The Battery Report 2022

January 15, 2023

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

In this annual report, we summarize what we consider to be the most significant developments in the battery industry in 2022. This report seeks to provide a comprehensive and accessible overview of the current state of battery research, industry, talent, and policy. We hope to catalyze in-depth conversations on the state of batteries and trajectory for the future.

We consider the following key dimensions in our report:

Section 1: Industry	Commercial milestones in battery development and manufacturing
Section 2: Research	Academic breakthroughs in fundamental battery science
Section 3: Talent	Supply, demand, and insights on talent working in the field
Section 4: Policy	Government targets, incentives, regulations, and their implications
Section 5: Predictions	Trends we believe are likely to happen in the next 12 months

A project by the Volta Foundation

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Section 1
Industry

Industry | Overview

2022 marked a year of acceleration in the growth of the global battery industry - wider adoption of EVs continued to drive increasing demand for battery raw materials and manufacturing capacity. In spite of macroeconomic headwinds, the industry grew to $48.4B and capital raised increased from $33B in 2021 to $39B in 2022. Beyond commercial developments, policy makers globally have turned their attention towards nationalization efforts, examples include: the US Inflation Reduction Act (IRA) with an epochal $369B in funding for clean energy and climate incentives, European policy, Indian incentives, nations choosing to keep critical raw materials in-house, and East Asian countries maneuvering to maintain its incumbency.

In terms of challenges, publicly traded EV, battery products, and battery materials companies have underperformed the broader market in 2022. Battery prices increased for the first time in 20 years by 7% year-on-year to $161/kWh at the pack level, pushing back the anticipated timeline for EVs to reach cost-parity with ICE vehicles to 2026. Manufacturing challenges related to yield and ramp rates, complicated by shortages in equipment, raw materials, personnel, and manufacturing know-how have all engendered sobering moments of reflection. A number of safety and reliability incidents, along with the aforementioned obstacles have slowed commercialization efforts and depleted cash reserves.

Evolutions in cell chemistries have shifted the industry's focus, prime examples include the shift to LFP and the use of higher silicon content in anodes, while cathode optimization and other enabling technologies continue to be the focus for commercial R&D and entrepreneurial energy in the space.

Notable Events | Industry Players & Movement | Investments | Cell Chemistry Development | Technology Applications

Costs | Supply Chain | Recycling | Manufacturing | Safety / Legal

2022 Notable Events

January 2022

Week 1

Northvolt assembles the very first Li-ion battery cell in Sweden gigafactory.

StoreDot closes Series D funding round of $80 million, led by Vietnam OEM VinFast.

Panasonic will use Redwood's recycled materials in battery cell production at Tesla Gigafactory.

Week 2

Voltaiq, Batemo, and Energy Assurance release the first independent battery index.

QuantumScape announces collaboration with Fluence stationary storage on solid-state lithium metal batteries.

Volvo launches battery electric truck, VNR with 275 miles range and fast charging.

LG Chem will invest $419 million by 2025 in cathode material plant in Gumi, South Korea.

Week 3

Honda signs a joint development agreement with SES in the area of Li metal batteries.

Factorial Energy raises $200 million to accelerate commercialization of its solid-state batteries, round led by Mercedes-Benz and Stellantis.

CATL launches battery swap service EVOGO for electric cars.

Week 4

GM and LG Energy Solution invest $2.6 billion to build third Ultium Cell manufacturing plant in Lansing, MI.

ProLogium and Mercedes-Benz enter into a technology cooperation agreement to develop solid-state battery cells for electric vehicles.

2022 Notable Events

February 2022

Week 1

Addionics raises $27 million Series A round to scale up 3D electrodes.

Zeta Energy closes $23 million in Series A funding for its advanced lithium sulfur battery technology.

Ford Motor partners with Sunrun on EV charging, home energy management solutions.

Week 2

Rivian and SDI drop talks over joint venture.

SES Korea builds a pre-production facility in South Korea to accelerate A-sample joint development with GM, Hyundai, and Honda.

Australia Liontown signs a 5-year supply deal with Tesla to supply lithium spodumene concentrate.

Week 3

DOE launches $140 million program to develop America's first-of-a-kind critical minerals refinery.

LG Energy Solution acquires 100% share of NEC Energy Solutions, a non-automotive lithium-ion battery and system integration business.

Eurocell plans to build its first European gigafactory.

Week 4

The US Department of Transportation and Department of Energy announce nearly $5 billion earmarked for a national electric vehicle charging network.

QuantumScape expands to Asia-Pacific region with new R&D center in Japan.

2022 Notable Events

March 2022

Week 1

- Ola Electric announces plans to build gigafactory with 50 GWh capacity in India.
- Panasonic announces plans to build another battery cell factory in the US to supply Tesla.
- Sony and Honda pair up to develop and sell battery electric vehicles.

Week 2

- GM and POSCO to build $400 million factory in Canada to produce cathode active materials.
- Ascend Elements and SK Battery America announce plans to work together to recycle manufacturing scrap
- Samsung SDI begins construction of solid-state pilot line in Suwon, Korea.

Week 3

- Northvolt announces its third gigafactory to be established in Germany.
- Mercedes-Benz announces new 2,500-ton battery material recycling plant in Kuppenheim, south Germany.
- LG Energy Solution invests $2 billion to build its first American cylindrical cell plant in Queen Creek, AZ with a capacity of 11 GWh.

Week 4

- Stellaints and LG Energy Solution to invest $5 billion CAD in JV for battery production in Canada.
- South Korean steelmaker Posco invests $4 billion in new lithium mining project in Argentina.
- Suzuki Motor to invest $1.3 billion for EV and battery production in India.

2022 Notable Events

April 2022

Week 1

Taiwanese battery swapping company Gogoro launches IPO.

BYD and Shell partner on EV charging across China and Europe.

Europe's first Li-ion battery anode plant Talga commissioned and operating in Sweden.

VinFast to invests $2 billion to build EV factory in North Carolina.

Week 2

GM and Honda announce plans to co-develop affordable EVs.

CATL partners with Indonesia to boost e-mobility through an investment of $6 billion.

Envision AESC to invest $2 billion to build a 30 GWh gigafactory in Kentucky.

Week 3

LG Chem and LG Energy Solution announce strategic partnership with Li-Cycle as their preferred lithium-ion battery recycler in North America

US DOE grants $107 million to Australia mining company Syrah Resources.

Umicore and Automotive Cells Company (ACC) sign a long-term supply agreement for EV cathode materials in Europe

Week 4

Volkswagen and bp launch strategic partnership to roll out fast charging for EVs in Europe.

South 8 Technologies raises $12 million to commercialize next generation electrolytes for high performance lithium-ion batteries.

FreeWire raises $125 million Series D financing to develop EV charging.

2022 Notable Events

May 2022

Week 1

Sila starts building Si anode plant in Washington state, US..

Amprius Technologies with DOE awarded $3 million contract from USABC for Si nanowire technology development.

US DOE announces up to $45 million in funding to support domestic development of advanced batteries for EVs

Week 2

BMW i Ventures announces lead investment in green lithium refining technology Mangrove Lithium.

Farasis unveils a new cell prototype that has an energy density of 300Wh/kg that can charge in 15 minutes

Stellantis and Samsung SDI invest over $2.5 billion in joint venture for lithium-ion battery production plant in United States.

Week 3

Nano One Materials acquires Johnson Matthey Battery Materials for $10.25 million CAD.

Norwegian Morrow Batteries raises EUR 100 million in new investment round led by Siemens.

Polestar invests in extreme fast charging battery company StoreDot.

Week 4

Toyota releases battery storage system for residential use based on EV technology.

CATL to supply BMW with cylindrical cells from 2025.

2022 Notable Events

June 2022

Week 1

CATL to supply LFP batteries equipped with novel CTP technology to Poland Solaris for e-bus.

Tata Motors acquires Ford's Sanand factory in Gujarat, India to expand production.

BYD leadership announces they will supply batteries to Tesla.

Week 2

Eurobattery Minerals purchases 40% of Finnish Hautalampi battery mineral mine project.

Solid Power announces installation of EV solid state cell pilot line.

Ion Storage Systems closes $30 million Series A round.

Our Next Energy announces partnership with BMW to demonstrate dual chemistry Gemini battery pack, enabling 600 miles of range in an iX.

Week 3

ProLogium Technology announces automated SSB mass production to start by 2023.

Foxconn builds the first battery cell plant in southern Taiwan and will begin production in Q1 2024.

LG Energy Solution will build 9 GWh 4680 cylindrical cells in Ochang, Korea

CATL launches CTP battery Qilin with record volume utilization and energy density.

Week 4

Gotion to build facility in Argentina capable of producing up to 60,000 tons of lithium carbonate per year.

Volkswagen and Siemens make joint equity investment of $450 million in Electrify America.

2022 Notable Events

July 2022

Week 1

VinFast partners with ProLogium on the development of solid-state batteries.

GM and Pilot Company will build out coast-to-coast EV fast charging network.

Wildcat Discovery Technologies raises more than $90 million in Series D financing.

Week 2

LG Energy Solution may supply batteries to India's Mahindra & Mahindra.

CATL and Ford announce strategic cooperation. CATL to supply LFP packs to Ford.

Samsung SDI invests 1.7 trillion KRW in cylindrical battery lines in Malaysia.

Week 3

Panasonic Energy plans to build a state-of-the-art electric vehicle battery facility in Kansas City region.

US Department of Energy to loan $2.5 billion to GM and LG Energy Solution battery joint venture Ultium Cells.

General Motors and Livent enter long-term lithium hydroxide supply agreement.

Week 4

Cuberg achieves major milestone with 672 cycles and 380 Wh/kg in lithium metal cell development.

SK On, Ford, and EcoPro BM will jointly invest in cathode material production facility in North America

2022 Notable Events

August 2022

Week 1

Nikola acquires battery pack supplier Romeo Power for $144 million.

Nexeon raises over $200 million to fund battery materials manufacturing.

Ascend Elements announces plans to invest $1 billion to make battery materials in Kentucky.

Tesla secures battery precursor material supply deals with two big Chinese companies, Zhejiang Huayou Cobalt Co. and CNGR Advanced Material Co.

Week 2

CATL postpones decision on North American factory.

Biden-Harris administration launches $675 million bipartisan infrastructure program to expand domestic critical battery materials supply chains.

Week 3

China's EVE Energy will supply BMW with large cylindrical batteries for its EVs in Europe,

Mercedes-Benz to source battery material lithium hydroxide from Rock Tech Lithium.

The Inflation Reduction Act of 2022 (IRA) signed into effect on August 16, 2022 authorized **$369 billion** in spending to invest in clean energy and address climate change.

Biggest News of the Year!

Week 4

CATL signs five-year strategic agreement with SERES to supply Qilin batteries.

Celgard enters into strategic alliance for high-performance LFP battery separator technology with American Battery Factory.

Honda and LG Energy plan $4.4 billion EV battery factory in U.S.

2022 Notable Events

September 2022

Week 1

ONE reveals 1007 Wh/l anode-free cell enabling an EV that could travel 600 miles.

Toyota pledges $5.6 billion for ramping up investment in North Carolina EV battery plant.

SK invests $50 million in Ascend Elements.

CATL to supply BMW with cylindrical cells for NEUE KLASSE from future battery plants in China and Europe.

Week 2

Mercedes-Benz and Rivian sign Memorandum of Understanding for strategic partnership and joint production of electric vans.

Iontra raises $38 million Series B to advance battery charging and development platform.

Week 3

CATL and Flexgen sign 10 GWh multi-year battery energy storage system supply agreement.

Fujifilm invests an additional $20 million as the 2nd round in 24M Technologies.

Gotion will invest $3.6 billion to develop battery manufacturing plant near Big Rapids, MI, US.

CATL unveils module to bracket battery technology for heavy trucks.

Week 4

Faraday Future resolves investor dispute, raises up to $100 million to launch FF 91.

Mercedes-Benz Trucks unveils its longest-range electric truck eActros LongHaul at IAA.

CATL to supply 123 GWh EV batteries to Honda by 2030.

2022 Notable Events

October 2022

Week 1

Form Energy raises $450 million in Series E round.

GM enters collaboration agreement with Queensland Pacific Metals for nickel from Australia.

OneD collaborates with GM to develop Si battery technology.

Week 2

Ascend Elements and EcoPro Group announce collaboration to supply recycled battery materials to North American EV industry.

SK On signs battery grade lithium supply deal with Australia's Lake Resources.

Week 3

BMW signs supply agreement with Envision AESC for battery cells in the US.

Our Next Energy announces $1.6 billion investment in a new battery cell manufacturing plant in Van Buren Township, MI,

Week 4

CATL and VinFast reach strategic cooperation such as CTP battery supply to promote global e-mobility.

US DoE reveals the first 20 companies that will benefit from the US Bipartisan Infrastructure bill, in total these companies will receive $2.8 billion in support.

2022 Notable Events

November 2022

Week 1

SAUDIA plan to purchase and operate 100 aircrafts from Lilium in Middle East/North Africa region.

Saudi Arabia's public investment fund launches electric vehicle brand Ceer in collaboration with Foxconn.

Foxconn acquires additional equity in Lordstown Motors for $170 million.

Week 2

Vale and GM sign long-term supply of battery grade nickel from Canada.

LG Energy Solution secures multi-year lithium carbonate supply from Compass Minerals.

Department of Energy announces $12 million to support extraction and conversion of lithium from geothermal brines.

Week 3

Coulomb Solutions inc to supply Phoenix Motorcars with unique CATL battery solutions.

BYD to mass produce sodium-ion batteries in Q2 2023.

Week 4

Volkswagen in talks with Foxconn on manufacture electric pickup trucks and SUVs in America.

Tesla Semi completes first 500-mile trip with a full load as a Class 8 truck with a test run weighing 81,000 pounds

2022 Notable Events

December 2022

Week 1

Panasonic Energy and Lucid announce lithium-ion battery supply agreement for Lucid Air luxury EVs.

CATL to supply 123 GWh BEV batteries to Honda from 2024 through 2030.

Week 2

Hyundai Motor Group and SK on to build EV battery facility in Bartow County, GA.

Rivian pauses joint venture plans with Mercedes-Benz to make electric vans in Europe.

Week 3

Department of Energy issues $2.5 billion loan to help joint venture Ultium Cells LLC make EV batteries.

Startup Group14 Technologies raises $214 million in Series C funding.

Redwood Materials plans $3.5 billion plant in South Carolina.

QuantumScape ships first 24-layer prototype battery cells to automotive OEMs.

Week 4

BMW to produce Solid Power's solid state cells at pilot scale in Germany under licensing agreement.

Form Energy announces $760 million battery plant in Weirton, WV.

Ford and CATL considering battery plant in Michigan or Virginia.

Industry | Overview

- Notable Events
- Industry Players & Movement
- Investments
- Cell Chemistry Development
- Technology Applications
- Costs
- Supply Chain
- Recycling
- Manufacturing
- Safety / Legal

Industry Players | Large Cap Landscape

Overview of public companies and incumbents with >$1B Market Cap/Valuation*

2030 Total:

RAW MATERIAL MINING AND REFINING	MATERIALS PROCESSING	COMPONENT MANUFACTURING	CELL & PACK MANUFACTURING	BATTERY DATA AND EV/ESS APPLICATION	RECYCLING AND 2ND LIFE
Market: $58.4B	Market: $62B	Market: $25.4B	Market: $184B	Market: $36B	Market: $40.6B
CAGR: 15.2%	CAGR: 8.75%	CAGR: 30%	CAGR: 18.5%	CAGR: 21.2%	CAGR: 26.5%

Raw Material Mining and Refining: SQM, RioTinto, BARRICK, ALBEMARLE, LithiumAmericas, GanfengLithium, GLENCORE, TIANQI LITHIUM, VALE, Livent, AngloAmerican, CMOC, BHP, HUAYOU COBALT

Materials Processing: umicore, BASF, Hitachi Chemical, Sumitomo, ShinEtsu, posco, TARGRAY, EcoPro BM, BTR (Better our world), Outotec, 3M, CNGR, Dow, DUPONT, CYTEC, LG Chem, MITSUBISHI CHEMICAL, NICHIA, Nippon Carbon Co., Ltd.

Component Manufacturing: TINCI, ENOVIX, AsahiKASEI, CELGARD, PUTAILAI, LiMETAL, GS YUASA, LEAD, Dynanonic, SEMCORP (POWER YOUR FUTURE), SHINZOOM, CAPCHEM

Cell & Pack Manufacturing: CATL, BYD, LG Energy Solution, TESLA, CALB, Panasonic, SAMSUNG SDI, Gotion, ATL, LISHEN, EVE, SK innovation, SUNWODA, QuantumScape, FARASIS, SES (Beyond Li-ion™), northvolt, Envision AESC

Battery Data and EV/ESS Application: TESLA, GM, TOYOTA, STELLANTIS, Ford, RIVIAN, HONDA, DAIMLER, LUCID, VINFAST, BMW, VW, XPENG, NIO, Li Auto, NEXTera ENERGY

Recycling and 2nd Life: BRUNP, saft, GEM, Neometals, BOSCH, SOLVAY, suez, VEOLIA, SMS group, IBERDROLA, urbaser, STENA, Recylex, Aurubis, BOLIDEN

*Company valuation fluctuates with time, the category is a rough estimation, valuation as of December 31, 2022

Industry Players | Startup and Small Cap Landscape

Overview of startups and private companies with <$1B Market Cap/Valuation*

2030 Total:	RAW MATERIAL MINING AND REFINING	MATERIALS PROCESSING	COMPONENT MANUFACTURING	CELL & PACK MANUFACTURING	BATTERY DATA AND EV/ESS APPLICATION	RECYCLING AND 2ND LIFE
Market	$58.4B	$62B	$25.4B	$184B	$36B	$40.6B
CAGR	15.2%	8.75%	30%	18.5%	21.2%	26.5%

Raw Material Mining and Refining: tmc, loke, Impossible Metals, Lilac solutions, EnergySource Minerals, Summit Nanotech, Novalith, KoBold Metals, P+L Pure Lithium, EnergyX, aepnus technology, Lithios, Cornish Lithium, ElectraLith Sustainable Lithium, Saltworks, Adionics The Advanced Ionic Solution, M Li

Materials Processing: Mitra Chem, OneD Battery Sciences, Sila, Group14 Technologies, Enevate Innovating Energy Storage, Echion Technologies, nexeon, E-NexT, NanoGraf Technologies, StoreDot, Conamix, Ionobell, GDI, SICONA Battery Technologies, volexion, G1, Lyten, Urbix, HiT Nano, Ionic Mineral Technologies, amprius

Component Manufacturing: Solid Power, Coreshell Technologies, Sila, AM Batteries, Soteria, LeydenJar Energising Technologies, Poly Plus, Addionics, Sepion Technologies, Ionic Materials, Nanoramic Laboratories, ED Power, Prieto Battery, Altris, South 8 Technologies, Unigrid, P, SVX, LionVolt, Lyten, 6K, Mitra Chem, Wildcat Discovery Technologies, amprius

Cell & Pack Manufacturing: ONE our next energy, ProLogium, 24m, Lyten, Sion Power, Sakuú, Factorial, SVOLT, Zeta Energy, Cuberg, iM3NY, ion Storage Systems, 卫蓝新能源, nyobolt, CustomCells Ahead in cell innovation, Battrion, anthro, gaussion, Intecells, Solid Power, amprius

Battery Data and EV/ESS Application: Voltaiq, TWAICE, Aionics, Titan Advanced Energy Solutions, About:Energy, infyos, BrillPower, liminal, BattGenie., Qnovo, Parthian Energy, Batemo Understanding Batteries, chemix, Automat Solutions, EnergSoft, PowerUp Manage & extend batteries life, GBatteries, Accure, Aviloo, Fova Energy, Zitara, Electra, AmpLabs

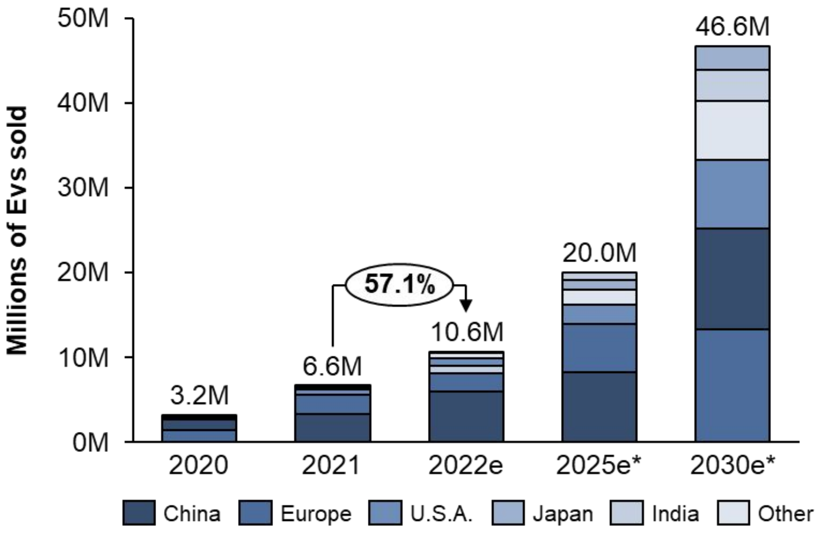
Recycling and 2nd Life: Ascend Elements, Redwood Materials, Nth Cycle, Rejoule, Samsar, Lithion, Renewance, cling, Li-Cycle, Princeton NuEnergy, Aceleron, Li Industries, RecycLiCo Battery Materials, Relectrify, Lohum, TerraCycle, betteries, moment energy, Cylib, tozero, Revolta, fortum, green li-ion, Circu Li-ion

*Company valuation fluctuates with time, the category is a rough estimation, valuation as of December 31, 2022

Industry Movement | Auto OEMs | Market Overview

Passenger electric vehicles continued to surge in popularity this year, and EV's are estimated to account for 10-13% of new cars sold in 2022. Aggressive policy incentives and announcements, such as the IRA and net-zero carbon goals, have dramatically moved the needle in the transition to EV's.

Global EV sales grew ~57% YoY in 2022



Data accurate as of November, 2022
EV Sales include BEV's and PHEV's
2025e* & 2030e* numbers projected from IEA data, EV-Volumes

2022 EV Highlights

China accounted for over 50% of new EV sales in 2022, with an estimated 6 million EV's registered.

BYD led new EV sales with ~17% market share globally between BEV and PHEV models, although Tesla is still the leader in pure BEV sales.

BCG estimates 20% of light vehicles sold globally in 2025 will be BEV's, rising to 59% in 2035. By comparison, the previous year's projection was 11% in 2025 and 45% in 2035.

Charging infrastructure, critical mineral supply for batteries, and vehicle manufacturing continue to be major areas of focus for large auto OEMs in transitioning to the EV economy.

Source: 1. IEA 2022 Global EV Outlook, 2. InsideEVs Top 2022 Brands 3. BCG EV Projections, 2022 EV Sales Projections

Industry Movement | Auto OEMs | U.S.

Tesla

Partnership

Panasonic
$4B (30 GWh) battery plant planned for Kansas

BYD
Speculated partnership with BYD to supply "Blade Batteries" for Model Y

Lincoln Tech
Partnering with technical school Lincoln Tech to train the next generation of EV technicians

Talon Metals
6-year, 75 kilotons total of Ni concentrate supply

Investment

Austin Gigafactory Scaling
$770M investment for additional capacity

Texas Lithium Refinery
Refinery in Corpus Christi for battery grade lithium

Cathode Production
Permit to extend Gigafactory Austin for cathode production

GM

Investment

GM Energy
New business unit dedicated to energy and infrastructure needed to enable EV's

Plant Upgrades
$7B for plant upgrades and development for EVs

Queensland Pacific Metals
$69M investment to secure Ni and Co

Partnership

Pilot and EVgo
Addition of 2,000 charging stations across 500 locations

Ultium
$2.5B loan from DoE to expand LGES/GM Ultium battery production

LG Chem CAM
LG Chem to provide more than 950 kilotons of CAM over eight years

Ford

Investment

$50B Investment Pledge
Planned EV investments through 2026

Ohio Assembly Plant
$1.5B to develop new EV for 2025 launch

Cavnue
$130M Series A led by Ford for autonomous road building technology

Partnership

CATL
LFP prismatic cells for Mach-E and F-150 Lightning

60 GWh of Battery Supply
Contracts with CATL, LG Chem, and SK Innovation to support 600k EV's/year

ECOPRO BM
$700M investment in cathode plant with SK On and EcoPro BM

Industry Movement | Auto OEMs | Asia (ex-China)

TOYOTA

Investment

- **$35B Investment**
  Investment of $35B from 2022 to 2030 for EVs
- **$5.6B for Battery Plants**
  $2.33B in North Carolina and $2.87B in Japan

Partnership

- **ChargePoint and EVgo**
  Infrastructure development for fast charging
- **Suzuki, Dalhatsu, and CJPT**
  Partnership to develop commercial electric vans
- **BYD**
  Small electric sedan developed jointly by Toyota and BYD
- **ioneer**
  Joint venture with Panasonic to buy lithium carbonate from Nevada mine

HONDA

Investment

- **SES**
  Joint development agreement, SES to go SPAC
- **Ohio Plant Upgrades**
  $700M to retool manufacturing facilities for EVs
- **$40B for Electrification**
  Plan to launch 30 BEVs by 2030

Partnership

- **LGES**
  Joint venture to invest $4.4B in 40 GWh battery plant in US
- **GM**
  Partnership to develop affordable EV's

HYUNDAI

Investment

- **$26B Investment**
  $16B for electrification, $10B for software capabilities through 2030
- **$5.5B for Production**
  EV and battery manufacturing plant in Georgia
- **EV Battery Plant**
  $205M for plant in Montgomery, Alabama

Partnership

- **Iveco**
  Joint venture develops hydrogen powered van
- **BorgWarner**
  Integrated drive module selected for new EV
- **Rolls-Royce**
  Partnership to develop all-electric and hydrogen flight technology

NISSAN

Investment

- **Solid-State Prototype Facility**
  Launching EV powered by solid-state in 2028
- **$500M for Production**
  Retooling factories in Canton, Mississippi

Partnership

- **McLaren**
  Technical partnership for Formula E
- **Zap-Map**
  EV's include subscription to charger mapping
- **Renault**
  In talks to optimize EV investments and share technology as part of alliance

Industry Movement | Auto OEMs | China

SAIC

Investment

- **$43B Investment** – SAIC group planning large investment over next decade for smart EVs
- **Thailand Expansion** – $75M for battery plant ahead of local EV production

Partnership

- **Tsingshan Group** – Joint 20 GWh power battery project
- **Alibaba** – Joint venture producing IM L7 luxury sedan
- **CATL and PetroChina** – Joint venture to supply swappable batteries

CHANGAN

Investment

- **$12.6B Investment** – Significant investment through 2025 to launch neighborhood EV's
- **Shenlan SL03 Release** – Competitor to Tesla Model 3 released

Partnership

- **Huawei and CATL** – Launch of premium EV brand AVATR Technology
- **AVATR and BP** – 100 fast-charging stations across China

DFM

Investment

- **Voyah** – $698M raised in Series A for subsidiary premium EV brand Voyah
- **Off-Road Vehicles** – Wuhan plant to produce 10k vehicles by 2023

Partnership

- **Protean Electric** – In-wheel motor technology development
- **Honda, Guangzhou Automobile** – Joint venture for battery procurement
- **Sunwoda** – Joint venture to build 30 GWh plant in Yichang

FAW

Investment

- **Horizon Robotics** – Strategic investment in AI chipmaker for self-driving vehicles
- **Hubei Zhongxing Materials** – Investment in $745M round for cathode supplier

Partnership

- **Audi** – Joint venture for $3.3B plant in Changchun
- **Toyota and BYD** – BYD to supply motors and battery for bZ3 sedan
- **BYD** – 45 GWh plant planned for northeastern China

Note: BYD is #1 EV producer in China (between PHEVs and BEVs, but is included in cell manufacturers section

Industry Movement | Auto OEMs | EU

Volkswagen

Investment

- **PowerCo** – EUR 20B investment in battery manufacturing spinoff
- **NorthVolt** – Part of $1.1B convertible note

Partnership

- **Umicore** – Joint venture investment of EUR 3B for production of cathode material
- **Redwood Materials** – Supply chain to recycle EV batteries
- **Elli and Elia Group** – Partnership to showcase integration of EV's into electric grid
- **Canada** – MOU to explore battery manufacturing and raw material supply chains

Mercedes-Benz

Investment

- **The Mobility House** – $50M Series C for smart charging and vehicle-to-grid integration
- **Wind Power** – 100 MW wind farm at Papenburg test track
- **ProLogium** – Significant investment to develop solid state battery cells

Partnership

- **Rock Tech Lithium** – 10 kilotons of lithium per year starting 2026
- **Rivian** – MOU for joint production of electric vans

STELLANTIS

Investment

- **Factorial** – Joint development agreement and investment in Series D to scale solid state technology
- **Vulcan Energy Resources** – EUR 51.5M for 10 years of LiOH production
- **$2.8B for Production** – Upgrades to plants in Windsor and Brampton

Partnership

- **Samsung SDI** – $2.5B for 23 GWh factory in Kokomo, Indiana
- **LG Energy Solutions** – $4.1B for 45 GWh plant in Windsor, Ontario
- **GME Resources** – Offtake agreement for battery grade nickel and cobalt

BMW

Investment

- **$1.7B for Production** – $1B for vehicle factory and $700M for battery assembly in Spartanburg, South Carolina
- **China Plant Expansion** – $1.4B to expand battery plant for i3 and iX3 cars

Partnership

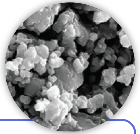
- **CATL** – Supplying new cylindrical cells starting in 2025
- **Envision AESC** – 30 GWh new cell factory in South Carolina
- **SolidPower** – $20M licensing agreement for SolidPower cell design and manufacturing process

Industry Movement | Notable Public Company Joint Ventures and Partnerships

Battery Industry Value Chain Deals

Chemicals Separation

orbia | SOLVAY
November 2022
JV to develop PVDF, which is used as a lithium-ion binder and separator coating.



Components Manufacturing

gm | microvast
November 2022
Separator plant JV between GM and Microvast

VinES | 国轩高科 GOTION HIGH-TECH
November 2022
VinES and Gotion joint venture to build LFP CAM Plant plant

LG Chem | 华友钴业 HUAYOU COBALT
June 2022
LG Chem and B&M, subsidiary of Huayou Cobalt, joint venture to produce NCMA with an annual capacity of 60kt

gm | posco
May 2022
POSCO and GM finalize Ultium CAM joint venture with a capacity output of 30ktpa

PowerCo | umicore
September 2022
PowerCo and Umicore battery materials (pCAM and CAM) JV

LG Chem | Korea Zinc
June 2022
LG Chem and KEMCO, a subsidiary of Korea Zinc, joint venture to produce 20kt of precursor material

Cell & Pack Manufacturing

RENAULT | MINTH GROUP
June 2022
Renault and Minth plan JV to produce battery housings at Renault's Ruitz plant

STELLANTIS | SAMSUNG | SAMSUNG SDI
May 2022
Stellantis and Samsung SDI joint venture into battery plant with a capacity of 23 GWh per Annum

LG Energy Solution | HONDA
October 2022
40GWh (2025) Fayette County, OH

Ford | SK
July 2022
60GWh per Annum Tennessee & Kentucky

Applications (OEMs & ESS)

SONY HONDA
June 2022
Sony and Honda create JV to manufacture EVs; the new company is called "Sony Honda Mobility Inc."

FOXCONN | ptt GLOBAL CHEMICAL
June 2022
Foxconn and PTT gain approval of $1.04 billion BEV JV from Thailand's BOI

Nidec | FREYR
August 2022
Joint venture to establish a provider of utility scale battery energy storage products

Recycling

posco | GS Energy
October 2022
POSCO and GS Energy sign agreement to establish a recycling joing venture

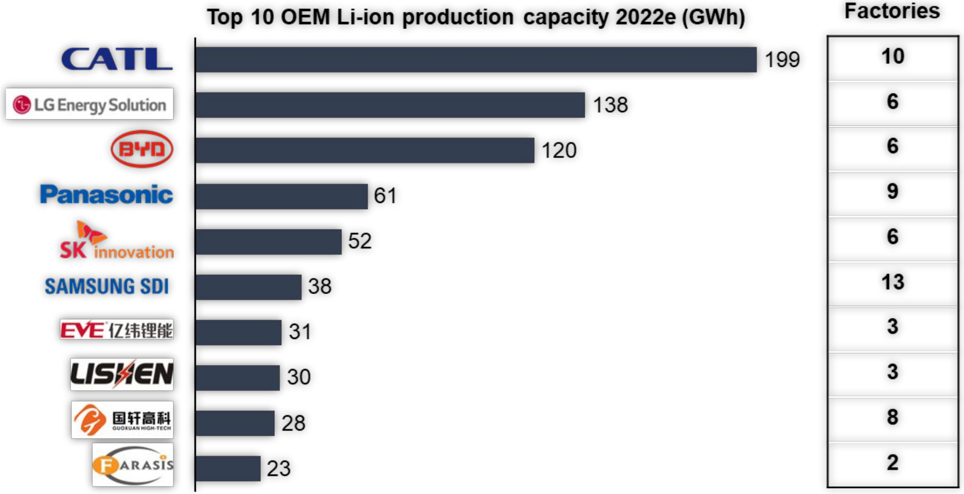
GLENCORE | BRITISHVOLT
February 2022
Glencore and Britishvolt form a recycling joint venture with a capacity of 10ktpa

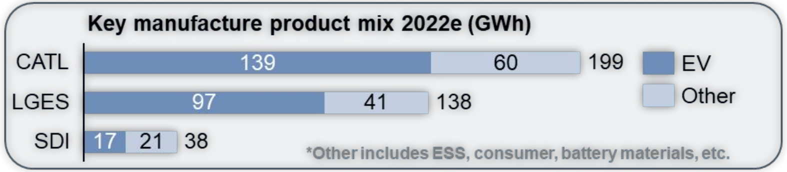
LG Chem | 华友钴业 HUAYOU COBALT
July 2022
LG Chem and Huayou Cobalt joint venture to recycle nickel, cobalt, and lithium

Sources: Honda and LGES, VinES and Gotion, Solvay and Orbia, Ford and SK On, GM and Microvast, PowerCo and Umicore, Stellantis and Samsung SDI, LG Chem and Huayou Cobalt, LG Chem and B&M, Nidec and FREYR, Foxconn and PTT, POSCO and GS Energy, Glencore and Britishvolt, Renault and Minth Group, POSCO and GM, Sony and Honda

Industry Movement | Cell Manufacturers | Overview

In 2022, cell manufacturers continued to expand production capacity (~600 - 700 GWh[1,2,5,6]) to meet growing demand (~450 GWh) primarily from auto OEMs (EVs), but included other segments like ESS and consumer.





Note* Battery production plants usually have a capacity utilization rate of ~70% of theoretical maximum capacity; thus, nominal capacity needs to be well above actual battery demand [1]

Cell Manufacturer Trends 2022

The top 6 cell manufacturers accounted for ~82% of Li-ion production capacity in 2022. [1]

CATL remains significantly ahead of the market, with 70.9 GWh of cells produced for EV's in the first half of 2022 and several plants planned globally to further expand operations. [3]

BYD is challenging LGES in Li-ion production, overtaking LGES at least twice in 2022 by out-producing LGES in the months of July and August. [3, 4]

Furthering partnerships with OEM's, securing critical mineral supplies, and reducing manufacturing costs were some of the key development areas top cell manufacturers focused on in 2022.

Source: 1. Automotive Battery Supply Chain 2022, 2. IEA - Li-ion production capacity, 3. Electrive.com, 4. BloombergNEF, 5. SNE Research, 6. Company Data

Industry Movement | Cell Manufacturers

CATL

Investment

- **Luoyang City** — $1.9B for Chinese expansion
- **CMOC Group** — 25% stake in cobalt producer
- **Aimsphm** — Invested in Series C for smart factory
- **Shanshan Technology** — $470M investment with BYD, ATL, and others to expand anode production

Partnership

- **Ford** — Considering battery plant in Virginia or Michigan
- **Hungary Super Plant** — $7.6B, 100 GWh capacity in partnership with Mercedes-Benz, BMW, VW, Stellantis
- **Commercial Trucking** — Daimler Truck, Trailer Dynamics, MOU with Kyberg Switzerland
- **Kia** — First time Kia has accepted non-Korean batteries
- **FlexGen** — 10 GWh multi-year ESS storage contract

LG Energy Solution

Investment

- **Ochang, South Korea** — $568M to expand production capability
- **OnePredict** — $25M Series C for factory intelligence software
- **LGES Battery Challenge** — $1M cash prizes for innovative start-ups
- **CAPEX Increase** — $5.3B to boost EV battery production
- **Li-Cycle** — $50M PIPE from LGES and LG Chem

Partnership

- **Honda** — $4.4B for EV battery production in Ohio
- **GM** — Ultium JV to invest $2.6B on 3rd plant (50GWh)
- **North American Raw Material Supply** — Snow Lake Resources, Electra, and Avalon Advanced Materials bolster Li/Co supply
- **Smart Factory** — Agreements with Siemens and RIST to implement smart factory systems
- **Hyundai** — JV with LGES considering two new battery plants in US

Industry Movement | Cell Manufacturers

BYD

Investment

- **Battery Production** – $4.1B planned for co-located mine and production plant (30 GWh) in Yichun
- **Lithium Mines** – Undisclosed amount for 6 lithium mines in Africa

Partnership

- **Inchcape** – EV market entry in Belgium and Luxembourg
- **FAW Group** – 45 GWh production in Changchun
- **Shell** – EV charging infrastructure across Europe/China
- **Sixt** – Planned purchase of 100k BYD EV's by 2028

SK innovation

Investment

- **Ascend Elements** – SK Eco invests $50M for recycled Li-ion material
- **Terra Power** – SK invested $250M ($750M round) for SMR tech
- **US Expansion** – $30B to be invested in US by 2025 for clean energy / technology (EVs, hydrogen, storage)

Partnership

- **Ford and Koç** – JV for Ford EV batteries in Turkey (30-45 GWh)
- **Hyundai** – $5.54B MOU for battery supply in North America
- **Lake Resources (Lithium)** – 10% stake, 5-year off-take, 15-25 kilotons/year

Panasonic

Investment

- **Gigafactory 1 Optimization** – Optimizing output from 39 to 43 GWh capacity
- **Kansas Factory** – $4B for 30 GWh factory producing 4680's

Partnership

- **Nouveau Monde Graphite (NMG)** – North American supply of graphite
- **Redwood Materials** – Recycled cathode and copper materials
- **Lucid Motors** – Supplying cells for Lucid Air luxury EV's

SAMSUNG SDI

Investment

- **R&D Expansion** – Opening battery research facilities in US, Germany, and China
- **Malaysia Battery Factory** – $1.3B for cylindrical cell factory in Malaysia
- **Solid State** – Solid-state pilot production in early 2023

Partnership

- **Stellantis** – $2.5B for 23 GWh Li-ion plant in Indiana
- **EcoPro EM** – JV for 54 kilotons/year of cathode material

Industry Players | Cell and EV OEM Supply Relationship Map

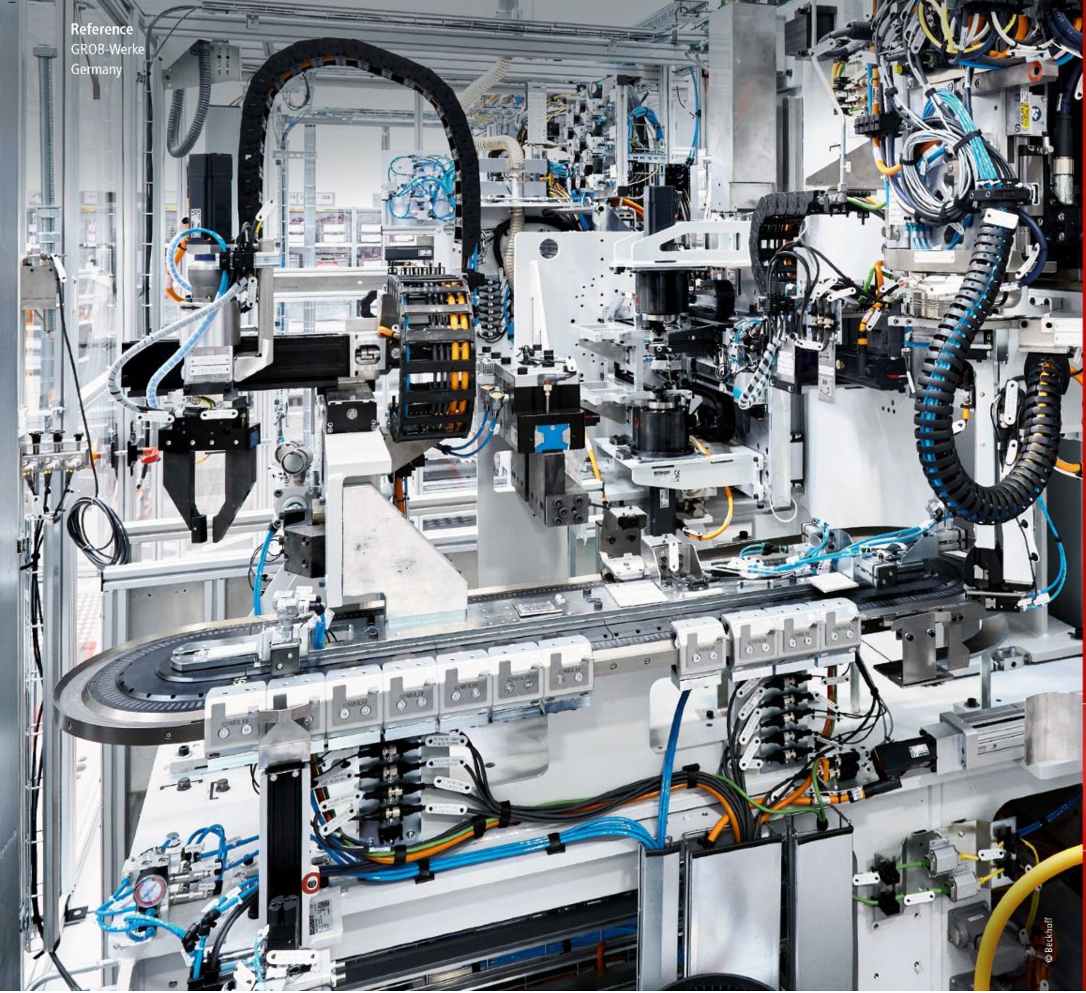
In 2022 auto OEMs and cell manufacturers continued to develop new JV’s and partnerships to provide steady supply of battery cells for electric vehicles

	2022e EV Li-ion market share	*34%*	*14%*	*12%*	*10%*	*7%*	*5%*	*4%*	*3%*	*11%*	
	Auto OEM	**CATL**	**LGES**	**BYD**	**Panasonic**	**SKI**	**SDI**	**CALB**	**Gotion**	**Others**	**Most common form factor**
U.S.A.	Tesla	✓	✓	✓	✓						Mostly cylindrical, prismatic
	GM	✓	✓								Pouch
	Ford	✓	✓	✓	✓	✓	✓				Pouch & Prismatic
	Rivian		P				✓		P		Cylindrical
Europe	BMW	✓					✓				Prismatic, cylindrical
	Mercedes-Benz	✓	✓	✓			✓	✓			Pouch, prismatic, cylindrical
	VW Group	✓	✓			✓	✓		✓		Mostly prismatic
	Stellantis	✓	✓			✓					Pouch and Prismatic
Asia	BYD			✓							Prismatic
	Toyota	✓		✓	✓			✓			Prismatic, cylindrical, pouch
	Honda	✓	✓		✓						Pouch
	Nissan	✓	✓		✓						
	Hyundai/Kia	✓	✓			✓					Pouch and Prismatic
	SAIC	✓						✓	✓		Prismatic

Legend ✓ Current battery supply relationship; P Potential battery supply

*not exhaustive list

Source: Elektric Drive, SNE Research, E Source, Company data


Reference
GROB-Werke
Germany
© Beckhoff

Industry Players | Battery Manufacturing Supply Relationships

	CATL	LG Energy Solution	BYD	Panasonic	SK innovation	SAMSUNG SDI	CALB	国轩高科 GUOXUAN HIGH-TECH
Cathode	Ningbo Rongbay BASF Dynanonic (LFP) Liyuan New Energy Shenghua New Materials	CNGR LG Chem Ningbo Ulica POSCO Umicore Beijing Easpring	Ningbo Rongbay Xiamen Tungsten Dynanonic (LFP) Liyuan New Energy Shenghua New Materials Beijing Easpring	Fangyuan Sumitomo Metal Mining Zhejiang New Power Umicore Beijing Easpring	Ningbo Rongbay EcoPro Fangyuan	Ningbo Ronbay EcoPro Fangyuan GEM Umicore	Xiamen Tungsten Guoxuan Keleng New Energy	Guoxuan Keleng New Energy Xiamen Tungsten
Anode	BTR Guangdong Kajin Ningbo Ulica Novonix Shanghai Putailai Zhongke Electric	BTR Ningbo Ulica Novonix Shanghai Putailai Hitachi Chemicals	BTR Jiangxi Zichen Ningbo Ulica Shanghai Putailai Zhongke Electric	BTR Novonix Hitachi Chemicals	BTR	BTR Putailai	BTR Guangdong Kajin	BTR Guangdong Kajin
Electrolyte	Ningbo Ulica Tinci Materials Jiangsu Guotai Enchem	Jiangsu Guotai Ningbo Ulica Enchem	Ningbo Ulica Capchem	Capchem Enchem	Enchem	CapChem Technology GTHR Panax-Etec Enchem	Capchem Tinci Materials	Senior Technology Material Enchem
Metal foils	Anhui Tongguan Copper Dingsheng New Materials Hubei Zhongyi Jiayuan Nuode	Dingsheng New Materials Nuode	Anhui Tongguan Copper Dingsheng New Materials Henan Mingtai Aluminium Nuode	Nuode	SK Nexilus IlJin Materials	Panax-Etec	Nuode	Anhui Tongguan Copper Dingsheng New Materials Nuode
Separators	SEMCORP Shanghai Putailai Senior Technology Material Suzhou Greenpower New Energy Materials	SEMCORP Shanghai Putailai Senior Technology Material Asahi Kasei	SEMCORP Shanghai Putailai Senior Technology Material	SEMCORP Sumitomo Metal Mining Asahi Kasei Celgard	SKI	Asahi Kasei Toray Tonen SKI	Shanghai Putailai Canzhou Mingzhu	SEMCORP Senior Technology Material

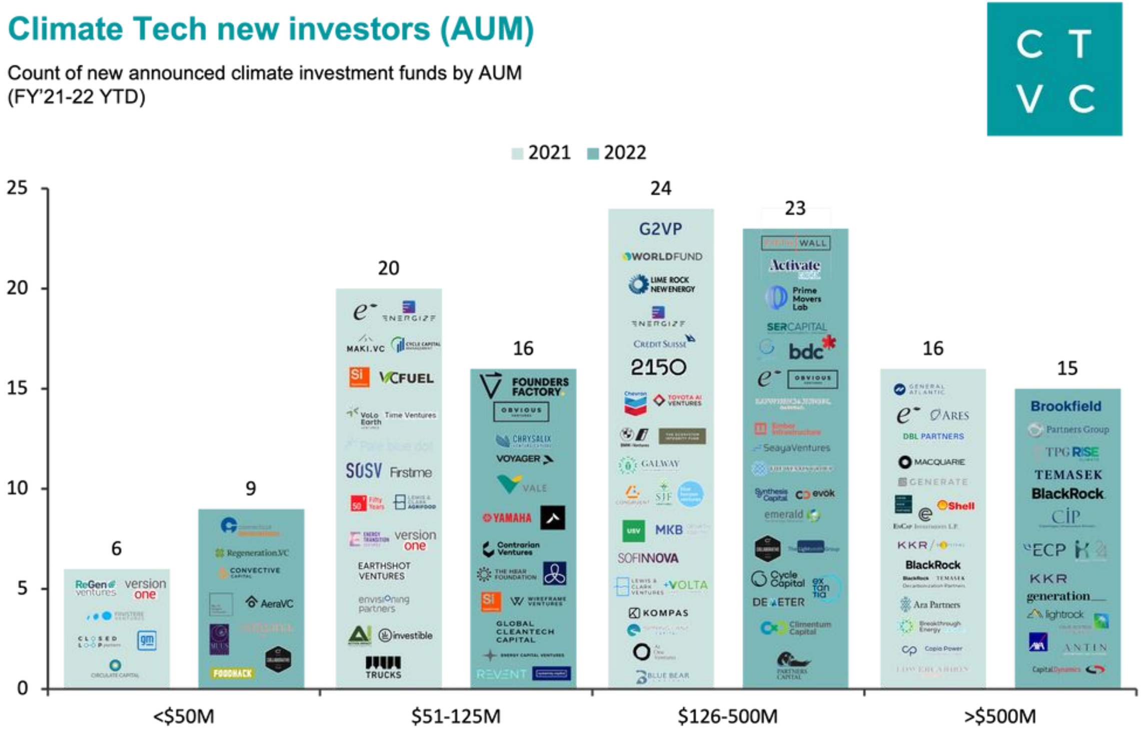
Source: Exawatt analysis of 2021 and 2022 financial disclosures of cell manufacturers and suppliers. NB the list is not exhaustive

Industry | Overview

- Notable Events
- Industry Players & Movement
- Investments
- Cell Chemistry Development
- Technology Applications
- Costs
- Supply Chain
- Recycling
- Manufacturing
- Safety / Legal

Investments | Climate Tech VC

Funding doubled from 2021 to 2022, with mega funds (>$1B) entering climate tech investment



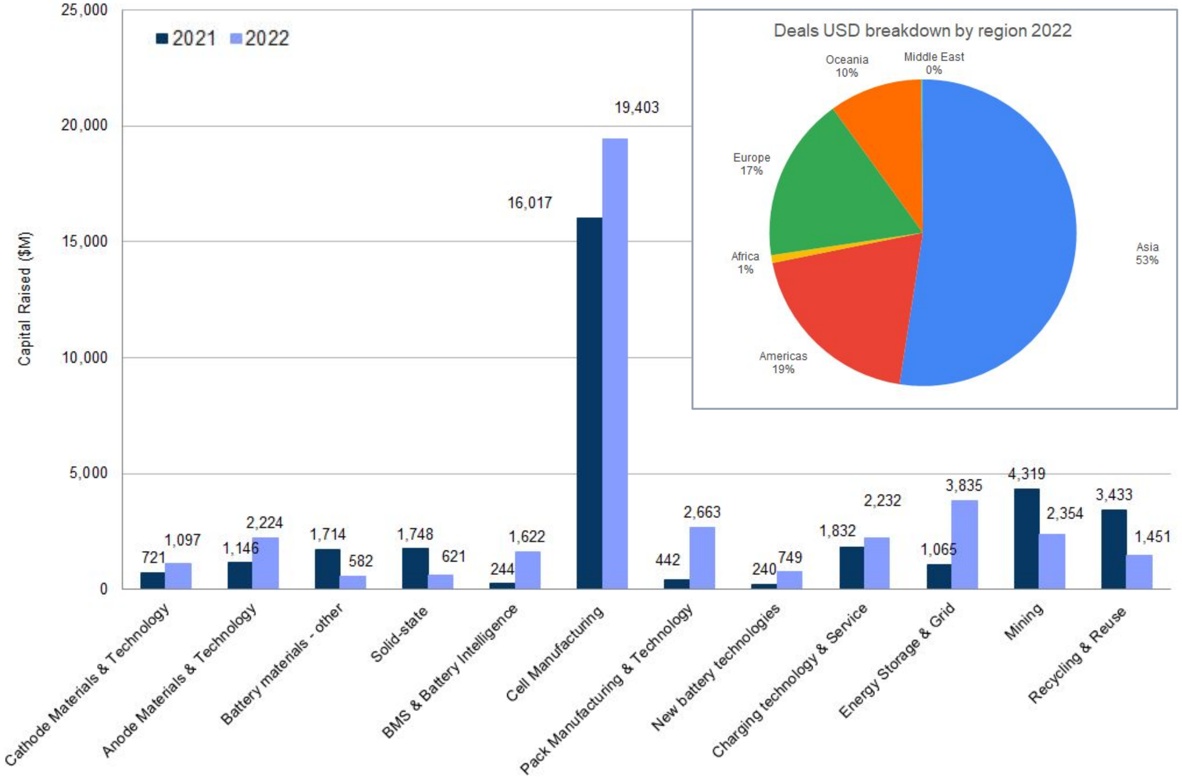
According to Climate Tech VC, 63 climate funds raised **$64B in 2022** up from 62 climate funds raising **$30B in 2021**. With $94B raised since 2021, there remains an estimated $37B in dry powder for climate investing.

5 mega funds (>$1B) were raised in 2022: Brookfield Global Transition Fund ($15B), TPG Rise Climate ($7B), Temasek GenZero ($3.6B), Energy Capital Partners ($3B), and Generation Investment Management ($1.7B)

Source: Climate Tech VC

Investments | Battery Industry Deals

Total investment in the battery sector continues to grow year on year



Key Trends

- Total raised in 2021: $33B
- Total raised in 2022: $39B

These figures include PE/Growth, Venture, Buyout/LBO, Corporate, Debt, Reverse Merger (SPAC), PIPE (Private Investment in Public Equity), and IPOs based on Pitchbook data.

Investment in **BMS & Battery Intelligence, Pack Manufacturing Technologies, New Battery Technologies** as well as **Anode Materials** saw the most growth in 2022 as compared to last year.

Cell Manufacturing had continued momentum and attracted the largest amount of capital in 2022.

The figures do not include the massive LG Energy Solution IPO which raised ~$10B at $60B valuation in January 2022.

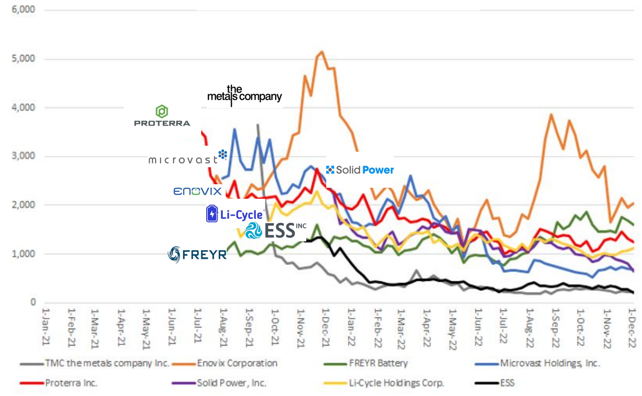
Source: Pitchbook as of Nov 2022

Investments | Battery SPAC Trends

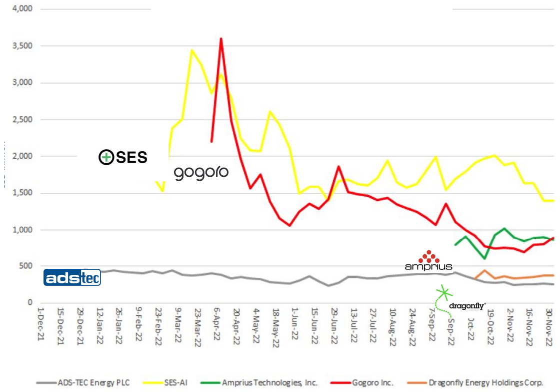
Market performance of battery SPACs since 2020

2020 Battery SPACs

2021 Battery SPACs



2022 Battery SPACs



The market capitalization of 2020 and 2021 battery SPACs continued to trend downwards below their original valuation, as financial results have underperformed. One exception is Norwegian cell manufacturer Freyr Battery, which is currently above its initial valuation.

2022 battery SPACs are also underperforming, with even the amount of funds raised in each SPAC decreasing over the course of the year. Despite investor losses at current valuations due to initial overhype, the significant amounts raised via SPACs could still enable innovation and achieve long-term value as these new technologies reach the market.

Source: Capital IQ as of Nov 2022

Investments | Notable SPACs and IPOs

In 2022, we counted 9 SPACs and 5 IPOs from e-mobility companies (focusing on batteries, energy storage, EVs, eVTOLs, and EV charging).

E-Mobility SPAC Exits in 2022

Key Trends

SPAC activity fell sharply in 2022. E-mobility companies with exits via SPACs raised just $3B, considerably less than the $12B raised by 32 e-mobility companies with SPAC exits in 2021.

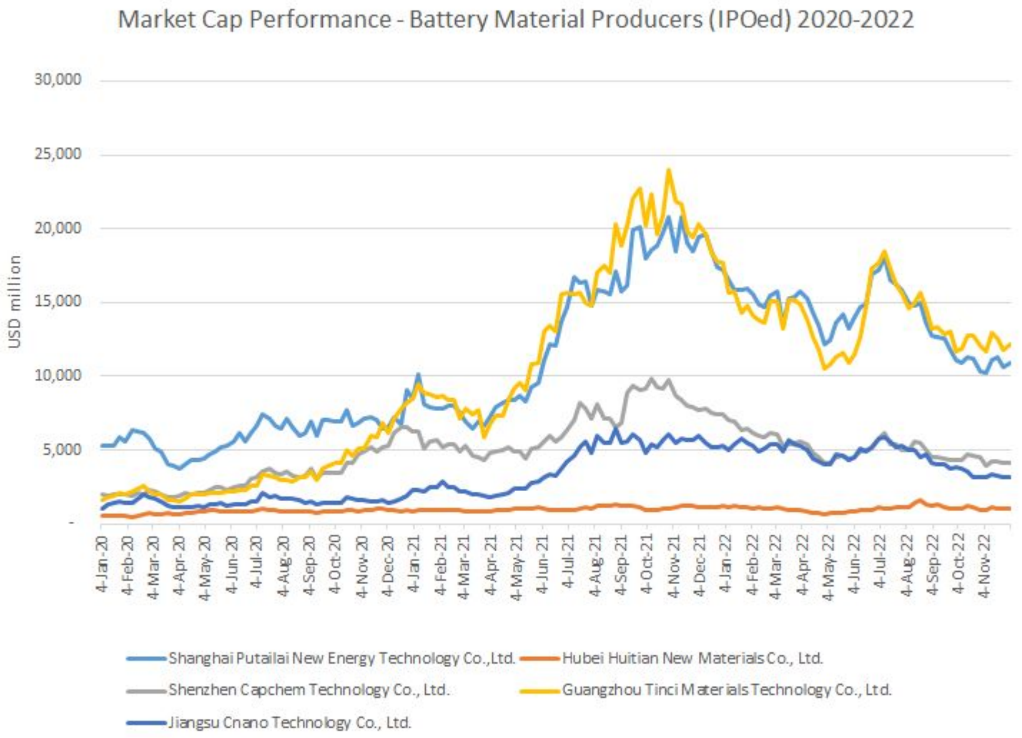
SPAC activity could decrease again in 2023 due to their poor performance on the stock market. By the end of 2022, nearly every e-mobility company with a SPAC exit was trading at a loss relative to its IPO price. One reason is that many of the startups with SPAC exits had little to no revenue.

LG Energy Solutions and Leapmotor had the most notable e-mobility IPOs. LG Energy Solution is one of the world's largest battery manufacturers and Leapmotor is an emerging Chinese EV manufacturer. Atlis Motors, SebitChem (battery recycling) and Phoenix Motor also had smaller IPOs.

Source: Bloomberg News, press releases. Note: (*) Excludes loans.

Investments | Market Trends of Battery Materials Producers

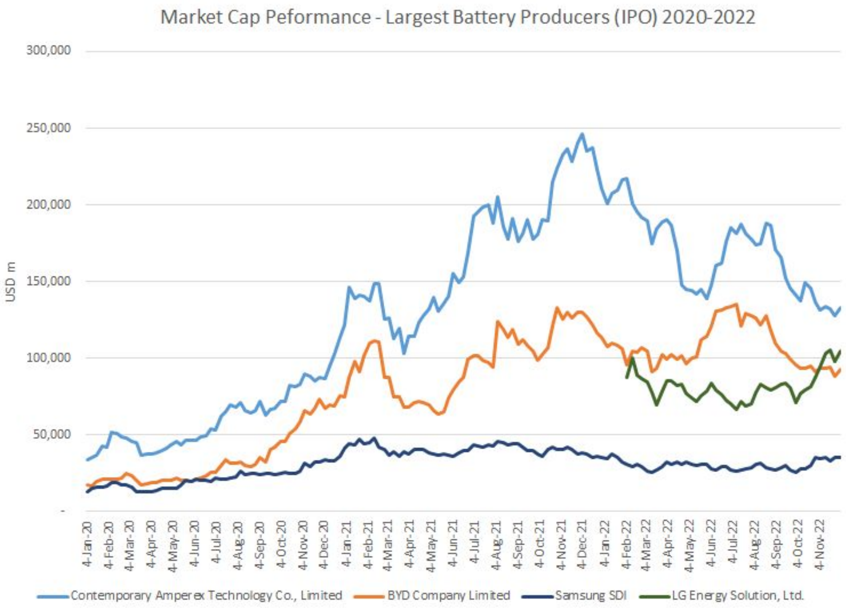
Market capitalizations of major public battery materials companies with traditional IPOs are up 3-4x since 2020, but down from their peaks in late 2021.

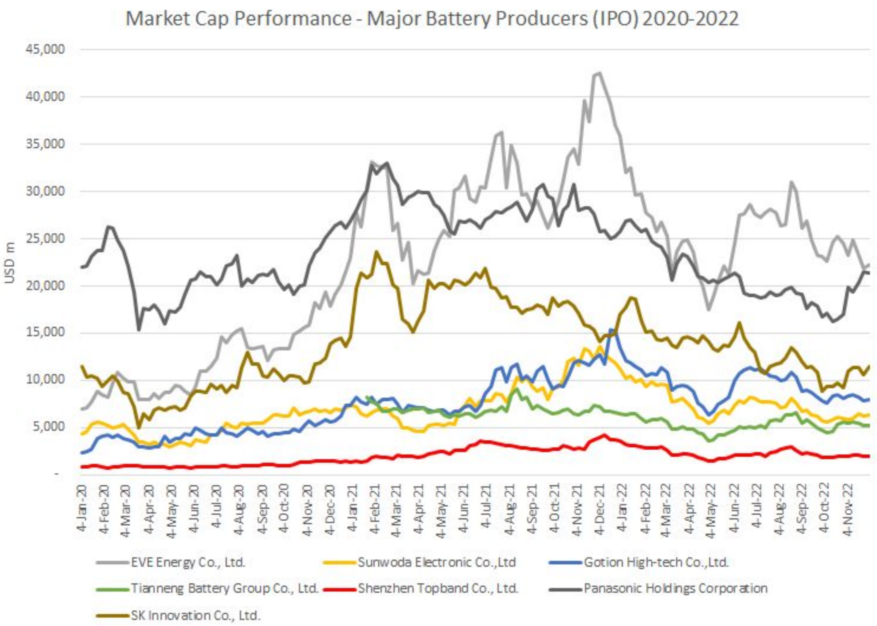


Source: Capital IQ as of Nov 2022

Investments | Market Trends of Battery Manufacturers

Market capitalization of major public battery companies with traditional IPO's are up 2-3x since 2020, but down from their peaks in late 2021.





Source: Capital IQ as of Nov 2022

Source: Capital IQ as of Nov 2022

Investments | Major Corporate and Financial Investors

EASTBRIDGE Partners
Vertex Ventures
IMM In Manus Mundus
InnoEnergy
Engine No.1
ABB Technology Ventures
Lightspeed
Cycle Capital
DCT capital
Creative Ventures
博华资本 Broad Vision Funds
Fidelity Investments
Chrysalix Venture Capital
Equinor
3ONE4 Capital
Plastic Omnium
Energy Revolution Ventures
EIF Ecosystem Integrity
Engie New Ventures
Fifth Wall
H+ Partners
VoLo Earth
DBL Partners
IDG Capital
foothill ventures
SK ecoplant
Demeter
Hermitage Capital 和暄资本
Cornerstone 基石资本
Sequoia
TigerGlobal
Temasek
君联资本 Legend Capital
Moore Ventures
BlackRock
bp ventures
顺为 Shunwei
GAC
Blume
日初资本 Dayone Capital
CAT
IQ Capital
Applied Ventures
Decarbonization Partners
Glencore
Clean Energy Ventures
深圳市创新投资集团有限公司 Shenzhen Capital Group Co., Ltd.
Första AP-Fonden
bnw
Porsche Ventures
Volvo
ZhenFund 真格基金
Energy Impact Partners
BMW i Ventures
TDK Ventures
Doral
InMotion
Koch
Breakthrough Energy
GIC
Coatue
Anzu Partners
Mirae Asset
Arctern Ventures
gm Ventures
NIO Capital
Good Growth Capital
OMERS
Baillie Gifford
EDP Ventures
PIVA
Reliance Industries Limited
+Volta Energy Technologies
/Detroit Venture Partners
LG Chem
LG Energy Solution
5AM Ventures
helios Capital Ventures
POWERHOUSE
Assembly Ventures
ibex Investors
catalus
Baruch Future Ventures
Gaorong Capital 高榕资本
LG Technology Ventures

Source: Pitchbook as of Nov 2022

outliers

Turn Science Fiction into Scientific Facts and Technological Inventions through Collective Intelligence-Driven Investing

Outliers Fund is a venture capital fund started by MIT students and professors in 2016. In the last six years, Outliers has evaluated 6,000+ ventures, invested in 50 and incubated 10 with 2 filing IPO, 3 being acquired and $100M+ raised collectively. These include Quantstamp, XYO Network, and Prysmatic Labs (Ethereum 2.0).

Outliers Fund I / II have returned over 16x and 11x respectively. Outliers Fund III is a $50M VC fund focusing on infrastructure-level research innovations. Outliers Fund IV will expand the scope to Metaverse and Deep Tech, which includes Quantum Physics, Reality Computing, Clean Tech, Time and Space Travel.

Poseidon Ho (Founding Partner) started Outliers Fund I, II, III and Outliers Lab. He is known for Ant-Inspired Collective Intelligence / Reality Computing research at MIT Media Lab, San Diego Zoo Research and Microsoft Research. He received his B.S. MIS from National Taiwan University and dropped out from University of Washington and Tsinghua University. Poseidon's mission is to identify, scale and connect outliers, those who are able to turn science fiction into scientific facts and technological inventions.

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Facebook: https://www.facebook.com/poseidon.vc

Industry | Overview

Notable Events

Industry Players & Movement

Investments

Cell Chemistry Development

Technology Applications

Costs

Supply Chain

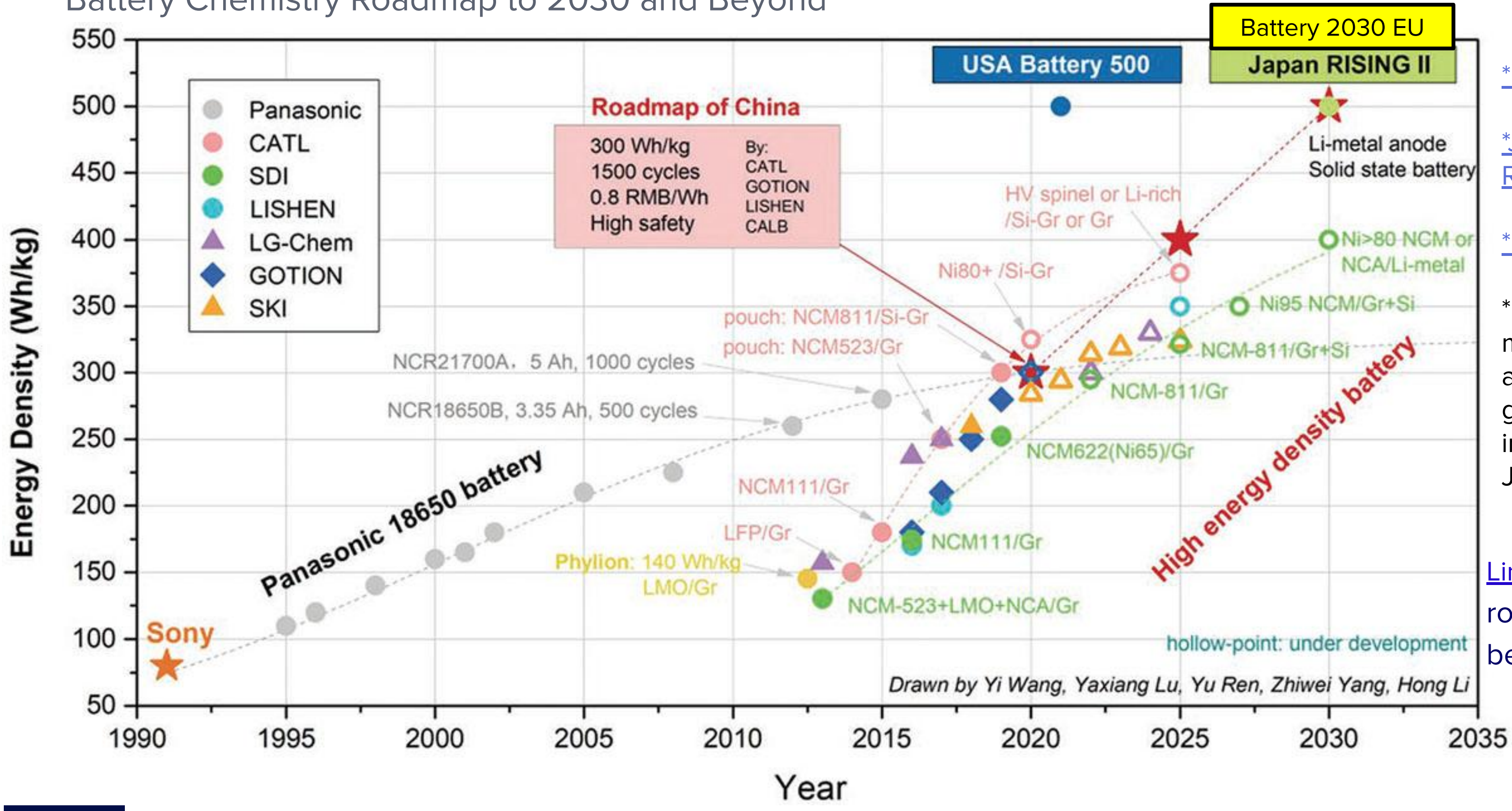
Recycling

Manufacturing

Safety / Legal

Technology | Cell Chemistry Development Roadmap

Battery Chemistry Roadmap to 2030 and Beyond



*USA Battery 500

*Japan Rising II (now Rising III)

*Battery 2030 EU

** 500 Wh/kg lithium metal solid-state cells are the goal of government agencies in the US, EU, and Japan

Link Battery chemistry roadmap to 2030 and beyond (graphic)

Source:

Technology | Cell Chemistry Tradeoffs (Processes)

Manufacturing Processes for Key Battery Chemistries

Battery Talk: Battery Application Break Down 101/2023		Li-Ion (NMC811-Gr)		Li-Ion (NCA-Gr)		Li-Ion (LFP-Gr)		Li-Ion (LCO-Gr)		Li-Ion High Voltage (LNMO)		Lithium Metal (High Ni-Li)		Silicon (High Ni- Majority Silicon)		Sodium ion (NaMOx) **Not Commercial		Lithium Sulfur Battery (LSB) ** Not Commercial		Solid State Sulfidic Lithium Metal Anode **Not Commercial			Solid State Oxidic Lithium Metal Anode **Not Commercial		
Manufacturing Processes for Key Battery Chemistries		Anode	Cathode	Anode	Cathode	Anode	Cathode	Anode	Cathode	Anode	Cathode	Anode	Cathode	Anode	Cathode	Anode	Cathode	Anode	Cathode	Anode	Electrolyte	Cathode	Anode	Electrolyte	Cathode
Electrode Production	Extruding and Calendering											X				X		X		X			X		
	Gassing											X				X		X		X			X		
	Lamination											X				X		X		X			X		
	Mixing	X	X	X	X	X	X	X	X	X	X		X	X	X		X		X		X	X		X	X
	Coating Active Material	X	X	X	X	X	X	X	X	X	X		X	X	X		X		X			X			X
	Coating Electrolyte																				X				
	Sintering																								X
	Calendering	X	X	X	X	X	X	X	X	X	X		X	X	X		X		X		X	X			
	Slitting	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
	Drying	X	X	X	X	X	X	X	X	X	X		X	X	X		X		X						
Cell Production	Cutting	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
	Aerosol Deposition																							X	
	Tempering																							X	
	Stacking	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Pressing																			X	X	X			
	Contacting	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Enclosing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Filling	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
Conditioning	Formation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
	Ageing	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

** X = process used for column's material and cell type

Resource Link: Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0)

Source: Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0) , BatteryBits

Technology | Cell Chemistry Tradeoffs (Performance)

Performance Metrics for Key Battery Chemistries

Performance Metrics for Key Battery Chemistries	Li-Ion (NMC811-Gr)	Li-Ion (NCA-Gr)	Li-Ion (LFP-Gr)	Li-Ion (LCO-Gr)	Li-Ion High Voltage (LNMO)	Lithium Metal (High Ni-Li)	Silicon (High Ni- Majority Silicon)	Sodium ion (NaMOx) **Not Commercial	Lithium Sulfur Battery (LSB) **Not Commercial	Solid State Sulfidic Lithium Metal Anode **Not Commercial	Solid State Oxidic Lithium Metal Anode **Not Commercial
Gravimetric Energy Density Wh/kg (cell level)	265-290	250-280	160-200	180-200	150-165	400-450	325-350	~150	**~500	**300 to 450	**300 to 450
Volumetric Energy Density Wh/L (cell level)	~735	~550	~390	~400	280-300	~800	750-900	~190	**~600	**~800	**~800
Power Density W/kg (cell level) (5Ah, 3C rate)	1100	700	200	380	1400	2000	1100	1000	500	**	**
Nominal Voltage (V)	3.7 (2.5 - 4.2)	3.6 (3.0-4.2)	3.2 (2.5 - 3.65)	3.6 (3.0 - 4.2)	4.0 (3.0 -5.0)	3.7 (2.5 - 4.2)	3.7 (2.5 - 4.2)	3 (1.0 - 4.2)	2.1 (1.8 - 2.4)	3.7 (2.5 - 4.2)	3.7 (2.5 - 4.2)
Cost $/kWh (Cathode BOM) (Q1 2022 pricing)	$57.00	$52.00	$62.20	$82.60	$41.70	$67-75	$55-60	**	**~$10 estimated	Typically High Nickel ~$60	Typically High Nickel ~$60
Cost $/kWh (cell level at GWh+ production) **Materials and Production Cost only	$113.77	$107.97	$118.17	$138.57	$97.67	$124.07	**	**	**$58.61 estimated	**Higher than traditional Li-Ion / Li Metal	**Higher than traditional Li-Ion / Li Metal
Cost $/kWh/Cycle (cell level at GWh+ production)	$0.0758	$0.1080	$0.0591	$0.1848	$0.2605	**	**	**	**$0.5861 estimated	**Higher than traditional Li-Ion / Li Metal	**Higher than traditional Li-Ion / Li Metal
Cycle Life (C/2+ rate)	1500	1000	2000	750	250-500	200-400	500	**	**150	**250-500	**250-500
Self Discharge (Qual)	Avg	Avg	Avg	Avg	Bad	Bad	Avg	**Avg	**Bad	**Good	**Good
Calender aging (Qual)	Avg	Avg	Avg	Avg	Bad	Avg	Avg	**Avg	**Avg	**Bad	**Bad
Rate Capability (Qual)	Avg	Avg	Avg	Good	Avg	Good	Good	**Avg	**Poor	Good	**Poor
Safety (Qualitative)	Poor	Poor	Avg	Poor	Good	Bad	Poor	**Good	**Avg	**Poor	**Good
High Temperature Operation (60C+)(Qual)	Bad	Bad	Bad	Bad	Bad	Bad	Bad	**Good	**Good	**Good	**Good
Low Temperature Operation (10C-)(Qual)	Avg	Avg	Avg	Avg	Avg	Avg	Avg	**Bad	**Bad	**Bad	**Bad
Recycle Value (Li, Co, Ni, Cu) for Cost/Effort	Avg	Avg	Poor	Avg	Bad	Avg	Avg	**Bad	**Poor	**Poor to Bad	**Poor to Bad
Possible Form Factors and Challenges	No Restriction	No Restriction	No Restriction	No Restriction	No Restriction	No Restriction	*High Swelling*	No Restriction	No Restriction	*manufacturing limitations*	*manufacturing limitations*

Legend
Great
Good
Avg
Poor
Bad

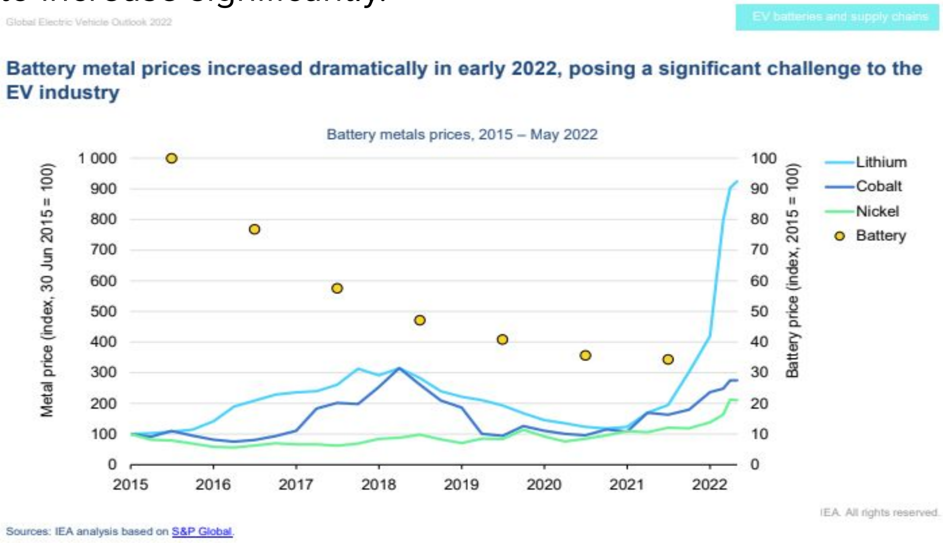
Resource Link: Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0)

Source: Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0)

Technology | Cell Chemistry Tradeoffs (Costs)

LIB cost reduction reaching limit due to surging critical metal prices

Battery metal prices surged in 2022, with supply unable to meet surging demand, causing cathode and cell costs to increase significantly.



US $/kWh	LFP			NMC811	
	Q1 2020	Q1 2022		Q1 2020	Q1 2022
Total Material Cost	**$38.20**	**$108.40**	**Total Material Cost**	**$50.30**	**$104.00**
Cathode	**$14.50**	**$62.20**	**Cathode**	**$20.80**	**$57.00**
All Metal	$3.70	$33.30	All Metal	$11.30	$36.50
Lithium Carbonate	$3.60	$33.20	Nickel sulfate	$6.60	$12.00
Iron	$0.10	$0.10	Cobalt sulfate	$1.80	$4.20
Additive, binder, solvent, etc	$10.90	$28.90	lithium hydroxide	$2.80	$20.10
			Manganese sulfate	$0.10	$0.10
			Additive, binder, solvent, etc	$9.50	$20.50
Anode	**$10.20**	**$15.70**	**Anode**	**$12.70**	**$15.70**
Graphite based anode	$3.50	$5.50	Graphite based anode	$7.10	$8.00
Battery Foil	$5.90	$8.20	Battery Foil	$4.80	$6.70
Additive, binder, solvent, etc	$0.70	$2.10	Additive, binder, solvent, etc	$0.80	$1.00
Electrolyte	**$6.30**	**$22.80**	**Electrolyte**	**$5.10**	**$18.30**
Lithium Salt (LiPF6)	$2.00	$14.90	Lithium Salt (LiPF6)	$1.60	$11.90
Liquid Electrolyte	$4.30	$7.90	Liquid Electrolyte	$3.50	$6.30
Seperators	$4.20	$4.60	**Seperators**	**$6.70**	**$8.00**
non-Major Raw Materials	$3.00	$3.00	non-Major Raw Materials	$5.00	$5.00

LFP Cost Increase	283.77%	NMC Cost Increase	206.76%
LFP Cathode Cost increase	428.97%	NMC Cathode Cost increase	274.04%
All Metal Cost increase	900.00%	All Metal Cost increase	323.01%
Lithium Carbonate increase	922.22%	lithium hydroxide	717.86%
Electrolyte cost increase	361.90%	**Electrolyte cost increase**	358.82%
Lithium Salt (LiPF6)	745.00%	Lithium Salt (LiPF6)	743.75%

Costs per LG Chem production and spot metal costs

Source: Iccsino, Antaike, Asian Metals, Wind, BNEF, J.P. Morgan estimates. Note: Based on spot raw material prices and actual sourcing cost might be different.

Source:

Technology | Cell Chemistry Tradeoffs (Application Requirements)

Applications Matched to Preferred Performance Metrics for Key Battery Chemistries

Applications Matched to Preferred Performance Metrics		Li-Ion (NMC811-Gr)	Li-Ion (NCA-Gr)	Li-Ion (LFP-Gr)	Li-Ion (LCO-Gr)	Li-Ion High Voltage (LNMO)	Lithium Metal (High Ni-Li)	Silicon (High Ni- Majority Silicon)	Sodium ion (NaMOx) **Not Commercial	Lithium Sulfur Battery (LSB) ** Not Commercial	Solid State Sulfidic Lithium Metal Anode **Not Commercial	Solid State Oxidic Lithium Metal Anode **Not Commercial
Aerospace	Planes (Wh/Kg > Rate > Safety/Reliability)	Avg	Bad	Bad	Bad	Bad	Bad	Avg	**Bad	**Good	**Good	**Good
	Drones (Wh/Kg > Rate > Cost)	Avg	Bad	Avg	Avg	Bad	Great	Great	**Avg	**Good	**Poor	**Poor
	Low Earth Orbit Satellites (Wh/kg > Cycle Life > Safety/ Reliability)	Avg	Avg	Poor	Avg	Bad	Bad	Poor	**Avg	**Good	**Good	**Good
	Medium Earth Orbit Satellites (Cycle Life > Wh/kg > Safety / Reliability)	Avg	Avg	Poor	Avg	Bad	Bad	Avg	**Avg	**Avg	**Avg	**Avg
	Geostationary Orbit Satellites (Cycle Life > Wh/kg > Safety / Reliability)	Avg	Avg	Poor	Avg	Bad	Bad	Poor	**Avg	**Avg	**Avg	**Avg
Automotive	Moped (Wh/Kg > Cost > Self Discharge)	Avg	Avg	Good	Poor	Poor	Bad	Avg	Poor	Bad	**Bad	**Bad
	Motorcycle (Rate > Wh/L > Wh/Kg)	Avg	Avg	Poor	Poor	Bad	Avg	Good	**Bad	Poor	**Avg	**Avg
	Sports Car (Wh/L > Rate > Cycle Life)	Good	Good	Avg	Avg	Poor	Bad	Avg	**Bad	Bad	**Poor	**Poor
	Sedan (Cost > Wh/L > Cycle Life)	Poor	Poor	Avg	Poor	Avg	Bad	Bad	**Avg	Poor	**Bad	**Bad
	Sports Utility Vehicle (Wh/L > Cost > Cycle Life)	Avg	Avg	Avg	Avg	Poor	Bad	Poor	**Bad	Poor	**Bad	**Bad
	Pickup Trucks (Wh/L > Wh/Kg > Cycle Life)	Poor	Poor	Poor	Bad	Bad	Bad	Avg	**Bad	**Avg	**Good	**Good
	Heavy Duty Trucks (Wh/Kg > Cycle Life > Cost)	Poor	Poor	Poor	Bad	Bad	Bad	Poor	**Bad	**Good	**Bad	**Bad
Consumer Electronics	Computers & Tablets (Wh/L > Cost > Safety / Reliability)	Avg	Poor	Avg	Poor	Good	Bad	Poor	**Poor	**Bad	**Poor	**Poor
	Smart Phones & Smart Watches (Wh/L > Cost > Safety / Reliability)	Avg	Poor	Avg	Poor	Good	Bad	Poor	**Poor	**Bad	**Poor	**Poor
	Power Tools & Gardening Equipment (Rate > Cost > Safety / Reliability)	Poor	Poor	Avg	Avg	Good	Bad	Poor	**Poor	**Bad	**Bad	**Bad
	E-Bikes (Cost >Wh/Kg > Rate)	Avg	Avg	Avg	Avg	Good	Poor	Poor	**Good	**Good	**Bad	**Bad
Grid	Grid Balancing (Cost/kWh/Cycle > Safety / Reliability > Cycle Life)	Bad	Bad	Bad	Bad	Poor	Bad	Bad	**Good	**Poor	**Bad	**Bad
	Residential Storage + Smart Grid (Safety / Reliability > Cost/kWh/Cycle > Cycle Life)	Bad	Bad	Poor	Bad	Avg	Bad	Bad	**Great	**Bad	**Bad	**Bad
Military	Infantry (Safety / Reliability > Wh/Kg > Wh/L)	Poor	Poor	Poor	Poor	Bad	Bad	Avg	**Bad	**Good	**Good	**Good
	Backup Power (Communications) (Safety/Reliability > Wh/Kg > Wh/L)	Poor	Poor	Bad	Poor	Bad	Bad	Avg	**Bad	**Good	**Avg	**Avg
	Missiles (Rate > Wh/Kg > Wh/L)	Avg	Avg	Poor	Poor	Bad	Avg	Good	**Bad	**Bad	**Avg	**Avg
	Drones (Wh/Kg > Rate > Safety / Reliability)	Avg	Poor	Poor	Poor	Bad	Poor	Avg	**Bad	**Poor	**Avg	**Avg

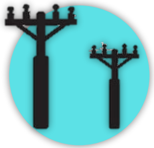
Legend
- Great
- Good
- Avg
- Poor
- Bad

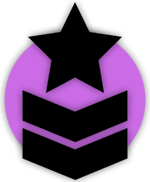
Source: Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0)

Technology | Battery Chemistries, Application Landscape, Overview

Ranking of top 3 key metrics for each sub-industry, starting with most valued metric



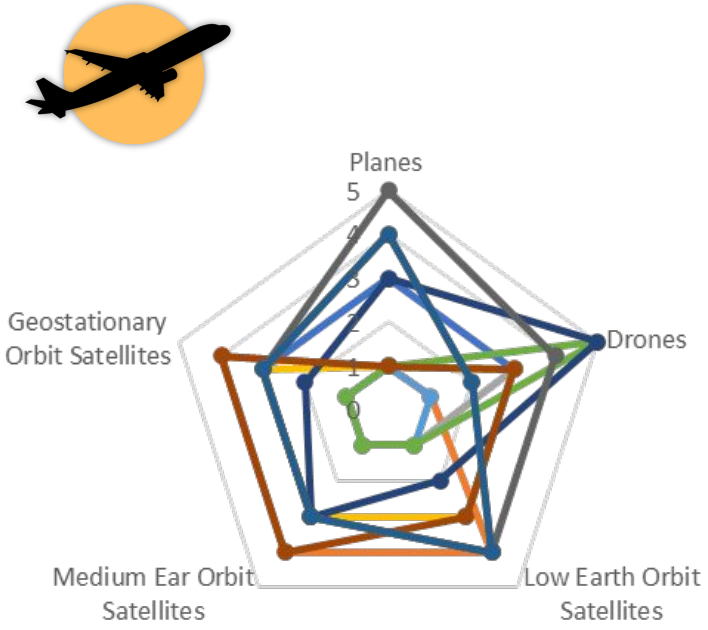



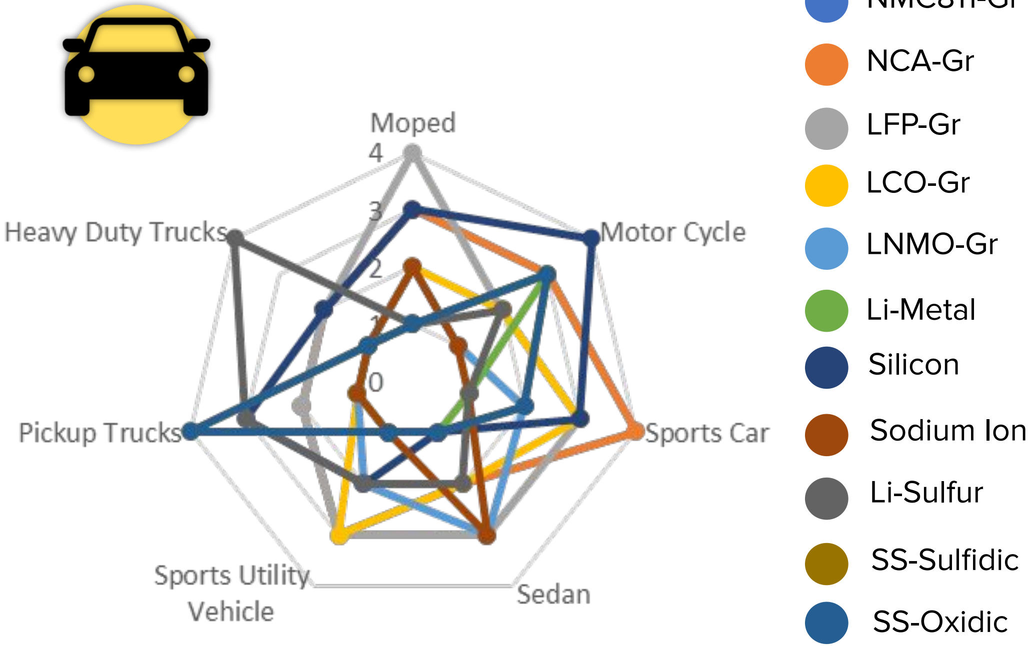


Planes Wh/Kg > Rate > Safety/Reliability	**Moped** Wh/Kg > Cost > Self Discharge	**Computers & Tablets** Wh/L > Cost > Safety / Reliability	**Loading Balancing** Cost/kWh/Cycle > Safety / Reliability > Cycle Life	**Defibrillators** Safety / Reliability > Rate > Wh/L	**Infantry** Safety / Reliability > Wh/Kg > Wh/L
Drones Wh/Kg > Rate > Cost	**Motorcycle** Rate > Wh/L > Wh/Kg	**Smart Phones & Smart Watches** Wh/L > Cost > Safety / Reliability	**Frequency Balancing** Cost/kWh/Cycle > Safety / Reliability > C-Rate	**Surgical Tools** Safety/Reliability > Rate > Cycle Life	**Backup Power (Communications)** Safety/Reliability > Wh/Kg > Wh/L
Low Earth Orbit Satellites Wh/kg > Cycle Life > Safety/ Reliability	**Sports Car** Wh/L > Rate > Cycle Life	**Power Tools & Gardening Equipment** Rate > Cost > Safety / Reliability	**Residential Storage + Smart Grid** Safety / Reliability > Cost/kWh/Cycle > Cycle Life	**Pacemakers** Safety/Reliability > Cycle Life	**Missiles** Rate > Wh/Kg > Wh/L
Medium Earth Orbit Satellites Cycle Life > Wh/kg > Safety / Reliability	**Sedan** Cost > Wh/L > Cycle Life	**E-Bikes** Cost > Wh/Kg > Rate		**Monitoring Devices** Cycle Life > Cost > Safety / Reliability	**Drones** Wh/Kg > Rate > Safety / Reliability
Geostationary Orbit Satellites Cycle Life > Wh/kg > Safety / Reliability	**Sports Utility Vehicle** Wh/L > Cost > Cycle Life				
	Pickup Trucks Wh/L > Wh/Kg > Cycle Life				
	Heavy Duty Trucks Wh/Kg > Cycle Life > Cost				

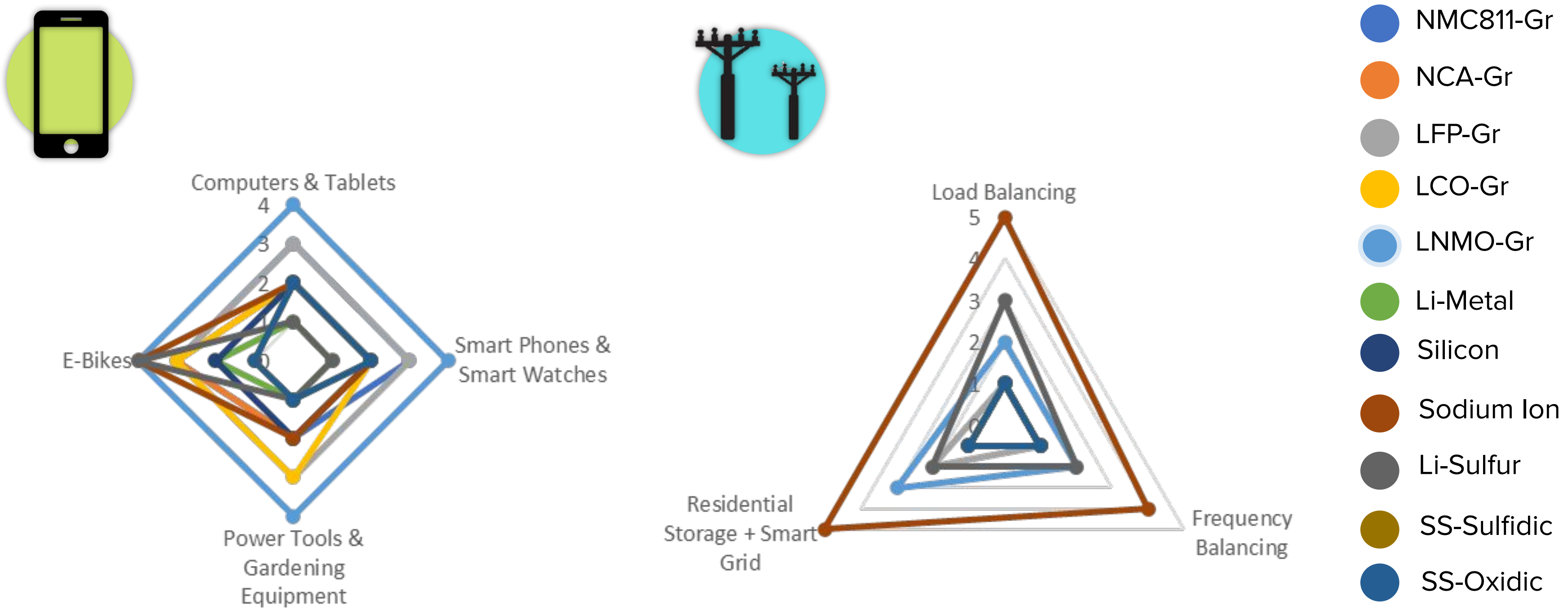
Source: Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0)

Technology | Battery Chemistries, Application Landscape, Overview



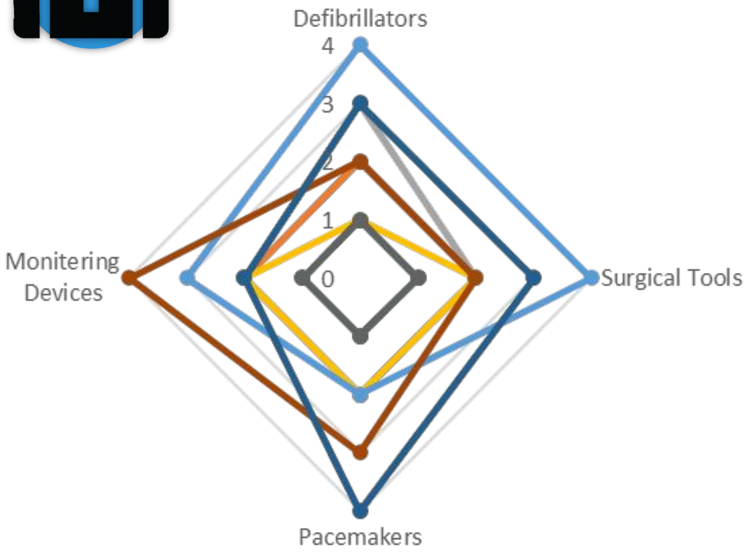


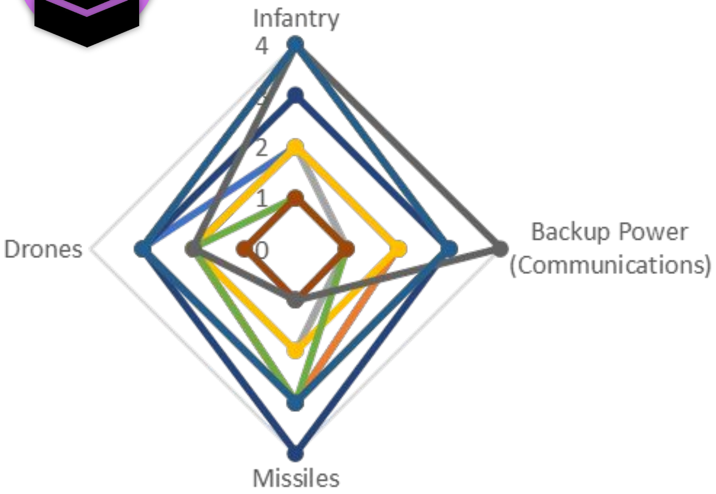
Technology | Battery Chemistries, Application Landscape, Overview



Source: [Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0)]

Technology | Battery Chemistries, Application Landscape, Overview





- NMC811-Gr
- NCA-Gr
- LFP-Gr
- LCO-Gr
- LNMO-Gr
- Li-Metal
- Silicon
- Sodium Ion
- Li-Sulfur
- SS-Sulfidic
- SS-Oxidic

Source: Battery Talk: Battery Application Break Down 1/01/2023 (Version 1.0)

Technology | LFP vs. NMC SWOT Comparison

Pros and Cons of Lithium Iron Phosphate (LFP) vs. Nickel Manganese Cobalt (NMC)

S

LFP Strength
- Safety
- Good cycle life
- Abundance of iron

NMC Strength
- Energy density
- Low temperature performance
- Power
- Strong battery supply chain
- High recycle value

W

LFP Weakness
- Weight
- Energy density
- Low temperature performance
- Weak material supply chain (material demand > supply)
- Power
- Difficult to read state of charge
- Low recycle value
- Cost (*2022)

NMC Weakness
- Cost
- Safety
- Ni/Co supply chain

O

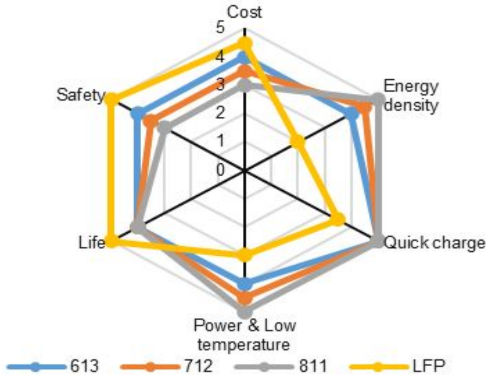
LFP Opportunity
- Low/mid-range/entry -level EVs
- e-Bus, e-Bicycle
- Stationary storage
- Cost sensitive applications

NMC Opportunity
- Long range/high-end EVs
- Stationary storage
- e-Bus, e-Bicycle, e-Motorcycle
- Power tools / performance sensitive applications

T

LFP Threat
- NMC/high-voltage LNMO
- Na-ion battery
- Regulations on energy density
- Increasing material cost

NMC Threat
- LFP/high-voltage spinel LNMO
- Increasing raw material cost

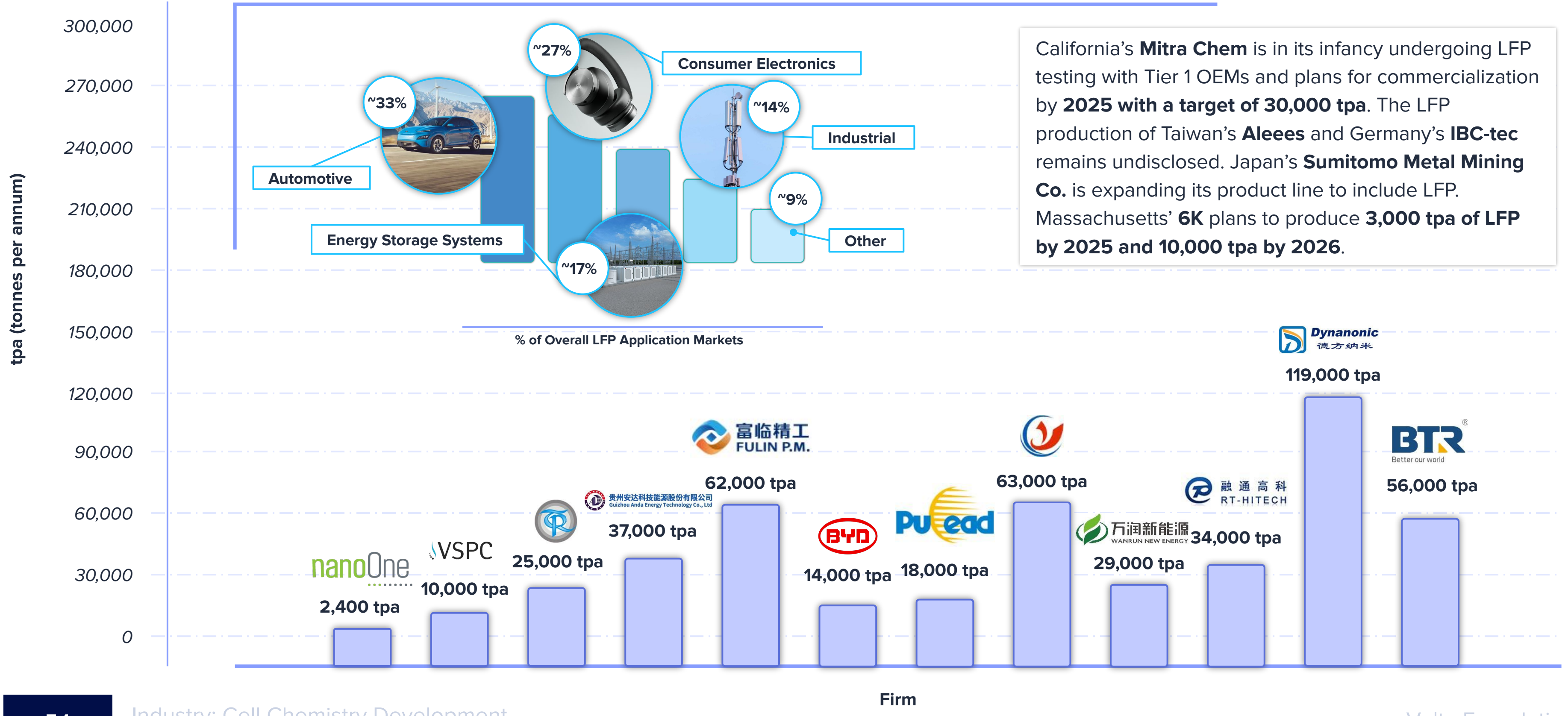


Source: LFP Pros and Cons, PNNL's LFP vs. NMC Comparison, Eco Tree Lithium's LFP vs. NMC Comparison, BatteryBits

Technology | Lithium Iron Phosphate (LFP)

Main companies in LFP and 2022 production capacities

California's **Mitra Chem** is in its infancy undergoing LFP testing with Tier 1 OEMs and plans for commercialization by **2025 with a target of 30,000 tpa**. The LFP production of Taiwan's **Aleees** and Germany's **IBC-tec** remains undisclosed. Japan's **Sumitomo Metal Mining Co.** is expanding its product line to include LFP. Massachusetts' **6K** plans to produce **3,000 tpa of LFP by 2025 and 10,000 tpa by 2026**.



Source: Wood Mackenzie, LFP Production, GEM Co. Ltd., VSPC, IBU-TEC, Aleees, Mitra Chem, Nano One, Lithium Werks, Nano One Production, Sumitomo Metal, DOE Bipartisan Infrastructure Law, LFP Markets, Industrial Applications

Technology | Lithium Iron Phosphate (LFP)

LFP Notable Events in 2022

2022Q1

January 2022

SVolt presents new LFP "short blade battery" cells. L300 and L600 models are for battery EVs, L400 for hybrids, and L500 for commercial vehicles.

2022Q2

April 2022

IBU-Tec expanded its product family of LFP battery materials with a second variant with smaller particles.

May 2022

CATL signed an agreement to supply LFP batteries with cell-to-pack technology for Solaris electric buses.

May 2022

Morrow Batteries and IBC-tec sign MOU for the development and qualification of commercial scale supply of LFP.

May 2022

Nano One acquires Johnson Matthey Battery Materials Ltd. for approximately $8 million. Current LFP production at the facility is 2,400 tpa with room for expansion.

2022Q3

July 2022

ICL Signs Memorandum of Understanding with Aleees for Production of lithium iron phosphate battery cathode materials.

July 2022

GAC unveils new LFP technology at GAC Tech Day, showing an increase of 13.5% in mass energy density, 20% in volume energy density, about 10% in low temperature capacity at -20°C, and a fast charge of more than 2C.

August 2022

BYD is reportedly going to supply Tesla with Blade Batteries, an LFP-based cell.

August 2022

SK On, EVE Energy, and BTR New Materials Group joint venture into an LFP cathode manufacturing plant.

September 2022

Gotion plans to invest $2.4B in a battery manufacturing plant near Big Rapids, Michigan.

September 2022

Aleees signs MOU with Avenira and the Northern Territory Government to develop first LFP cathode plant.

September 2022

Mitra Chem ships LFP samples to Tier 1 cell manufacturers for testing.

2022Q4

October 2022

FREYR sourcing LFP cathode material from Itochu.

October 2022

Our Next Energy announces $1.6 billion investment in 20 GWh LFP battery manufacturing plant.

October 2022

Freyr signs a licence and service agreement with Aleees, a Taiwanese manufacturer of LFP cathode materials.

October 2022

ICL Group plans to build a $400 million LFP cathode manufacturing plant in St. Louis, Missouri.

November 2022

Gotion and VinES announce a 5GWh/year LFP battery manufacturing plant.

Source: Linked to descriptions above

Technology | LMFP/M3P

LMFP

LFP and LMFP shares the same olivine crystal structure but the addition of manganese gives LMFP a theoretical energy density of up to 230 Wh/kg.

Pros and Cons

\+
- Higher energy density by 15-20% compared to LFP
- Low cost compared to NMC/NCA
- Safer than NMC/NCA
- Excellent low-temperature performance

\-
- High internal resistance
- Lower battery cycle life compared to LFP
- Recycle value is low

➔ CATL expects to mass produce LMFP batteries in 2023 and is on track to becoming the first manufacturer to take this chemistry to market.

Companies working on LMFP batteries

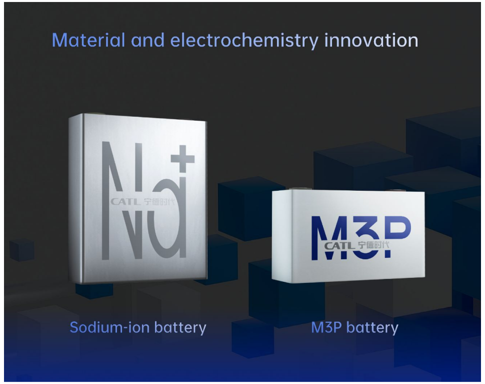
CATL | 国轩高科 GOTION HIGH-TECH | EVE 亿纬锂能
NIO | SUNWODA | acc AUTOMOTIVE CELLS Co

M3P

The M3P battery developed by CATL is based on the olivine structure of LFP, with some of the iron replaced by doping with magnesium, zinc, and aluminum. CATL calls it a ternary lithium battery of the phosphate chemistry system, but M3P synthesis is derived from the LMFP process and much closer in cost to LFP than to a nickel-based ternary battery.

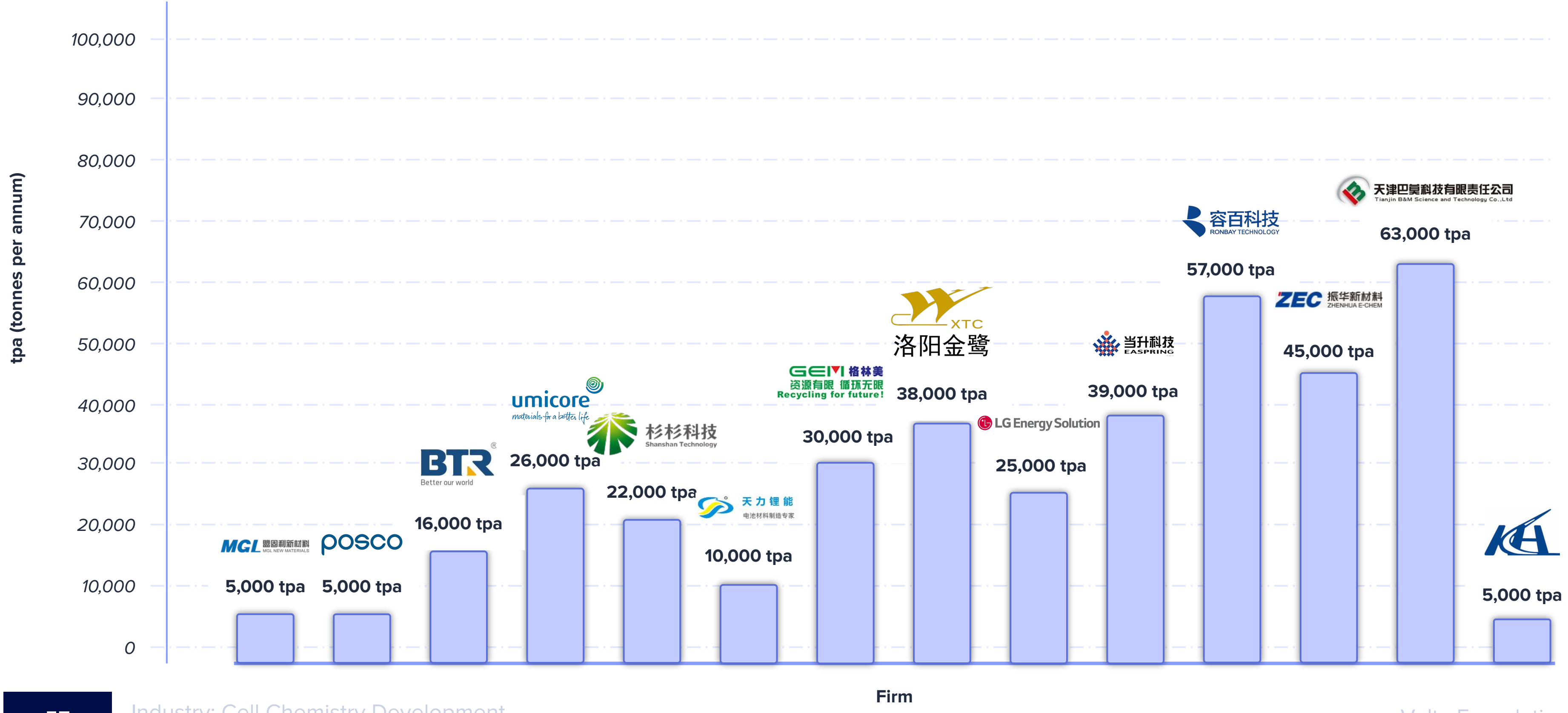
CATL will target the EV market segment with a range of more than 700 km.

➔ CATL to supply M3P batteries to Tesla in Q4 2022 for Model Y in China.



Technology | Nickel Manganese Cobalt (NMC)

Major NMC producers and 2022 production capacities



Source: Wood Mackenzie

Technology | Lithium Cobalt Oxide (LCO) vs. Lithium Iron Phosphate (LFP)

Pros and Cons of LCO vs. LFP

S

LCO Strength
- Energy density
- Weight
- Rate capability

LFP Strength
- Safety
- Cycle Life (1500-2000 Cycles)
- Abundance of iron

W

LCO Weakness
- Cycle life (500 cycles)
- Safety
- Low discharge current
- Cost (*2022)

LFP Weakness
- Weight
- Energy density
- Low temperature performance
- Power
- Cost (*2022)

O

LCO Opportunity
- VR headsets
- Compact, portable drones
- Small portable electronics

LFP Opportunity
- Low/mid-range/entry -level EVs
- e-Bus, e-Bicycle
- Stationary storage
- Cost sensitive applications

T

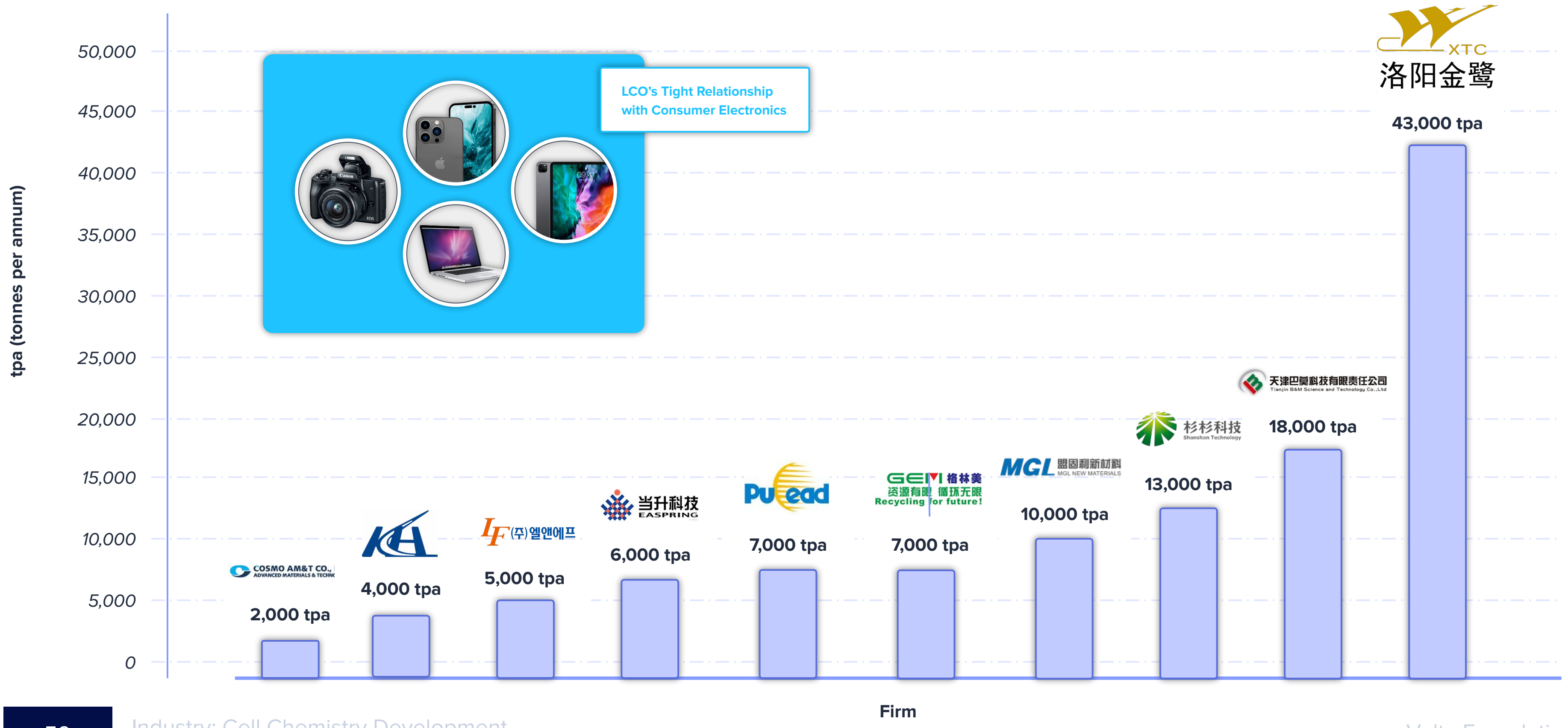
LCO Threat
- Increasing material cost
- Geopolitical risk (DRC)
- Regulations on cobalt mining

LFP Threat
- NMC/high-voltage LNMO
- Na-ion battery
- Regulations on energy density
- Increasing material cost

Source: LCO Overview, LFP Pros and Cons, LCO vs LFP, LCO Life Cycle, Congo's Cobalt Controversy,

Technology | Lithium Cobalt Oxide (LCO)

Major LCO producers and 2022 production capacities



Source: Wood Mackenzie

Technology | Lithium-Sulfur (Li-S)

Pros and Cons of Li-S vs. NMC

S

Li-S Strength
- Cost
- Safety
- Specific energy
- Abundance of sulfur

- **NMC Strength**
- Energy density
- Low temperature performance
- Power
- Strong supply chain
- High recycle value

W

Li-S Weakness
- Cycle life
- Energy density
- Battery supply chain
- Power
- Difficult to read state of charge

NMC Weakness
- Cost
- Safety
- Ni/Co supply chain

O

Li-S Opportunity
- Low/mid-range/entry-level EV's
- e-Bus
- e-Trucking
- Cost sensitive applications

NMC Opportunity
- Long range/High-end EVs
- Stationary storage
- e-Bus, e-Bike, e-Motorcycle
- Power tools/performance sensitive applications

T

Li-S Threat
- NMC/high-voltage LNMO
- Na-ion battery
- Regulations on energy density and pack cycle life
- Increasing material cost

NMC Threat
- LFP/high-voltage LNMO
- Increasing raw material cost

Source: OY Research

Technology | Lithium-Sulfur (Li-S)

Notable Events in 2022

1Q22

January 2022

Lyten receives award to demonstrate battery technology for space applications. Lyten also secures Other Transaction (OT) agreement in support of the Defense Innovation Unit (DIU) around high specific energy storage and management solutions to increase the duty cycle of small satellites for the US Space Force, one of many applications for the new Li-S battery technology.

February 2022

Zeta Energy closes $23M Series A round led by Moore Strategic Ventures for its advanced lithium-sulfur technology. Zeta Energy uses a patented carbon nanotube graphene hybrid material as its anode.

2Q22

February 2022

Researchers at Drexel discover a new way of producing and stabilizing a rare form of sulfur that functions in a carbonate electrolyte. This development has the potential not only to make sulfur batteries commercially viable, but also to provide 3 times the capacity of Li-ion batteries for 4,000 cycles.

April 2022

Theion's new CEO Dr. Ulrich Ehmes unveils their Li-S Crystal Battery for all mobile applications. Theion's patented production process uses crystalline sulfur as the cathode, carbon nanotubes as the anode, and a proprietary solid electrolyte.

3Q22

August 2022

Li-S Energy enters into an agreement with magniX USA to develop and evaluate its lithium sulfur and lithium metal cells, containing its patented nano-composite boron nitride nanotube and Li-nanomesh technology, for electric aviation.

September 2022

NexTech Batteries receives UN 38.3.5 safety certification for their 5.4 Ah semi-solid-state lithium-sulfur cell. These test standards are required for transporting battery cells.

4Q22

October 2022

NASA's solid-state battery research exceeds initial goals using its sulfur-selenium active material on holey graphene coupled with a solid electrolyte. The team has used new materials to increase the cell discharge rate dramatically while redesigning battery architecture to achieve a gravimetric density of 500 Wh/kg.

LITHIUM-SULFUR: The Mass Market Battery Chemistry

Lyten's LytCell™ technology is the future of sustainable batteries for automotive, aerospace, and defense applications that require high energy density, light-weight, safety, low cost, and a North American supply chain.

The Lyten Advantage

Lyten is an advanced materials company that developed a supermaterial called **Lyten 3D Graphene**™ which is engineered by decarbonizing methane gas. Our 3D Graphene technology enables us to make our cathode out of abundant **sulfur**, rather than increasingly scarce and expensive nickel or cobalt.

This will enable our development of one of the first **North American-sourced high-performance battery platforms** for EVs and beyond. What's more, we can apply our innovative chemistry to the pouch *and* cylindrical form factors making this a meaningful chemistry for the widest range of applications.

Find out more

We're always on the lookout for those who want to join our mission to innovate breakthrough solutions. Check out our website and our career page for more information about how Lyten is changing, ...and charging our world.

Technology | Lithium-Sulfur (Li-S)

Company	Technology	No. of Employees	No. of Patents	Total Funding ($)	Remarks
LYTEN	Sulfur Cathode-Li Metal Anode	169	117	210M	Well funded startup with large headcount and patent portfolio, Lyten is positioned to make a strong contribution to the space but has not released any public data. Based on employee count, they are most likely in pilot stages of development and will be a leader in the space.
theion	Mono-Clinic Sulfur Cathode-Li Metal Anode	24	4	undisclosed seed funding	Recently founded company based off research from Drexel. With an undisclosed amount of funding and low employee count, Li-S energy is most likely in early stages of research and scale up.
Li-S Energy	Sulfur Cathode-Li Metal Anode	8	1	167M (Market Cap as of 1/14/2023)	Li-S Energy went public early with their boron nitride based cathode. Based on employee count and patents, the company is most likely trying to figure out how to position their capital for the best return on development.
NexTech Batteries	Sulfur Cathode-Li Metal Anode	15	3	1M	The low employee and patent count would suggest early stages of development, but the recent UN 38.3 certification is evidence of significant pouch cell development. Nextech is most likely shipping samples but their low patent count may not provide enough of a barrier to entry.
Zeta ENERGY	Sulfur Cathode-3D Carbon Anode	17	5	27.2M	Recently awarded a DOE grant, Zeta Energy is a new player in the Li-S space with great potential. Although they have recently secured significant government funding, their employee and patent count indicates early stages of development.

Technology | Na-ion

Notable Events

1970s | 2011 | 2017 | 2021 | 2022 | 2023

1970s

Sodium intercalation materials are first reported.

2011

Faradion is established to bring sodium-ion batteries to market.

2017

HiNa Battery, the first first sodium-ion battery company in China, is established.

June 2021

HiNa Battery and the Institute of Physics, Chinese Academy of Sciences develop the first 1 MWh sodium-ion battery.

July 2021

CATL reveals sodium-ion battery with an energy density of 160 Wh/kg.

March 2022

HiNa Battery receives RMB 100 million in Series A round and sets up first mass production line for sodium-ion batteries.

October 2022

Natron Energy and Arxada start large-scale production of Prussian Blue for sodium-ion batteries.

November 2022

BYD is rumored to have plans for producing sodium-ion batteries for use in EV's.

December 2022

Three Gorges partners with HiNa Battery on 1 GWh battery plant in Fuyang.

January 2023

Jiana Energy raises millions of dollar to build pilot plant.

Key players in Na-Ion

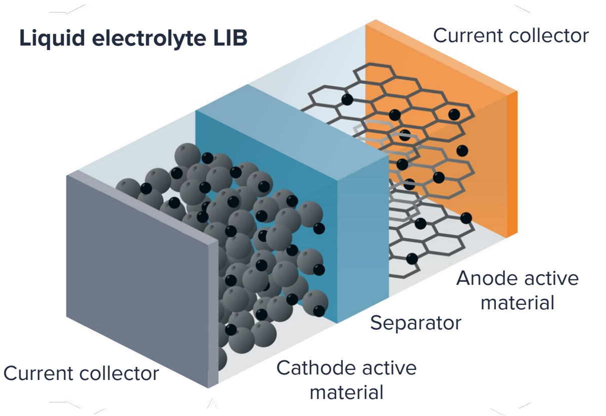
Source: BatteryBits

Technology | Solid State

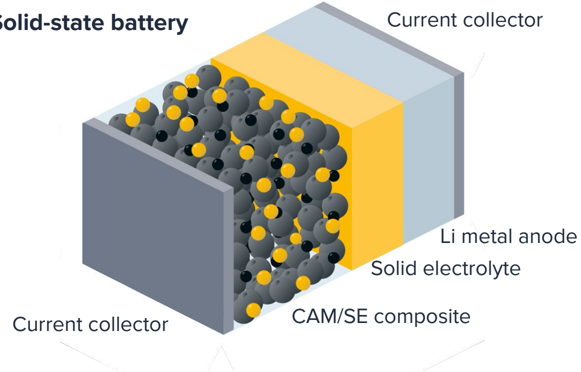
Cell structure

The general structure of solid-state batteries combines a solid electrolyte separator with an anolyte, a catholyte, and anode and cathode active materials. Various options exist for each of these components, opening up a wide range of possible combinations.

Liquid electrolyte LIB

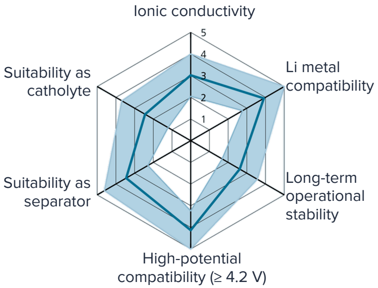


Solid-state battery

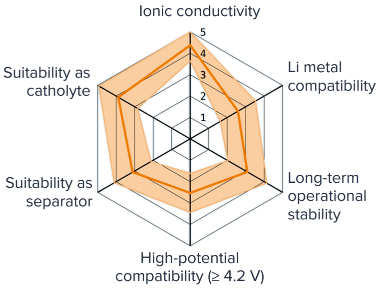


Current collector	Anode active material	Anolyte	Separator	Catholyte	Cathode	Current collector
	Lithium metal	Solid	Solid	Solid	LFP	
	Silicon	Oxide	Oxide	Oxide	NMC	
	Graphite	Sulfide	Sulfide	Sulfide	NCA	
	LTO	Polymer	Polymer	Polymer	Sulfur	
		(Liquid)		(Liquid)	High voltage cathode, e.g. LMNO	

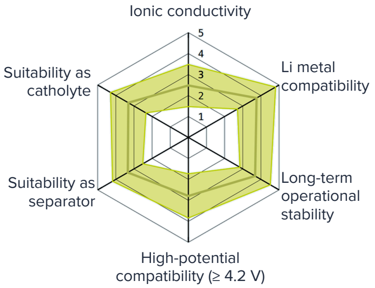
Oxide electrolytes



Sulfide electrolytes



Polymer electrolytes



Source: Solid-State Battery Roadmap 2035+, Fraunhofer ISI, BatteryBits

Technology | Solid State

Notable Events in 2022

Q1

StoreDot closes Series D funding round of $80 million, led by Vietnamese OEM VinFast.

Fluence enters into an agreement with QuantumScape to introduce oxide-based solid-state technology in stationary storage applications.

Factorial raises $200 million as part of a Series D round of funding led by Mercedes-Benz and Stellantis.

SES builds a pre-production facility in South Korea to accelerate A-sample joint development with GM, Hyundai and Honda.

Joint development and commercialization agreement between Li-Metal and Blue Solutions to advance solid-state batteries.

ProLogium announces world's first swappable battery prototype for Gogoro's scooters.

Nissan unveils its prototype production facility for all-solid-state battery cells in Japan.

Toyota announces that its first solid-state battery vehicles will go on sale by 2025 in hybrid vehicles (HEV) first.

Honda signs a joint development agreement with SES in the area of Li metal batteries.

Prologium enters into a technology cooperation agreement with Mercedes-Benz.

QuantumScape expands to asia-pacific region with new R&D center in Japan.

WeLion breaks ground on a 100 GWh solid-state lithium battery project in Zibo (China) with projected annual capacity of 20 GWh.

Samsung SDI begins construction of the pilot line for manufacturing solid-state batteries in South Korea.

Newly founded Swiss Clean Battery AG establishes the first Gigafactory for pure solid-state batteries in Switzerland.

Q2

Source: Linked to descriptions above

Technology | Solid State

Notable Events in 2022

Polestar invests in StoreDot.

Gotion to mass-produce semi-solid-state batteries this year.

Solid Power announces installation of EV solid state battery cell pilot line.

VinFast partners with and invested in ProLogium for solid-state batteries development.

Svolt builds battery cell factory in Germany, for european market.

POSCO JK Solid Solution opens solid electrolyte factory with initial production of 24 tons per year.

WeLion completed its first semi-solid-state battery cell for Nio's 150 kWh pack.

QuantumScape ships first batch of energy dense, 24-layer solid-state batteries to EV automakers.

Q3

ProLogium reveals its automated SSB mass production to start by 2023.

Svolt successfully develops 20 Ah solid state cell with sulfide-based electrolyte.

Solvay inaugurates state-of-the-art innovation pilot unit for solid state batteries in France.

StoreDot achieves major milestone of 1000 cycles for 30 Ah silicon-anode cells and starts shipping to OEM partners.

Q4

MoU between Prologium and Automotive Cells Company to cooperate in the development of solid-state batteries.

Factorial opens new solid-state battery facility in South Korea.

SES shares 50 Ah and 100 Ah Li metal cells performance metrics.

Source: Linked to descriptions above

Technology | Solid State Key players

All-solid state | Semi-solid

Company	Technology	Tot. Funding, Stage	Partnerships / Investments
IONIC materials	Li/graphite, polymer SE	$65M, Series D	Hyundai, Mitsubishi Motors, Renault, A123 Systems
ProLogium	Li/graphite/Si, oxide ceramic SE	$426M, Series E	Mercedes-Benz, NIO, ACC Automotive Cells Co, EVA AIR, NOVATE
Solid Power	Li/Si, sulfide ceramic SE	$186M, Public	BMW, Ford, Hyundai, Samsung, A123 Systems
ilika	Si, oxide ceramic SE	$43.8M, Public	Jaguar, Land Rover, Honda The Power of Dreams, McLaren
QuantumScape	Anode-free, ceramic SE, gel catholyte	$1.2B, Public	VW, Fluence A Siemens and AES Company
WELION 卫蓝新能源	Li, PEO-based SE	$302.7M, Series D	Xiaomi, Tianqi Lithium, NIO
StoreDot	Nanosized Si, semi-solid SE	$269M, Series D	Mercedes-Benz, bp, Daimler, VinFast, TDK, Geely, Volvo, EVE, Samsung
SES Beyond Li-ion™	Li, semi-solid SE	$600.1M, Public	Hyundai, Kia, Honda The Power of Dreams, gm, SK innovation
Factorial	Semi-solid SE	$240M, Series D	Hyundai, Kia, Mercedes-Benz, Stellantis
SVOLT	Sulfide ceramic SE (+ gel)	$2.9B, Series B	Stellantis, BASF, Exide
Sion Power	Li, ceramic+polymer SE	$70M, Private	BASF, Samsung, Cummins

Technology | Silicon Anode

Silicon anode overview

Silicon-based materials can provide a huge improvement in energy density since 1 silicon atom can hold 4 lithium atoms (compared to the incumbent graphite which takes 6 carbon atoms to hold 1 lithium atom. Silicon has a theoretical capacity of 3600 mAh/g compared to graphite which has 372 mAh/g.

Downsides include large volumetric expansion (300-400%) in Li alloying/dealloying. This can cause solid electrolyte interphase (SEI) development through excess silicon exposure and can disintegrate the whole anode. As a result, it has been challenging to make silicon dominant anodes and only a sprinkle (3-8%) is generally used.

In the next slide, we explore several startup companies by looking at the publicly available information.

Anode Materials	**C**	**Li**	**Si**	**Sn**	**Sb**	**Al**	**Mg**	**$Li_4Ti_5O_{12}$**	**Bi**
Lithiated phase	LiC_6	Li	$Li_{4.4}Si$	$Li_{4.4}Sn$	Li3Sb	LiAl	Li_3Mg	$Li_{12}Ti_5O_{12}$	Li_3Bi
Theoretical specific capacity (mAh g_{-1})	372	3,862	4,200	994	660	993	3,350	175	385
Theoretical volume capacity (mAh cm^{-3})	837	2,047	9,786	7,246	4,422	2,681	4,355	613	3,765
Volume change (%)	12	100	320	260	200	96	100	1	215
Potential vs. Li (~v)	0.05	0	0.4	0.6	0.9	0.3	0.1	1.6	0.8

Source: https://www.batterypowertips.com/li-ion-batteries-part-3-anodes-faq/, BatteryBits

Technology | Silicon Anode - Deep Dive on Startup Players

Silicon Startups Continue Raising and Building Partnership with Industry Players

Company	Sila	ENEVATE	ENOVIX	amprius	GROUP14	IONBLOX	nexeon	OneD Battery Sciences	StoreDot	ADVANO	LeydenJar
HQ / Date	CA, USA 2011	CA, USA 2005	CA, USA 2007	CA, USA 2008	WA, USA 2015	CA, USA 2017	UK 2006	CA, USA 2013	Israel 2012	LA, USA 2016	Netherlands 2016
Employees*	327	71	220	51	69	18	81	23	119	30	58
Money Raised/Valuation	$933M/3.3B	$202M/501M	$414M/1.1B	$622M/939M	$435M/3B	$34M/74M	$262M/352M	$48.4/325M	$269M/1.27B	$40/Unknown	$29M/Unknown
Company Stage	Series F	Series E	PIPE	PIPE	Series C	Series B	Series D	Series C	Series D	Series A	Series A
Si %	50%	70-100%	100%	100%	50%		80%			5-75%	100%
Technology Route	Si dominant porous microparticles with a rigid carbon shell	Silicon microparticles up to 40um with a SiC/carbon shell	Si particles coated in thin metal-semiconductor layer, 3D cell architecture	Si nanowires with a silicon oxide shell	Elemental Si impregnated in an activated porous carbon scaffold	Elemental Si and SiOx nanoparticles wrapped in carbon matrix, with metal coating	Si nanoparticles wrapped in silicon oxide, silicon carbide shells	Si nanowires grown onto graphite powders with a Cu catalyst to control size and connections	Metal coated Si nanoparticles with conductive matrix materials	Si nanoparticles with functionalized surfaces produced from scrap silicon.	Porous Si anode grown on the Cu substrate via PECVD
Claimed Performance	800 Wh/L	350 Wh/kg, charge in 5min to 75%	900 Wh/L 297 Wh/kg	435 Wh/kg, 1200 Wh/L, 1000 cycles	/	305 Wh/kg 640 Wh/L	400-450mAh/g	/	5-min extreme fast charge	350 Wh/kg at $90/kWh	450 Wh/kg 1350 Wh/L
Targeted Application	EV, consumer electronics	EV, consumer electronics	Consumer electronics	Defense, EVTOL	Consumer electronics	EVTOL	EV, Consumer electronics	EV	EV	EV, Consumer, ESS	Defense, EVTOL
Partnership/ Investment	Mercedes, Whoop, CATL, TDK, Samsung	RNM Alliance; LGES, Samsung	Intel, Qualcomm	Airbus, US Army	ATL(TDK), BASF, Showa Denko, SK	Applied Materials, Lilium	WACKER, SK Chemicals	GM Ventures, Volta Energy Technologies	BP, EVE, Daimler, Vinfast,Samsung, TDK	Mitsui Kinzoku	EIB

Source: Pitchbook & Intercalation Station Silicon Series (1, 2, 3, 4)

Industry | Overview

Notable Events

Industry Players & Movement

Investments

Cell Chemistry Development

Technology Applications

Costs

Supply Chain

Recycling

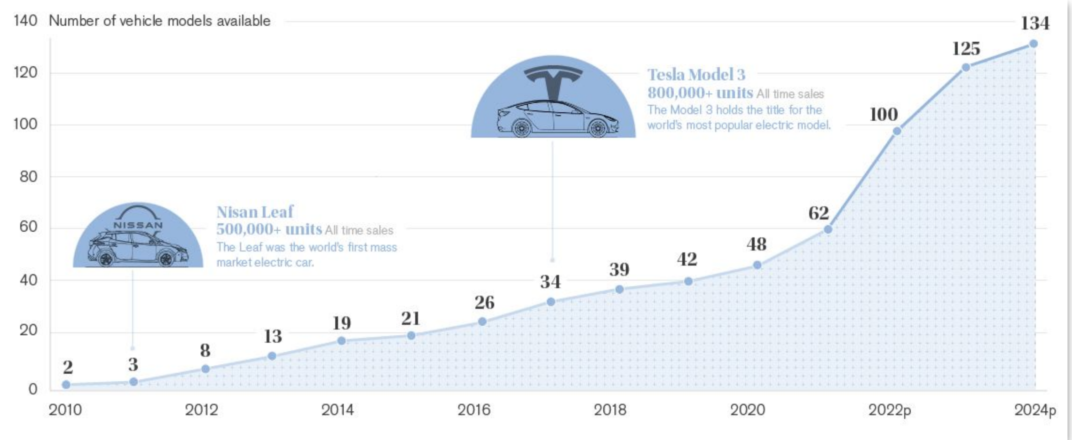
Manufacturing

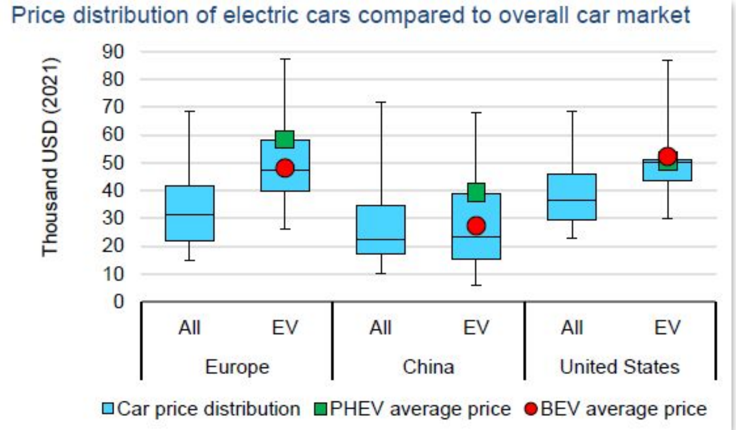
Safety / Legal

EVs | Consumer Options for Battery Electric Vehicles (BEV)

BEV lineup expands as legacy manufacturers announce ambitious plans and begin scale manufacturing

Legacy automakers are expanding their lineup of battery electric vehicles, with several planning to offer only BEVs by 2030-35.





Several models, however, are still targeted at the luxury segment. Consequently,

- Battery pack sizes are increasing steadily
- OEMs are focusing electrification efforts on larger and expensive SUVs, trucks and crossovers
- EV prices are still higher than the average vehicle price, with the exception of China

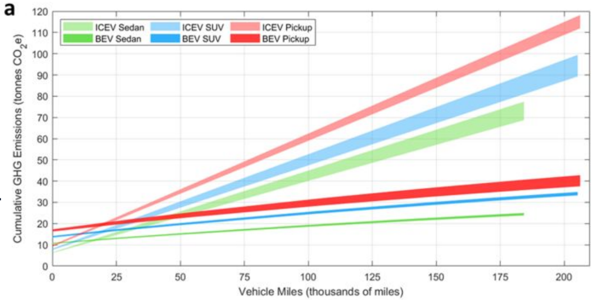
Source: Visual Capitalist, IEA Global EV Outlook 2022, BatteryBits

EVs | Pickup Trucks

Several electric pickups were released in 2022, with more launches expected in 2023. But larger vehicles require even larger battery packs, extending times for carbon crossover

Researchers from U. Michigan and Ford studied the role of pickup trucks in electrification. The benefits of electrification depend on the carbon intensity of grid electricity of a particular geographic location.

Based on the assumptions in this study, on average, BEV pickups reach CO_2e parity with ICEVs before 25k miles and with HEVs before 40k miles. Still, at 100k miles for BEV pickups, 50% of CO_2e is expected to come solely from battery manufacturing. In the short term and in regions with high grid carbon intensity, HEVs are likely to lead to CO_2e parity more quickly.



Lifetime CO_2 emissions for ICEV and BEV pickup trucks. BEVs are shown to reach CO_2 parity before 25k miles.

	ICEV	HEV	BEV
Pickup	543-573 100%	388-410 72%	182-207 35%
SUV	435-485 82%	317-345 59%	162-170 31%
Sedan	373-420 71%	262-287 49%	129-136 24%

Lifetime cradle-to-grave GHG emissions (base and premium models) for each combination of vehicle class and powertrain in g CO_2e/mile and average GHG emissions as a percentage of ICEV pickup truck emissions.

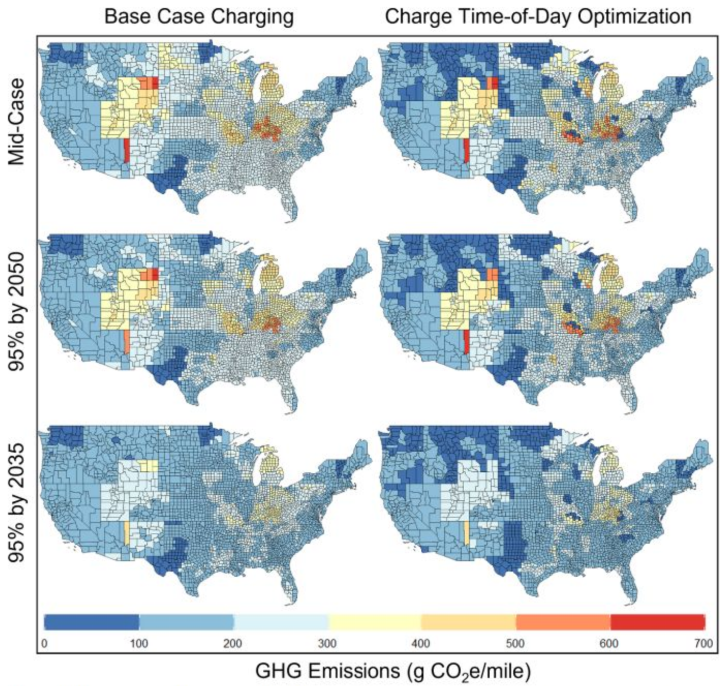


Figure 7. GHG emissions of a BEV pickup truck for base case grid emissions projections, a rapid decarbonization scenario, charge time-of-day optimization, and charge time-of-day optimization combined with rapid grid decarbonization.

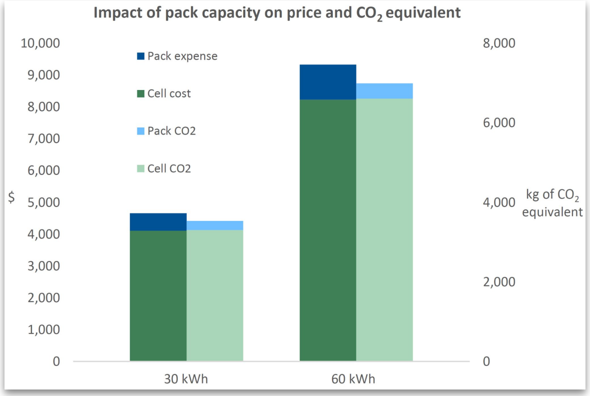
Source: Woody et al., Burton et al., BatteryBits

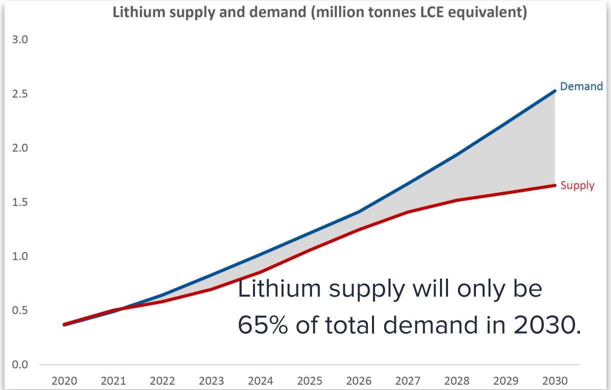
EVs | Impact of Battery Energy on Lithium Supply and Carbon Emissions

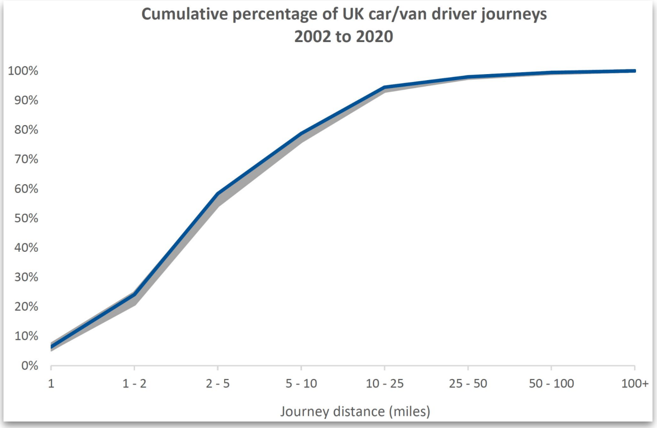
Smaller battery packs minimize costs for the OEM, raw material use and CO_2 emissions

Exawatt and *Minviro* published a whitepaper detailing the need for smaller battery packs as a solution to the crunch in materials supply, and ultimately for a sustainable battery industry. Smaller battery packs in EVs can minimize costs for the OEM, the use of raw materials and emissions, while meeting a large portion of the consumer requirements.

99% of UK car journeys are under 100 miles, and 80% of all trips are under 10 miles. As an example, shifting from a 60 kWh battery pack to 30 kWh could save up to $9,000 in costs and 3,500 kg of CO_2 emissions.







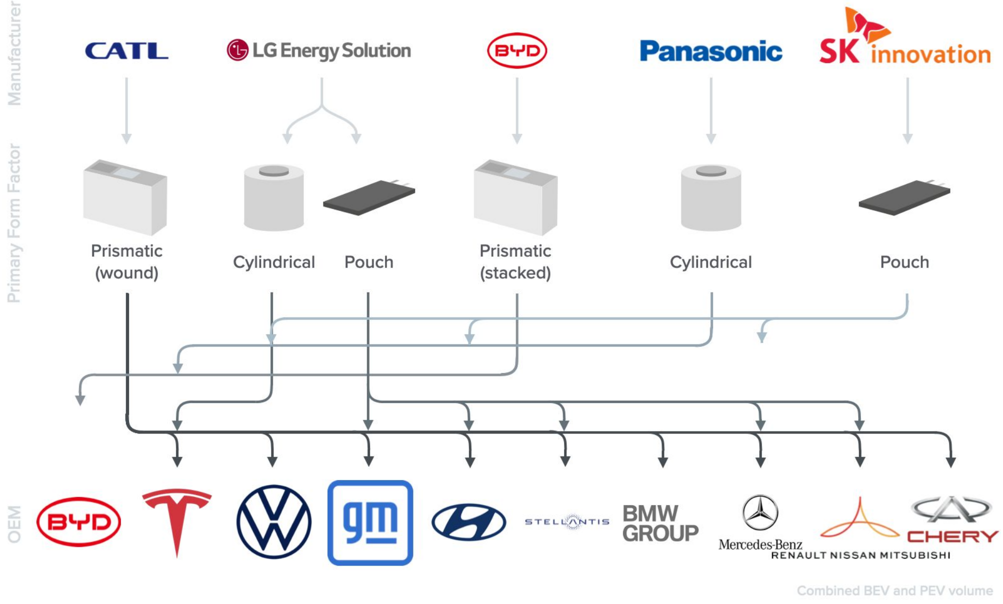
Source: Edward Rackley, Aaron Wade, Elijah Santos, Catherine Kohler, Jordan Lindsay, Robert Pell. Size Matters. The Economic and Environmental Impact of Smaller EV Batteries.

EVs | Cell Form Factor Adoption: Status Quo

Choice of cell design largely driven by application demands & chemistry

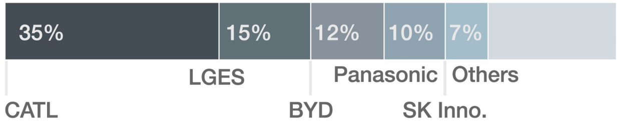
Primary Adoption Breakdown by Cell Manufacturer

by decreasing volume (2022) (–) ⟶



Source: Public announcements, J. P. Morgan

Cumulative Global EV Battery Supply (2022)



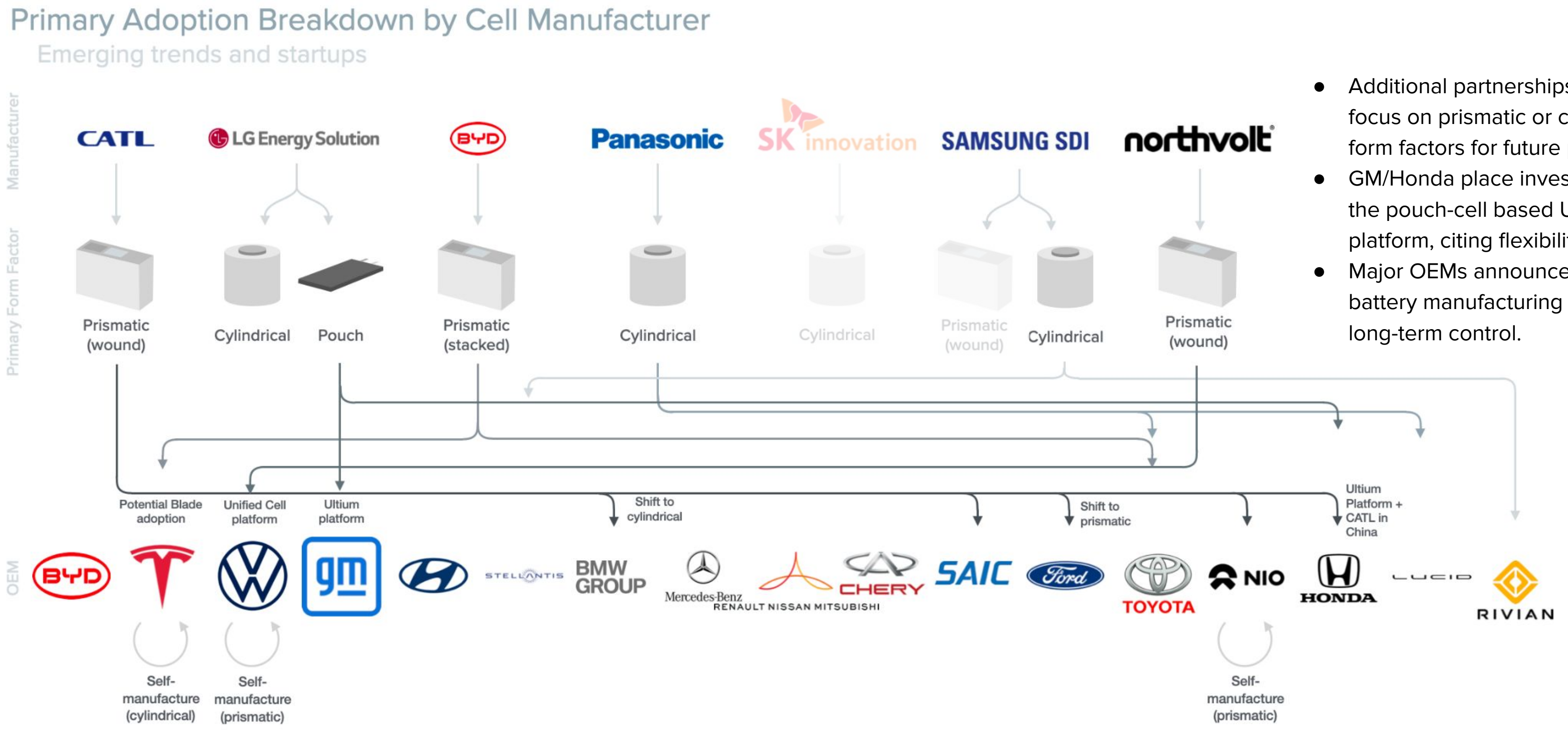
The significant trade-offs between cell form factors occur between Volumetric Energy Density (VED), Packing Efficiency and Safety (Thermal Runaway Propagation Resistance (TRP).

First generation EVs comprised mostly of cylindrical and pouch cells owing to their advantage in cost and manufacturability due to existing factory tooling.

Form Factor Scorecard

EVs | Cell Form Factor Adoption: Emerging Cell Partnerships

OEMs and startups begin to make long-term bets on form factors in joint ventures and announcements



Source: Public announcements, J. P. Morgan

- Additional partnerships formed focus on prismatic or cylindrical form factors for future platforms.
- GM/Honda place investments into the pouch-cell based Ultium platform, citing flexibility in design.
- Major OEMs announce their own battery manufacturing plants for long-term control.

Sources: Electrek, VW 1, VW 2, GM 1, GM 2, CATL 1, CATL 2, CATL 3, Ford, NIO, Panasonic, Forbes, Reuters

EVs | Cell-to-Pack (CTP) Integration

Pack designs are evolving, with a move towards monolithic designs, intended to eliminate dead weight, enable higher packing efficiency and lower costs

Advantages

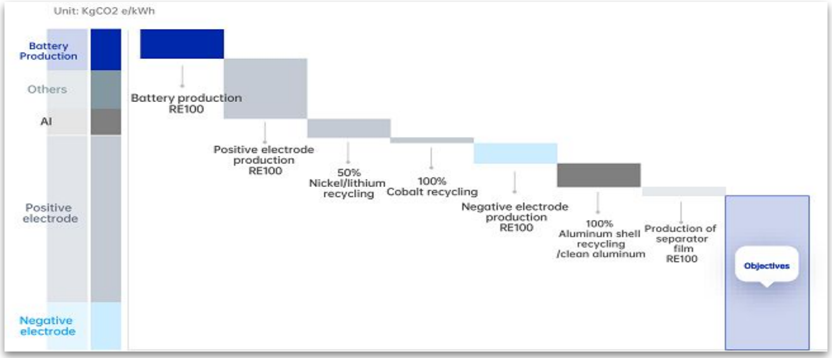
Elimination of the module assembly level reduces number of components and battery assembly costs, and increases packing efficiency. CTP concepts generally employ larger cell form factors, resulting in fewer cells. These advantages are also projected to reduce carbon intensity (kg-CO_2/kWh).

Challenges

But engineering challenges such as safety and thermal propagation remain before CTP can achieve the claimed cost reductions. Safety challenges still remain, indicated by the recent recall of BYD Blade batteries.

What companies are doing

CATL Qilin Structural Battery
BYD Blade Structural Battery
Tesla 4680 Structural Battery



Contribution of different materials and processes to CO_2 emissions

Source: Images from The Limiting Factor

EVs | Tesla 4680 Structural Battery

Overview

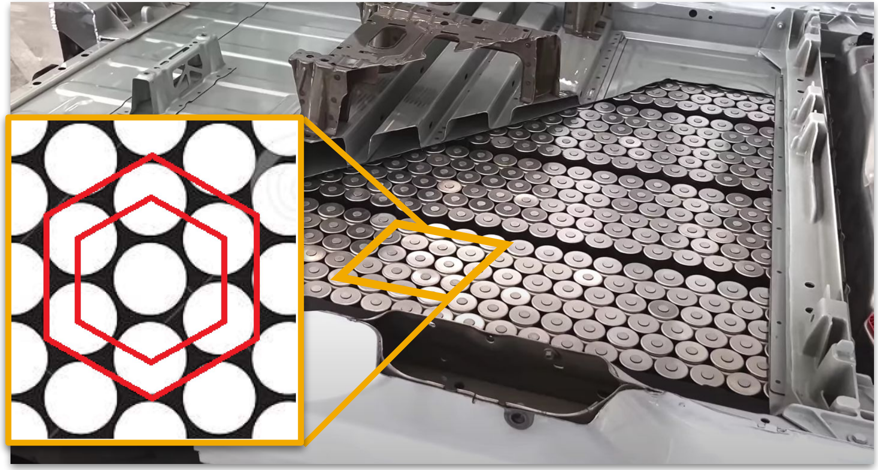
- Cell-to-pack integration with 4680 cylindrical cells, launched first in the 2022 Model Y.
- Battery pack (67.5 kWh, 445 kg*) serves as the floor and cross-car support for the vehicle, while meeting safety and noise, vibrational, and harshness (NVH) standards.
- Cells are assembled into 4 groups of hexagonally packed Tesla 4680 cells, all of which are formed into a single structure by filling the interstitial spaces of the pack with highly rigid urethane foam, which is also directly adhered to the pack lid.

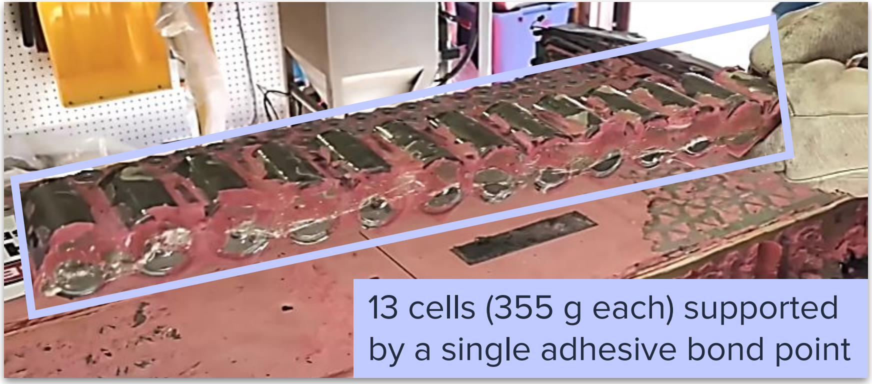
Advantages

- Improved rigidity and vibration absorption in axial direction, especially when cell-to-cell gaps are filled with urethane foam.
- The honeycomb layout is a unique advantage to cylindrical cells that cannot be translated to pouch or prismatic cells.
- Enables ease of assembly and reduction in part complexity.
- Final assembly is more robust and less prone to quality failure.

Drawbacks

- This structural pack is NOT serviceable.



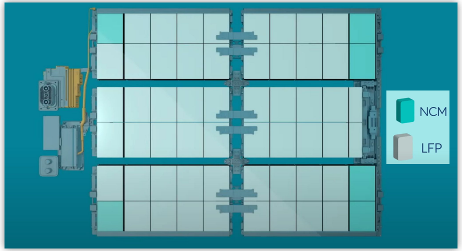


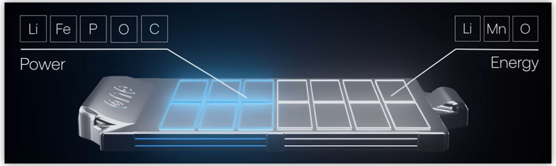
Source: MunroLive

* Measured by Munro Live

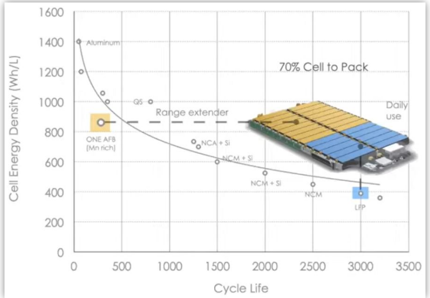
EVs | Hybrid Chemistry Architectures

Paired chemistry combinations compensate for shortcomings in performance, cost and lifetime





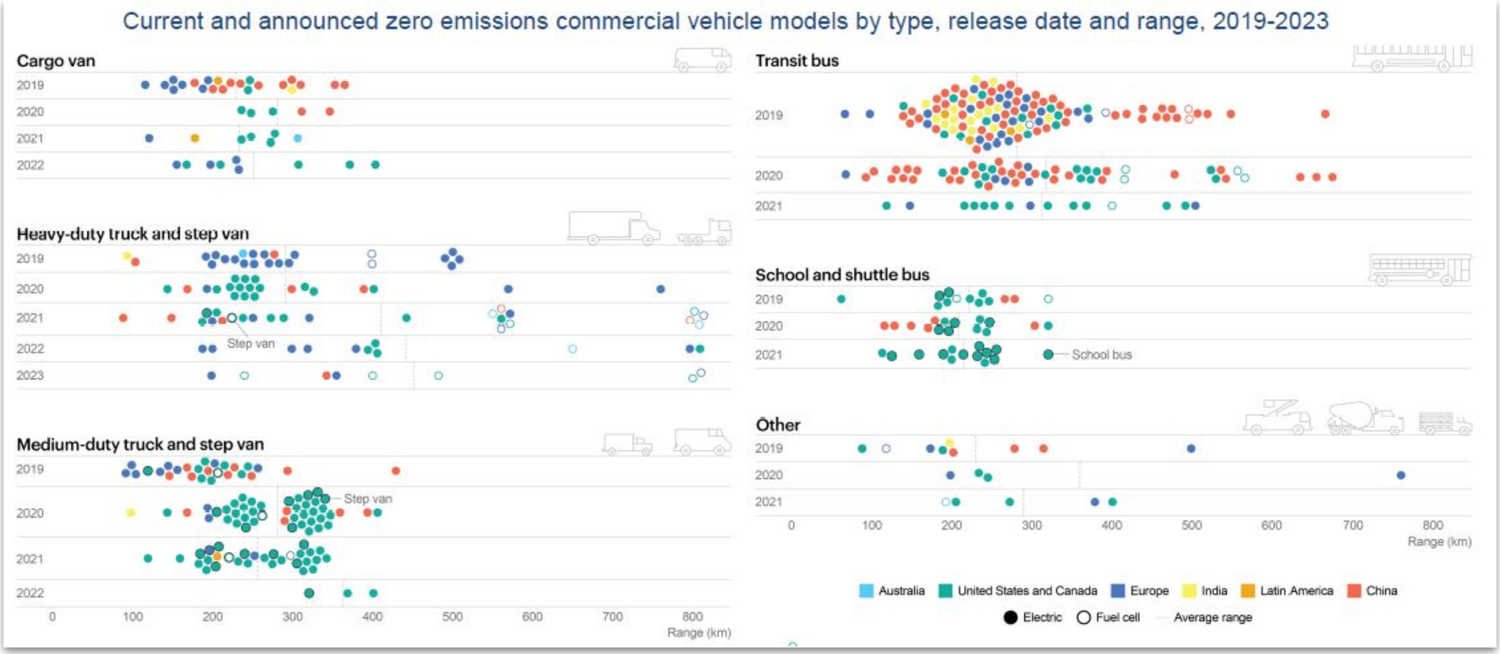
	Nio	CATL Li+Na	ONE Gemini
Chemistry	NCM + LFP	Li^{+} + Na^{+}	Anode-free LMO + LFP
Energy Density	142 Wh/kg	200 Wh/kg *(targeted)*	310 Wh/kg, 420-475 Wh/L
Intent	Improve performance of LFP at low-temperatures	Reduce cost and improve safety of CTP architecture	LFP for traction power and cycle life, LMO for range extender (high energy density, low cycle life)
Trade-offs	LFP for cost, NCM for low-temp. performance and optimizing SoC estimation	Na-ion for lower cost and safety, LFP for power capability	



- Hybrid chemistry packs show promise for reducing cost by using low-cost cathode materials, but introduce additional complexity in electrical architecture and BMS design.
- Similar to energy-power hybrid packs that have been investigated in the past, chemistry hybrids are potentially only an interim solution to test newer chemistries in real-world (but niche applications) before they are deployed at scale.

EVs | Commercial Vehicles and Last Mile Solutions

Commercial vehicle announcements slow down, but several products enter production across markets



- The number of product launches decreased in 2021/22 as most manufacturers focused on execution of previously announced vehicles.
- Medium and heavy duty vehicles are mostly below 250 mi in range.
- Battery EVs more prominent than Fuel Cell EVs in all vehicle segments.
- Medium duty and school buses are the most common segments in North America, while transit buses are the focus in China and India.

Source: IEA Global EV Outlook 2022

EVs | Commercial Vehicles (Semi Trucks)

Electrification in the heavy duty sector is ambitious, but products are showing promise for gradual growth

- Manufacturers are approaching all heavy-duty vehicle classes (5-8). Several products are entering production and delivery.
- Class 8, however, has attracted the most attention due to Tesla's first deliveries of semi-trucks in Q4 2022.
- Vehicle range for different products on the market is between 125 and 500 mi, enabled by large batteries between 400 and 1000 kWh. offered by each automaker spans achieved by each vehicle is dependent on battery size and energy efficiency,. Penetration in this sector is expected to grow slowly through this decade.

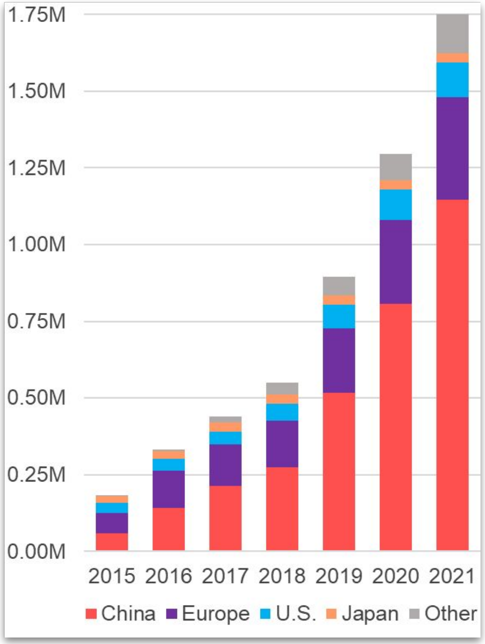
Class 8 Truck Manufacturer	Model	Battery Pack Supplier	Battery Energy [kWh]	Range [mi]*	Efficiency [mi/kWh]	Max. Charge Power [kW]	Max Torque [lb-ft]	GCWR (lbs)	Claimed Charging Time	Availability
BYD	BYD 8TT	BYD	409	125	0.3	185	1770	105,000	0-100% / 2.5 hr	In operation
FREIGHTLINER	eCascadia	CATL	438	230	0.52	270	23000	82,000	0-80% / 1.5 hr	2021
KENWORTH	T680E	Formerly Romeo Power (Current N/A)	396	150	0.38	120	1623	82,000	0-100% / 3.3 hr	2022
Mercedes-Benz	eActros	CATL	448	250	0.56	160	N/A	~88,200	20-80% / 1.5 hr	2024
NIKOLA MOTOR COMPANY	Tre BEV	Formerly Proterra Current Nikola/Romeo	733	330	0.45	170	28027	82,000	0-80% / 2.2 hr	2022
Peterbilt	579EV	Formerly Romeo Power (Current N/A)	396	150	0.38	150	N/A	82,000	0-100% / 3 hr	2022
TESLA	Semi	Tesla	850-1000	500	0.5-0.59	N/A	N/A	81,000	0-70% / 0.5 hr	2022
VOLVO	VNR Electric	Volvo	565	275	0.49	250	4,051	54,000	0-80% / 1.5 hr	2022

* Range as announced by each manufacturer

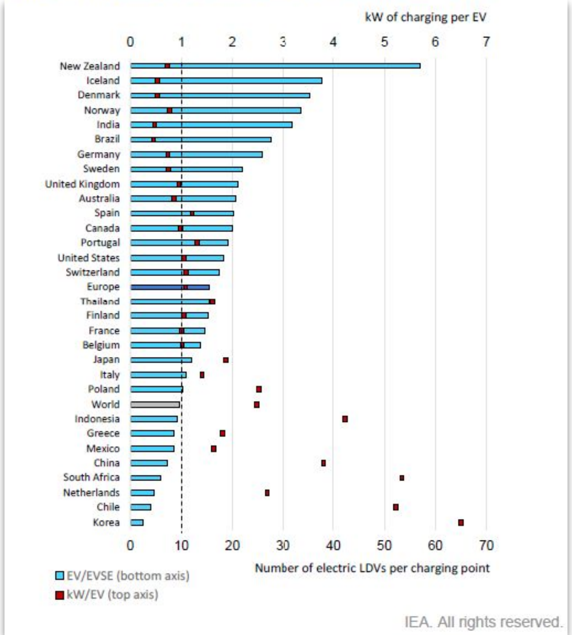
EVs | Charging Infrastructure

Public charging networks are growing quickly with governments, utilities, O&G companies, and pure-play companies all making sizeable investments. However, faster growth will be needed to enable wider EV adoption.

Number of Public Charge Points



EV Drivers Per Charge Point



Key Trends

The global number of public charge points grew by 37% in 2021 (and at a 46% CAGR over 2015–2021). The total number of now exceeds 1.75 million.

However, many more charge points are needed. The slow roll out of charging networks is a major roadblock to widespread EV adoption.

Lack of chargers is not the only problem. As of 2021, 70% of public charge points were slow chargers.

The main barriers to greater fast charger deployment are high hardware/installation/permitting costs, low uptime, and unpredictable utilization.

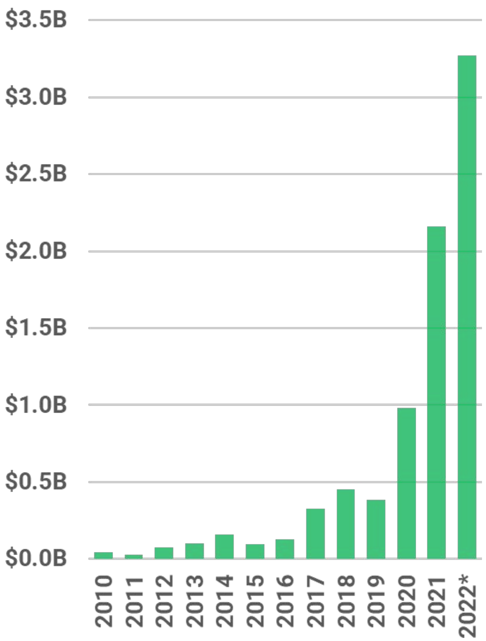
By 2030, the global number of charge points needs to increase to 13–15 million, and the proportion of fast chargers needs to approach 40%.

Source: Axios, BloombergNEF, International Energy Agency, World Economic Forum.

EVs | Charging Infrastructure Investments

Private investment into EV charging hardware & software startups is booming, and annual investment into EV charging infrastructure could reach $140–190 billion in 2030.

Annual EV Charging VC/PE



Note (*) Data through October. 2022

Annual EV Charging Capex

Key Trends

VC/PE investment into EV charging hardware & software startups exceeded $3.25B in 2022. Cumulative VC/PE into EV charging startups now exceeds $8.25B.

Global capital expenditure on EV charging infrastructure exceeded $10B in 2021. Through year-end 2021, cumulative investment in the sector exceeded $50B.

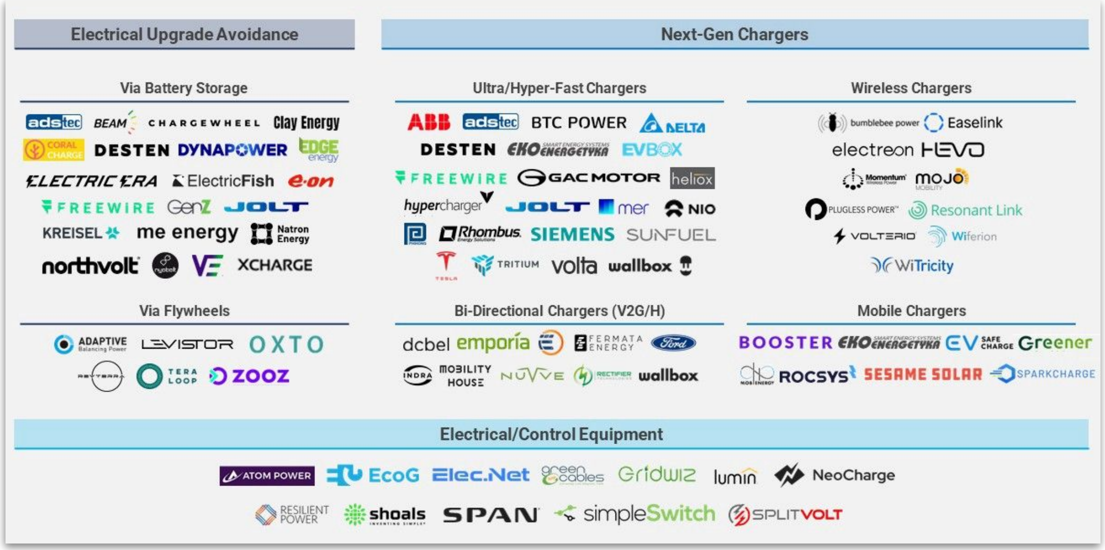
By 2030, global annual capex on (public and private) EV charging infrastructure will need to reach $140–190 billion to support the forecast adoption of EVs, according to the International Energy Agency.

Source: BloombergNEF, International Energy Agency, The Westly Group.

EVs | Charging Infrastructure Technology

Startups are pioneering the next generation of EV charging, developing new solutions for fast charging, vehicle-to-everything (V2X), electrical upgrade avoidance, charge management and more.

Notable Companies Tackling Common EV Charging Pain Points



Notable Charging Pain Points & Solutions

Electrical Upgrades: Fast and ultra-fast chargers require large volumes of electricity, often requiring costly power grid upgrades. According to McKinsey, for example, the grid upgrades needed for four 150kW chargers can cost over $150,000. Hardware startups like Electric Era, FreeWire, Jolt and others are integrating battery storage into their chargers to mitigate the need for grid upgrades.

Low Uptime: Many public EV charging networks have low uptime due to everything from poor build quality, weather, and connectivity to user error. Companies like ChargerHelp and others are helping charging networks to better track and remedy charging stations that go offline.

Source: Company websites

EVs | Vehicle-to-X (V2X)

Vehicle-to-grid (V2G) and vehicle-to-home (V2H) is almost ready for prime time. EV adoption is accelerating, automakers are launching V2G-capable EVs, and demand for grid services is growing.

Notable Companies with Recent V2X Pilot Projects

SDGE, Nuvve, revel, ninedot energy, conEdison, inc., Fermata Energy, Duke Energy, Pacific Gas and Electric Company

Notable Companies with V2X Hardware/Software Solutions

blink, Nuvve, Rectifier Technologies, wallbox, gigElev, Jedlix, emporia, Link-U Tech, Fermata Energy, Mobility House, dcbel

Why V2X is Interesting

Bi-directional charging enables electric vehicles – from passenger cars and trucks to buses and tractors – to power equipment, buildings and the power grid. Given that the majority of battery storage lives in EVs, and will continue to do so, integrating EVs and the grid will be crucial.

Past Headwinds: V2X activity has been limited because most EV manufacturers were concerned that bi-directional charging would impact EV battery longevity and did not enable V2X capabilities. Moreover, bi-directional are expensive and have lacked standardization.

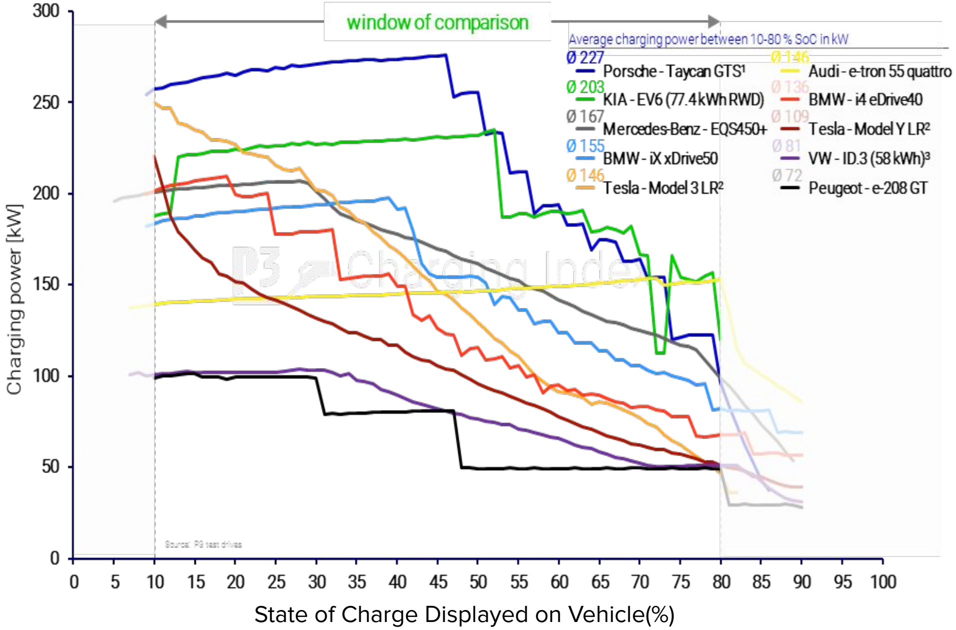
Recent Tailwinds: Thanks to improved BMS solutions, automakers like Nissan, Ford and Lucid are already selling V2X-capable vehicles. GM, Hyundai-Kia, Volvo, VW and others, meanwhile, have announced plans to do so. Notably, Ford's F-150 Lightning has the same battery capacity as 7 Tesla Powerwalls (enough to, in theory, power a U.S. home for up to three days).

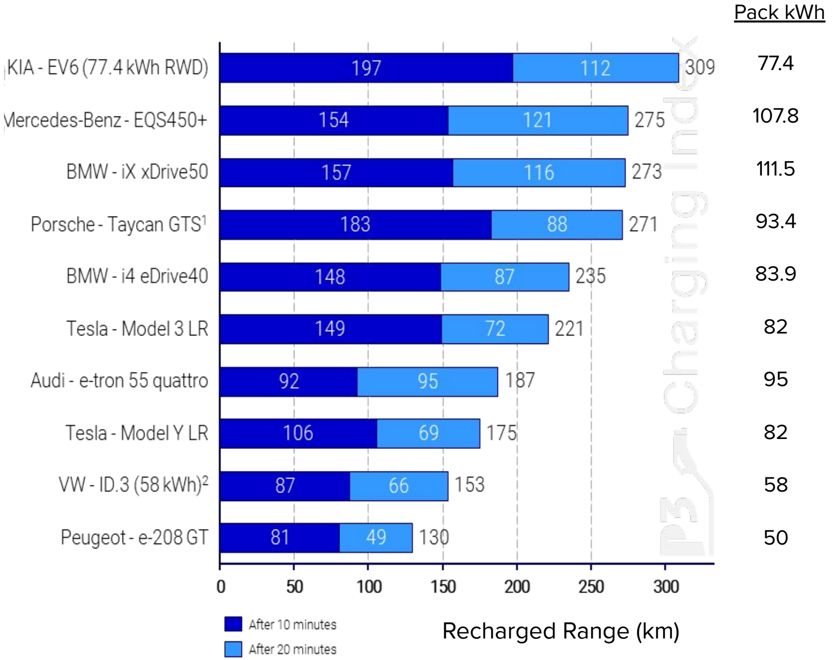
Source: Company websites, news reports.

EVs | Vehicle Charging Comparisons

Charging experience is dependent on both charging power, battery size and vehicle efficiency

- The Kia EV6 and Porsche Taycan add the most number of miles in the first 10 min.
- EV6 has lower battery pack energy than most cars on this list, but the highest added range in 20 min.





Source: P3 Group; [1] Porsche Taycan GTS Sport Turismo model under review, named in the graphic as Porsche Taycan GTS [2] ID.3 measured with ID.Software 2.3, BatteryBits

Electric Aviation | Notable Industry Events 2022

Selected news pieces in 2022

Q1

Textron announces acquisition of Pipistrel to develop sustainable aircraft

Q2

EASA releases Proposed Means of Compliance with the Special Condition VTOL

EASA releases Prototype Designs Specifications for Vertiports

Cuberg releases data from external performance validation of 5.1 Ah cells

Eve Holding, Inc. begins trading on NYSE as EVEX

Q3

Lilium and SAUDIA announced an MoU to purchase and operate 100 aircrafts in the MENA region

Wisk and Boeing release Concept of Operations for Uncrewed Urban Air Mobility

Kittyhawk decides to wind down

FAA Releases Vertiport Design Standards to Support the Safe Integration of Advanced Air Mobility Aircraft

FAA changes approach to certify EVTOLs from Aircrafts (21.17a) to Powered-Lift (21.17b).

United Invests Another $15 Million in Electric Flying Taxi Market with Eve

Q4

Archer unveils production aircraft named Midnight.

(Event link)

Lilium Raises $119 Million Capital Raise to Fund Continued Development of Electric Aircraft

Air New Zealand announces partnerships with Beta Technologies, Cranfield Aerospace, Eviation and VoltAero

FAA releases airworthiness criteria for Joby JAS4-1 and Archer M001.

Electric Aviation | Overview

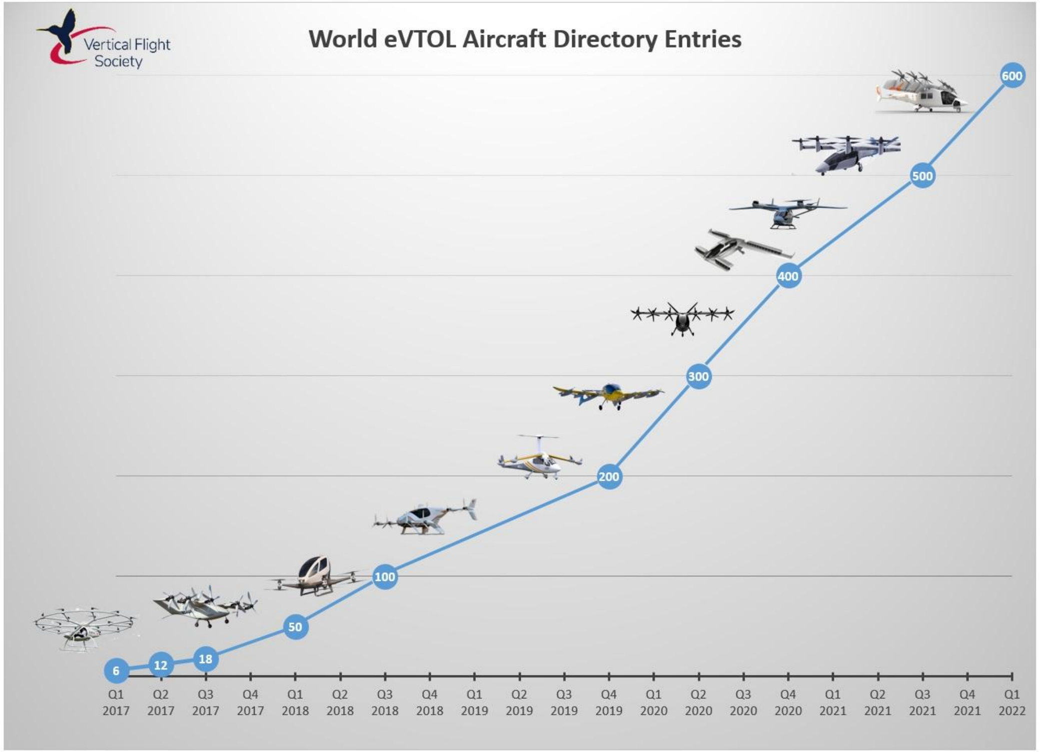
Efforts taking off rapidly, spurred by advancements in tech, increased funding, and improved regulatory clarity

The number of startups exploring the Urban Air Mobility and Electrified Aviation markets is growing rapidly.

In Q1 2022, the VFS eVTOL directory reached 600 concept aircrafts. By Q3 2022, over 700 concept aircrafts had been catalogued in the VFS directory. While EVTOLs garner the most attention, several concepts also explore short take-off and conventional takeoff.

In 2021/22, more than 10 prototypes conducted test flights, with 3 aircrafts (KittyHawk, Beta, Joby) completing more than 100 miles.

Aircraft certification is kicking off, with the FAA publishing the first airworthiness criteria for the Joby JAS4-1 and Archer M001 in the powered lift category. It is unclear how many companies will actually reach certification, given the capital intensive nature of aircraft development especially for urban environments.



Source: eVTOL Aircraft Directory

Electric Aviation | EVTOLs for UAM

Wide range of aircraft concepts being attempted, with most targeting launch around 2025, although consolidation is expected due to the capital intensive path to achieve certification as powered lift aircrafts

	wisk	LILIUM	VERTICAL		ARCHER	supernal	KITTYHAWK	BETA	VOLOCOPTER	EVE MOBILITY REIMAGINED	The ePlane Company
Aircraft (Propulsion type)	6th Gen (L+C/VT)	Lilium Jet (VT)	VX4 (L+C/VT)	JAS4-1 (VT)	Midnight (L+C/VT)	- (L+C)	Heaviside (VT)	Alia (L+C)	VoloCity (Multicopter)	EVE	E200 (L+C/VT)
Take-off mass [kg] Payload [kg] # Passengers	- - 4	3175 - 6 + 1 pilot	- 450 4 + 1 pilot	2180 362 4 + 1 pilot	2950 455 4 + 1 pilot	- - 5	402 - 1	3175 - 2 + 1 pilot	900 200 1 + 1 pilot	1000 - 4-6	- 200 2 + 1 pilot
Range [mi]	90	100	100	150	100	60	100	250	40	60	124
Battery energy [kWh] En. Density [Wh/kg]	-	*211 kWh *220 Wh/kg	-	*200 kWh *245 Wh/kg	142 kWh *170 Wh/kg	-	- *210 Wh/kg	- *240 Wh/kg	-	-	-
Partnerships/ Collaborations	Boeing, formerly Kittyhawk	Saudia, Netjets, Ionblox	American Airlines, AirAsia, Molicel	Toyota, Delta Airlines	United Airlines, Molicel	Hyundai, EP Systems	Boeing, Wisk	UPS, Air New Zealand	Mercedes, Honeywell	Embraer, United Airlines	-
Certification/ Launch	~2028	2025	2025	2024	2024	2028	Wound down in 09/ 2022	2025	2024	2026	2024

<u>Legend</u>
L+C Lift & Cruise
VT Vectored Thrust

Source: * Estimates from Sripad et al., eVTOL Aircraft Directory, AAM Reality Index, Company websites

Electric Aviation | ECTOLs and ESTOLs

Conventional and Short Take-Off aircraft are not as power hungry as EVTOLs, and more suitable for Regional Air Mobility, with hybrid and electric powertrains

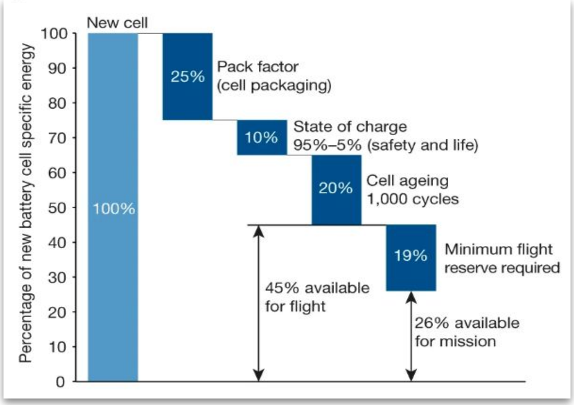
	Jetson	AIRBUS	ELECTRA.AERO	ZEROAVIA	EVIATION	Heart Aerospace	PIPISTREL	PIPISTREL	NASA
Aircraft	One (Multicopter EVTOL)	CityAirbus (EVTOL)	- (ESTOL)	HyFlyer II (ECTOL)	Alice (ESTOL)	- (Hybrid)	Velis Electro (ECTOL)	Alpha Electro (ECTOL)	X-57 Maxwell Mod IV (ECTOL)
Take-off mass [kg] Payload [kg] # Passengers	175 85 1	2200 250 4 + 1 pilot	- 1134 9 + 2 pilots	- - 9-19	8350 1134 3-5 + 1 pilot	- - 30	600 172 1 + 1 pilot	550 182 1 + 1 pilot	3000 - 2 pilots
Range [mi]	16	19	460	345	288	120	86	98	100
Battery energy [kWh] Energy Density [Wh/kg]	-	110 kWh	-	Hydrogen Electric	-	-	24.8 kWh	21 kWh	47 kWh 120 Wh/kg
Partnerships/ Collaborations	-	-	Welojets, Lockheed Martin	United Airlines	MagniX, Air New Zealand	United Airlines	Textron	Textron	-
Certification/Launch	-	2025	-	2025	2027	2028	EASA Type Certified	EASA Type Certified	Experimental platform

Source: eVTOL Aircraft Directory, Company websites

Electric Aviation | Cells and modules

Standardized, safety-certified modules can help accelerate integration into aircraft, but several aircraft designers prefer inhouse development for better integration efficiency.

Aviation-specific cells are some time away from scale production. Aircrafts leveraging existing technology are likely to have the jump on certification and first-mover advantage, while only being able to support short-range aircrafts.
For aviation, the entire specific energy of a cell cannot be used for the mission profile. Packaging, safety, ageing and regulatory requirements for reserve energy mean that only 26% of the new cell specific energy is realizable for the flight mission.



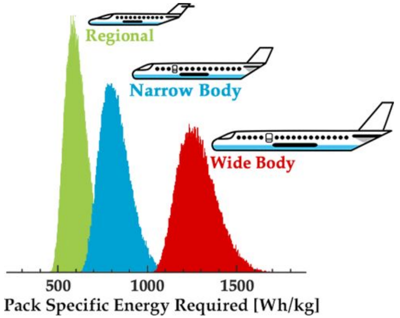
	Product (Cell/Module)	Chemistry	Targeted ED [Wh/kg]	Power	Select Aircraft partners
CUBERG	C (pouch)	Li metal	380	2 kW/kg	-
amprius	C (pouch)	Si nanowire	360-500 1150 Wh/L	10C	-
IONBLOX (fka Zenlabs)	C (pouch)	811 NCM, >90% SiOx	>300 Wh/kg (340 at C/3)	>3 kW/kg	Lilium
MOLICEL	C (cyl.)	NMC/A, Gr	>230 Wh/kg	-	Archer
EP SYSTEMS	Module	-	205	-	NASA, Supernal, Plana
MOBIUS energy	Module (Husky2P50)	Molicel cells	215	7C (6 min), 1.56 kW/kg	Dovetail
Electroflight	Module (cyl. cells)	-	196	-	Rolls Royce, Heart, Cuberg
H55	Module (cyl. cells)	-	200	-	Piper, Pratt & Whitney, BRM Aero
TRUE BLUE POWER True Blue Power	Module (TB60,24P8S)	LFP (A123)	66	-	Conventional aircrafts

Source: Viswanathan et al., Company websites

Electric Aviation | Alternate Chemistries for Electric Aviation

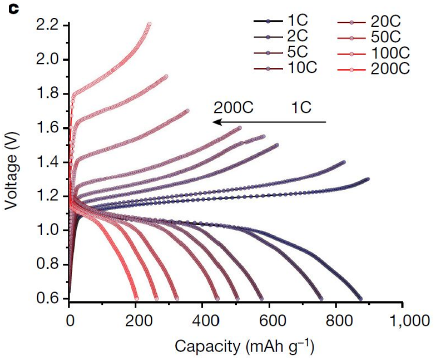
Current aircrafts rely on Li-ion for certification, but long-range and high payloads will require other chemistries

Electrification of regional aircrafts requires both high energy density (>500 Wh/kg) and power (>3-10C). While Li-ion is being used for the UAM sector, other chemistries may be suitable for long-range regional aircrafts. Molten salt and metal-air chemistries are potential alternatives, which also offer higher levels of safety.



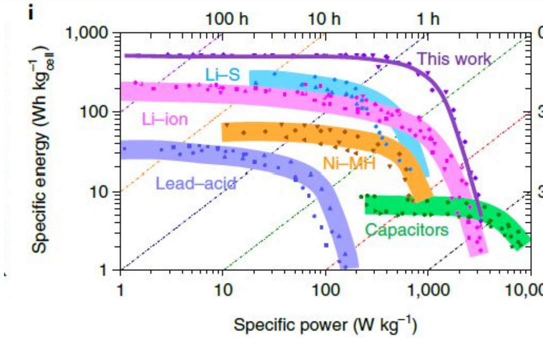
Aluminum | Sulphur: Pang et al. presented a study on Aluminum-chalcogen batteries that can operate up to 200 C (equivalent to 335 A/g_S, and have the potential for very low cost (~$9/kWh).

Projected energy density of the Al-S battery cell employing molten salt electrolyte is on a par with that of NMC622-Gr LIBs (526 Wh/L), but the battery pack may not need an active cooling system. Mild superambient operating temperatures of around 90°C can be maintained by the combination of internal joule heating generated while cycling and by adequate thermal insulation.



All-Solid-State Rechargeable Zn | Air: Shinde et al. demonstrated all-solid-state Zn-air pouch cells with high cell-level energy densities of 460-523 Wh/kg and 1389-1609 Wh/L, and up to 1100 cycles of life for 70% depth of discharge. Power capabilities >1 kW/kg was also demonstrated for time periods >60 s.

Cell material design included 3D-sponge copper phosphosulfide (CPS), anti-freezing chitosan-biocellulosic super-ionic electrolytes and patterned Zn-metal anodes.

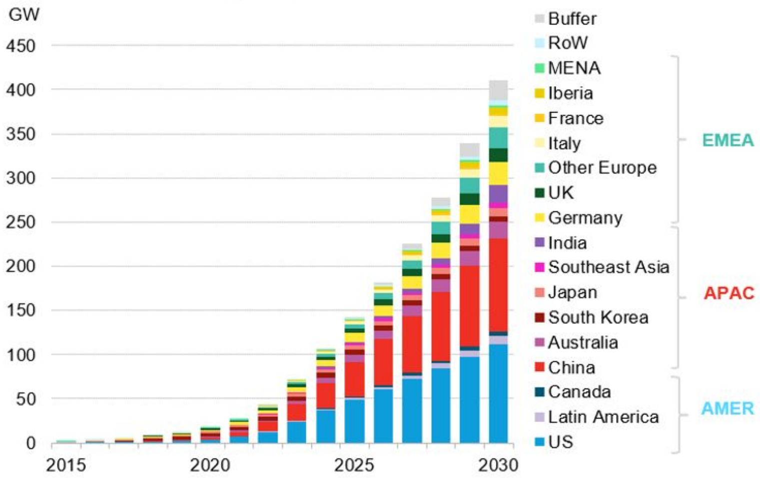


Source: Bills et al., Pang et al., Shinde et al.

Stationary Storage | Grid Storage Market Trends (Li-ion)

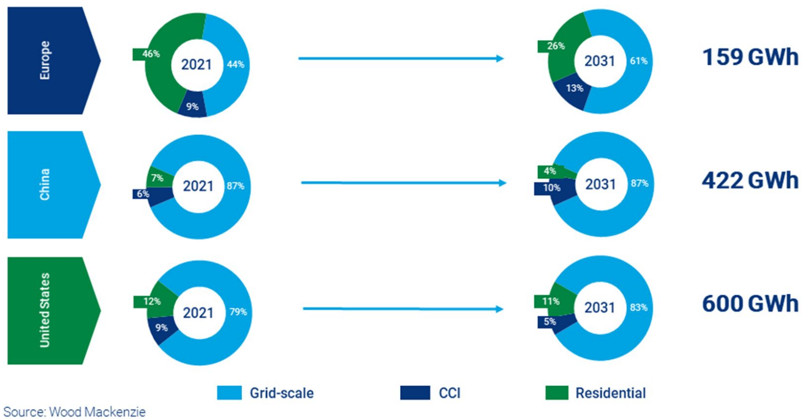
ESS installation projected to grow 15x & reach 1194 GWh by 2030

Figure 1: Global cumulative energy storage installations, 2015-2030



European energy storage demand lags that of the US and China

Cumulative energy storage market by segment (GWh)



Source: Wood Mackenzie

- US and China remain the largest ESS markets.
- Major policies such as Inflation Reduction Act (IRA) and RePowerEU+ stimulate ESS market growth
  - IRA drives development of 111 GWh (30 GW) of energy storage from 2022 to 2030, 15X the installed capacity of 2021
- Grid-scale ESS installations dominate the storage capacity, with steady growth of behind-the-meter markets
- Li-ion-based (particularly LFP) ESS is likely to dominate for the next decade due to price competitiveness, while emerging non-Li-ion technologies progress towards demonstrations/commercialization for utility markets

Source: BloombergNEF (Oct 2022), Wood Mackenzie (July, 2022)

Stationary Storage | Residential ESS (Li-ion)

Increasing number of manufacturers now offer residential batteries to pair with rooftop solar.

Market	Major States/Countries	Notable Players
US	CA, PR, FL, HI, TX, MA, AZ	Tesla, LG Chem, ENPHASE, GENERAC, SUNPOWER, lunar energy, solaredge
EU	Germany, Italy, UK	Tesla, PYLONTECH, sonnen, BYD, SENEC Your Life. Your Energy., ENERGY STORAGE E3/DC
APAC	Australia, Japan	Tesla, AlphaESS, HUAWEI

Market Growth: Global residential battery market size to grow $28 Billion by 2030, led by regions with unreliable grid & high untapped solar market

Use Case: Backup is the primary use case for residential ESS. Utility bill savings (with approval of CA NEM3) and grid service (i.e. ERLP, ConnectedSolutions) can be attractive in some markets, but overall project economics is typically lower than non-residential segments.

Competition: While Tesla remains the top 1 home battery brand, 2022 marked an influx of home battery players, including numerous battery / Inverter / PV module / home appliance manufacturers

Safety: Recent residential battery fires [1] [2] in Germany and LG Chem RESU recalls increase concerns on safety

Stationary Storage | Alternative Chemistry Developments

By 2025, IDTechEx forecasts >10% of the stationary market to be non-Li-ion chemistries, up from <5% in 2021

- More long-duration storage expected to enable higher penetration levels of variable renewable power sources
- Li-ion batteries, while providing strong peak power demands in the 6-8 hour range, are not cost-competitive to provide multi-day storage that may be needed for reliability events & lack of solar/wind coverage

Company	Technology	Duration (Single Cycle)	2022 Developments
Form energy	Iron-Air battery	100-150 hours	• Announced partnership with West Virginia government for a $760 million battery plant in Weirton • Raised $450 million in Series E funding led by TPG RiseClimate
Ambri	High-temperature Antimony-based liquid metal batteries	4-24 hours	• Announced partnership with XCel Energy for a liquid battery system installation in Aurora, CO to evaluate performance at Solar Technology Acceleration Center
ENERVENUE	Nickel-Hydrogen battery	8 hours	• Launched EnerVenue Energy Storage Vessels (ESVs) with buildable flexible capacity
Highview Power®	Cryogenic storage / Liquid air	1 hour (peak demand)	• Announced plans to raise £400m for Manchester plant to service 600,000 homes with liquid air energy storage
MALTA	Electro-thermal	200 hours	• Announced that Southwest Research Institute (SwRI) completed assembly & commissioning of the 1st-of-a-kind PHES utility-scale ESS as part of a grant from ARPA-E

BatteryBits (Article 1, Article 2)

Industry | Overview

Notable Events

Industry Players & Movement

Investments

Cell Chemistry Development

Technology Applications

Costs

Supply Chain

Recycling

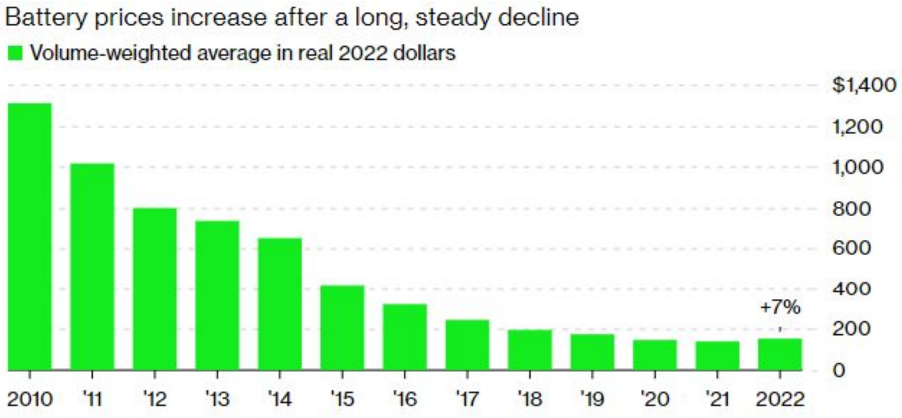
Manufacturing

Safety / Legal

Costs | Battery Pack

Volume-weighted average battery pack prices increased for the first time by 7% in 2022, according to BNEF 2022 annual price survey. Over 2010–2022, prices fell by 88%.

Volume-weighted average battery pack price, from BNEF*



Impact on EV price parity. Though some automakers have locked in long-term supply contracts, BNEF now expects battery pack prices will remain above $100/kWh until 2026. This is two years later than originally expected. While some premium EVs are already at upfront price parity with their gasoline counterparts, batteries around the $100/kWh price point will be needed for middle-market EV adoption to take off.

Key Trends

Rising prices over the short term. In July, BNEF expected the volume-weighted price of lithium-ion battery packs in 2022 to rise by approximately 2%. As of December, prices in 2022 had risen by 7% (to $151/kWh) and are forecast to hold steady in 2023.

- **Factors increasing price:** Soaring lithium, cobalt & nickel, electrolyte prices due to supply constraints; inflation; geopolitical conflict; and lingering Covid-19 supply chain issues were the main drivers of the price increase.

Falling prices over the long term. Stabilized and/or lower commodity prices, new cell chemistries (e.g. chemistries that use more nickel and less cobalt, and higher adoption of LFP), and economies of scale should start to bring average battery pack prices back down in 2024.

Prices vary by application, region and chemistry.

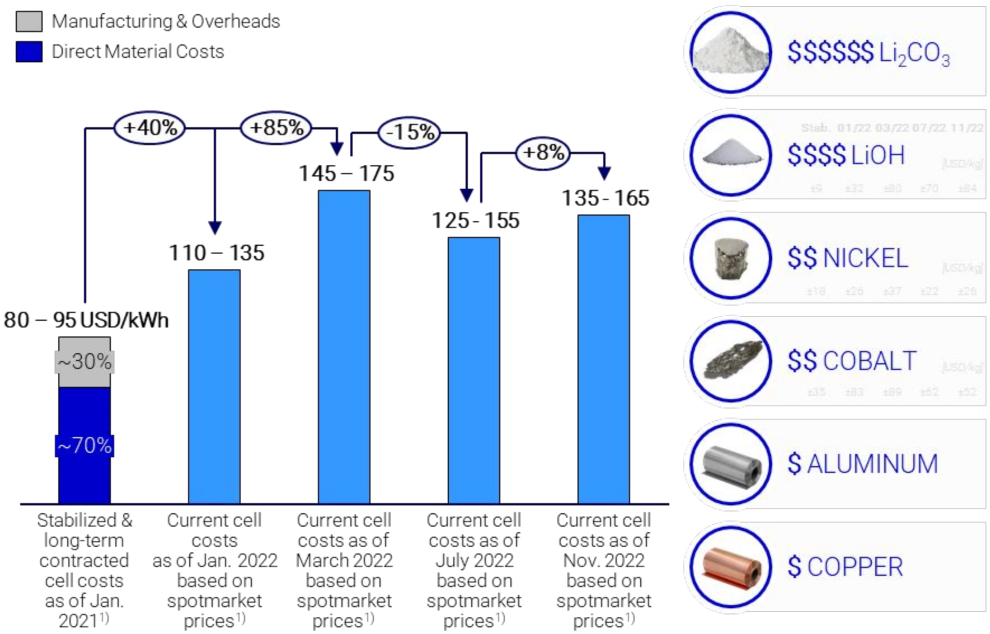
- **Application:** Passenger BEVs ($138/kWh) had lower prices than stationary storage ($169/kWh) and passenger PHEVs ($345/kWh)
- **Region:** Prices were lowest in China ($127/kWh), followed by the U.S. ($157/kWh) and Europe ($169/kWh).
- **Chemistry:** LFP cells were 20% cheaper than NMC cells.

Source: BNEF, P3 Group. (*) Values are averages across passenger EVs, commercial EVs, e-buses and stationary storage. Includes cell and pack.

Costs | Raw material price increase

Historically, cell costs decreased along with decreasing material prices. This year, the rise of raw material prices will raise challenges especially for new market entrants.

IMPACT OF RAW MATERIAL PRICE INCREASES ON CELL COSTS [USD/KWH]



1)High Ni NMC-based cell cost references.

- Raw material prices rising throughout the whole value chain, mainly driven by **strong price increases of cathode active material, electrolyte and current collectors** leading to cell cost increases of >40% as of 01/2022 and >85% as of 03/2022. Current market conditions and crisis has resulted in strong raw material price fluctuations since mid-2022
- **NMC materials almost tripled** over the last 1.5 years mainly due to ~2X price increases for Ni and Co, but especially due to the 4-8X **LiOH price increase** compared to 2020/21
- **LFP variants impacted by rising prices of Li_2CO_3** (6-10x increase over 2020/21).
- **Dependence on Li price doubled electrolyte component costs** (conductive salt $LiPF_6$)
- **Al and Cu price increased by >50%**
- Rising prices raise **additional challenges for new market entrants**, who cannot rely on previously established long-term contracts

Source: All analysis by P3 group, Spot market prices from LME and ICC Sino

Industry | Overview

- Notable Events
- Industry Players & Movement
- Investments
- Cell Chemistry Development
- Technology Applications
- Costs
- **Supply Chain**
- Recycling
- Manufacturing
- Safety / Legal

Supply Chain | Rankings by Nation

China continues to dominate supply chain, with Canada a close second

China dominates BNEF's global li-ion battery supply chain ranking for the 3rd time in a row, with:

- 75% of all battery cell manufacturing capacity
- 90% of anode and electrolyte production
- 60% of global battery-grade Li refining capacity
- Increased investments in carbonate and hydroxide refinery facilities

Canada rises to #2 this year with its investment in upstream clean energy supply and increased demand in the US-Mexico-Canada Agreement (USMCA)

Most European countries declined in overall performance compared to 2021.

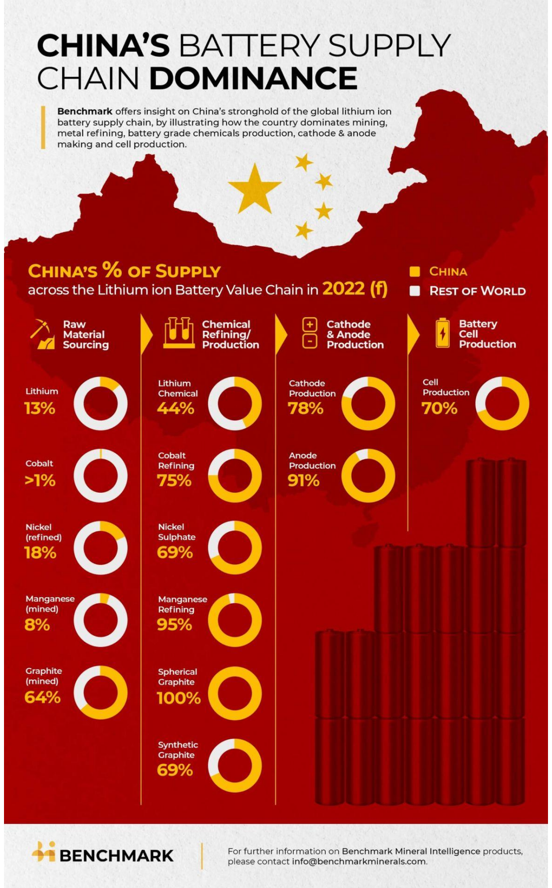
Most resource-rich countries have low rankings due to a lack of domestic battery manufacturing capabilities and electric vehicle demand.

Access to key raw materials and manufacturing capacities are key factors impacting 2022 BNEF rankings.

Figure 1: BNEF 2022 global lithium-ion battery supply chain ranking

Country	Raw Materials	Battery manufacturing	ESG	Industry, innovation and infrastructure	Downstream demand	Overall ranking
China	1	1	17	9	1	1
Canada	3	8	6	4	10	2
US	6	4	16	5	2	3
Finland	9	15	2	1	11	4
Norway	18	10	1	3	7	5
Germany	21	6	4	7	2	6
South Korea	17	2	10	6	5	6
Sweden	21	9	3	2	8	8
Japan	13	3	8	12	8	9
Australia	2	15	9	13	11	10
France	24	10	5	10	5	11
UK	26	15	7	8	4	12
Czechia	23	10	11	11	18	13
Poland	24	5	15	16	15	14
Hungary	26	6	13	14	20	15
Chile	7	18	14	23	19	16
Turkey	15	18	21	15	13	17
India	13	10	26	21	13	18
Vietnam	20	10	20	18	17	19
South Africa	8	18	19	17	26	20
Brazil	4	18	23	22	20	21
Indonesia	5	18	22	27	25	22
Argentina	11	18	12	19	26	23
Slovakia	26	18	18	25	24	24
Thailand	26	18	24	20	16	25
Philippines	10	18	29	28	22	26
Mexico	16	18	27	26	23	27
Morocco	19	18	25	24	28	28
DRC	11	18	30	29	30	29
Bolivia	26	18	28	30	28	30

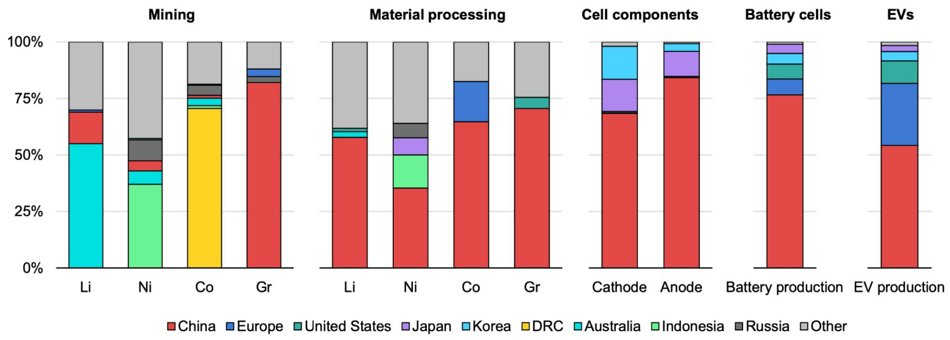
Source: BloombergNEF. Note: "III" stands for infrastructure, innovation, and industry.



Source: Bloomberg, BNEF, BatteryBits

Lithium, nickel, cobalt, graphite and manganese are the five key minerals in EV batteries. Australia, Indonesia, and the Democratic Republic of Congo dominate mining, but China dominates the downstream supply chain.

Geographic distribution of the global EV battery supply chain, from the IEA



Breakdown of minerals in an EV battery in 2020, from TNE

Mineral	Cell Part	Amount Contained in the Avg. 2020 Battery (kg)	% of Total
Graphite	Anode	52kg	28.1%
Aluminum	Cathode, Casing, Current collectors	35kg	18.9%
Nickel	Cathode	29kg	15.7%
Copper	Current collectors	20kg	10.8%
Steel	Casing	20kg	10.8%
Manganese	Cathode	10kg	5.4%
Cobalt	Cathode	8kg	4.3%
Lithium	Cathode	6kg	3.2%
Iron	Cathode	5kg	2.7%
Total	**N/A**	**185kg**	**100%**

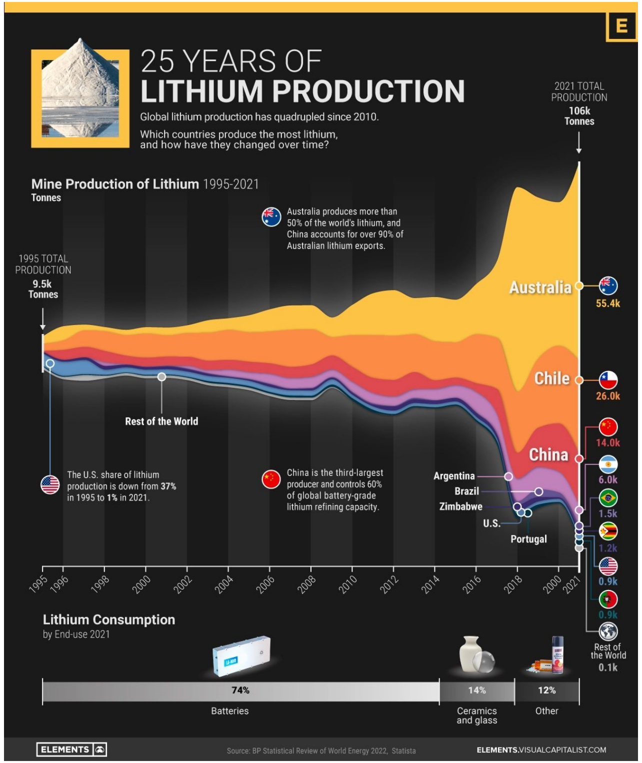
Supply Chain Geography: China is the largest processor of lithium, nickel, cobalt and graphite, as well as the top producer of battery cell components and cells by a wide margin. The country is also the largest producer of graphite. Europe and the U.S. have plans to play larger roles in battery manufacturing, but the IEA expects China to remain the dominant play through 2030.

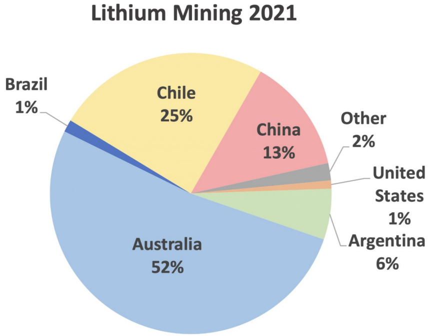
Battery Metals Mix: According to the U.K.-based Transportation and Environment, the average EV battery with a 60kWh capacity (i.e., the same size as that in Chevy Bolt) contained about 185 kg of materials in 2020. Graphite, aluminum, nickel and copper were the top materials by weight.

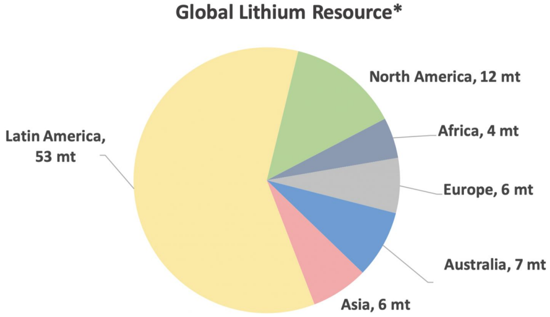
Source: Transport and Environment (via Visual Capitalist), International Energy Agency. Note: Li = lithium, Ni = nickel, Co = cobalt, Gr = graphite.

Supply Chain | Minerals | Lithium

The current Li market is highly concentrated: 90% of global lithium production stems from 3 countries: Australia, Chile, China.







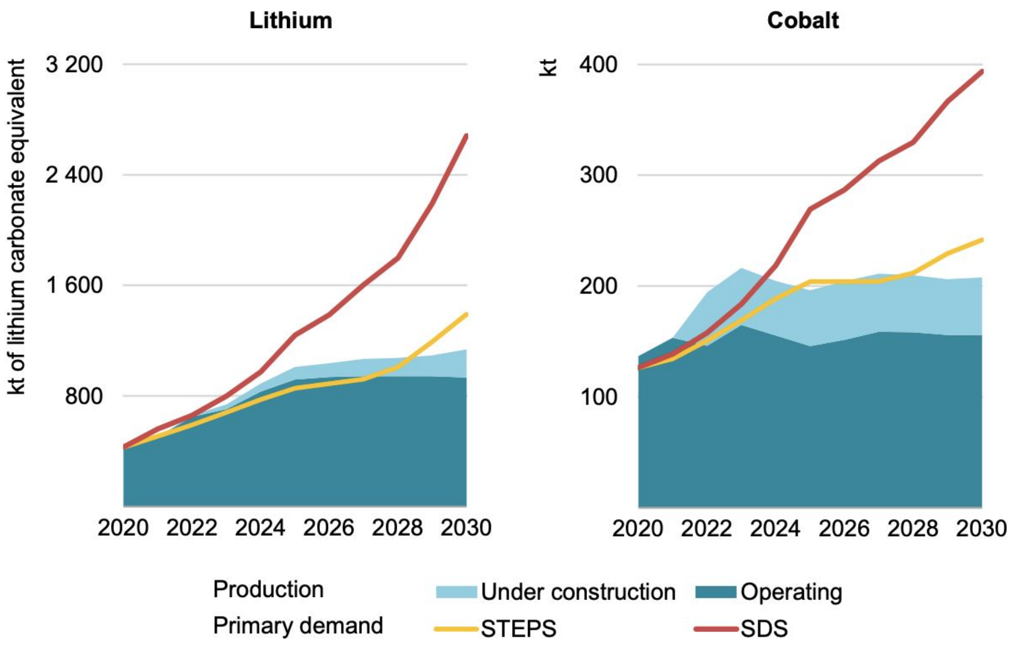
- A highly concentrated market pose supply chain risks in the event of unforeseen events (e.g. earthquake in Chile)
- Untapped Li reserves exist in Latin America (primarily Chile, Argentina, Bolivia, which form the Lithium Triangle) and North America (Thacker Pass, Nevada; Salton Sea, California), sufficient to meet future demand in theory
- However, not all reserves will achieve production status, especially to meet near term surge in demand. The world could face lithium shortages as early as 2025 without sufficient investments to expand production (IEA).
  - Lithium mines that started operations between 2010 and 2019 took an average of 16.5 years to develop (12 years for exploration & feasibility, 4-5 years for construction) (IEA)
  - Lithium extracted from recently developed, lower grade brines carry higher operating costs and CO2 emissions due to heavier chemical use (BatteryBits)

Source: Visual Capitalist, ISS Insights

Supply Chain | Minerals | Lithium & Cobalt

The supply of lithium for EV batteries could remain tight this decade, based on consensus EV sales forecasts and battery pack chemistry/size expectations.

Lithium & cobalt market balance, from the IEA (showing committed mine production vs. two primary demand scenarios)

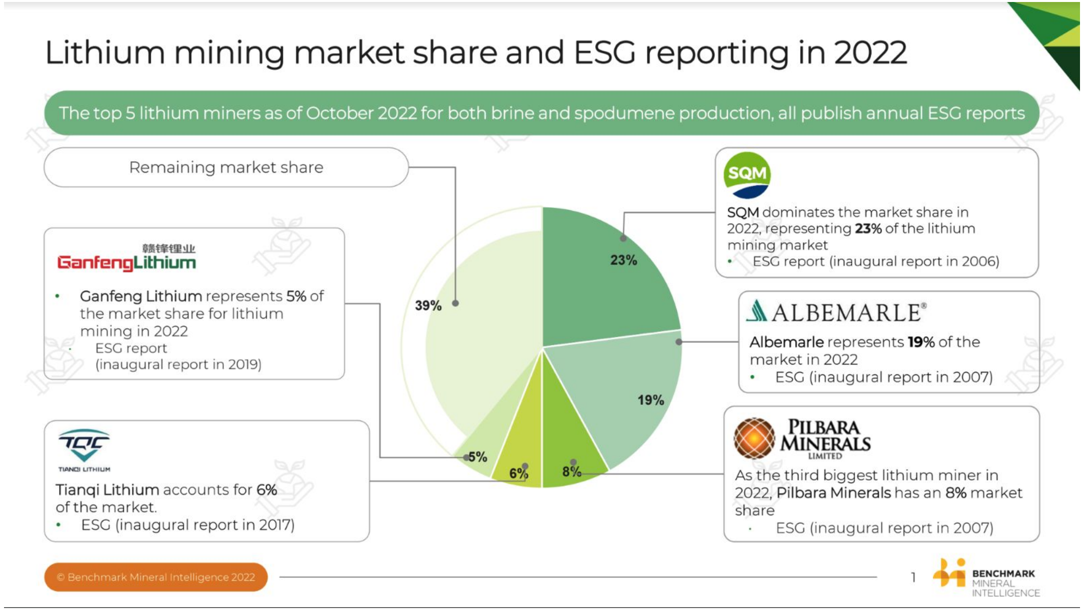


- Lithium prices started to decline at the end of 2022, but remained roughly 3X higher than prices from December 2021 due to tightness in the market.
- Over the near-term, Bloomberg expects that "the lithium industry could struggle to meet growing demand from EVs unless new projects are ramped up quickly over the next two years." S&P Global also expects a tight market in 2023.
- Over the long-term, the International Energy Agency notes that meeting the rapid growth in lithium (and cobalt) demand will likely require "strong growth in investment to bring forward new supply sources over the next decade".
- Automakers, however, are already switching to less cobalt-intensive batteries, so the cobalt supply challenge is a relatively less challenging problem to tackle than the lithium one.

Source: BloombergNEF, IEA

Supply Chain | Minerals | Lithium

ESG (Environmental Social Governance) is a key risk management tool with growing importance to shareholders as mining projects faces strong push back from local communities. ESG reporting is only adopted by 42% of current operating lithium miners.



Lithium Mining ESG Concerns

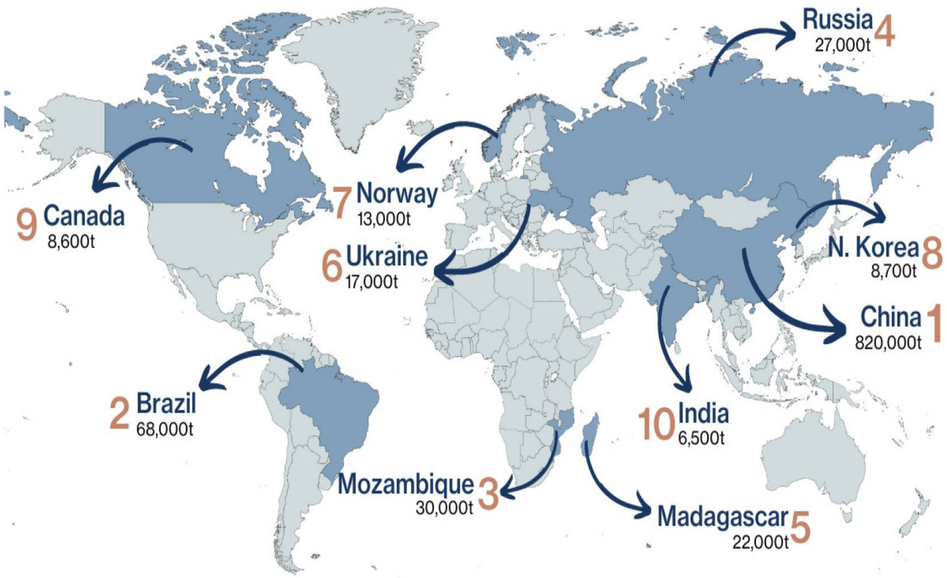
- There are 2 main types of lithium extraction methods
  - Hard-rock mines “spodumene” (common in Australia)
  - Brine evaporation (common in Latin America)
- Brine evaporation is a **water-intensive process** and lithium reserves are often located in drought-prone regions.
  - 1 ton of Li extraction can consume 2+ million litres of water, which can lead to groundwater depletion, soil contamination and other forms of environmental degradation
  - The Lithium Triangle (Chile, Argentina, Bolivia) has 56% of the world’s known reserves and exhibit medium to high levels of water stress
- Local communities **push back on lithium mining projects** across the globe
  - Serbian government stops Jadar lithium project
  - New projects in Australia faces civil and legal scrutiny
  - Strong opposition to development in Thacker Pass, Nevada

Source: ESG Reporting by Benchmark Mineral Intelligence, ISS Insights

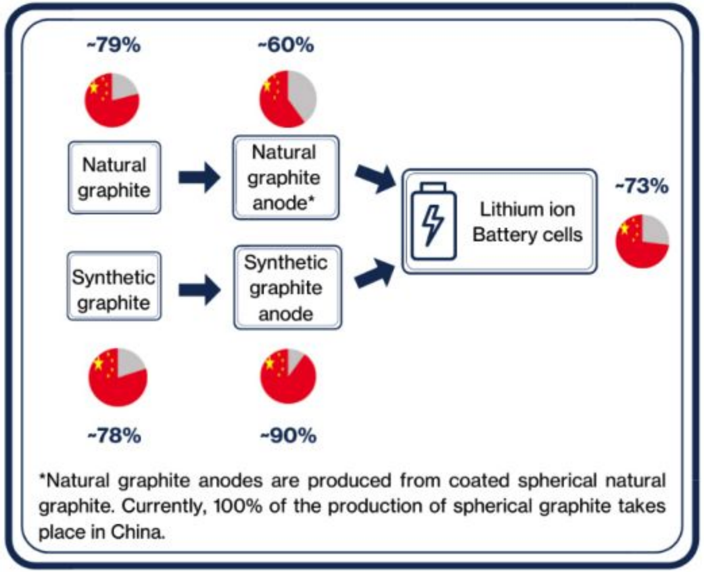
Supply Chain | Natural graphite

China dominates natural flake graphite production and holds **monopoly** on the conversion process for producing spherical graphite used for anode electrodes. The chemical purification process for spherical graphite requires intensive acid treatment, requiring hazardous materials like HF, which are highly regulated in jurisdictions like the EU.

2021 Top 10 Producers of Natural Flake Graphite Production (tons)



China's Graphite Supply Chain Dominance



Source: Hague Centre for Strategic Studies

Supply Chain | Synthetic Graphite

Synthetic graphite 2022 market size: $8833M

Up Stream

Mid Stream

Down Stream

Raw Material Suppliers

Needle coke (high end)

BAOWU, Hongte, PHILLIPS 66, BTL 宝泰隆 BAOTAILONG, 中国石油天然气集团公司 CHINA NATIONAL PETROLEUM CORPORATION, EWAY 亿维, MORITA, Chem 株式会社シーケム C-Chem Co., Ltd.

Petroleum Coke (low end)

中碳科技 ZTTECH, Seadrift Coke L.P., 中国石油天然气集团公司 CHINA NATIONAL PETROLEUM CORPORATION, HYSH, 中国海油 CNOOC, KAL

Synthetic graphite anode manufacturers

璞泰来 PUTAILAI, BTR power your life, 杉杉股份 Shanshan Corporation, KAIJIN 凯金, 尚太科技 SHANGTAITECH, 中科星城, 紫宸科技 Jiangxi Zichen Technology Co.,Lt, Nippon Carbon Co., Ltd., IMERYS, MITSUBISHI CHEMICAL, HITACHI Inspire the Next, BASF We create chemistry, ASBURY CARBONS

Cell Manufacturers

国轩高科 GOTION HIGH-TECH, CATL, EVE, FARASIS, SK on, Panasonic ideas for life, BYD, SVOLT 蜂巢能源, SUNWODA 欣旺达, SAMSUNG SDI, LG Energy Solution

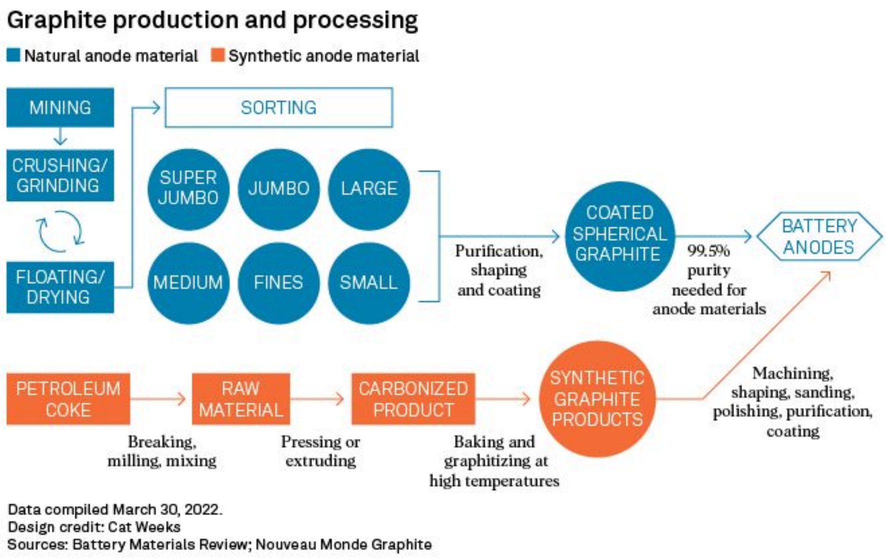
Source: Leadleo: overview of Li-ion batteries' anode in China 2022; Synthetic anode market size

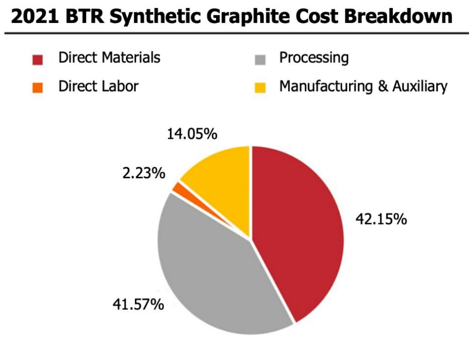
Supply Chain | Natural v. Synthetic Graphite Processing

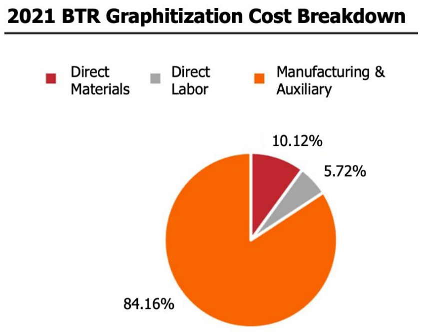
Natural graphite is cheaper and ~55% less carbon intensive to produce. The high costs associated with synthetic graphite stems from its graphitization process, which requires high temperature heating to remove impurities.

	Natural	Synthetic
Price Range ($/kg)	4-9	8.5-13
Global warming potential (kg Co2 eq./ kg of graphite anode)	7 (China average)	14 (China average) 24 (Inner Mongolia)

*Production location plays huge factor in carbon intensity depending on energy source used







*Electricity price fluctuations has huge impact on manufacturing costs

Source: Noveau Monde, East Asia Qinghai Securities Co., Ltd, Benchmark Minerals

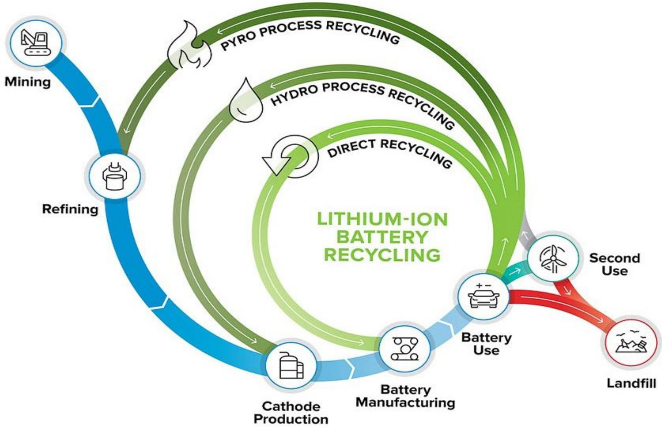
Industry | Overview

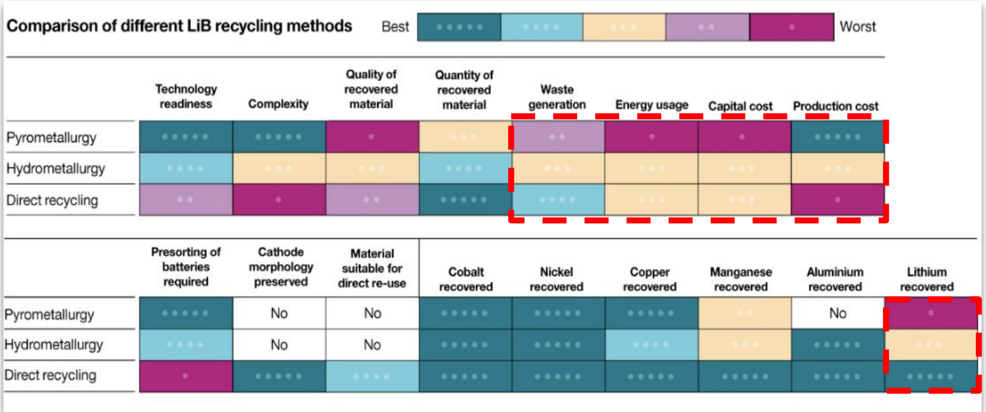
- Notable Events
- Industry Players & Movement
- Investments
- Cell Chemistry Development
- Technology Applications
- Costs
- Supply Chain
- **Recycling**
- Manufacturing
- Safety / Legal

Recycling | Overview

Circular value preservation driven by different recycling technologies

Pyrometallurgy was first generation of recycling but requires significant re-processing (recycling into active material precursors) however Hydrometallurgy and direct recycling have higher probability of preserving material quality (structure, coatings, morphology) but require more technology investment. Direct Cathode Recycling is in earlier stages of development and commercialization but is of highest value for manufacturers. Majority of leading companies are opting for hydrometallurgy process given the key technology, cost, material recovery, and sustainability factors.





Comparison of different LiB recycling methods (Best ••••• → •••• → ••• → •• → • Worst)

	Technology readiness	Complexity	Quality of recovered material	Quantity of recovered material	Waste generation	Energy usage	Capital cost	Production cost
Pyrometallurgy	•••••	•••••	•	•••	••	•	•	•••••
Hydrometallurgy	••••	•••	•••	••••	•••	•••	•••	•••
Direct recycling	••	•	••	•••••	••••	•••	•••	•

	Presorting of batteries required	Cathode morphology preserved	Material suitable for direct re-use	Cobalt recovered	Nickel recovered	Copper recovered	Manganese recovered	Aluminium recovered	Lithium recovered
Pyrometallurgy	•••••	No	No	•••••	•••••	•••••	••	No	•
Hydrometallurgy	••••	No	No	•••••	•••••	••••	•••	•••••	•••
Direct recycling	•	•••••	••••	•••••	•••••	•••••	•••••	•••••	•••••

Key factors

Pyrometallurgy: A heat-based extraction and purification process involves steps Roasting, Smelting, Refining. A vast amount of energy is required, as LIB are heated to between 1200°C and 1600°C. only a few raw materials, such as cobalt and nickel, can be recycled. Lithium, aluminum, and manganese end up in the slag and are not recovered, as this is not economically feasible.

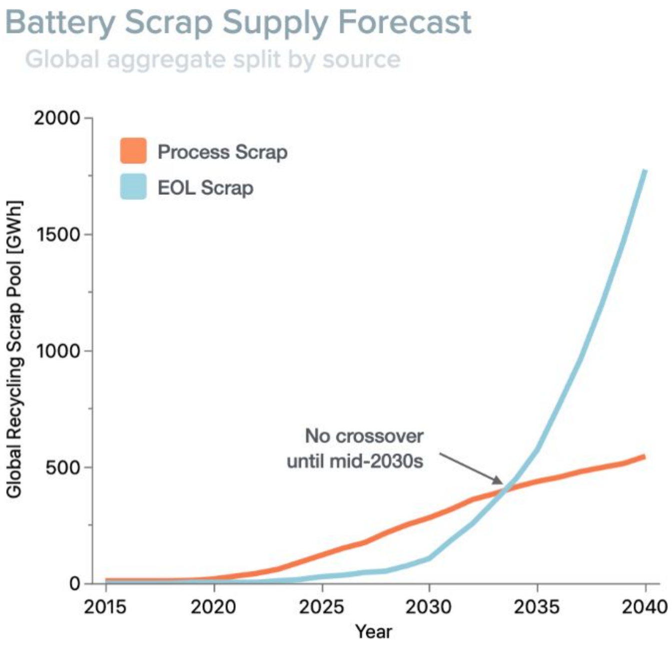
Hydrometallurgy: This process is used to extract metals from ore, which is achieved by recovering and dissolving the metals as salt in successive water-based steps, involving leaching, purification, and recovery of the targeted metal by selective precipitation or electrowinning. This method plays an essential role in extracting strategic and rare metals.

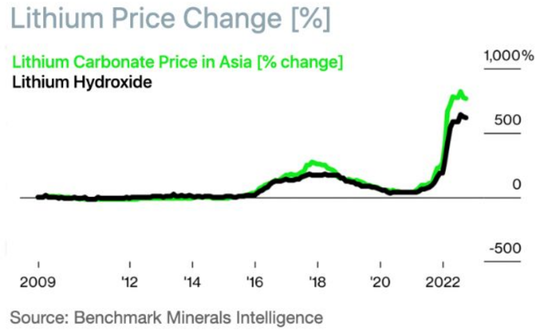
Direct recycling: Direct recycling first involves shredding the battery to separate battery components without breaking down the chemical structure of the active materials. The resulting material—often called black mass—is ideal for recovery, regeneration, and reuse in battery designs.

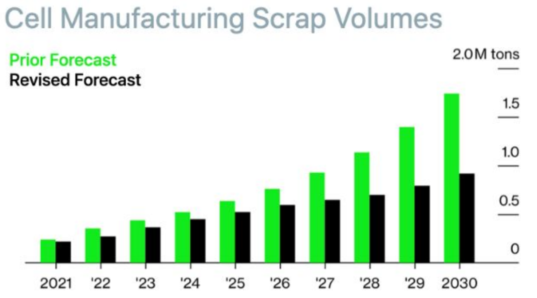
Source: DOE launches its first lithium-ion battery recycling R&D center: ReCell, Recycling lithium-ion batteries from electric vehicles

Recycling | Market Forecast

Uncertainty in Li supply chain intensifies competition between recycling and yield efficiency/second life
Overall forecast: Li-ion battery recycling market size predicted to reach $19.9B USD by 2030 with a forecasted 7.6% CAGR







Charts from BloombergNEF

- For the next decade, scrap from cell manufacturing yield loss will dominate the supply of recycling scrap due to a six-fold increase in EV production demand.
- Continuing lithium supply constraints in the past 12 months could inflate both incentives and competition from process scrap yield improvement as well as second life use.
- Recycling would face more supply restraints from its lower position in the waste hierarchy.
- Some forecasts further temper process scrap supply expectations through improvements of in-line diagnostics. However, cell manufacturers have yet to validate these new tools.

Source: BloombergNEF, Benchmark Minerals

Recycling | Key Challenges

Increased battery production, tightening regulations, sustainability, and raw materials scarcity drive the need for recycling. However, recycling faces challenges on multiple fronts.

LARGE NUMBER OF COMPETITORS

- There is a small window opportunity for new entrants, with over 30 recycling projects already announced in the EU.
- Cell manufacturers, auto OEMs, and traditional recyclers are all seeking to lead the energy transition and capture margin.

HIGH BARRIERS TO ENTRY

- Current technologies require high opex and capex.
- Economies of scale are required to compete in new markets.
- There may be no sustainability premium.
- Uncertainty due to challenges with scale-up and variable scrap rate from cell and cathode manufacturers.
- Recycling technologies recover different materials at different costs.

ALTERNATIVES AT END OF LIFE

- Second life applications delay the time at which batteries can be recycled.
- Disparate hazardous waste regulations across markets can landfill disposal, especially for battery chemistries that use lower value materials.

BARGAINING POWER OF BUYERS

- Refined materials markets are dominated by a few players, typically cathode manufacturers or integrated cell manufacturers, giving them high bargaining power.
- Refining companies need long term offtake agreements to recoup capex, giving buyers higher bargaining power.

BARGAINING POWER OF SUPPLIERS

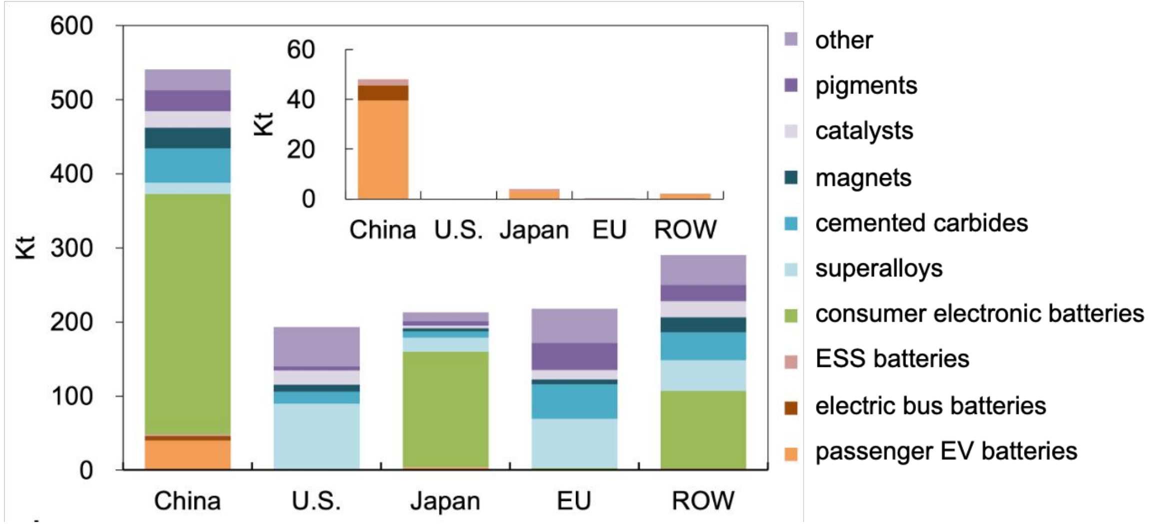
- The highest volume of feedstock currently comes from the cell scrap of cell manufacturers, a highly concentrated market with a lot of bargaining power.
- Cell manufacturing is concentrated regionally and often colocated with suppliers to reduce transportation cost. This gives regional players high bargaining power.

Recycling | Cobalt

Are we due for an inevitable cobalt shortage?

A team from China, Denmark, and Norway analyzed 20 years of historic cobalt use and various future scenarios for the next 30 years and concluded that even the most technologically optimistic scenario with long battery lifetimes, high recycling rates, and accelerated adoption of low/no cobalt cathode chemistries will not be enough to prevent a cobalt supply shortage in the intermediate term (2028–2033). The authors urge boosting primary cobalt supply to prevent critical bottlenecks via increased exploration, investment, and technology development.

Cobalt consumption by region and application, in metric kilotons

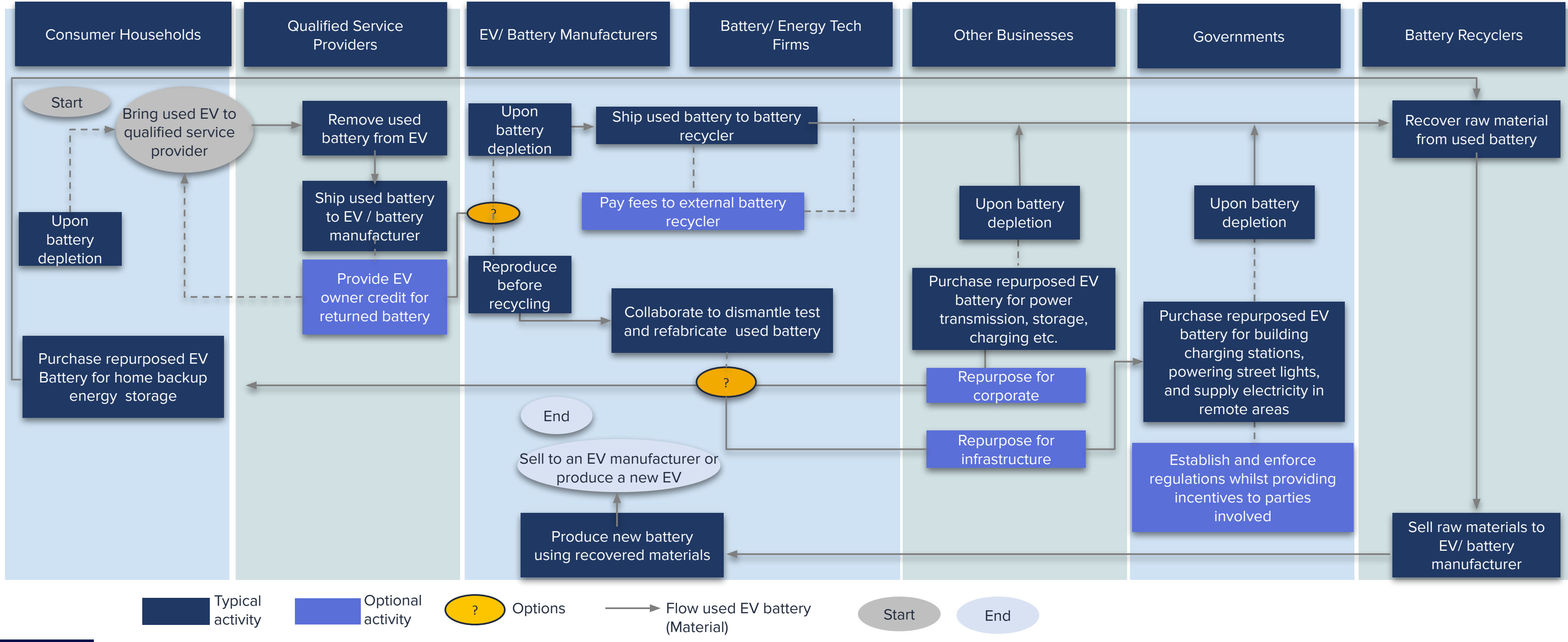


A cobalt shortage is looming within the next decade, even with optimistic cathode use and recycling conditions, unless we see rapid supply chain expansion

Source: Zeng, Chen, Rasmussen, Zhu, Lundhaug, Müller, Tan, Keiding, Liu, Dai, Wang, and Liu

Recycling | Supply Chain Complexity

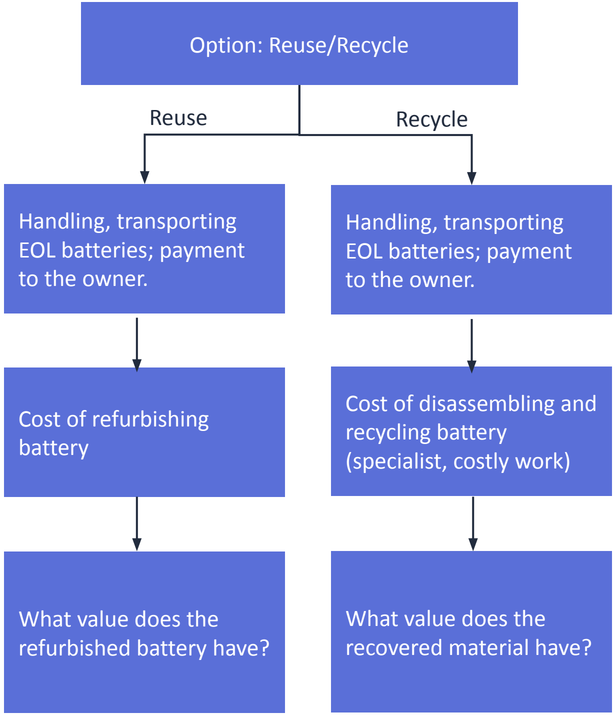
Recycling's complex supply chain limits profitability in various segments, and may result in increased export of EV batteries to countries that do not regulate hazardous waste. Standardization of international waste disposal legislation, clarifying producer responsibility across countries will help regulate and incentivize key stakeholders.



*Source: Financial viability of electric vehicle lithium-ion battery recycling, Graphic credits: Benchmark Mineral Intelligence

Recycling | Reuse or Recycle?

Capturing the most value is the key determinant of EOL battery flows, with owners currently selling to the highest bidder, creating an inherent tug of war between reuse and recycling.

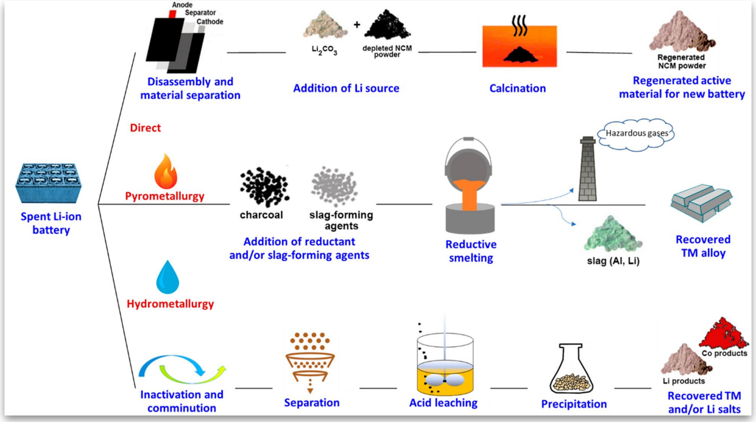


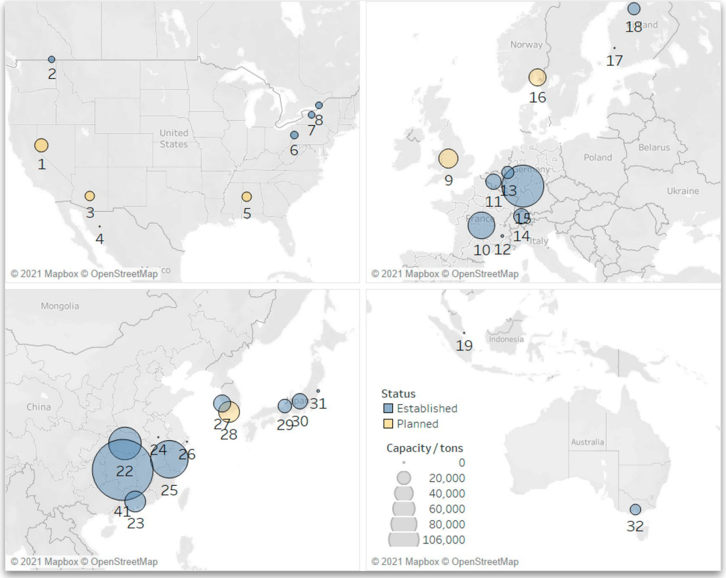
	Reuse	Recycle
Value	Refurbished batteries holds higher value* (Melin, Update on used EV battery prices) than recycled content: cells with minimal issues/cosmetic damage that can operate like a first life battery pack.	Closed loop recycling of batteries and the use of those recycled metals can support in De-risking of supply chain for materials required for battery production, reduce landfill & CO_2 emissions in the life cycle of batteries, and also support in meeting "Rules of Origin" laws.
Costs	New battery pack pricing has increased to an average of $151/kWh thus increasing the demand for re-use of batteries wherever possible (e.g., ESS applications) instead of choosing new battery packs.	Recycling costs Asia 10 - 14 $/kWh (pyro); 8 - 10 $/kWh (hydro) West 18 - 22 $/kWh (pyro); 12 - 14$/kWh (hydro)
Success Factors	Ability to win over the competition posed by new batteries, procurement of reliable and continuous feedstock, and granular data access. .	Ability to scale, ability to handle multiple chemistries or have a homogenous supply of right scale, high capacity utilization, access to feedstock
Challenges	All battery chemistries may not be appropriate for re-use given the safety, cycle life, degradation curve and discharge characteristics.	Collection and transportation costs, recovery rates, value of recovered materials, waste produced in the recycling process may pose challenges

Recycling | Trends in Academic Research and Patents

Battery recycling is growing rapidly in both publication count and global capacity

A team from the Chemical Abstracts Service, a division of the American Chemical Society, performed a meta-analysis of the battery recycling literatures. Noticeably, battery recycling patents outnumber publications by 200%, as compared to the 1:2 patent:paper ratio for the overall chemical literatures. Most focus on active metal recovery was placed on Li, followed by Co, Ni, Mn, and finally Fe. There is over 300,000 tons per annum installed capacity for battery recycling with more on the horizon.





Established and planned battery recycling facilities worldwide

Number of battery recycling publications in literature is increasing at 8x the growth rate of overall scientific publications.

Source: Bird, Baum, Yu, and Ma; Baum, Bird, Yu, and Ma

Recycling | Upstream and Downstream Collaborations

Several collaborations between upstream and downstream recycling players have been announced recently

Tech Collaboration

Feb 2020: Collaboration to establish recycling cluster

July 2020: R&D collaboration to develop advanced recycling methods

April 2021: Collaboration to develop efficient European LIB recycling value chain

October 2021: Collaboration in recycling and raw materials

Joint Venture

June 2020: Joint Venture HydroVolt to recycle batteries from Norwegian EVs

August 2020: Joint venture Primobius to construct demo plant

December 2021: Joint Venture build up precursor and cathode material production and recycling capacities

Joint Venture to establish facility in Norway by 2023

February 2022: Joint Venture to establish facility in UK

Letter of Intent

Mar 2020: Letter of Intent to establish recycling cluster

MoU

March 2021: MOU to develop recycling plant next to gigafactory

Joint Operation Agreement

July 2021: Joint Operation Agreement to construct demo plant

Recycling | Investments by Startup and Incumbents

CATL takes the biggest move among large cell manufacturers and major material companies to build recycling facilities

Company	Investments planned (in $Millions)	Remarks
CATL	5000	CATL forms joint venture with Hubei Yihua Chemical Industry Co Ltd to recycle used EV batteries for chemicals such as cobalt and lithium. Company will begin construction of a recycling factory by 2025.
BASF We create chemistry	50	BASF to build commercial scale battery recycling black mass plant in Schwarzheide, Germany. With an annual processing capacity of 15,000 tons of EV batteries and production scrap.
umicore	525	Umicore to build a $525m battery recycling facility which will be 15 times the size of its current facilities in Europe by 2026, capable of processing 150,000 tpa of waste battery materials.
SungEel HiTech	65 (in EU) 37 (in US)	Sungeel Hitech, South Korean battery recycling company to open a pre-processing plant for EV batteries in Hungary with a capacity of 50,000 tonnes of battery packs. The 10,000 tpa plant in Hungary outside of Budapest is located close to the plants of Samsung SDI and SK Innovation.
posco 华友钴业 HUAYOU COBALT	91.6	Huayou enters into a joint venture with POSCO HY Clean Metal (Posco Huayou Recycling Korea Co., Ltd.) to invest 120 billion won to build battery recycling facility. The project is scheduled to be completed in the second half of 2022 will treat 12000 tons of battery black powder annually.
posco GS Energy	121	POSCO, GS Energy to launch $121 million battery recycling joint venture to focussing on disassembling used batteries and extracting minerals such as lithium, nickel, cobalt and manganese.
	17.73	Mercedes battery recycling project to take off with Mercedes in Kuppenheim Germany as German Federal Ministry for Economic Affairs and Climate Protection (BMWK) is funding LiBinfinity project for 16.66 million euros to enable efficient recycling management of battery materials.
Korea Zinc	332	Korea Zinc, the world's largest lead and zinc smelter, buys a majority stake in a US-based electronic Igneo, waste recycling company for $332 million. This acquisition will expand Korea Zinc's copper smelting capacity from the current 30,000 tpa for supply to its wholly-owned copper foil producing unit KZAM.

Recycling | Investments by Startup and Incumbents

Startups focusing on battery recycling leap frog by advanced recycling technology to co-locate with giga factories

Company	Investments raised (in US $Millions)	Remarks
Li-Cycle	200	Li-Cycle, Canada-based company has been publicly listed with SPAC in 2021 is scaling its hub and spoke model by 2023, with expansion planned in Europe. It has also received an investment of $200 million from Glencore.
REDWOOD MATERIALS	700	Redwood Materials, a battery recycler raised more will scale up recovery of lithium, cobalt, nickel and other metals. Company is scaling its recycling process to increase share of recycled materials for production to achieve it closed loop ambition.
ASCEND ELEMENTS	1000	Ascend Elements raised $1 billion for several possible future phases, to build a sustainable lithium-ion battery materials facility in Hopkinsville, United States. SK Ecoplant also invested $50 million in Ascend Elements.
	92.98 + undisclosed	Lithion Recycling has got CA $125 (USD92.98) million from IMM investment in series A funding. GM ventures will also invest an undisclosed amount and Lithion plans to launch commercial operations in 2023. In 2025, Lithion will launch its first hydrometallurgical plant for extracting battery minerals.
northvolt	$13.94 Million by JV partners and $4.5 Million by Norwegian Govt.	Hydrovolt has begun commercial operations at the Hydrovolt battery recycling plant (10900 tpa capacity) in Norway, a joint venture (JV) between Hydro and Northvolt. Hydrovolt aims to increase its recycling capacity to 63,500 tonnes of battery packs by 2025 and 272,000 tonnes by 2030.
Cirba Solutions	82	In Oct 2022, Cirba Solutions receives $75 million grant to boost LIB recycling capacity and in Nov 2022 received additional $7+ Million from the DOE.

Recycling | Commercialization Plan

Most of the existing commercialization uses hydro/pyro technologies either individually or in combination

	Company Name	Country	Current Capacity → Announced Future Capacity (t/y)	Process
Hydro or Mech + hydro	ATTERO	India	700 → 20,000	Mech + hydro
Hydro or Mech + hydro	Duesenfeld	Germany	<1,000	Mech + hydro
Hydro or Mech + hydro	EXIGO (Ethical | Transparent | Recycling)	India	450 →10,000	Mech + hydro
Hydro or Mech + hydro	fortum	Finland	3,000	Mech + hydro
Hydro or Mech + hydro	GEM 格林美 资源有限 循环无限 Recycling for future!	China	2,000	Mech + hydro
Hydro or Mech + hydro	华友钴业 HUAYOU COBALT	China	>1,000 → 10,000	Mech + hydro
Hydro or Mech + hydro	Li-Cycle	North America	10,000	Mech + hydro
Hydro or Mech + hydro	Cirba Solutions	Canada	<1,000	Mech (aqueous) + hydro
Hydro or Mech + hydro	SMC Sungeel Metallica Americas	USA	NA → 5,000	Mech + hydro
Hydro or Mech + hydro	tele recycle	China	<1,000	Mech + hydro
Hydro or Mech + hydro	Primobius (Battery recycling without limits)	Germany	18,250	Hydro
Hydro or Mech + hydro	TATA CHEMICALS	India	0.1 (pilot)	Hydro

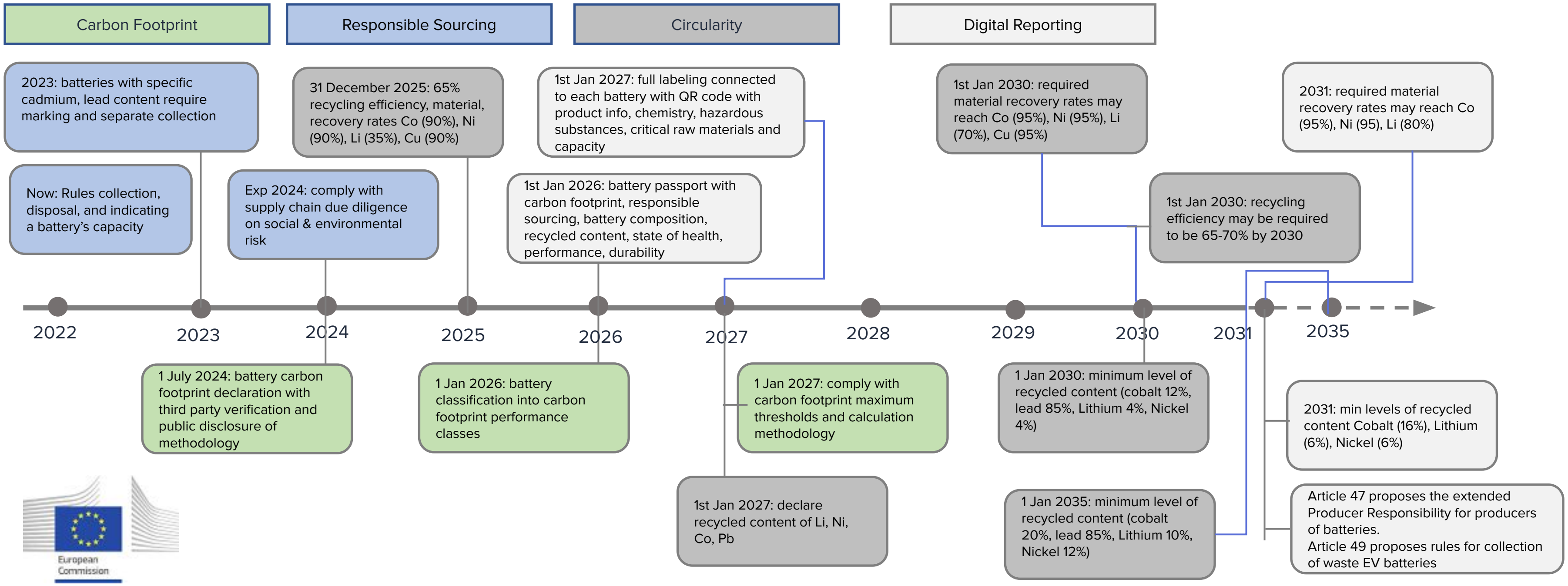
Pyro or Pyro +Hydro	KYOEI SEIKO	Japan	>1,000	Pyrometallurgical
Pyro or Pyro +Hydro	eramet	France	20,000	Pyrometallurgical
Pyro or Pyro +Hydro	ACCUREC	Germany	3,000	Thermal + mech + pyro + hydro
Pyro or Pyro +Hydro	DOWA ECO-SYSTEM / NHA Nickelhütte Aue	Japan	1,000	Thermal + pyro + hydro
Pyro or Pyro +Hydro	HIGHPOWER 豪鹏科技	China	>1,000	Mech + pyro + hydro
Pyro or Pyro +Hydro	umicore	Belgium	10,000 → 150,000	Pyro + hydro
Pyro or Pyro +Hydro	Nickelhütte Aue GmbH / NHA	Germany	7,000	Thermal + pyro + hydro
Thermal + Mech + Hydro	BRUNP CATL	China	6,000	Thermal + mech + hydro
Thermal + Mech + Hydro	JX金属	Japan	600	Thermal + mech + hydro
Thermal + Mech + Hydro	SungEel HiTech	Korea	8,000 → 160,000	Mech + thermal + hydro
Thermal + Mech + Hydro	AKKUSER	Finland	1,000	Mechanical + unknown
Mechanical + Unknown/Inert gas/Direct	SARPI VEOLIA	France	<1,000	Mech (aqueous shredding) + unknown
Mechanical + Unknown/Inert gas/Direct	REDUX	Germany	<1,000	Thermal + mech + unknown
Mechanical + Unknown/Inert gas/Direct	TES	France	<1,000	Mechanical (inert gas)

Source: NITI

Recycling | Regulatory Framework EU

Governments are aiming for circular economy and battery recycling regulation, that also ask for minimum recycled material content.

Milestones for the EU Battery Regulation



Source: [T&E analysis on European commission law]

Industry | Overview

Notable Events

Industry Players & Movement

Investments

Cell Chemistry Development

Technology Applications

Costs

Supply Chain

Recycling

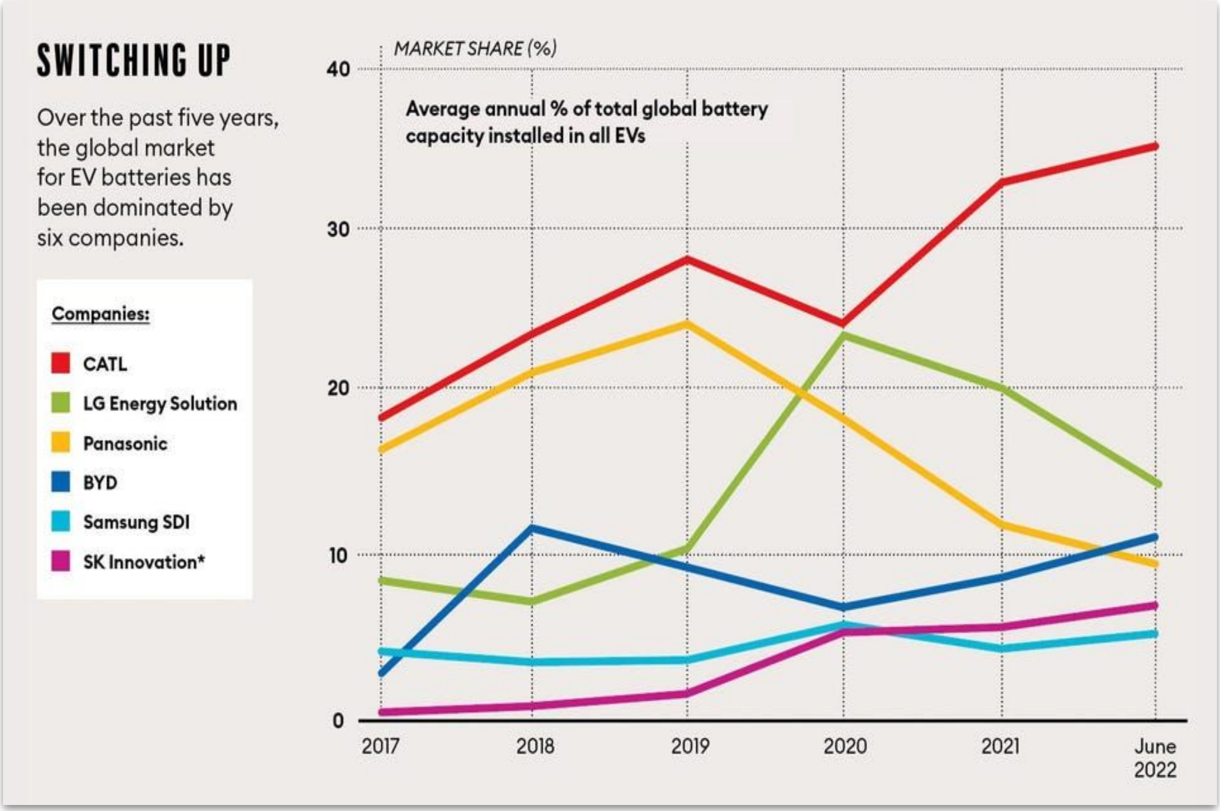
Manufacturing

Safety / Legal

Manufacturing | Global Overview

Summary For 2022 - Sustained Production Growth, Global Capacity Approaches One Terawatt Hour

- Capacity up ~54% from 492 GWh in 2021 despite rising material prices (BNEF)
- CATL & BYD are leading growth with highest market share increases
- Implied utilization rate of GWh manufacturing capacity estimated at ~85% for commissioned facilities
- End of year maximum manufacturing capacity ~985 GWh (Aug '22 BNEF Conference) and full year delivered capacity ~757 GWh (BNEF)
- 2022 average manufacturing capacity using EOY 2021: ~893 GWh
- Factory Database Link: excel of all battery factories created as public resource



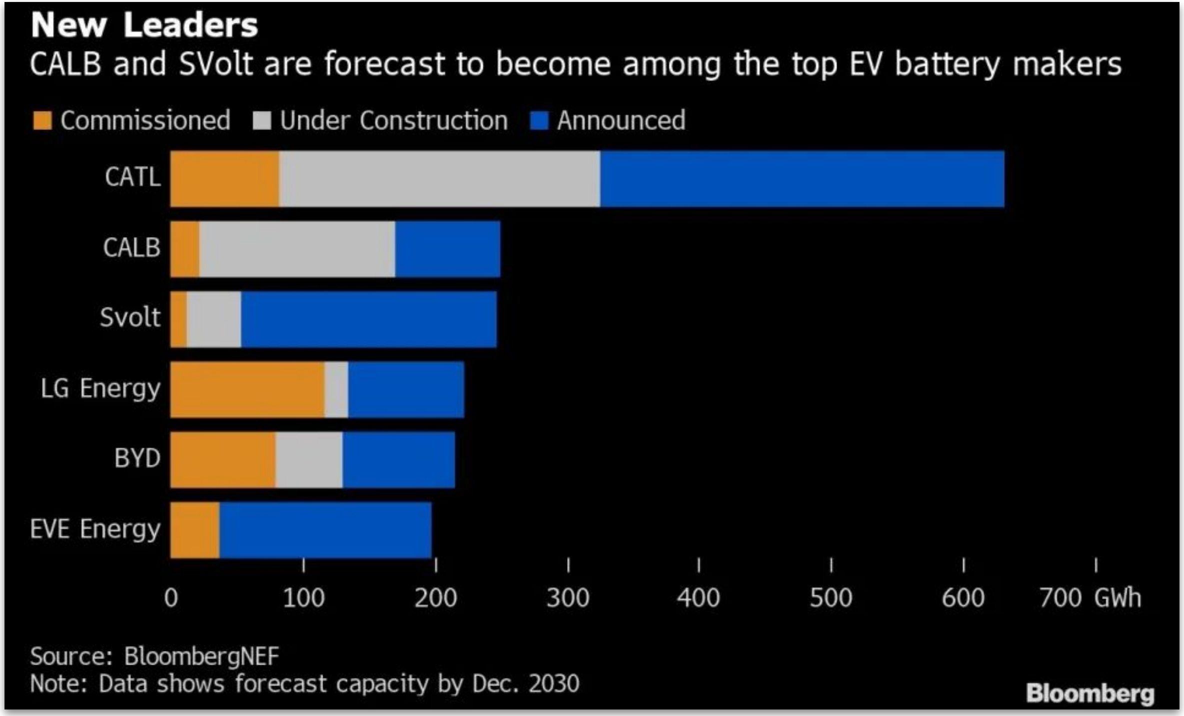
Source: Forbes

Manufacturing | Global Forecasting

High variability seen in manufacturing capacity forecasts due to uncertainty in demand, raw materials, plant implementation, and methodology.

Company	2030 Capacity Forecast (GWh)
Wood Mac	5,500
S&P Global	5,900
BNEF	7,396
McKinsey*	5,625
Roland Berger	4,200
Goldman	7,800
SNE	8,247

* Assumes 80% OEE on demand of 4,500 GWh



"Announced" = Uncertainty

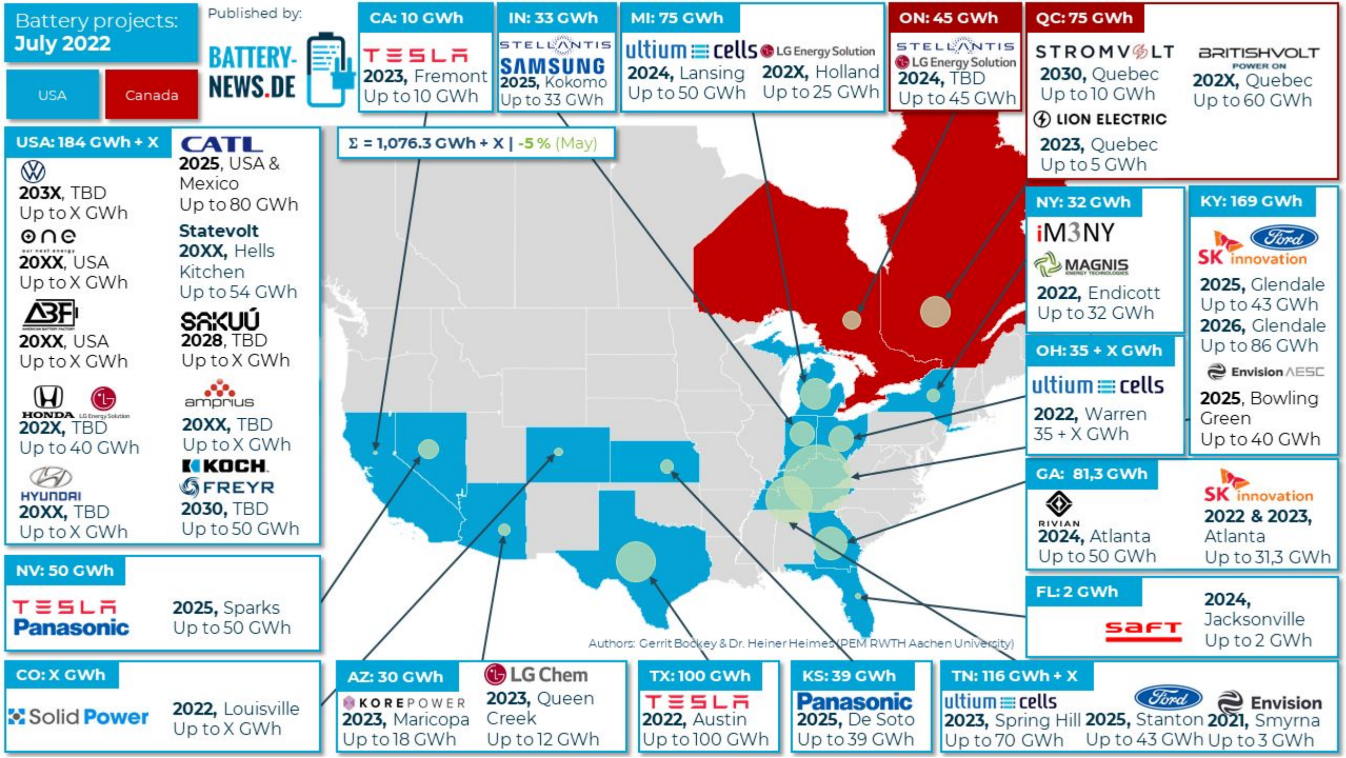
Source: BNEF/Yahoo Finance

Manufacturing | Regional Overview

North America - Post Inflation Reduction Act announcements have caused a spike in anticipated capacity.

“Everybody’s got their mind on the IRA”

Yet-Ming Chiang
MIT Professor & Serial Battery Entrepreneur



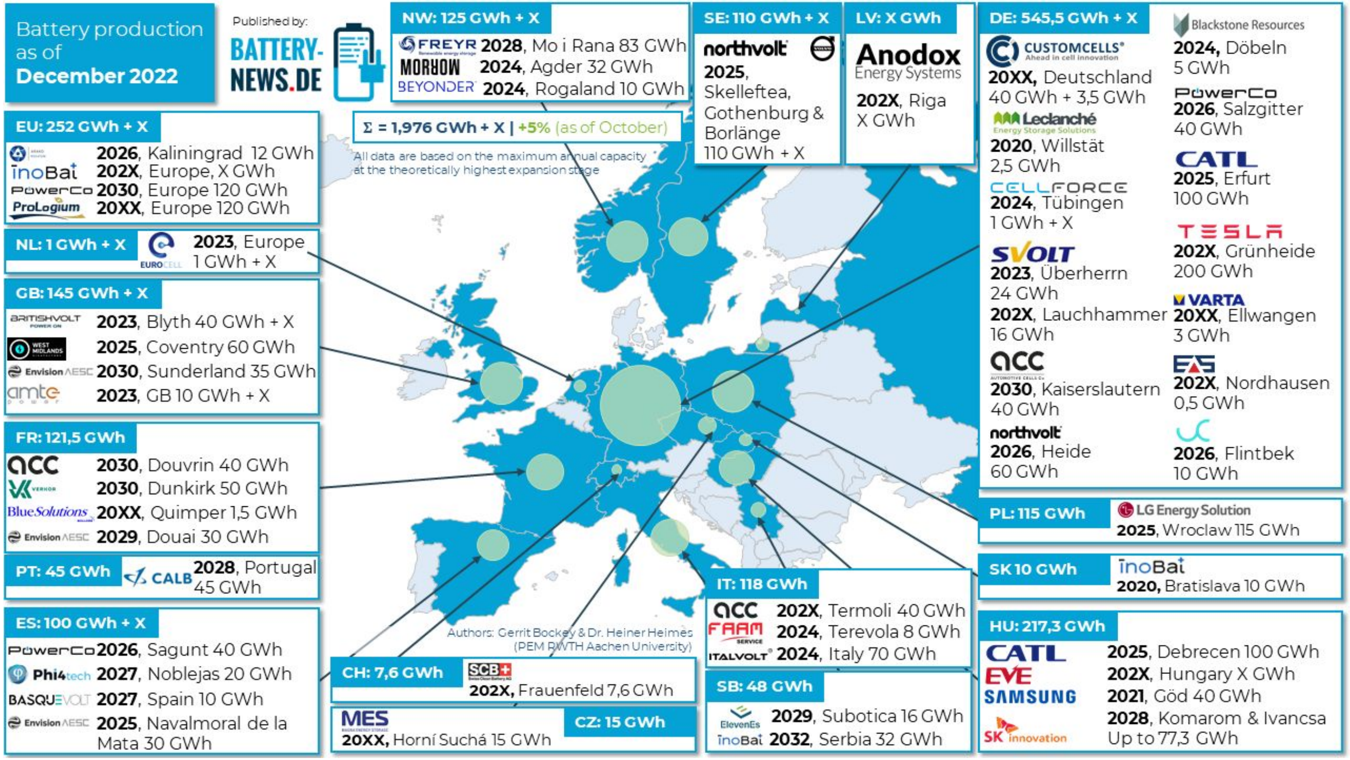
Source: Battery News Map

Manufacturing | Regional Overview

Europe - Recent concerns over energy prices and market conditions have paused or canceled large projects including Northvolt and Varta.

"We need to give our answer, our European IRA"

Ursula von der Leyen
European Commission President



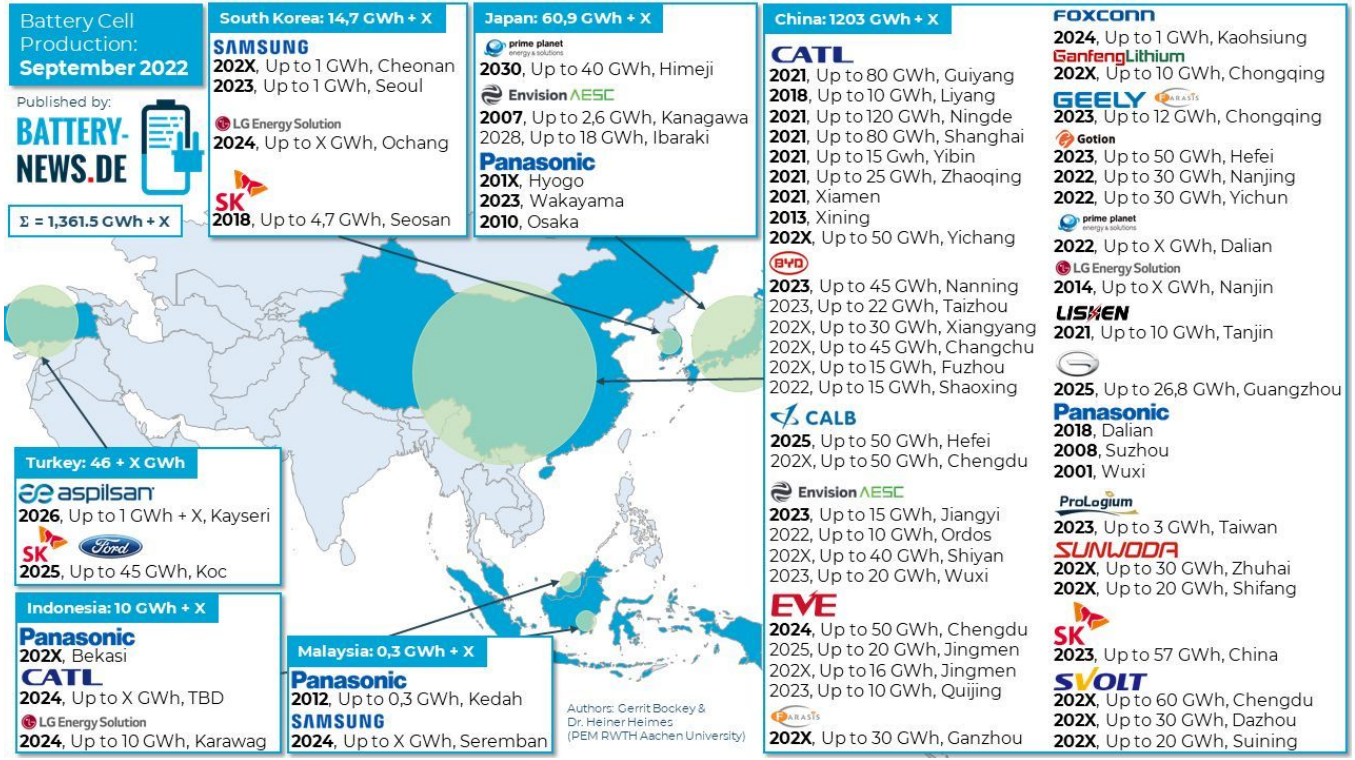
Source: Battery News Map, European Battery Alliance Joint Statement, "We need to give our answer, our European IRA," - European Commission President Ursula von der Leyen

Manufacturing | Regional Overview

Asia - China is anticipated to lose some global market share but will continue to increase production capacity throughout the supply chain.

“The likely growth of EV infrastructure in China over that period is going to be so massive that it will still outstrip Europe and the US.”

Ross Gregory
Partner at New Electric Partners



Source: Battery News Map

Manufacturing | Global Overview

Gigafactory Suppliers - Upstream Manufacturing Techno-Economics

- The material ‘gigafactories’ supplying the battery gigafactories will need to scale material supply capacity to meet demand.
- Various global policy initiatives encourage localization throughout the value chain including domestic battery material production.
- The battery materials sector is viewed as more investible than battery manufacturing itself and faster to respond to demand signals.
- Scarcity of CAPEX equipment will be a dominating factor in timing of manufacturing launch.

Battery material economics overview

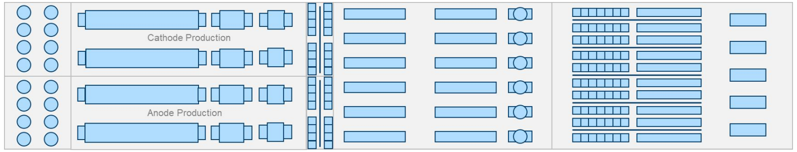
	Content Per 1GWh	ASP	Sales Per GWh	CAPEX Per GWh	EBITDA Per CAPEX
Cathode	1.8kt	$31.5/kg	$56M/GWh	$14M/GWh	35%
Anode	1.4kt	$5/kg	$7M/GWh	$7M/GWh	22%
Separator	13mn sqm	$0.9/sqm	$10M/GWh	$14M/GWh	31%
Copper foil	0.7kt	$17/kg	$11M/GWh	$8M/GWh	22%

Source: Company data. J.P. Morgan..

Manufacturing | Gigafactories & Industrial Parks

Cell factories are becoming crystallization points for new industrial parks and colocated supplier networks.

Material Manufacturing → **Cell Manufacturing** → **Module/Pack Manufacturing**



On-Site (Collocated) Suppliers

Can suppliers: Readily produced cans have very low packing efficiency in transport and often are stamped/formed on-site.
Electrolyte suppliers: Final mixing of electrolyte is often connected by pipeline to the cell factory, to ensure optimal electrolyte quality.

Candidates For Supplier Colocation

Close-distance Suppliers

CAM Suppliers: CAM makes up a large part of cell weight. Large volume of material inputs require short logistic routes.
Module & Pack Assembly: Transport of cells comes with special transport regulations and high costs. Large-scale operations tend to place module & pack close to cell production.
Recyclers: Waste from battery production can ideally be used in a closed loop. Recyclers benefit in two ways: short way from an important input source and short way to a main customer.

International Suppliers

Raw Material Suppliers: Raw material supplies are bound by natural reserves. Raw material supply will remain as a international supply chain.
Equipment Suppliers: Cost pressure and supply constraints keep equipment supply on an international level.
Foil Suppliers: Metal foils are supplied mainly from Asia and can be handled efficiently in transport but with supply chain risk.

Larger cell factories and supply constraints push for more localized supply chains.

Manufacturing | Bottlenecks and Challenges of Current Traditional Manufacturing

Identifying and Quantifying Challenges By Process Step

Boston Consulting Group conducted a techno-economic analysis by battery manufacturing process step, summarizing key process steps, costs, and challenges commonly faced by manufacturers and a factory map of potential technology solutions in "The Battery Factory of the Future".

CELL ASSEMBLY: 20% of battery cell production costs

Process	Electrode shaping	Compound generation	Electric contacting	Case insertion	Case closure
Description	Cutting out electrode shapes from coils	Generating active material compounds	Creating an electrically conductive joint	Inserting compound into cell housing	Closing cell housing using laser welding
Cost	29% of assembly	54% of assembly	5% of assembly	4% of assembly	8% of assembly
Challenges	Edge quality Particle generation	Assembly tolerance Processing speed	Particle generation Processing stability	Insulation quality Particle generation	Particle generation Yield rate

ELECTRODE PRODUCTION: 39% of battery cell production costs

Process	Mixing	Coating and drying	Slitting	Calendaring	Vacuum drying
Description	Mixing of raw material powder	Pasting slurry on foil; removing solvent	Cutting coated metal foil into strips	Compressing electrode foils	Removing leftover solvent in electrodes
Cost	8% of electrode	54% of electrode	4% of electrode	11% of electrode	23% of electrode
Challenges	Material quality Slurry waste	Processing time Utilization losses	Edge quality Tool wear	Process settings Electrode waste	Processing time Yield rate

CELL FINISHING: 41% of battery cell production costs

Process	Electrolyte filling	Precharging	Filling hole closure	Formation	Aging
Description	Filling ion-conductive liquid into cell	Precharging cell after filling	Closing electrolyte filling hole	Initiating battery and defining performance	Identifying micro short circuits in cells
Cost	10% of finishing	7% of finishing	3% of finishing	35% of finishing	45% of finishing
Challenges	Soaking time Number of filling steps	Processing safety Yield rate	Particle generation	Processing time Yield rate	Processing time Yield rate

Manufacturing | Bottlenecks and Challenges of Current Traditional Manufacturing

Scrap Is Still a Major Challenge For Large Format Cells

- Large format li-ion battery manufacturing can be economically squeezed by low yield and low margins, the results of tight manufacturing tolerances and high-volume commodification, respectively.
- A general lack of rapid in-line inspection exists with some process steps having none at all.
- Slow feedback loops with inspectional data and iterative process improvements usually lead to multi-year production ramp periods.
- Large format market leaders like CATL have implemented better engineering, process control, controlled feedback loops, and benefited from standardized facility design to reduce scrap.

Line Commission	Ramp Period (Years 1-5)	Steady-State
70%	80% Average Yield (20% Scrap)	90%

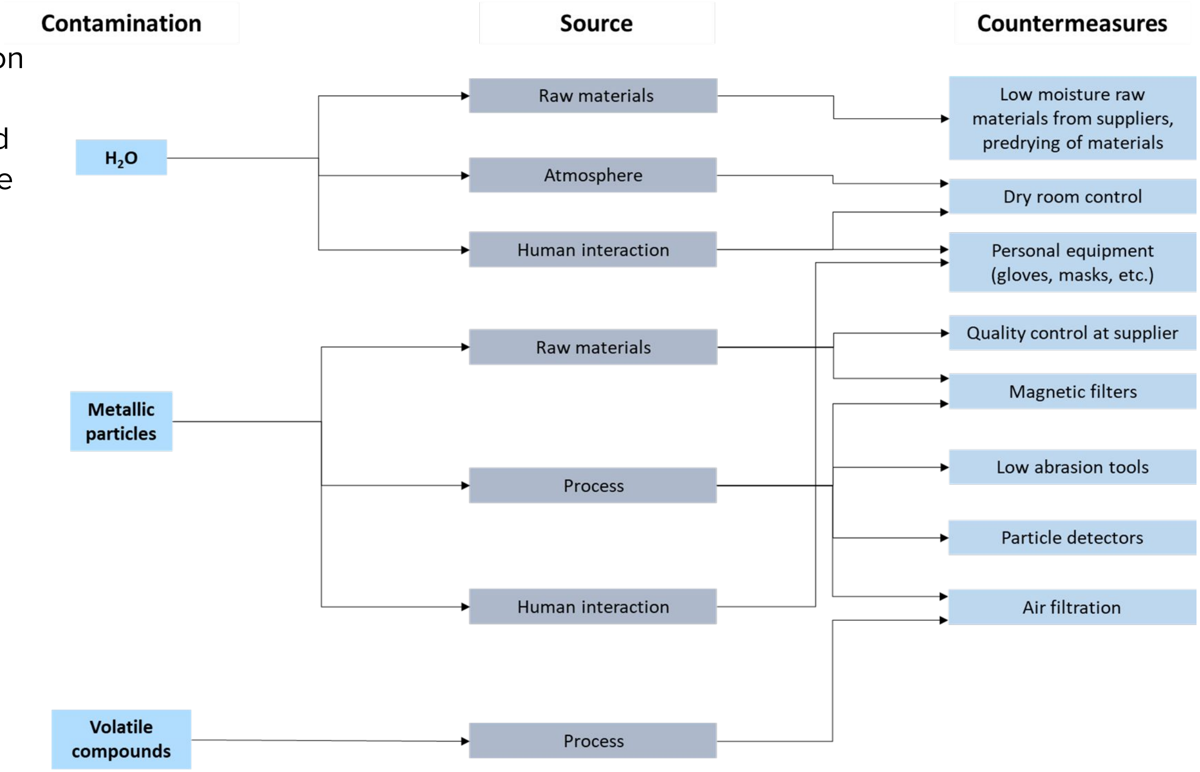
	Electrode	Assembly	Formation	End-of-Line
Dropout (Scrap Rate)	5%	5%	9%	1%
Cumulative Cell Cost	60%	93%	96%	99%

Source: For Manufacturing Yield: NREL, ANL, DOE, MIT & Carnegie Mellon, TU Braunschweig

Manufacturing | Bottlenecks and Challenges of Current Traditional Manufacturing

Technical cleanliness in production remains a key challenge for safe & high performance batteries.

- Technical cleanliness remains a key issue in manufacturing with impacts on product performance and potentially product safety. Especially particle and material contamination play a key role in cell manufacturing.
- Inspection and traceability of particle contamination is especially challenging, due to difficulties in detection and delayed impact on cell quality over lifetime.
- Cell manufacturers need to operate under strict quality management protocols and apply common quality management tools (e.g. Ishikawa, FMEA, etc.) to a high level of detail.



Source: Adapted from ELIBAMA

Manufacturing | Bottlenecks and Challenges of Current Traditional Manufacturing

Cell producers have to ensure a high level of fire protection for safe operations.

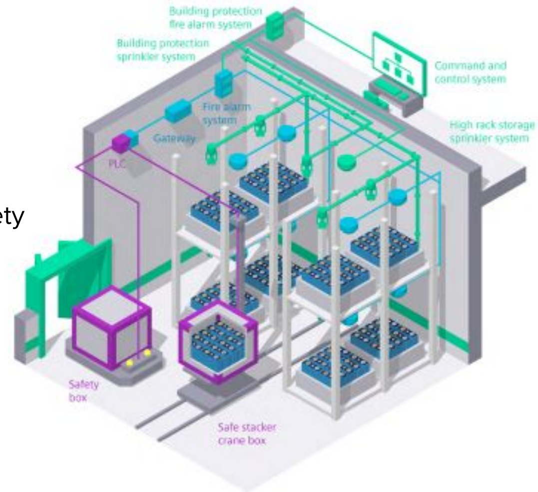
- Common fire hazards are caused by particle contamination during welding or from static charge in the assembly process.
- Formation and aging have high fire loads, especially in large factory setups, and require dedicated, advanced fire protection concepts.
- With increasing energy and power density of produced cells, fire protection needs to be advanced and adapted.
- Fire protection includes actions on building, process, machinery and operations level to ensure long term safety.

Building Safety

Process Safety

Machinery Safety

Operative Fire Safety



Risk Level

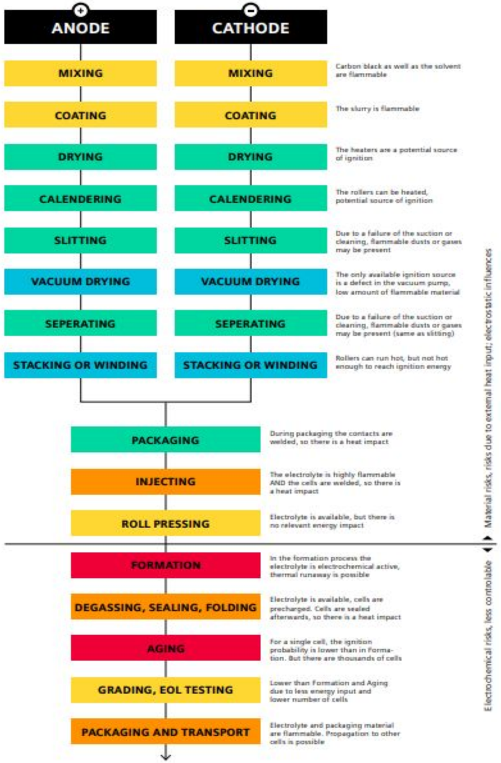
Very Low

Low

Medium

High

Very High



Source: TUV SUD, SIEMENS

Manufacturing | Bottlenecks and Challenges of Current Traditional Manufacturing

Flexibility in production is the key to reduce costs for niche-applications and small-scale production.

- Flexibility is highly relevant in cell assembly and cell finalization (formation & aging). Different cell formats and cell chemistries require variance in tooling, automation and process atmosphere. State-of-the art production facilities mainly achieve flexibility by adding parallel machinery.
- Flexibility needs to be improved in automation, machine functionality and tooling. This poses a direct trade-off to costs and speed, making it a complex economic & technological challenge.

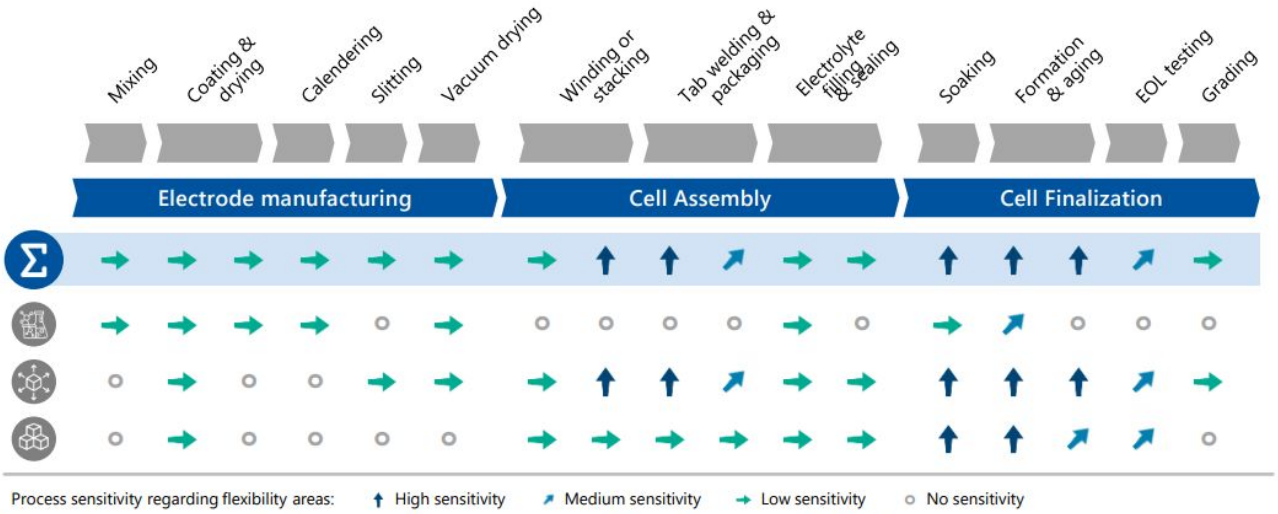


Figure 6: Process sensitivity of current production equipment with regard to product flexibility areas (Top-to-down: Overall, Material, Size & Shape, Tabs & Terminals)

Source: Flexfactory, PEM

Battery Informatics | Battery Analytics and Use Cases

Hybrid electrochemical algorithms with machine learning are essential to track batteries through their life

Stage	Research	Manufacturing	Field operation	Second Life
Use Cases	• Material and environmental evaluation • Virtual simulation of lifetime testing • Thermal and battery sizing • Safety evaluation	• Simulation of Battery formation post battery assembly • Finding co-relational models among production process and battery capacity	• Remaining useful Life (RUL prediction • Precise in-field alerts • Data Feedback loop with edge devices (BMS optimization)	• Remaining useful Life (RUL prediction • Precise in-field alerts • Data Feedback loop to design and edge devices (BMS optimization)
Data Source	• Battery Archive • Bespoke data pipelines • Battery Data Genome • Voltaiq Community	• Sample batch production data for similar chemistries, materials and coating data • Manufacturing execution systems (MES)	• BMS, Drivetrain, synthetic data generators	• Anonymized full / partial lifecycle data • Knowledge of 2nd life application
Impact	• Simulation with digital twin methodology, faster Go-to-market	• "Battery formation" is the biggest bottleneck • Process improvement of complex electrode manufacturing	• Increased energy efficiency • Decreased energy costs	• Improved material recovery • Regulatory compliance
Challenges	• Data normalization over vast pool • Low ROI on continuous learning due to rapid change in battery technology architectures	• Most data collection happens at operation time • Cross industry standard process (CRISP) and data mining is not very common among manufacturers	• Connectivity, data formats, OTA channels • Data platform value over longer periods is not obvious	• Introduction of tech in 2nd life tooling process • Not all batteries generate / collect data
Beneficiaries	• Manufacturers / researchers	• Manufacturers	• OEMs / consumers/ Insurance operators	• Manufacturers / recyclers / OEMs

Industry | Overview

- Notable Events
- Industry Players & Movement
- Investments
- Cell Chemistry Development
- Technology Applications
- Costs
- Supply Chain
- Recycling
- Manufacturing
- **Safety / Legal**

Safety | Incidents by Region by OEM

EV Recalls due to safety risks

2020

Hyundai / LG Energy Solution
EV Model: Kona, IONIQ
Size of Recall: 90,000
Cost of Recall: $900M
Incident: 15 reported fires
Potential Cause: Folded Anode tab

Weltmeister 威马汽车
EV Model: EX5 EV
Size of Recall: 1,282
Cause: Contaminants in cell that could lead to short circuit

Ford
EV Model: Kuga PHEV
Size of Recall: 28,000
Incident: Overheating during charging and fires
Cause: Contamination of cells during production

BMW / Samsung SDI
EV Model: all PHEVs
Size of Recall: 26,900
Incident: thermal events
Cause: Debris in battery that could cause short circuit

2021

BAIC Motor / Farasis
EV Model: EX360, EU400
Size of Recall: 31,963
Incident: fast charging at high temperatures pose fire risk
Cause: Issues with battery conformity

GM / LG Energy Solution
EV Model: Chevy Bolt
Size of Recall: 141,000
Cost of Recall: $2B
Incident: 24 reported fires
Cause: Torn anode tab & separator folds

Renault / LG Energy Solution
EV Model: ZOE
Size of Recall: 733
Cause: increased risk of fire due to internal short circuit in battery

Chrysler / Stellantis / LG Energy Solution
EV Model: Pacifica PHEV
Cell Maker: LGES
Size of Recall: 19,808
Incident: 12 fires
Cause: Under investigation, related to battery pack

2022

BMW / Samsung SDI
EV Model: i4, iX
Size of Recall: 83
Cause: Cathode debris poses fire risk

Volkswagen
EV Model: ID4
Size of Recall: 351
Cause: Incorrect soldering inside battery may cause unreliable connection, making the car prone to crash

GM
EV Model: GM Hummer EV
Size of Recall: 424
Cause: Battery connector corrosion poses risk for water to enter battery pack

Volkswagen
EV Model: ID.3, ID.4
Size of Recall: 10,130
Potential Cause: Manufacturing defect causes battery cells undergo increased self discharge

Source: Published news articles, linked to each event

Safety | Stationary Storage Battery Fires

Continued challenges seen in system engineering, emergency responses, and community engagements when deploying utility-scale storage projects.

Victoria Big Battery Fire (Tesla Megapack)

- **Incident Date**: 7/31/2021
- **Final Report Date**: 1/25/2022
- **Reported Cause**: Liquid coolant leakage led to electrical short, heat build-up, eventually initiating thermal runaway in adjacent battery modules in the incident unit. *Not battery quality issue.*
- **Damage**: Total loss of two Megapack units (~1% of 212 units installed), one incident and one neighboring. No injury reported.
- **Impact**: Shelter-in-place advisory issued for approx. half a day starting ~1 PM local time. Communities as far out as 4.5 km impacted.

Moss Landing Phase 1 & 2 Thermal Incidents (LG Energy Solutions & Fluence)

- **Incident Dates**: Sept. 4, 2021 & Feb. 13, 2022
- **Final Report Date**: 1/21/2022
- **Reported Cause**: Sensor programming error triggered premature filling of water suppression system with leaky pipes, leaking water onto battery racks, causing electrical short, heat build-up, and ultimately thermal events. *Not battery quality issue*.
- **Damage**: ~7% of all modules installed for Phase 1; no estimate or figure provided for Phase 2. No injury reported.
- **Impact**: No fire reported, no local emergency warning was issued, no road closure implemented, surrounding communities were not impacted.

Future Challenges:

- System integration, commissioning, and operation remains a work-in-progress.
- Though damages were contained to the facilities, community impacts were immediate and significant.
- Highly visible events, regardless of scale relative to system size, cause significant community concerns.
- The industry must continue to address these concerns head-on with standardization and clear, concrete answers.
- This dynamic may be local currently, but will go global as installations multiply around the world.

Victoria Big Battery Fire (Above & Below)
Scale of Incident vs. Installed System

Source: Victoria Big Battery Fire (Top Image) , Victoria Big Battery Fire (Bottom Image), BatteryBits (Article 1, Article 2)

Safety | Emergency response to EV fires

Although vehicle fires occur less frequently in EVs than in ICEs, fighting EV fires require more resources and specialized training.

Critical Event Detected | **First Response** | **Second Response**

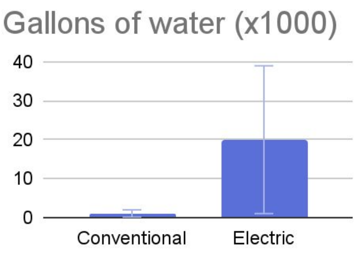
Detection and alert

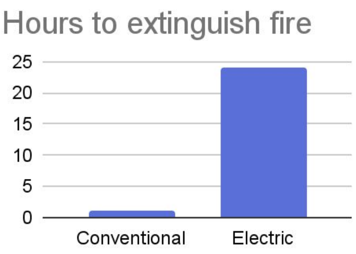
Emergency responders lack information and methods to monitor pack conditions* and thermal runaway hazards.

*Temperature, SOC, voltage, gas, etc.

Fire suppression and pack cooling

Fighting EV fires can require up to 40x more water than conventional vehicle fires and take over 24 hours due to reignitions.





Tow

Stranded energy can lead to battery fire reignitions which can occur anywhere, including on the tow bed.

Fully submerging a damaged BMW EV for transport in the Netherlands

Storage

Damaged EVs are space inefficient to store. Recommendations call for a 50-ft radius around the damaged EV in tow yards and, if possible, full submersion in water. Reignition hazards can remain even weeks later.

(Figure adapted from the Tran 2021 conference presentation)

Source: NTSB Report, CTIP, BatteryBits (Article 1, Article 2)

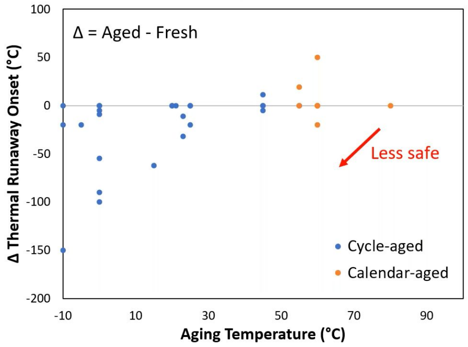
Safety | Influence of battery ageing on safety

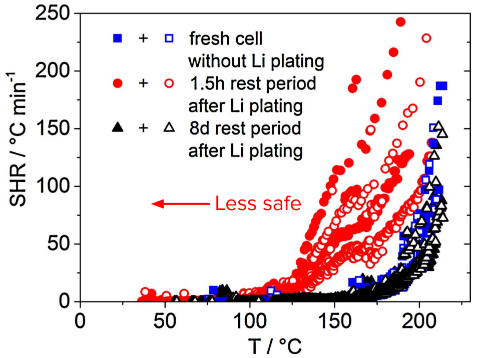
Influence of battery aging on safety has limited published literature, and needs more research

Safety against thermal failure (ARC)

Until recently, the effects of calendar and cycle ageing on battery safety are relatively unexplored.

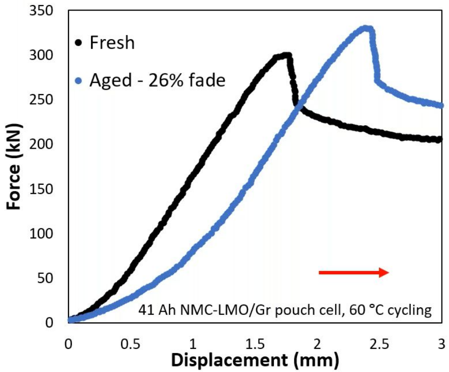
Accelerating Rate Calorimetry (ARC) showed that aged cells generally have a higher thermal runaway onset temperatures. **Li plating can lower** the onset temperature by up to 50 °C. Increasing the resting time after Li plating improves cell safety.

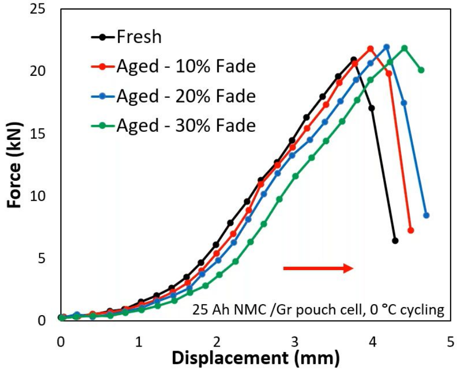




Safety against mechanical intrusion

For mechanical failures, aged cells showed higher resistance to internal shorting, making them safer, but sample sizes and variety in cell designs need to be explored further to make stronger conclusions.





Sources: Preger et al., Jeevarajan et al., Waldmann et al., Kovachev et al., Liu et al., BatteryBits

Section 2
Research

Overview | Popular Topics in Academic Research

We identified some of the most noteworthy research papers from this year in the following fields:

Cathode	Anode	Electrolyte	Solid-State	Li Metal	Sulfur
Na-ion	Fast Charging	Manufacturing	Recycling	Diagnosis	Battery Informatics

Cathode – Emerging contenders include Co-free and low Ni cathodes, with NMCA still dominant on balance between performance and stability.

Anode – Interfacial and microstructural engineering are being investigated to advance Si and Gr anode materials.

Electrolyte – Non-aqueous, aqueous, and solid-state electrolytes are all making progress in electrolyte research.

Solid state – More classes of hybrid electrolytes are being studied, and debate continues over the relative merits between polymer, oxides, and sulfides.

Li metal – Steady progress has been made to improve performance, specifically around cycle life and safety.

Sulfur – Limited success with new electrolyte and electrode design.

Na-ion – Sodium batteries are gaining attention on electrolytes (including solid state). Current challenges include limited anode and cathode choices.

Fast charging – Purpose-built electrodes and temperature control are emerging as prerequisites to accomplish extreme fast charging.

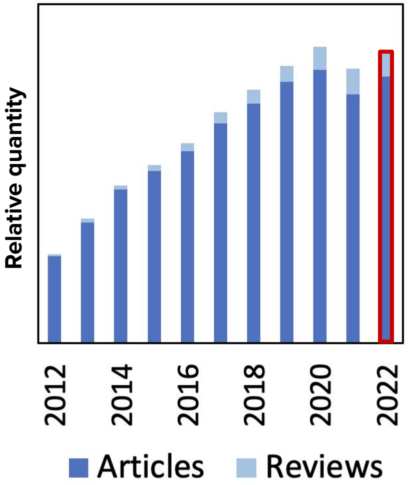
Manufacturing – Many innovative approaches are being developed to achieve scaling and integrability with existing gigafactories.

Recycling – Methods with low cost and low energy consumption are being studied. An emerging area of research topic, expect continued growth.

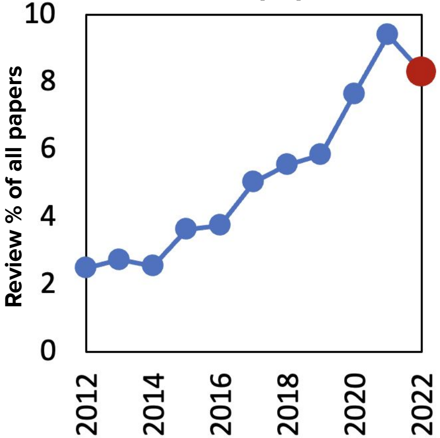
Overview | Trends in the Research Community

High-level trends across publication types and countries

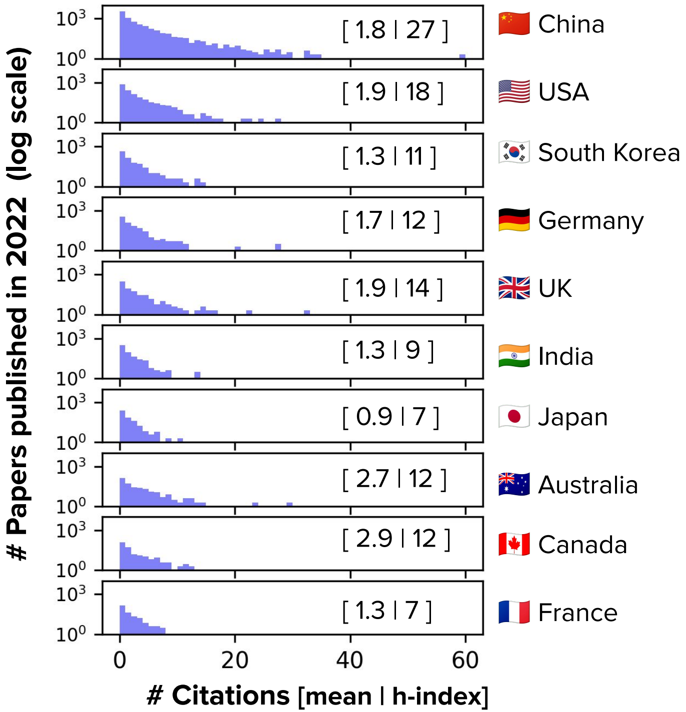
Papers published



Review papers



2022 battery publications *vs* citations



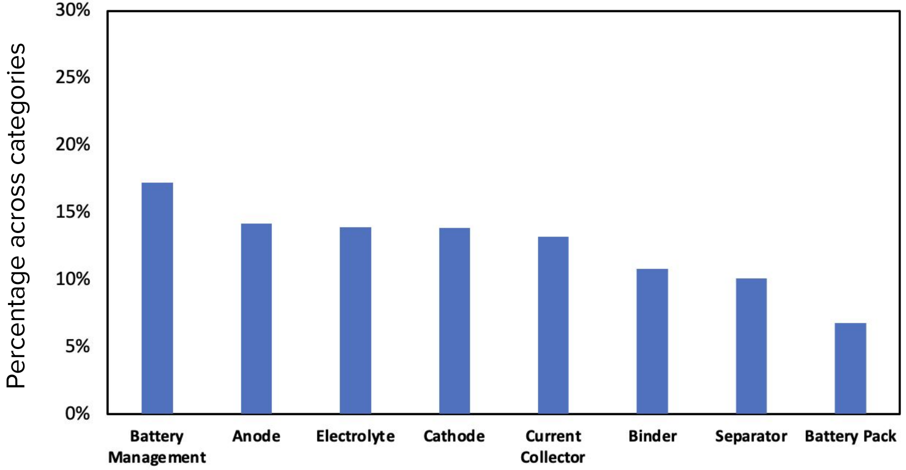
Bounce-back in original battery research *vs.* review papers

China leads in total 2022 publications, Canada leads in average citations per paper in 2022

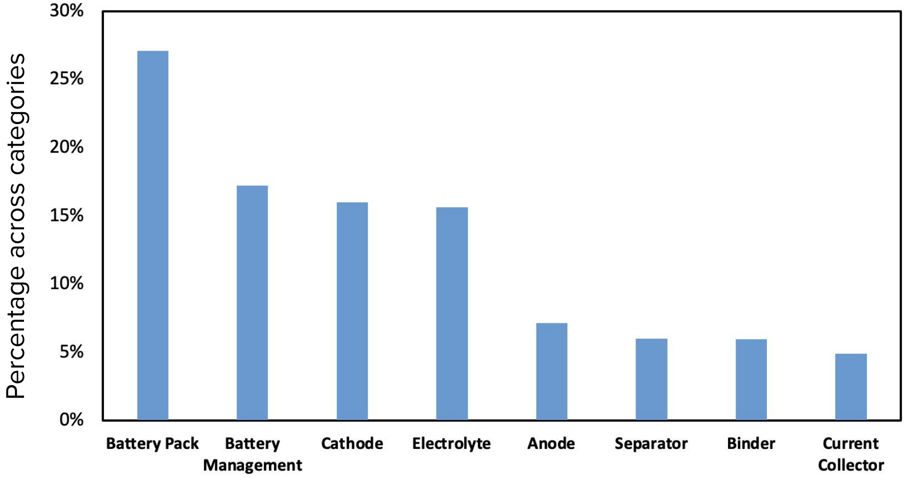
Source: Web of Science query: "lithium ion battery", accessed 2022-12-11

Overview | Trends in the Research Community

Publications by topic



Patent filings by topic



Clear academic focus towards materials research on anodes/electrolytes/cathodes

Battery management maintains attention

Primary industry focus remains on systems-level innovations: battery packs and management

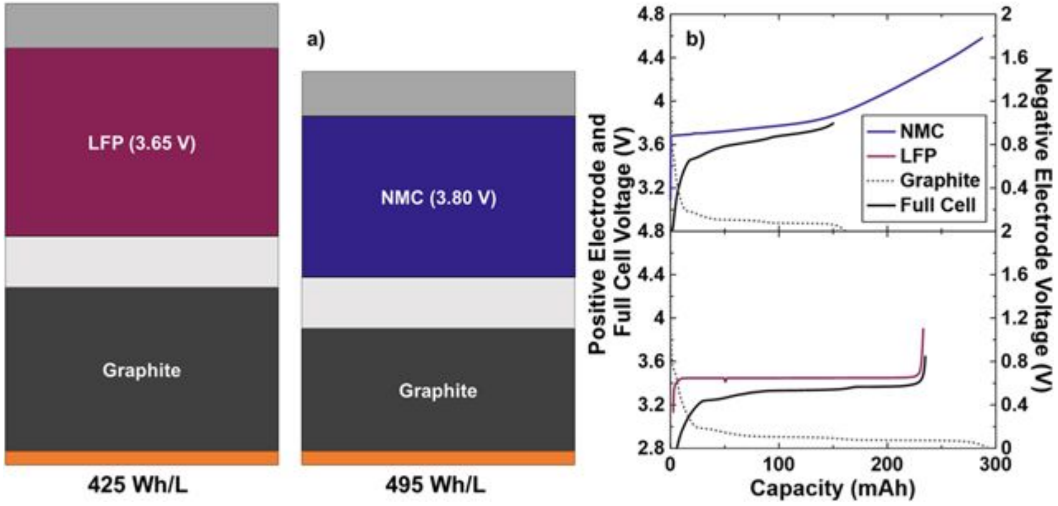
Source: Web of Science query

Cathode | NMC | Cycling Optimization

Jeff Dahn's 100 year battery

There has been significant research showing LFP has superior lifetime over NMC. However, work from Jeff Dahn's group demonstrated that NMC532 cells cycled to 3.65 V and 3.8 V demonstrate superior coulombic efficiency, less capacity fade, and higher energy density compared to LFP.

At the 2022 International Battery Seminar, Dahn's NMC cells had reached 15,000 cycles with <5% loss in capacity. This enables the option to use high-nickel/low-cobalt without suffering from structural degradation at higher voltages, and opens up vehicle-to-grid and second-life applications.



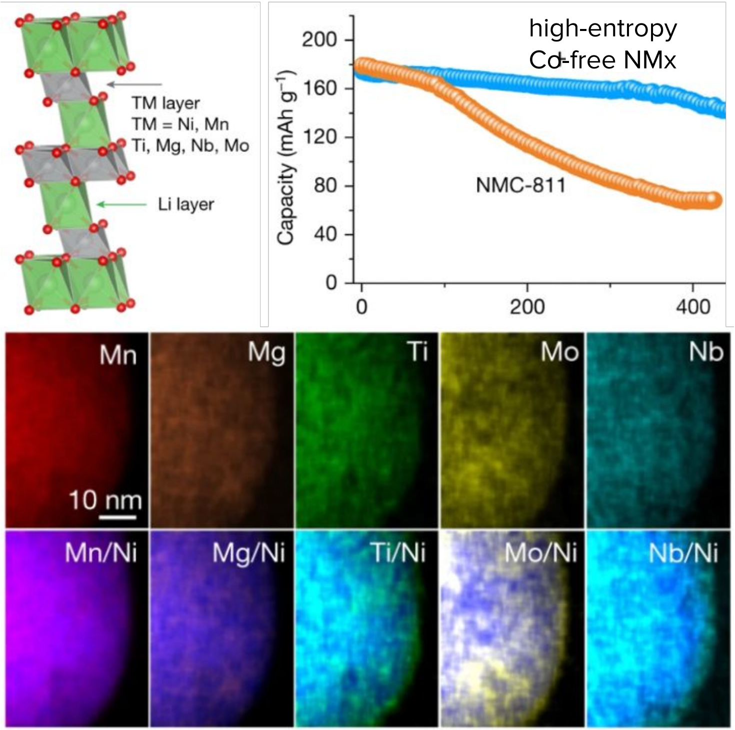
Schematic of the approximate stack energy density for $LiFePO_4$//graphite and $Li[Ni_{0.5}Mn_{0.3}Co_{0.2}]O_2$//graphite pouch cells used

Limiting the voltage window of an NMC//graphite cell has enabled 15,000 cycles with 95% capacity retention while maintaining an energy density that exceeds LFP//graphite.

Source: Aiken, Logan, Eldesoky, Hebecker, Oxner, Harlow, Metzger, and Dahn; Griffith

Cathode | NMC | Stabilizing Ni-rich cathodes with extrinsic dopants

Almost every element has been tested, though their structure–property mechanisms differ



Development in NM(C)A cathodes is heading toward increased Ni content. However, $LiNiO_2$ undergoes detrimental phase transitions that lead to particle cracking and capacity fade. Dopants can suppress these phase transitions and stabilize long-term cycling.

Two research teams recently developed orthogonal doping strategies. Zhang et al. created a high-entropy Co-free layered cathode with Ni, Mn, Ti, Mg, Nb, and Mo mixed on the transition metal site. Wang et al. added a single element, lanthanum, which did not actually dope into the NMC811 structure but rather formed perovskite-like $La_4Li[Ni,Mn,Co]O_8$ as an intergrown secondary phase. Both strategies minimized volume change during cycling and extended the cycle life.

Elemental doping and secondary phases can stabilize Ni-rich cathodes for applications requiring high energy and long cycle life

Source: Zhang, Wang, Zou, Lin, et al.; Wang, Liu, Wu, and Lu

Cathode | NMC | Stabilizing Ni-rich cathodes with coatings

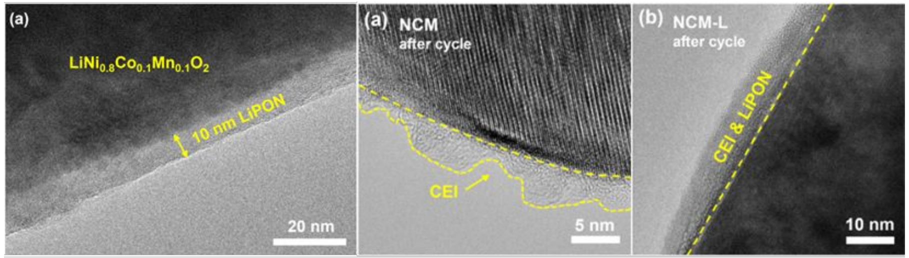
A thin solid electrolyte works well as NMC811 coating

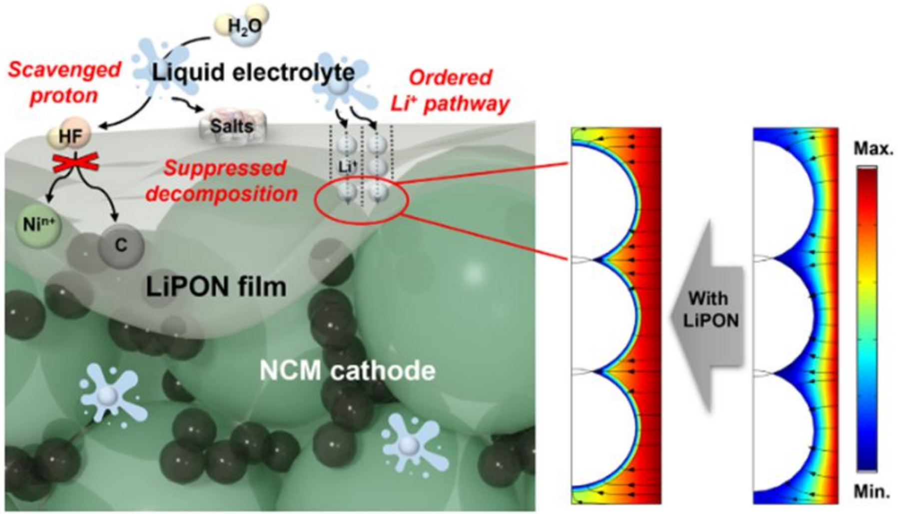
Surface coatings have been effective at suppressing side reactions between NMC and the electrolyte, e.g., electrolyte decomposition, oxygen loss at high voltage, and transition metal dissolution. These side reactions contribute to capacity fading, power loss, and safety risks.

A 10-nm layer of lithium phosphorus oxynitride (LiPON) was sputtered on an NMC811 cathode, leading to the stabilization of the particle surface and to the formation of a more uniform CEI. Moreover, the HF scavenging capability of LiPON can inhibit the dissolution of transition metals into the electrolyte.

The researchers found lower impedance, longer cycle life, and better safety for batteries with the LiPON-coated cathode. They demonstrated a 1.3 Ah pouch cell with an energy density of 364 Wh kg^{-1} and a capacity retention of 80% over 745 cycles at C/2.

Ultrathin LiPON coated onto the NMC811 surface can effectively stabilize the cathode–electrolyte interface and lead to an improved cycle life.

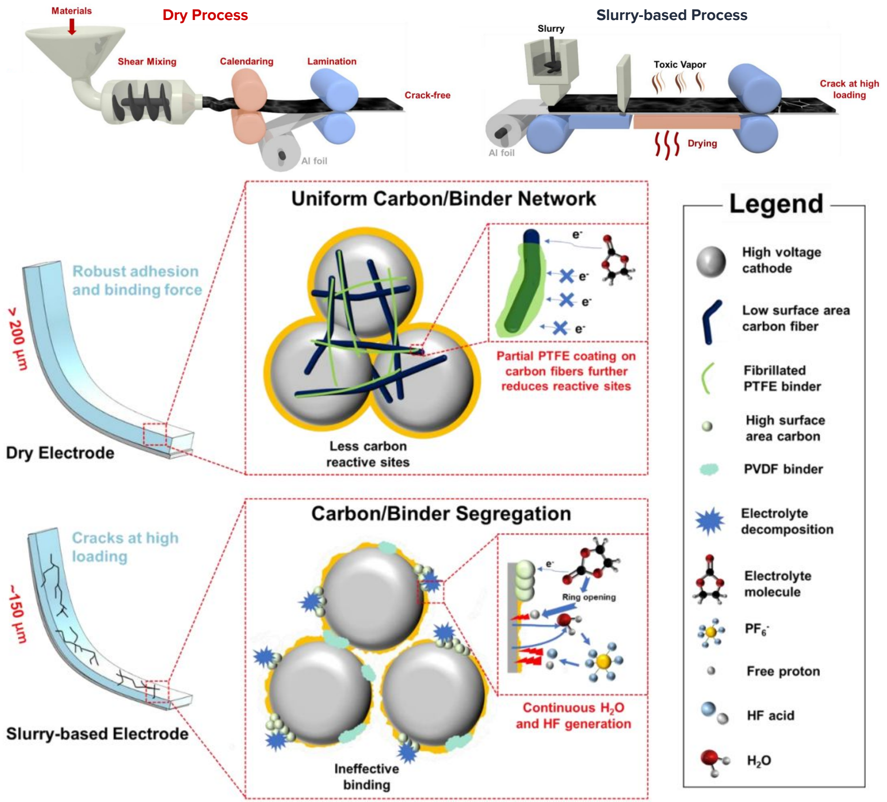




Source: Yang, Shadike, Wang, Yue, Xia, Bak, Du, Li, and Fu

Cathode | LNMO | Dry coating for high-loading electrodes

Leveraging a dry electrode coating process to achieve excellent cycling stability



The spinel-type $LiNi_{0.5}Mn_{1.5}O_4$ (LNMO) cathode material has attracted great interest due to its high operating voltage and Co-free chemistry. However, severe capacity degradation and poor interphase stability have thus far impeded its practical application.

A dry coating process, i.e., casting the cathode without the use of a solvent-based slurry, was demonstrated to enable high-loading electrodes (up to 9.5 mAh/cm^2) having a better long-term cycling than slurry-based electrodes. The performance improvement was explained in terms of diminished parasitic reactions with the electrolyte, a highly distributed and interconnected electronic percolation network, and robust mechanical properties. Electrodes with a loading of 3 mAh/cm^2 showed an average coulombic efficiency of 99.96% after 1000 cycles at a C/3 rate.

The dry electrode coating method is a cost-effective and sustainable manufacturing solution for high-loading LNMO cathodes (up to 9.5 mAh/cm^2) with a long cycle life.

Source: Yao, Chouchane, Li, Bai, Liu, Li, Chen, Sayahpour, Shimizu, Raghavendran, Chen, Tan, Sreenarayanan, Waters, Sichler, Gould, Kountz, Lipomi, Zhang, and Meng

Cathode | Disordered rocksalt | Harnessing anionic redox for high energy density

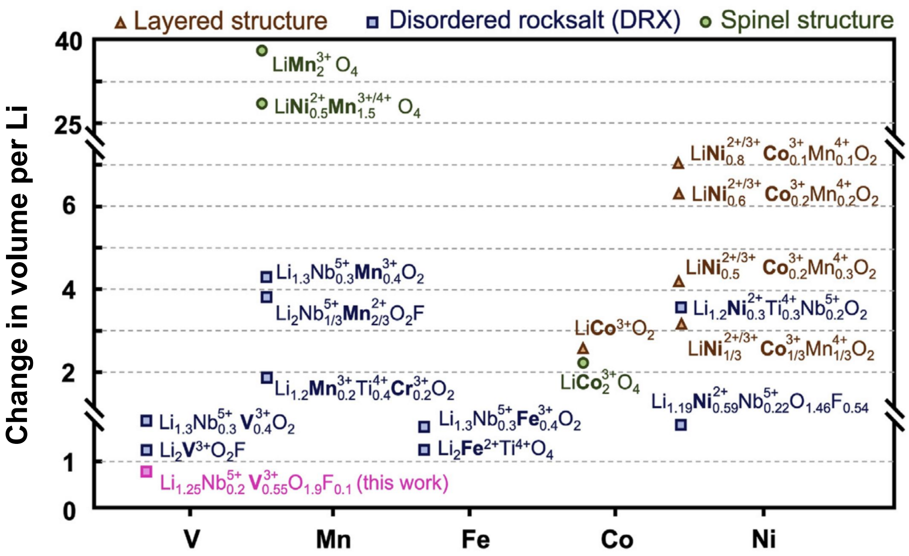
Minimizing volume changes over cycling to limit mechanochemical degradation

Lithium-rich compounds with the disordered rocksalt structure provide percolating pathways for lithium transport. The excess lithium also enables higher capacities than traditional $Li(Ni,Mn,Co)O_2$ layered cathodes. Like nearly all electrode materials, volume changes during lithium insertion and extraction can lead to particle fracture and capacity fading in disordered rocksalts.

Researchers from UC Berkeley discovered a mixed cation and mixed anion composition of the disordered rocksalt structure that has less than 1% volume change over its charge or discharge to 200 mAh/g.

A few months later, an international team found a disordered rocksalt with less than 0.01% volume change.

> Tuning the lithium, metal cation, and anion compositions can lead to zero-strain disordered rocksalt cathodes that are expected to be mechanically stable during cycling.



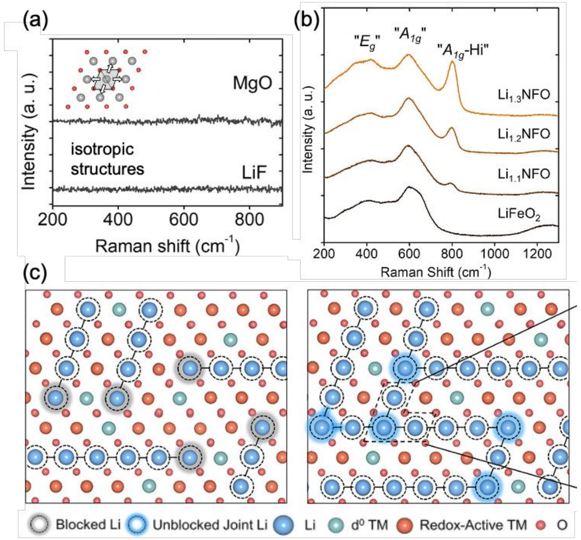
Plot of volume change per unit of lithium inserted or extracted for disordered rocksalt, layered, and spinel cathode materials.

Source: Zhao, Tian, Lun, Cai, Chen, Ouyang, and Ceder; Zhou, Li, Ha, Zhang, Dachraoui, Liu, Zhang, Liu, Liu, Battaglia, Yang, Liu, and Yang

Cathode | Disordered rocksalt | Locally structured domains

"Disordered rocksalt" cathodes are not fully disordered, and the order impacts lithium-ion diffusion

Disordered rocksalt cathodes may have layered domains (like those in LCO) that can facilitate diffusion between disordered domains.



(a) Isotropic disordered structures with no Raman signals. (b) Raman signals from cubic disordered rocksalts. (c) Structure models for DRX with layered domains.

In the idealized model of the disordered rocksalt structure, lithium and transition metal ions randomly occupy every cation site, making it isotropic (i.e., the same in all directions). In Raman spectroscopy, signals are forbidden in a perfectly isotropic cubic structure.

A team from the University of New Mexico and NTNU demonstrated that $Li_{1+x}Nb_xMn_{1-2x}O_2$ and $Li_{1+x}Nb_xFe_{1-2x}O_2$ with XRD peaks corresponding to the disordered rocksalt structure do give several Raman signals. Layered domains within the disordered rocksalt phase can explain their results.

Layered compounds like LCO and NMC with 1:1 Li:transition metal ratios have native lithium diffusion planes between the layers. Disordered rocksalts do not have lithium diffusion pathways unless the Li:transition metal ratio is > 1 (closer to 1.2). Importantly, the authors note that lithium excess compositions are still required for ion transport, even with the presence of layered domains.

Source: Wang, Huang, Raji-Adefila, Outka, Wang, and Chen

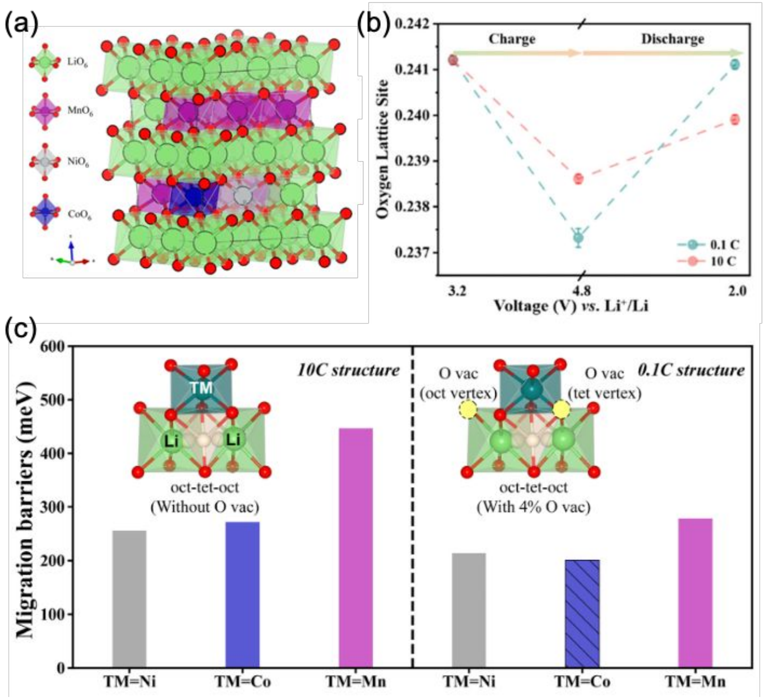
Cathode | Li- and Mn-rich | Harnessing anionic redox for high energy density

Rate affects reaction pathways and redox reactions

Li- and Mn-rich (LMR) layered cathodes are similar to disordered rocksalts in that they contain excess lithium that can be removed, yielding high capacities. However, in LMR cathodes, there are still distinct lithium layers and the excess lithium simply goes onto the transition metal layer.

A recent paper showed different structure evolution mechanisms in LMR as a function of charge/discharge rate. It was suggested that fast charging hinders subsequent lithiation whereas slow charging facilitates lithium diffusion.

Fast charging of Li- and Mn-rich layered cathodes suppresses oxygen vacancies which, surprisingly, increases the lithium migration barriers on subsequent cycling.



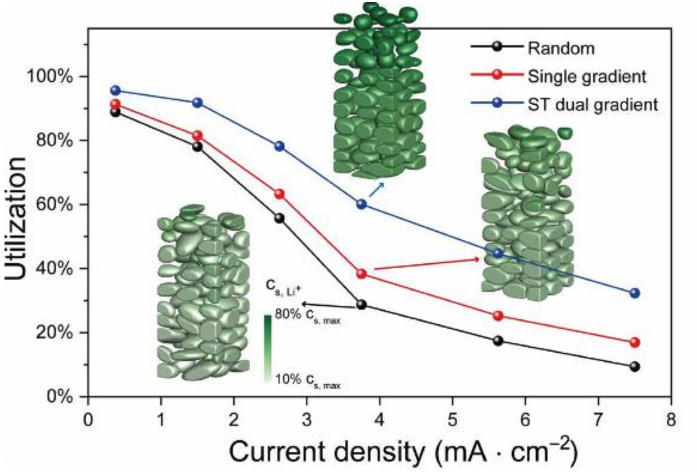
(a) Crystal structure of Li- and Mn-rich layered oxide. (b) Varying oxygen loss and reversibility at 10C vs C/10 rate. (c) Structure models and migration energy barriers for $Li_{1.2}Ni_{0.16}Co_{0.08}Mn_{0.56}O_2$ at 10C and C/10.

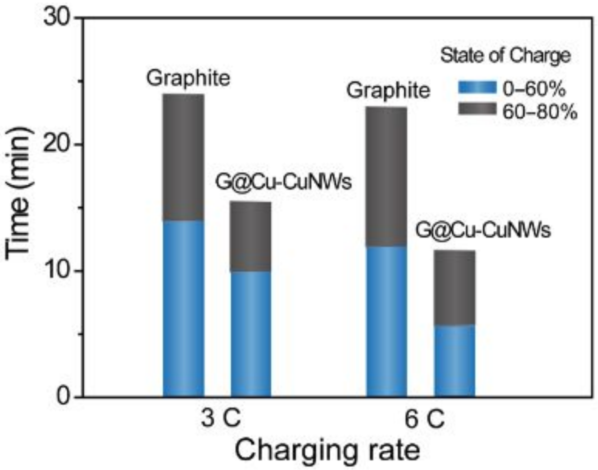
Source: He, Wu, Zhu, Liu, Li, Zhou, Hou, Wang, Zhang, Bresser, Fu, Crafton, McCloskey, Chen, An, Liu, Jain, Li, Yang, Yang, Winter, and Kostecki

Anode | Graphite | Extremely fast charging with dual-gradient structure design

A novel electrode design to overcome the bottleneck of extremely fast-charging lithium-ion batteries

Lithium-ion battery charge rates are limited by the graphite anode. To enable extremely fast charging, researchers proposed a novel electrode design called a dual-gradient structure. With this design, the porosity decreases in the electrode from the separator side to the current collector side, while the particle size increases in the same direction. To achieve this architecture, a polymer binder-free slurry route was developed involving copper-coated graphite (G@Cu) particles and copper nanowires (CuNWs). The G@Cu-CuNWs battery reached 60% recharge in 6 min and a high volumetric energy density of 701 Wh/l at the high charging rate of 6 C.





Graphite anodes with a dual-gradient structure outperformed traditional homogeneous electrodes in extremely fast charging conditions.

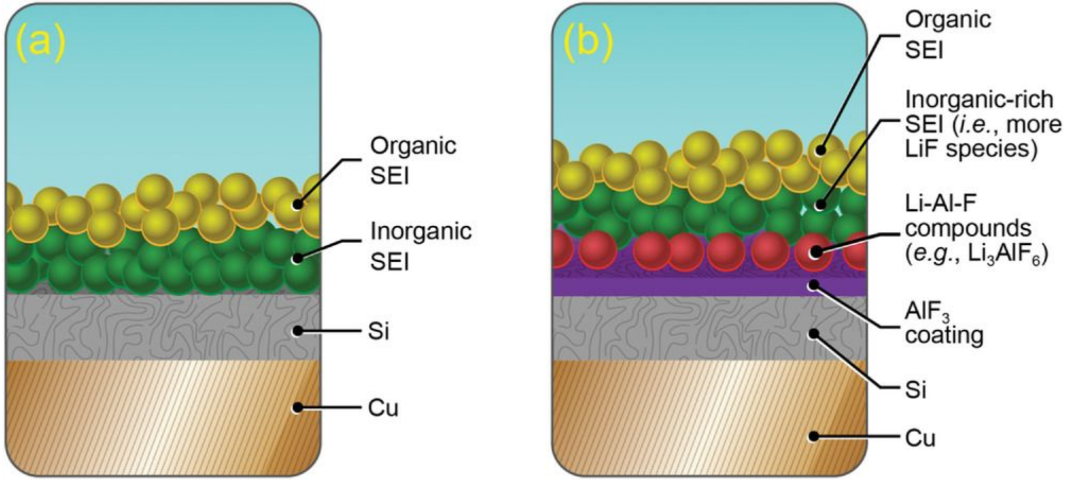
Source: Lu, Lu, Zhu, Shao, Yao, Wang, Zhang, Ni, Wang, and Yu

Anode | Silicon | Artificial SEIs to help the stability of silicon anodes

On route for the adoption of high energy density silicon anodes

While silicon is a promising anode technology for high energy density batteries, there are significant challenges with solid–electrolyte interphase formation.

Research at the University of Münster demonstrated thin 5–20 nm AlF_3 coatings on silicon thin films can provide protection at the interface by improving the composition of the SEI to promote Li-Al-F compounds which support Li^+ ionic conductivity and enhance charge transfer kinetics.



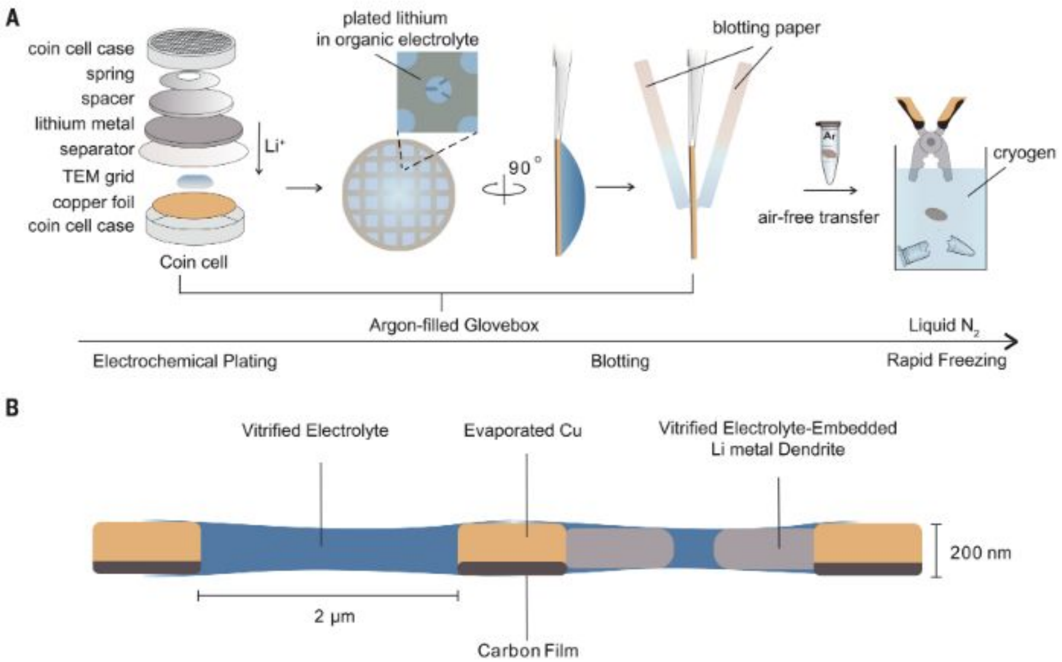
Schematic illustrations of the SEI on a) uncoated Si and b) AlF_3-coated Si electrodes. In coated Si electrodes, the SEI formation mechanism involves the transformation of AlF_3 to Li-Al-F compounds (e.g., Li_3AlF_6).

AlF_3 coatings can help extend lifetime and performance of silicon anode materials

Source: Adhitama, Wickeren, Neuhaus, Frankenstein, Demelash, Javed, Haneke, Nowak, Winter, Gomez-Martin, and Placke

Anode | SEI | Capturing the swelling of SEI in lithium metal batteries

SEI swelling analysis enabled by modified cryo-microscopy and spectroscopy



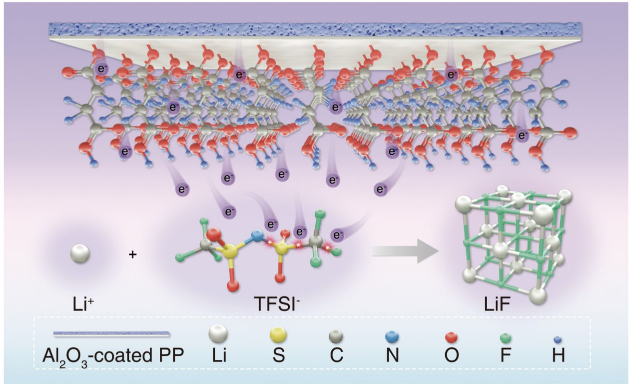
Imaging of the solid–electrolyte interphase (SEI) at the nanoscale is critical and challenging. Researchers from Stanford University used a thin-film vitrification method to preserve the SEI of lithium metal at native states and enable high-resolution imaging during operation. They applied cryo-electron microscopy and spectroscopy to quantitatively measure SEI content and investigate swelling behavior in electrolyte. They revealed that the SEI is in a swollen state and the influence of swelling on Li-ion transport.

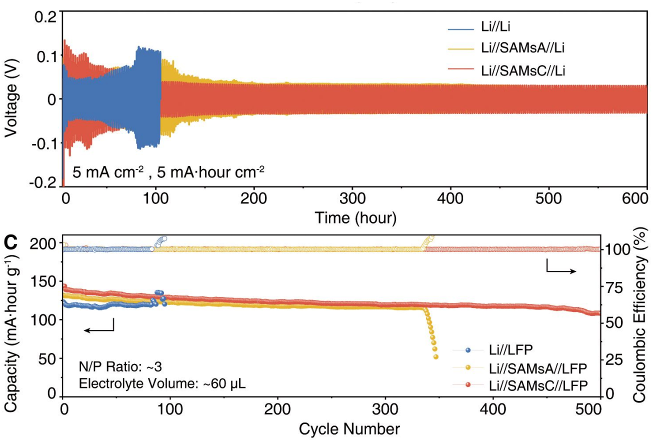
A new method to provide nanometer-resolution SEI images and investigate the SEI swelling behavior.

Source: Zhang, Li, Xu, Zhou, Li, Oyakhire, Wu, Xu, Wang, Yu, Boyle, Huang, Ye, Chen, Wan, Bao, Chiu, and Cui

Anode | Li metal | Self-assembled monolayers

Self-assembled monolayers towards lithium metal batteries with ultralong life spans





Researchers from Nanyang Technological University and Zhejiang University of Technology improve the cycling stability of Li metal batteries by using self-assembled monolayers (SAMs). The SAMs containing polar carboxylic groups are deposited on the aluminum oxide–coated polypropylene separator. SAMs enhance the formation of an LiF-rich solid electrolyte interphase (SEI), thereby promoting lithium-ion diffusion and mitigating lithium dendrite growth.

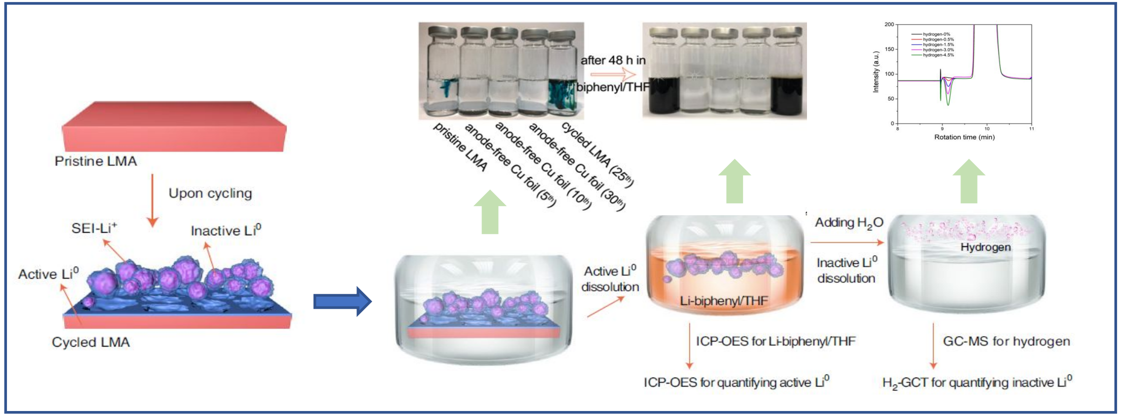
Self-assembled monolayers (SAMs) containing carboxylic groups deposited on an aluminum oxide-coated polypropylene separator promote the formation of LiF-enriched solid–electrolyte interphase (SEI).

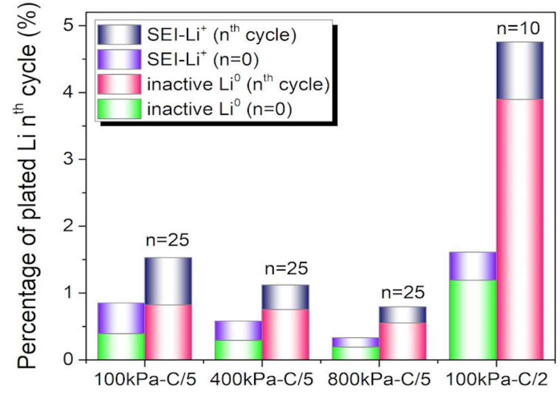
Source: Liu, Tao, Wang, Jiang, Ma, Sheng, Lu, and Lou

Anode | Li metal | Quantification of reversible and irreversible Li

Assessing lithium loss in lithium-metal batteries

Researchers from UChicago and NIMTE report a novel methodology to differentiate and quantify active vs. inactive Li in a cycled Li metal anode to evaluate the reversibility of lithium-metal batteries. The study evaluated the impact of pressure and current density on the reversibility of Li plating and stripping, and the results suggest that high stack pressure suppresses inherent Li loss by minimizing cracking of the SEI. Agglomeration of “dead Li” occurs at high current densities.



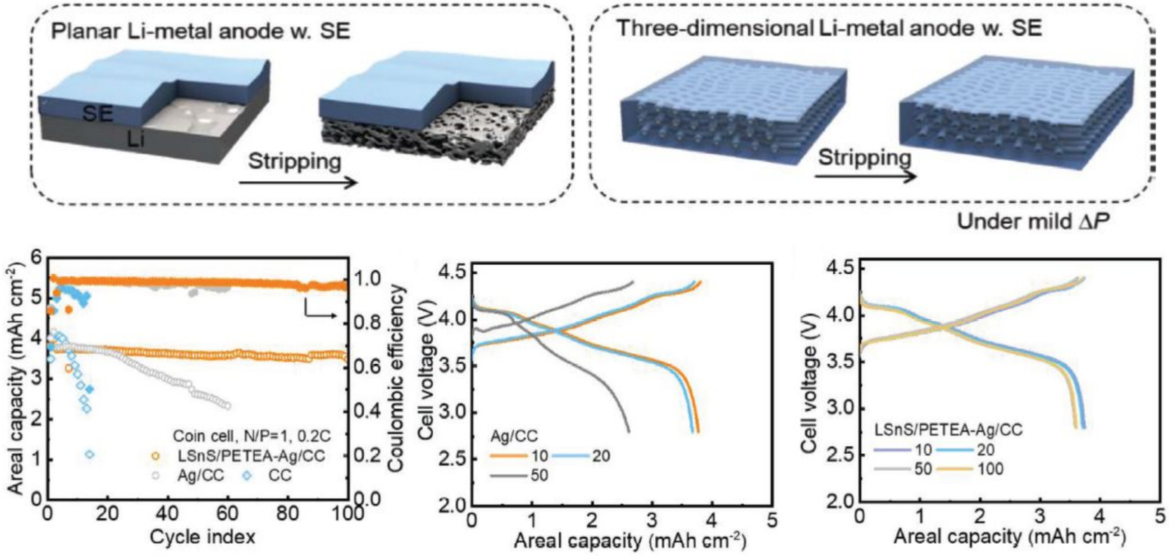


Excess lithium in most lithium metal batteries hinders the accurate diagnosis of the lithium inventory state-of-health. This paper reports a methodology to assess the degradation mechanism(s) and cycle life of lithium metal batteries.

Source: [Deng, Yin, Bao, Zhou, Hu, He, Qiu, Meng, and Liu]

Anode | Li metal | A composite electrolyte-protected 3D Li-metal anode

A 3D scaffold to host lithium metal at low stack pressure



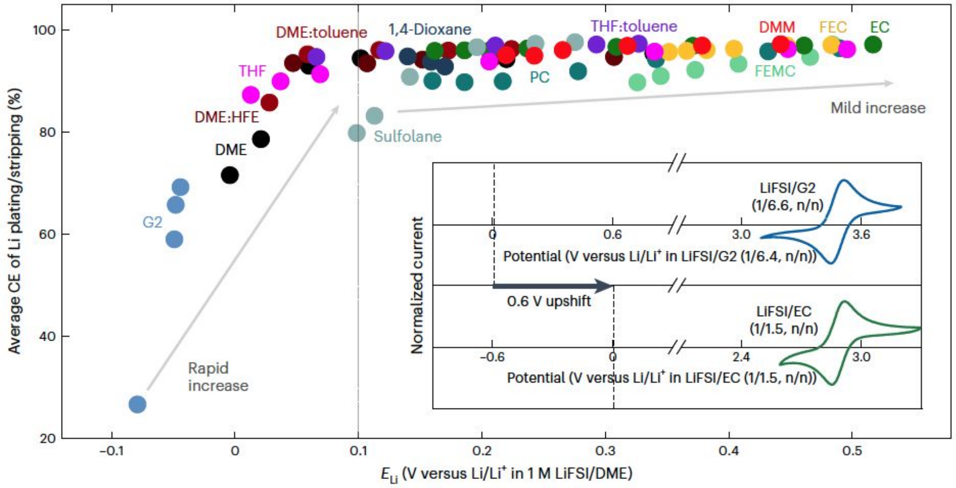
An inorganic solid electrolyte can offer high energy density, reversibility, and safety when paired with lithium metal. However, the poor interfacial contact requires high stack pressure. Researchers at UT Austin developed a three-dimensional hollow silver/carbon scaffold Li metal anode. The scaffold Li metal anode operated with a reasonable stack pressure, as low as 320 kPa, and achieved capacity retention of 90.5% after 100 cycles.

The composite electrolyte formed a kinetically stable interface with Li metal. The silver/carbon scaffold reduces the local current density and preserved an intimate content with the composite electrolyte.

Source: Ren, Shin, and Manthiram

Anode | Li metal | Electrode potential influences on Coulombic Efficiency

Positive correlation between Coulombic Efficiency and Li electrode potential



Electrolyte properties directly affect the electrode potential of Li metal, which impacts Coulombic Efficiency. High E_{Li} suppresses electrolyte decomposition and yields high plating/stripping efficiency for Li-metal batteries.

The coulombic efficiency of Li plating and stripping is largely influenced by the thermodynamic electrode potential of Li metal (E_{Li}). Increasing the E_{Li} reflects a decrease in Li metal's propensity towards reduction, which can minimize the reductive decomposition of the electrolyte and thus enhance coulombic efficiency. The trends identified in this work are consistent with coulombic efficiencies reported for other state-of-the-art electrolytes for Li-metal batteries (weakly solvating electrolytes, concentrated electrolytes, and locally concentrated electrolytes).

Source: Ko, Obukata, Shimada, Takenaka, Nakayama, Yamada, and Yamada

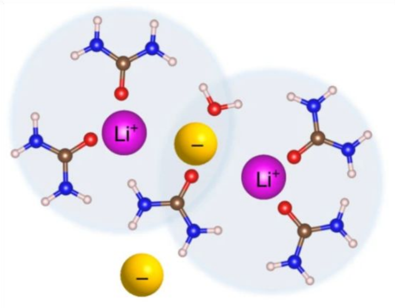
Electrolyte | Aqueous | Long-lifetime water-based electrolytes

High-concentration salt for a 2.5 V LMO//LTO aqueous battery

High-concentration electrolytes contain enough salt to bind essentially every water molecule and minimize degradation reactions between electrode surfaces and free water.

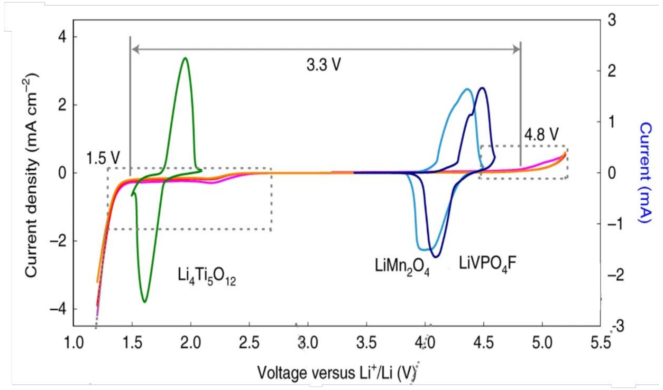
Taking this a step further, researchers from the University of Maryland concocted a water-based lithium-ion electrolyte with LiTFSI salt, potassium hydroxide, and urea. This ternary mixture with an intermediate salt content is even more stable than ultra-concentrated electrolytes owing to strong water–urea interactions. Potassium hydroxide assists the formation of a stable LiF-rich SEI.

$Li_{1.5}Mn_2O_4//Li_4Ti_5O_{12}$ pouch cells with the new electrolyte can cycle for 500 cycles with >90% capacity retention



$Li(CO(NH_2)_2)_{2.5}(H_2O)_{0.7}(TFSI)_{0.8}$

High salt concentrations are not the only way to stabilize aqueous electrolytes. Additives that interact strongly with water can be even more effective at suppressing side reactions.



Electrochemical activity of LTO (green), LMO (light blue), LVPF (dark blue), and 4.1–5.1 m LiTFSI ternary electrolytes.

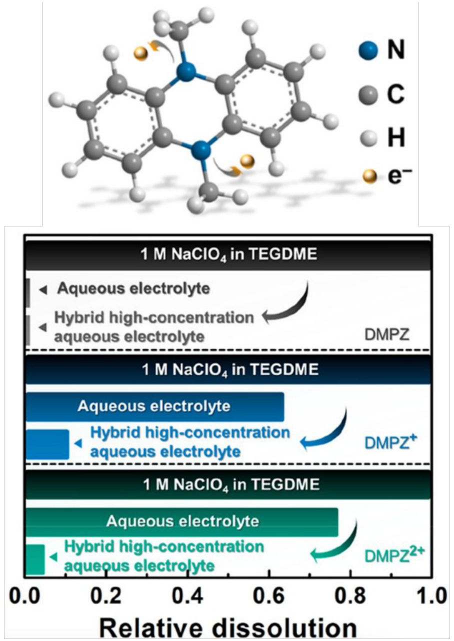
Source: Xu, Ji, Zhang, Yang, Wang, Liu, Ludwig, Chen, Kofinas, and Wang

Electrolyte | Aqueous | Suppressing dissolution of organic electrodes

High-capacity organic electrodes can be stabilized with advanced aqueous electrolytes

An organic molecule called 5,10-dihydro-5,10-dimethylphenazine (DMPZ) can reversibly store two electrons at its two nitrogen centers, reaching over 225 mAh/g. However, it suffers from severe dissolution issues in its various oxidation states when the electrolyte is 1 M $NaClO_4$ in tetraglyme (TEGDME) or water.

Researchers from Seoul National University leveraged a hybrid high-concentration aqueous electrolyte with 17 m $NaClO_4$ and 0.5 m $Zn(CF_3SO_3)_2$ salts that effectively suppresses DMPZ dissolution by 90–95% vs. tetraglyme. This hybrid electrolyte had been previously developed by a different group to reversibly deposit zinc metal without dendrites. In the new work, the electrolyte allowed DMPZ cathode to cycle against a zinc metal anode for 1000 cycles at C/5 or 1C rates with about 200 mAh/g capacity and 80% capacity retention.



Molecular structure of 5,10-dihydro-5,10-dimethylphenazine (DMPZ) and its relative solubility in the neutral, +1, and +2 oxidation states in different electrolytes.

Designer aqueous electrolytes may alleviate compatibility issues for organic redox-active molecules that tend to dissolve in organic electrolytes.

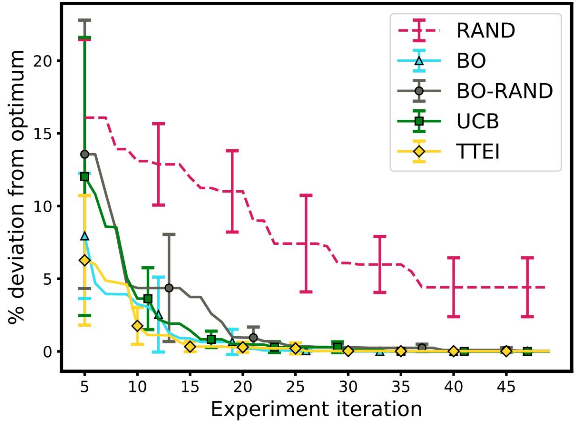
Source: Lee, Kwon, Lim, Kim, Kim, Lee, Kim, Eum, Song, Park, Seong, Jung, and Kang

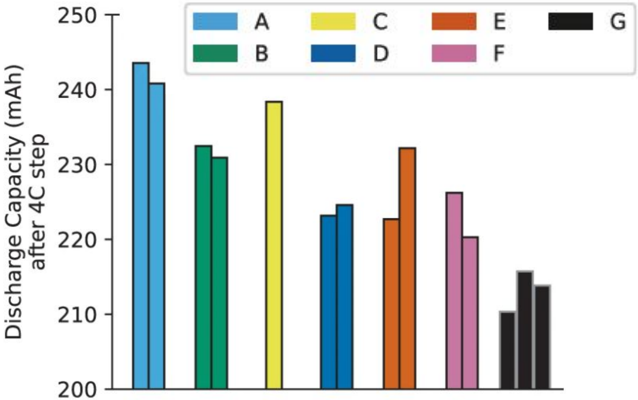
Electrolyte | Non-aqueous | Autonomous optimization

Use of robotic experimentation and machine learning to accelerate search for better electrolytes

Liquid electrolytes are particularly challenging to optimize because there are many choices for solvent and salt, and optimized compositions often contain more than three or four species. Researchers from Carnegie Mellon University developed a robotic platform capable of autonomously performing a closed-loop optimization of non-aqueous electrolyte solutions. A system of ternary solvents with a single salt was chosen with the objective of optimizing the electrolyte conductivity for fast-charging applications. With the use of various Bayesian optimization strategies (BO, BO-RAND, UCB, TTEI) the researchers reached a six-fold time acceleration compared to a random search (RAND) performed by the same automated experiment. The electrolytes developed by the robotic platform (A-F) were tested in pouch cells, demonstrating improved fast-charging capability against a baseline experiment (G).

Battery innovation is hindered by the time-consuming and laborious electrolyte optimization process. A combination of robotics and machine learning can accelerate the development of novel electrolyte compositions.



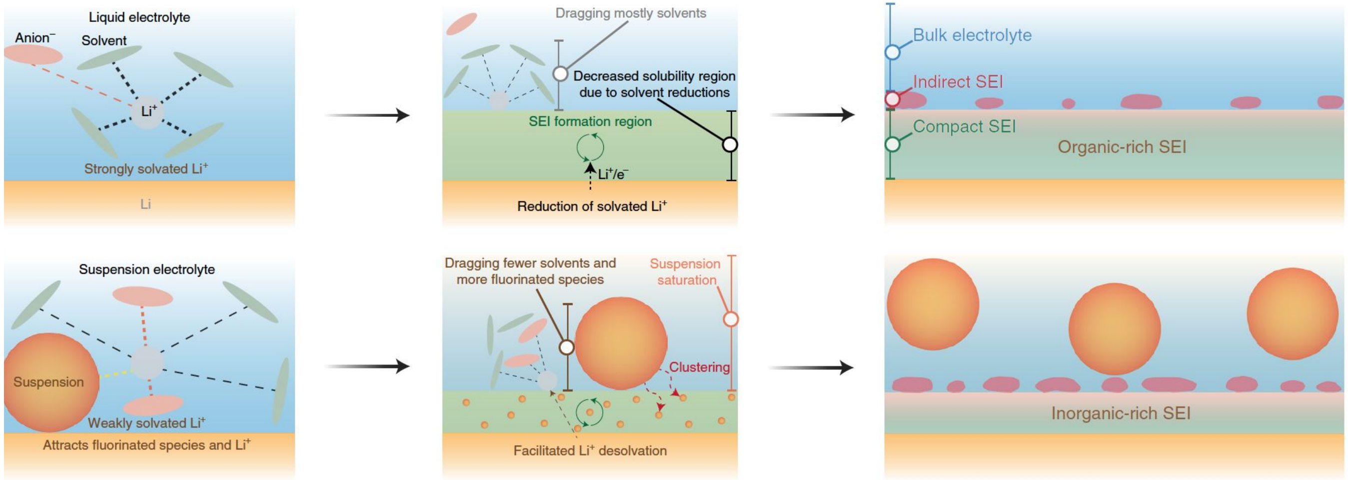


Source: Dave, Mitchell, Burke, Lin, Whitacre, and Viswanathan

Electrolyte | Lithium metal | Suspension electrolyte

Designing a stable solid–electrolyte interphase (SEI) with nanoparticles suspended in liquid electrolytes

A stable SEI is fundamental for long-lasting and safe lithium metal batteries with liquid electrolytes. Researchers at Stanford were able to form a stable inorganic-rich SEI via electrolytes containing a suspension of inorganic Li_2O nanoparticles in standard non-aqueous electrolyte formulations. Li_2O nanoparticles suspended in three liquid reference electrolytes were investigated as a proof of concept. The addition of Li_2O improved coulombic efficiency, lowered the Li nucleation overpotential, and stabilized the Li-ion conductivity of the interphase region.

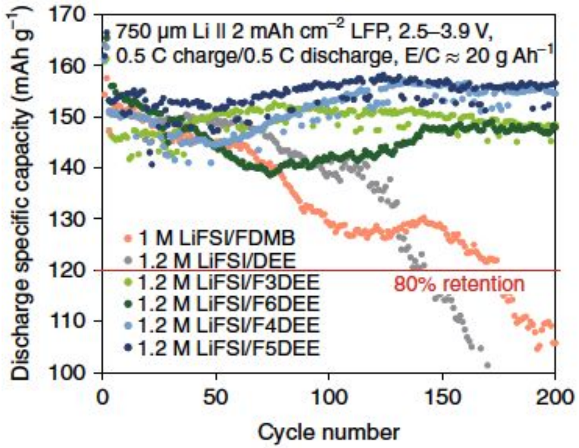


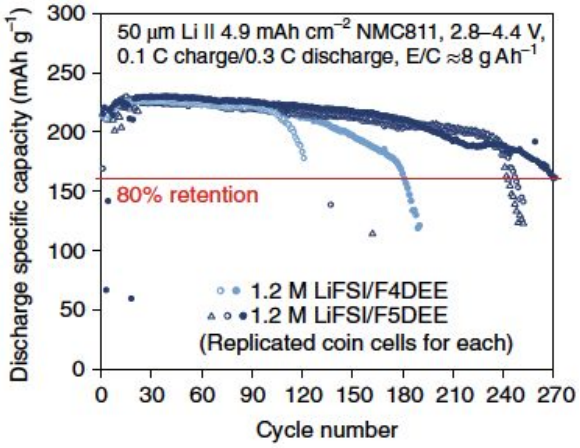
Adding inorganic nanoparticles to liquid electrolytes can help form a stable SEI, resulting in longer-lasting and safer lithium metal batteries.

Source: Kim, Zhang, Rudnicki, Yu, Wang, Wang, Oyakhire, Chen, Kim, Zhang, Boyle, Kong, Xu, Huang, Huang, Bent, Wang, Qin, Bao, and Cui

Electrolyte | Lithium metal | Tuning solvent

Increasing coulombic efficiency by tuning solvent molecular design





Fluoroether electrolytes can stabilize Li metal batteries. The position and number of F atoms functionalized on 1,2-diethoxyethane (DEE) strongly affect electrolyte performance.

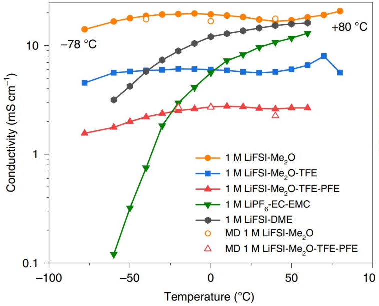
The authors concluded that the $–CHF_2$ group, rather than the commonly assumed $–CF_3$ group, is optimal for electrolytes with high ionic conductivity, low and stable overpotential, and long cycle life in Li // NMC811 and Li // LFP cells.

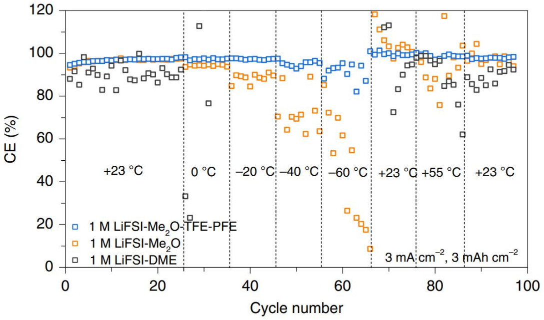
Balance between fast ion conduction and electrode stability must be achieved through molecular design and chemical synthesis.

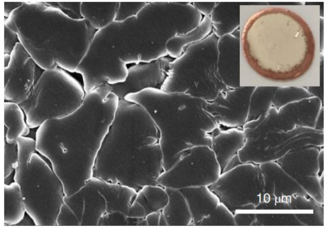
Source: Yu, Rudnicki, Zhang, Huang, Celik, Oyakhire, Chen, Kong, Kim, Xiao, Wang, Zheng, Kamat, Kim, Bent, Qin, Cui, and Bao

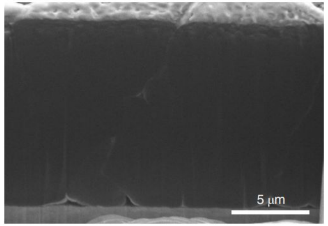
Electrolyte | Lithium metal | Liquified-gas electrolyte

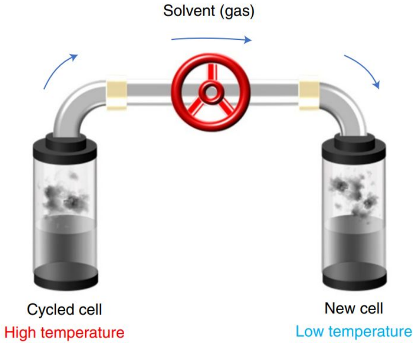
Simultaneously achieving high-energy density, improved safety, temperature resilience and sustainability











Schematic of the practical process of liquefied-gas solvent collection and recycling

Although non-flammable solvents for Li metal batteries exist, their long-term electrochemical stability is often problematic, caused mainly by their instability with Li metal.

Researchers found inherently safe liquefied-gas electrolytes based on 1,1,1,2-tetrafluoroethane and pentafluoroethane (fire-suppressing agents) that maintain more than 3 mS cm^{-1} ionic conductivity from −78 to +80 °C. Symmetric Li//Li cells were cycled above 99% coulombic efficiency for over 200 cycles at 3 mA cm^{-2} and 3 mAh cm^{-2}, in addition to stable cycling of Li//NMC622 batteries, from −60 to +55°C.

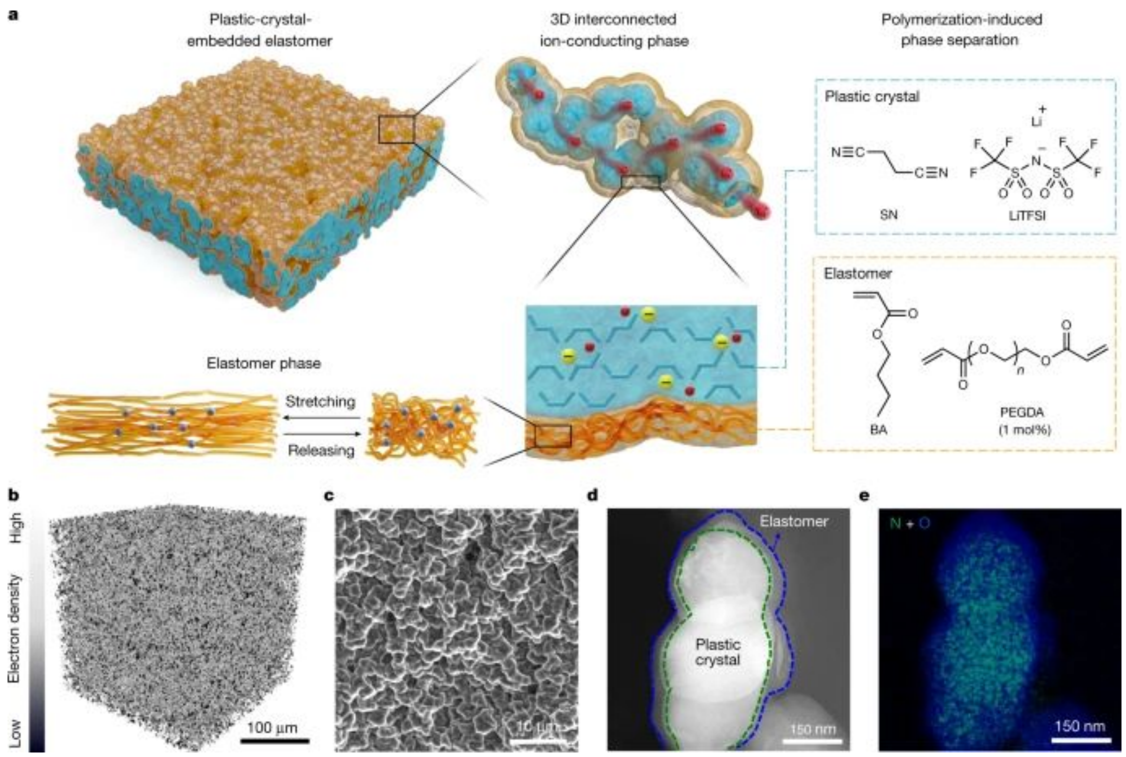
Moreover, an effective one-step solvent recycling process based on the vapour pressure difference at different temperatures of the electrolytes is promising for sustainability at manufacturing scales.

A novel electrolyte paves the way for sustainable, temperature-resilient Li metal batteries operating over a very wide temperature range (−60 to +55 °C).

Source: Yin, Yang, Cheng, Mayer, Holoubek, Li, Raghavendran, Liu, Lu, Davies, Chen, Borodin, and Meng

Solid State | Electrolyte | Elastomeric polymer electrolytes

A new class of polymer solid electrolytes promote high-energy solid-state lithium batteries



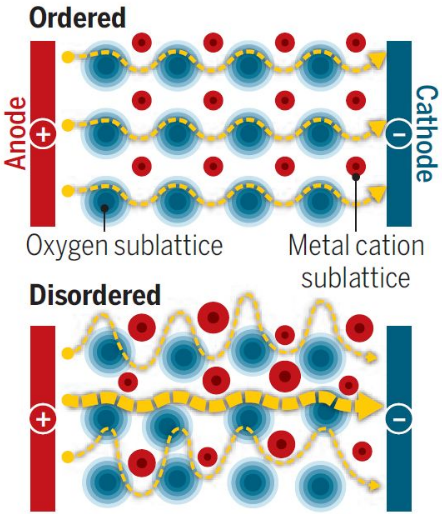
Researchers from the Georgia Institute of Technology and Korea Advanced Institute of Science & Technology designed a new class of elastomeric electrolytes which have a 3D interconnected plastic-crystal phase within the elastomer matrix. The elastomeric electrolytes have high ionic conductivity and mechanical robustness, enabling stable operation of full cells under constrained conditions of a limited Li source, a thin electrolyte, and a high-loading Ni-rich cathode, delivering a high specific energy exceeding 410 Wh kg^{-1} at the electrode stack level (anode + electrolyte + cathode).

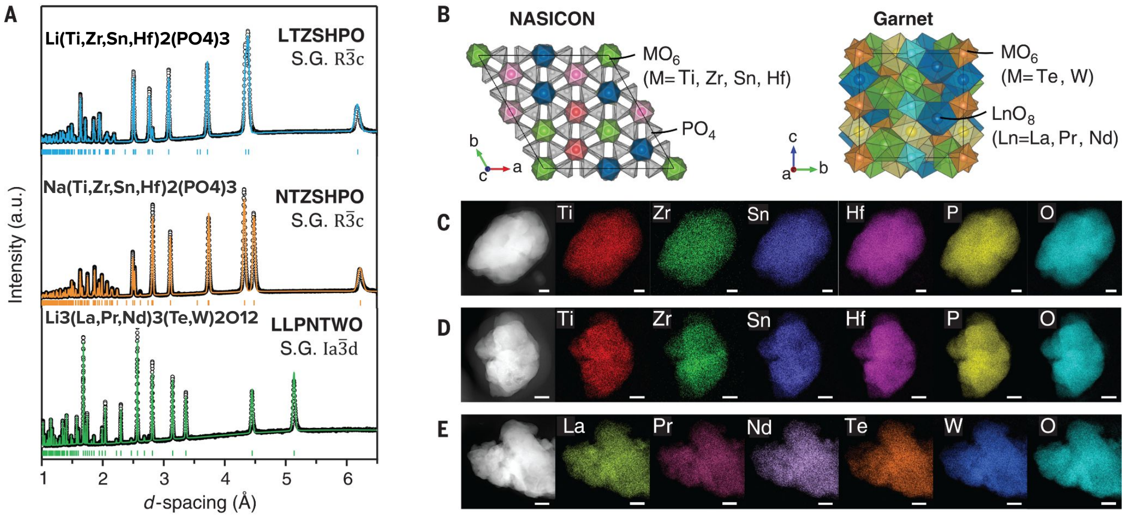
Elastomeric electrolytes, having a high ionic conductivity while maintaining mechanical robustness, enable high-energy solid-state Li metal batteries.

Source: Lee, Han, Lee, Lee, Kim, Jung, Kim, and Lee

Solid State | Electrolyte | High-entropy oxide solid electrolyte

High entropy enhances ionic conductivity in inorganic oxide solid electrolytes





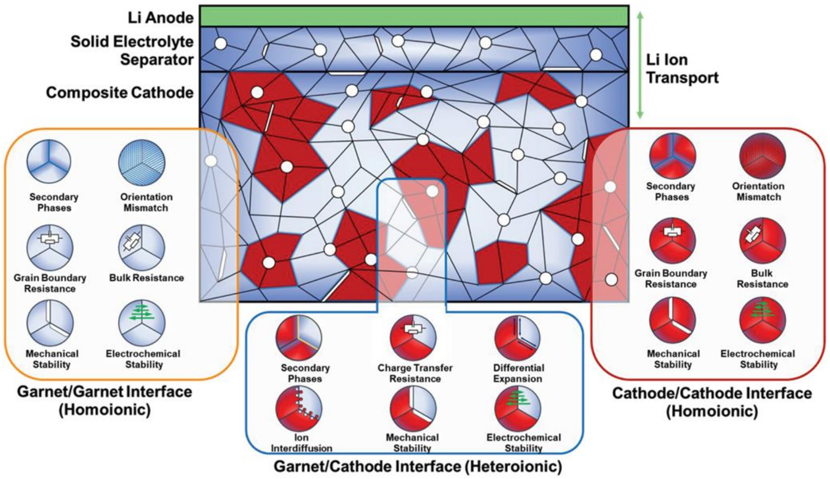
Researchers from Lawrence Berkeley National Laboratory and Florida State University developed a high-entropy lithium and sodium solid electrolytes with superionic conductivity for solid-state lithium/sodium-based batteries. High-entropy metal cation mixing in the solid electrolytes induces disorder, enabling an overlapping distribution of site energies, and reducing the activation energy of lithium diffusion, thereby promoting ionic conductivity by orders of magnitude.

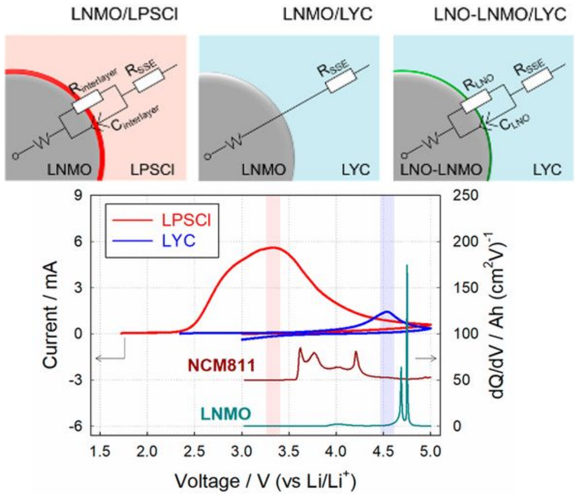
A new strategy to enhance superionic conducting structural frameworks for solid-state lithium and sodium batteries

Source: Zeng, Ouyang, Liu, Byeon, Cai, Miara, Wang, and Ceder; Botros and Janek

Solid State | Cathode and Cathode/Solid Electrolyte Interface

Chemical stability of interface, multiple impedances and lattice mismatch needs to be addressed





The cathode and cathode–solid electrolyte interface are major roadblocks in solid-state battery development. Challenges include volume changes, mechanical degradation, and impedances from grain boundaries, reaction products, and multiple interfaces.

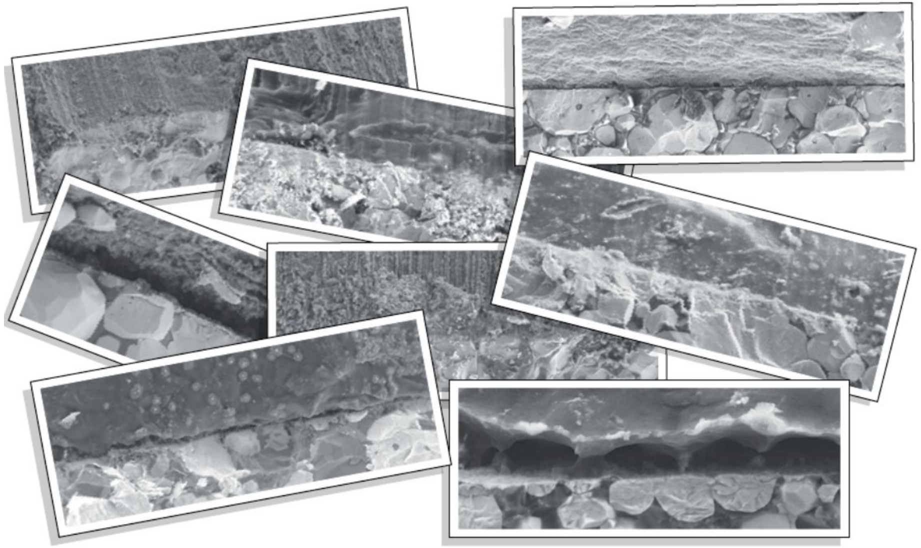
UC San Diego researchers demonstrated that LNMO has intrinsic chemical compatibility with argyrodite solid electrolytes, which minimizes cell impedance and increases stability.

A chemically and mechanically compatible cathode/solid electrolyte pair is a key to solid-state battery development

Source: Jang, Chen, Deysher, Cheng, et al; Ren, Danner, Moy, et al.

Li metal | Solid State | Influence of interlayers on interfaces

A metal interlayer can homogenize the Li/solid electrolyte interface and suppress dendrite growth



Voids are expected to form at the electrode–electrolyte interface owing to the accumulation of Li vacancies during Li dissolution. Interlayer design which minimizes the void formation will also improve the cell performance

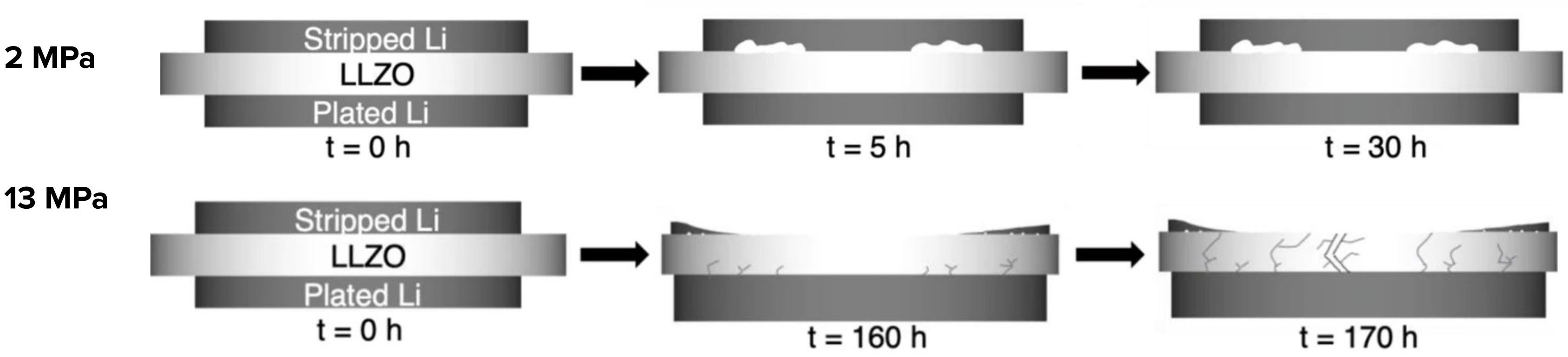
Researchers from Indian Institute of Science and Carnegie Mellon have suggested that voids at Li/SE interface precedes dendrite growth. The researchers propose using a very thin refractory metal between the anode and the solid electrolyte to enhance the rate capability of the battery while suppressing dendritic growth. Using this nanoscopic interfacial layer, they demonstrate an increase in charge–discharge rates by 2.5x compared to a cell with conventional Li-alloying Al interfacial layer.

Furthermore, their theoretical calculations show that Al favors the formation of voids, whereas W, which has a low solubility for Li, does not. Hence, interface engineering can have a much stronger influence on dendrite formation than the bulk properties of the solid-state electrolyte.

Source: Raj, Venturi, Kankanallu, Kuiri, Vishwanathan, and Aetukuri; Pacchioni

Li metal | Solid State | Influence of pressure on interfaces

High stack pressure homogenizes the Li/SE interface but also accelerates dendrite growth



Researchers from Columbia University investigated the role of stack pressure on the interface Li//LLZO*//Li interfaces using a synchronized operando setup that can probe both the microstructure and mechanics of a buried interface during cycling. They found that a stack pressure of 2 MPa or less is unable to maintain interfacial homogeneity over cycling. At a high stack pressure of 13 MPa, interfacial homogeneity is maintained, but high pressure also accelerates dendrite growth. This happens because of the increase in local hydrostatic stress which leads to solid electrolyte fracture and Li metal penetration. Such high pressures are likely impractical for commercial battery development.

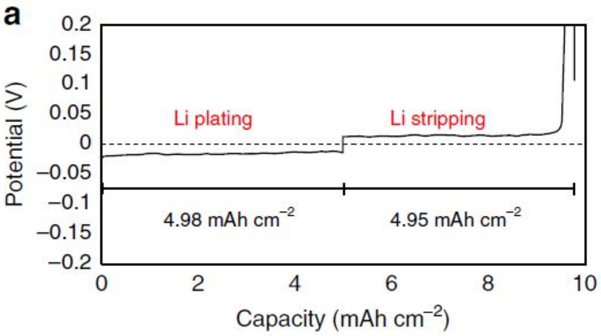
High stack pressures are neither beneficial nor practical for solid state battery development. Strategies are needed to homogenize the interface at lower stack pressure.

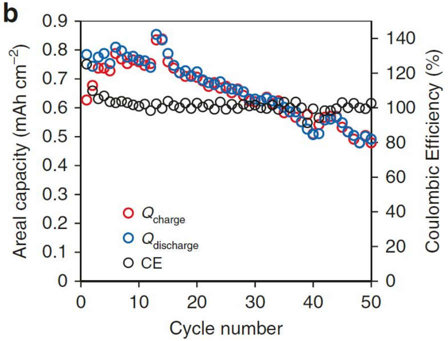
*lithium lanthanum zirconium oxide

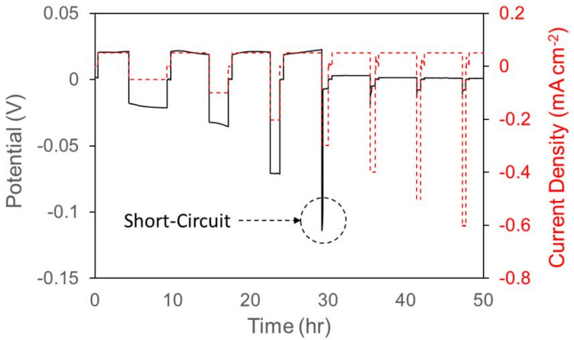
Source: Chang, May, Wang, Thorsteinsson, Sakamoto, Marbella, and Steingart

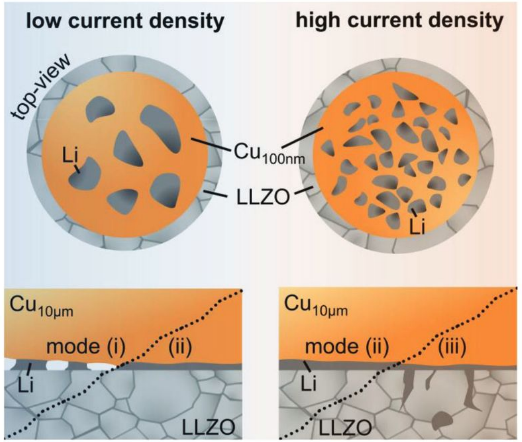
Li metal | Solid State | Anode-free Approach

Mechanical properties of current collector aids in minimizing dendrites in anode free SSB









In late 2020, researchers from University of Michigan investigated the feasibility of an anode-free SSB architecture with Li coming solely from the cathode. They successfully demonstrated a high coulombic efficiency for Li stripping (>99.9%). However, the operating current densities were relatively low and the cells were prone to dendrite growth.

A 2022 study by researchers at Justus-Liebig-University Giessen investigated this issue of dendrite growth at such low current densities. They hypothesize that one of the prime culprits is heterogenous plating of Li metal during the first charge. Their work suggests that using a thicker current collector and an optimised plating current density helps in homogenizing lithium plating by decreasing the probability of Li whisker penetration through the current collector and solid electrolyte.

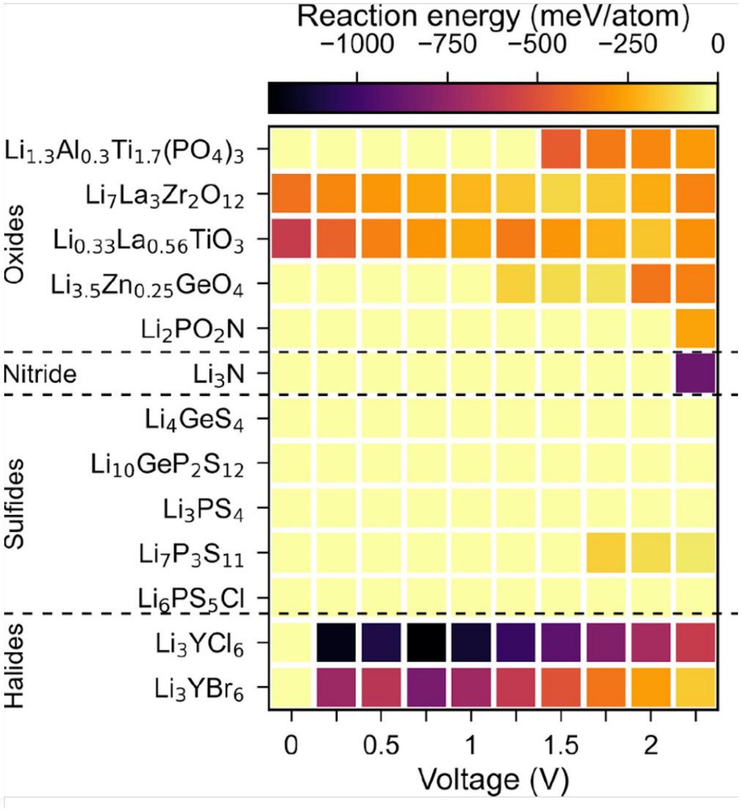
An optimal current collector thickness and Li plating protocol can help prevent dendrite formation in anode-free solid-state batteries

Source: Fuchs, ecker, Haslam, Lerch, Sakamoto, Richter, and Janek; Wang, Carmona, Gupta, Albertus, and Sakamoto

Sulfur | Interface kinetics and thermodynamics

Cathode–solid electrolyte interface stability in Li-S chemistries

Researchers from the University of California, San Diego simulated the thermodynamics and kinetics of the cathode–electrolyte interface for a variety of electrode buffer layers and solid electrolytes against charged sulfur and discharged Li_2S cathodes. Sulfide solid electrolytes were found to be the most thermodynamically stable against S_8 cathodes and served as highly effective buffer layers for Li-sulfur chemistries. The team used density functional theory, nanosecond-scale ab initio molecular dynamics, and machine learning with passive and active learning.



Calculations predict that sulfide solid electrolytes are the most stable against sulfur cathodes, but other solid electrolytes (e.g. oxides, halides) can benefit from the binary and ternary in situ reaction products that serve as buffer layers.

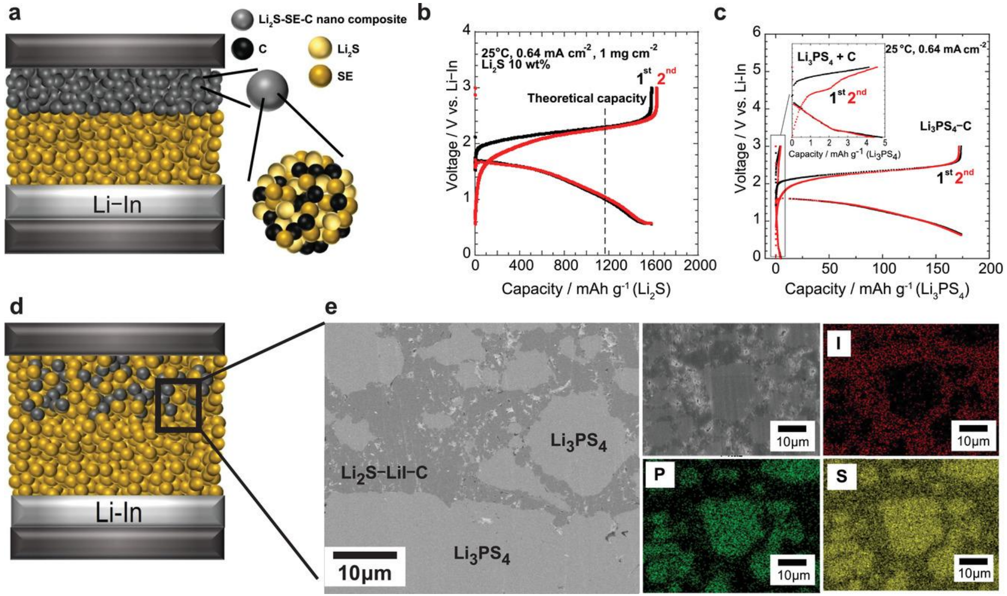
Source: Chandrappa, Qi, Chen, Banerjee, and Ong

Sulfur | High capacity Li-S electrodes

Enhancing the solid electrolyte oxidation stability

All-solid-state Li-S batteries have the prospect of offering high energy, power, and better safety compared to cells with liquid electrolyte. However, high interfacial resistance and lower than predicted energy densities has stalled research.

Researchers from Osaka Prefecture University have demonstrated the use of solid electrolytes with high critical oxidation stability to increase the capacity of Li-sulfur cells yielding high-capacity (500 Wh kg^{-1}) cells.



Solid electrolytes with high critical oxidation stability are compatible with Li_2S-based positive electrodes for high-energy cells

Solid state battery characterisation containing a common composite positive electrode comprising (b) Li_2S, C, and solid electrolyte and (c) with an Li_2S content of 10 wt% ; (e) Scanning electron microscopy (SEM) images and energy-dispersive X-ray spectroscopy (EDX) mappings of the positive electrode

Source: Hakari, Fujita, Deguchi, Kawasaki, Otoyama, Yoneda, Sakuda, Tatsumisago, and Hayashi

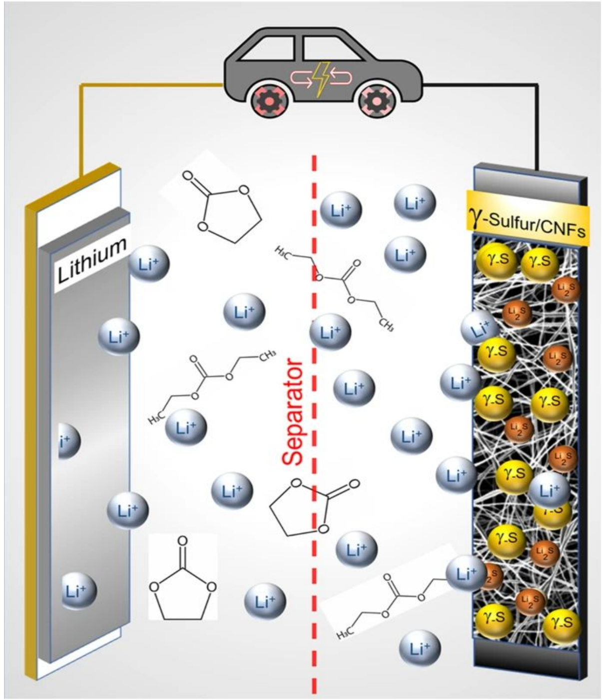
Sulfur | Gamma-sulfur Li-sulfur batteries

Addressing the problems with Li-S polysulfide shuttling

Carbonate-based electrolytes tend to have reactions with polysulfides which limit the cycling ability of Li-S batteries. This process is called the polysulfide shuttle effect and involves the dissolution of intermediate lithium polysulfide species in the electrolyte and is one of the main reasons for low cycling in Li-S batteries.

Research from Drexel University demonstrated redox mechanism from γ-monoclinic sulfur to Li_2S without and sulfide intermediates (Li_2S_8, Li_2S_6, etc.), enabling cycling stability. Researchers synthesized the material via deposition of this sulfur phase on carbon nanofibers.

Overcoming the challenges of the polysulfide shuttle effect in Li-S batteries may open the door for commercially viable Li-S chemistry



Gamma-monoclinic sulfur is deposited on the external surface of carbon nanofibers. Yellow balls signify surface-deposited monoclinic gamma-sulfur and red-orange balls indicate lithium sulfide, the product formed after the reduction of sulfur. Grey spheres are Li ions.

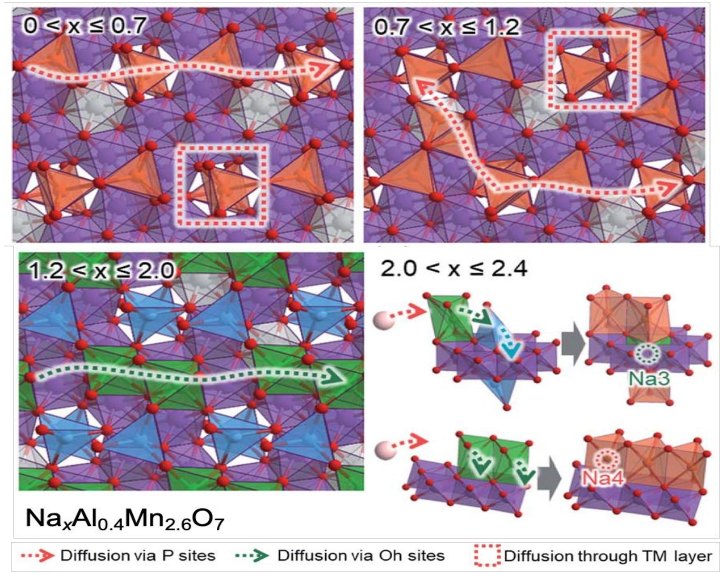
Source: Pai, Singh, Tang, and Kalra

Sodium aluminum manganese oxide cathodes with oxygen-redox activity

Sodium-ion batteries avoid looming constraints in the lithium supply chain. They are unlikely to match lithium-ion energy density but put more emphasis on cost and sustainability, so earth-abundant materials are critical.

Researchers from Lancaster, UCL, and Diamond Light Source showed that the Na-rich compound $Na_{2.4}Al_{0.6}Mn_{2.6}O_7$ (derived from $Na_2Mn_3O_7$) can cycle over 200 mAh/g at an average voltage of 3.0 V.

$Na_{2.4}Al_{0.6}Mn_{2.6}O_7$ is a transition-metal-deficient layered compound and its high capacity is attributed to a combination of manganese and oxygen redox activity.



Al-doping of $Na_2Mn_3O_7$ unlocks Mn redox and more O redox, yielding a high-capacity Na-ion cathode

Source: Soares, Silván, Choi, Celorrio, Seymour, Cibin, Griffin, Scanlon, and Tapia-Ruiz

Sodium | Benchmark commercial progress | Prussian blue analogues

Power electronics company ABB evaluated Prussian-blue-based pouch cells from Natron Energy

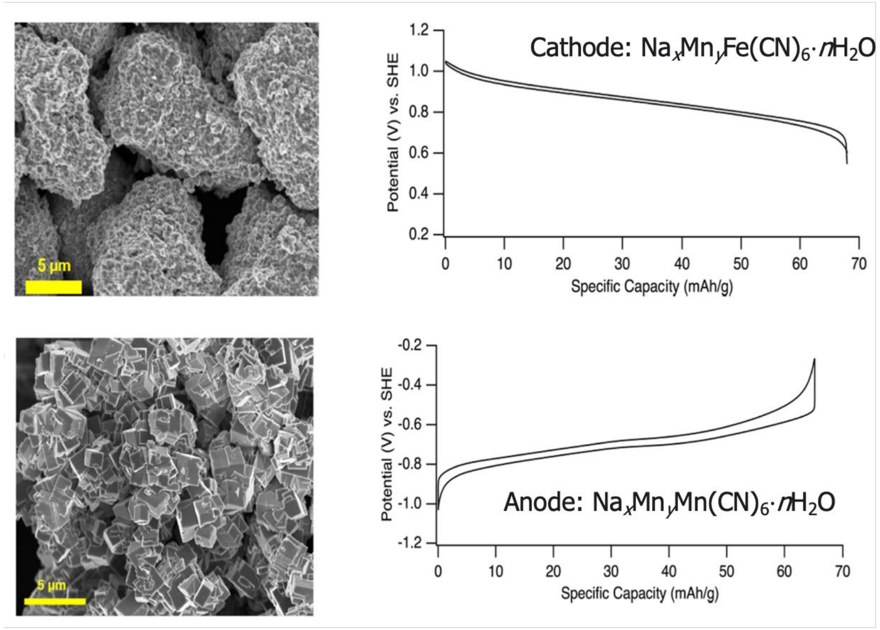
Published data on commercial-format cells provide context for academic research and industrial targets. The electrode characteristics include:

Cathode: $Na_xMn_yFe(CN)_6 \cdot nH_2O$ with 10–20 µm secondary particles comprising 200–500 nm primary particles

Anode: $Na_xMn_yMn(CN)_6 \cdot nH_2O$ in 2–3 µm agglomerated cubes

Active material capacity (anode or cathode): 67–68 mAh/g

Cell characteristics: E_{avg} = 1.56 V; 23 Wh/kg and 37 Wh/l at 1C/1C from 1.81 V upper cutoff voltage to 1.0 V lower cutoff voltage; >80% capacity accessible at 10C/10C; >4000 cycles to 100% depth-of-discharge with 98% capacity retention at 10C/10C (40,000 cycles to 80% according to Natron directly)



Commercial-format Prussian-blue-analogue sodium-ion batteries provide low energy density and long cycle life

Source: He, Davis, Chartouni, Johnson, Abplanalp, Troendle, and Suetterlin

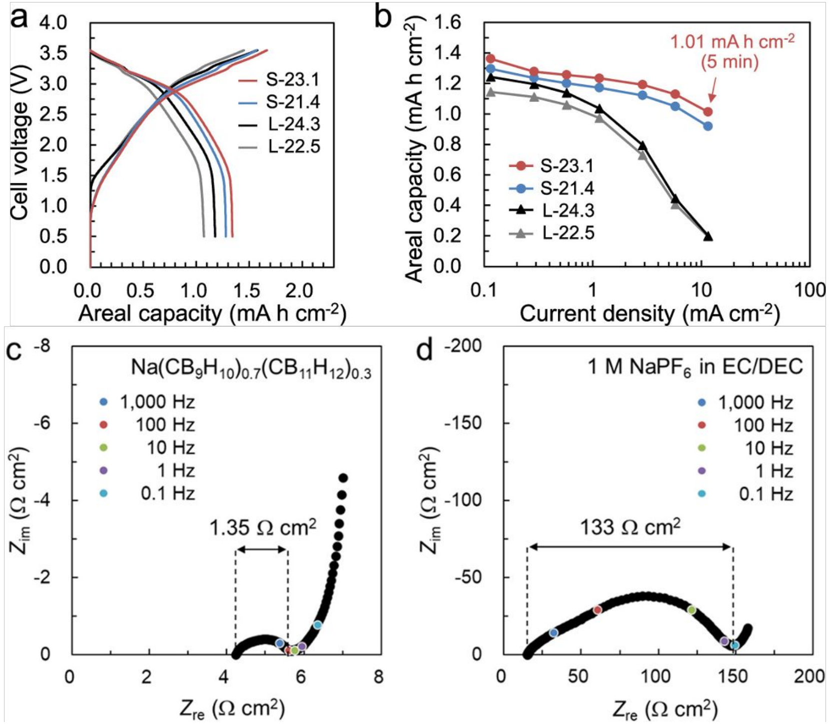
Sodium | Anode | All-solid-state battery

Electrode–electrolyte interface optimization

Researchers at Toyota investigated the use of a hard carbon anode with a sodium borohydride solid electrolyte to enable fast-charging in all-solid-state sodium-ion batteries.

The low-resistance interface between hard carbon and $Na(CB_9H_{10})_{0.7}(CB_{11}H_{12})_{0.3}$ enabled high current densities of 10 mA/cm^2 while retaining over 1 mAh/cm^2 capacity. The all-solid-state cell significantly outperformed an analogous conventional cell with a liquid Na-ion electrolyte.

Compatible electrode/electrolyte interfaces unlock fast-charging all-solid-state sodium-ion batteries

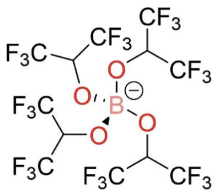


(a) Voltage curves and (b) rate performance of solid- and liquid-state Na-NMC//hard carbon cells. S-23.1 and S-21.4 are solid electrolyte cells with 23.1 and 21.4 mg cm^{-2} of cathode active mass loading. L-24.3 and L-22.5 are liquid electrolyte cells with 24.3 and 22.5 mg cm^{-2} of cathode active mass loading. (c) Solid-state and (d) liquid-state impedance curves.

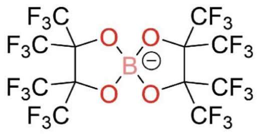
Source: Niitani, Ushiroda, Kuwata, Ohata, Shimo, Hozumi, Matsunaga, and Nakanishi

Sodium | Electrolyte | Sodium borate salts for liquid electrolytes

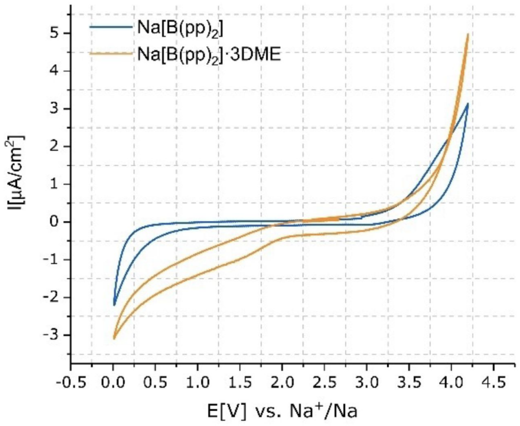
Sodium-ion battery electrolytes and additives are less established than their lithium analogues, work continues to find optimal properties and performance



$Na[B(hfip)_4]$



$Na[B(pp)_2]$



Sodium-ion batteries commonly use $NaPF_6$ as the electrolyte salt, but it is hygroscopic and forms HF, which can hinder long-term cell cycling. Two groups from the University of Cambridge, in collaboration with Faradion, developed a series of sodium borate salts (see Figure) that are relatively stable to atmospheric conditions, form good SEIs, and yield better electrochemical performance than $NaPF_6$. The $Na[B(pp)_2]$ salt (Figure, top) is tolerant toward air and water with a conductivity over 8 mS/cm (1 M in EC:DEC 1:1 v/v) and promising stability against sodium metal (Figure, bottom). It also shows good initial electrochemical performance in a ca. $Na_{0.79}Ni_{0.27}Mn_{0.42}Mg_{0.15}Ti_{0.17}O_2$//hard carbon cell.

Electrolyte development is an important factor in the advancement of beyond-lithium battery chemistries

Source: Ould, Menkin, Smith, Riesgo-Gonzalez, Jónsson, O'Keefe, Coowar, Barker, Bond, Grey, and Wright

Fast Charge | Cathode

NMC811 may be better suite to extreme fast charging than lower Ni-content NMCs

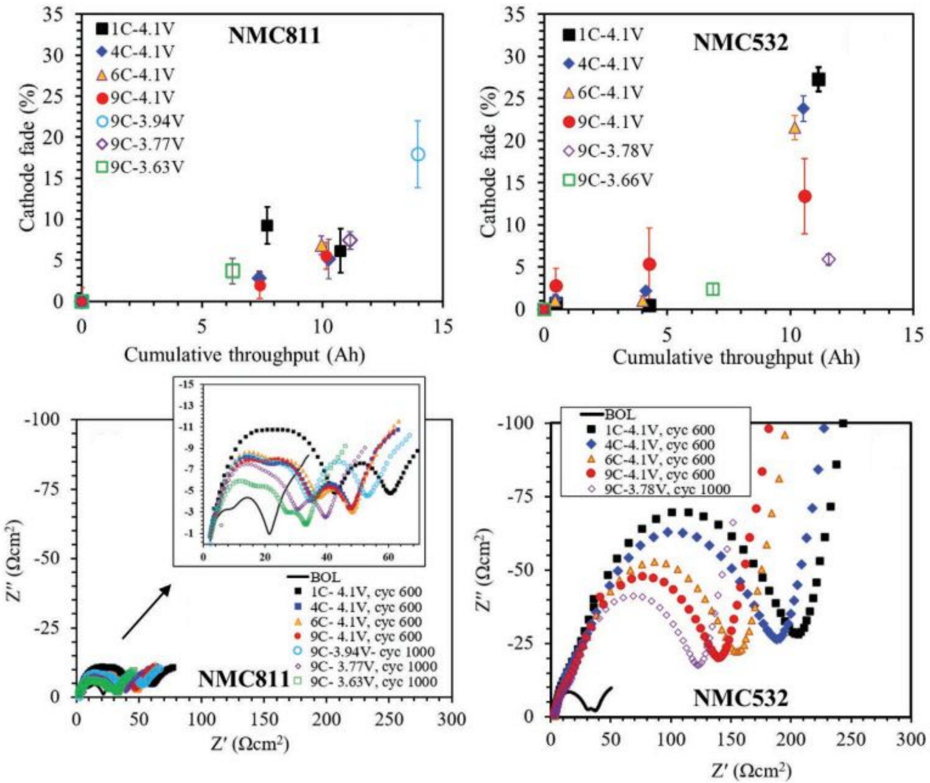
Researchers at Argonne National Laboratory, Idaho National Laboratory, and National Renewable Energy Laboratory have evaluated the impacts of extreme fast charging on Nickel Manganese Cobalt (NMC) based lithium-ion batteries with varying nickel contents.

Extreme fast charging (XFC) infrastructure must be able to charge the batteries in 15 minutes or less to compete with refueling times of combustion engine vehicles.

Superior beginning of life (BOL) and cycle life performance was reported for NMC 811 over NMC 532.

NMC 811 showed between 3.15x and 4.6x improved capacity retention over NMC 532 under XFC. NMC811 showed distinctly lower impedance when compared to NMC532.

Appropriate electrode composition support the ability for extreme fast-charging in lithium-ion batteries

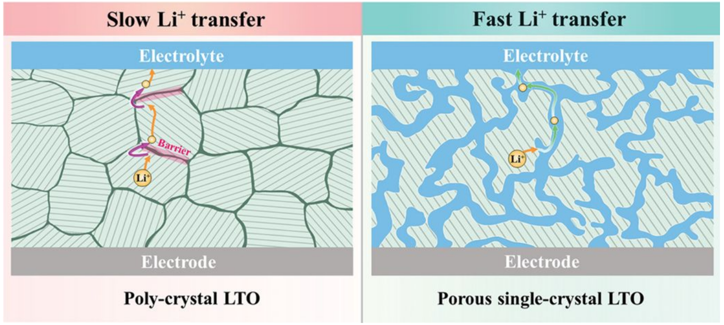


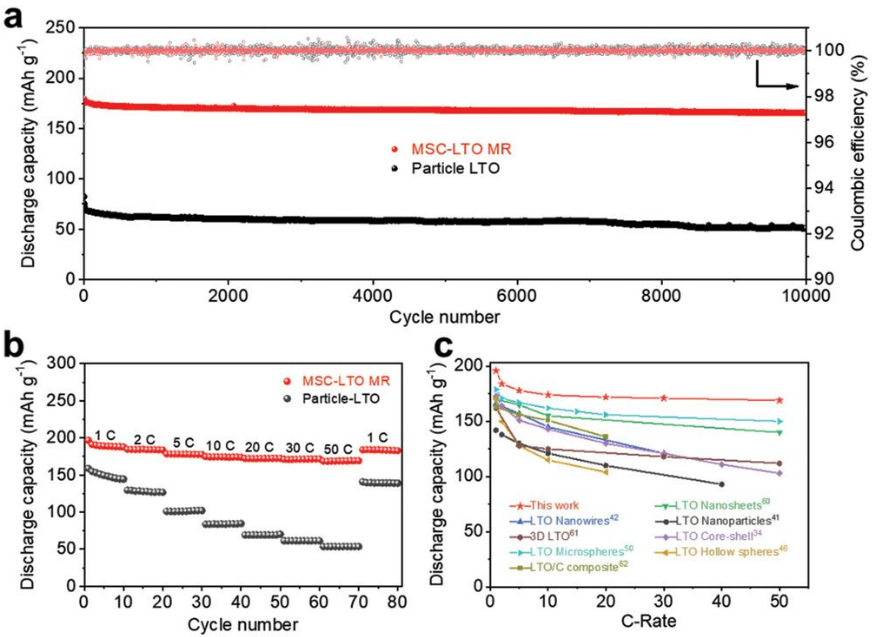
Capacity fade and impedance after XFC of different NMC compositions

Source: Tanim et al, Tanim et al, Yang et al

Fast Charge | Anode | 20 C lithium titanate (LTO)

20C ultrafast charging and 10000-cycle lifetime enabled by mesoporous single-crystal LTO anode





Researchers at PetroChina and University of Science and Technology of China designed mesoporous single-crystal lithium titanate ($Li_4Ti_5O_{12}$, LTO) microrods as a fast-charging anode material for LIBs. The single-crystalline microstructure and interconnected pores are beneficial for lithium-ion diffusion and electrolyte penetration. The anode exhibited stable cycling (92% retention after 10,000 cycles at 20 C) and outstanding rate performance (≈169 mAh g^{-1} at 50 C) at low loadings and 136 mAh g^{-1} at 5C at 8–11 mg/cm^2.

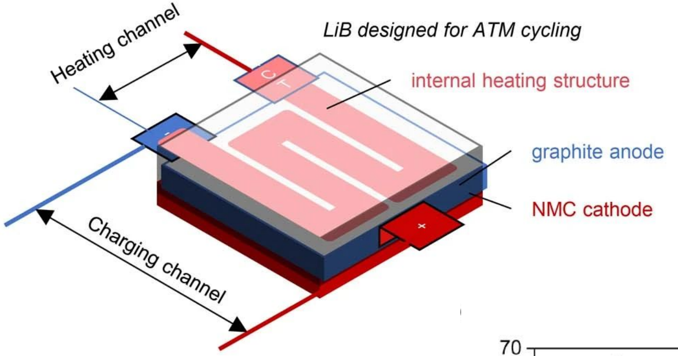
A LTO anode featuring ultrafast and stable cycling to realize extreme fast-charging in lithium-ion batteries

Source: Jin, Han, Zhang, Chen, Li, Yang, Wang, Li, Han, Wang, Liu, Jiao, Ke, Sui, Cao, Zhang, Tang, Yan, and Jiao

Fast Charge | Internal Thermal Modulation for Fast Charging

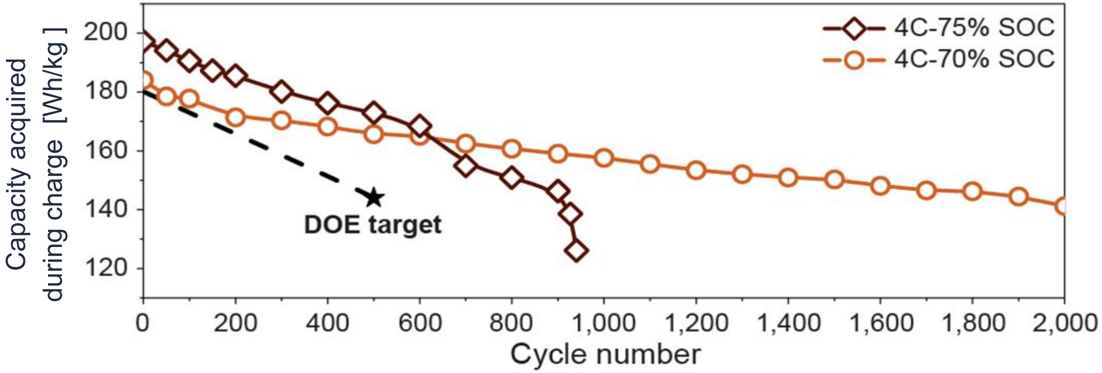
A method to reach fast charging rates by internally heating up cells

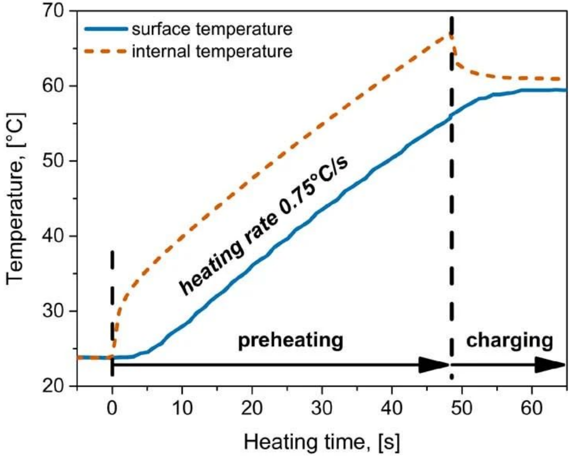
A team from Penn State University and startup EC Power has developed a novel thermal management solution to actively modulate the internal temperature of cells, called asymmetric thermal modulation. An embedded nickel foil resistive heater between layers of the electrodes preheats the cell to enable high C-rate charging. In addition, ionic transport was improved using a dual salt ($LiPF_6$–LiFSI) electrolyte and higher anode porosity.



Fast charging protocol:

1. **Internal cell heating up to 60 °C in <1 min**
2. **Constant current 4C-rate charging**



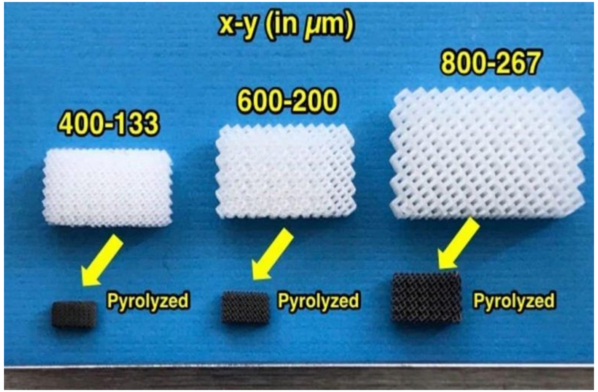


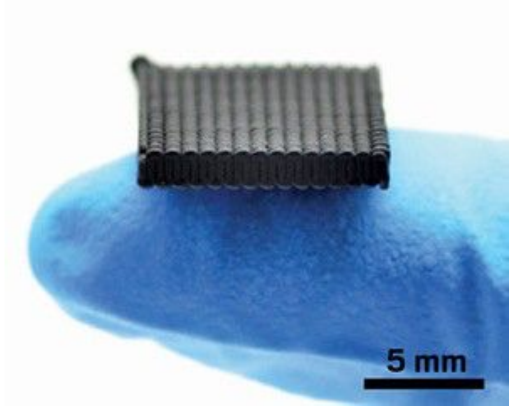
Source: Wang, Liu, Yang, Ge, Stanley, Rountree, Leng, and McCarthy

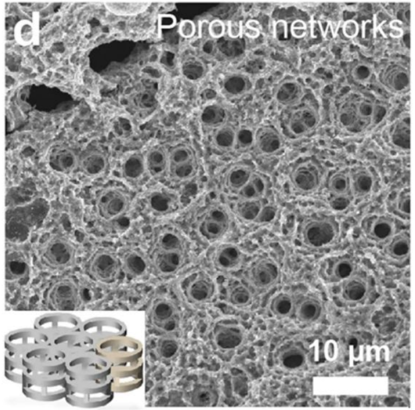
Manufacturing | Additive manufacturing of 3D electrodes

3D structures are being explored to increase power and/or accessible capacity

3D-printed free-standing carbon lattice	3D-printed carbon anode	3D-printed MoS_2 foam anode
Technique: Stereolithography (SLA) Key achievement: 21.3mAh/cm^2 @ 98 mg/cm^2 Challenges/scalability: 50 um light penetration depth in carbon, 36mm/hour with micro surface finish, low capacity utilization	Technique: Polylactic acid (PLA) extrusion, 3D printing Key achievement: 77 mAh/g in 1-mm thick electrode Challenges/scalability: Print speed only 200 mm/h, low capacity utilization	Technique: Electrohydrodynamic (EHD) 3D printing Key achievement: 1200 mAh/g @ 5 A/g Challenges/scalability: MoS_2 is scalable but not a commercialized anode, low volumetric energy density







Source: Katsuyama, Kudo, Kobayashi, Han, Chen, Honma, and Kaner; Park and Fu; Wei, Lin, Wu, Qaiser, Cai, Lu, Qi, Fu, Chiang, Yang, Ding, Ali, Xu, et al.

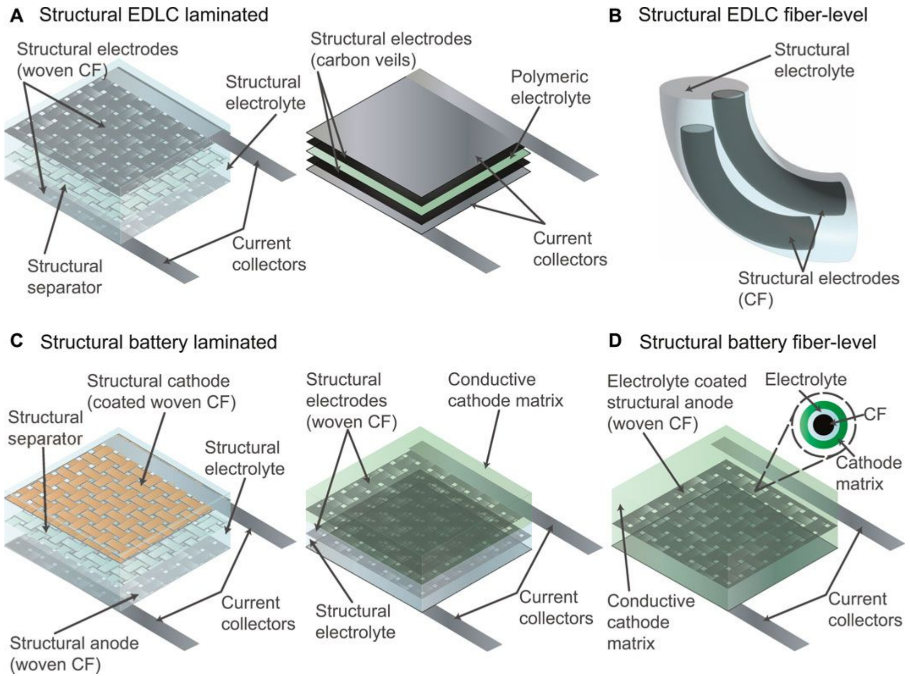
Manufacturing | Enhanced structural properties in battery cells

Combining mechanical and energy storage functions

One method to improve battery performance is to give them a second function that lowers the need for ancillary components: e.g., the ability to withstand mechanical loads while storing and providing energy. This could be important in systems where weight management is critical, i.e., structural power.

Examples of research in 2022 include Xu et al. embedding cells between carbon fiber and/or glass fiber composite sheets, and Dong et al. demonstrating a carbon fiber woven fabric (CFWF) anode with a CFWF cathode, glass fiber woven fabric (GFWF) electrolyte and GFWF/epoxy pack.

Energy and power densities of structural batteries are two orders of magnitude lower than traditional batteries. With improvements, they could serve niche applications, although significant engineering and manufacturing challenges remain.



Source: Navarro-Suárez and Shaffer

Manufacturing | Resource impacts on the environment | Rock-to-metal ratio

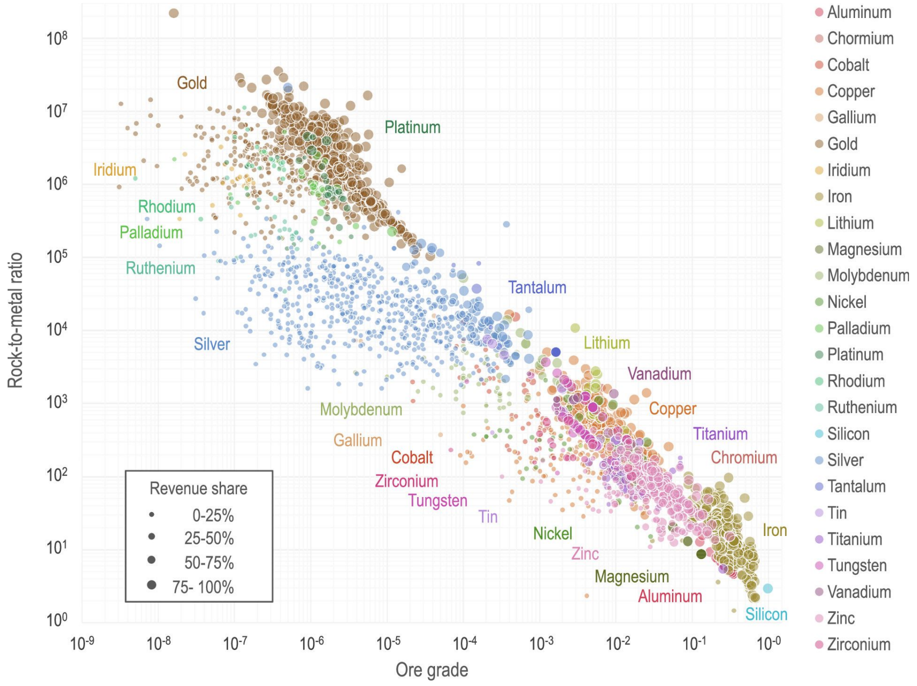
The quantity of earth moved per unit of elemental metal varies by some 7 orders-of-magnitude

A team from the U.S. Geological Survey and Apple analyzed, calculated, and estimated mine and refinery data for 25 commodities including battery-relevant elements like Li, Co, Ni, Fe, Cu, Al, Zn, V, Zr, and Mg.

The data incorporates not only ore grade but overburden and processing efficiency to yield an overall rock-to-metal ratio, which is broken down, where possible, by individual operation.

It is no surprise that Pt and Au are more resource intensive than Co and Ni, but the differences within battery metals and between operations may be surprisingly substantial. For example, the average rock-to-metal ratio for Ni is 329 vs 564 for Cu, but individual Cu operations vary from 2.3 to 17,000.

Rock-to-metal ratios are a valuable way to evaluate the environmental impact of material and supplier choices

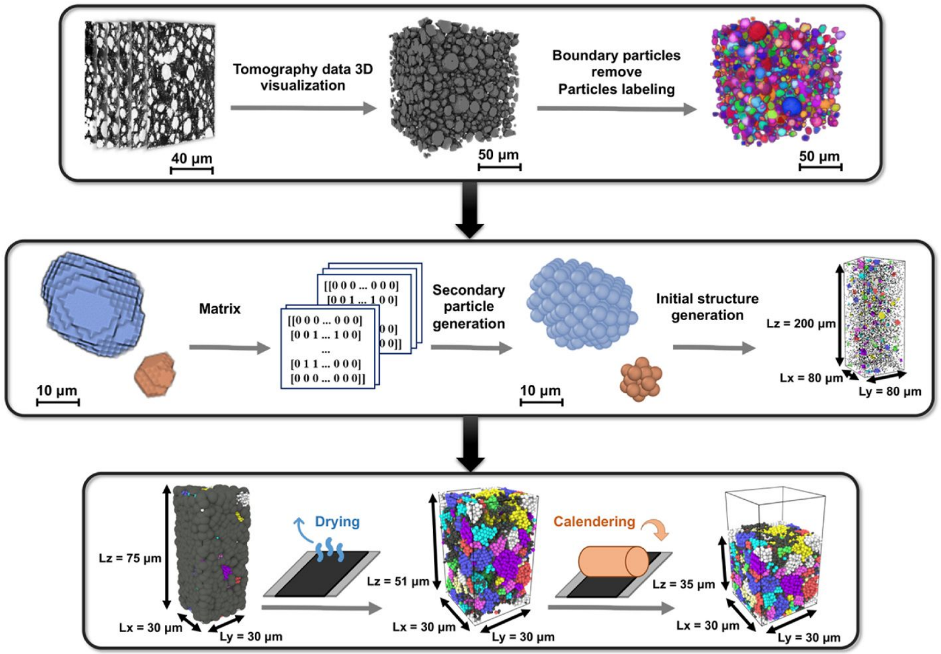


Rock-to-metal ratio for 25 mineral commodities according to ore grade. Multiple data points for a single element represent different individual operations. Circle size is indicative of whether the element is produced as a primary or secondary product.

Source: Nassar, Lederer, Brainard, Padilla, and Lessard

Manufacturing | Modeling | 3D Active Material Particles Models

Integrating experimental particle morphology with manufacturing forces



Researchers from Universite de Picardie Jules Verne developed a new 3D physics-based modeling workflow to predict the influence of manufacturing parameters on the electrode microstructure. The simulations start from experimental active material particle shapes obtained from X-ray micro-computed tomography and then track the variation in secondary particle deformation and electrode heterogeneity during the manufacturing process.

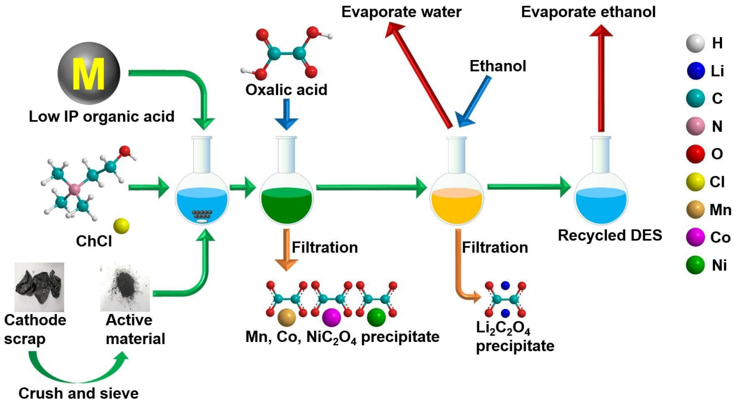
To increase LIB production and reduce costs, the development of digital twins to optimize the manufacturing processes is essential. This model links manufacturing parameters with real electrode microstructure.

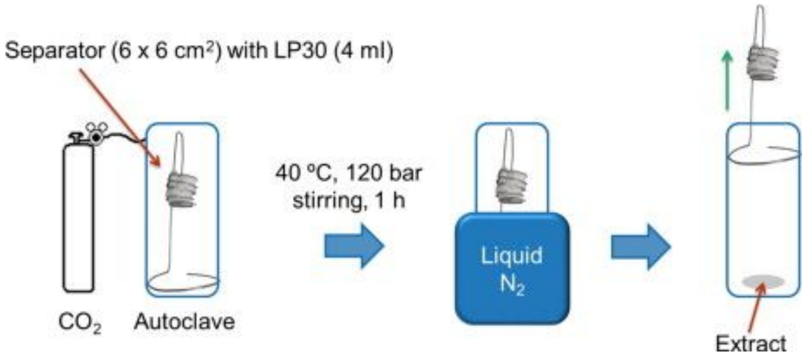
Source: Xu, Ngandjong, Liu, Zanotto, Arcelus, Demortière, and Franco

New methods target efficient metal extraction, regulatory satisfaction, and fluorine recovery

Battery recycling conventionally involves pyrometallurgical or hydrometallurgical techniques to recover valuable metals or salts with Co, Ni, Cu, and, Li. Direct methods recover active materials without returning to primary reagents. New methods seek to recover more of the battery with higher efficiency.

Deep eutectic solvents are attractive for metal leaching because they offer tunability and selectivity while being less toxic than traditional acids used in hydrometallurgy. Supercritical CO_2 extraction is also being investigated as a method to recover the $LiPF_6$ electrolyte salt, which can be problematic in waste streams due to its proclivity for HF formation. Both methods suffer from being relatively slow and requiring high temperatures.





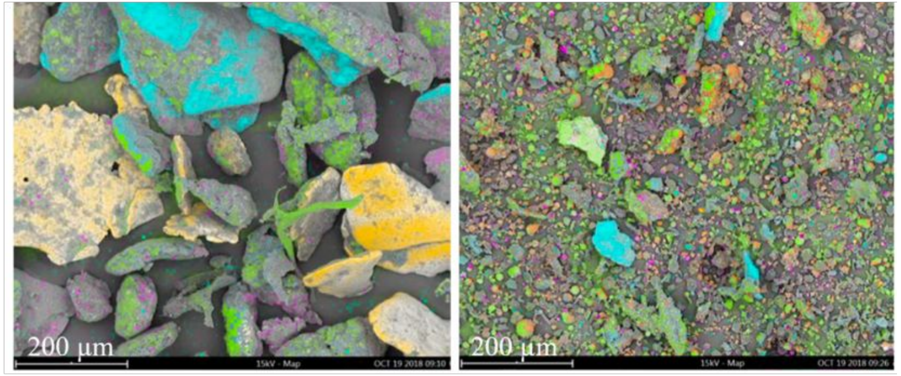
Source: Nowak and Winter; Hua, Sun, Fan, Wang, Xu, Zhao, and Zhang

Recycling | Impact of impurities

Metallic Cu, Mg, and Si accelerate degradation in directly recycled cells

Researchers from the National Renewable Energy Laboratory and Argonne National Laboratory studied the impact of some common metallic impurities that are present in black mass and could exist in regenerated electrodes produced from direct recycling methods.

Iron, aluminum, magnesium, copper, and silicon were identified as major likely contaminants. Of these, copper and silicon are most detrimental at the cathode. They cross-over during cycling and disrupt SEI formation. On the anode side copper and magnesium are most problematic because they form alloys and catalyze electrolyte decomposition.



purple = Ni, Co; orange = Mn; light blue = Al; gold = Cu; green = O

Heterogeneous make-up of shredded batteries.
Larger particles on the left, finer grains on the right.

Residual impurities from the recycling process can be detrimental to long-term cycling in batteries with recycled electrodes. Impurities must be understood and effectively managed.

Source: Fink, Polzin, Vaughey, Major, Dunlop, Trask, Jeka, Spangenberger, and Keyser

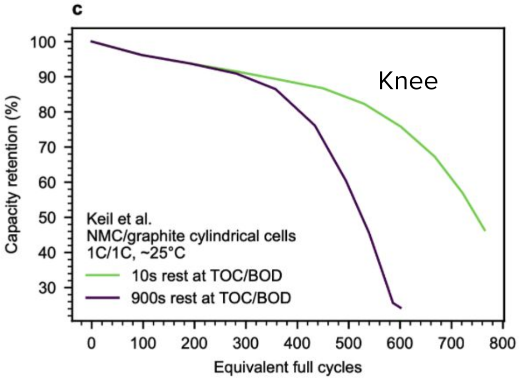
Diagnosis | Degradation

Understanding root causes for nonlinear capacity loss over long term cycling

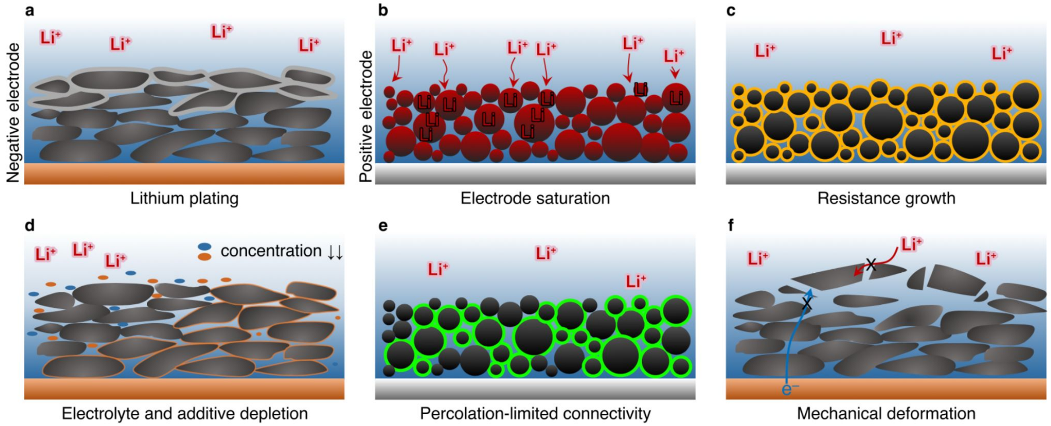
A large international team of researchers investigated root causes of rapid, nonlinear capacity fading observed during battery cycling, also known as the “knee” effect.

Many degradation pathways, such as lithium plating and electrolyte depletion, can cause a knee. These pathways can interact across length scales and are sensitive to small differences in cell manufacturing and usage.

While modeling and predicting knees is challenging, this work is a first step towards a comprehensive understanding of this phenomenon.



“Knees” threaten efforts towards "million-mile batteries" and have many complex root causes, but an arsenal of diagnostic techniques can help us understand and prevent knees for a given battery application.



Source: Attia, Bills, Planella, Dechent, Reis, Dubarry, Gasper, Gilchrist, Greenbank, and Howey

Diagnosis | Ultrasound characterization and inspection

Growing research around non-destructive battery inspection using ultrasound

Ultrasound is becoming an increasingly popular method to characterize and inspect battery cells to ensure reliability and safety. High-frequency sound waves can probe electrode and complete cell properties.

Researchers at Sogang University and the University of Washington demonstrated an air-coupled non-contact method to inspect sealing integrity and any defects between the lead tab and the laminate casing in a pouch-format battery.

Ultrasound technology can rapidly identify manufacturing issues and thus improve factory efficiency.

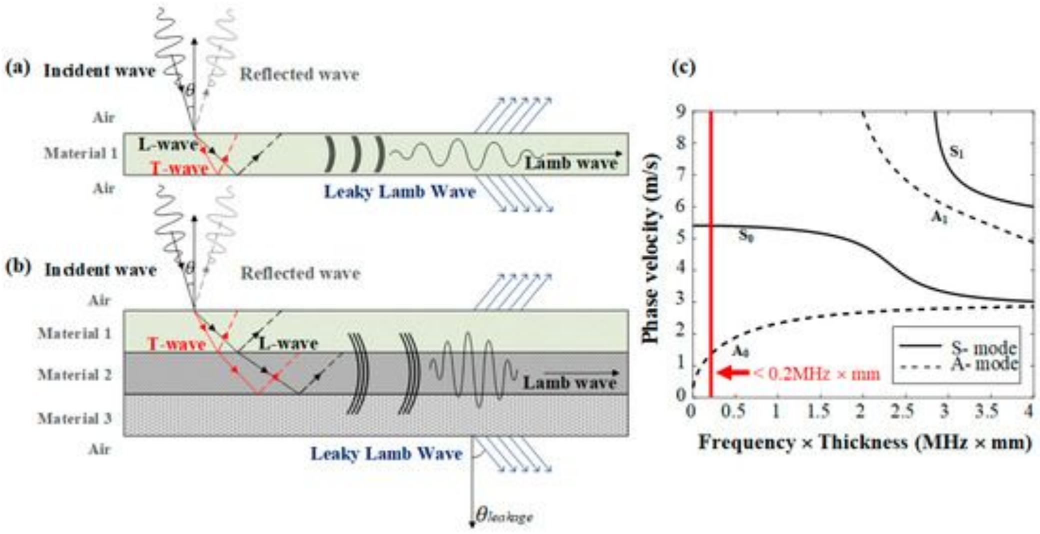


Illustration of Lamb wave generation, propagation, and leakage in (**a**) a single plate and (**b**) a multi-layered structure. (**c**) The phase velocity dispersion curve in Al.

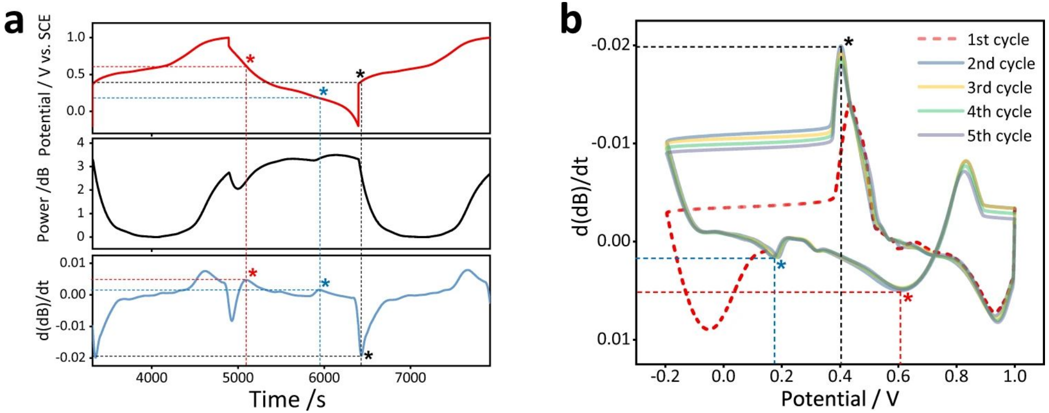
Source: Cho, Kil, Jang, Kang, Song, and Yoo

Operando detection of surface reaction mechanisms with embedded fibers

A fiber-optic sensor was developed to track insertion mechanisms. Surface plasmon resonance sensing is achieved with a tilted fiber Bragg grating in a commercial fiber. The sensor had no observable impact on electrochemical performance and is relatively unique among operando diagnosis tools in that it selectively detects surface phenomena.

When the technique was demonstrated on an aqueous MnO_2//Zn cell, features in the power spectrum from the sensor correlated with multi-step electrochemical features that have been assigned to H^+ and Zn^{2+} insertion (Figure panel a). The detection method also picked up on the irreversible 1st cycle processes that occur with MnO_2//Zn (Figure panel b).

A fiber-optic technique based on surface plasmon resonance sensing has been developed for operado reaction monitoring. It is sensitive to surface phenomena and electrolyte concentrations.



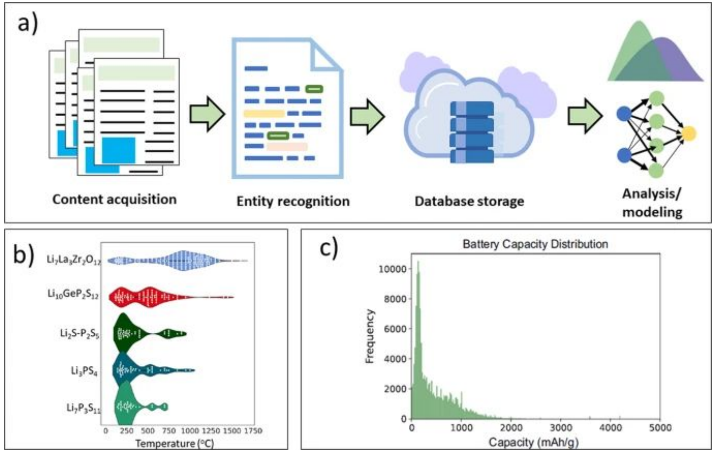
Relating optical measurements with electrochemical features in an aqueous MnO_2//Zn cell. (left, top down) Galvanostatic curve, optical power, and its time derivative. (right) Derivative curves of optical power over the first five electrochemical cycles.

Source: Wang, Zhang, Liu, Liu, Han, Liu, Li, Xiao, Albert, Lu, and Guo

Battery Informatics | Machine Learning

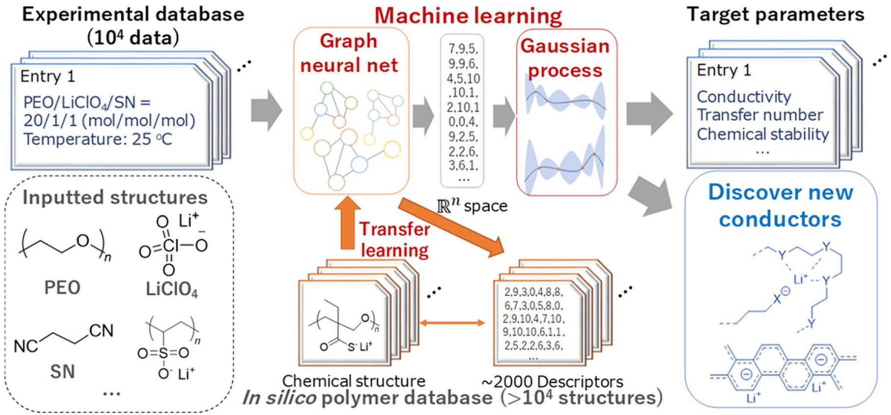
Toyota Research Institute summarizes a dozen ways machine learning can improve battery development and cross the data chasm.

Temperature and Capacity Extraction Example



Text classification techniques can extract test information, such as temperature, and material information, such as capacity, from over 229k research papers to produce a materials knowledge database

Conductivity Prediction Example

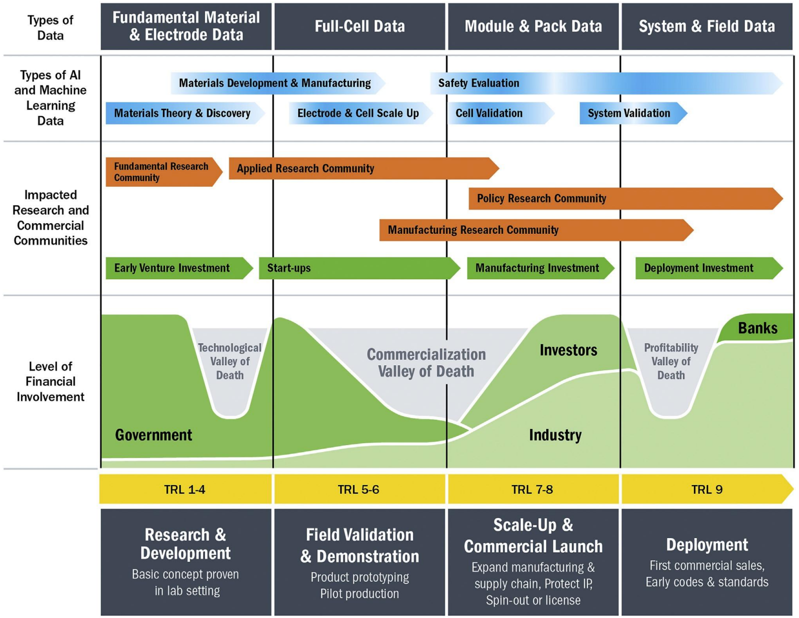


A transfer-learned graph neural network accurately predicted conductivity (mean absolute error of less than 1 on a logarithmic scale) on the largest database of lithium-conducting solid polymer electrolytes (~10,000 entries)

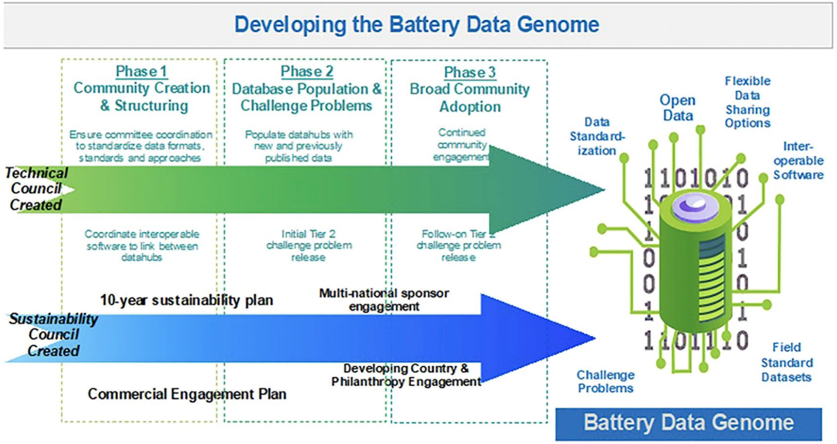
Source: Ling

Battery Informatics | Battery Data Genome

28 Authors from 15 Institutions propose the launch of a Global Battery Data Science Initiative



Battery AI/ML innovations of all types span all technology readiness levels (TRLs) and create positive impacts to stakeholders in both research and commercial communities



Implementation roadmap for the Battery Data Genome —a multiphase approach with technical and sustainability-focused councils

The Battery Data Genome (BDG) faces two significant data challenges: (1) **heterogeneity**—establishing the data and metadata conventions that will make heterogeneous battery data useful and enable interoperability (2) **scale**—rapid, large-scale capture of data from many sources and contributors

Source: Ward, Babinec, Dufek, Howey, et al.

Section 3

Talent & Community

Talent | Jobs

The battery value chain provides a great opportunity for job creation with many new roles to come.

Profiles by stage of the Battery Value Chain

	Raw materials	Active materials	Cells and Battery Packs		Applications			Recycling & 2nd life
White Collars	▪ Electrochemistry ▪ Material refinement and purification processes ▪ Environmental management	▪ Electrochemistry ▪ Wet chemistry processes ▪ Cleanroom processing ▪ Integration of processes in the environment ▪ Materials synthesis	▪ Inorganic chemistry ▪ Materials science ▪ Electrochemistry and cell design ▪ Energy storage ▪ Power and energy density ▪ Energy conversion efficiency ▪ Performance factors and optimisation ▪ Modelling and simulation ▪ Data Science	▪ Packaging and Security ▪ Testing and Monitoring ▪ Data Science ▪ Mechanical Engineering ▪ Systems Management ▪ DC system design ▪ Thermal and kinetic properties	▪ EV typologies ▪ Charging infrastructures ▪ Vehicle to Grid ▪ Sustainable mobility ▪ Business models ▪ Policy and Regulation ▪ Batteries in trains and planes	▪ Smart buildings ▪ Sustainability ▪ Energy management ▪ Power plants ▪ Smart grids, off grids and micro grids ▪ Battery banks ▪ Business models ▪ Policy and Regulation	▪ Solar Energy Storage ▪ Control and regulation of wind turbines ▪ Coupling to fuel cells ▪ System optimisation ▪ Cost calculation ▪ LCA ▪ Policy and Regulation	▪ Material properties and life cycles ▪ Rare resource processing and recovery ▪ Chemical resources ▪ Separation processes and technologies ▪ Electrochemistry ▪ Control and processing ▪ Circular economy models ▪ Environmental management and legislation ▪ Standardisation
Vocational & Professional	▪ Materials extraction and refining ▪ Sourcing ▪ Logistics ▪ Measurement and Control ▪ Chemical safety ▪ Waste management ▪ Environmental management	▪ Chemical processes ▪ Physical processes ▪ Design of chemical equipment ▪ Measurement and control ▪ Chemical safety and waste management	▪ Physical processes ▪ Mixing, coating, drying ▪ Measurement and control ▪ Chemical safety ▪ Waste management ▪ High speed mechanical assembly	▪ Electromechanical manufacturing ▪ Automation engineering ▪ Vehicle technology ▪ Electronics ▪ Electrical safety	▪ EV Fundamentals ▪ Operation, diagnosis and repair ▪ Systems ▪ Electric motors and controllers ▪ Diagnostic tools and equipment	▪ Energy installations ▪ EV charging systems ▪ Automation and control ▪ Electronics ▪ Digital ▪ System security	▪ Robotics and Automation ▪ Renewables and Electrical Grids ▪ Digital skills ▪ Electrical safety	▪ Materials extraction and refining ▪ Chemical and physical processes ▪ Logistics ▪ Digital skills ▪ Chemical and electrical safety ▪ Waste management

Source: CIC energiGUNE, InnoEnergy

Talent | Headlines

Batteries jobs were the hardest to recruit for among technology and communications companies

Average length of time job ads closed in Q2 2022 had been online for

	Job type	Days	Departure from average*	Jobs closed
1	Batteries	56.0	+65%	1,291
2	Blockchain	52.0	+21%	1,469
3	Quantum Computing	47.8	NA	454
4	3D Printing	47.0	+35%	1,476
5	RegTech	42.0	+9%	506

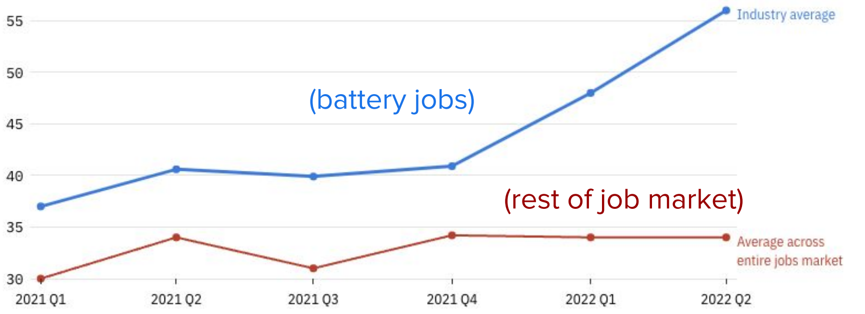
*Shows, for each job type, how much more/less time it took to recruit roles in the sector compared to the average across the entire job market

Source: GlobalData VERDICT

[Verdict]

In Q2 2022 it was much more difficult than average to hire for batteries roles in the tech industry

Average number of days job ads closed in each quarter had been online for



Source: GlobalData VERDICT

Ford slashing 3,000 jobs as it looks to make EV transition

The move comes as automakers grapple with the transition to zero-emission cars and trucks, and the prospect of job losses industry-wide

[Washington Post]

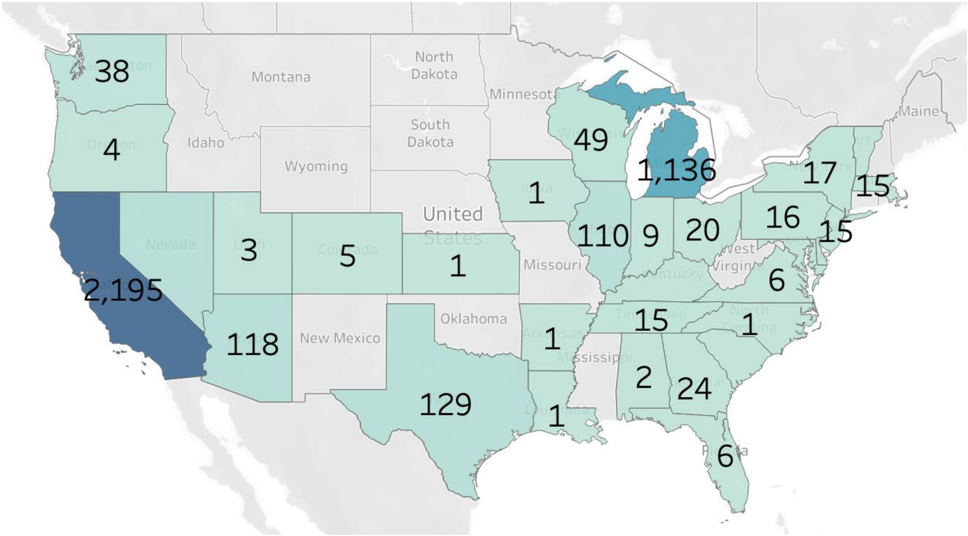
Battery Manufacturing Is Creating Lots & Lots & Lots Of Jobs

Companies seeking to rapidly expand output and avoid supply chain disruptions are building domestic battery manufacturing plants in the US. In some states, these are some of the largest, if not the largest, economic development projects in the state's history.

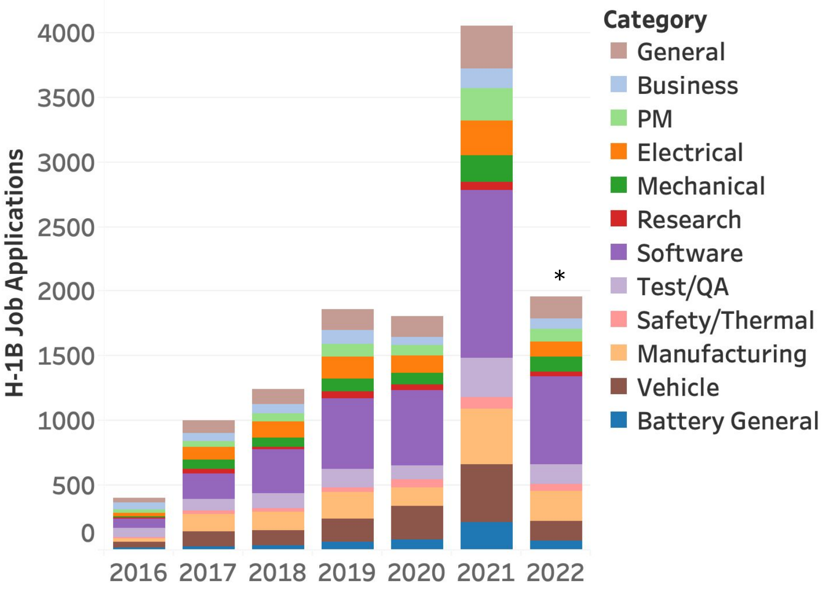
[CleanTechnica]

Talent | 2022 US H-1B Survey

The H-1B is a visa in the United States under the Immigration and Nationality Act, Section 101, that 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.



Plot shows heatmap of H-1B applications submitted between Jan 3, 2022 and Apr 29, 2022, filtered for battery-related companies (battery producers or electric vehicle producers).
Source: h1bdata.info. Code: GitHub.



*includes data up to Apr 29, 2022

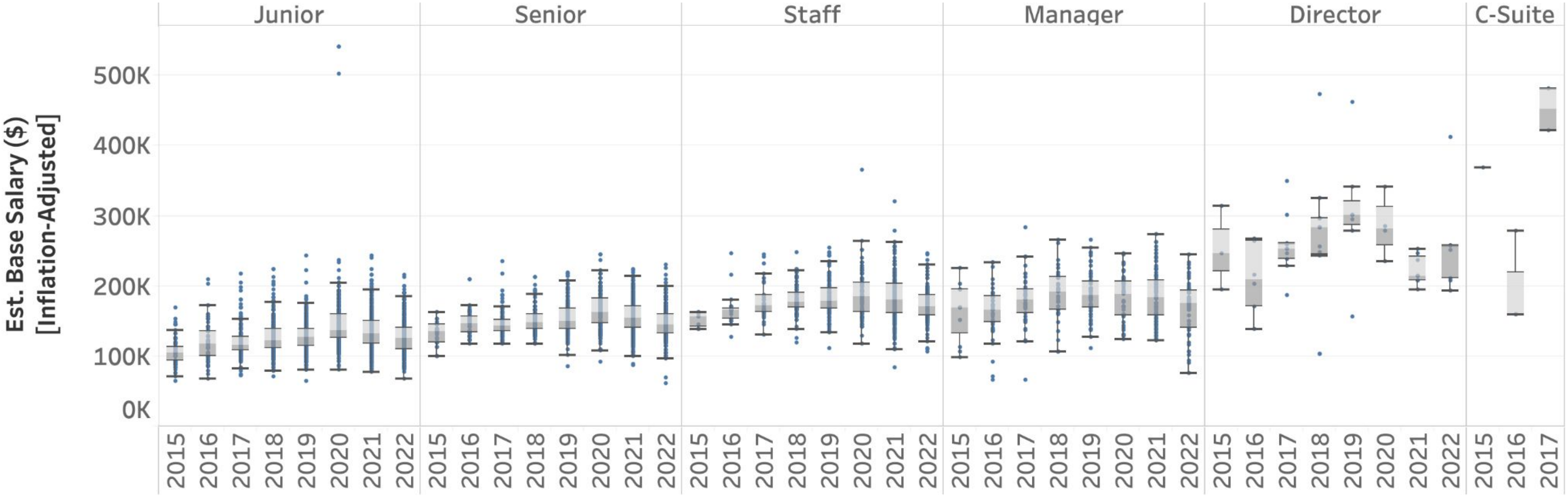
Resources

2022 H-1B General Policy Changes (Forbes)

2022 H-1B Trends (Waylit)

US H-1B Survey | Are Salaries Growing?

Large variability in base salaries across all companies and titles.



Plot shows salaries indicated on H-1B job applications submitted between Jan 1, 2011 to Apr 29, 2022, filtered for battery-related companies (battery producers or electric vehicle producers). Salaries are inflation-adjusted to 2022. Job levels are determined based on the rubric shown here. Source: h1bdata.info. Code: GitHub.

Talent | Manufacturing Jobs: A Year of Promises

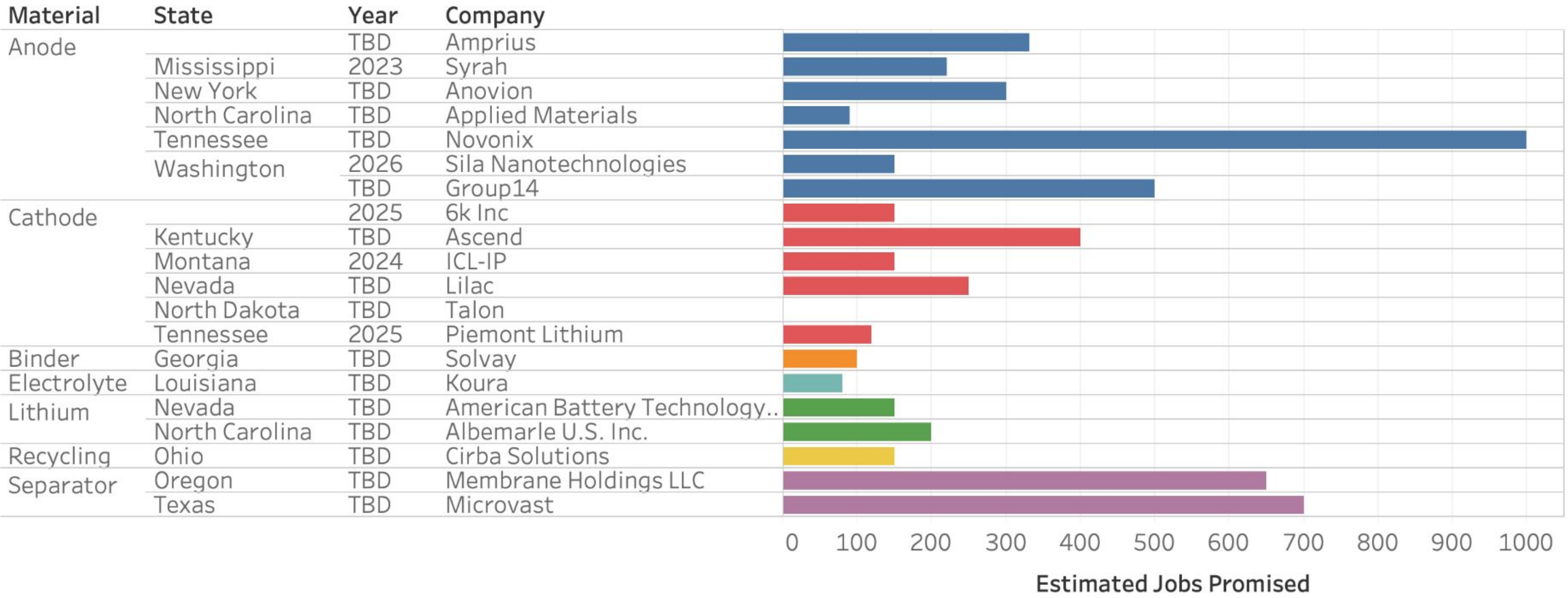
Company | OEM	Location	Promised Jobs	Planned Capacity	Source
Panasonic	De Soto, Kansas	4,000	30 GWh by 2025	InsideEVs, 11/6
Canoo	Pryor, Oklahoma	2,000	3.2 GWh by 2023	InsideEVs, 11/3, Canoo
Envision AESC | BMW	Kentucky	2,000	30 GWh by 2025	InsideEVs, 5/16
Electrovaya	New York	250	1.5 GWh by 2023	InsideEVs, 10/24
Our Next Energy	Michigan	2,112	20 GWh by 2027	InsideEVs, 10/11
Toyota	North Carolina	2,100	TBD	InsideEVs, 8/31
Samsung SDI | Stellantis	Kokomo, Indiana	1,400	23 GWh by 2025	InsideEVs, 5/24
LG Chem | Stellantis	Ontario (Canada)	2,500	45 GWh by 2024	InsideEVs, 6/5
SK Innovation	Georgia	3,000	22 GWh by 2023	AJC, 3/28
SK Innovation | Ford	Kentucky	5,000	43 GWh by 2026	Ford, 9/29 (2021)
SK Innovation | Ford	Tennessee	6,000	43 GWh by 2025	Ford, 9/21 (2021)
Gotion	Big Rapids, Michigan	2,350	TBD	MLive, 10/5
Ford	Michigan	3,200	TBD	MLive, 6/2
LG Energy Solutions | GM	Holland, Michigan	1,200	50 GWh by 2025	AP News, 3/22
LG Chem | GM	Spring Hill, Tennessee	1,300	35 GWh by 2023	GM, 4/1 (2021)
LG Energy Solutions | GM	Warren, Ohio	1,100	30 GWh by 2022	GM, 12/05 (2021)
Hyundai	Georgia	8,100	TBD	georgia.gov, 5/20
Rivian	Savannah, Georgia	7,500	TBD	savannahnow, 12/17 (2021)

Related perspectives: European perspective "Mega" trends

Talent | Manufacturing Jobs: A Year of Promises

"**Bipartisan Infrastructure Law** Funding Going to 20 Companies Across 12 States Will Strengthen America's Energy Independence, Create Good-Paying Construction and Manufacturing Jobs, and Lower Costs"

DOE Announcement and Project Fact Sheet



Talent | Education and Training

What skills are needed and where should they be taught?

	Trade School	In-House Training	2-Yr College	4-Yr University	Post Graduate	Total Responses
Battery Materials	11%	13%	21%	57%	57%	79%
Mining	9%	7%	9%	13%	11%	25%
Electrical	7%	7%	25%	27%	13%	41%
Power Electronics	7%	5%	20%	30%	18%	43%
Software / Battery Management	4%	5%	21%	39%	21%	55%
System Design	4%	7%	14%	38%	25%	54%
Prototyping	9%	20%	20%	32%	16%	45%
Battery Testing	23%	25%	38%	41%	16%	63%
Design for Waste Management	11%	11%	16%	29%	14%	36%
Battery Recycling	16%	14%	23%	32%	27%	48%
Environmental Engineering	4%	5%	7%	25%	14%	30%
Project Management	5%	13%	21%	29%	11%	38%
Technical Lead / Management	5%	16%	13%	34%	20%	45%
Supply Chain Management	5%	13%	20%	29%	9%	43%
Manufacturing Including Plant Design	4%	9%	18%	39%	20%	50%
Applications (Installation, Operation)	11%	11%	21%	23%	11%	38%
Installation of Battery Systems	20%	16%	25%	14%	9%	38%
Operation and Maintenance of Systems	25%	23%	20%	18%	4%	39%
Electrical Skills for Techs (High Voltage)	29%	23%	36%	23%	7%	52%
Safety (Electrical, Hazmat, Fire)	20%	20%	27%	25%	14%	41%
First Response to Battery Fires	18%	25%	23%	14%	9%	36%
	48%	46%	63%	77%	75%	

32 out of 56 respondents stated that they need to hire, in the near future, someone with battery material knowledge from a university level education.

- Greatest gaps for educational programs at the community and 4-year-college level.
- Training gaps for first response, safety, electrical skills, O&M, and installation at the trade school and community college level or through internal training programs.
- Knowledge of trade school, in-house training programs may be limited in responding population.

Source: Table adapted from NAATBatt job skills survey, with 56 total participants. (Alyssa McQuilling - Project Lead, Energy Storage Southern Research, 2022)

Talent & Community | Popular Content in 2022

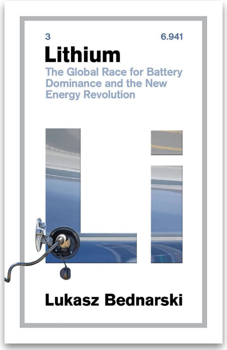
Newsletters

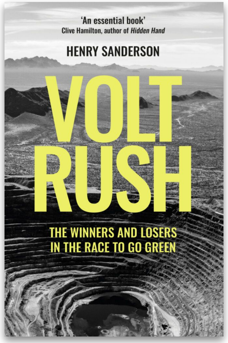
- Intercalation Station Newsletter
- The Electric
- Techtricity Newsletter
- Better Batteries Newsletter
- Lithium Valle Newsletter
- Green Rocks Newsletter
- Electrode Newsletter

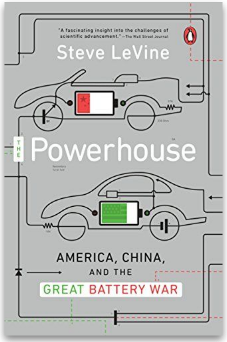
Content

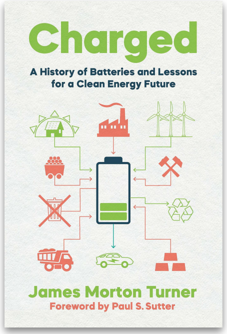
- The Limiting Factor YouTube
- The Global Lithium Podcast
- Recharge by Battery Materials Review
- Battery Generation Podcast
- Battery + Storage Podcast
- Redefining Energy

Books

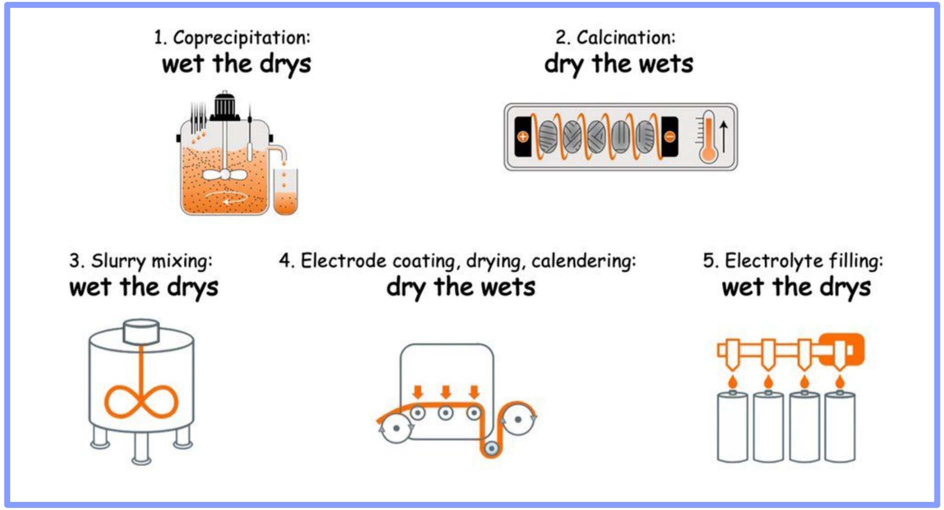






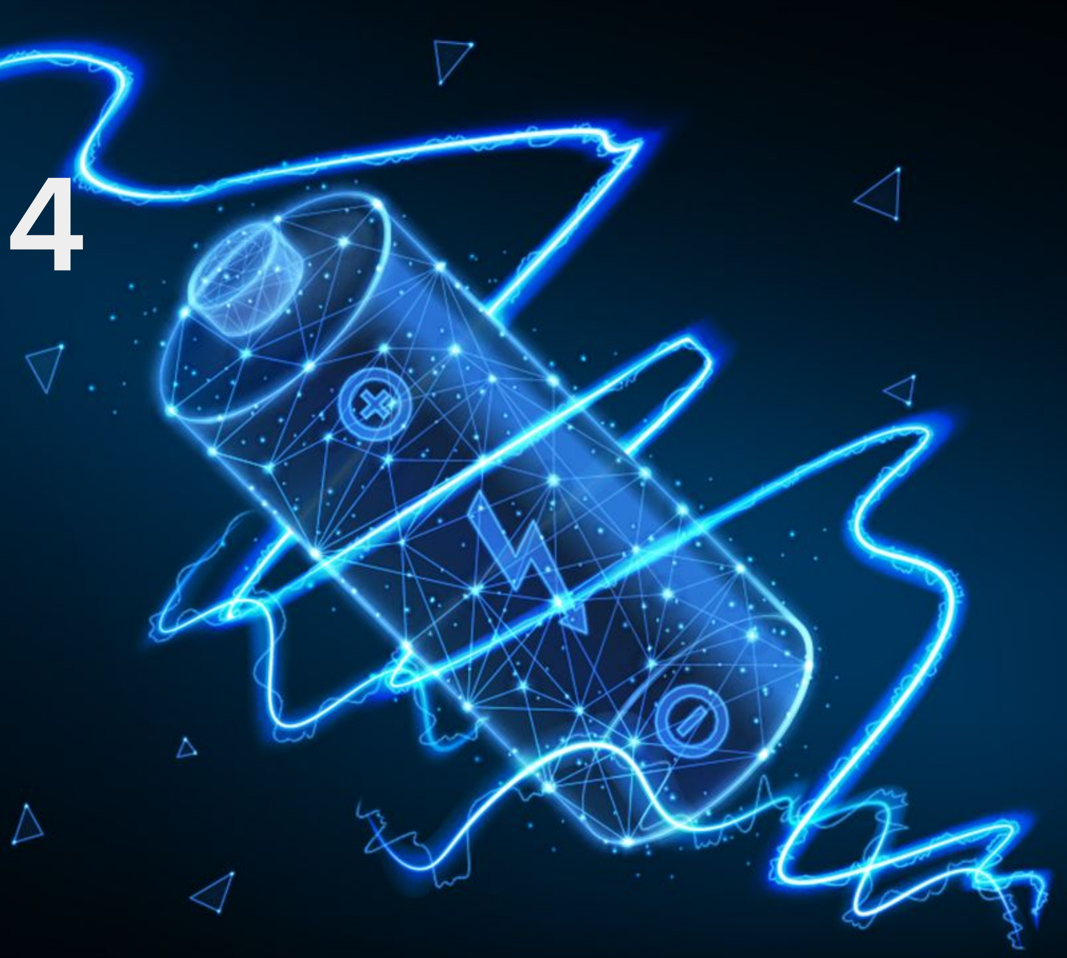


Battery manufacturing and fried chicken



Source : [Twitter]

Section 4
Policy

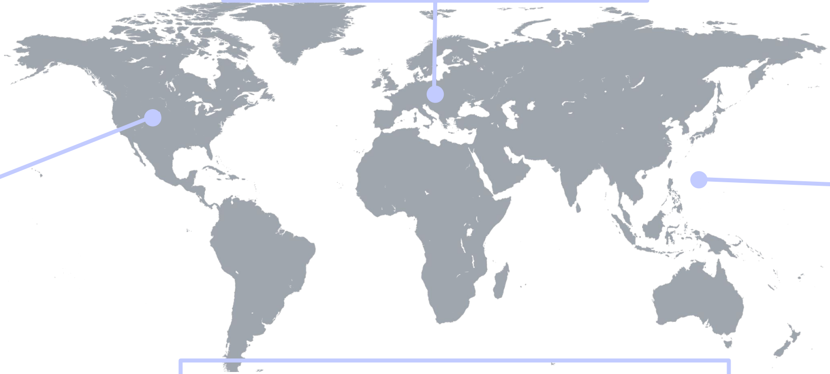


Overview | Global Overview

Regional approaches differ to achieve policy goals, most involving localization. The supply chain will commit to development where there is opportunity and where the carrots outnumber the sticks.

Europe

- European Parliament - EU Batteries Regulation
- UK Transport



United States

- Inflation Reduction Act
- BIL Awards

Canada

- Federal Policies

Asia & Australia

- East Asia
- India Auction Results
- Indonesia Raw Material Taxes
- Australia Mining

International Bodies & Industry Groups

- Global NGOs
- Associations & Coalitions

US | Inflation Reduction Act (IRA)

Billions in Supply Side & Demand Side Incentives To Create A Domestic Battery Value Chain

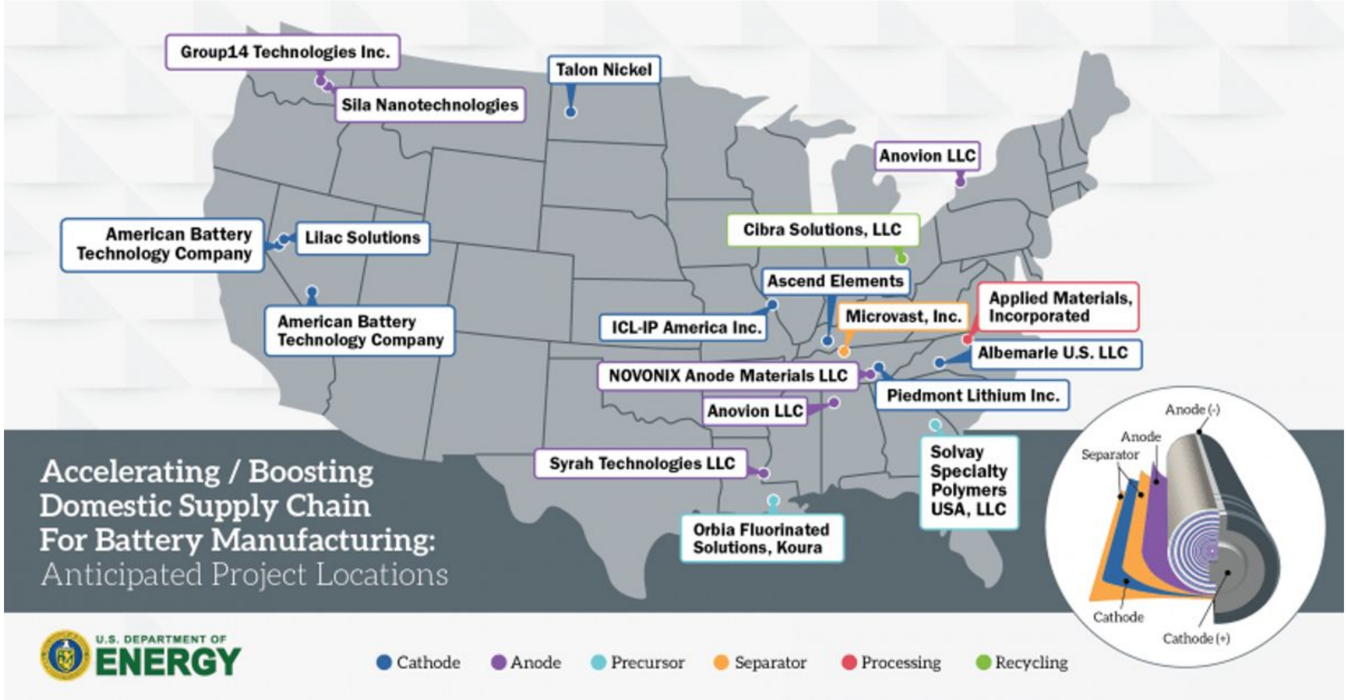
Section	Description	Estimated Value ($ Billion)
30D: Clean Vehicle Tax Credit	• Up to $7,500 for new EVs, $4,000 for used • Material sourcing requirements, EV price cap, and consumer income limits	8.9
45W: Commercial EV Tax Credit	• Eligible for tax credit equal to 30% of the vehicle cost	3.6
30C: Alternative Fuel Vehicle Refueling Infrastructure Tax Credit	• Individual: Lesser of $1K or 30% of the installed cost • Commercial: Maximum incentive for project is 30% up to $100K	1.7
45X: Advanced Manufacturing Production Credit	• $35/kWh for cells, $10/kWh for modules • Production in US or US possession • Phase out starting in 2029, reducing by 25% each year	30.6
Advanced Energy Project Tax Credit	• Includes technologies, components, materials for EVs, and associated charging or refueling infrastructure • Also applies to processing, refining, or recycling	6.3
Postal Service Vehicle Electrification	• $1.3 billion for vehicles, $1.7 billion for supporting infrastructure	3.0
Loan Programs Office	• Increases existing and new loan authorities by up to $350 Billion	11.7

Source: Inflation Reduction Act (H.R.5376) IRA Guidebook Congressional Budget Office Analysis Treasury (Nov), Treasury (Dec) & IRS Guidance

US | Bipartisan Infrastructure Law

$2.8 Billion Awarded To 20 Companies

10 Largest Awards	
Ascend Elements	$481 MM
Syrah Technologies	$220 MM
ENTEK	$200 MM
Microvast	$200 MM
ICL-IP	$197 MM
Solvay	$178 MM
NOVONIX	$150 MM
Albemarle	$150 MM
Piedmont Lithium	$142 MM
Anovion	$117 MM



DOE Announcement and Project Fact Sheet

Canada | Net Zero Accelerator and Critical Minerals Strategy

New Policies Are Aided By Legacy Trade Agreements

Net Zero Accelerator

- $8 billion over 7 years to expedite decarbonization projects with large emitters, including automotive. Priority given to projects with domestic IP/supply chain/manufacturing, or generate significant domestic job creation/retention

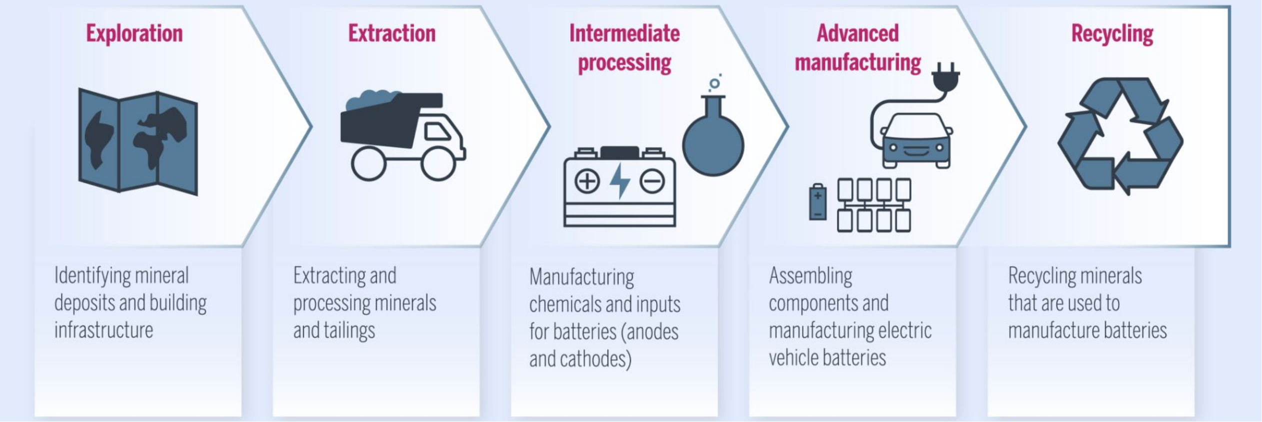
Critical Minerals Strategy

- $3.8B for domestic critical mineral value chain, accounted for in Federal Budget
- Allocation not confirmed, but probable focus on lithium, graphite, nickel, cobalt, copper, and rare-earth elements
- Focus on exploration/prospecting, expedited project development and approval, infrastructure development for processing

These policies complement the US IRA, especially in terms of FTA Partner or North American critical minerals and battery component sourcing

Canada's Whole Value Chain Goal

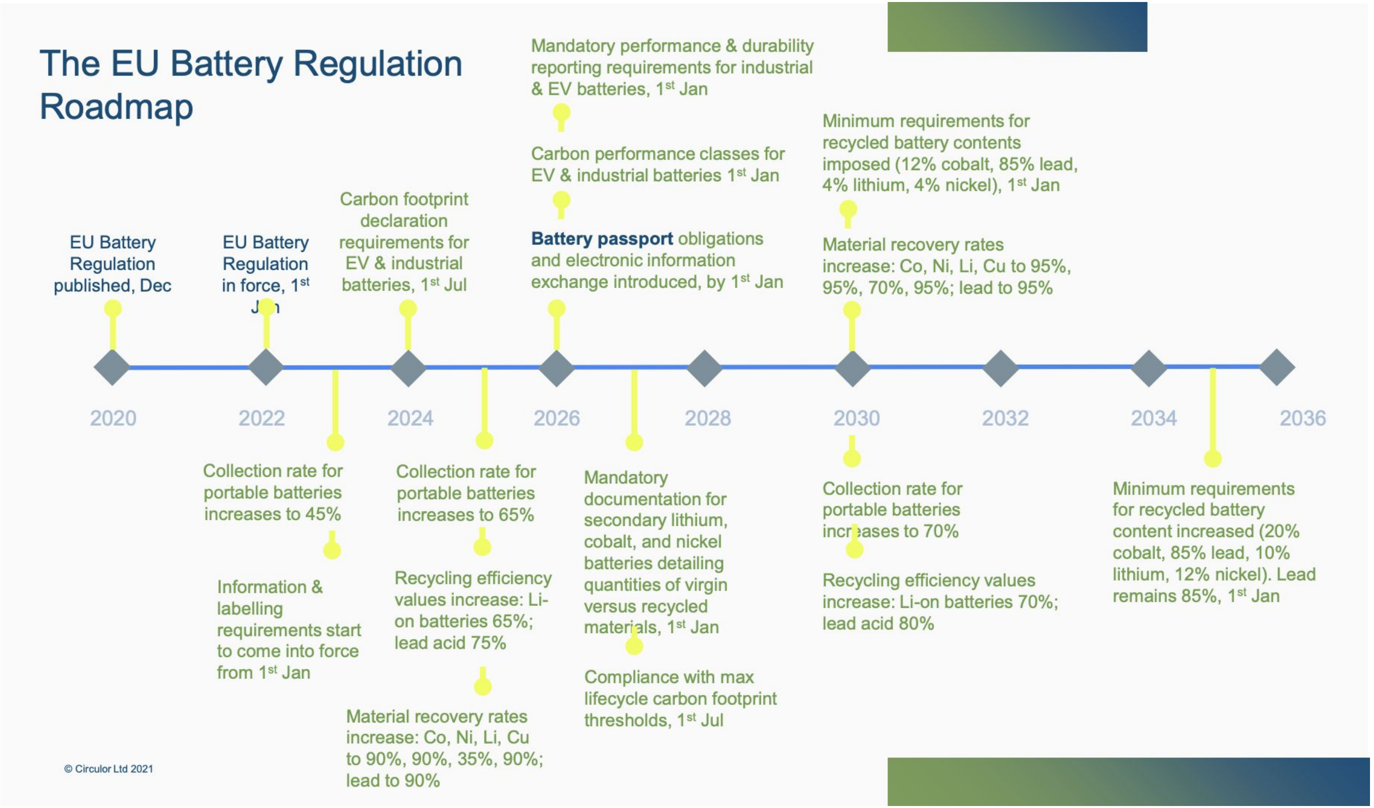
- Like other countries, Canada has ambitions to develop downstream value chain segments into regional and global market leaders.



European Union | EU Batteries Regulation, Innovation Funding

In Force In 2022, Certain Key Regulation Metrics Still Undecided

- Industry leaders in EU now see Batteries Regulation and other industrial policies as competitive barrier after IRA
- €3 billion Innovation Fund for "innovative clean-tech manufacturing" including energy storage
- EU Batteries Regulation
- December 9th 2022 Batteries Regulation Update

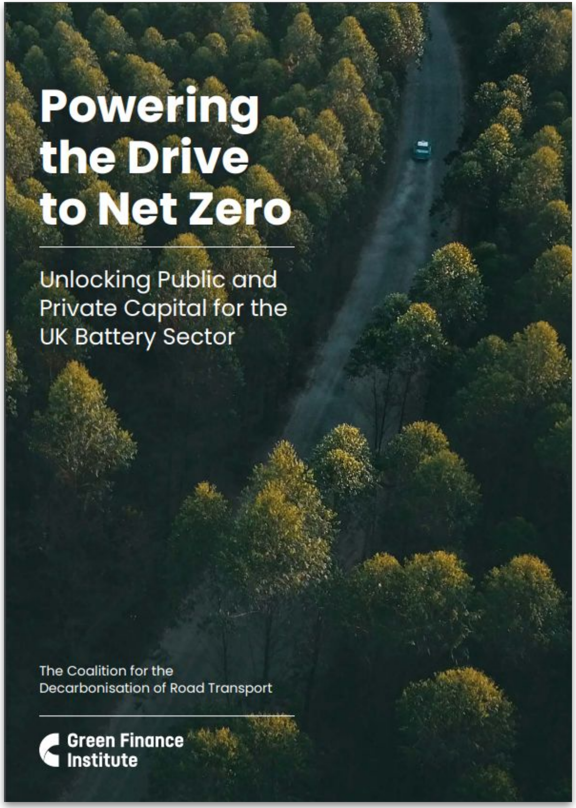


Source: Circulor

United Kingdom | A2Z, Infrastructure, R&D, Market-Based Solutions

Developing The Supply Chain On A Smaller Scale Presents Unique Challenges

- Updates to COP 26 declaration for all new cars and vans to be fully zero emission at the tailpipe by 2035.
- Updates to have all car and van business fleets ZEV by 2030.
- A £422m investment (with £200m being a cornerstone investment by Government) which is managed and invested on a commercial basis by a private sector fund manager. The fund is dedicated to catalysing the rollout of a robust and diversified public EV charging infrastructure. Four investments have been made from the CIIF so far: InstaVolt, Liberty Charge, char.gy, and Zest.
- £211 million of government funding confirmed for battery research through the Faraday Battery Challenge.
- Green Finance Institute - Coalition for the Decarbonization of Road Transport takes a finance first approach on policy to implement market-based solutions for the UK battery sector.

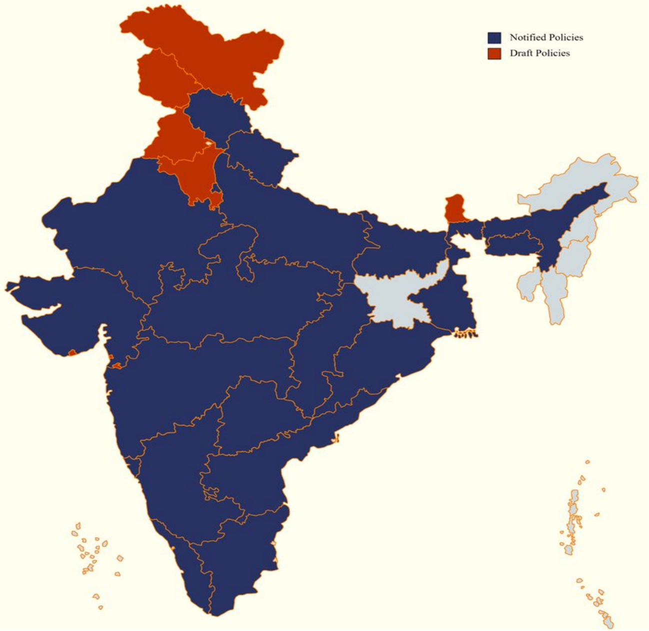


India | Cell Manufacturing Auction Results & Regulations

Federal & State Policies

Auction results were announced in 2022 with the facility to be set up within a period of two years. The incentive will be disbursed over a period of five years on sale of batteries manufactured in India. 3 bidders selected: Reliance New Energy Limited, Ola Electric Mobility Private Limited and Rajesh Exports Limited for incentives equivalent to ~$2.2 B USD with capacities allocated by the Ministry of Heavy Industries under the PLI Program. Private players are expected to create battery manufacturing capacity to the tune of ~95 GWh.

State Consumer/Demand Incentives	State Industry/Supply Incentives
• Segment-wise subsidy incentives of up to Rs 10,000/kWh ($USD 125 / KwH) • Early bird discounts • Scrappage benefits • Road tax and registration fee waive off • SGST amount reimbursement on purchase of EV • **Benefits offered over and above the Federal Government incentives**	• Land allocation for EV / battery parks • Setting up of incubation centers • Subsidy offered on capex on land value • Subsidized energy costs • Interest-free loans • State-specific Production Linked Incentives



Indonesia & Australia | Commodities Giants

Different Pathways On Supply Chain Development

Indonesia	Australia
• Indonesia wants to develop an integrated electric vehicle EV supply chain and become an EV battery producer and exporter. Southeast Asia's largest economy has the ambitious goal to make batteries with a capacity of 140 gigawatt hours (GWh) in 2030. • Deputy Minister of the Ministry of State-Owned Enterprises (BUMN Pahala) Nugraha Mansury said 50 GWh could be exported abroad. The rest, according to Pahala, will be used by the Indonesia Battery Corporation (IBC) to produce electric vehicles in the country. • The value of the investment needed is estimated at IDR 238 trillion (USD $17B). • Indonesia's first battery plant under construction is a 50:50 joint venture of Hyundai and LG Eenergy Solutions and in proximity to Hyundai's EV plant east of the current capital Jakarta.	• Government support has helped Australia become a global leader in lithium mining and refining. • Development of new copper and nickel mines have committed to achieving net zero greenhouse gas emissions to help gain EPA approval. • Australia's *Critical Minerals Strategy: Discussion Paper* doesn't mention national security or China, but hints at Australian concern about China's domination of supply chains for critical minerals. • Future Battery Industries sets goal to develop a national battery strategy. • $2.2-$2.8 billion sought to develop Australia's clean energy infrastructure.

East Asia | Maintaining Incumbency

New efforts to protect market share

China	Korea	Japan

• Purchases of new energy vehicles (NEVs) that occur between January 1, 2023, and December 31, 2023, will continuously be exempted from vehicle purchase tax.
• Only NEVs included in the List of NEV Models Exempted from Purchase Tax are eligible for tax exemption.
• “Supportive industrial policies” helped keep China in the top spot for the third time in a row in BloombergNEF’s (BNEF) global lithium-ion battery supply chain ranking.
	• Government-backed battery alliance to better source key metals in a bid to support the country’s battery industry: Hyundai, LGES, SK On, Samsung SDI, Posco Chemical.
	  ○ The Ministry of Trade, Industry and Energy said South Korean companies planned to invest a combined KRW50trn (US$35bn) locally by 2030 to develop advanced technology for secondary batteries, used mostly in EVs, and in factories.
	  ○ KRW19.5trn is allocated for research and development by 2030 with a further KRW30.5trn to be spent on domestic facility investment.
		• Specialist panel tasked with formulating battery strategy also set a target of securing 30,000 trained workers for battery manufacturing and supply chains by 2030
		• The panel has already set targets for domestic production capacity of EV and energy storage batteries at 150 gigawatt hours by 2030, and global capacity of Japanese makers at 600 GWh.
		• An estimated 3.4 trillion yen ($24 Billion USD) from private and public sector needed for development.
		• Japan asked the United States to be more flexible on electric vehicle (EV) purchase incentives for non-American carmaker

Global NGOs & Industry Groups | Shaping Global Policy

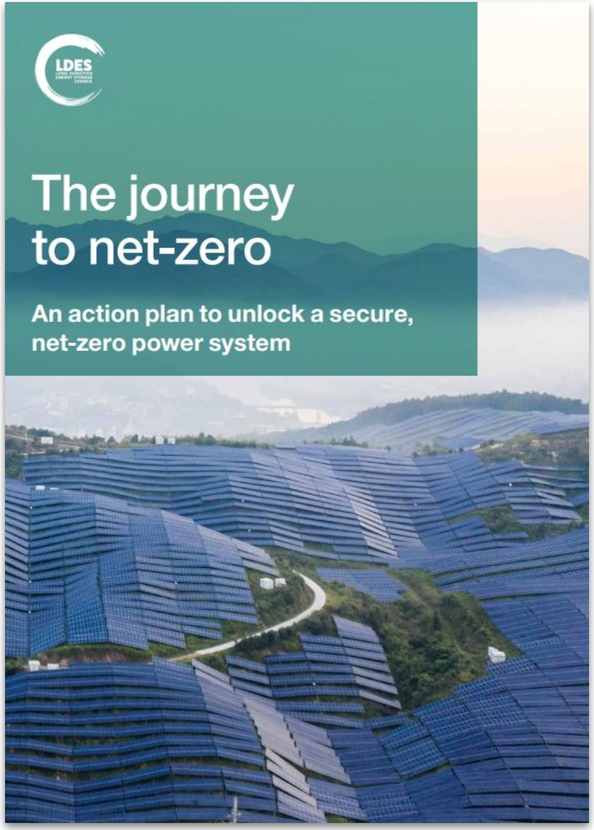
Policy Influencers, Powerful Stakeholders

Non-Governmental Organizations

- World Bank/IFC/IDA - COP 27
- United Nations - Call For 'Global Coalition On Battery Storage' by UN Secretary-General António Guterres
- ICCT - Supports a number of zero-emissions organizations and technical research on batteries.

Industry Groups

- Volta Foundation - Professional association with wide ranging programs including coalition building, workforce development, and policy advocacy
- Accelerating to Zero (A2Z) Coalition - Debut at COP 27
- Long Duration Energy Storage Council - Debut at COP 26, one year later Regulatory/Policy Options are a priority topic
- Zero Emissions Transportation Association - Release of Annual Report
- Global Battery Alliance - Businesses - Governments - Academic partnership helping ensure regulatory compliance through Action Partnerships like the Battery Passport.



Section 5
Predictions

Predictions | The next 12 months

1. Investments into batteries and EVs will continue to accelerate relative to 2022 levels, particularly in themes related to local and regional battery manufacturing, battery materials, components, equipment supply chain, and EV infrastructure. Funding for battery and EV investments to top $45B in 2023.

2. Cell-to-Module and Cell-to-Pack designs will reach maturity and be commercialized in serial production vehicles.

3. Cost of battery raw materials will increase as supply chain capacity lags soaring demand. Cathode active materials prices for NCM cathodes to see at least 10% increase in 2023.

4. Manufacturing scale-up for both pilot-scale and gigafactories will encounter growing pains particularly in the USA and Europe. At least 5 new delays to production timelines will be announced in 2023.

5. EV prices for consumers will fall as global OEMs compete to capture market share in a race to reach economy of scale. ASP (average sales price) for similar EV product lines will decrease by at least 10% in 2023.

6. Novel battery technologies will receive attention for addressing beyond-EV applications such as grid storage, wearables, drones, robotics, IoT, and others. At least 5 new or existing companies will be funded to make batteries for beyond-EV markets.

7. The US will require assistance from other countries in order to jump-start its domestic battery supply chain and manufacturing capacity. IRA incentives will be open to countries beyond the 20 currently listed free-trade-agreement countries with the US.

8. EV market penetration continue to accelerate - global EV sales will top 10 million passenger vehicles for the first time.

Outro

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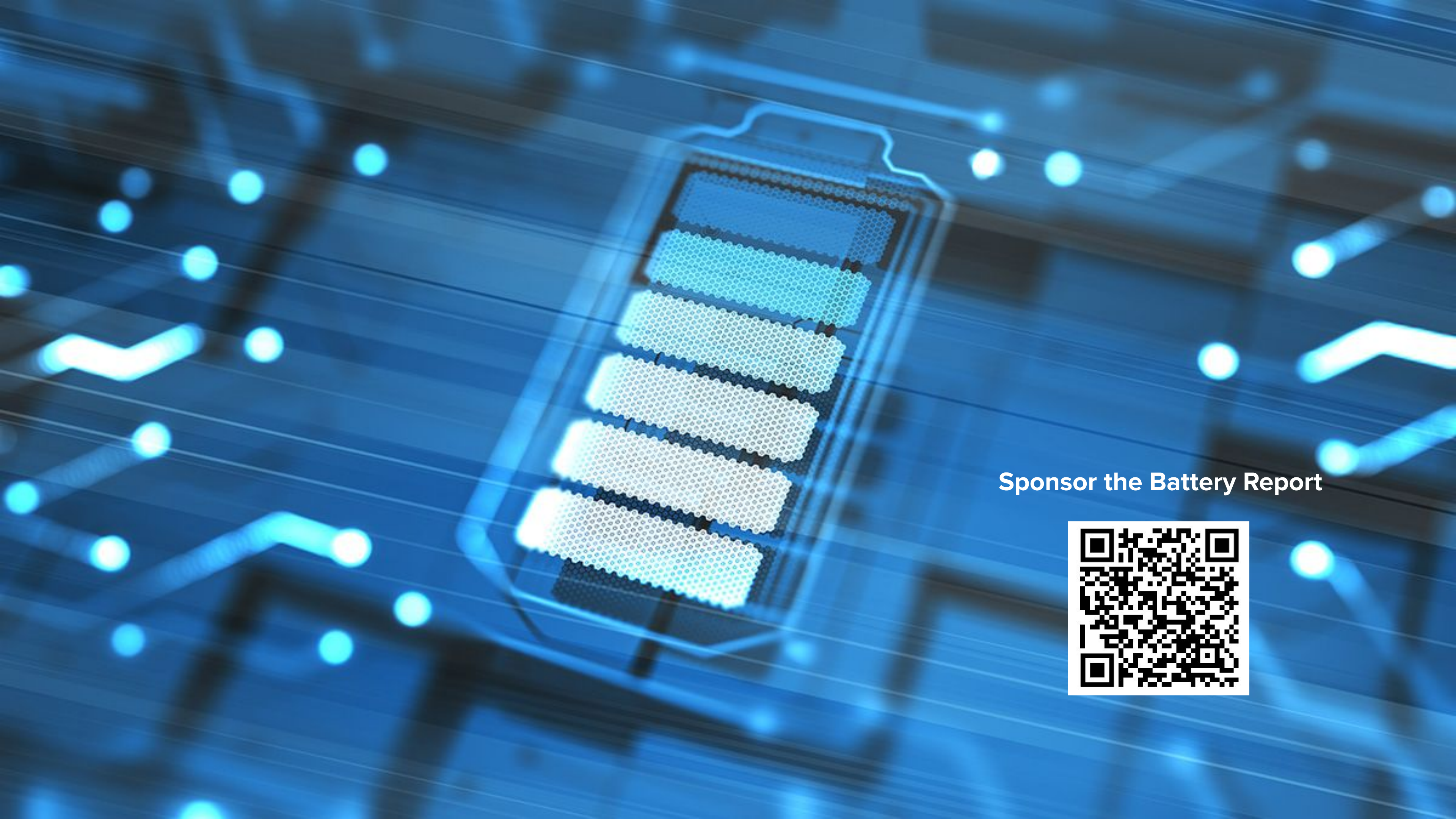
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