive (N/P) capacity ratio of 1.02 and energy density of **282 Wh/kg** in full cells. These findings challenge prior models by showing that nanopores actively shape Na^+ storage behavior.





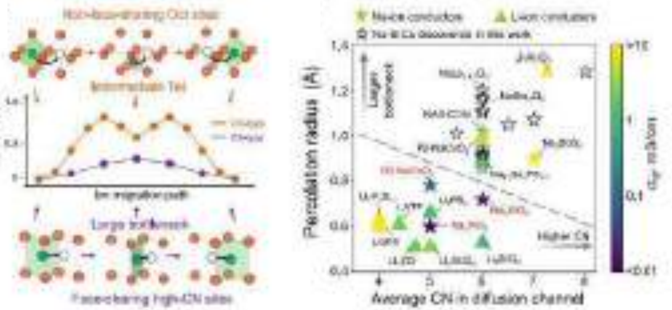
Source:
[1] Li, Y., Vasileiadis, A., Zhou, Q. et al. Origin of fast charging in hard carbon anodes. Nat Energy 9, 134–142 (2024)
[2] Lu, Z., Yang, H., Guo, Y. et al. Consummating ion desolvation in hard carbon anodes for reversible sodium storage. Nat Commun 15, 3497 (2024).

Fundamental Advances In Solid-State Electrolyte Engineering

DESIGN OF SODIUM SUPERIONIC CONDUCTORS

Wang et al. [1] establish face-sharing high-coordination sites **(CN ≥ 5)** as a **critical structural feature** for fast sodium-ion conduction, unveiling a chloride-based family of sodium superionic conductors ($Na_xM_yCl_6$) with the high ionic conductivity (1.4 mS/cm at room temperature).

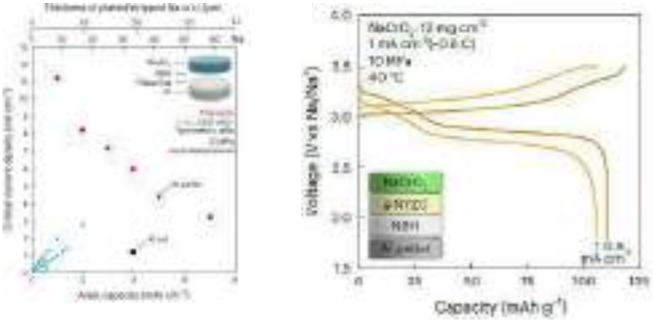
Advanced computational screening identified **35 new structural candidates**, including $NaLa_{1.67}Cl_6$, whose face-sharing octahedral pathways yielded **low activation barriers** (~0.13 eV). This discovery surpasses the conductivity of previous materials like Na_2ZrCl_6 (0.02 mS/cm) and also consolidates **design principles** that reconcile large bottleneck sizes with low diffusion barriers.



DESIGN PRINCIPLES IN ANODE-FREE APPROACH

Deysher et al. [2] achieve a breakthrough by enabling stable cycling of an anode-free sodium all-solid-state battery over 400 cycles at a **Coulombic efficiency of 99.96%** under 10 MPa stack pressure and 40°C.

The use of a sodium borohydride ($Na_4B_{10}H_{10}B_{12}H_{12}$) solid electrolyte, with a dense morphology formed through cold pressing, allowed for cycling at current densities exceeding **6 mA/cm²**. The study demonstrated **uniform sodium plating and stripping** with an areal capacity of 1 mAh/cm², achieved via an innovative aluminium pellet current collector that **improved solid-solid interfacial contact.** This collector reduced interfacial resistance and enabled the deposition of dense sodium layers, a key requirement for **mitigating dendritic growth** and maintaining cell integrity.

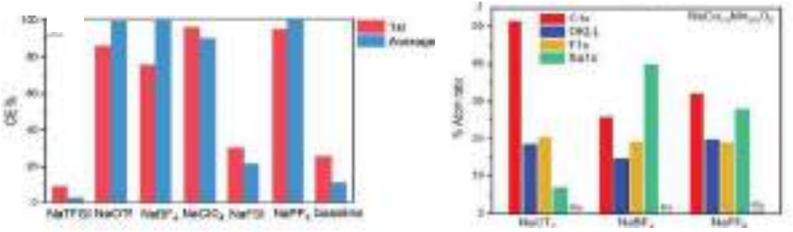


Source:
[1] Wang, S., Fu, J., Liu, Y. et al. Design principles for sodium superionic conductors. Nat Commun 14, 7615 (2023)
[2] Deysher, G., Oh, J.A.S., Chen, YT. et al. Design principles for enabling an anode-free sodium all-solid-state battery. Nat Energy 9, 1161–1172 (2024).

Liquid Electrolytes To Enable Na-Metal/Na-Ion Batteries

EXCELLENT CYCLING STABILITY OF SODIUM ANODE ENABLED BY A STABLE SOLID ELECTROLYTE INTERPHASE FORMED IN ETHER-BASED ELECTROLYTES

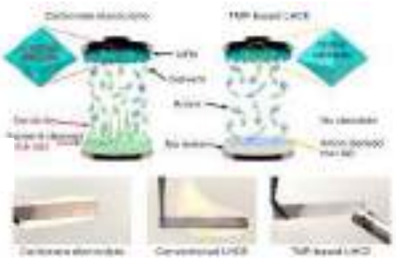
Le et al. [1] demonstrate that 1M $NaBF_4$ in G4 is able to achieve a coulombic efficiency of 99.9% with a Na anode for over 1000 cycles at a current density of 0.5 mA cm^{-2} with an areal capacity of 0.5 mAh cm^{-2}. Against hard carbon anode, the electrolyte is able to reach 95% capacity retention over 300 cycles. XPS results reveal that the electrolyte generates a N-F and Na_2-O rich CEI. Similarly on the anode side, XPS shows an SEI dominated by inorganic species.

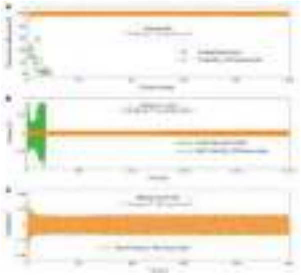


Le et al. show that G4 electrolytes containing 1M $NaBF_4$ or 1M $NaPF_6$ are promising candidates for practical Na-metal/Na-ion batteries.

TUNING THE SOLVATION STRUCTURE WITH SALTS FOR STABLE SODIUM-METAL BATTERIES

He et al. [2] use $NaNO_3$ salt as a diluent to tune the solvation structure and create a 1.1 M NaFSI-$NaNO_3$-trimethyl phosphate electrolyte that stabilizes the Na metal anode - electrolyte interface. In Na || NFM cells, the electrolyte enabled a capacity retention of 80% over 500 cycles at a C/5 rate. Due to the presence of TMP, the electrolyte also demonstrates fire retarding abilities.





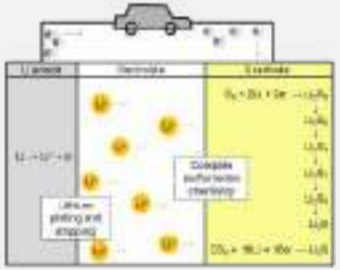
Novel 1.1 M NaFSI-$NaNO_3$-trimethyl phosphate electrolyte enables capacity retention of 80% over 500 cycles at a C/5 rate in Na || NFM cells.

Source:
[1] Le, Phung ML, et al. "Excellent cycling stability of sodium anode enabled by a stable solid electrolyte interphase formed in ether-based electrolytes." *Advanced Functional Materials* 30.25 (2020): 2001151. ; [2]He, J., Bhargav, A., Su, L. *et al.* Tuning the solvation structure with salts for stable sodium-metal batteries. *Nat Energy* 9, 446–456 (2024). https://doi.org/10.1038/s41560-024-01469-y

2 ACADEMIA

Li-S Battery Technology Confronts Rapid Growth In 2024 With Contrasting Strengths And Weaknesses

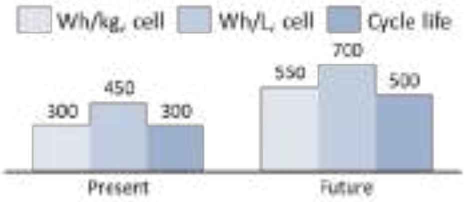
OPERATING PRINCIPLE



- Anode: Li ⇔ $Li^+ + e^-$
- Cathode: $S + 2Li+ + 2e^- \Leftrightarrow Li_2S$
- Overall: $S_8 + 2Li \Leftrightarrow Li_2S_8$

E ≈ 2.15 V vs. Li / Li^+

STRENGTH



WEAKNESS

ANODE

Li dendrite

Volume expansion

Unstable SEI

Chemical reactivity

CATHODE

S/Li_2S conductivity

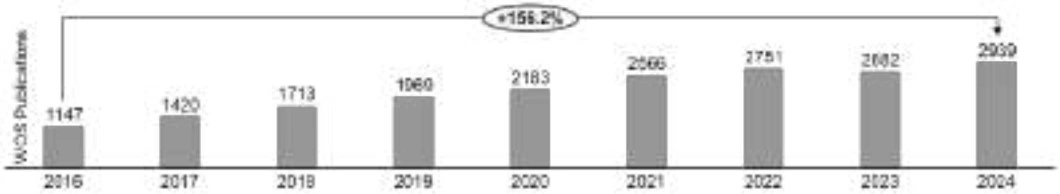
S/Li_2S volume expansion

Polysulfide shuttle

Sluggish kinetics

Li metal anode

Soluble polysulfides (Li_2S_x, 6≤x≤8)



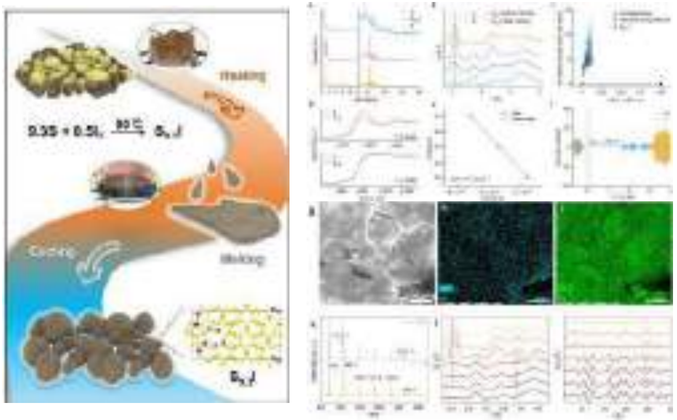
From 2016 to 2024, the number of publications in the web of science focused on Li-S battery increased by 156.2%

In 2024, there were 2939 publications with “Li-S battery” as one of the keywords

Source: https://iolitec.de/node/657, Web of Science, Alternative Battery Technologies Roadmap 2030+ (Fraunhofer ISI, doi:10.24406/publica-1342), Adv. Sci. 2022, 9, 2103879, Front Chem., 2020, 8:409

A New Sulfur Iodide Molecular Crystal, $S_{9.3}I$, As Solid-State Li-S Battery Cathode To Address Sulfur's Poor Conductivity And Interfacial Instability

MATERIAL PROPERTIES



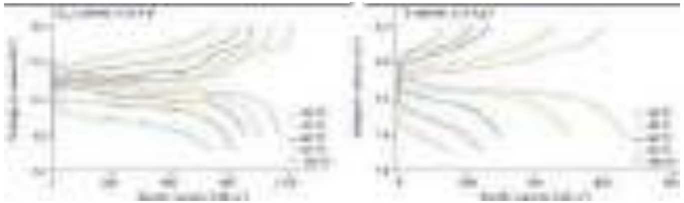
Synthesis: The material is synthesized by grinding S and I_2 powders, followed by heating to 80°C. The I_2 molecules are integrated into the S lattice, forming a unique crystalline structure.

Key Properties: $S_{9.3}I$ exhibits semiconductor-level conductivity (5.9×10^{-7} S cm^{-1} at 25°C) and features a low melting point (~65°C), enabling self-healing of damaged interfaces through periodic remelting.

EC PERFORMANCE

Pristine S

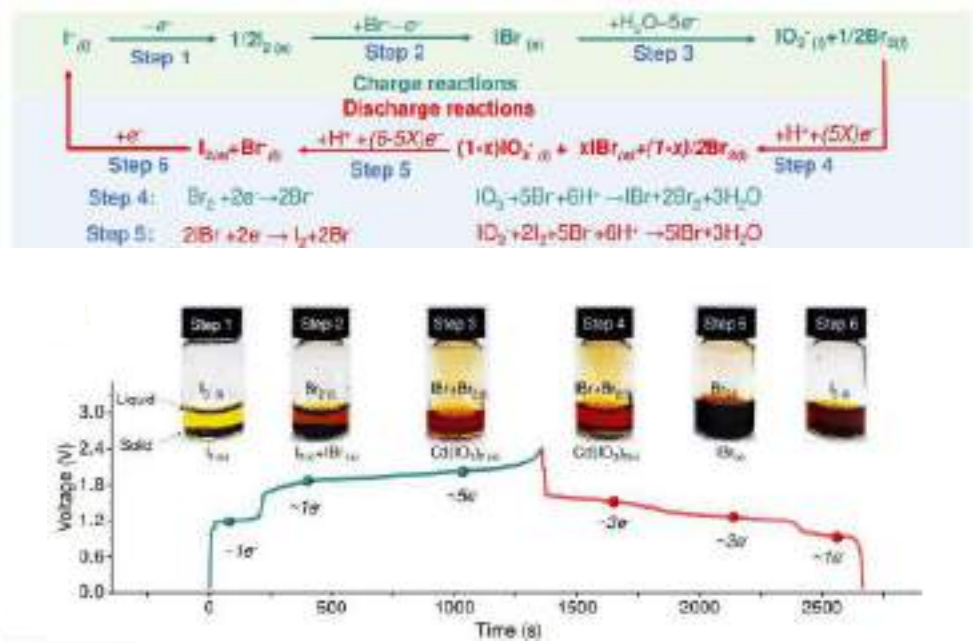
$S_{9.3}I$



Electrochemical Advantages: 87% capacity retention at 400 cycles.
High specific capacities (811.8 - 1211.3 mAh g^{-1}) over a range of temperatures (25–100°C).

Source: Zhou, J., Holekevi Chandrappa, M.L., Tan, S. et al. Healable and conductive sulfur iodide for solid-state Li–S batteries. Nature 627, 301–305 (2024).
https://doi.org/10.1038/s41586-024-07101-z

Reversible Multi-Electron Transfer I^-/IO_3^- Cathode Enabled By Hetero-Halogen For Ultra-High Energy Density Aqueous Batteries



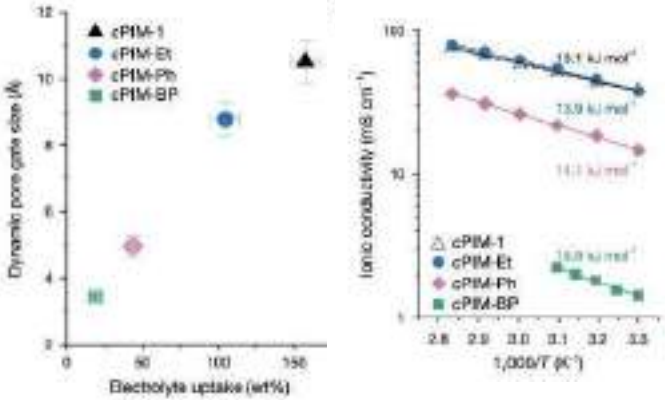
Xie et al. explored a new aqueous battery system based on halide ions. Although still in the early stages of development, they achieved:

- High Energy Density: Over 1200 Wh L^{-1} (at catholyte level) using a high hetero-halogen electrolyte and multi-electron transfer in the I_2/IO_3^- couple.
- Efficient Performance: Maintained 72% energy efficiency at a current density of 120 mA cm^{-2}.
- Long Cycle Life: Demonstrated over 1000 cycles with improved stability

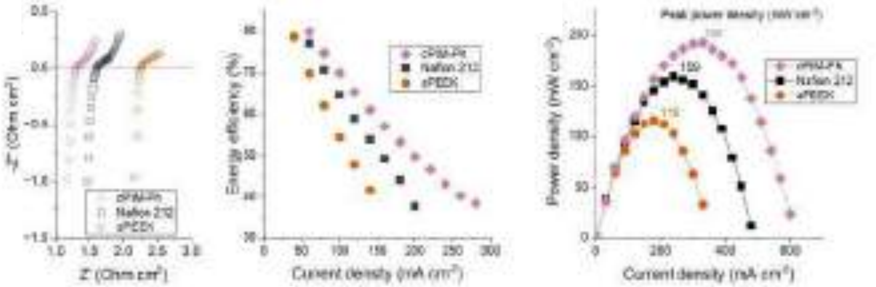
Source: Xie et al., Nat. Ener 2024

Selective Ion Transport Through Hydrated Micropores In Polymer Membranes

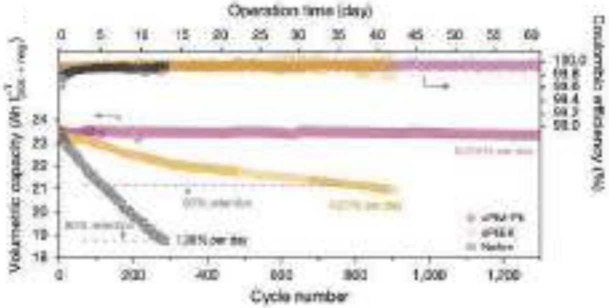
1. Among fabricated polymers, carboxylated polymers of intrinsic microporosity with phenyl groups (cPIM-Ph), with a pore gate size of 5.0 ± 0.3 Å, strike the best balance between high ion conductivity and low permeability to redox-active species.



2. cPIM-Ph outperforms Nafion 212 and sPEEK, offering superior energy efficiency across a wide range of current densities, higher peak power density, and lower interfacial resistance.



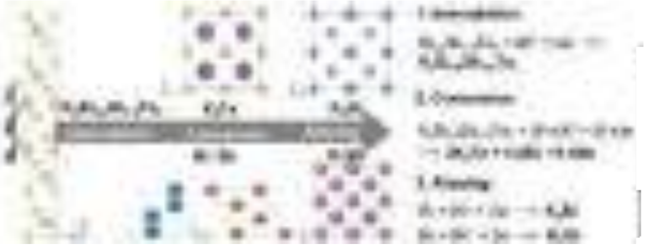
3. In AORBF applications, capacity delay was reduced to 0.014%/day, cycling for 1,000 hours.

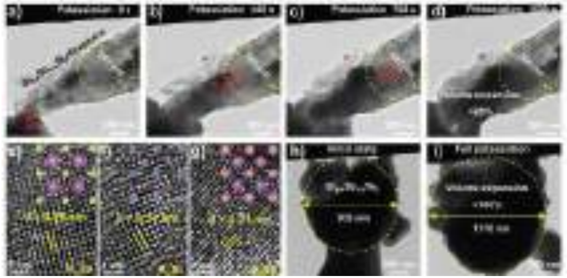


Excessive swelling in hydrated states compromises the selectivity and conductivity of separatory membranes in aqueous organic redox flow batteries (AORBF). Wang et al. address this by tuning the hydrophilicity and rigidity of pores in various fabricated polymers.

Source: Wang et al. Nature, 2024

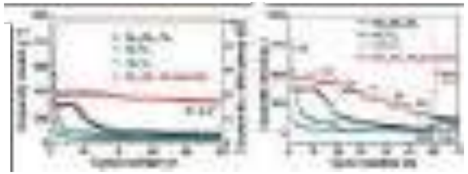
A Composite Anode Consisting Of A Layered Ternary $Bi_{0.4}Sb_{1.6}Te_3$ And Graphene Developed For Potassium-ion Battery





Synthesis: A composite anode was designed using a layered ternary $Bi_{0.4}Sb_{1.6}Te_3$ anchored on graphene layers, where Bi atoms act as a lattice softening agent on Sb.

Source: Adv. Mater. 2024, 36, 2313835

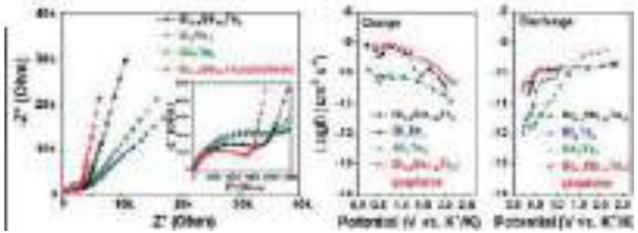


Cycling stability and rate capability

$Bi_{0.4}Sb_{1.6}Te_3$/graphene//KPB full cell

STRUCTURE-PERFORMANCE CORRELATION:

Due to its lattice arrangement and structure, $Bi_{0.4}Sb_{1.6}Te_3$/graphene exhibits a mitigated expansion of 28% during the potassiation/depotassiation process and demonstrates facile K^+ ion transfer kinetics, enabling a lifetime of 500 cycles at high rates.

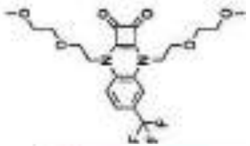


Both theoretical calculations and electrochemical examinations elucidate the K^+ migration pathways and indicate a reduction in energy barriers within $Bi_{0.4}Sb_{1.6}Te_3$/graphene.

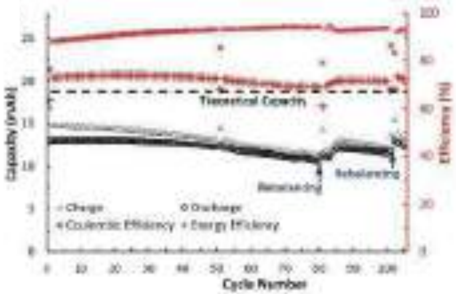
Development Of The Squaramide Scaffold For High Potential And Multielectron Catholytes For Use In Redox Flow Batteries

Synthesizing high-potential catholyte materials with low capacity fade and high solubility for nonaqueous organic redox flow battery (N-ORFB) applications remains a challenge. To address this, Tracy et al. report a new class of catholyte materials derived from squaric acid quinoxaline (SQX) and squaric acid amide (SQA) materials.

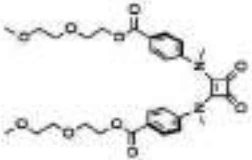
SQX-1



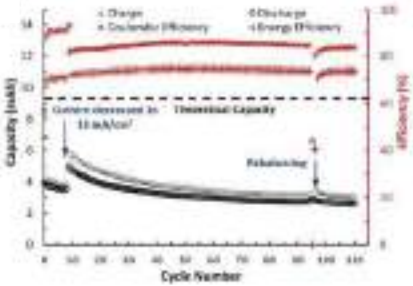
$E_{1/2}$ vs Fc/Fc$^+$: 0.51 V
% Fade/h: 0.23%
Cycles/time: 100 cycles/ 22.5 h
Max SOC: 88%



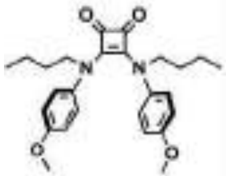
SQA-1



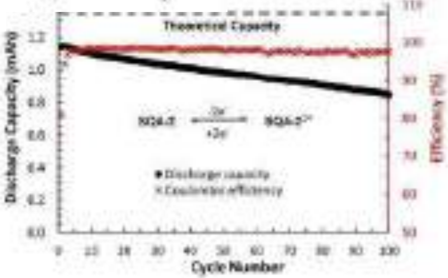
$E_{1/2}$ vs Fc/Fc$^+$: 0.81 V
% Fade/h: 0.36%
Cycles/time: 100 cycles/ 20.8 h
Max SOC: 81%



SQA-2



$E_{1/2}$ vs Fc/Fc$^+$: 0.48 V, 0.82 V
% Fade/h: 0.56%
Cycles/time: 100 cycles/ 40.2 h
Max SOC: 86%



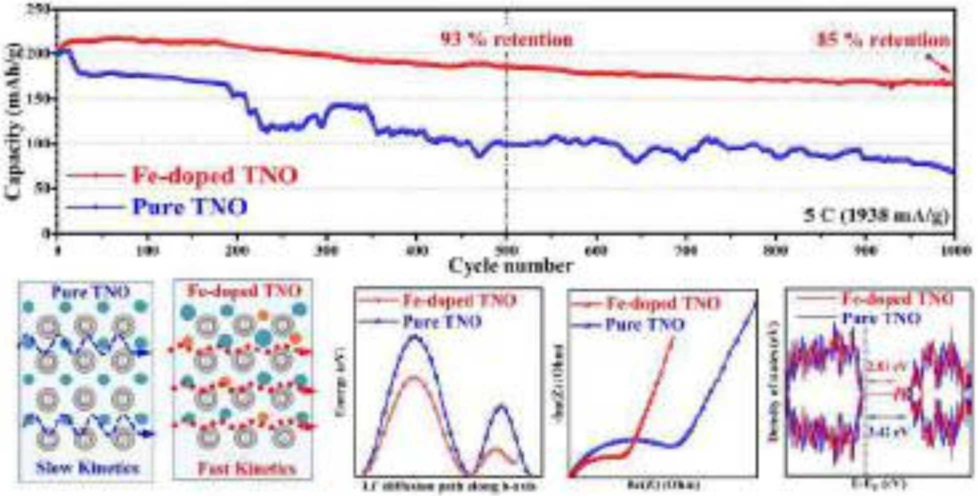
Note: SQX-1 and SQA-1 were tested in a flow batteries and SQA-2 in an H-cell set up.

Source: Tracy et al. Journal of American Chemistry, 2024

2 ACADEMIA

Substitutional Doping Of $TiNb_2O_7$ Anode For Extreme Fast Charging

Yu et al. report an ultra-fast charging anode with long-term cycling stability enabled by Fe substitution in single-crystal $TiNb_2O_7$ nanostructures. The underlying mechanism by which Fe substitution affects the material's electronic properties, ionic diffusion kinetics, and structural stability is revealed through combined theoretical modeling and experimental characterization. The optimal Fe^{3+}-doped TNO monocrystalline material ($Fe_{0.05}Ti_{0.95}Nb_2O_{6.975}$) provides a remarkable **charge capacity of 238 mAh/g under a 10 C (6 min charging time only)** extreme fast-charging protocol (coupled with 1 C discharge), and a capacity of 200 mAh/g at **5 C** with a cycling retention of **85% after 1000 cycles**. The calculations suggest that Fe^{3+} substitutional doping leads to a lowering of the band gap coupled with a reduction in the energy barrier for Li^+ diffusion.



An ultra-fast charging and long-cycling $TiNb_2O_7$ anode was synthesized via DFT-guided Fe^{3+} substitutional doping

Source: F. Yu, etal., "Fe3+-substitutional doping of nanostructured single-crystal TiNb2O7 for long-stable cycling of ultra-fast charging anodes", Nano Energy 133 (2025) 110494

Magnetic Fields Enhance Diffusion Kinetics And Extend Lifetime

Chen et al. report that magnetic fields can improve electrode kinetics, ionic transport, and lifetime of lithium-ion and sodium-ion cells.

Adding a NdFeB magnetic spacer within coin cells led to significantly more uniform formation cycles for NMC 622/Cu, as demonstrated by the voltage vs. time evolution in formation cycles in Figure 1 for the control group (a) and the magnetic group (b). The magnetic group also shows dramatically improved capacity in the 1st (c) and 2nd (d) cycles.

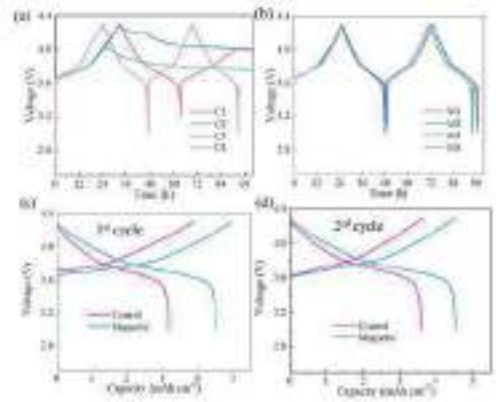


Figure 1

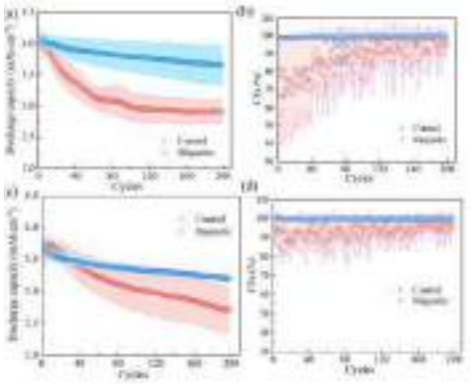


Figure 2

Furthermore, when cycling the NMC 622 - Graphite cell over a longer period of time (Figure 2), there is a clear improvement in capacity retention and coulombic efficiency when a magnet is applied to the cells. Cycling performance with/without the magnetic field for NMC622//graphite: discharge capacity (a) and Coulombic efficiency (b) of the two groups at a current density of 0.5 mA cm^{-2}, and discharge capacity (c) and Coulombic efficiency (d) of the two groups at a current density of 2 mA cm^{-2}.

Source : Chen et al, Journal of Power Sources Volume 602, May 2024, DOI:https://doi.org/10.1016/j.jpowsour.2024.234323

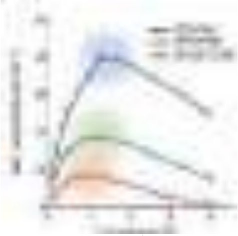
Combining Fluoroacetonitrile (FAN) With Lithium Bis(Fluorosulfonyl)Imide Salt To Enable Ultrafast Lithium-Ion Conduction

A novel ligand-channel mechanism is introduced, where the small-sized fluoroacetonitrile (FAN) solvent forms dual solvation sheaths around Li+ ions, resulting in fast Li⁺ transport channels and stable SEI.

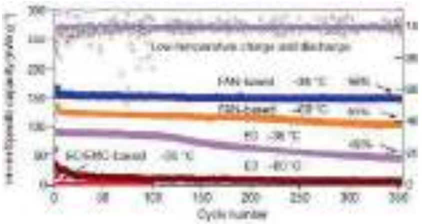
REPRESENTATIVE PERFORMANCE:

- At −80°C, a pouch cell delivered reversible capacities at 51% of its room-temperature capacity
- In high-rate charging tests (6C), the FAN-based electrolyte outperformed traditional electrolytes with a capacity retention of 80% over 3,000 cycles

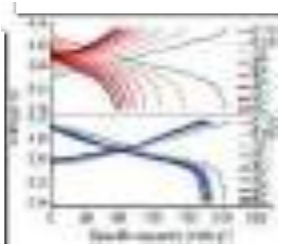
ULTRAHIGH IONIC CONDUCTIVITY

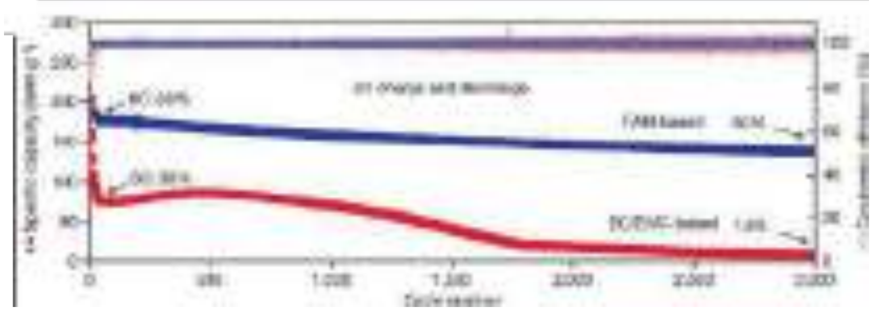


LOW TEMPERATURE PERFORMANCE



FAST CHARGING CAPABILITY





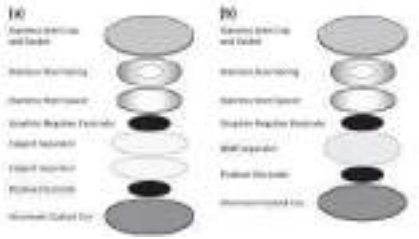
Source: Nature, 2024, 627(8002): 101-107 (https://www.nature.com/articles/s41586-024-07045-4)

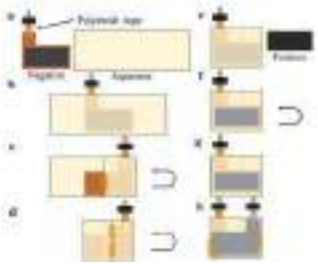
2 ACADEMIA

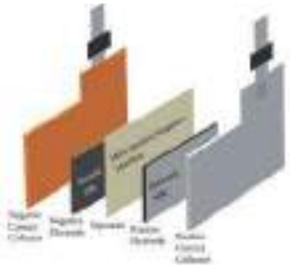
Coin Cells vs. Pouch Cells For Battery Research

	Coin Cell	Pouch Cell
Process	Electrodes and separator disk punching, then crimping of disks, spacer, and spring into coin cell. For statistical analysis, 3-10 cells/batch is recommended.	Electrode cutting and stacking, tab welding, pouch sealing, electrolyte injection, formation, degassing and resealing.
Electrode Alignment	Alignment of cathode and anode is important (ideally 100%). Murray et al. show that coin cells built with equal sized electrodes, a single layer of BMF separator, and a vacuum pen instead of tweezers are more repeatable than other coin cell configurations [2].	Major risk of misalignment due to many manual steps. Garayt et al. demonstrate that single layer pouch cells without anode overhang perform better [3].
Cell Pressure	Internal pressure comes from spring and stack thickness.	Fixture provides external pressure.
Electrolyte	Electrolyte amount needs to controlled (excess can lead to spilling during crimping).	Pouch cell drying and electrolyte wetting are more significant given larger surface area.

> "To achieve accurate and reliable data on new materials for batteries, repeatability, and quality of cell fabrication are critical to ensure reproducible findings" [1]



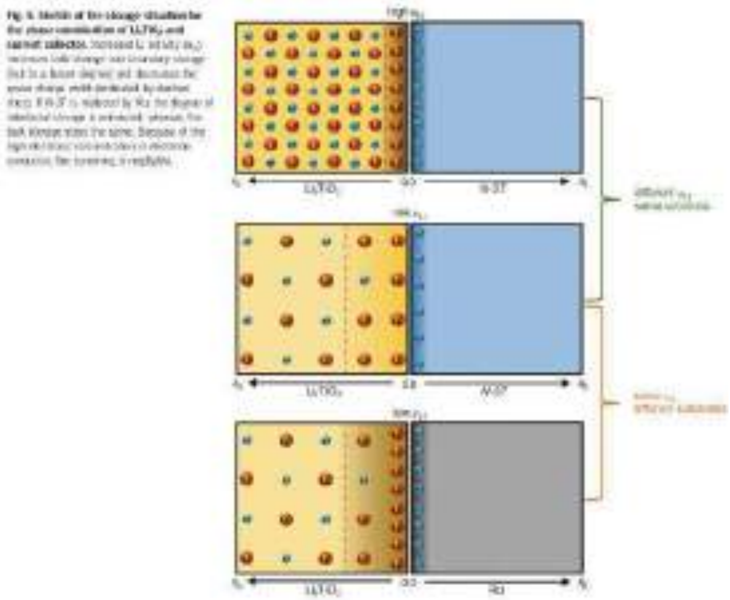




Source:
[1] Dai, F., Cai, M. Best practices in lithium battery cell preparation and evaluation. *Commun Mater* 3, 64 (2022). https://doi.org/10.1038/s43246-022-00286-8
[2] Vivian Murray et al 2019 J. Electrochem. Soc. 166 A329
[3] Matthew D. L. Garayt et al 2023 J. Electrochem. Soc. 170 080516

Unification Of Insertion And Supercapacitive Storage Concepts - Storage Profiles In Titania

This study bridges the gap between insertion-type batteries and supercapacitors, offering a unified approach for understanding the tradeoff between high energy density and rapid charge-discharge capabilities in energy storage.



Insertion storage in battery electrodes and supercapacitive storage are typically considered to be independent phenomena and thus are dealt with in separate scientific communities. Using tailored experiments on titanium oxide thin films of various thicknesses, Xiao et al. demonstrate the simultaneous occurrence of both processes.

Thick samples and/or high electronic (free) energies of the current collector favor the insertion mode, whereas thin samples and/or easy accommodation of excess electrons in the current collector favor the supercapacitive mode.

Source Xiao et al. Science 2024

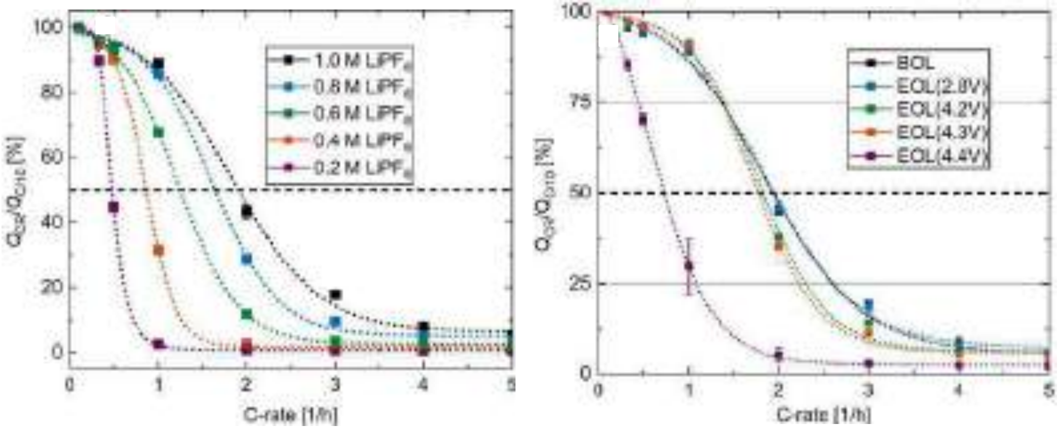
Depletion Of $LiPF_6$ During Calendar Aging Hinders Fast Charging Capability

Electrolyte oxidation at the positive electrode causes a decrease of $LiPF_6$ concentration in the electrolyte. This reduction of $LiPF_6$ concentration is not observable from slow-rate capacity checks or DC pulses, but severely impacts fast charging performance. Hartmann et al. use single-layer pouch cells to clearly demonstrate the effect of $LiPF_6$ concentration on low- and high-rate performance. This work highlights the critical need for oxidatively stable electrolytes to enable consistent fast-charging performance for EVs throughout their lifetime.

Artificial $LiPF_6$ variation in single-layer pouch cells (left) validates $LiPF_6$ depletion as the dominant cause of rate capability loss of calendar aged cells (right). $LiPF_6$ depletion in calendar aged cells was verified by ion chromatography and NMR, and reaction pathways for $LiPF_6$ detailed in the work.

(Left) Discharge rate capability at 25 °C in single-layer pouch cells with different electrolyte $LiPF_6$ concentrations. Electrodes were extracted from a beginning-of-life commercial high-nickel (85%) NMC and Graphite cell.

(Right) Discharge rate capability at 25 °C for single-layer pouch cells calendar aged at 45 °C under a constant voltage hold for 1 month.



Source: Hartmann et al, Journal of the Electrochemical Society 171 060506

Dynamic Cycling Enhances Battery Lifetime

Dynamic cycling improves battery lifetime compared to constant current cycling.

Calendar aging regardless of cycling is identified as the dominant factor in degradation.

Constant current cycling does not accurately represent real-world aging in EVs.

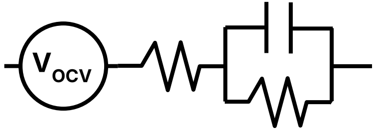
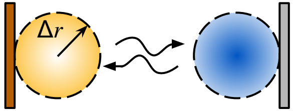
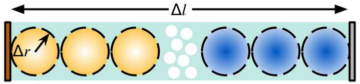
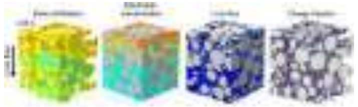
Battery chemistries and designs need to be evaluated using more realistic load profiles to better understand aging mechanisms at various levels (chemistry, material, and cell). Consequently, there may be opportunities for improving battery performance and longevity by revisiting aging mechanisms based on realistic cycling conditions.

Source: Nature Energy, 2024: 1-9 (https://www.nature.com/articles/s41560-024-01675-8)

2 ACADEMIA

Electrochemical And Reduced Order Modeling - Model Types And Applications

Simple but practical ⟷ *Insightful but complex*

	EQUIVALENT CIRCUIT MODEL (ECM)	SINGLE PARTICLE MODEL (SPM)	PSEUDO-2D MODEL (P2D)	MICROSTRUCTURALLY RESOLVED MODEL
				From [2]
DESCRIPTION	Resistors, capacitors, and other electrical circuit elements	Interfacial charge transfer, solid phase mass transport, and electrical resistance	Same as SPM but with multiple particle domains and electrolyte mass transport	Governing equations solved over a 3D reconstruction of an actual electrode
SPATIAL DIMENSIONS	None	1 (r: radial in particles)	2 (r: radial in particles, l: thickness in electrolyte)	3 dimensional in all phases
R&D APPLICATIONS	Module/pack/system design BMS development, EIS, cell degradation analysis	Module/pack/system design Charge protocol optimization BMS development	Cell and electrode design Module/pack/system design Charge protocol optimization BMS development	Nano-, micro-, or meso-scale design of particles and electrodes

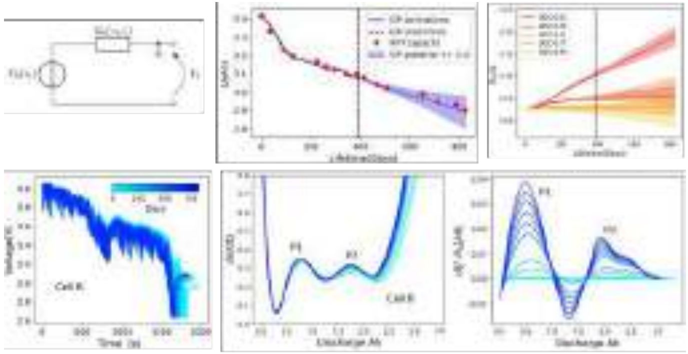
Sources: [1] "The evolution of battery modelling: From electrochemical to data-driven approaches"; [2] Lu et al. Nature Comm. (2020) 11 2079; [3] Battery modelling – Why 'physics-based' is not always best Other key references: Marquis et al 2019 J. Electrochem. Soc. 166 A3693; Plett and Trimboli, Battery Management Systems Vol. II and Vol. III; DeCaluwe et al 2018 J. Electrochem. Soc. 165 E637

Integrating AI Into Battery Performance Models For Accurate Extrapolation From Limited Data

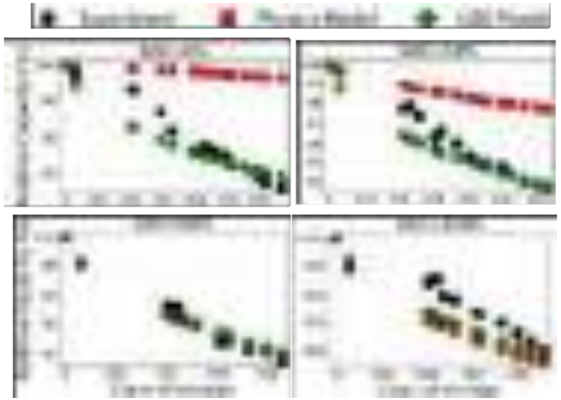
Identifying models that simultaneously predict battery performance (i.e., predicting battery response versus SOC, temperature, and C-rate) and degradation (change in performance over battery life) is hugely challenging. Empirical models of performance and lifetime, including equivalent circuit models, are easier to fit but extrapolate poorly to new operating conditions.

Physics-based models extrapolate well to new operating conditions, but it is extremely challenging to define differential equations that accurately describe the changes in battery performance observed during testing. Integrating AI into battery performance models mitigates this downside by learning from available testing data to compensate for model errors, and shifts lifetime forecasts from deterministic to probabilistic.

Zhou et al. [1] demonstrate augmenting of an extremely basic equivalent circuit model with Gaussian process learned states for performance and health parameters. The learned model is able to compensate for OCV changes over lifetime.



Kuzhiyila et al. [2] demonstrate using a Universal Differential Equation (UDE) to augment a physics-based model of SEI growth to enable the simple model to predict SEI growth for a NMC811|Gr-Si cell.



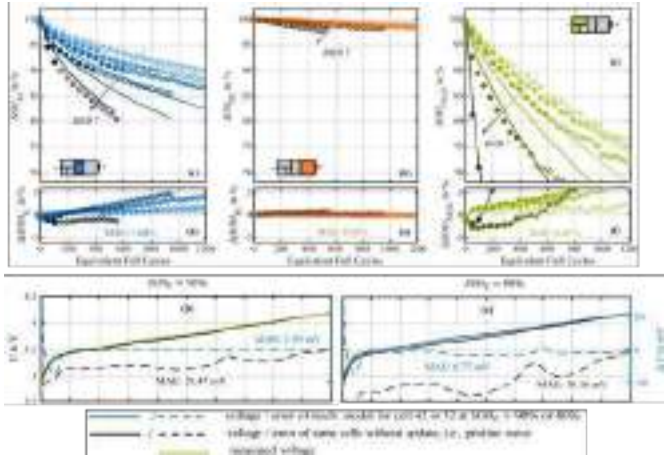
Source: [1] Zhou et al arXiv 2407.06639v2, [2] Ayyangatu Kuzhiyil et al SSRN 4948229

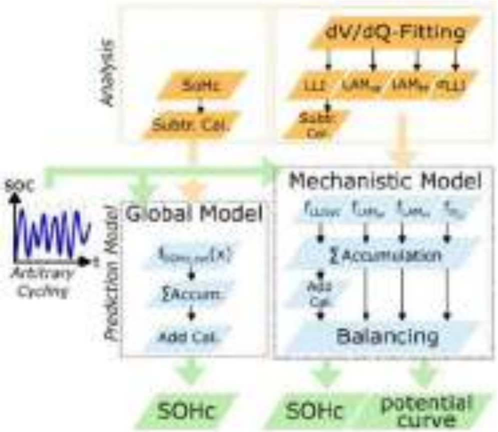
Estimating And Extrapolating Degradation Modes From Accelerated Aging Data To Estimate Both Capacity Fade And Open-Circuit-Voltage Curve Shifts Throughout Battery Lifetime

Degradation modes like loss of lithium inventory (LLI) and loss of active material in positive and negative electrodes (LAM_{PE}, LAM_{NE}) have been calculated using differential voltage or incremental capacity analysis for many years. Karger et al. [1] and Stadler et al. [2] demonstrate mapping of LLI, LAM, and capacity evolution across many operating conditions, enabling estimation of open-circuit-voltage curve shifts and capacity changes in dynamic real-world operation. This approach can be implemented using standard accelerated aging data and substantially improves predictive accuracy.

(Left) Karger et al. [1] fit empirical models for LLI and LAM evolution versus operating conditions, including temperature, depth-of-discharge, upper cut-off voltage, of an NCA|Gr-Si cell. The resulting model reduces estimation error of the shape of the open-circuit-voltage curve by up to 8x, versus predicting using only capacity.

(Right) Stadler et al. [2] summarize the workflow for identifying ('Analysis') and then extrapolating ('Prediction') capacity and OCV models.



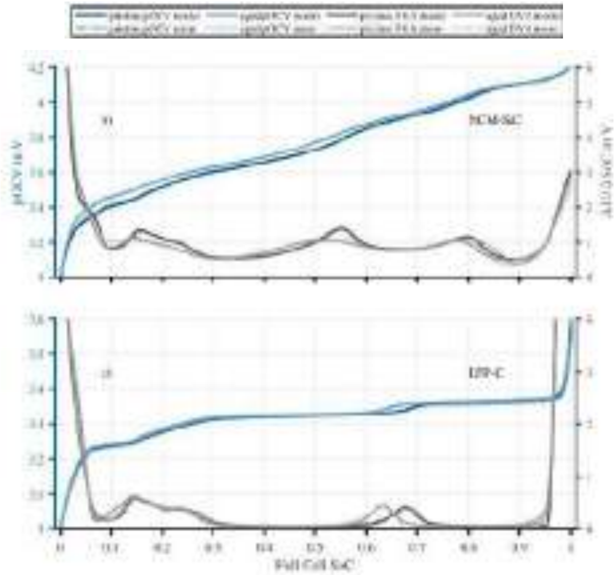


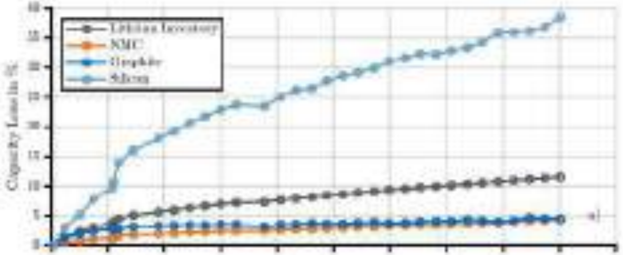
Source: [1] Karger et al Journal of Power Sources 593, [2] Stadler et al Batteries and Supercaps e202400211

Kirst et al. Estimate Half-Cell Electrode Potentials And Degradation Modes Throughout A Battery’s Lifetime, Enabling Non-Destructive Degradation Mode Analysis - No Half Cells!

Degradation mode analysis traditionally requires extracting samples of both negative and positive electrodes, and then carefully constructing half-cells versus metallic lithium to measure electrode potential curves, limiting degradation mode analysis to cases where destructive characterization of cells is possible.

Kirst et al. [1] develop a method to non-destructively estimate electrode potential curves as well as LLI and LAM throughout battery lifetime. This method enables performing degradation mode analysis on any cell without any destructive characterization of the electrode materials.

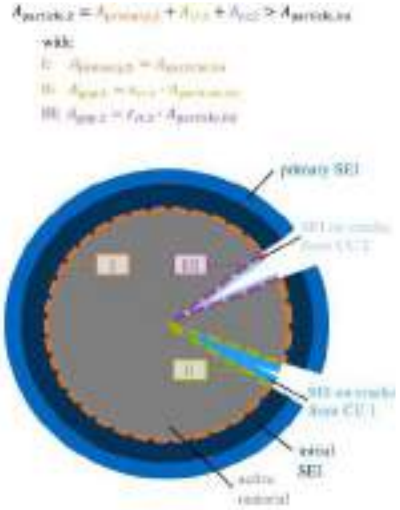


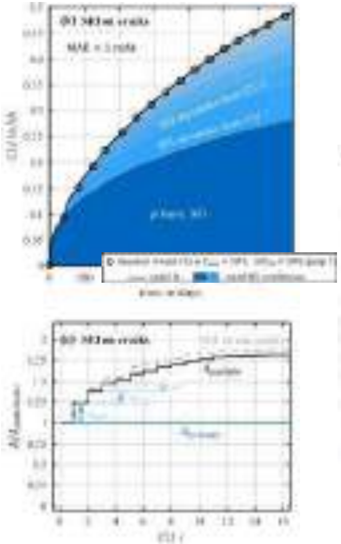


Source: Kirst et al Journal of Power Sources 602

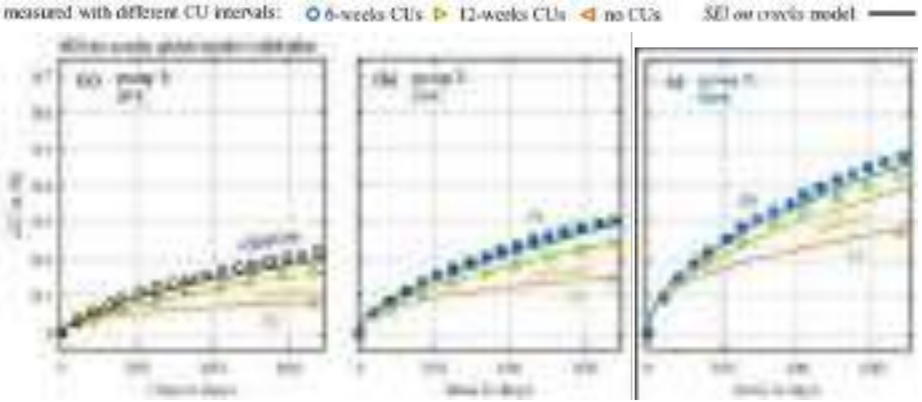
Modeling Particle vs. SEI Cracking In Lithium-Ion Battery Degradation

The impact of check-up cycle frequency on the calendar degradation rate is described using a single set of parameters for SEI growth by accounting for the effect of cracking. The developed models are publicly available in PyBaMM, enabling other researchers to immediately implement the model.





Physics-based models for SEI growth during calendar aging need to include both solid particle cracking and SEI cracking to be accurate.

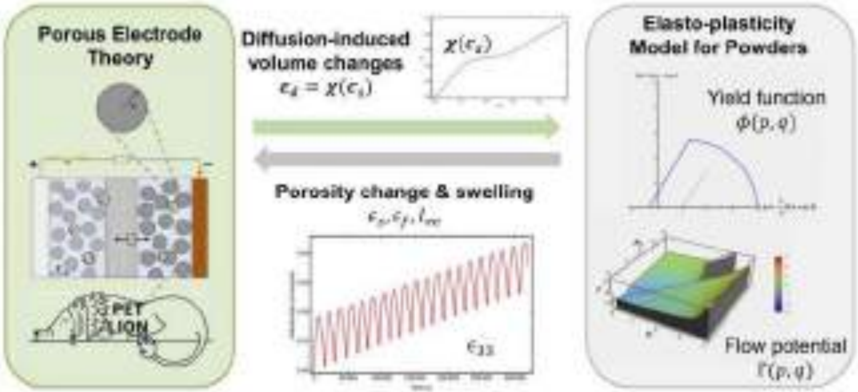


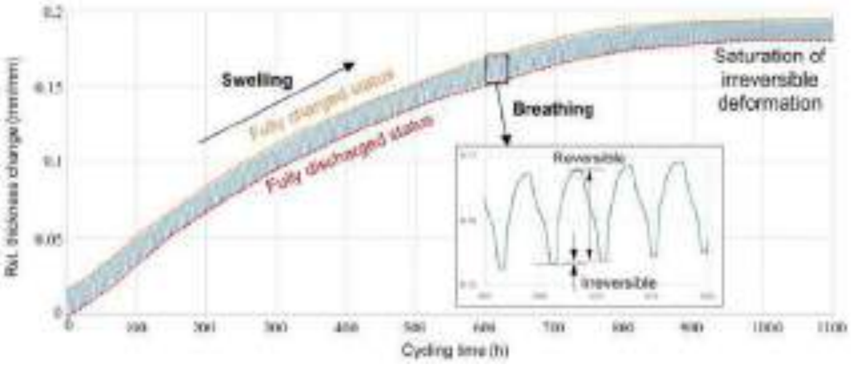
Source: Karger et al Journal of the Electrochemical Society 171]

Rapid Simulation Of Electro-Chemo-Mechanical Deformation Of LIB Based On Porous Electrode Theory

Researchers at MIT and Northeastern extend the porous electrode theory (PET) model to include **intercalation-induced mechanical changes**, capturing \reversible and irreversible changes in electrode thickness and porosity over cycling.

Porous Electrode Theory (PET) a.k.a Doyle-Fuller-Newman (DFN) + Drucker-Prager/Cap (DPC) model for mechanical deformation in powders = **Deformable PET**

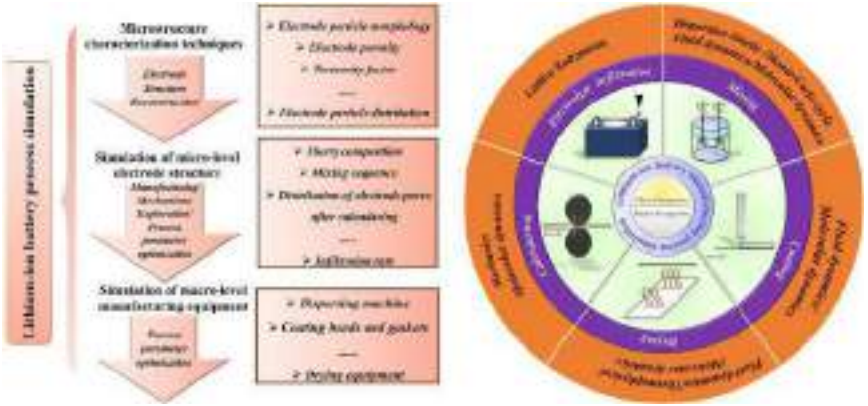




Source: Ipers, Pathak, Bazant, Zhu *et al.* *J. Electrochem. Soc.* 2024.

2 ACADEMIA

Optimizing Cell Manufacturing Using Simulations Saves Cost And Development Time



CHALLENGE & OUTLOOK

- Gaps: Better models are needed to tackle the complexities associated with scaling up from lab to production
- Future directions:
    - Artificial intelligence (AI) technology to enhance process predictability
    - Integration of multiscale models to improve simulation accuracy

KEY STEPS

MIXING

It is necessary to have a homogeneous slurry with controlled viscosity and particle dispersion. Parameters like temperature, mixing speed, and sequence impact quality.

COATING

Many processes, including slot-die coating, aim for uniform thickness and material distribution. Simulation models address parameters like coating speed and slurry rheology.

DRYING

Drying removes solvents and creates porous structures in the process. Optimizing drying conditions minimizes defects and ensures uniform binder distribution.

CALENDERING

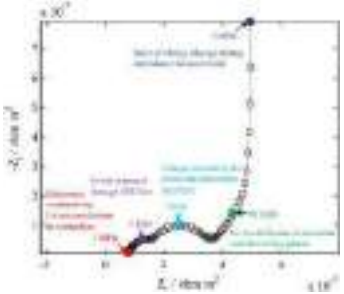
Electrodes are compacted to improve density and conductivity. Simulations can be used to optimize compaction parameters and prevent excessive pressure from damaging materials.

Source: J. Power Sources 610 (2024) 234717

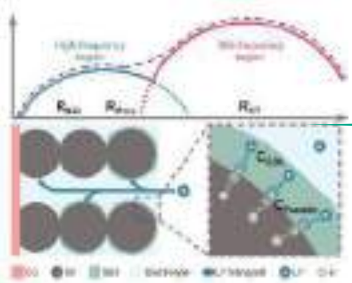
EIS Analysis Of Porous Electrodes Using A “Three-Electrode” System

Objectives: Re-interpret the EIS of porous electrodes by employing reference electrodes, analyzing frequency-dependent behaviors, and understanding their relationship to ion transport and capacitance.

POPULAR UNDERSTANDINGS

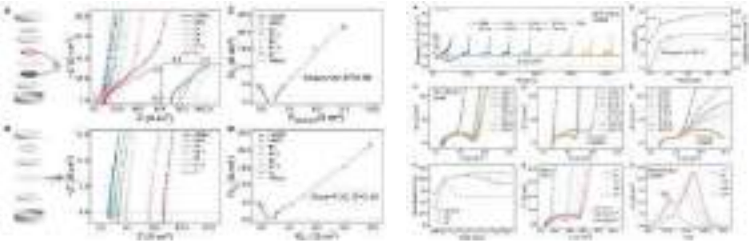


NEW UNDERSTANDINGS

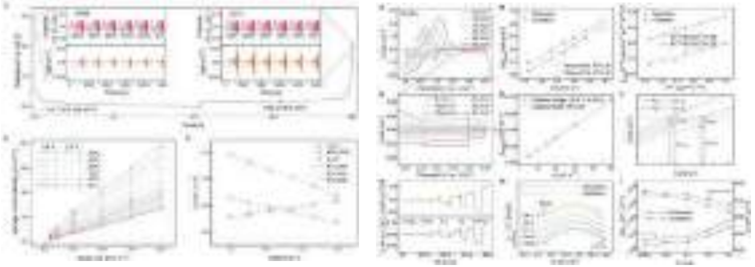


Experimental Configuration: three-electrode systems implemented in order to isolate working electrode responses

EIS Analysis: Nyquist plots and Distribution of Relaxation Times (DRT) to deconvolute overlapping processes



High-frequency: Dominated by ion transport within pore channels and solid electrolyte interphase (SEI)



Mid-frequency: influenced by pseudo-capacitance, distinct from electrical double layer (EDL) capacitance

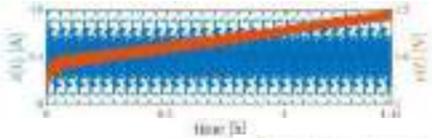
Source : Angew. Chem. Int. Ed. 2024, 63, e202406054 (doi.org/10.1002/anie.202406054), J. Electrochem. Soc., 162 (13) A7037-A7048 (2015)

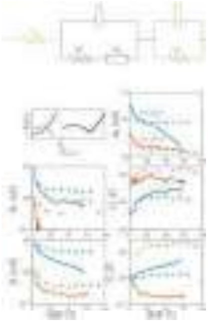
Mapping Battery Kinetics Using Minimal Charges And Discharges

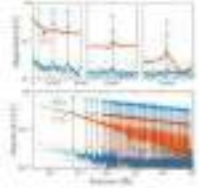
Mapping of battery kinetics using traditional methods, such as recording EIS at various SOCs and temperatures, takes an enormous amount of time, making these methods impractical for industrial R&D or cell production. Various new methods for mapping electrochemical kinetics from just one charge or discharge using AC [1] or both AC and DC signals [2] have been recently demonstrated, enabling highly detailed characterization of batteries for materials development or cell production and quality control purposes without requiring any additional test time.

NONSTATIONARY ODD RANDOM PHASE MULTISINE IMPEDANCE AND EQUIVALENT CIRCUIT MODELING

As well as being an exceptional review of nonlinear and nonstationary EIS, Hallemans et al [1] demonstrate kinetic mapping and equivalent circuit model fitting using a single charge or discharge.





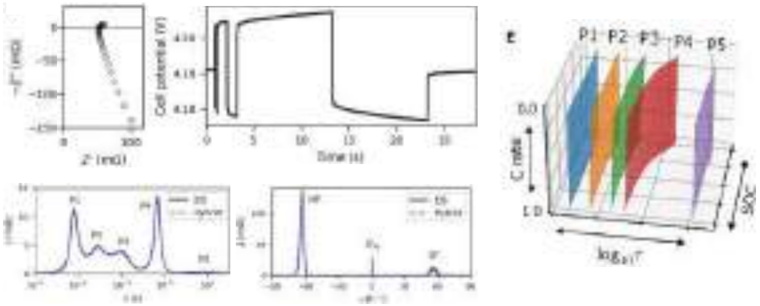


(Top) Voltage and current of nonstationary EIS over charge. (Right) Frequency dependent current and voltage spectra. Note at low frequency the increase in OCV due to charging obscuring the impedance response.

RAPID ELECTROCHEMICAL MAPPING VIA COUPLED AC+DC

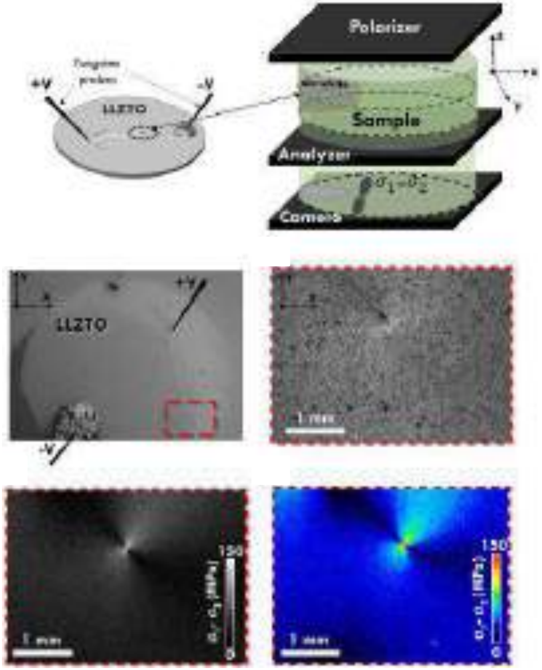
Huang et al. [2] report both a novel measurement technique and a new method for model agnostic EIS analysis (DRT+DOP), using Bayesian methods to estimate continuous surfaces across SOC and C-rate from discrete measurements.

EIS (9.4s) + rest (2s) + DC pulses (28.2s) = Hybrid (40s)



Source : [1] Hallemans et al, Electrochimica Acta 466 142939, [2] Huang et al, Joule 8 2049-2072
Further theory and application of nonlinear EIS: Ji and Schwartz, Journal of the Electrochemical Society, Part 1 and Part 2

Operando Photoelastic Stress Measurements In Solid Electrolytes



PROBING DENDRITE-INDUCED STRESSES BY PHOTOELASTIC MEASUREMENT

Measuring the stress fields within ceramic solid electrolytes can be challenging due to their brittle nature and the difficulty of obtaining a direct measurement.

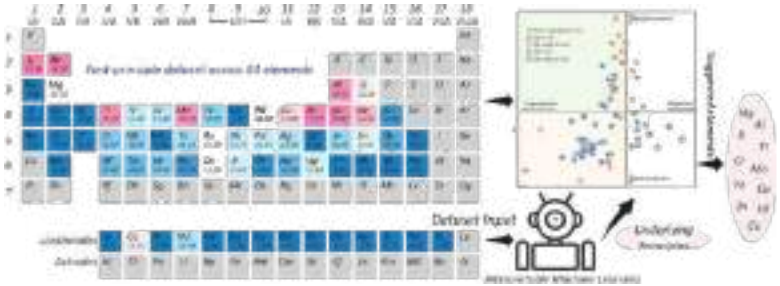
Researchers from Brown and MIT have developed a novel method for directly measuring the stress fields around dendrites in operando solid state batteries via photoelasticity. The measurement relies on measuring through-thickness-averaged retardance of polarized light passed through a translucent LLZTO disk. The change in retardance can be mapped to a change in stress states to generate an in operando map of the stress states at the dendrite tip.

This measurement mode allows for the first direct observation of the stresses around dendrites as they grow. The stress values measured match with those expected from dendrite propagation. Additional modeling was performed via Abaqus to account for outside effects such as Poisson contractions.

Photoelastic stress measurements allow for direct measurement of dendrite tip stress-fields in an *operando* solid state battery.

Source: Athanasiou, Fincher, Gilgenbach, Gao, Carter, Chiang, Sheldon

Grain Boundary Engineering In Nickel-Rich Cathode: A Combination Of High-Throughput First-Principles And An Interpretable Machine Learning Study



A synergistic approach combined high-throughput first-principles calculations and an interpretable machine learning (ML) framework to assess the feasibility of enhancing GBs through segregation-induced strengthening via doping.

The results suggested using dopant elements that can effectively anchor and reinforce GBs, such as Mg, Al, Si, Ti, Cr, Mn, Fe, Cu, Zn, Hf, and Ce, some of which have already been used successfully in experiments.

The machine learning (ML) workflow includes feature preparation, feature engineering, ML model selection, and model application (brief representations of each process on the top and bottom).

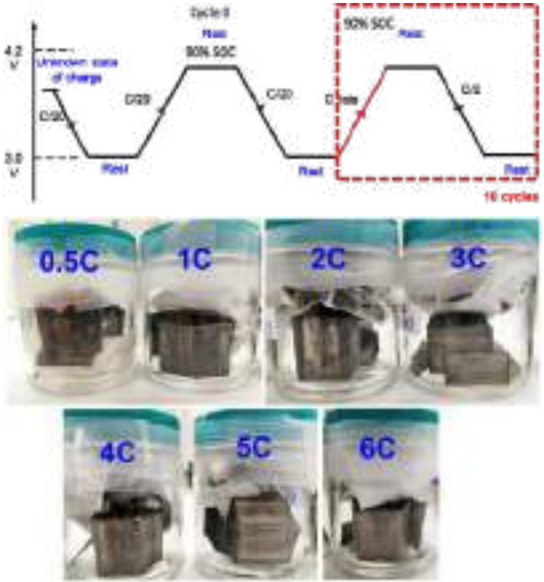
For GB strengthening through doping, elements should be placed at Ni sites and near the GB, rather than directly at the boundary itself. In additional, selecting a dopant with a lower period, higher bulk modulus, and smaller atomic radius increases the probability of GB strengthening.

Source: Acta Materialia 276 (2024) 120144 (DOI: 10.1016/j.actamat.2024.120144)

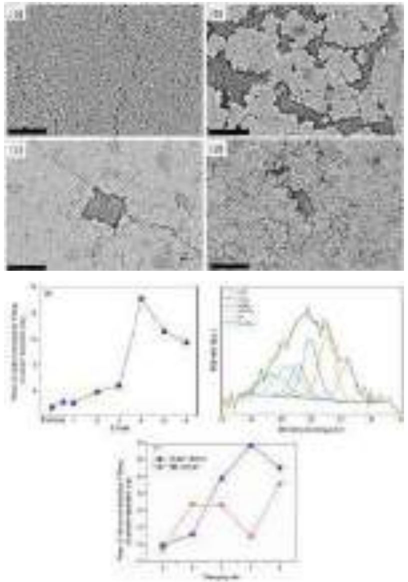
2 ACADEMIA

Materials Recovery From NMC Batteries With Water As The Sole Solvent

ELECTROCHEMICAL CONCENTRATION



WATER PURIFICATION



An environmentally benign recycling approach is reported for large-capacity nickel manganese cobalt (NMC) batteries through the electrochemical concentration of lithium on the anode and subsequent recovery using only water.

Cycling of the NMC pouch cells indicates the potential for maximum lithium recovery at a 5C charging rate. The anodes extracted from discharged and disassembled cells were submerged in deionized water, resulting in lithium dissolution and graphite recovery from the copper foils.

A maximum of 13 mg of lithium salts per 100 mg of the anode, copper current collector, and separator was obtained from NMC pouch cells cycled at a 4C charging rate. The lithium salts extracted from batteries cycled at low C-rates were richer in lithium carbonate, while the salts from batteries cycled at high C-rates were richer in lithium oxides and peroxides.

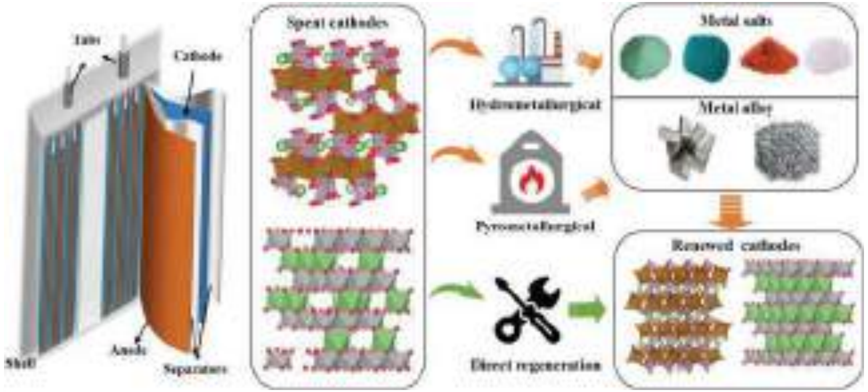
Source: Journal of Environ. Manage. 366 (2024) 121710 (https://doi.org/10.1016/j.jenvman.2024.121710)

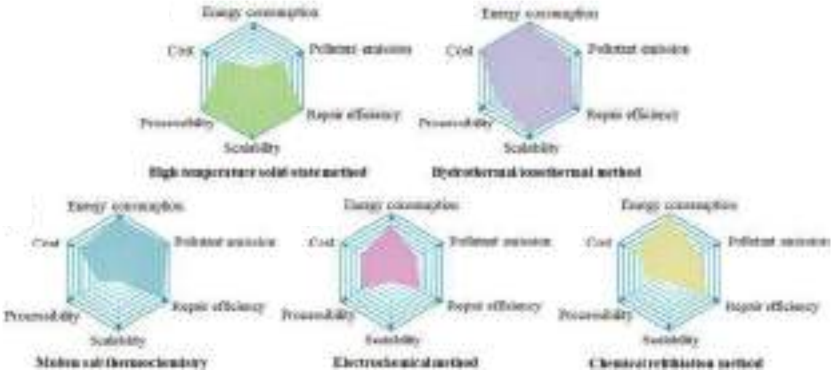
Direct Recycling Of LIBs

Conventional recycling processes are projected to have scalability but direct regeneration techniques are projected to yield higher economic return

- Valuable elements (Li, Ni, Co) are the focus of conventional recycling
- Hydro and pyrometallurgical routes → Focused on element extraction
- Direct regeneration routes → Focused on extraction of the cathode

- Five major routes of direct recycling for cathodes
- Hydrothermal route shows a lot of promise
- Hydrothermal process anneals spent cathode with external Li source



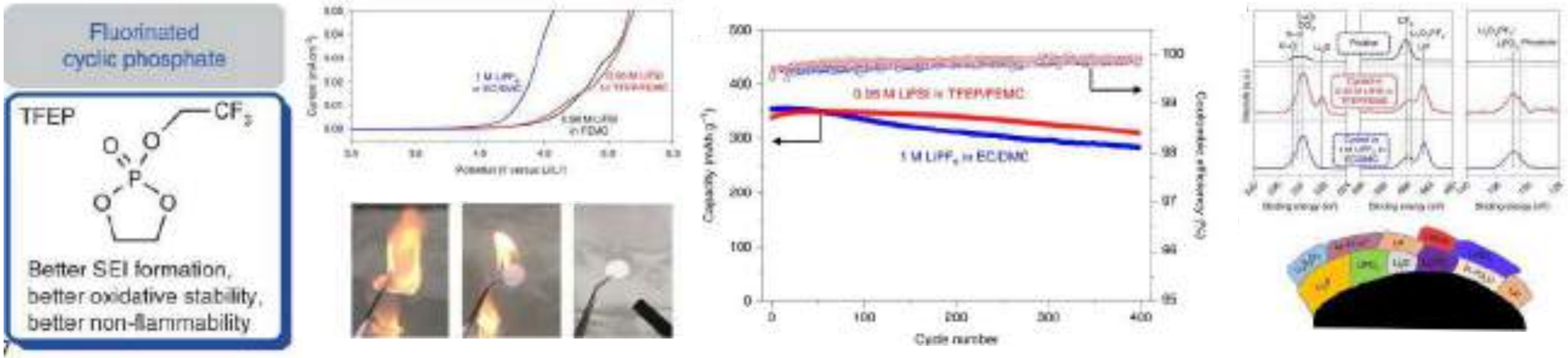


Source Lan, Y., Li, X., Zhou, G., Yao, W., Cheng, H., & Tang Y.

2 ACADEMIA

Cyclic Phosphate-Based Battery Electrolyte For Safe Operation

Inspired by the structures of ethylene carbonate (EC) and triethyl phosphate (TEP), Zheng et al. synthesized a fluorinated cyclic phosphate solvent, 2-(2,2,2-trifluoroethoxy)-1,3,2-dioxaphospholane 2-oxide (TFEP). Combining it with LiFSI salt and FEMC co-solvent, the electrolyte demonstrates **oxidative stability over 5.0 V versus Li as well as fire retarding ability** due to the functional phosphate group. Cycling of graphite | Li half cells at C/2 rate achieves a coulombic efficiency of 91.4% over 400 cycles. XPS results of SEI on graphite reveal the presence of Li_2O, LiF, Li_2CO_3, and various S-containing and N-containing inorganic species, which are believed to be critical for increasing interfacial stability and extending cycle life.



A new electrolyte formulation with TFEP is discovered that shows excellent non-flammability while enabling stable operation of graphite anodes (~0.1 V versus lithium) and high-voltage $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO) cathodes (~4.7 V versus lithium).

Source: Zheng, Q., Yamada, Y., Shang, R. *et al.* A cyclic phosphate-based battery electrolyte for high voltage and safe operation. *Nat Energy* 5, 291–298 (2020).

3 TALENT

VOLTA FOUNDATION

Key Findings and Trends in “Talent” from 2024

This year’s Talent section integrates insights from the Battery Talent Census—primary data collected from 1000+ battery professionals in the Volta Foundation community — H-1B job statistics and educational resources. Launched in October 2024, the Census uncovers workforce trends, identifies skill gaps, and explores demographic data. We received 1,081 responses in three months, representing 246 hours of participant input. Data in the forthcoming slides are excerpts from **Talent Census Report**, to be published in mid-2025.

ATTRACTING TALENT

DEMAND-SIDE

- “Manufacturing,” “Scale-up,” and “Process Engineering” are most in-demand skills
- Hiring managers place greater importance on non-technical skills than employees might typically expect.

SUPPLY-SIDE

- Students are optimistic about industry’s future but not their ability to land jobs
- Half of professionals are job hunting

RETAINING TALENT

COMPENSATION

- US leads in salary globally
- 2 in 3 people’s compensation do not match their expectations
- US salaries plateau early while European salaries grow with age

SENTIMENT

- Overall high satisfaction reported by those currently in the industry
- Higher positions linked to higher job satisfaction but worst work-life balance

DIVERSITY

- Gender disparity is evident at entry level and executive level
- Women are paid 30% less at the entry level yet think they are paid fairly and are no less satisfied at work

RETENTION

- Workers cite “challenge,” “learning,” and “growth” as top reasons for joining a company
- Yet, when asked for reasons for changing companies, “salary” becomes the top reason

3 TALENT

Overview of Volta Foundation's Workforce and Talent Development Efforts

INITIATIVES

VF | BATTERY CAREERS

- The **world's largest virtual Career Fair** for the battery industry.
- 22 companies, 2000+ job candidates registered in 2024.
- **April 3 and October 2, 2025.**

VF | BATTERY WORKFORCE

- Promotes the **development and implementation of initiatives** that enhance the battery workforce.
- Volta will **assemble leaders from industry, government, and academia** to address industry-specific challenges, promote professional development in green collar jobs, and ensure that the industry attracts, retains, and develops top talent.
- Volta will **publish a Battery Workforce Report**, and strengthen partnerships with leading workforce organizations, such as the Battery Workforce Challenge.

RESEARCH & FOUNDATIONS

BATTERY TALENT CENSUS

- Launched in October 2024 with the goal of **collecting actionable data on workforce trends, compensation, diversity, and talent gaps** within the industry.
- **Gather primary data to** uncover gaps between talent supply and talent demand.
- Data in the forthcoming slides are excerpts from **Talent Census Report**, to be published in mid-2025.

3 TALENT

2024 Battery Talent Census

OBJECTIVES

SKILLS GAPS

Identify skill gaps and emerging training needs

COMPENSATION TRENDS

Gain insights into pay, bonuses, benefits, across different levels, roles, and regions

WORKPLACE SENTIMENT

Quantify workplace happiness across different levels, roles, and regions

STUDENT PERSPECTIVE

Learn the perspective of the next generation entering the workforce

IMPACT

SUPPORT WORKFORCE POLICY

Guide policy strategies for workforce development and education

PROMOTE DIVERSITY & INCLUSION

Empower initiatives fostering inclusive hiring and workplaces

The following slides contain excerpts from the

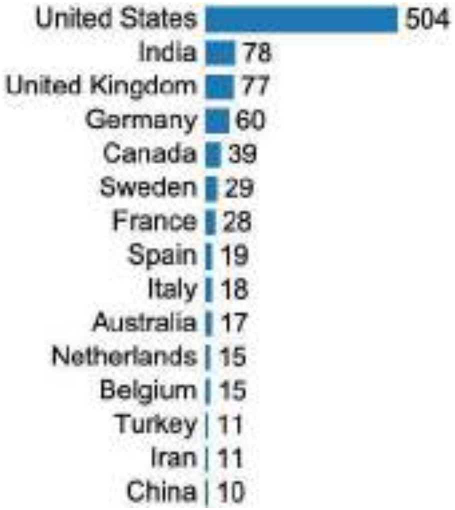
BATTERY TALENT CENSUS REPORT

which will be published in mid-2025.

Who Took The Census (1/5)?

We received **1,081 responses** over a three-month period between Oct 3 and Dec 31, 2025. Respondents spent a total of **246 hours** filling out the Census questions.

47% of responses were from the U.S. The remaining were mainly from European countries (UK, Germany, Sweden, France), India, and Canada.



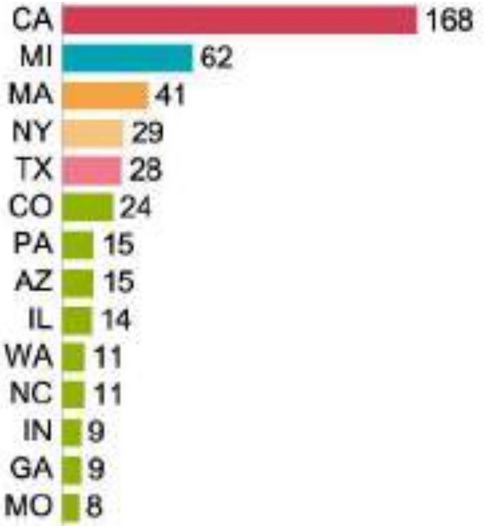
This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Who Took The Census (2/5)?

Within the U.S., we received **504 unique responses** spanning **364 unique ZIP codes.**

Size of markers indicate number of respondents within a given ZIP code.

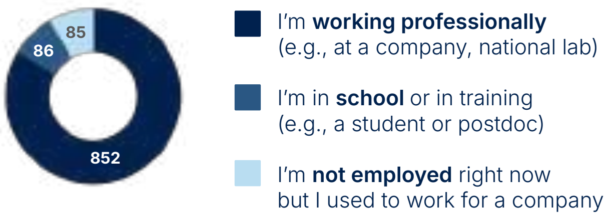
Within the U.S., **California and Michigan** had the most responses, followed by Massachusetts, New York, Texas, and Colorado.



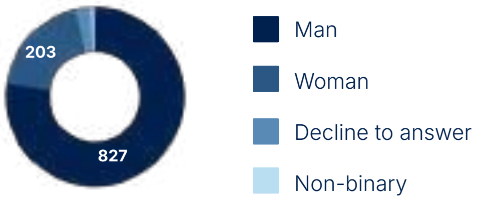
This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Who Took The Census (3/5)?

"WHAT IS YOUR CURRENT EMPLOYMENT SITUATION?"

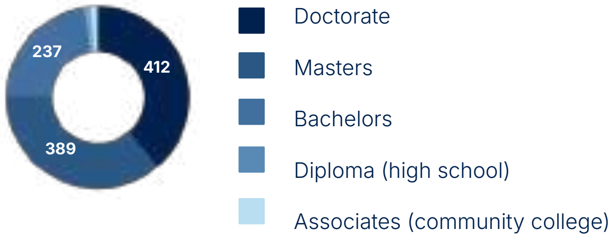


"TO WHICH GENDER DO YOU MOST IDENTIFY WITH?"



"WHAT IS YOUR CITIZENSHIP STATUS?"

"WHAT IS YOUR HIGHEST LEVEL OF EDUCATION?"



80% of respondents currently work in the industry
(852 of 1063)

8% were students
(86 of 1063)

Respondents were highly educated
75% had at least a master's degree; 39% held doctoral degrees.

20% were women
(203 of 1068)

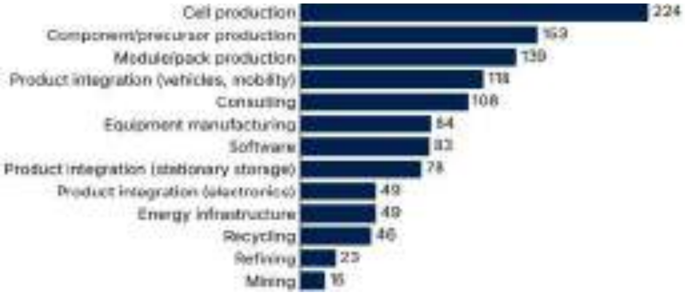
In the U.S., **3.4% of workers held H1-B visas**
(29 of 852)

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

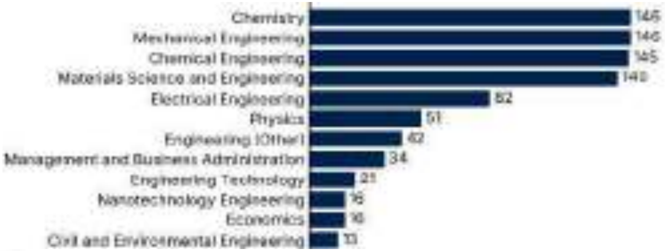
Who Took The Census (4/5)?

For those currently in industry, we asked if they could **fill out an additional 37 questions about their company, role, compensation,** etc. 75% of respondents (640 of 852) agreed. These respondents generally had **technical backgrounds,** worked for **companies across the value chain,** and included **individual contributors and managers at all levels.**

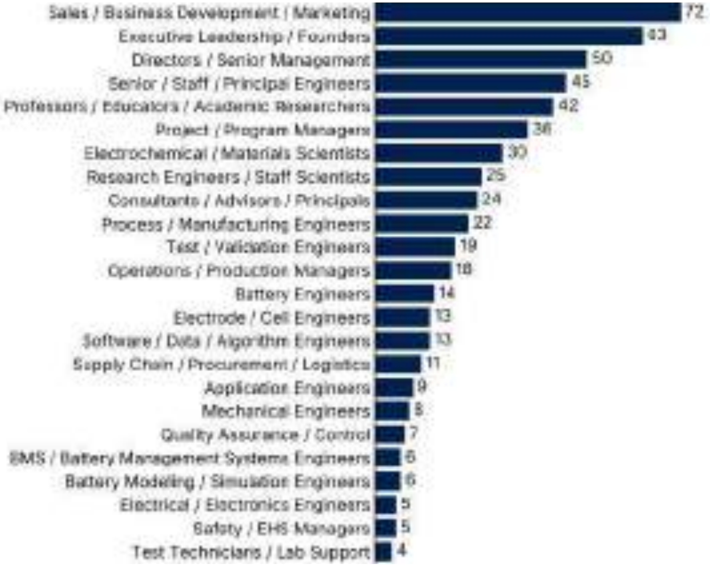
"WHERE [IS YOUR COMPANY ON THE] VALUE CHAIN?"



"WHAT DID YOU STUDY IN SCHOOL?"



"WHAT IS YOUR CURRENT JOB TITLE?"



This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Who Took The Census (5/5)?

For those currently in industry, we asked if they could **fill out an additional 37 questions about their company, role, compensation,** etc. 75% of respondents (640 of 852) agreed. These respondents generally had **technical backgrounds,** worked for **companies across the value chain,** and included **individual contributors and managers at all levels.**

ROWS: "HOW WOULD YOU CLASSIFY YOUR COMPANY'S STAGE OF DEVELOPMENT?"
COLUMNS: "WHAT IS YOUR CURRENT LEVEL?"

	ENTRY	DEVELOPING	CAREER	SENIOR	EXPERT	MANAGER	DIRECTOR/VP	EXECUTIVE	*TOTAL*
Pre-startup	1	4	2	2	4	5	1	1	***20***
Startup	9	20	36	54	26	28	23	21	***220***
Scale-up	4	18	32	47	30	20	19	16	***186***
Mid-sized	2	9	12	11	11	15	8	3	***72***
Established	11	17	33	60	29	31	15	4	***202***
TOTAL	**27**	**71**	**116**	**176**	**101**	**99**	**66**	**45**	**937**

Table shows number of respondents within each category. Since different companies use different leveling rubrics, we provided respondents with a standard leveling rubric.

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

“In Your Opinion, What Are The Top Three Skills Most In Demand In The Battery Industry?”

Respondents were asked to provide up to three answers.

They were **allowed to put *anything* they deemed relevant**; we did not pre-define the skill categories.

THEIR RESPONSE:

Scale up, the ability to keep up with and foresee research/industry trends and directions, language abilities (Chinese, Korean, Japanese) to learn from the bigger battery markets Design for Reliability,   Test Agile, Innovative, Communication design, manufacturing, and testing Electrochemistry, Process, Data Analysis Scientific Observation, Data Analysis, ability to contribute to a team Data analysis; research and experimentation; presentation skills data science, manufacturing, pouch cells Technical Knowledge; Software; Entrepreneurship BMS, Safety, and process engineer [cell knowledge] Electrical knowledge / organisational skills / poise Manufacturing scale-up Knowledge, Research, Analytical Power MATLAB optimisation 1; COMSOL 2; Skill 1 - Cell Engineering (R&D and Mature Products), Skill 2 - Product Pricing/Cost Engineering, Skill 3 - Strategic Partnership software/programming battery chemistry design testing Material Synthesis, Material Characterization, Data Analysis, Long term vision and planning skills. Product knowledge. People communication Leadership; Project Planning; Manufacturing Basics failure analysis; techno-economic analysis; codes/standards electrochemistry, adaptability, perserverance Cell cycling experience, electrode fabrication experience, SEM hands-on experience building cells; materials research for dry processes; interdisciplinary collaboration Battery Health Estimation Algorithm, Battery Field Systems Engineering, Battery Cost and Estimation Expertise Design process test Battery code and standards, Battery products strategy and management,Battery system design and operation, Communications; integration instead of verticality Technical background, customer relationship, industry understanding Data analysis, statistics, communication Creativity; problem solving; eye for detail Communication, presentation, abstraction Analysis, engineering, business skills small molecule development for liquid electrolyte 1. BMS, 2. Battery pack scale performance and safety concept, 3. Failure analysis and feedback to design/process/application intrapersonal skills, technical knowledge, grid knowledge Process Engineering, Equipment Engineering and scale up for production Skilled battery techs Supply Chain, Embedded Systems, Unit Economics Unk Cell design; Cell manufacturing; Pack design Manufacturing Experience, Industrial Knowledge, Quality Engineering "Analytics; Physics; Engineering" Systems, modeling and tools, supply chain cell fabrication Skill 1: Good knowledge about science of batteries, Skill 2: Familiarity with new approaches such as AI and Machine Learning, Skill 3: Networking and communication skills Cell design, cell manufacturing process ramp-up, battery simulation and analytics Strong manufacturing knowledge, financial planning in the industry, end consumer market knowledge troubleshooting, learning, communication Modelling; Testing; Algorithms Electrochemical analysis, resilience, adaptability rawmaterials value chain, long term safety and circular econmy Creativity materials science, electrochemistry, eagerness/ability to learn Market Knowledge, Product Knowledge on New Technologies, Strong Work Ethic Fundamental electrochemistry knowledge, Material characterization, Data analysis and interpretation Design of experiment (DoE); communication; leadership Skill 1: Application/Integration Engineering. Skill 2: Systems Engineering. Skill 3: Marketing Networking; fundraising; risk assessment analytics; chemistry; negotiation Electrochemistry. Data Analysis. Data Presentation Realistic project planning, cell working principle knowledge, customer management Understanding of interrelationships between processes; Understanding of Deviation; QMS Critical Mineral commercial expertise Manufacturing, cell and testin I think that polymer science fundamentals are under appreciated in the battery space Adaptability, Resilience, Creativity Patience; dexterity; statistical analysis Cell design, Chemistry, Manufacturing and automation engineering. Strategic Growth, B2B Lead Gen, D2C Growth Marketing Technical, Problem solving and Management 1. Electrochemistry, 2. Cathode materials synthesis 3. Metallurgy electrochemical analysis; data analysis; logical thinking Test bench, integration, pack-level assembly AI/ML, Electrochemical Expertise, Thermal Management Manufacturing; AI optimization; Safety testing Battery modelling, testing and maintenance, battery safety cross-functional work, bsuiness/tech junction Sales "electrochemistry fundamentals; AI methods; interdiscipinarys" Scientist, AI/ML, Supply Chain Gigafactory manufacturing experience; knowing how to work with Asian companies (technically, culturally, etc); multidisciplinary engineering (knowing how to speak the language of other parts of batteries) System engineering basics Innovation, comperhensive understanding, contineous seeking for additional knowledge cell modeling ; political maneuvering; networking Data evaluation/statistics skills; genuine people skills; entrepeneurial mindset Creative engineering, clear communication and expectations, multidisciplinary thinker Design, Thermal, Packaging Battery safety experience -- understanding how to minimize potential failures/TR. Battery Management Systems, Battery Modeling, Battery Charging, Battery Thermal Controls Process scale-up, Electrolyte development, Electrochemical data analysis Engineering supply chain project development Battery manufacturing; go-to-market experience; thermal management Technical expertise; basic chemistry knowledge; presentation and communication skills Manufacturing excellence; supply chain logistics management; safety Material Characterization; Programming; Hardware Knowledge sales, energy market architecture, public speaking Product development, business development, sales & marketing Complex problem solving, manage preassure, innovation 1, 2, 3 Marketing, Manufacturability, Leadership Skill 1 Prior knowledge of industry Skill 2 ability to formulate effective procedures skill 3 flexibility EIS, design of experiment, pouch cell build experience Skill 1 - Problem solving skills Subject Matter Expertise, Market Research, Commercial Negotiations Faire protection engineering; maintenance; manufacturing technician Software skills, commercial/technical expertise, systems based approaches Skill 1: basic chemistry and electrochemistry knowledge skill2:mechanical design; skill3:clear communication Material Development Battery manufacturing skills, capabilities to quickly build prototype, simulation skills Battery energy storage system; electrical engineering Materials knowledge; research experience; understanding of basic science Chemistry Materials knowledge, python, leadership 1) Basic understanding of a battery 2) Battery manufacturing 3)Battery failures Mandarin; Presentation skills; Metrology project management; critical thinking; communication Experience with deposition techniques; Experience with batteries; Experience with imaging techniques Characterizstion;testing;syntheshis Electrochemistry, mechanical and electrical engineering Work prioritization and planning, advanced problem solving methods, core engineering methods (GD&T, and other traditional tools) Manufacturing experience; failure analysis; pack design battery management systems, Testing, validation Cell Production; Cell Design; Simulation Manufacturing; Materials Science; Data Analytics Process Engineering; Product; Controls & Automation People leadership, chemistry, data analysis Skill 1 - ability to think independently to solve problems that cut across the academic areas of study, Skill 2 - abilit electrical engineering, data science, manufacturing Coding; Electrochemistry knowledge Advanced manufacturing; supply chain; cell development Data analysis, presentation, coding strong team work skills and intercultural competence, know how in data science, frustration tolerance :-) software engineering (as opposed to data science) strategy, networking, leadership creativity, knowledge, methodology Materials Science Knowledge, Engineering, cathode fabrication Process development; statistics; electrochemistry Electrochemistry, Materials Science, Critical Thinking data analysis Manufacturing manufacturing; software; reliability Materials Science, electrochemistry, process engineering Cell quality, supplier negotiation, battery SOC Manufacturing, Electrochemistry, Team building "Computer science; Electronics; Modelling" The ability to improve the process; software automation [Critical thinking], [Problem solving], [Team work] [multilingualism 1] [product design 2] [marketing 3] leadership, honesty, economics Motivation, Innovation, AI Coordinated BMS / cell strategy. Battery case manufacturing. Battery case cover materials. ISO26262, FUSA, Thermal Runaway perserverance, adaptablility, attention to detail integration into bigger picture, understanding numbers Materials characterization skills; bench to pilot scale-up ability; processing/properties understanding Manufacturing experience; Understanding technology from lab to product; understanding market segments Electrochemistry data analysis/data science; manufacturing/scale-up knowledge; good communication of scientific findings [cell chemistry], [electronics],[systems engineering] Control engineer, process engineer, manufacturing engineer Systems level thinking; battery data understanding; voice of customer Electrochemistry and battery chemistry; BMS; Modeling [Full Battery Chemistry and Cell Design understanding and Experience],[High Volume Manufacturing Process and Equipment Experience], [Accurate Cost and Time Planning for R&D to Pilot to Manufacturing] Open minded, technical expert, negotiator Leadership Communication Empathy Curiosity; Perseverance; Teamwork Data analysis, coding, Critical thinking; data visualisation and analysis; depth and breadth together Programming; electrochemistry; mechanical design Skill1: Firmware Controls development; Skill2: Battery Testing; Skll3: Cell Testing; Skill4: Test Pipeline Knowledge; Skill4: Charging Test Knowledge data analysis; quality control; hands-on know-how Electrochemistry fundamentals [Process Engineering]; [Chemical Engineering]; [Electrode Fabrication] Skill 1: systems approach with scientific methodologies; skill 2: both chemistry and engineering process R&D; skill 3: safety testing and mitigation analysis Material Synthesis; Cell design; cell modeling Mass production related skills such as the knowledge to setup the production line, the knowledge of how to improve the yield in the short time frame and how to find the best match between the equipment and raw materials Simulations; Electrical Circuits; Test Plan Design Lean Manufacturing for Cell Production; Software engineering, product marketing, market optimization experts Product management [Battery modelling] [project management] [market knowledge] "Fundamental knowledge of the electrochemical kinetics", "Experience", "Global economic status" Project management; operations experience (in commercial sized manufacturing plant, scale up experience communication, power electronic knowledge, compliance knowledge Problem solving; communication; experience [technical knowledge beyond a very specialized field]; [market knowledge beyond cherry-picked studies and forecasts] I can make cathodes and anode materials for Li,]Na, and Zinc-ion batteries Reactor / Scale-up engineers, equipment engineers interdisciplinary (mechanical + electrical skills), high voltage design knowledge, excellent general design skills Soft Skills Problem solving; collaboration, manufacturing Data science, process engineering, failure analysis deep work, experimental design, reasoning chemistry, electrochemistry and fabrication (1) hands-on experience in battery manufacturing at the MP scale (2) Difference between testing for R&D vs production, (3) how to balance between "science experiment" vs "something the customer cares about" Mechanical design "Communication; collaboration;team work;AI") data analysis, electrochemistry, systems engineering Process optimization, system engineer, manufacturing engineer Battery Integration, Practical Thinking, Regeneration of electric power 1. PLC programming ,in depth knowledge of battery management system and quick decision JMP (data analysis, experimental design), CAD, project management Electrolyte development; Simulation and battery design Certification; Specification; Procurement SOH prediction; thermal management; BMS Materials science expertise, battery management system (BMS), and data analysis Manufacturing, Data science, Electrochemistry knowledge flexibility in thinking; strategic action; endurance Manufacturing, Manufacturing, Manufacturing Technical understanding, result oriented, drive Cell knowledge, battery project experience with big OEM, supply chain foresight; adaptibility, resilience Scale up engineering Innovation, project management, teamwork [manufacturing]; [design-to-cost]; [system integration] [Ability to forecast price trends],[Technology trends] data science knowledge; AI based algorithm capability; battery design expertise Thermodynamics, coding, guesstimating Skill 1; Battery material design for the high storage capacity electro-thermal simulation, soild-solid interfacial chemistry, solid polymer electrolyte Leading a technical team with emotional intelligence,, failure analysis standardized in residential battery industry(honesty versus marketing, could help clear up issues to standardize, sexual harassment trainings for technical managers Technology transfer; Cell reliability analysis; Process engineering electrochemisty, process engineering, BMS [Critical thinking]; [Market-driven thinking]; [Strategic analytical capability] Innovation; Business Development; Cross-cultural Understanding Predicting battery deterioration and failure Artificial intelligence; Analytical Development; Team Management System Integration characterization, manufacturing, recycling Process Engineering, Product Management, Technology Development Flexibility, Knowledge, Qualification "Clear communication with chinese suppliers";"understanding ageing of batteries";"system thinking for fast charging" Explaining complex things in a simple way; data handling and manipulation; production process knowledge data analysis, electrical engineering, programming Maintenance engineers, skilled production operators, skilled process engineers Electrochemistry; knowledge about real batteries; programming for data processing Understanding of manufacturing and data visualization Electrical/power electronics systems development, next generation modeling (I.e beyond porous continuum modeling), leadership/organizational skills Adaptability; polyvalence Cell Modeling; High Power Electrical Engineering; Mechanical Engineering Problem solving, communication Technical know how; flexibility; market knowledge Automation and AI integration into the manufacturing process; handling hazardous materials and chemical engineering Pilot line operation and scaling; testing protocol; customer development Creativity; interdisciplinarity; communicativeness Technical project/program management; Business acumen Coding; modelling; cell assembly Pragmatism; cost analysis; Chinese language Technical writing; Engineering economic analysis; Industrial engineering & design for manufacturability Hollistic understanding, material, battery regulations domain expertise; ability to construct BMS; willingness to keep up with industry developments Curiosity, team spirit Data Science; Cell physics; metallurgy Fundamental materials science knowledge; fundamental materials processing knowledge; data science applied to materials science. All types of battery manufacturing expertise (from cathode active material to formation), failure analysis for yield improvement in manufacturing. Communication, Getting things done, working under pressure safety; cost optimization; economy of scale Equipment design, process optimization, facility design and implementation Lean manufacturing, Robotics, Logistics Industry experience; data processing / data analysis; vendor management. battery pack design, systems engineering, cross-functional teamwork "Battery design", "Cell research", "BMS" electrochemistry background, materials science, data analysis Lean six sigma; Electrochemistry, Presentation/documentation "Data Driven Decision Making", "IOT Base Decision Making", "Communication soft Skills"" battery testing results interpretation; more time efficient battery testing methodologies; interaction between chemists and engineers Modeling/simulation, algorithms, testing material synthesis, material analysis, electrochemistry [CAD Skills]; [production experience]; [project management] Data Analysis; Leadership; Fast-paced learning [Basic electrochemistry];[Impedance spectroscopy] scaling technology; battery recycling; battery manufacturing Digitalization; Quality; Logistics "[Analysis];[characterization];[Understanding]" System integration, mechanical engineering, chemical engineering High volume manufacturing experience; experience with high volume manufacturing tools - how they work, how to spec them, Digital Architecture for a battery factory... MES/SCADA R&D engineers Modeling experience, quantitative analysis Comprehensive knowledge of cell design and end to end process interactions, process control, understanding what a comprehensive cell safety evaluation really needs to include. [communication];[controls oriented modeling];[physics intuition] [Compliance]; [Functional Safety]; [Testing] Electrical Engineering, Town Planning, C Suite Diverse Mindset; Interdisciplinary Communications; Public Engagement Electrolyte, Testing Protocol, New Materials (endurance); (problem solving thinking); (specialist knowledge)) Open Minded, Future problem solves, passionate about decarbonization. communication, digital, technical Analytical Skill; Knowledge Sharing; Mutual Understanding Cross department collaboration, process improvement, efficient record keeping / data entry "Understand the battery production process; Have electrochemical knowledge; Understand market dynamics and influences" [Competences within the specific manufacturing processes.] [Emission/effluent abatement systems and environmental control.] Curious, level-headed, adaptable, Surface analysis knowledge; Material characterization Domain knowledge, Coding and data interpretation data science, battery recycling expertise, circular economy expertise Curiosity; Agility; Patience knowledge in electrochemistry, material chemistry, system design [Chemistry];[Battery management systems];[Product & system design]; Persuasion; Synthesis of divers information; Production know-how [global strategic view] ;[real compromise for action against climatic change] materials, electrochemistry, electric Manufacturing, Upscaling, cell design integration;

We wrote code to analyze the text, define skill categories, and count the number of responses within each category.

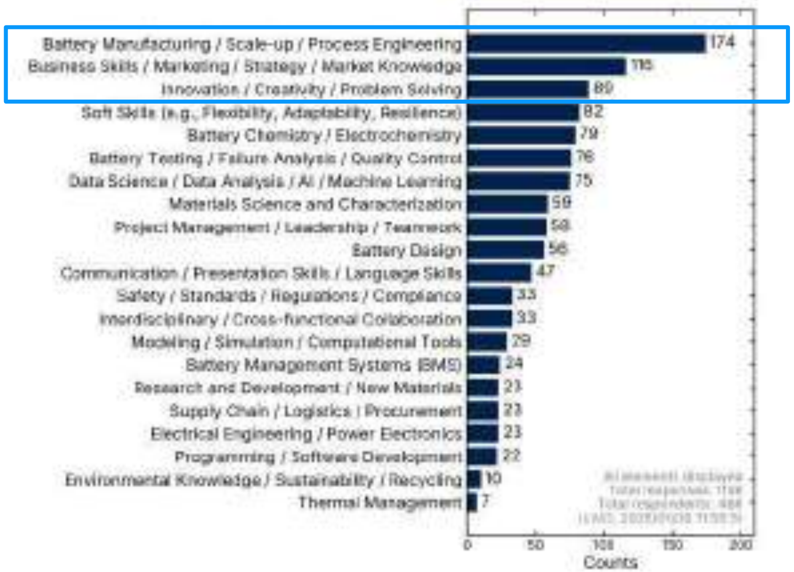
The next slides show excerpts of the findings.

The full report of the findings will be released as part of the Talent Census Report in mid-2025.

Among Leading Skills - “Manufacturing”, “Problem Solving”, “Business/Market Knowledge”

“IN YOUR OPINION, WHAT ARE THE TOP THREE SKILLS MOST IN DEMAND IN THE BATTERY INDUSTRY?”

(According to **senior staff members** and **managers with hiring authority**)



> *On the manufacturing side, the [supply and demand] gap is larger since there’s little to no undergraduate or graduate training in the top universities. This is a deep-seated issue in academic strategy. Government policy is oriented around [materials] innovation but not around process and manufacturing engineering.*
>
> \- **Richard Wang**, Founder and former CEO of Cuberg

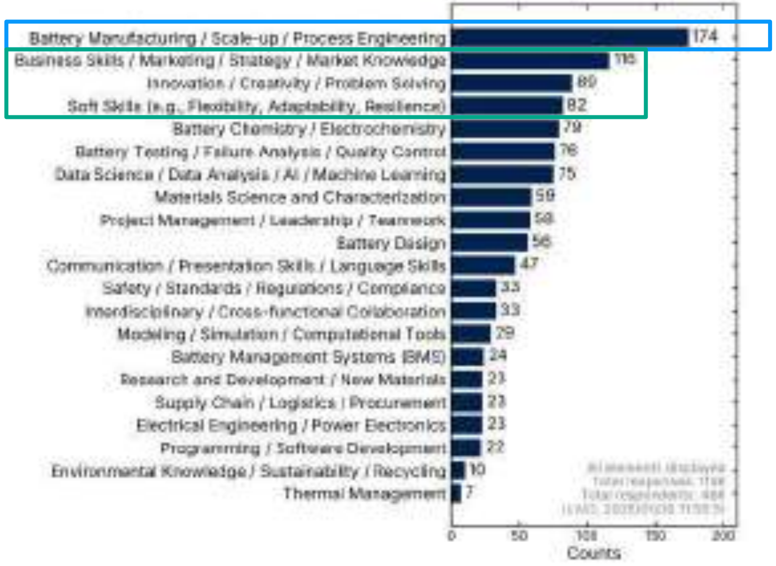
> *Companies aren’t looking for Research Scientists anymore, they’re looking for Process Engineers. At the end of the day the VCs want their money back, so it’s all about executing.*
>
> \- **Matt Anders**, Pangea Talent Solutions

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Hiring Managers Value Non-Technical Skills More Than Employees Would Expect

"IN YOUR OPINION, WHAT ARE THE TOP THREE SKILLS MOST IN DEMAND IN THE BATTERY INDUSTRY?"

(According to **senior staff members** and **managers with hiring authority**)



(According to **everyone**)

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

“In Your Opinion, What Are The Top Skills That Contributed To Your Success?”

Respondents were asked to provide up to three answers.

They were **allowed to put *anything* they deemed relevant**; we did not pre-define the skill categories.

THEIR RESPONSE:

Doing a PhD on the same class of materials as start up, ability to be adaptable and troubleshoot, strong network Curiosity Communication, Ambition growth mindset, communication, and more practicing Battery fundamentals Observation, proficiency in applied mathematics, willingness to learn materials science; communication; characterization Technical Knowledge; Presentation Skills; Data Analysis learning Knowledge, Problem Solving Skills, Innovative Thinking MATLAB 1; CAE 2; Skill 1 - Excel, Skill 2 - Powerpoint, Skill 3 - Quick Comprehension Continuous learning; Diligence; Marketing planning skills mathematical people skills Communication, product knowledge, self-motivation. communication; depth of knowledge; consulting experience openness to learn; previous internship experience; good communication Communication Communication Energy Engineering, BMS and Electrical Collaboration; multi-potential; influence capabilities People skills, product applications skills, Creativeness; Eagerness to take on new projects critical thinking, project planning, tenacity strategic planning, strong technical articulation, setting clear and decisive vision sales Hard work Interdisciplinary environment, project involvement, mentorship Knowledge, engineering background, communication data analysis; literature review; people skills Test and validation, leadership Communication, systems thinking, fast learning Adaptability, specific market knowledge, communication materials, electrochemistry and social skills Communication; Organization; Diligence hard work; chemistry; creativity deep learning and observation toleration; listening ; hard work Persistence 1, Vision 2, Creativity 3 Collaboration; critical thinking; patience Robotics, Automation, and Energy Resourcefulness. Communication. Leadership Passion, common sense, thin-film deposition electrochemical analysis; logical thinking test bench, cell fabrication Problems solving, communication, adaptability Software Development; Python; Industrial IoT Leadership, curiosity, attention Network to a wide range of people to understand fully the industry; learning quickly and trial by fire ; Personal responsibility taking; communication skills; domain knowledge Experience in battery field critical thinking; problem solving; software development Drive/ambition, desire to learn, systems-level knowledge about batteries Electrochemical cell testing, Materials characterization, Interpersonal relationship building Interpersonal skills; problem solving; organization Curiosity; common sense; frustration tolerance Quick learning, coding & analytical skills, communication speaking, negotiation, listening Complex problem solving, innovation, efficiency Lean Startup independent learner, good networker, good presentation skills Problem solving skills Strategic Sourcing and Supplier Management, Cost Management, Risk Management, Leadership and Team Development Program Management; Communication; Leadership analytical thinking 1) problem solver 2) fundamental understanding of batteries 3) ability to apply knowledge to different topics time management; innovation; tenacity science communication; data science; problem solving Software development, analytical skills, self-teaching skills Strong fundamental technical skills, interpersonal skills, communication skills Fundamental understanding, electrochemistry, market knowledge testing research hypothesis , synthesis, writing Experimentation; Mechanical Testing; Electrochemistry People skills; business acumen; testing & validation Skill 1 - Thinking outside the box; Skill 2 - Willingness to ask questions; Skill 3 - Willingness to work until the job is done agility, communication, strategy Ability to learn; Adaptability; Critical thinking Rigor, work ethic profound electrochemistry know-how, passion for the field, endurance fund raising open to change Ability to adapt and learn; electrochemistry; materials science engineering fundamentals; willingness to learn; communication problem solving, team work, organizational skills research 1, networking 2, languages 3 Ehh Publishing, Research, Public Speaking Flexibility, well-roundedness, perseverance willingness to learn, curiosity, attention to detail Year-long internship assembling cells, testing cells and observing material characterization studies Good command of fundamentals of engineering (heat transfer, mass transfer, etc) and chemisty; creativity (envisioning solutions); willingness to accept new challenges. independent thinker; electrochemistry fundamentals; good communication battery data;customer voice [Multi-tasking], [Project Financial Planning],[Communication] battery research, electrode manufacturing, cell assembly Hard work Cummins, Inc engineering veteran, Rivian Startup model - These companies have sound engineering practices, well balanced ethics and community responsible concept. That honed my engineering DNA Science/engineering fundamentals; programming; communication skills No Answer Skill 1: both basic research and applied manufacturing knowledge; skill 2: managerial skills; skill 3: flexibility and learning mindset Quick learner; good analytical skill; adaptable Fundamental knowledge, problem solving ability and quick learning ability Computer programming, Calculus, Circuit Design Communication, scope management, strategic analysis Industry analysis, data visualization ability to learn, adapt, communicate Problem solving; communication; curiosity "ability to ask the right questions"; "ability to research efficiently"' Deep Work, Experimental Design, Molecular Design broad knowledge and expertise in different science areas Grit, luck, curiosity prioritization, data analysis Math; Broad knowledge Perseverance, Quick Learning, Experimental Approach. Adaptability, knowledge and agile JMP, Project Management, Analyzing test data Mayerila Electrochemical analysis; cell formation and testing; product development TAKING RESPONSIBILITY; ABILITY TO GRASP CONCEPTS FAST; ATTENTION TO DETAIL Battery knowledge, Data analysis, Passion for the problem analytic thinking; life long learning; people skills Organization, willingness to learn, growth mindset technical, program management, industry knowledge Long term views, Forecasting,Networking "ambitious";"inquisitive", team player Profound knowledge; coding skills; hands-on mentality management, sales channel, marketing Attention to detail, pushing myself to speak my mind and learning to trust my. Gut Data analysis; technology transfer; experiment design Electrochemistry, leadership Critical thinking; Market-driven thinking; Strategic analysis Communication; Strategy Planning; Business Development Curiosity Creativity; energy; persistance Drive, focus Problem Solving, Critical Thinking, Innovation Good background, Flexibility, Team working "Enthousiasm;High standards;Work smart" Foundational knowledge on batteries; knowing how to learn new things quickly; python materials science, presentation skills, electrochemistry Open mind, quick decision making, strong management Battery fundamentals; motivation and ownership; communication Fundamental knowledge of electrochemistry, flexibility in work Thick skin regarding being queer at my first few jobs, first principles knowledge of batteries developed in grad school, willingness to take on new tasks and learn quickly, Polyvalence; adaptability Communication, fast learning Grit Creativity, Fast learning; Curiosity Written and oral communication; program management; managing expectations Electrode manufacture; adaptability; priority management Networking; languages; interest also in non-lab topics Technical writing; Market research; Chemical engineering education Attention to details; problem solving; mathematical foundation; interpersonal skills Materials science knowledge Mix of technical and commercial understanding Hands on learning in lab environment Prioritization, data analysis, problem solving flexibility, chemistry and engineering background, organised Leadership; public speaking; general engineering knowledge direct experience, cross-functional knowledge, teamwork Persistence, electrochemical knowledge, communication skills Curiosity; Tenacity Data Driven Decision Making, Eagerness to learn, continuous improvement, creating and maintaining relationships communication, leadership, professional Analytical thinking; computer skills; people skills; Fast learning; Team player; Data Analysis Digitalization; Modelling; Communication Open mind, being involved, determination to learn new skills, Multi-disciplinary state of mind adaptability & drive engineering skills, people skills, ability to see big picture and future potential Administrative experience, technical experience, public engagement experience (Motivation); (electrochemical battery knowledge) Passion for the industry, future problem solver, Proactiv communication, flexibility, transparency Quick Learning, Pushing on the Job, Mutual Understanding Self motivation [Positive attitude.] [Courage to try and to be in the wrong (and admit so).] [Curiousness.] Sales, marketing, strategy, organisation, Polyfunctionality, Agility, Knowledge pragmatic; organised; experienced Flexibility; Synthesis of diverse info base knowledge, motivation to learn, knowledge transfer Adaptability, ambition to learn, communication, being prideful of my effects on the products, detailed and organized, owning the responsibilities Coding, Electrochemistry, Hands On [ability to synthesize and integrate insights from different field of knowledge]; [hands-on skills]; [curiosity-driven Learning] Strategic thinking, knowledge and understanding of micro and macro environments 20 years of experience in electronic design, method, curiosity for knowledge Innovative Mindset, Creativity, Curiosity creativity, innovation, Analytical Thinking; Self-learning; Self-Motivation collaboration; curiosity; scientific approach Sales and commercial astute Supplier relationships. Training 30 years ago as a 53D electric generator repair in the Army Reserves. time management; fine motor skills; presentation skill Critical thinking; Analytical skills; Communication instrumentation, communication, sense of humor flexibility, pick things up quickly Multidisciplinary constraint management; visualizing models in my head; Microsoft excel Adaptability;problem solving;communication Adaptability, resilient, curious Skill 1: domain know-how knowledge, Skill 2: project managment Analytical skills, chemical analysis, effective communication initiative, curiosity, openness Electrochemistry; Test and validation methods; Design thinking Collaboration & communication Collaboration, attention to detail Education; Social Interactions; Self-Motivation Innovation;self motivated; leadership Analytic Thinking; Open minded; Basic Principles Customer/market focus; Maximum use of resources; Dedication Know the science very well; keep up with current research findings; manage up Not giving up, take it home, write all your functional uses Strategic ideas; Communication; Research Continuous learning approach, Problem solving, communication Persistence; Emotional Intelligence Understanding datasheets; Schematic Design; Hardware Testing Battery fundamentals, my research topic Ability to create right network, Passionate, hard worker Chemistry, Unit Operations, Materials Science Hard-work, Willingness to do everything, Communication Commitment; Curiosity; Focused System Engineering, Practical knowhow, digital engineering adaptability; resilience; focus problem solving, communication, creativity Non-linear thinking; problem solving; willingness to learn sector knowledge; interoperability; resiliency techno-economic / cross-disciplinary skills/thinking; confidence (speaking + leadership); vulnerability (willingness to ask questions, gain trust) Materials science; Electrochemistry; Synthesis Communication; expert knowledge; strategic thinking Electrochemistry, Materials, Problem solving independence, logic thinking, people skills 1: battery internship; 2: cross-functional education (chemical engineering & material science); 3: passion/curiosity of the battery sector Resiliency; problem solving; eye for detail Willingness to learn; electrochemistry; coding Determination; Interest in learning; Curiosity Engineering experience Analytical thinking; System and Safety knowledge Leadership, general battery knowledge, regulations Self guided learning organizational skills, data analytics Hands on Utility PV experience, technical background,fast learner Personal Motivation; Necessity; Education Personal Interest and curiosity about various types of batteries and Production capability checks Dedication and good memory, strategic thinking, and continuous learning. "[Critical thinking skill];[material synthesis skill];[data analysis skill]" Problem solving; technical; project management Creativity, Experience, Hands-on Communication Project management, engineering fundamentals Python, Deep Learning, Electrochemistry, Battery Deep industry knowledge, people skills, project management skills Problem solving, networking Flexibility; Pattern Recognition; Continuous Learning Troubleshooting the equipment Independent thinking, research oriented mentality Fundamental knowledge, Research experience, Continous development mindset Soft skills Persistence; Communication; Project Management, Systems Engineering, Requirements Management Communication; Project Management; English listening, imagination, chemistry, understanding applications Flexibility, adaptability, resiliance Quick learning, autonomy Ability to learn quickly; battery physics and chemistry; data analysis [Innovation][electronics][curiosity] Multi-Tasking Ability, Innovative and Crazy Mindset, Identifying Mistakes Open mindedness; scripting; full cell design experience No success Experience, Salesmanship, Drive Data analysis, continuous learning, python Flexibility, desire to learn Industrial Automation and mechatronics, automobile repairs, power systems troubleshoot Ambition; Endurance; Project Management Good foundational knowledge, self-taught, curiosity Asked questions, Spoke to everyone Knowledge about batteries, willingness to take ownership, [Battery knowledge], [Hands on testing], [Automotive background] Endurance; Overseeing complex problems; strategic thinking Relentless learner; physics theory knowledge; listening Experience in adjacent markets; technical & commercial mix; questioning attitude Knowledge; learning; working hard Collaboration; Quick Learning; Compliance Experience Hands-on experience; constantly learning new information perseverance, curiosity, critical thinking grit Communication, Problem Solving, Powder Handling Fundamentals Fast learning, precision, big picture thinking Communication; Neuroticism; Fast Learner research capability, open minded meticulous, drive, passion networking, eagerness to learn, electrochemistry knowledge Problem-solving; Data Analysis; Literature screening "commitment; keep learning; keep improving what you learn;" Process Design, Optimisation, Excel Connections in the industry; communication skills; keeping up with the development of the industry (technology and product) Background in battery R & D PM, Management, Organization, battery knowledge, Data Analysis Clear thinking; clear communication; solid state chemistry Goal oriented; flexible; organized Empathy, efficiency, experience managing in startups; manufacturing background;strong engineering/technical skills"Strategic" "hard working" "curious" knowledge; communication; analysis Cell design, materials science, Python Verbal, written and visual communication Systemic understanding; battery construction; quality commitment; curiosity; attentiveness Experimental testing, modeling, electrical circuit analysis Communication; Simulation; Business Scientific knowledge, hand's on ability, willingness to learn and work Creative thinking; team player; attention to details people management, project management, inquisitiveness Relationship building, Analytical problem solving, Curiosity The ability to search for information quickly; data analysis; clear communication Persistence, Vision, Humbleness Industry knowledge; CAD; application familiarity soft skills, fundamental materials science and electrochemistry, analysis communication, computers, precision testing, Tesla Proactive, call to action, process creation Independent worker; Thirst for knowledge; Problem Solving test/troubleshooting; data analysis; physics fundamentals 1) communication 2) problem solving 3) presentation Enthusiasm, sincerity and technical depth Programming, data analysis Perseverance, curiosity, troubleshooting Adaptability, Curiosity, Strategic thinking Battery Quality, production, maintenance observation and analysis speed of execution Eagerness to solve problems, strategize product plan considering market sentiments, improving profitability. Teamwork, Collaboration in cross functional things, analytical understanding of changes. materials discovery;electrochemistry;sales Managing people, engineering Research, Critical Thinking, Data Analysis Problem solving, leadership, strategic thinking Communication, strategic thinking, Resilience, Curiosity, Ambitious Electrochemistry; material science; process engineering People, solid state chemistry, innovation Measurement & Test; Materials Science; Semiconductor industry experience Technical knowledge on batteries and cost analysis Networking, customer engagement, technology expertise People skills:leadership:commercial Battery knowledge; Customer focus; Dedication Attention to detail; organisational skills; Efficient; Time management Communication skills, self-confidende, strategic view Specific software knowledge; Breadth of materials knowledge Dynamic learning, Conversation Deep R&D experience; Love for batteries; Always-learning mentality Technical Sales analyzing data, managing team, getting swarm intelligence Tenacity : Perspicacity : Listening “[communication];[hands-on battery skills];[ex-tesla]” organization; materials development; Initiative, accountability, grit Leadership, Technical, Finance Engineering Fundamentals; Hands-on Training; Process/Quality Training Electrochemistry, Electrochemistry, Electrochemistry Operational Management, Product Development and launch Collaboration, Adaptation, Learning Fast Learning; Outgoing personality Dedication and hard work Communication; Technical Understanding; Attitude/Care for work Industrial experience, team work, electrochemistry knowledge Data science; data processing Analytical; communication; holistic problem solving interdisciplinary skills, technology, policy Being able to think across disciplines; willingness to learn by lots of observation, tenacity Electrochemistry; Fast Learning; Flexible Financial modelling, communication, adaptability communication, willingness to fail, listening WORKING HARD, ANALYTICAL THINKING huge prior experience with electrochemistry Analytical, fast learner, Communication skill 1: materials science skill 2: battery design skill 3: battery components Creativity; project management; learning Electrochemistry, materials science, leadership stakeholder management Human skills Ability to adapt; Recruitment skills; Leadership skills persistence, effort, communication programming, excitement, perspective Analytics technical expertise in mineral exploration, excellent communication, curiosity to learn Intellectual Curiosity, networking, perseverance Willingness to work, online courses skill 1 language; skill 2 polymer background Stakeholder management; sales; visionary Negotiation ; New Technology Knowledge ; Meeting Regulation for Safer EV Manufacturing openness; perseverence; flexibility; courage scientific expertise; data processing; adaptability; core technical skills; adaptability; communication; self-confidence; communicative; rare in the field innovative; disruptive; Electrical / electronic system knowledge Attention to detail, Follow up, focus Manufacturing;electrochemistry;analytical instruments strategic thinking; sales skills; listening Communication Flexibility, Desire to Learn, Networking Experience, Knowledge, Technical proficiency Electrochemical knowledge; being a quick learner; communication lifelong Learning attitude Time management; open communication; basic programming Finance, accounting, tax Willingness XRD/crystallography, Python communication, efficiency, attention to detail openess to ask questions Generalist, Battery Knowledge (PhD), hands-on engineering Problem solving, Empathy, Public speacking, strategy Mindset/willingness to learn; critical thinking and reasoning; Endurance; teamwork; experience [Leadership];[Knowledge];[Multitasking];[Communication];[Experience] previous experience with electrochemistry Industrial Automation, Battery energy storage system integration, Microsoft excel Solid state chemistry, people management 1. Ability to bread on experiences from different industries, 2. Crisis management, 3. Curiosity Adaptability, tenacity, continuously learner Program management, technical, engineering Critical thinking; Analytical; Persistent "Adaptation; Research" Research and Development; Technical; Analytical Management skills, patience, Projects- deep handling 1. Hardworking 2. Experience 3. Management [Excellent Quality]; [Support to Customers]; [Hard-Working] Hardworking [hard-working]; [not giving up]; [patience] Programming, Electronics Fast learning, autonomy, curiosity flexibility, curiosity, dedication Logical thinking; quickness of mind; wide professional knowledge incl. Business science Problem-solving; Teamwork; Time management Problem solving; Mechanical mind; Cross-functional knowledge Automotive ecosystem understanding, business acumen, networking Flexibility; Open Mindness; Sociability; Technical and scientific mastery; Management; Strictness Skill 1 - read a lot - learn quickly grit, determination, big picture thinking, optimism Can do attitude, flexibility, experience Communication; Project Management; Data Analysis; Empathy; Proactivity; Teamwork; Critical Thought;Materials Knowledge Problem solving skills, Curiosity, Strategic Thinking product development; material knowledge; sales knowledge; marketing; mentoring Agility, Easy Learning skills, Social skills Technical knowledge, hands-on experience, materials science Battery and energy industry expertise; being a "full stack" marketer [engineering][electronics][manufacturing system] problem solving, communication, perseverance Adaptability; Fundamental Electrochemistry Knowledge multidisciplinary knowledge, willingness to learn, creative thinking "Engineering ; Technical ; Applications" global contacts; process experience; economics critical thinking, wanting to learn, self starter Electrochemistry, communication Quick learner Flexibility 1. Broad Technical Knowledge 2. Industrial Industry Experience 3. VOC skills Multitasking; adaptability; diplomacy detailed mindset, data science, communication curiosity, adaptability, social skills Asking questions; intellectual humility knowledge, personality, academic history Flexibility Practical knowlwdge about battery prosuction, teoretical knowledge about li-ions battery,statistical skills 1. Knowledge 2. Risk Taking 3. Problem Solving Curious; motivated; autonomous mechanical design, high volume product design, first principle thinking, curiosity, drive decision making; cost analysis; relationship building Engineering; practical hands on skills; adaptability Communication; analytical thinking; Resilience, humility, determination connections, experience, professional knowledge Expertise in wholesale and retail, regulated and deregulated power markets; strong analytical skills; adaptability engineering, project management, strategy Independent learning; Teamwork; Being organized Good Communication Skills; Broad knowledge in many engineering diseplines; Materials science background Creativity; chemistry; discipline Deep understanding of technology, strategy, and leadership Software, networking, electronics Fundamental knowledge (Cell testing) ; (battery Pack Testing); (BMS Testing) Project management, business strategy, analysis Battery knowledge; Lab experience; Willing to learn Chemistry knowledge, impedance analysis, intuition Critical thinking, communication, and engineering background Skill1: Networking, Skill2: Expermental Subject knowledge, Skills 3: knowhow market Picking up concepts quickly Software Development Physics background, programming, data analysis Technical understanding of energy storage ; experience with required equipment ; communication skills Curiosity, grit, adaptability Ability to learn; good communication; coding in python Proactive, good communication, presentation Flexibility, fast learning, perseverance Python data analysis; test engineering; battery electrochemistry Research, Data analysis, Communication Materials synthesis, testing and advanced analysis global knowledge of battery innovation "Simulation study; Cell Manufacturing; Electrode synthesis" Team management, quick learning, innovation, team leadership perseverance, curiosity, courage, vehicle integration Continuos learning, foundational knowledge, programming flexibility; understanding of start ups; emerging tech approach Fundamental knowledge; persistency; critical thinking Being quick learner, taking risk, agile product development approach Data analysis, molecular quantum mechanics, cell modelling Network Communication; perseverance; programming determination; perserverance; UNC's chemistry program Experience; Education; Scientific Curiosity; Leadership, planning Fast learner; analytical mindset; detail-oriented 1. Electrical background 2. Understanding of the renewable energy industry 3. I had a wide knowledge base t Generalism, open mindedness, collaboration International; network; business development People leadership, techno-economics, communication [DoE],[Python Programming],[Data Analysis] Team leadership skills, mentorship of peers, inter-team collaboration Laboratory skills Troubleshooting, question formulation, communication electrical, electronic knowledge; project managment; testing knowledge Focus, network, interesr experience across multiple disciplines, productization focused, solution selling creativity; fundamental knowledge of batteries ndt, testing Electrochemistry Product Knowledge (Battery structure + chemical transport phenomena); Problem Solving Acumen luck; communication; product knowledge Material Synthesis, Analytical Characterization Expertise, Teamworking, business analytics, strategic planning Dedication; enthusiasm; resilience Drive, quality, interpersonal skill Deep knowledge in several technologies, experience in many R&D projects oriented to bring up new market products Education, Ambition, Fiction Battery industry knowledge, automotive industry knowledge, communication skills Adaptability and Flexibility, Technical Proficiency, Problem Solving Mathematical modeling; mentorship; experiment design keeping my mouth shut, when my employer lies to customers and investors Synthesis, testing via electrochemical method, structural characterization people skills; project managemnet; technical knowledge Problem solving and critical thinking; Hands on approach; Hard work adaptability; strive for excellence; synthesis Matlab, Technical Understanding, Analysis Experience from many different fields technical knowledge, knowing the customer, soft skills analytical abilities - able to solve problems and combine solutions Learn Quick Fail Fast Electrochemical Data Analysis; Material Characterization Autonomy ; open-minded ; commitment Electrochemistry knowledge, previous experience in battery industry and critical thinking Communication; solid state chemistry; attention to detail Communication; project leading; business strategy chemistry; hardware; software Adaptability, Resourcefulness, Communication Analytical Chemistry; Lab Management ; R&D Duty cycle understanding, Battery Basics, Simulations Learning, hands on work Communication skills. Ability to write articles. Networking. technical ceramic knowledge Adaptability Data analysis, critical thinking Knowledge, relevant experience, creativity Ability to simplify, root cause problem solving, listening to customers for problem statements Experience, Chemistry, Creativity Grit; passion; planning vast knowledge of many industries Observation, Self study, Learn from breakdown/faults Desire to learn; Engineering Background; Positive Attitude Fundamental knowledge; Experimental skill; Adaptation skill; Communications, leadership, tact, technical Ability to adapt quickly, 12 years of marketing & comms experience in a different industry and educating myself on technical partindustry Curiosity; determination; creativity [pilot-line production]; [cell production]; [Test and validation] Characterization techniques; Electrochemistry experience; Data analysis utility industry knowledge from internship; emotional intelligence; teamwork

We wrote code to analyze the text, define skill categories, and count the number of responses within each category.

The next slides show excerpts of the findings.

The full report of the findings will be released as part of the Talent Census Report in mid-2025.

Respondents Attributed Personal Success Mainly To “Soft Skills,” Not Technical Skills

“IN YOUR OPINION, WHAT ARE THE TOP SKILLS THAT CONTRIBUTED TO YOUR SUCCESS?”

(According to **senior staff members** and **managers with hiring authority**)

The vast majority of responses emphasized the **ability to learn, problem-solve, communicate, lead, network, and adapt**.

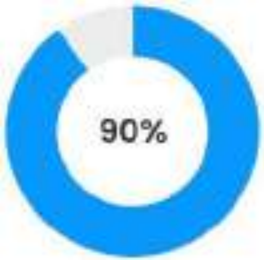
Technical skills were comparatively less important:

- Battery/electrochemistry was ranked 8th
- Materials science was ranked 11th
- Domain-specific technical skills was ranked 14th
- Coding was ranked 15th

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

In Industry, On-The-Job Training Is Par For The Course

"WHEN YOU FIRST STARTED YOUR ROLE, HOW WERE YOU TRAINED?"

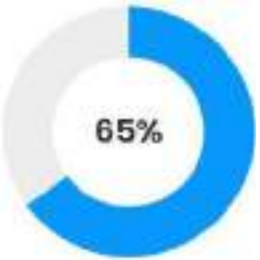


of respondents **learned on the job** when starting their role

ON-THE-JOB LEARNING IS PERVASIVE

of respondents received **formal training programs**

FORMAL TRAINING PROGRAMS REMAIN RARE



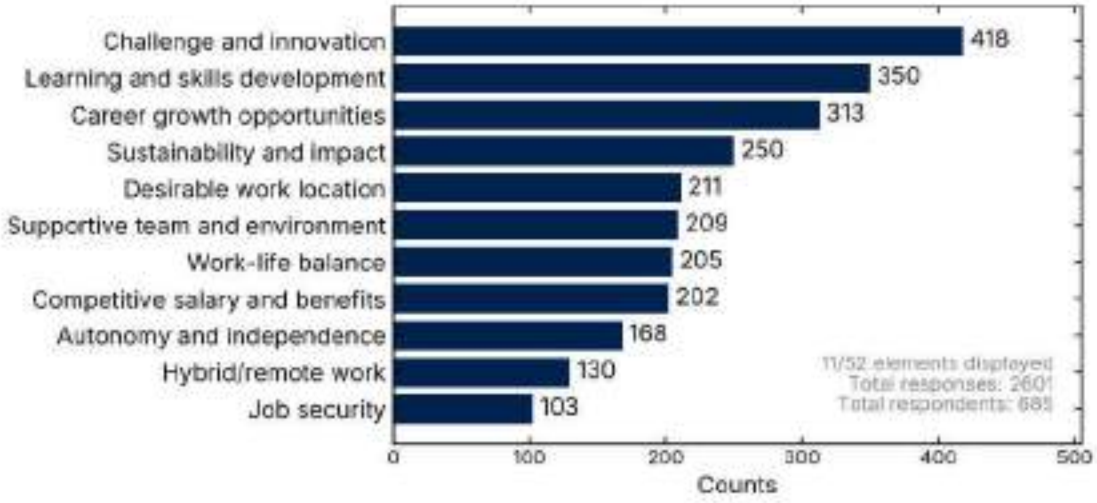
of respondents cited "**better foundational knowledge**" as key to improving job performance on day one.

FOUNDATIONAL KNOWLEDGE STILL MATTERS

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Key Drivers Behind Choosing A Company - Challenge, Innovation, Impact, Learning, Growth

“WHY DID YOU CHOOSE YOUR CURRENT ROLE AND COMPANY?”



Among the top reasons are **challenge, innovation, impact, learning, and growth.**

Work-life balance, work location, and salary come second.

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

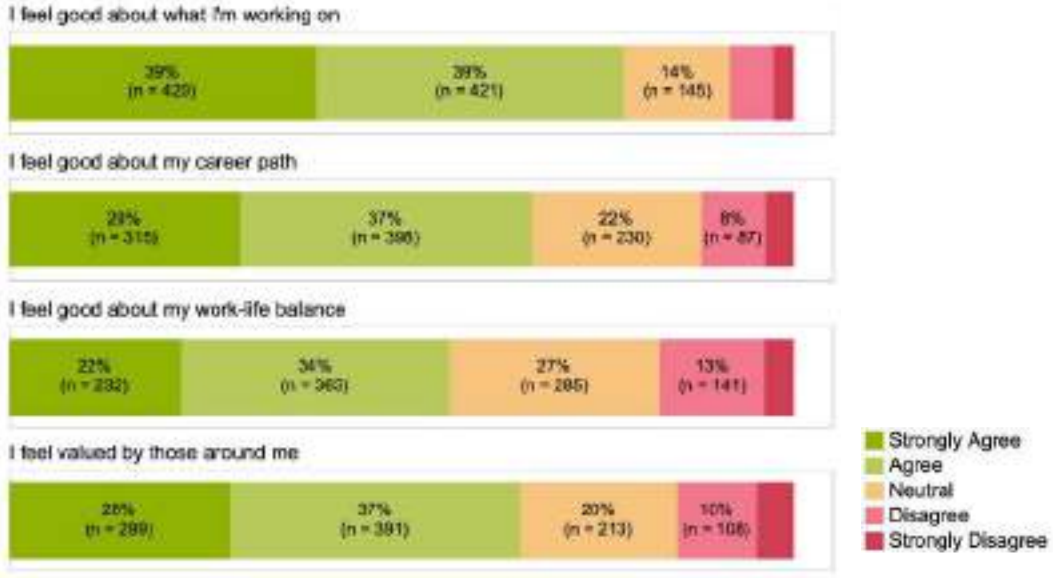
Workplace Happiness - Strong Foundations With Room For Growth

78% felt good about what they're working on.

66% felt good about their career path.

56% felt good about their work-life balance.

65% felt valued by those around them.



This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

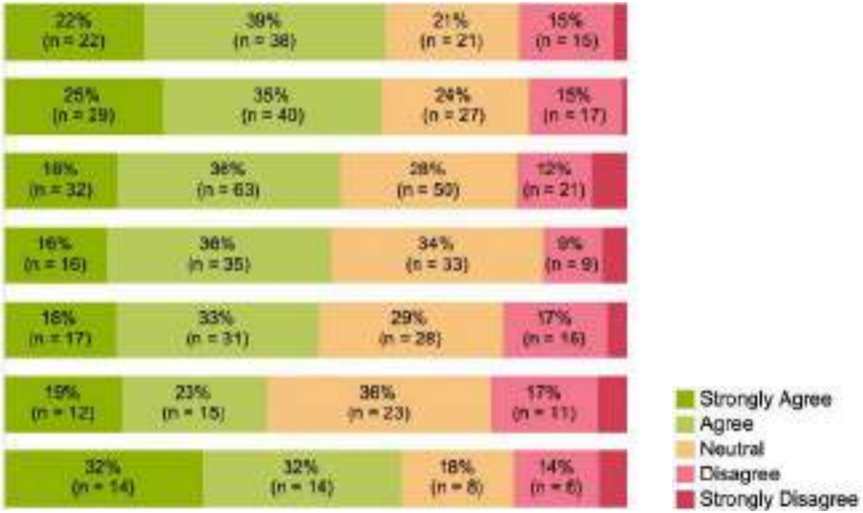
Higher Positions Linked To Higher Job Satisfaction But Worst Work-Life Balance

91% of executives feel good about what they're working on, compared to 75% for entry roles.

Work-life balance perceived to worsen at higher levels, except for executive who report feeling the best about their work-life balance.

"I FEEL GOOD ABOUT WHAT I'M WORKING ON"

"I FEEL GOOD ABOUT MY WORK-LIFE BALANCE"



This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025. Role definitions: Entry/Developing: contributes to projects, Career: owns projects; Senior: leads small projects; Expert: leads large projects; Manager: provides direct supervision; Director/VP: manages sr. leaders.

Confidence, Retention, And Optimism In The Industry

Majority (72%) of industry respondents are confident in their ability to find their next job, suggesting optimism about their skills and the industry's demand for experienced workers.

> *Regardless of the dynamic and somewhat unpredictable nature of the battery industry in recent times, the majority (over 90%) of battery professionals we speak with have an optimistic view for the long term ... being fully committed to building our batteries for the future.*
>
> \- **Jamie Sheard,** Strativ Group

RESPONSES FROM INDUSTRY (N = 665)

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Student Perspective - Optimism Tempered By Skills And Employability Gaps

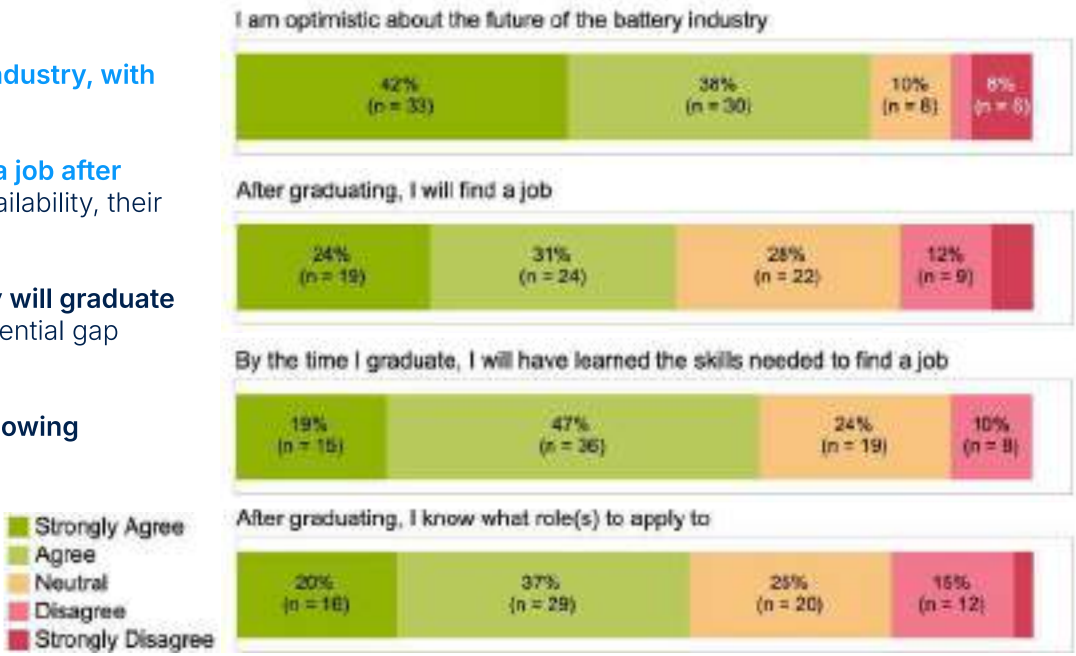
Students are optimistic about the future of the battery industry, with 80% expressing positive sentiment.

However, only 51% of students agree that they will find a job after graduation. This could indicate uncertainty around job availability, their own employability, or both.

34% of students expressed neutrality or doubt that they will graduate with the skills needed for employment, highlighting a potential gap between education and industry expectations.

43% of students expressed neutrality or doubt about knowing which roles to apply to, suggesting there is room for clarifying industry roles and pathways.

RESPONSES FROM STUDENTS (N = 79)



This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Half Of Industry Professionals Are Actively Seeking New Opportunities

HIGH INTEREST IN NEW OPPORTUNITIES AMONG ENTRY-LEVEL PROFESSIONALS

- **64% of entry/developing professionals are seeking new opportunities,** the highest percentage across all career levels.
- **Insight:** This could reflect a strong desire for growth, learning, or upward mobility. Companies need to focus on engaging this group through mentorship, training, and clear advancement paths.

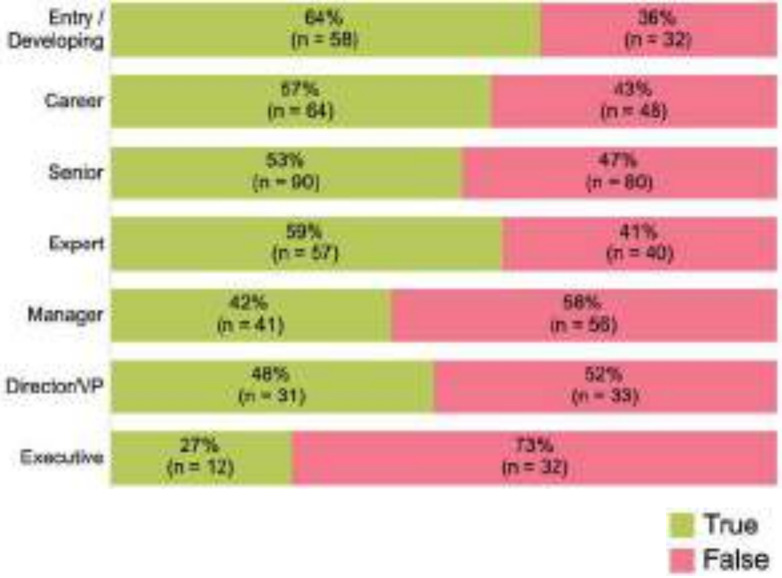
MID-CAREER JOB MOBILITY

- **Career (57%), senior (53%), and expert (59%) levels demonstrate consistent interest in seeking new roles.**
- **Insight:** These groups might be looking for promotions, better compensation, or cultural alignment. Companies could create targeted retention strategies, such as leadership pipelines or flexible career paths, to reduce turnover.

DECLINE IN JOB-SEEKING AT LEADERSHIP LEVELS

- **27% of executives are seeking opportunities—**the lowest percentage.
- **Insight:** Senior roles often come with greater stability, satisfaction, or investment in the organization. This may also indicate that executives feel more entrenched and less willing to take risks by moving roles.

"ARE YOU CURRENTLY SEEKING NEW JOB OPPORTUNITIES?"



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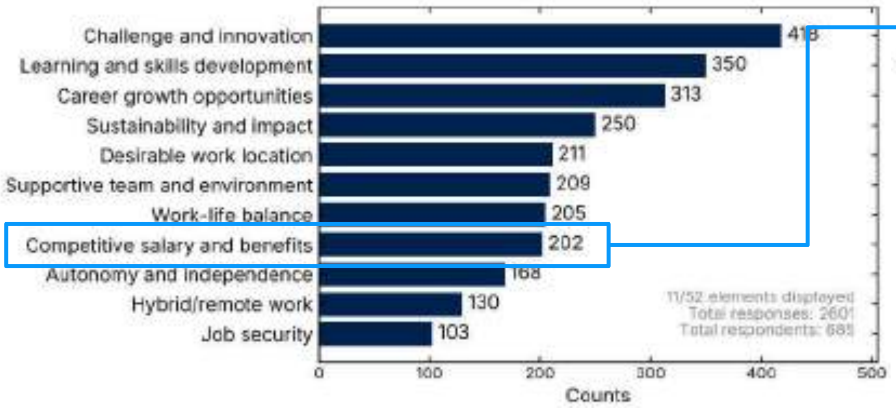
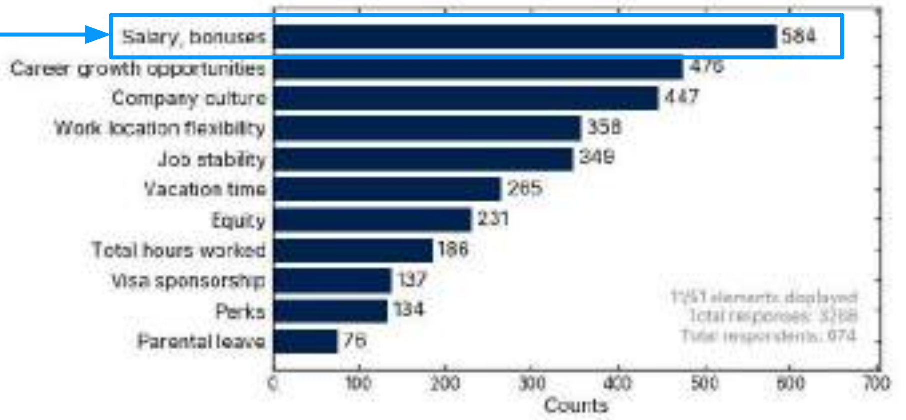
Came For The Challenge, Left For The Money

Salary is the 8th most common reason for joining a company but the top reason for leaving to join another.

“WHY DID YOU CHOOSE YOUR CURRENT ROLE AND COMPANY?”



“IF YOU WERE OFFERED A SIMILAR ROLE WITH A DIFFERENT COMPANY, WHAT FACTORS WOULD INFLUENCE YOUR DECISION TO ACCEPT THE OFFER?”



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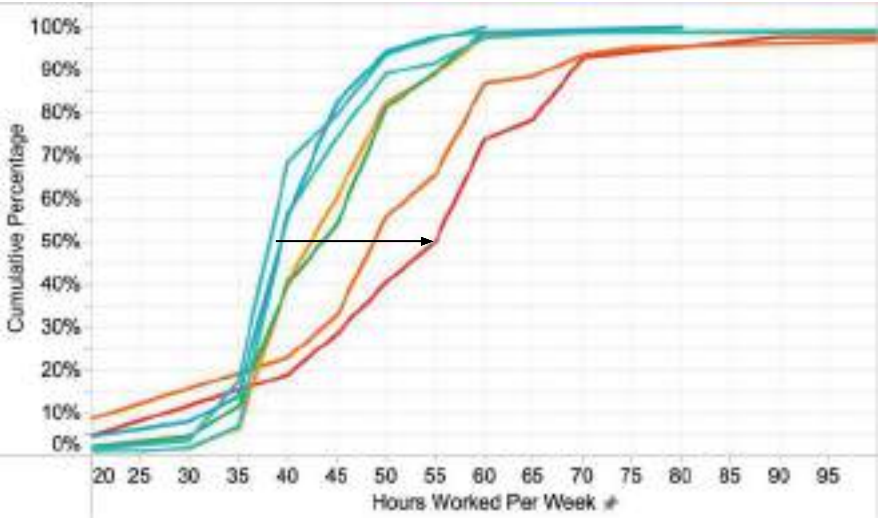
Leaders Tend To Work Longer Hours Than Individual Contributors

“HOW MANY HOURS DID YOU WORK LAST WEEK?”



LEVEL

~40 hours per week

~45 hours per week

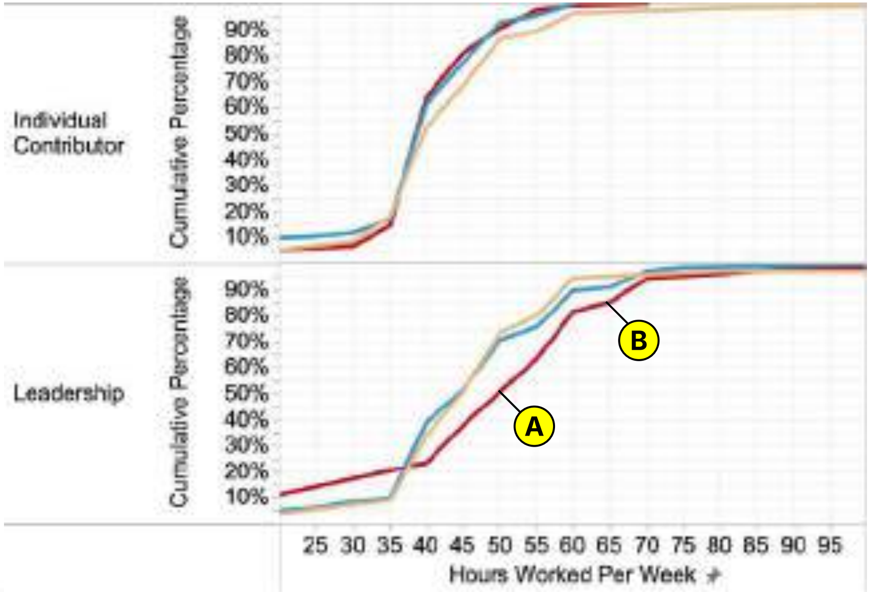
>50 hours per week

“Hours Worked Per Week” comes from respondents’ answer to the question “How many hours did you work last week?” Excluding data from holiday periods (e.g., November/December) does not significantly change the distributions. The company’s stage of development comes from respondents’ answers to the question” How would you classify your company’s stage of development?”

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025. Role definitions: Entry/Developing: contributes to projects, Career: owns projects; Senior: leads small projects; Expert: leads large projects; Manager: provides direct supervision; Director/VP: manages sr. leaders.

During Scale-Up, Leadership Team Works 5 to 10 More Hours Per Week

“HOW MANY HOURS DID YOU WORK LAST WEEK?”



COMPANY STAGE

- 🟦 Pre-startup / Startup
- 🟥 Scale-up
- 🟧 Mid-sized / Established

DURING SCALE-UP:

A **50%** of leaders work more than 50 hours per week

B **15%** of leaders work more than 65 hours per week

“Hours Worked Per Week” comes from respondents’ answer to the question “How many hours did you work last week?” Excluding data from holiday periods (e.g., November/December) does not significantly change the distributions. The company’s stage of development comes from respondents’ answers to the question” How would you classify your company’s stage of development?”

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Do You Think You’re Being Underpaid Or Overpaid?

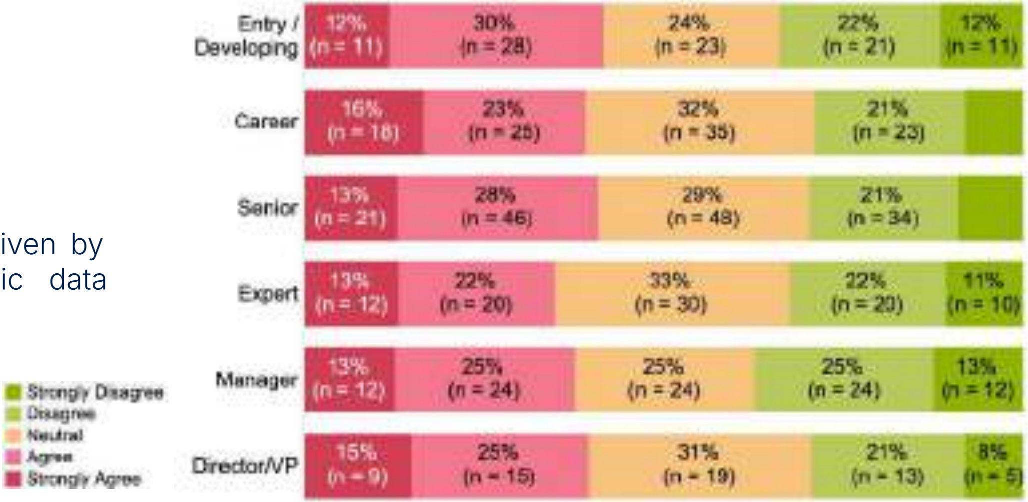
2 IN 3 PEOPLE’S COMPENSATION DON’T MATCH THEIR EXPECTATIONS

1 in 3 feel like they're overpaid.

1 in 3 feel like they're underpaid.

Implication: Expectation mismatches could be driven by lack of clear benchmarks and industry-specific data around pay transparency.

“I AM BEING UNDERPAID COMPARED TO OTHER ROLES”



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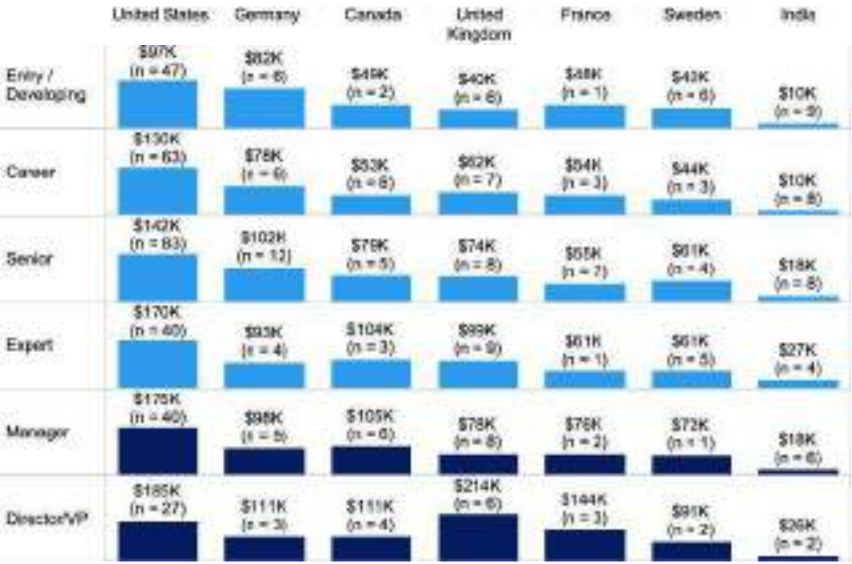
“What Is Your Annual Base Salary?”

COMPARISON ACROSS DIFFERENT COUNTRIES

Median Base Income in USD

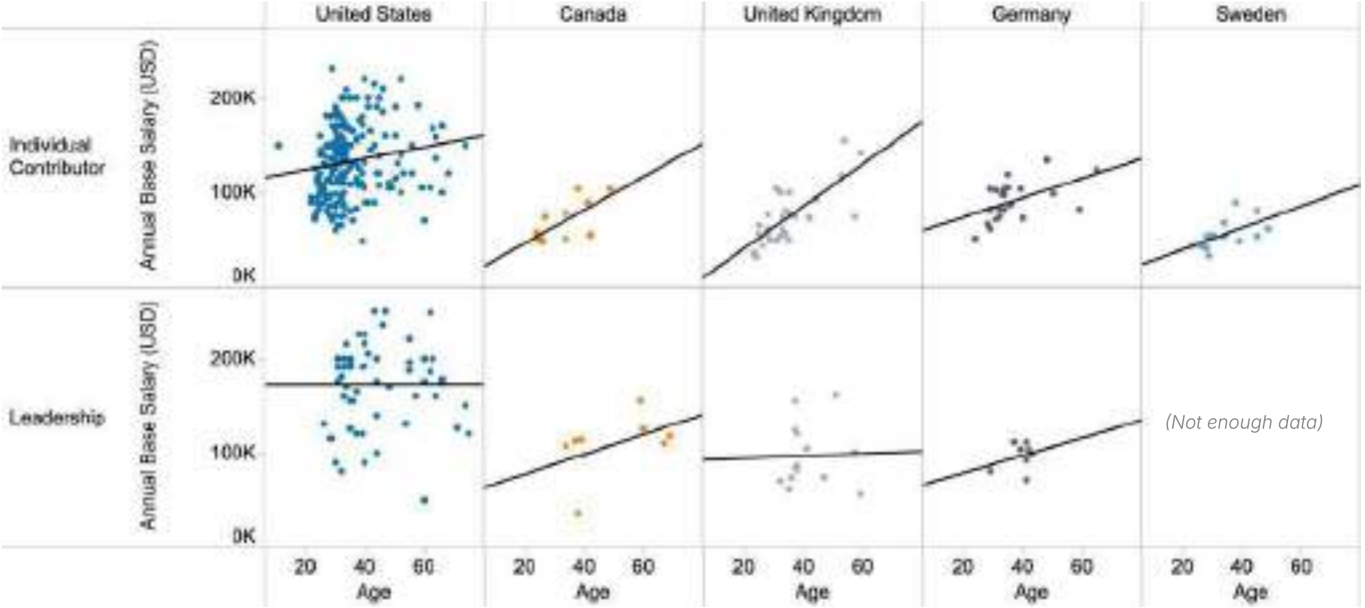


COMPARISON ACROSS DIFFERENT STATES (U.S. ONLY)

Median Base Income in USD

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025. Role definitions: Entry/Developing: contributes to projects, Career: owns projects; Senior: leads small projects; Expert: leads large projects; Manager: provides direct supervision; Director/VP: manages sr. leaders.

How Correlated Is Your Age To Your Salary? It Depends On Where You Live.



In the U.S., individual contributor salaries plateau early, requiring leadership roles for further growth. **In Europe, salaries tend to grow more consistently with age,** reflecting stronger career progression tied to tenure and experience.

Countries correspond to the answer to the question "In what country is your office located?" Responses are further grouped by role level, where "Individual Contributor" includes entry / developing / career / senior / expert roles and "Leadership" includes manager / director / VP / executive roles. Regression lines indicate best fit after excluding outliers. Base salary is reported in USD using exchange rate from Dec 2024. The scatter plot includes a total of 375 data points.

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Men And Women Scored Similarly In Workplace Happiness

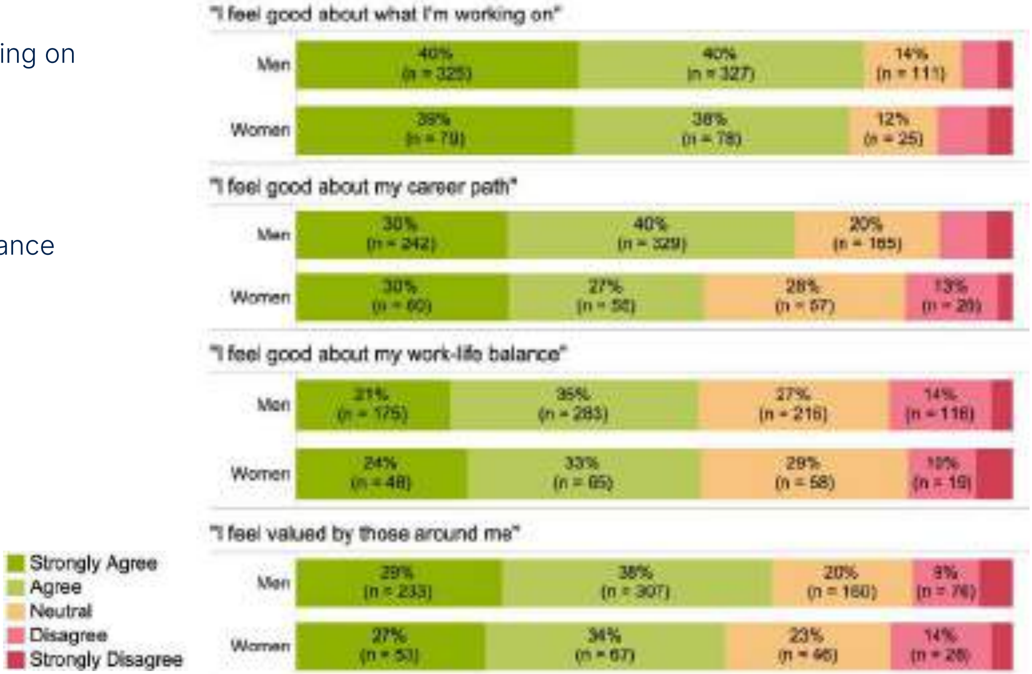
80% OF MEN
77% OF WOMEN felt good about what they're working on

70% OF MEN
67% OF WOMEN felt good about their career path

56% OF MEN
57% OF WOMEN felt good about their work-life balance

67% OF MEN
61% OF WOMEN felt valued by those around them

> *When people feel valued and empowered, they don't just work—they innovate, they inspire, and they drive change.*
>
> \- **Katherine Mackland Rivera**, Senior Director Human Resources at AM Batteries



This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025.

Gender Ratio Drops With More Senior Roles

Gender ratio **declines from 22% to 15%** with increasing seniority in individual contributor roles, a 32 percentage decline.

Gender ratio **declines from 21% to 9%** with increasing seniority in management roles, a 57 percentage decline.

POSSIBLE REASONS

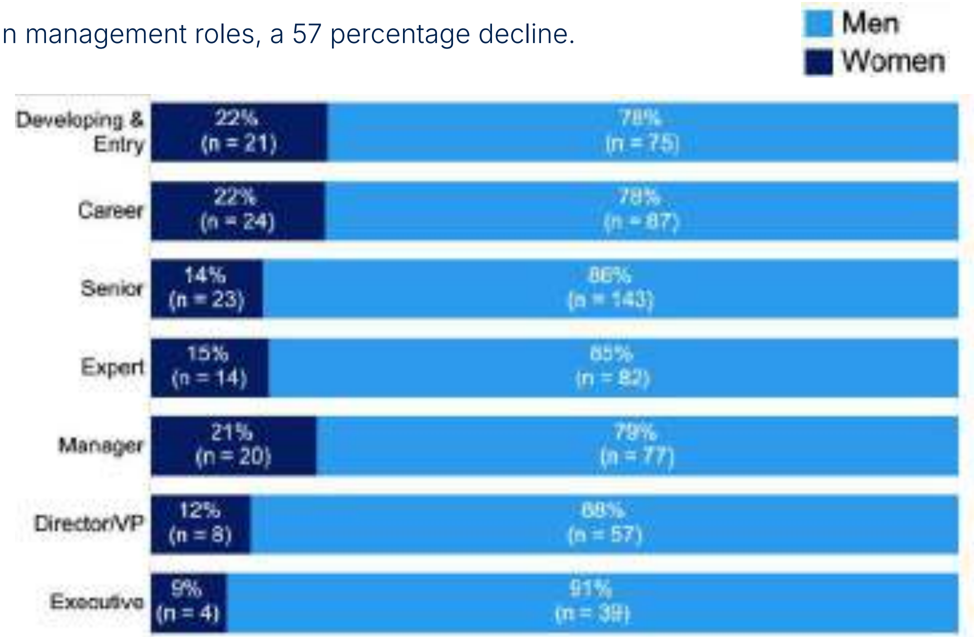
(1) **Glass Ceiling**: Barriers to advancement for women, such as limited access to mentorship, networking, or leadership opportunities.

(2) **Retention:** Issues with organizational culture, work-life balance; systemic biases that hinder the retention and promotion of women into senior roles.

CALL FOR ACTION

Targeted strategies, including mentorship initiatives, and enhanced family leave policies, can empower more women to advance into executive roles.

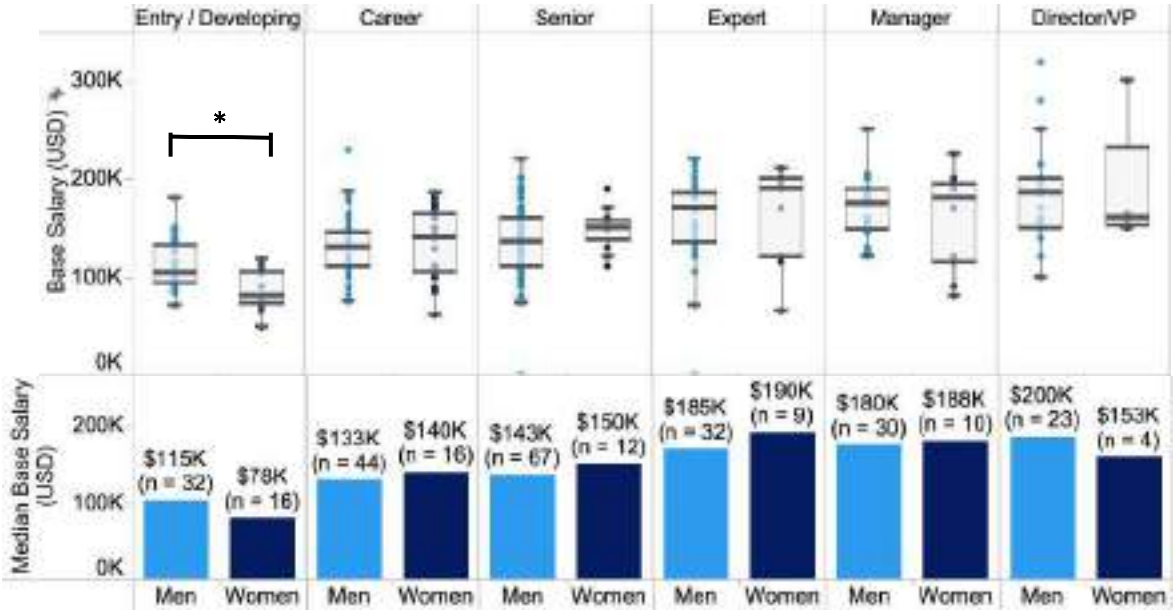
By fostering an inclusive culture, companies can unlock the full potential of their talent pool and drive greater equity in leadership.



This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025. Role definitions: Entry/Developing: contributes to projects, Career: owns projects; Senior: leads small projects; Expert: leads large projects; Manager: provides direct supervision; Director/VP: manages sr. leaders.

Gender Pay Gap Prevalent In Entry Roles But Closes With Seniority

“WHAT IS YOUR ANNUAL BASE SALARY?”



At the Entry/Developing level, women are paid 30% lower on average.

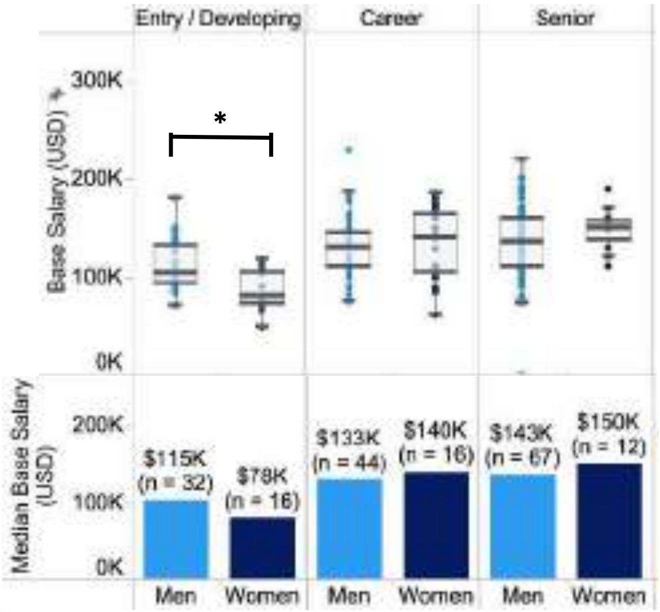
This finding is statistically significant, with p-value < 0.05 (marked by *). Differences in role types do not explain difference in pay (both groups comprise predominantly technical roles).

Boxplot shows 25th, 50th, and 75th percentiles. Whiskers show range excluding outliers. Respondents with $0 salary excluded. Only respondents currently working are included. U.S. only. Statistical significance testing was performed on the “entry/developing” category using a standard t-test. The boxplots consist of 209 data points.

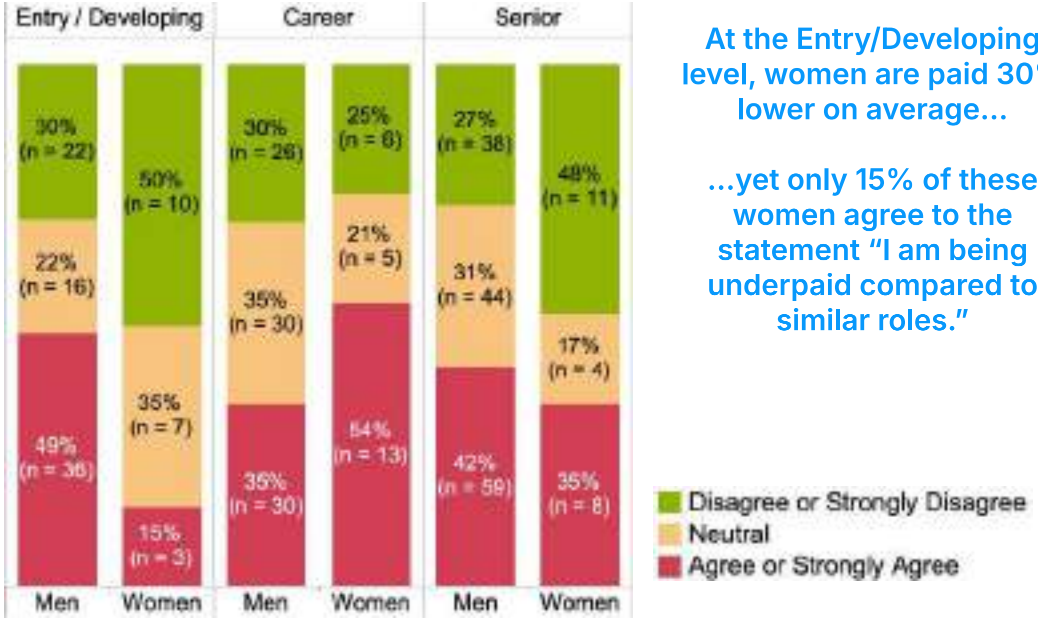
This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025. Role definitions: Entry/Developing: contributes to projects, Career: owns projects; Senior: leads small projects; Expert: leads large projects; Manager: provides direct supervision; Director/VP: manages sr. leaders.

At The Entry Level, Women Are Underpaid But Don’t Think They Are

“WHAT IS YOUR ANNUAL BASE SALARY?”



“I AM BEING UNDERPAID COMPARED TO SIMILAR ROLES”



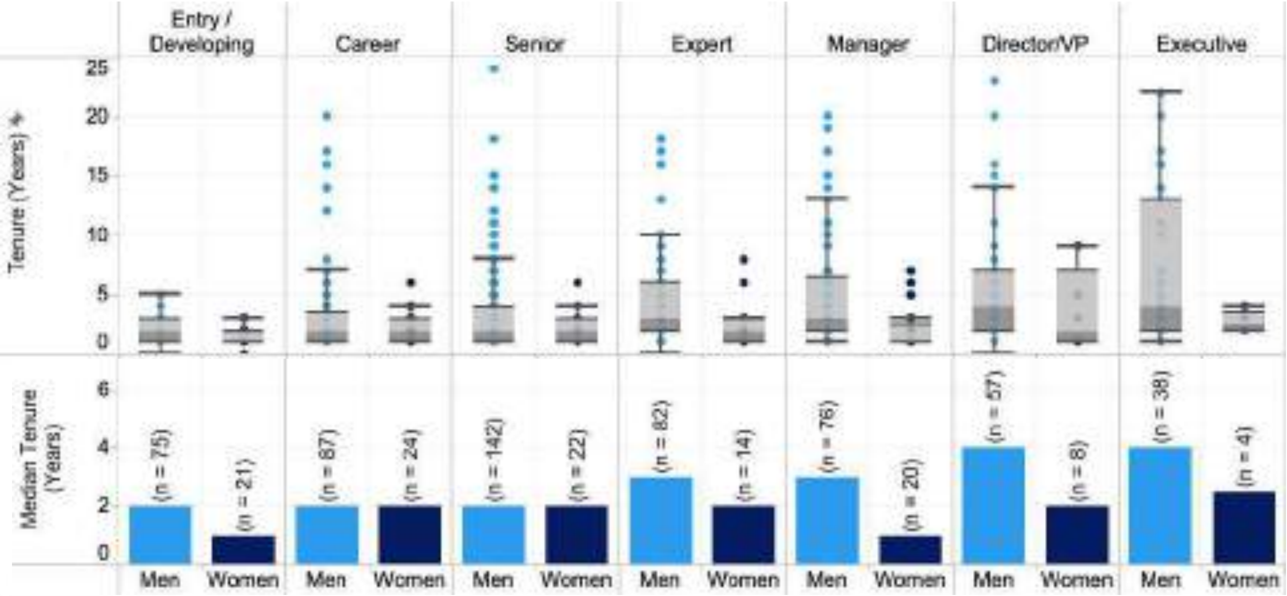
At the Entry/Developing level, women are paid 30% lower on average...

...yet only 15% of these women agree to the statement “I am being underpaid compared to similar roles.”

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025. Role definitions: Entry/Developing: contributes to projects, Career: owns projects; Senior: leads small projects; Expert: leads large projects; Manager: provides direct supervision; Director/VP: manages sr. leaders.

Gender Disparities In Tenure - Reflecting Historical Barriers And Workforce Evolution

"HOW MANY YEARS HAVE YOU BEEN WITH THE COMPANY?"



The battery industry, like many STEM-related fields, has been male-dominated historically.

Women entering these spaces may still be navigating cultural and structural challenges, leading to shorter tenures in some cases.

This slide contains excerpts from the Battery Talent Census Report to be released in mid-2025. Role definitions: Entry/Developing: contributes to projects, Career: owns projects; Senior: leads small projects; Expert: leads large projects; Manager: provides direct supervision; Director/VP: manages sr. leaders.

Driving Change - Conversations On Reducing Gender Bias In The Battery Industry

Q1 2024

FEB 12, 2024

Women in Battery Research:
Pioneering Innovation and Equality

Gender Equality Committee
BATTERY 2030+

Q2 2024

Q3 2024

2024 WOMEN IN BATTERIES CONFERENCE

JULY 26, 2024

Initiative to dive deeper into the challenges faced by women in the batteries industry & brainstorm strategies to drive positive change

Q4 2024

OCT 10, 2024

Panel on Catalysts of Change:
Senior Leaders Advancing Women in the Battery Industry

THE BATTERY SHOW NORTH AMERICA

Women in Battery Meet-up
@Future Battery Forum 2024

NOVEMBER 5, 2024

Meet-up for female battery experts in technical positions

In 2025, we anticipate these efforts will continue to expand, with initiatives like the **DOE's Battery Workforce Challenge Program,** launching regional training hubs to enhance skill development and workforce readiness.

3 TALENT

VF | VOLTA FOUNDATION

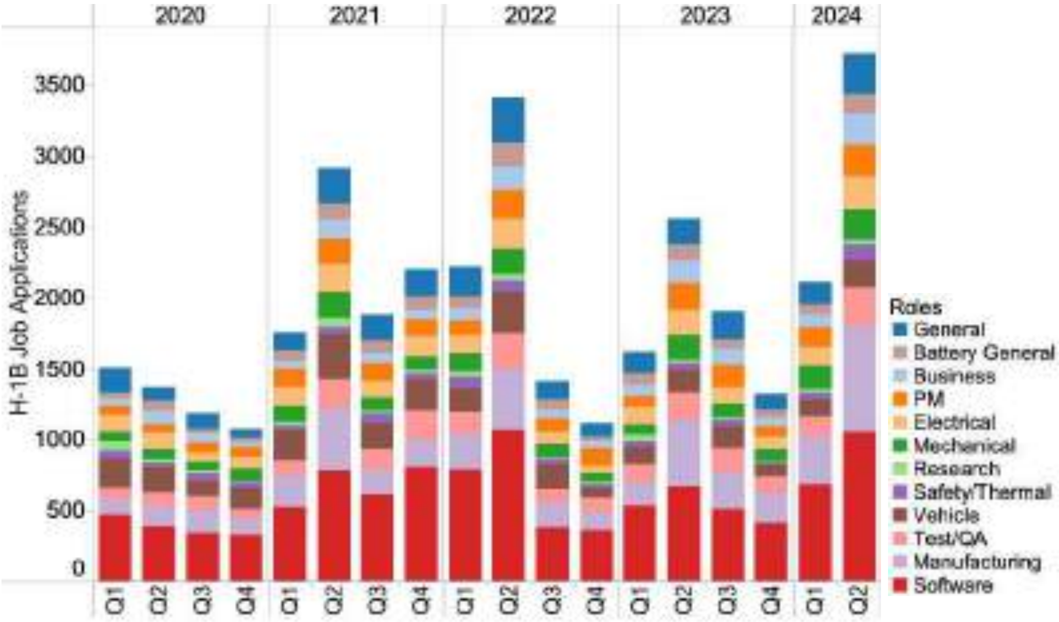
H-1B Application Submission Map From Jan 2023 To June 2024

TOP SIX STATES FOR H1-B APPLICATIONS:

1. California
2. Michigan
3. Texas
4. Illinois
5. Arizona
6. Nevada

The H-1B is a visa allows US employers to temporarily employ foreign workers in specialty occupations. H-1B application information, including companies, titles, and salaries, is publicly available through **h1bdata.info**. We analyzed this data to summarize the latest trends. Source code: **GitHub**

Rising H-1B applications, With Increased Demand For Manufacturing Roles



H-1B applications increased overall from 2020 to 2024, with a record set in Q2 2024.

Applications for **software and manufacturing roles dominated**, accounting for ~50% of all H1-B applications in 2024.

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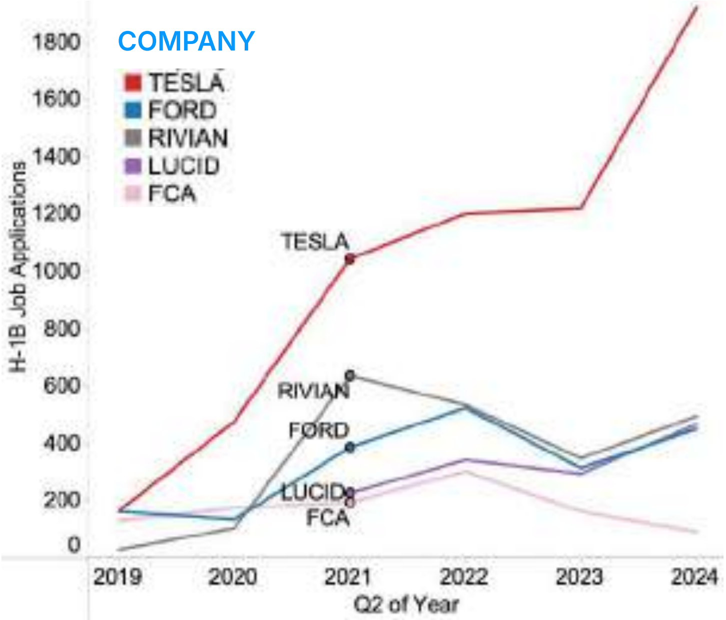
Which Companies Are Hiring For H-1B personnel?

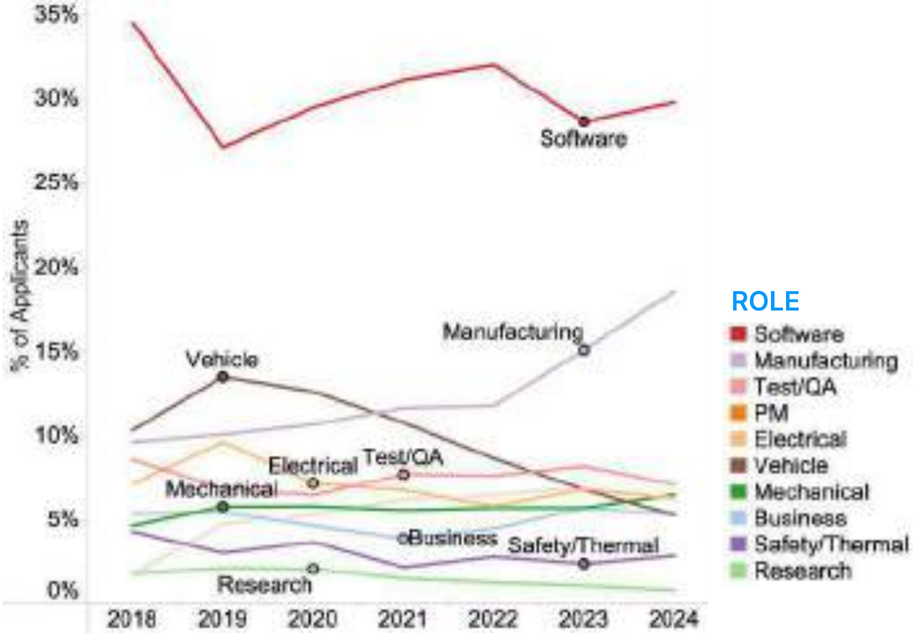


The biggest H-1B employers are auto firms.
Tesla, Rivian, Ford, Lucid, FCA

Tesla is on an H-1B hiring spree in 2024.
Tesla filed more H-1B applications in the first two quarters of 2024 (3,020) than all of 2023 combined (2,752)

The H-1B is a visa allows US employers to temporarily employ foreign workers in specialty occupations. H-1B application information, including companies, titles, and salaries, is publicly available through **h1bdata.info**. We analyzed this data to summarize the latest trends. Source code: **GitHub**

Which Roles Are On The Rise?



Manufacturing roles are on the rise.

Vehicle and research roles are declining.

Roles that remain steady: Software, Test/QA, PM, Electrical, Mechanical, Business, Safety/Thermal

The H-1B is a visa allows US employers to temporarily employ foreign workers in specialty occupations. H-1B application information, including companies, titles, and salaries, is publicly available through **h1bdata.info**. We analyzed this data to summarize the latest trends. Source code: **GitHub**

Comparing H-1B Salary Trends - California vs Michigan By Job Level

Salaries continue to rise overall.

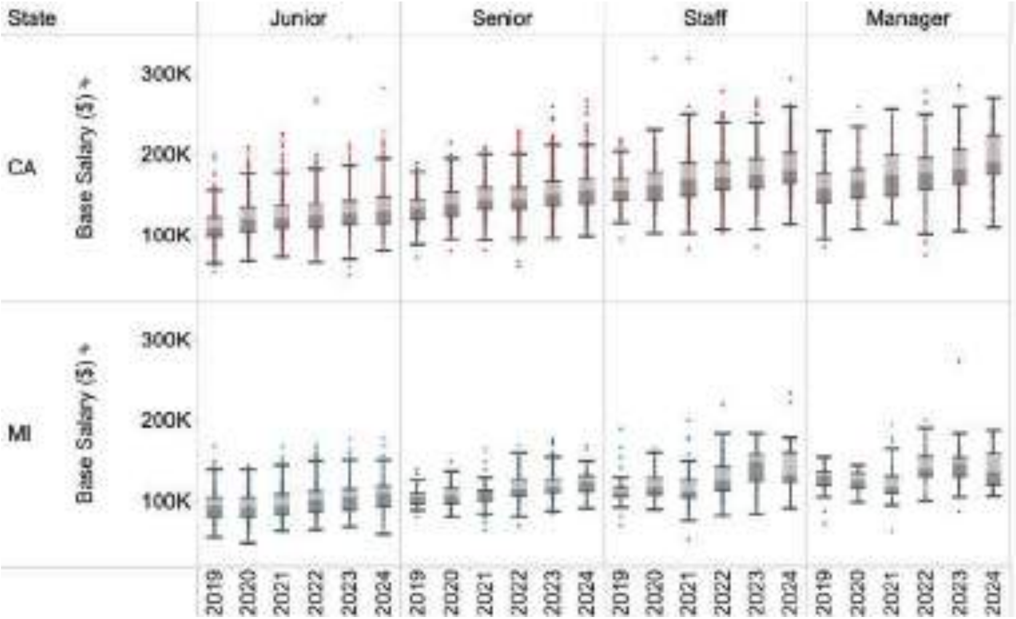
An exception is in staff/manager roles in Michigan, which appear to be falling

Gap remains between MI and CA salaries.

Pay in California is ~30% higher, but so is cost of living.

The H-1B is a visa allows US employers to temporarily employ foreign workers in specialty occupations. H-1B application information, including companies, titles, and salaries, is publicly available through **h1bdata.info**. We analyzed this data to summarize the latest trends. Source code: **GitHub**

Salaries Vary Widely - Negotiate Your Salary!



Base salary ranges are wider in California, possibly reflecting more varied roles, regional cost-of-living differences, rapid-growth companies, talent shortages, flexibility in negotiation, inequities in pay, and economic uncertainty.

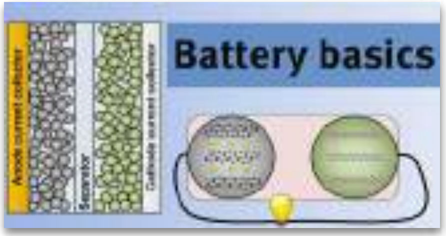
The H-1B is a visa allows US employers to temporarily employ foreign workers in specialty occupations. H-1B application information, including companies, titles, and salaries, is publicly available through **h1bdata.info**. We analyzed this data to summarize the latest trends. Source code: **GitHub**

3 TALENT

New To Batteries And Short On Time? Here Are Our Favorite Free "Battery Crash-Courses."

Battery Basics - An introduction to the science of lithium-ion batteries

22 minutes



Channel: Billy Wu

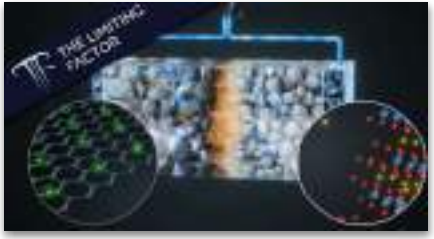
How a Lithium Ion Battery is Made [Using Food!]

24 minutes

Channel: Across the Nanoverse

How a Lithium Ion Battery Actually Works / Photorealistic

17 minutes



Channel: The Limiting Factor

BATTERY UNIVERSITY

General battery knowledge with resources for understanding charging methods and battery monitoring

Battery Design
from chemistry to pack

Practical resources for battery engineers with information on cell design, cell types, BMS, modules, pack integration, and benchmarks

Do you want to recommend your favorite educational resource for next year's Battery Report?
Email **andrew@volta.foundation.**

Source: Linked above

Skills In Demand And Where To Learn Them - Battery Manufacturing And Design

UNIVERSITY OF MICHIGAN

Battery Cell Manufacturing, Testing, and Design

Online | $1200 | 30 hrs | Self-Paced

Starts April 2025

Industry-relevant take on large-scale manufacturing challenges, process fundamentals, defects, testing methods, and cell design; taught by an industry veteran.

ECS The Electrochemical Society
Advancing solid state & electrochemical science & technology

Manufacturing of Lithium Ion Batteries and Pack Design

Online | $399+ | 25 hrs | Self-Paced

Starts March 2025

Industry-relevant take on methods for preparing laminate electrodes, electrode stacking/winding, and pack construction; taught by an industry veteran.

udemy

Li-ion Battery Manufacturing Fundamentals

Online | $45 | Self-Paced | 2 hrs

Start Now

A tour of major manufacturing steps with relevant insights.

Do you want to recommend your favorite educational resource for next year's Battery Report? Email **andrew@volta.foundation.**

Source: Linked above

Skills In Demand And Where To Learn Them - Battery Management Systems

Ania Mitros, PhD

Ania's Battery Management System (BMS) Course

Online | Free | Self-Paced

Start Now

Industry-relevant take on BMS implementation including safety, testing, and reliability considerations; taught by an industry veteran.

UCCS University of Colorado Colorado Springs

Algorithms for Battery Management Systems Specialization

Online | Free | Self-Paced

Start Now

Taught by Dr. Gregory Plett and hosted by Coursera, learn how to model lithium-ion battery cells and use them to manage battery packs.

udemy

Mastering Advanced Battery Management for Electric Vehicle

Online | $13.99 | Self-Paced

Start Now

Focuses on designing BMS for EVs, covering everything from component selection and algorithm design to hardware circuits and code implementation on STM32 microcontrollers.

Do you want to recommend your favorite educational resource for next year's Battery Report? Email andrew@volta.foundation.

Source: Linked above

Skills In Demand And Where To Learn Them - Electrochemistry And Battery Materials

The Electrochemical Society
Advancing solid state & electrochemical science & technology

Preparing Future Leaders of the Lithium Ion Battery Industry

Online | $399+ | 15-25 hrs

Start Now

Two courses: (1) "Materials Science in Lithium Ion Battery Components: Electrolytes, Anodes, and Cathodes", and (2) "Electrochemical Techniques and Diagnostics for Batteries"

MIT OpenCourseWare

Electrochemical Energy Systems

Online | Free

Start Now

Taught by Dr. Martin Bazant, lectures on the principles of electrochemical devices focusing on mathematical model development.

PURDUE UNIVERSITY nanoHUB

Intro to the Materials Science of Rechargeable Batteries

Online | Free

Start Now

Taught by Dr. Edwin Garcia, learn the materials science of rechargeable batteries using a unique, "bottom up" approach.

UNIVERSITY OF OREGON

Electrochemistry Video Lectures

Online | Free

Start Now

A collection of lectures on electrochemical thermodynamics, advanced electrochemistry, and electrochemical engineering.

Do you want to recommend your favorite educational resource for next year's Battery Report? Email **andrew@volta.foundation.**

Source: Linked above

Skills In Demand And Where To Learn Them - Technician Training Programs

Technician Short Course

In person | $2.2k | Monthly | 3 days

Course for technicians within energy storage highlighting fundamentals of batteries.

Battery Technician Program

Online | $2.4k | On Demand | 25 hrs

Course covers designing, operating, testing, maintaining, and replacing battery cells and packs.

EV Technician Training

Online | On Demand

Two-part course focused on safety and maintenance of test instruments and equipment for high-voltage vehicle components.

NENY Battery Academy

Online | Free (NY Res. Only)

Flexible learning platform for workforce training including Introduction to Energy Storage and Battery Technician program.

Battery Technician Training

Online (Async.) | $500 | 8 weeks

Focuses on **new skills** needed for designing, operating, testing, maintaining, and replacing battery cells and packs.

Do you want to recommend your favorite educational resource for next year's Battery Report? Email **andrew@volta.foundation.**

Source: Linked above

Skills In Demand And Where To Learn Them - Battery Safety

CHARGING

Free Battery Safety Short Online Course

Online | Free | On Demand | 4 hours

Focuses on battery fundamentals; **safe handling, charging, and maintenance of e-bikes**; managing hazards; safe disposal and recycling of used batteries

MANUFACTURING

Introduction to Battery Safety

Online | $385 | On Demand | 3 hrs

Focuses on essential **safety aspects of battery** manufacturing, testing, storage, handling, and disposal.

THERMAL

Short Course on LIBs: Fundamental Concepts, Battery Safety, and Modeling Techniques

Online | Free | On Demand | 2 hours

Focuses on **thermal safety, thermal modeling, and thermal runaway.**

RECYCLING FACILITIES

ReMA Battery Safety Courses

In Person & Online | On Demand

Focuses on **safety in recycling facilities**; help recycling facilities face new risks.

Do you want to recommend your favorite educational resource for next year's Battery Report? Email **andrew@volta.foundation.**

Source: Linked above

Training Hubs That Offer A Menu Of Content, From The General To The Specific

HOSTS	LINK	DESCRIPTION
BatteryMBA	**Battery MBA**	Combines technical and business knowledge
L&T EduTech	**L&T EduTech E-Mobility Program**	Electric mobility focus: battery systems, charging infrastructure, and EV technology
renac	**Battery Energy Storage Systems for Grid Ancillary Services**	Application of battery energy storage systems in grid ancillary services
eit InnoEnergy	**Skills Institute Free Courses**	A range of free courses related to energy and battery technologies
SAE	**SAE International Courses**	Fundamental knowledge and insights into various battery technologies and applications
NENY	**NENY Battery Academy**	Flexible learning platform offering micro-credentialing programs for workforce training
	Battery Training Online	“Lifelong learning program ... combines cutting-edge knowledge with industry insights”
coursera	**Coursera**	Recommended courses: 1) Lithium Based Batteries, 2) Introduction to Battery, 3) Management Systems, 4) Innovations in Lithium Battery Technology
BIC	**BIC Educational Series**	In-person course offerings include Energy Storage Short Course, Quality Training, Technician Course and Operator Training
Soteria	**Battery Training Courses**	Training programs geared toward mitigating knowledge gaps in the battery industry

Webinars To Follow In 2025

HOSTS	LINK	DESCRIPTION
ECS The Electrochemical Society	**ECS Webinar Series**	Distinguished speakers presenting research in electrochemistry and solid-state science
THE FARADAY INSTITUTION	**Faraday Institution Masterclass**	Classes and events focused on battery technology and related research topics
UNIVERSITY OF MICHIGAN	**Modeling Webinar Series VENKAT**	Battery modeling research and advancements in battery technology
Rigaku	**Rigaku Battery Webinars**	X-ray analysis techniques to gain insights into battery performance and materials
Advanced Batteries & Energy Storage RESEARCH	**Advanced Batteries & Energy Storage Research Webinars**	Focuses on innovations across the battery lifecycle, including mining practices
physicsworld	**Physics World Webinars**	A range of scientific topics including energy storage technologies
BATTERY 2030	**Battery 2030 Excellence Seminars**	Future battery technologies and sustainability with various educational webinars
BENCHMARK	**Fastmarkets, CRU, Benchmark Minerals**	Commodity markets, battery technology and policy, supply chain, market dynamics
VOLTAIQ | NOVONIX	**Advanced Battery Quality Analytics Series**	Differential capacity (dQ/dV) and NOVONIX Ultra-High Precision Coulometry (UHPC)

Our Favorite Podcasts Of 2024

NEWS, INTERVIEWS, DISCUSSIONS

NEWS, CLIMATE, INVESTMENT, INTERVIEWS, DISCUSSIONS

RESEARCH, TECHNICAL TOPICS

Source: Linked above

4 POLICY

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.

4 POLICY

Policy Summary

2024 was a year of policies aimed at **diversifying supply chains, protecting domestic industries, and seizing control and influence in the battery industry and in new generation technologies.**

China implemented measures to address domestic overcapacity while also reinforcing its dominance in battery supply chains, battery technology, and battery end-use demand.

USA introduced targeted financial support for domestic projects while also ramping up restrictions on Chinese involvement in US-linked supply chains.

Europe hiked tariffs on Chinese EVs in an attempt to protect its domestic automotive industry, but it has also been open to Chinese investment. Europe is also suffering from attrition in EV subsidies and region-wide targets, but other policies have strengthened efforts in recycling and circular economies.

In the rest of the world, several countries have gradually ramped up protectionist policies in an effort to capture the economic and strategic benefits of the growing battery industry, but they largely remain open to Chinese partnership.

Despite some setbacks, nations worldwide are accelerating their efforts and investments in the energy transition off the back of abundant supply and exceptionally low costs for batteries.

Policy Summary

2024: The year of battery policy focused on securing and diversifying supply chains, protecting domestic industries, and seizing control and influence in the battery industry and in new generation technologies.

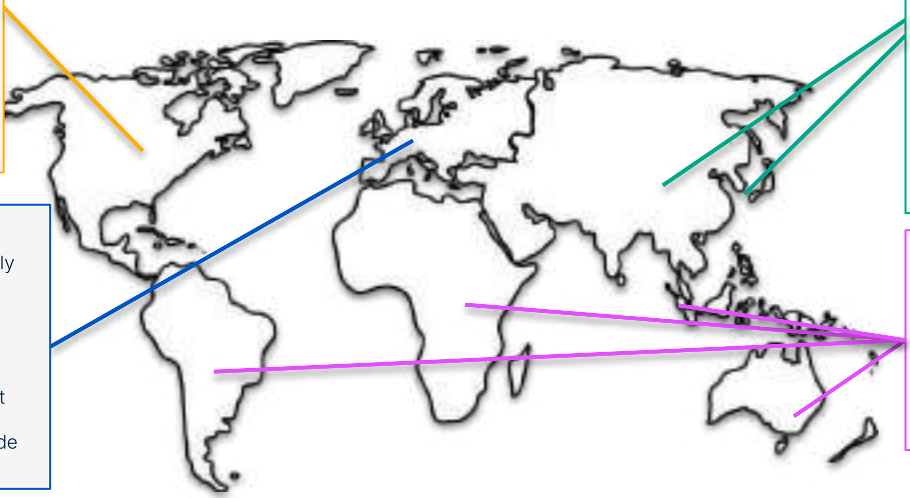
NORTH AMERICA

- The US DOE directed $3 billion in funding to **support EV and grid battery supply chain development**
- Canada launched the **critical minerals hub** and invested in production and traceability, but **paused EV rebates**
- **US** and **Canada** imposed higher tariffs on China-made EVs, batteries, and battery materials
- Mexico's proximity to U.S. auto market and the **USMCA realized new foreign investments and joint ventures**

EUROPE

- European **Critical Raw Materials Act** officially adopted
- **Substantial investments will be made by European Commission and the European Investment Bank** to support EV battery cell manufacturing products
- EV subsidies continue in many countries, but **Germany halted subsidies for 2024**
- **Increased tariffs up to 45.3%** on China-made EVs depending on the manufacturer

GLOBAL POLICY TAKEAWAY/TRENDS



ASIA

- China has introduced new industry standards aimed at **phasing out low-quality capacity**
- China set out a proposal to **ban the technology exports** for high-end LFP CAM and lithium processing
- China **reduced or removed the rebate on export taxes** on a range of battery-related products
- China extended the EV tax reduction and exemption policy to 2027, and has **introduced a vehicle scrappage scheme favouring EVs**

REST OF WORLD

- Indonesia started to enact policies that penalize low-grade and high-emitting **nickel smelting operations**
- Argentina signed a MoU with the US that would **grant it free-trade status with respect to critical minerals**

Key Events In 2024

JANUARY

In China, **tax exemption policy** for NEV begins, effective until 2027. EVs purchased before end of 2025 exempt from purchase tax up to RMB30,000.
EU announced €4b of state aid investments in new factories producing electric batteries for cars, heat pumps and solar panels.

MAY

China issues draft rules to regulate Li battery expansion, reducing manufacturing projects that 'purely' expand production capacity.
US imposes tariffs against a range of high-tech products from China, including 100% tariffs on EVs and 25% on EV batteries.

JUNE

European Commission announced **provisional penalty tariffs** ranging from 17.4% to 38.1% against EVs imported from China.

AUGUST

A number of new requirements under the **EU Batteries Regulation (2023/1542)** start to apply.

SEPTEMBER

The Department of Energy announced **$3B+ funding for 25 projects** across 14 states, aiming to boost the production of advanced batteries and materials for EVs.

OCTOBER

South Korea requires **automakers to disclose cell and battery information**.

DECEMBER

China announces stringent export restrictions on rare earth minerals and bans their shipments to the US. China also removes the export tax rebate on a range of battery-related products.

JANUARY 2025

China's Ministry of Commerce set out a proposal to **restrict the export of certain LxFP CAM and lithium processing technologies.**

Policy Highlights From Industry Section

FUNDING

- DOE Federal Funds in Battery Technology

BESS

- Regulatory Map For BESS Projects In Major Markets
- Overview Of Global Policy Support for BESS
- BESS: IRA Investment Tax Credit Guidelines
- BESS: IRA Domestic Content Bonus vs. Requirements
- BESS: IRA BESS Safe Harbor Policy

EV

- EU Hikes Tariffs On Chinese-made BEVs
- China's Subsidies For EV Companies Have Been Scaled Back

MINERALS

- Indonesia Nickel Curtailment Policy
- Recycling Legislation Across The Globe

OTHER

- Cybersecurity Standards and Regulations
- Right to Repair Act

4 POLICY

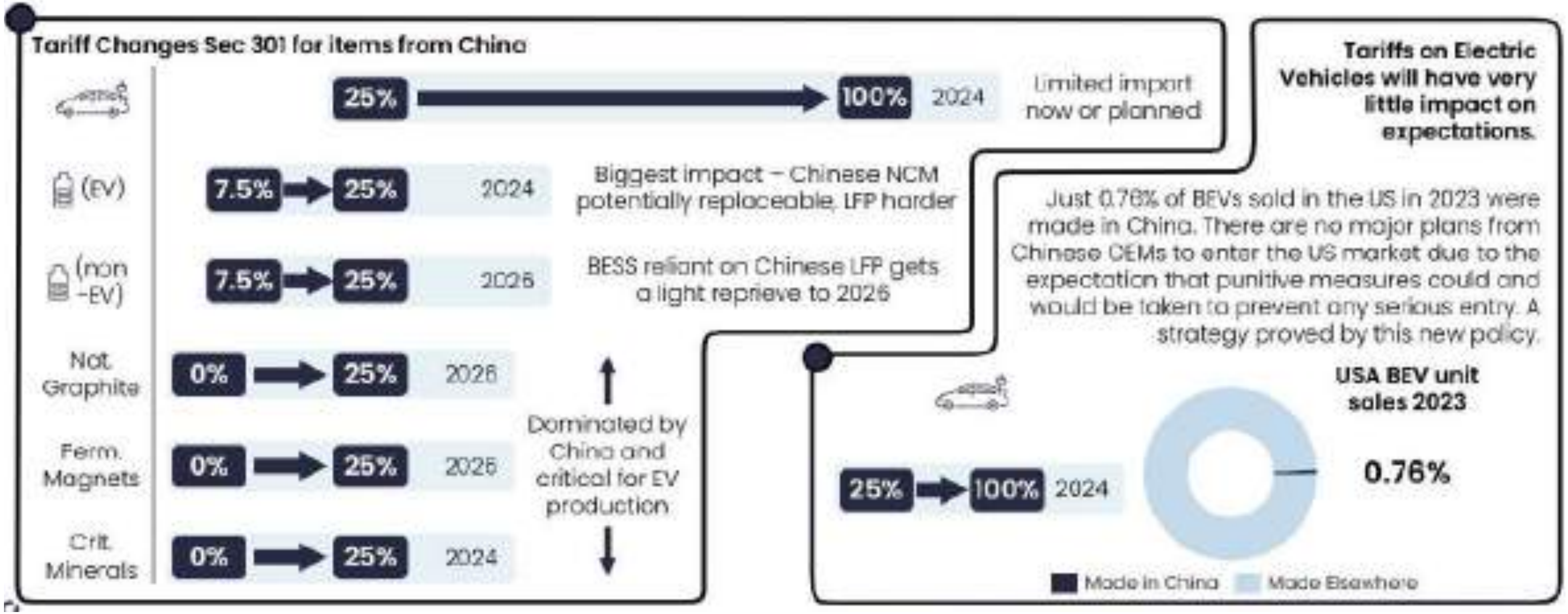
US IRA Tax Credits And What Is At Stake

New Trump admin aims to overhaul at least some of the IRA tax credits, starting with the EV credit.
Some industry stakeholders expect Foreign Entity of Concern requirements to be added to the production tax credits.

Raw materials	Components	Cell	Pack	Applications	End of life
Critical minerals production tax credit **10% of costs**	**Battery electrode active materials** production tax credit **10% of costs**	**Battery cells** production tax credit **$35/kWh**	**Battery modules** production tax credit **$10/kWh**	**EV tax credit $7,500** **Energy storage** investment tax credit **6% (base credit) Up to 30% + 10%**	**Critical minerals** production tax credit **Battery electrode active materials** production tax credit **Recycled materials** indirectly through EV tax credit

BloombergNEF Source: Content & analysis provided courtesy of BloombergNEF (Distinguished Partner). For more information, visit https://about.bnef.com/contact/.

US Tariffs On China Under Biden Is Expected To Increase Further Under Trump



Tariff Changes Sec 301 for items from China

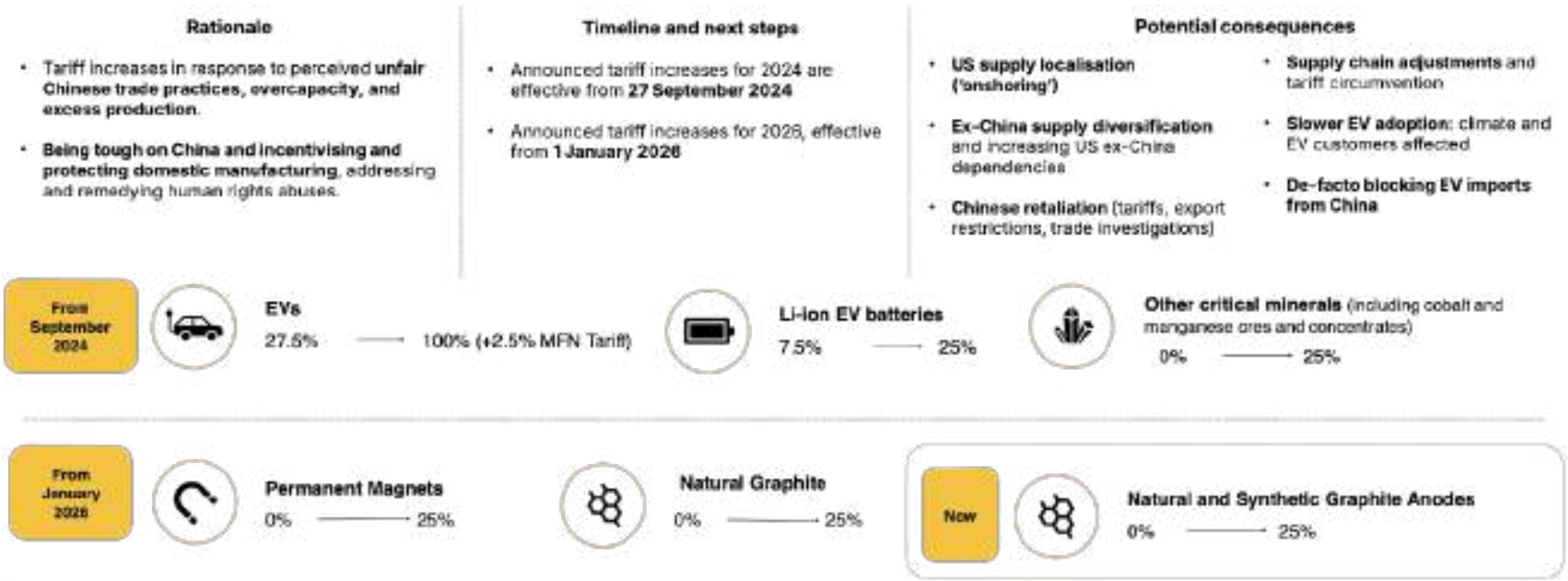
	25%	100%	2024	Limited import now or planned
(EV)	7.5%	25%	2024	Biggest impact – Chinese NCM potentially replaceable, LFP harder
(non -EV)	7.5%	25%	2026	BESS reliant on Chinese LFP gets a light reprieve to 2026
Nat. Graphite	0%	25%	2026	Dominated by China and critical for EV production
Perm. Magnets	0%	25%	2026	
Crit. Minerals	0%	25%	2024	

Tariffs on Electric Vehicles will have very little impact on expectations.

Just 0.76% of BEVs sold in the US in 2023 were made in China. There are no major plans from Chinese OEMs to enter the US market due to the expectation that punitive measures could and would be taken to prevent any serious entry. A strategy proved by this new policy.

Source: Content & Analysis provided courtesy of Rho Motion (Distinguished Partner). For more information, visit https://rhomotion.com/research/ev-battery-quarterly-outlook/.

US Section 301 Tariff Increases Impacting The EV Battery Supply Chain



Rationale

- Tariff increases in response to perceived **unfair Chinese trade practices, overcapacity, and excess production.**
- **Being tough on China and incentivising and protecting domestic manufacturing**, addressing and remedying human rights abuses.

Timeline and next steps

- Announced tariff increases for 2024 are effective from **27 September 2024**
- Announced tariff increases for 2026, effective from **1 January 2026**

Potential consequences

- **US supply localisation ('onshoring')**
- **Ex-China supply diversification** and increasing US ex-China dependencies
- **Chinese retaliation** (tariffs, export restrictions, trade investigations)
- **Supply chain adjustments** and tariff circumvention
- **Slower EV adoption:** climate and EV customers affected
- **De-facto blocking EV imports from China**

From September 2024

EVs
27.5% → 100% (+2.5% MFN Tariff)

Li-ion EV batteries
7.5% → 25%

Other critical minerals (including cobalt and manganese ores and concentrates)
0% → 25%

From January 2026

Permanent Magnets
0% → 25%

Natural Graphite
0% → 25%

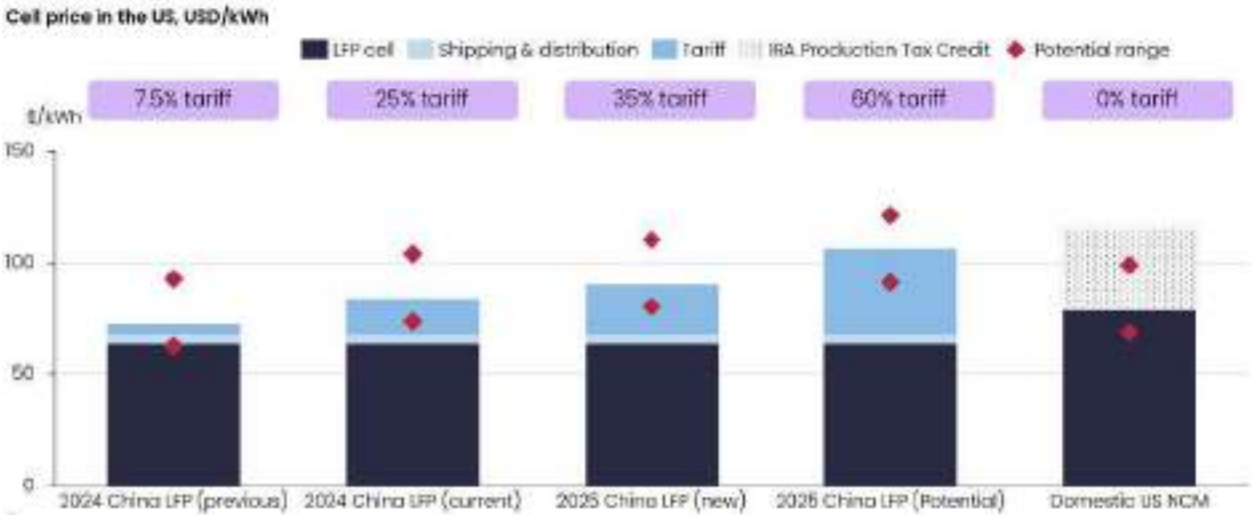
Now

Natural and Synthetic Graphite Anodes
0% → 25%

BENCHMARK

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/policy-newsletter.

US Battery Tariffs May Provide Upside To Domestic NCM

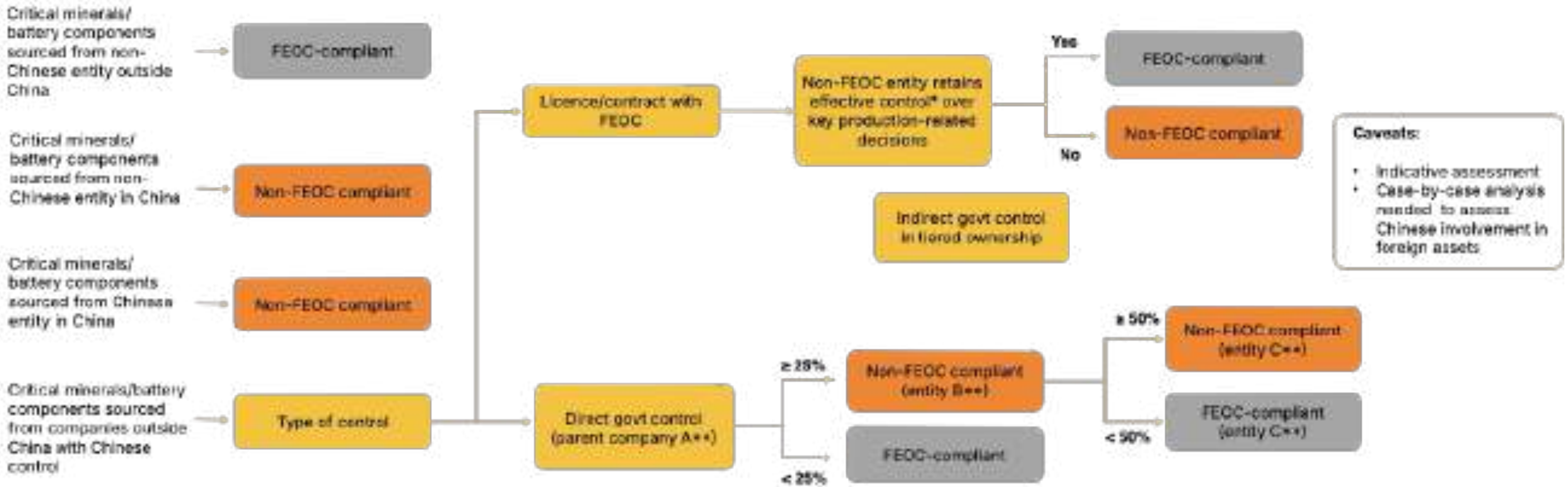


US President-elect Donald Trump has stated he will impose tariffs of 25% on all imports from Canada and Mexico, and an extra 10% on Chinese goods on his first day in office. The tariffs on China would apply to all imports and would come on top of existing levies. Given the recent increase on battery imports from China for EV applications to **25%**, from the previous **7.5%** level, this would result in a new tariff level of **35%** for batteries imported from China. Previously, a tariff level as high as **60%** has also been suggested.

Source: Content & Analysis provided courtesy of Rho Motion (Distinguished Partner). For more information, visit https://rhomotion.com/research/ev-battery-quarterly-outlook/.

How ‘Foreign Entity Of Concern’ Compliance Is Determined

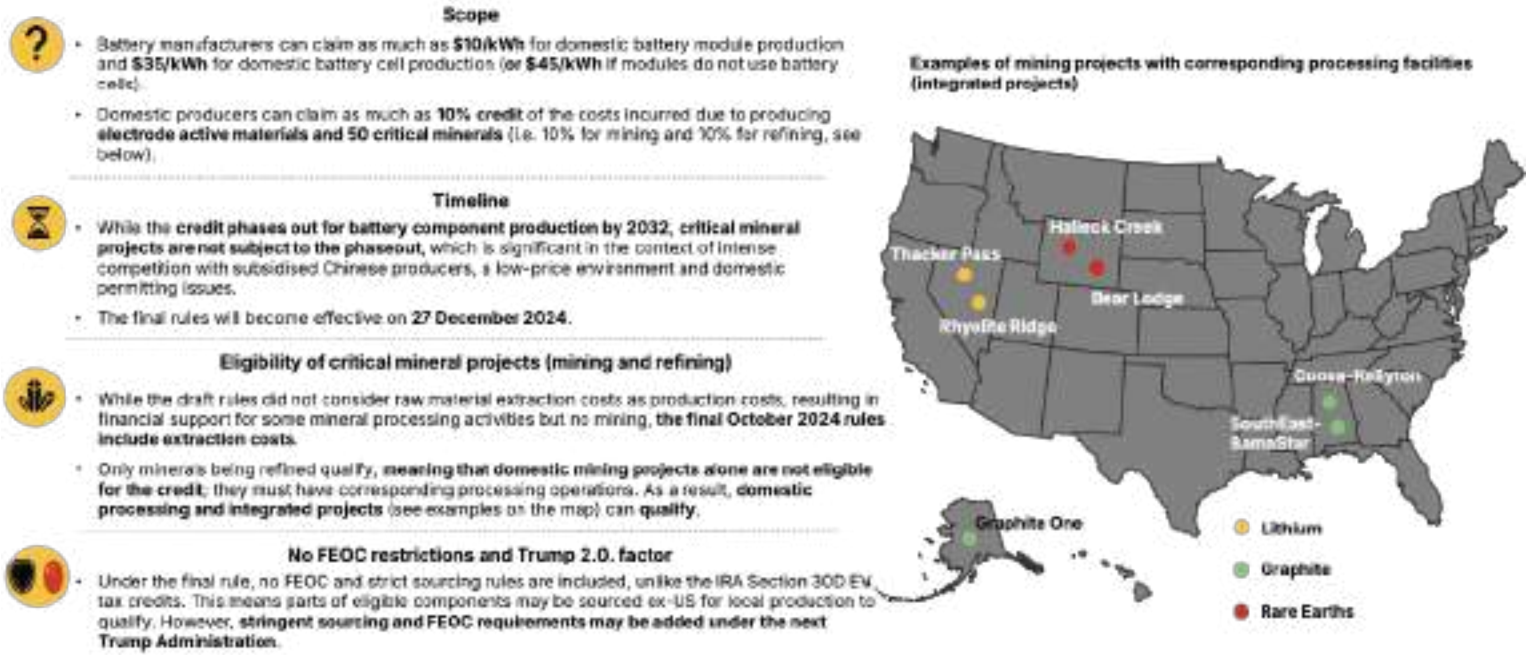
FEOC rules currently only apply to the EV tax credit (30D)



**Effective control = “the right to determine the quantity or timing of production and which entities may purchase or use the output of production; to restrict access to the site of production to the contractor’s own personnel; or the exclusive right to maintain, repair, or operate equipment that is critical to the production.*

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/policy-newsletter.

Final IRA Advanced Manufacturing Product (AMP) 45X Rules Favor Midstream, But Miners Say Incentives Fall Short



Scope

- Battery manufacturers can claim as much as **$10/kWh** for domestic battery module production and **$35/kWh** for domestic battery cell production (or **$45/kWh** if modules do not use battery cells).
- Domestic producers can claim as much as **10% credit** of the costs incurred due to producing **electrode active materials and 50 critical minerals** (i.e. 10% for mining and 10% for refining, see below).

Timeline

- While the **credit phases out for battery component production by 2032, critical mineral projects are not subject to the phaseout**, which is significant in the context of intense competition with subsidised Chinese producers, a low-price environment and domestic permitting issues.
- The final rules will become effective on **27 December 2024**.

Eligibility of critical mineral projects (mining and refining)

- While the draft rules did not consider raw material extraction costs as production costs, resulting in financial support for some mineral processing activities but no mining, **the final October 2024 rules include extraction costs**.
- Only minerals being refined qualify, **meaning that domestic mining projects alone are not eligible for the credit**; they must have corresponding processing operations. As a result, **domestic processing and integrated projects** (see examples on the map) can **qualify**.

No FEOC restrictions and Trump 2.0. factor

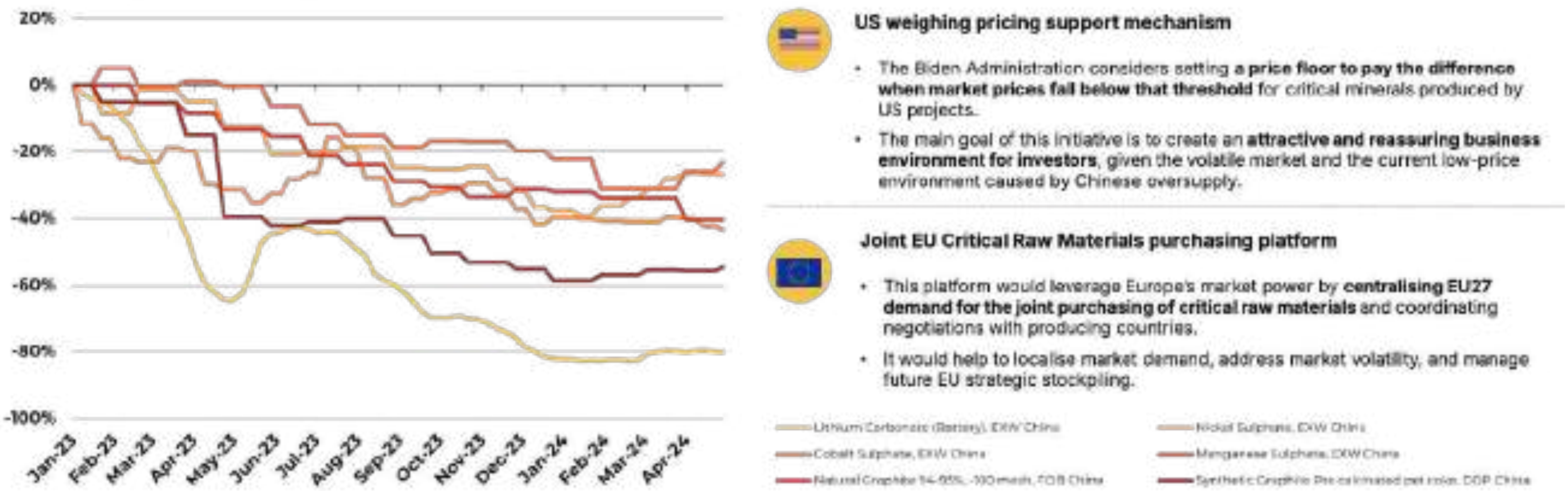
- Under the final rule, no FEOC and strict sourcing rules are included, unlike the IRA Section 30D EV tax credits. This means parts of eligible components may be sourced ex-US for local production to qualify. However, **stringent sourcing and FEOC requirements may be added under the next Trump Administration**.

Examples of mining projects with corresponding processing facilities (integrated projects)

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/policy-newsletter.

US & EU Weigh Market Intervention to Boost Domestic Critical Minerals

A LOW-PRICE ENVIRONMENT MAKES IT HARDER FOR MINING AND PROCESSING PROJECTS TO SECURE FUNDING



US weighing pricing support mechanism

- The Biden Administration considers setting **a price floor to pay the difference when market prices fall below that threshold** for critical minerals produced by US projects.
- The main goal of this initiative is to create an **attractive and reassuring business environment for investors**, given the volatile market and the current low-price environment caused by Chinese oversupply.

Joint EU Critical Raw Materials purchasing platform

- This platform would leverage Europe's market power by **centralising EU27 demand for the joint purchasing of critical raw materials** and coordinating negotiations with producing countries.
- It would help to localise market demand, address market volatility, and manage future EU strategic stockpiling.

BENCHMARK

Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/policy-newsletter.

4 POLICY

Countering Strong Incentives Outside, EU Attempts To Catch Up Using Various Subsidies

Relevant subsidy programs for battery ecosystem

TIME	FUND	FOCUS	BUDGET
2019 - 2031	IPCEI: Important Projects of Common European Interest	A European-wide initiative that aims to build up a sustainable and competitive battery value chain in Europe. 12 EU member states provide funding for more than 50 companies for the first industrial deployment of innovative battery technologies	€6.1 billion
2021 - 2027	Horizon Europe Programme and Co-Programmed Partnership Batt4EU	The aim of BATT4EU is to establish a European battery value chain by 2030. The objectives are to increase battery energy and power densities and charging rates, improve cycle lifetime, reduce battery costs, implement best-in-class operations for manufacturing and recycling, and reduce the carbon footprint. Battery research is also funded through other calls, such as those launched by the ERC and the EIC.	€95.5 billion (€925 million for BATT4EU)
2023 - 2025	TCTF: Temporary Crisis Transition Framework	Support measures in sectors that are key for the transition to the net-zero economy. Enabling investment support for the manufacturing of batteries, solar panels, wind turbines, heat-pumps, electrolysers, as well as financial support to build up the recycling industry for critical raw materials	€1.287 billion (transition measures)
2020 - 2030	Innovation Fund	The Innovation Fund aims to help businesses invest in clean energy and industry to boost economic growth, create local future-proof jobs, and reinforce European technological leadership on a global scale	€38 billion
Since 1958	European Investment Bank	The European Investment Bank is the lending arm of the European Union. We are one of the biggest multilateral financial institutions in the world and one of the largest providers of climate finance.	Green finance target of € 1 trillion by 2030

Source: Batteries Europe

Main Subsidies Are Oriented At Research & Development and Innovation, Upscaling And Clean-tech Debt Financing

HORIZON EUROPE

Research & Innovation

Under the framework of Horizon Europe (2021 - 2027), the BATT4EU Partnership has a dedicated budget of **€ 925 million** to fund consortiums working on **R&I activities** in the battery sector.

Topics include raw materials, novel chemistries, design, manufacturing, application (mobility & stationary storage, dismantling and recycling, transversal topics (LCA, battery passport etc.)

INNOVATION FUND

Upscaling to commercial level

16 energy storage manufacturing projects requesting **€ 1,27 billion** of public support in total.

Projects cover **component manufacturing, cell & pack manufacturing** and **recycling.**

Companies currently benefiting include FREYR, Northvolt, Vianode, talga, Gränges, fenecon, Eramet, BASF and Valeo.

New Innovation Fund call extends budget to **€ 3,4 billion**, with **€ 1 billion reserved specifically for cell manufacturing projects**

EUROPEAN INVESTMENT BANK

Debt Financing

Since 2018, **10 companies** across the battery value chain have been supported for a total of **more than € 370m EIB Financing**, leading to **more than € 700m of investments.**

Most known examples of venture debt investments are **Northvolt and Verkor.**

Source: BEPA, European Commission, European Investment Bank

Strong Differences Between National Battery Related Subsidies

GERMANY:

The Federal Ministry of Education and Research (BMBF) confirmed that "**from 2025, it is unlikely that any new battery research projects can be launched with the remaining funds**".

NETHERLANDS:

In December 2024, an innovation funding call was launched focusing on **battery circularity**. With a budget of **€ 90 million**, projects on battery recycling, next-gen chemistries, extending battery lifetime and circular batteries for heavy duty transport will be funded.

SPAIN:

As part of the PERTE funding programme, the Spanish Ministry of Industry has promised **Stellantis subsidies totalling 133 million euros for a potential battery cell factory** at the Figueruelas plant near Zaragoza. The ministry has also agreed to increase the funding for the **PowerCo battery factory in Sagunt from 98 to 152 million euros**.

Source: Spiegel Möbilitat, RVO, Reuters

EU Battery Regulation 2023-2024

2023

JULY 2023:
The European Council adopted the Battery Regulation 2023/1542, setting the legal framework for battery management in the EU

DECEMBER 2023:
Target for collecting used portable batteries - 45% of the amount introduced to the market

2024

FEBRUARY 2024:

Article 6
Limiting the use of hazardous substances in batteries (cadmium, mercury, lead)

AUGUST 2024:

Article 10
Introduction of performance and durability requirements for industrial batteries above 2kWh, LMT batteries and batteries for electric vehicles

Article 12
Safety rules for stationary energy storage systems

Article 14
Obligation to inform about state of health and expected battery life (ESS, LMT, EV)

Chapter IV
Introduction of the CE marking, the EU declaration of conformity and the assessment of compliance of batteries with the EU market

2025

Source: https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng

EU Battery Regulation Through 2025

2025

18 FEBRUARY 2025:
Article 7
Carbon footprint declaration for electric vehicle batteries - *suspended until the delegated act is issued (delay of at least 11 months)*

18 AUGUST 2025:
Battery Directive 2006/66/WE expires and the transitional period ends

Chapter VIII on waste battery management enters into force

Article 13
Obligation to mark batteries with the selective collection symbol

Article 48
Battery supply chain due diligence policies enters into force

31 DECEMBER 2025:
Achieving recycling efficiency targets:
75% of the average weight of lead-acid batteries
65% of lithium batteries
50% for other used batteries

*The European Union should publish by August 2025 an implementing act laying down rules for labeling batteries.

Member States shall lay down the rules on penalties applicable to infringements of the Regulation

2026

Source: https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng

While Regulatory Uncertainties Remain, EU Prepares The Implementation Of The Upcoming Battery Passport

The implementation of the passport brings **challenges and requires efforts** but will also **unlock value** once implemented

CURRENT CHALLENGES AND EFFORTS OF IMPLEMENTATION

- The battery passport is primarily a **data management effort** (~55%)
    - Standards, processes, and technologies to streamline data management are key impact areas to facilitate net value of the battery passport
- **Upstream data collection as well as software development** are considered the most significant sub-tasks of the battery passport implementation
    - Software and data savviness is a key lever that impacts passport implementation effort
- **90%+ of efforts translate to fixed costs** with significant tasks such as software development, maintenance, and project management being independent of the volume of sold batteries
    - Third-party service providers that can spread fixed costs across multiple clients may reduce implementation effort
- **Remaining regulatory uncertainties should be resolved**, such as the standardisation of data attributes and specification of how up-to-date dynamic data must be acquired and recorded.

VALUE CREATION BY PASSPORT IN SEVERAL DIRECT USE CASES:

- **Improved ESG data communication** and **informed purchasing decisions,** due to direct visibility to supply chain information.
- **Simplified residual value assessment,** with ~2-10% reduction of technical testing costs for independent operators.
- **More efficient recycling,** with ~ 10-20% reduction of pre-processing and subsequent treatment costs.
- Streamlined servicing of batteries and **easier trade of waste batteries.**

Inaction from businesses and policymakers could significantly reduce the value opportunity of the battery passport

Source: Battery Pass

EU Is Falling Behind Regional Targets For Domestic Critical Mineral Production

- The EU Commission received **170 strategic project applications – 71 % from within the EU** - covering all value chain stages (mining, processing and recycling). It is expected to share the final list in Q1 2025. Under the CRMA, strategic projects benefit from streamlined permitting procedures and easier finance access.
- Within the new EU Commission policy agenda, **CRMs will play a central role in the following future EU initiatives**: a **new Clean Industrial Deal** (expected on 26 February 2025), a **new Circular Economy Act,** and the launch of an **EU Critical Raw Materials Platform**, aimed at joint purchasing of CRMs creating global purchasing power and at managing strategic stockpiles.

Several months after the CRMA adoption and with just 5 years to go to meet the 2030 domestic production targets, the analysis below shows the scale of the challenge.

Only nickel is expected to meet the **10% mining target** to meet domestic demand from battery applications.

EU domestic processing of all battery SRMs is expected to **fall below the 40% target** to meet domestic demand from battery applications

Of the three goals, **recycling is the furthest away**, with cobalt, lithium, manganese and nickel expected to miss the 25% recycling target.

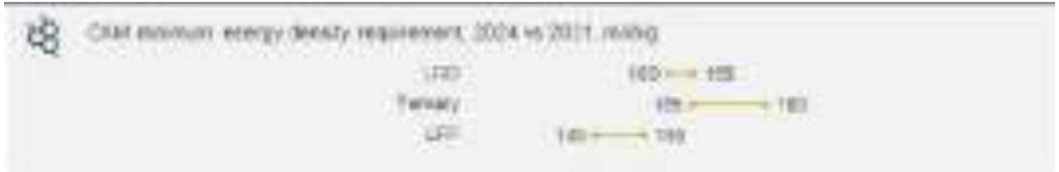
*The CRMA includes the following **non-binding and aggregate domestic production targets:** By 2030, at least 10% of the EU's annual consumption of SRMs must be covered by domestic extraction, 40% by processing and 25% by recycling, ensuring that not more than 65% of the EU's annual consumption of each SRM comes from a single third country.

**Based on Benchmark Q4 forecasts.

BENCHMARK Source: Content & analysis provided courtesy of Benchmark Minerals Intelligence (Distinguished Partner). For more information, visit https://www.benchmarkminerals.com/policy-newsletter.

4 POLICY

China Applies More Stringent Industry Standards To Phase Out Low-Quality Capacity



In May 2024, China's MIIT issued a draft of updated standards for the battery industry. Addressing challenges such as oversupply and inconsistent product quality, it imposes stricter standards on product performance and factory utilization rates.

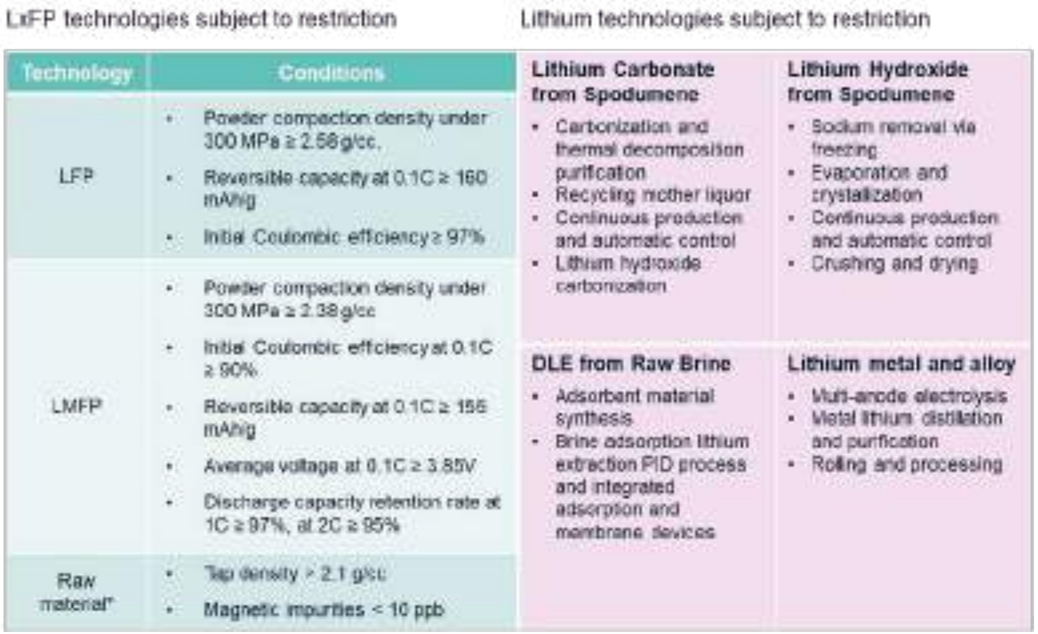
This is targeted at **phasing out low-quality capacity** and weaker companies rather than restraining supply growth.

Although the standards are merely guidance for the industry and not a legal mandate, it is expected that:

- **Companies not meeting the standards will face more difficulties in obtaining financing** and land for domestic capacity expansion
- More follow-up measures may be taken by the government if the overcapacity issue remains unresolved. A recent example is the removal of the export tax rebate.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com. Industry standard also includes requirements on AAM, separators, R&D investments, impurities, and factory utilization.

China Sets Proposal To Restrict Technology Exports For LxFP CAM And Lithium Processing



LxFP technologies subject to restriction

Technology	Conditions
LFP	• Powder compaction density under 300 MPa ≥ 2.58 g/cc. • Reversible capacity at 0.1C ≥ 160 mAh/g • Initial Coulombic efficiency ≥ 97%
LMFP	• Powder compaction density under 300 MPa ≥ 2.38 g/cc • Initial Coulombic efficiency at 0.1C ≥ 90% • Reversible capacity at 0.1C ≥ 156 mAh/g • Average voltage at 0.1C ≥ 3.85V • Discharge capacity retention rate at 1C ≥ 97%, at 2C ≥ 95%
Raw material*	• Tap density > 2.1 g/cc • Magnetic impurities < 10 ppb

Lithium technologies subject to restriction

Lithium Carbonate from Spodumene • Carbonization and thermal decomposition purification • Recycling mother liquor • Continuous production and automatic control • Lithium hydroxide carbonization	**Lithium Hydroxide from Spodumene** • Sodium removal via freezing • Evaporation and crystallization • Continuous production and automatic control • Crushing and drying
DLE from Raw Brine • Adsorbent material synthesis • Brine adsorption lithium extraction PID process and integrated adsorption and membrane devices	**Lithium metal and alloy** • Multi-anode electrolysis • Metal lithium distillation and purification • Rolling and processing

HIGH-END TECHNOLOGY WOULD REMAIN IN THE HANDS OF CHINESE COMPANIES

On 1/2/2025, China's Ministry of Commerce set out a proposal to **restrict the export of certain LxFP CAM and lithium processing technologies**.

Similar plans have been made by China for other high-tech industries, partially as a geopolitical response, and partially as a strategic move to maintain Chinese dominance in supply chain stages.

Most LFP pipeline projects are fully owned by Chinese companies, but this proposal would affect joint ventures with foreign partners, especially Korean companies.

The specifications for CAM exceed the current industry average - **correlating to new high-compaction-density LFP** - meaning lower-grade material and **'legacy technology' would not be restricted.**

If implemented, non-Chinese companies may take longer to achieve and scale up similar cost and technical advancements in LFP and lithium refining.

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

4 POLICY

South America - Policy & Innovation Are Vital For Lithium Supply

South America has (generally) the largest lithium resources with the lowest costs, albeit with **technical and legislative challenges:**

	Argentina	Chile	Bolivia
2023 Exports	$301 M	$7,825 M	$14 M
Growth since 2020	2.5x	2.5x	0.3x *
Growth to 2028	250 - 450 kt/y LCE	100 - 180 kt/y LCE	0 - 60 kt/y LCE
Policy & Innovation	▪ Western & Chinese technology	▪ Western technology	▪ Chinese (& Russian) technology
	▪ Tax credits, transparent licensing process & dynamic govt. oversight	▪ Govt. administration of operations, very opaque licensing process	▪ Govt. controlled extraction
	▪ Govt revenue via royalties + tax	▪ Complex escalating royalties + tax	▪ Direct operational revenues

Source: Content & analysis provided courtesy of CRU Group (Distinguished Partner). For more information, visit https://www.crugroup.com.

5 PREDICTIONS

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.

2025 PREDICTIONS

1. **Global EV demand** will continue to rise, driven by the introduction of mid- and low-priced options, charging network expansion, and wider public acceptance. **xEV sales to top 20M units** for the first time.
2. **PHEV** will continue to **gain market share** driven in part by larger mix of Chinese imports to Europe. **PHEV demand to grow >50%.**
3. **BESS demand** will continue to gain momentum, driven by improving economics, increased renewable energy integration, demand from AI data centers, and streamline interconnection processes. **BESS demand to grow >50%.**
4. **Global business models** will mature further in 2025, driven by the establishment of JVs and technology licensing agreements between leading manufacturers, technology innovators, and key market stakeholders. **5+ major JVs to be announced.**
5. **Startup cell manufacturers** will achieve significant milestones, with **C-sample solid-state batteries** entering advanced validation stages in 2025. However, **scaling to production will face challenges** due to raw material constraints and the limited availability of high-end production equipment, potentially slowing commercialization timelines.
6. **Inflation Reduction Act (IRA)** will continue to drive growth in the U.S. battery industry in 2025, with its tax incentives and manufacturing credits (e.g., 45X) catalyzing investments in domestic production facilities and supply chains. Political uncertainties and potential modifications to key provisions, such as clean energy tax credits and critical mineral sourcing requirements, may introduce short-term challenges. Despite this, **bipartisan support for job creation** and regional economic benefits will sustain the momentum for domestic battery manufacturing.

2024 | BATTERY REPORT

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