2023 | BATTERY REPORT

VF | VOLTA FOUNDATION

Revision: 2024042601

> ***"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 2023. This report seeks to provide a comprehensive and accessible overview of the current state of battery industry, research, talent, and policy. We hope to catalyze in-depth conversations on the state of batteries and its trajectory for the future.

We consider the following key dimensions in our report:

01 Industry	**Commercial milestones in battery development and manufacturing**
02 Academia	**Academic breakthroughs in fundamental battery science**
03 Talent	**Supply, demand, and insights on talent working in the field**
04 Policy	**Government targets, incentives, regulations, and their implications**
05 Predictions	**Trends we believe are likely to happen in the next 12 months**

Disclaimer: The views expressed herein are solely those of the authors, and have not been reviewed or approved by any other organization, agency, employer or company. The primary purpose of this work is to educate and inform. The Content is for entertainment and informational purposes only and you should not construe any such information as investment, financial, or other advice. Data and information is from publicly available sources and often self-reported by the companies. The authors declare no conflicts of interest in producing this report.

The Battery Report is a project by:

VF | VOLTA FOUNDATION

Sponsor The
Battery Report

Thank you

to our Members, Partners, and Sponsors

Albemarle
Anaphite
BECKHOFF
BTE BLACKTEAL ENERGY
Bry-Air EST. 1964
Coreshell

COVALENT METROLOGY
eatron TECHNOLOGIES
ELECTRA
ESi
Factorial
Fastmarkets

Ford
GLIMPSE
Group1.ai
Henkel
Honeywell
IKA designed to work perfectly

INOUE
iontra ENERGY UNLEASHED
JuliaHub
LYTEN
MONOLITH
Mühlbauer High Tech International

OneD BATTERY SCIENCES
piper maddox
TESCAN
SEPION TECHNOLOGIES
SES
SIEMENS

STEER
Strativ
UZ ENERGY
VOLTAIQ
Waters™ | TA Instruments
zitara

01 Industry

The Volta Foundation is an independent non-profit professional association dedicated to supporting the growth of the Battery Industry.

01 Industry | Overview

2023 marked a year of continued growth and calibration of the global battery industry - passenger EV sales topped 10M for the first time, representing 32% year-on-year growth in spite of higher interest rates. The average price paid for a new EV has declined by 25% over the past year, thanks in part to an EV "price war" as manufacturers compete for market share, bringing the average price paid for a new EV to just 4% higher than the overall new car market average. The cost of lithium has dropped 80% since its peak in late 2022, causing consternation for mining companies, but also contributed to lowering battery cell-level prices by 16% to $107/kWh.

Major trends include a dramatic acceptance by nearly all major OEMs of the NACS charging standard. Cell formats trending towards large-format prismatic cells influenced by continuing LFP adoption. 7 TWh of battery manufacturing capacity has been planned globally before 2030, with China accounting for 68.5% of this capacity, and the majority of the North American and European capacity being focused on NMC chemistries. In terms of regulations, US and EU governments have outlined official guidance over the past year to ensure greater security in the sourcing of critical minerals and developing a domestic battery supply chain.

BESS is a nascent yet rapidly growing market, opportunities and challenges remain for financing, integration, regulations, and battery chemistries to be developed to better support the growth of this segment.

Advanced cell chemistries continue to make progress towards commercialization, prime examples include LMFP, Na-ion, Sulfur, and Li-metal chemistries, while innovations in mining, supply chain, manufacturing, software, and other enabling technologies continue to be the focus for commercial R&D and entrepreneurial energy in the space.

Notable Events
Industry Value Chain
Finance
Cell Costs
Cell & Pack Manufacturing
Applications
Safety
Chemistry & Cell Components
Raw Materials
Recycling
Software & Analytics

Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

Recycling

Software & Analytics

Notable Events | January

Week 1

TESLA

Piedmont Lithium amends agreement with Tesla to supply spodumene concentrate.

Stellantis and Archer Aviation expand partnership to manufacture electric vertical take-off and landing (eVTOL) aircraft.

Week 2

Ford partners with LG Energy Solutions on 30 GWh battery plant in Turkey, drops SK On.

Nio announces roll-out of battery swap stations in the UK in 2023.

LG Energy Solution and Honda Motor formally establish JV to produce Li-ion batteries in the US.

LG Energy Solution

Week 3

CATL
宁德时代

UL Solutions and CATL sign MoU for strategic cooperation to create safer deployment and use of battery energy storage systems and EV batteries.

24M is selected to receive $3.2M in funding from the US Department of Energy Advanced Research Projects Agency-Energy (ARPA-E).

Britishvolt is declared insolvent.

BRITISHVOLT
POWER ON

Week 4

UK's Faraday Battery Challenge awards £27M of grants to various organizations for research-to-commercialization work

ChargePoint and Stem partner to accelerate deployment of EV charging and battery storage solutions.

Nth Cycle introduces premium domestic MHP (Mixed Hydroxide Precipitate) Product.

NTH CYCLE

Lotus Tech announces plans to go public in the US via SPAC.

Notable Events | February

Week 1

GM invests $650M into Lithium Americas to develop Thacker Pass Mine.

Umicore announces plan to source nickel from Terrafame.

Our Next Energy (ONE) raises $300M at $1.2B valuation, the latest unicorn in the battery industry.

Week 2

Ford cuts Rivian stake from 11% to 1.15%.

Redwood Materials receives conditional commitment for $2B Department of Energy loan for battery materials.

Posco Chemical locks in $32.6B order from Samsung SDI to manufacture cathode materials for EV batteries.

Week 3

Ionblox raises $32M Series B funding from Lilium, Applied Ventures, Temasek and Catalus Capital.

Volkswagen announces five-year plan to accelerate EV production and software strategy.

Nano One is awarded $10M from Sustainable Development Technology Canada.

Week 4

Ford announces $3.5B partnership with CATL to build LFP battery plant in Michigan.

Arrival announces $50M equity capital commitment to strengthen balance sheet and reduce debt by 38%.

Nanograf raises $65M Series B for silicon oxide anodes.

EO Charging secures $80M equity investment from Vortex Energy and Zouk Capital to expand EV fleet charging.

Li-Cycle receives conditional commitment for $375M loan from US DOE ATVM Program.

Hina Battery in China becomes first to put sodium-ion batteries into EVs.

Stellantis invests $155M to buy a minority stake in a copper mine in Argentina.

Tesla announces $5B factory in Mexico marking a push to broaden operations outside the US.

Tesla orders $2.9B of battery materials from South Korea-based cathode producer L&F Co.

Notable Events | March

Week 1

Tesla cuts U.S. Model S and Model X prices between 4% and 9%.

American Lithium Energy secures $13.2M in grants from the California Energy Commission to build pilot lithium-ion manufacturing facility.

Samsung SDI plans to build battery plant with GM.

Our Next Energy (ONE) announces plans to build $500M battery storage system manufacturing facility in West Virginia.

Week 2

Volkswagen announces first North American EV Battery Plant in Ontario.

Cirba Solutions and Jacobs form strategic alliance to expand manufacturing capacity across North America for EV battery materials.

CATL delays plans to raise $5B in Switzerland as regulators in Beijing raise concerns.

Volkswagen pauses on battery plant in Europe, prioritizing North American factory.

Week 3

Amprius announces 500Wh/kg power cell aimed at aviation market.

Gotion pauses battery plant in Big Rapids Township, Michigan.

Posco Future M announces plans to build NCA cathode facility in South Korea with 30,000 tpa production capacity.

US and Japan reach deal on vital minerals for EV batteries.

Week 4

pH7 Technologies receives $16M in a Series A for clean extraction and recycling of critical metals.

Li-Cycle and KION Group form lithium-ion battery recycling partnership and Li-Cycle announces new facility in France.

BMW Group announces new assembly site for high-voltage batteries in the Straubing-Bogen.

Gotion and Edison Power partner on energy storage and battery recycling in Japan.

Notable Events | April

Week 1

Redwood Materials expands partnership with Volkswagen of America to collect more end-of-life batteries from consumer electronics.

Poland overtakes the US as the world's second largest producer of lithium-ion batteries.

Stellantis and BMW announce talks with Panasonic over new EV battery plants.

Tesla confirms plans for second plant in Shanghai.

Week 2

Volkswagen announces investment of $1.1B in new R&D and procurement center for EVs in Hefei, China.

24M Technologies is awarded $3.8M contract from the United States Advanced Battery Consortium.

Samsung SDI opens new battery research center in Shanghai.

Volkswagen announces plans to build EV battery ecosystem in Indonesia, partnering with Vale, Ford and Zhejiang Huayou Cobalt.

Week 3

Freyr announces plans to cut gigafactory ramp time by at least 50% in partnership with Siemens.

6K Energy announces investment of $250M in new cathode plant in North America.

Novalith raises $23M to build processing plant using soda water to extract battery-grade lithium from ores more efficiently than existing techniques.

Week 4

Sila introduces new Titan Silicon anode for EVs.

Samsung SDI and GM announce $3B joint venture for battery manufacturing.

ElevenEs announces European LFP battery plant, with 500 MWh/yr capacity by 2024.

U.S. and South Korea sign MoU to expedite development of EV battery manufacturing in the US by South Korean companies.

Japan provides $1.8B in subsidies for energy storage batteries.

Notable Events | May

Week 1

QuantumScape announces plan to target smartphone batteries.

Thailand in talks with CATL and other battery manufacturers to build production facilities.

Tesla Giga Berlin starts production of Model Y with BYD batteries.

Hozon to produce EVs in Thailand for Southeast Asian market.

Week 2

Glencore and Li-Cycle announce plans for largest battery recycling plant in Europe, capable of processing 50 to 70 ktpa of black mass.

EVE Power announces plans to build $1.1B cell plant in Hungary.

Tesla breaks ground on $375M lithium refinery factory in Texas.

Honda and GS Yuasa establish JV for battery development.

Week 3

Microvast denied $200M grant from US Department of Energy after national security concerns.

Ganfeng Lithium announces mass production of solid-state batteries.

Energy and Pylon Technologies form JV to supply Europe with LFP batteries.

Morrow Batteries raises $52M to continue development in southern Norway, first factory to open in Q1 of 2024.

Stellantis resumes construction of $3.7B battery plant after Ontario government increases financial support.

Week 4

Ford EVs slated to use Tesla's supercharger network by early 2024.

Hyundai and LG announce $4.3B plant in Georgia to build batteries for EVs.

France opens first EV battery factory in partnership between TotalEnergies, Mercedes-Benz, and Stellantis.

GM and POSCO secure $224M from Canada's federal government to build battery materials facility.

Form Energy breaks ground on $760M battery plant with annual capacity of 550 MWh.

Toyota announces additional $2.1B investment for North Carolina battery plant.

Notable Events | June

Week 1

Panasonic to boost battery output at Tesla's Nevada Gigafactory by 10%.

ForgeNano raises $50M in Series C to build out battery production line.

Tata Group announces plans to build $1.6B EV battery plant.

Stellantis and Galloo form JV to recycle EV batteries.

Week 2

Saudi Arabia's Ministry of Investment signs $5.6B deal with Chinese EV maker Human Horizons.

Toyota unveils plans to make solid-state batteries for its EVs, aiming for 3.5M EVs by 2030.

RecycLiCo and Zenith Chemical announce $25M Li-ion battery recycling JV in Taiwan.

Week 3

Tesla announces that it has produced 10M 4680 battery cells at Giga Texas.

CATL announces plans to invest $1.4B to build lithium extraction plants in Bolivia.

Ford and SK On secure $9.2B loan to build 3 battery plants producing up to 120 GWh in the US, one in TN and two in KY.

Northvolt receives $400M investment from Canadian pension fund.

Week 4

Aston Martin and Lucid announce collaboration on new EVs.

Lordstown Motors files for bankruptcy.

Altris presents Prussian White cathode material with capacity of 160 mAh/g.

Nobel laureate John Goodenough, whose work led to invention of Li-Ion batteries, passes away at 100.

Porsche announces $21.9B investment in development of EVs and software.

Notable Events | July

Week 1

Nikola discontinued operations at battery supplier Romeo Power after buying the company for $144M in 2022.

UK EV maker Arrival cancels planned SPAC.

Colombia announces plans to convert 290 MW coal plant to solar PV and battery storage facility.

Tesla announces that it has produced 479,700 EVs and delivered 466,140 EVs in Q2 of 2023.

Week 2

Gotion High-Tech signs strategic cooperation agreements with Siemens Digital Industrial Software and BASF.

EU finalizes regulations targeting 50% lithium recovery from waste batteries by 2027.

Fisker has sells $340M in convertible notes to support additional battery pack line.

Li-Cycle and EVE Energy sign MoU to collaborate and explore lithium-ion battery recycling solutions.

Mercedes-Benz picks Tesla's charging standard for North American EVs starting in 2025.

Week 3

Tata announces plans to build EV battery plant in the UK.

BYD announces plans to build battery and EV plant in India, targeting annual production of 100k EVs.

Graphite One awarded $37.5M DOD grant under the Defense Production Act.

Tesla sues Cap-XX over EV over supercapacitors patented by subsidiary Maxwell Technologies.

Week 4

Enevate and JR Energy Solution announce joint venture to build electrode factory in the US.

Lion Electric opens EV plant with capacity to manufacture 20k electric buses.

Stellantis and Samsung SDI sign MoU to build 34 GWh battery plant by 2027.

Posco announces investment of $92B through 2030 to transform its EV battery materials business.

ProLogium and MAHLE sign MoU to develop next generation solid-state batteries.

Notable Events | August

Week 1

QuantumScape raises $300M from public offering.

EVE Energy invests $422M in new battery plant in Malaysia.

LGES and Zhejiang Huayou Recycling partner on battery recycling JV.

GM announces that all Ultium-based EVs will have vehicle-to-home charging.

Proterra files for bankruptcy.

Week 2

John Deere invests $70M in offices and manufacturing in North Carolina.

ICL Specialty Products breaks ground on $400M plant to produce LFP cathode, 30 ktpa by 2025.

Lamborghini introduces its first EV model at 2023 Monterey Car Week.

Fisker adopts NACS, giving customer access to Tesla Superchargers by 2025.

Week 3

Ecopro BM, SK, and Ford invest $1.4B in new cathode facility in Quebec with capacity of 45 tpa.

Accure raises $7.8M Series A2 to predict lithium-ion battery failures with AI.

Northvolt raises $1.2B to expand to North America.

CATL unveila Shenxing EV battery that can charge 400 km in 10 minutes.

Novonix announces plans to build $1B graphite plant in Chattanooga.

Week 4

Redwood Materials raises $1B in Series D to expand battery materials operations in US.

BYD acquires Jabil's mobility business for $2.2B.

Hyundai and LG invest additional $2B into Georgia battery plant for total investment of over $7.5B.

Hyundai invests $400M for 5% stake in Korea Zinc to develop nickel value chain.

Xpeng acquires Didi's smart EV unit for $744M.

ENGIE acquires Broad Reach Power to expand energy storage operations.

Notable Events | September

Week 1

Geely Automotive's premium brand Zeekr files for IPO in the US.

Tesla Shanghai sues chip and auto parts maker Bingling Intelligent Technology for IP infringement.

Gotion acquires 25% stake in Slovak EV battery startup Inobat.

CATL announces plans to produce fast-charging Shenxing battery in Germany and Hungary.

KKR acquires 45% stake in energy storage developer Zenobe for $1B.

Week 2

Rimac partners with Eve Energy to use 46XX cells in battery packs.

Verkor raises $2.14B for Dunkirk EV gigafactory.

Lyten raises $200M Series B for lithium sulfur batteries.

Gotion announces $2B battery plant in Illinois.

Stellantis announces plans to expand global battery capacity to 400 GWh.

Week 3

Gotion and InoBat announce plans to build 20 GWh battery plant in Europe by 2026 to supply VW EVs.

LGES raises $1B in bonds to finance for EV battery factories.

Northvolt announces plans for $5.2B battery factory in Quebec.

BYD launches new $31k Dolphin EV in Mexico.

Week 4

Varco Energy secures $70M in debt financing from NatWest to fund BESS projects.

SK Ecoplant and Ascend Elements announce JV to build battery $66M recycling facility in Kentucky, with capacity to process 12 ktpa of black mass.

Toyota implements self-propelled assembly lines and massive die casting to catch up in EV race.

US State Department announces plans to build battery factories in Africa for surging EV battery demand.

Notable Events | October

Week 1

LGES invests $3B to supply Toyota with EV batteries.

US Treasury Department allows EV tax credit to be used as point-of-sale rebate starting in 2024.

GM agrees to include EV battery manufacturing under UAW agreement.

Encorp and Natron Energy announce hybrid power platform using sodium-ion batteries.

Shanshan announces $1.35B synthetic anode plant in Finland with a capacity of 100 ktpa.

Week 2

US EV sales surpass 300k in Q3 of 2023.

Toyota and Idemitsu partner to manufacture all-solid-state batteries.

Novonix demonstrates dry cathode synthesis process.

NIO completes 30 million global battery swaps, further proving the process's viability.

LG Chem secures $2.15B cathode materials deal with Toyota for U.S. plant.

Week 3

Umicore and AESC enter long-term supply agreement for EV battery materials in North America.

EnergyX raises $50M in Series B led by South Korean conglomerate Posco.

Albemarle withdraws non-binding offer to acquire Liontown resources.

Electric truck maker Volta Trucks files for bankruptcy in Sweden.

Nio files to expand the use of solid-state batteries to 11 more EV models.

Week 4

American Battery Factory breaks ground on LFP gigafactory in Arizona.

Stellantis invests $1.6B for 20% of Leapmotor to accelerate Leapmotor's sales in China and Europe.

Toyota invests additional $8B into North Carolina EV battery plant.

Factorial announces $50M battery manufacturing facility in Massachusetts.

E3 Lithium announces 99.78% pure battery grade lithium hydroxide from DLE.

Indian EV startup Ola Electric raises $384M, including $240M of debt, from Temasek and SBI.

Notable Events | November

Week 1

24M Technologies claims improvements in energy density with electrode-to-pack design.

Stellantis announces new $3.2B battery plant with 25% pay hike under UAW agreement.

Nio cuts 10% of workforce amid fierce competition.

Polestar partners with SK On battery cell modules for its upcoming Polestar 5 EV.

BYD announces first European EV plant in Hungary.

Week 2

Rivian announces $5B EV factory for next-gen R2 vehicles, creating 7,500 jobs in Georgia.

Lucid releases a vehicle-to-vehicle charging feature called RangeXchange.

LUCID

VOLVO MATRIX RENEWABLES

Volvo Battery Solutions acquires Proterra Powered commercial vehicle business line for $210M.

Matrix Renewables acquires 3,280 MWh BESS portfolio from Emeren.

Week 3

Stellantis and CATL sign MoU for production of LFP batteries in Europe.

Northvolt announces 160 Wh/kg sodium-ion battery for energy storage.

northvolt®

US Department of Energy announces $3.5B to strengthen domestic battery manufacturing.

Toyota admits it plans to make only 10k vehicles with solid-state batteries in 2030.

Toyota announces recycling agreement to source cathode and anode copper foil from Redwood Materials.

Week 4

Our Next Energy (ONE) cuts 25% of workforce.

Tesla introduces congestion fee for Superchargers.

EU announces $4.4B in grants for clean energy projects, including energy storage.

one
our next energy

VW partners with Magna Steyr to revive Scout EVs by 2026 in $492M deal.

Lilium receives EU regulatory approval to design and operate its eVTOLs.

Gotion InoBat JV signs MoU with Slovakia to build 20 GWh EV battery plant.

LG and SK On lays off workers in Michigan due to sluggish demand for EVs.

Notable Events | December

Week 1

EcoPro BM announces long-term supply agreement with Samsung for $33.5B worth of NCA cathode between 2024 and 2028.

Nornickel increases forecast for global nickel surplus from 200 to 250 kt.

AM Batteries raises $30M Series B led by Toyota Ventures.

Nth Cycle raises $44M Series B to scale metals recycling and refining.

Generac invests $30M for a minority stake in Wallbox.

Rivian lays off 20 engineers from in-house battery cell development team.

Week 2

Panasonic and Sila sign supply agreement to use Sila's silicon anode material for EV cells.

ZEEKR begins deliveries to new customers in Europe.

Lucid's CFO, Sherry House, steps down.

United Arab Emirates announces first battery recycling plant.

Our Next Energy (ONE) names Paul Humphries as CEO, replacing founder, Mujeeb Ijaz.

Wildcat Discovery announces US plant for nickel-free and cobalt-free cathodes.

Week 3

VinFast signs MoU with Marubeni to recycle used EV batteries.

TotalEnergies begins construction on 216 MW solar plant with 500 MWh of battery storage.

NIO receives $2.2B investment from Abu Dhabi's CYVN.

Hancock and SQM acquire Azure Minerals for $1.1B.

Eramet and Vibrantz Technologies announce long-term supply agreement for manganese ore.

Thailand approves $970M in subsidies to boost local production.

47.6% of new cars in EU are electric or hybrid.

Week 4

NIO unveils $112k flagship ET9 EV.

GM and Ford lose tax credits on many EV models and are adjusting sourcing to regain eligibility.

US Treasury announces rules for 45X clean energy manufacturing tax credit.

LG Chem breaks ground on $3.2B cathode materials plant in Tennessee.

Mullen announces that it has delivered 121 Class 3 trucks.

EU and UK delay tariffs on electric vehicles through 2026.

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

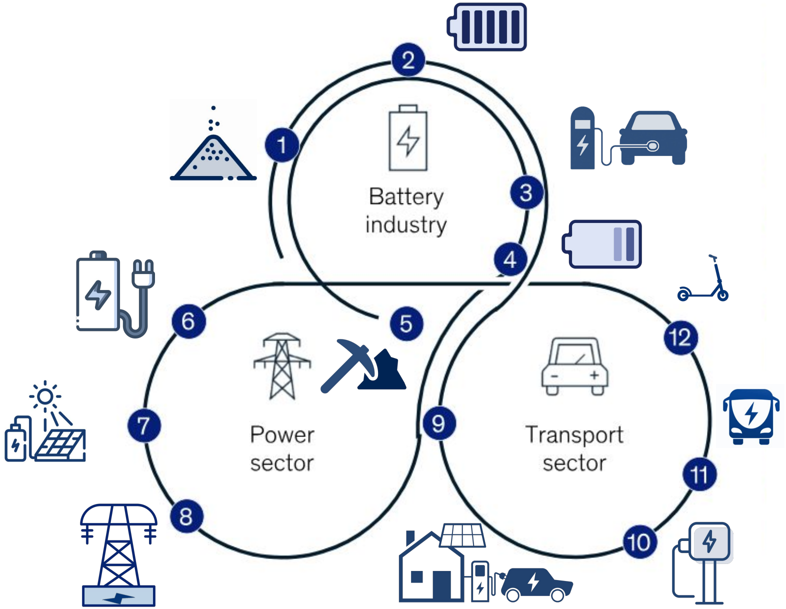
Recycling

Software & Analytics

Industry Value Chain

Circular Battery Value Chain

Expansion of global battery value chain is unlocking significant economic potential across multiple industries



1. Active materials
2. Battery cell and pack
3. Battery application
4. Battery repair and refurbish
5. Mining and Battery recycling
6. Battery 2nd life
7. Decentralized battery energy storage
8. Centralized battery energy storage
9. Vehicle to grid
10. Smart charging
11. Urban EV
12. Shared E-mobility

Source: McKinsey Li-ion Battery Demand Forecast 2030

Industry Value Chain

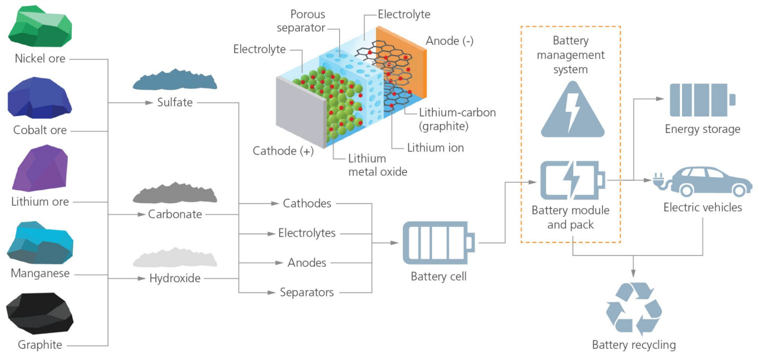
| Battery Industry Value Chain & Profit Margin Profile

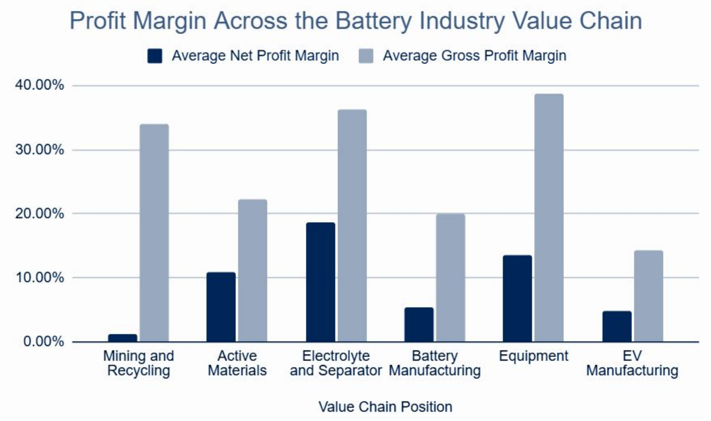
There is a wide range of profit margins and revenue profiles across the battery value chain

- The growing trend of vertical integration blurs traditional boundaries between upstream, midstream and downstream segments
- Cell & EV manufacturing companies capture more sections of the value chain (midstream & downstream). Despite having lower net profit margins compared to component businesses, they still dominate through their financial strength and scale.

- Mining and Recycling, Electrolyte & separator, and equipment companies enjoy higher gross profit margins due to lower Cost of Goods Sold. However, mining & recycling companies have low net profit margins due to high operating expenses (e.g. high upfront capex, licensing, permitting)

	Upstream		Midstream		Downstream	
	Raw materials	Materials processing	Cell component production	Cell manufacturing	Assembly	End users
2030 Total:	**Market: $58.4B** **CAGR: 15.2%**	**Market: $62B** **CAGR: 8.75%**	**Market: $25.4B** **CAGR: 30%**	**Market: $184B** **CAGR: 18.5%**	**Market: $74B** **CAGR: 21.2%**	**Market: $400B** **CAGR: 26.5%**





Data from Chinese publicly listed companies' financial report 2017-2022

Source: L.E.K. Research

Industry Value Chain

Incumbents And/Or Public Companies With >$1b Market Cap/Valuation*

Raw Materials

Lithium
- Albemarle
- SQM
- igo
- TQC TIANQI LITHIUM
- Allkem
- Livent
- MINERAL RESOURCES
- GanfengLithium
- Pilbara Minerals
- SINOMINE
- ZiJin
- SIGMA LITHIUM
- 青海盐湖工业股份有限公司 QingHai Salt Lake Industry Co.,Ltd.

Nickel
- VALE
- NORILSK NICKEL
- TSINGSHAN
- HUAYOU
- antam
- BHP

Cobalt
- GECAMINES
- ERG
- GLENCORE
- HUAYOU
- 盛屯矿业 CHENGTUN MINING
- CMOC

Materials Processing

Lithium Chemical
- Albemarle
- SQM
- canmax
- TQC TIANQI LITHIUM
- Allkem
- Livent
- 盛新锂能 CHENGXIN LITHIUM
- GanfengLithium
- Yahua

Nickel Chemical
- 力勤资源 LYGEND RESOURCES
- GEM
- HUAYOU
- BHP
- Brunp
- CNGR
- Terrafame

Cobalt Chemical
- HUAYOU
- GEM
- JINCHUAN 金川
- umicore
- 腾远钴业 Tengyuan Cobalt

pCAM
- CNGR
- GEM
- HUAYOU
- EcoPro
- JINCHUAN 金川

Cell Component

CAM
- Dynanonic
- 当升科技 EASPRING
- 容百科技 RONBAY TECHNOLOGY
- posco
- WANRUN NEW ENERGY
- BASF
- L&F Co., Ltd.
- umicore
- XTC
- 国轩高科 GOTION HIGH-TECH
- LG Chem

AAM
- BTR
- posco
- 杉杉 Shanshan
- KAIJIN 凯金
- PUTAILAI
- MITSUBISHI CHEMICAL
- SHINZOOM

Electrolyte & Separator
- 新宙邦 CAPCHEM
- AsahiKASEI
- SEMCORP
- TINCI
- SK
- 3M
- MITSUBISHI CHEMICAL

Cell Manufacturing

Cell
- CATL
- BYD
- LG Energy Solution
- Panasonic
- CALB
- SAMSUNG SDI
- FARASIS
- SK on
- LISHEN
- 国轩高科 GOTION HIGH-TECH
- northvolt
- TESLA
- SUNWODA
- EVE
- GREAT POWER
- Envision AESC
- TAFEL
- SVOLT
- BAK
- 瑞浦能源 REPT
- TIANNENG
- CB

System Assembly

Vehicle OEMs
- TESLA
- BYD
- GEELY
- HYUNDAI
- STELLANTIS
- SAIC
- BMW
- Mercedes-Benz
- GAC MOTOR
- Ford
- RENAULT NISSAN MITSUBISHI
- CHERY
- gm
- TOYOTA
- 长安汽车 CHANGAN
- GWM
- HONDA
- NIO
- XPENG

Energy Storage
- VISTRA ENERGY
- NEXTera ENERGY
- ABB
- CATL
- BYD
- TESLA
- 国轩高科 GOTION HIGH-TECH
- SIEMENS

Recycling

Recycling
- Brunp
- GEM
- 赣锋锂电 GanfengLiEnergy
- HUAYOU
- 杉杉 Shanshan
- umicore
- CNGR
- SungEel HiTech

* estimated as of December 2023

Industry Value Chain

| Startup And/Or Small Companies With >$30m Valuation*

Raw Materials

Lithium
- Lithium Americas
- Controlled Thermal Resources
- Lake Resources
- CriticalElements Lithium Corporation
- EnergyX
- Lilac solutions
- Core Lithium
- Summit Nanotech
- Novalith Li : innovated
- EnergySource Minerals
- European Lithium
- Liontown
- Cornish Lithium

Cobalt, Nickel
- CobaltBlue
- Impossible Metals
- KoBold Metals
- Jervois

Graphite
- NMG Nouveau Monde Graphite
- Renascor Resources
- Syrah Technologies
- talga

Materials Processing

Lithium Chemical
- Lithium Americas
- M Li
- RockTech Lithium
- Novalith Li : innovated
- Adionics The Advanced Ionic Solution
- Livista

Cobalt, Nickel Chemical
- Queensland Pacific Metals
- Jervois

pCAM
- nanoOne
- Ascend Elements
- SVX

Graphite and carbon
- Anovion
- Vianode
- Novonix
- sgl carbon

Other battery chemicals
- Koura
- pH7
- aepnus technology

Cell Component

CAM
- 6K
- Mitra Chem
- Stratus Materials
- IBU tec
- SVX
- Forge Nano
- Ascend Elements
- Redwood Materials

AAM
- amprius
- Sila
- Anovion
- nexeon
- Group14 Technologies
- Echion Technologies
- OneD Battery Sciences
- nyobolt
- Ionic Mineral Technologies
- Novonix
- E-NexT
- CarbonScape

Electrode
- 24m
- Dynami
- Coreshell
- Nanoramic
- Addionics
- Anaphite
- AM Batteries

Li-metal, Electrolyte, Separator
- Li-Metal
- Sepion Technologies
- Cuberg
- Sion Power
- sionic energy
- South 8 Technologies
- ionic materials

Cell Manufacturing

Lithium-ion Battery Cell
- Verkor
- Freyr
- PowerCo
- Morrow
- CellForce
- Enovix
- One our next energy
- microvast
- iM3NY
- ACC Automotive Cells Co
- amprius

Solid-state and Li-metal Cell
- QuantumScape
- Lyten
- ProLogium
- SES Beyond Li-ion
- Factorial
- BlueCurrent
- Solid Power
- 赣锋锂电 GanfengLiEnergy

Sodium-ion Battery Cell
- 中科海钠 HiNa Battery
- Natron Energy
- Zoolnasm
- Tiamat
- faradion
- Peak Energy
- 钠创 Natrium
- Transimage
- Unigrid

System Assembly
- Li Auto
- Leapmotor
- Neta
- Aiways
- HiPhi
- VinFast
- xiaomi
- Rivian
- Lucid
- Fisker
- Canoo
- Ola
- Rimac
- Volta Trucks
- Mullen
- One our next energy
- nyobolt

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

* estimated as of December 2023

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

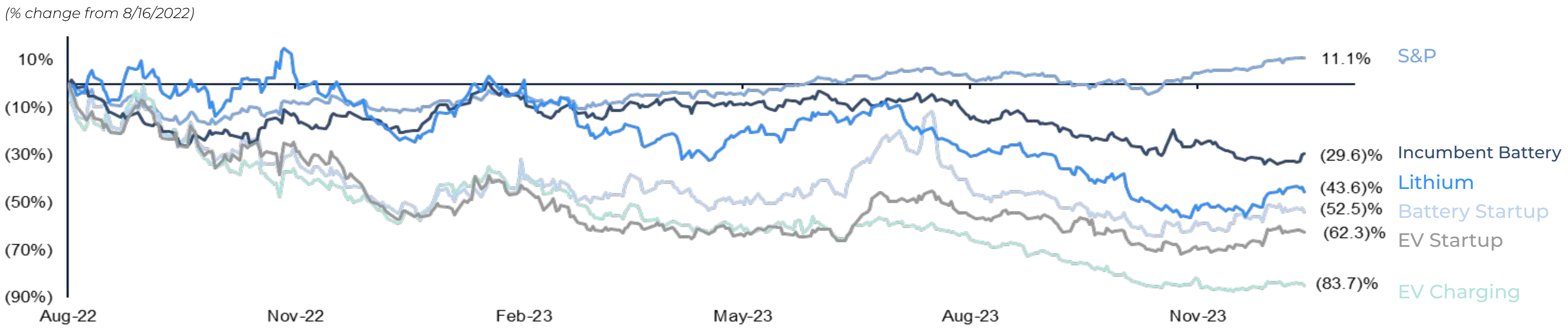
Raw Materials

Recycling

Software & Analytics

Finance | Public Equity Market Performance

Despite passage of the Inflation Reduction Act, most public battery companies have traded down in 2023 in context of the macro economic environment and the impact of higher interest rates on hard tech companies.



Categories	Incumbent Battery	Lithium	Battery Startup	EV Startup	EV Charging
Key Drivers	Lower than expected demand from some legacy EV OEMs in H2 2023 / negative sentiment for 2024	Lower LCE spot price down ~70% from 2022 highs	High CapEx requirements and delays in commissioning and scaling of plants	Timeline to scale / achieve volume, lower than forecasted demand	Low utilization, unforeseen maintenance issues, and poor user experience
Constituents	LG Energy Solution BYD CATL SAMSUNG SDI	SIGMA LITHIUM Albemarle Standard LITHIUM Livent PIEDMONT LITHIUM	QuantumScape FREYR nanoOne microvast ENOVIX	RIVIAN polestar FISKER LUCID VINFAST	chargepoint EVgo blink wallbox TRITIUM

Source: CapIQ (12/29/2023), Press Releases (1)Index weighted by market cap

Finance

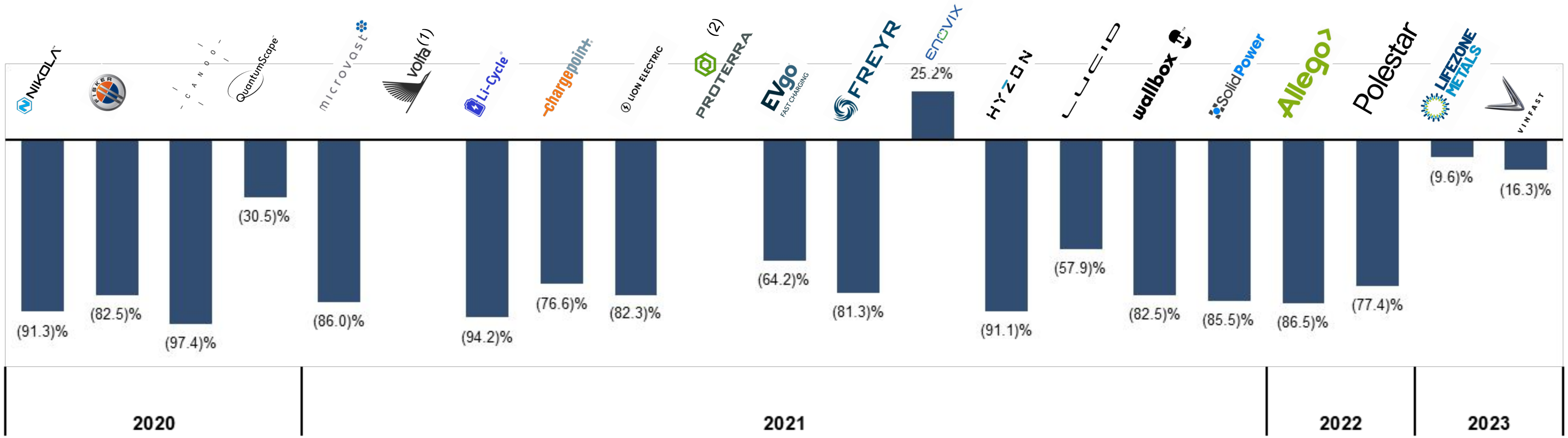
| SPAC Performance

Battery related SPACs have performed in line with the broader battery equity capital markets.

Energy transition SPACs trading price relative to initial par value

(% change from $10 SPAC par price)

Higher costs of capital driven by interest rates hikes have led investors to cycle out of pre-revenue companies with higher capital requirements



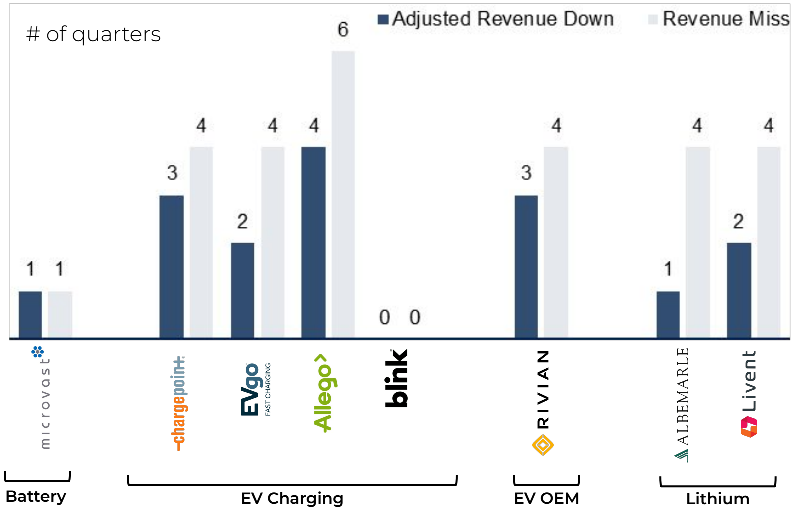
Source: CapIQ 12/29/2023 (1) Jan 2023, announced that Shell would acquire Volta (2) Nov 2023, Proterra sold to Volvo and Phoenix Motors

Finance | Issues Facing Public Battery Companies

Limited communication to investors and bearish investor sentiment has dragged on battery stocks

Revenue Estimate Adjustments and Misses since 2022

Many battery companies have been limiting communication to investors about the pace of growth, being cautious about the statements they make, leading to a disconnect between Wall Street analysts and company performance



Change in Short Interest Since Start of 2023 (% of public float)

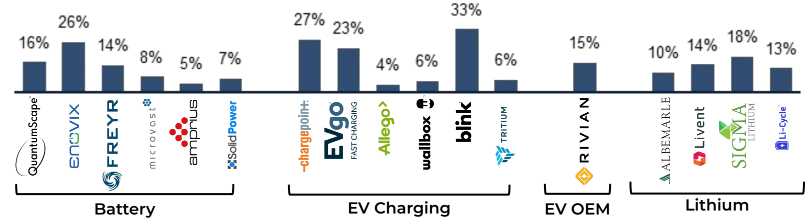
13 companies have seen an increase in their respective short interest as a % of public float, suggesting market participants have grown increasingly bearish

Decrease	Increase <5%	Increase <10%	Increase >10%
QuantumScape EVgo FAST CHARGING Allego TRITIUM	Li-Cycle amprius SolidPower wallbox blink Livent microvast	ALBEMARLE FREYR RIVIAN	ENOVIX chargepoint SIGMA LITHIUM

Current Short Interest

4 companies have a short interest in excess of 20%, suggesting a highly pessimistic outlook by public markets

(Short interest as % of public float)



Source: CapIQ(12/29/2023), Wall Street Research, Press Releases (1) Chart reflects companies which had revenue greater than zero for the period. "Revenue Revised Down" reflects a greater than 5% decrease in the analyst estimate in revenue 3 months prior to earnings release to the estimate the day of earnings. "Revenue Miss" reflects a greater than 5% actual revenue miss from the analysts estimates prior to quarterly reporting

Finance

| Select Equity Investment Into Batteries

Public market performance and high interest rates provide a difficult equity capital funding backdrop

	chargepoint	QuantumScape	EVgo FAST CHARGING	LUCID
Public Equity	$175mm At the market offering capital strategy to bolster the balance sheet Oct 2023	$300mm Following-on offering Working capital and GCP Aug 2023	$125mm Following-on offering GCP May 2023	~3,000mm Following-on offering Working capital and GCP May 2023

	one our next energy	REDWOOD MATERIALS	VERKOR	LYTEN
Growth Equity	$300mm Series B PMV $1.2bn Feb 2023	$1,000mm Series D PMV >$5.0bn Aug 2023	€850mm / €600mm Series C / debt financing Total raise > €2bn Sep 2023	$200mm Series B Total raise > $400mm Sep 2023

- Volumes in the U.S. equity capital market rebounded in 2023 to ~$170bn off of a recent history lows of ~$100bn in 2022.
- The only battery related primary issuance were VinFast's and LifeZone Metals deSPAC's.
- Climate tech venture capital fund raising dropped 40% in H1'23
- Secondary issuances generally favored ATM (at the market) facilities given the ability to sell shares into the market over time rather than selling large blocks through over-the-counter
- Notable M&A transaction include:

Acquiror		Target
REDWOOD MATERIALS	Sep 2023	REDUX
arcadium lithium	May 2023	Allkem Livent
Shell	Jan 2023	volta
VOLVO	Nov 2023[2]	PROTERRA

Source: Deal Logic, Public Filings, Press Releases, CTVC | PMV: Post Money Valuation; GCP general corporate purpose (1) $1.2bn in in the over-the-counter market sale of 173,544,948 shares common stock as well as $1.8bn sale of 265,693,703 shares of common stock to Ayar Third Investment Company (2)Reflects the sale of the battery business

Finance

| Select Credit Investment Into Batteries and EVs

Convertible debt and green bonds have broadened the access to capital for battery companies

northvolt

CAD 200mm

Convertible Bond Issuance

Use: Battery factory outside of Montréal

Nov 2023

RIVIAN

$1,725mm[1]

3.625% Green Convertible Bond Issuance

Use: projects related to clean transportation

Oct 2023

northvolt

$1,200mm

Convertible Bond Issuance

Use: European & North American expansion

Aug 2023

RIVIAN

$1,500mm

4.625% Green Bond Issuance

Use: Projects related to clean transportation

Aug 2023

FISKER

$340mm

0.0% Convertible Bond Issuance

Use: GCP, Battery pack, future development

Jul 2023

ENOVIX

$150mm

3.0% Convertible Bond Issuance

Use: manufacturing line in Malaysia

Apr 2023

northvolt

$1,100mm

Convertible Bond Issuance

Use: European battery manufacturing

Jul 2022

chargepoin+

$300mm

3.5% / 5.0% PIK toggle Convertible Bond Issuance

Use: Support growth initiatives

Aug 2022

- As a result of the difficult equity market environment and the maturing business profile, corporate issuers have explored alternative financing options, such as debt and green bonds
- Convertible bonds provide issuers with a low cost of capital and defer possible share dilution. Issuers of convertible bonds are able to issue at a discount to the respective vanilla bond, given the embedded equity optionality
- Private credit has been a growing capital base from alternative asset managers. 2023 marked the announcement of several large mega fund private credit / flexible capital funds dedicated to clean transition. These new funds will likely serve as a source financing to support the large CapEx needs for the battery industry
- With 9,920GWh of projected battery gigafactory capacity by 2030 across 410 plans (up from 1,722GWh in 2022), there will be an increasingly large demand to access large quantities of low cost capital

Source: Public Filings, Press Releases,

Finance | Private Capital Investors Investor Base

$121bn of total private climate assets under management (AUM) across 207 Early-stage VCs, Corporate VCs, Growth Equity, Infrastructure , and Private Equity funds since Jan 2021

Investor Type	Early Stage VC	Corporate VC	Late Stage VC / Growth Equity	Private Equity	Infrastructure	Sovereign Wealth Fund / Pension
Investment Characteristic	Early-Stage venture investments into pre-revenue / pre-product fit companies Seed – Series A	Early-Stage investments in pre-revenue companies. Likely synergies with VC's corporate parent. Corporate VC helps in validating new technologies	Revenue generating companies pre-earnings with revenue backlog Series B – Series D	Control investments into mature companies with defined cash flow profile and clear customer relationships	Asset heavy project based financing supported by long term offtake contract	Patient long term investors with a national mandate to progress climate sustainability
Investor Base	ARCTERN VENTURES ACTIVE IMPACT INVESTMENTS AeraVC ANZU PARTNERS AVAANA aiim Baruch FUTURE VENTURES Breakthrough Energy ClearSky CLOSED LOOP partners Earthshot VENTURES EIF ECOSYSTEM INTEGRITY eCAPITAL ENTREPRENEURIAL PARTNERS ENERGY IMPACT PARTNERS Keyframe material impact Prelude Ventures RIVERSTONE CAPITAL GROUP TIGERGLOBAL +VOLTA ENERGY TECHNOLOGIES	ABB TECHNOLOGY VENTURES bp ventures BMW i Ventures ENGIE New Ventures gm VENTURES Chevron Technology Ventures HITACHI Inspire the Next PORSCHE VENTURES HYUNDAI CRADLE LG Technology Ventures Microsoft Climate Innovation Fund Shell Ventures SOLVAY Solvay Ventures woven capital SAMSUNG SAMSUNG VENTURE INVESTMENT TDK TDK VENTURES TOYOTA VENTURES THE CLIMATE PLEDGE VALE Vale Ventures	Breakthrough Energy BAILLIE GIFFORD catalus Decarbonization Partners ENERGY IMPACT PARTNERS FIFTH WALL INVESTCORP KOCH MKB s2gventures a Builders Vision team SoftBank Vision Fund TPG RISE CLIMATE +VOLTA ENERGY TECHNOLOGIES	APOLLO Clean Energy Transition Ara Partners ARCLINE INVESTMENT MANAGEMENT CLEANHILL PARTNERS ECP	CIP Copenhagen Infrastructure Partners EQT GENERATE KKR climate-related investment fund VISION RIDGE PARTNERS zouk	ADIA CPP Investments GIC KI صندوق الاستثمارات العامة TEMASEK QIA جهاز قطر للاستثمار QATAR INVESTMENT AUTHORITY

Source: Pitchbook CTVC

Finance | Mega Fund Private Capital Announcements

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

	APOLLO Clean Energy Transition	KKR Global Climate	Brookfield Emerging Markets Transition	TPG RISE CLIMATE	JUST CLIMATE by generation	NGP	Morgan Stanley 1GT climate
Close / Release	**Spring 2023**	**Summer 2023**	**Winter 2023**	**Spring 2022**	**Summer 2023**	**Summer 2023**	**Spring 2023**
Amount	**$4bn**	**N/A**	**>$1bn**	**$7.3bn**	**$1.5bn**	**$700mm**	**$500mm**
Mandate	• Invest into a diversified global portfolio of yield and hybrid investments • Focused on decarbonization as an overarching theme rather than a specific asset class • Positioned to address the significant gaps that exist in the capital markets for climate and transition financing	• Investment scope includes scaling battery technologies, EV fleet electrification and EV Charging, decarbonizing agriculture and steel • The fund’s mandate is “climate” which encompass decarbonization of sectors like transportation, food, and industry	• Deploy capital exclusively for emerging and developing markets • supporting the four key pillars that underpin COP28’s Action Agenda: Energy Transition, Industrial Decarbonization, Sustainable Living and Climate Technologies	• Invests in energy transition, green mobility, sustainable fuels and sustainable molecules, and Carbon Solutions • Growth-stage investments in innovative climate solutions • Fund’s performance fee dependent on ability to deliver on greenhouse gas abatement goals	• Focused on hard to abate sectors which include energy, mobility, industry and buildings — in order to generate outsized emissions abatement in the next decade	• Provide growth capital to companies that drive / enable the growth of renewable energy, the electrification of transport, the efficient use of energy and resources and the management/reduction of carbon emissions • Focused on real assets within the energy transition	• focused on investments in growth-stage companies that will seek to collectively avoid or remove one gigaton of carbon dioxide-equivalent (CO2e) emissions from the Earth’s atmosphere

Source: Press Releases, CTVC

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

Recycling

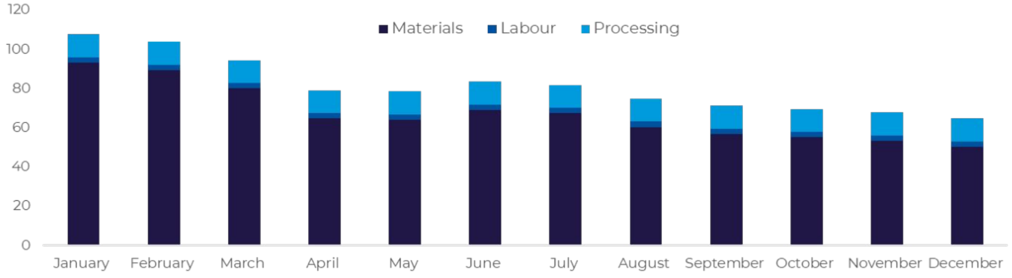
Software & Analytics

Cell Costs | 2023 Battery Cell Costs

Manufactured cell costs declined through 2023 due to falling raw material prices

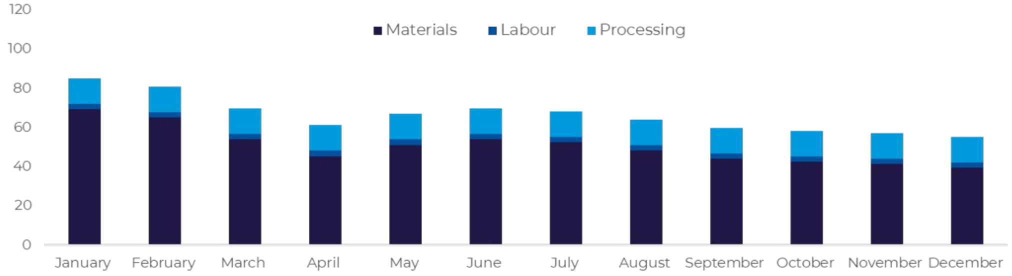
NMC 811

NMC 811 pouch cell – 2023 average production costs, $/kWh

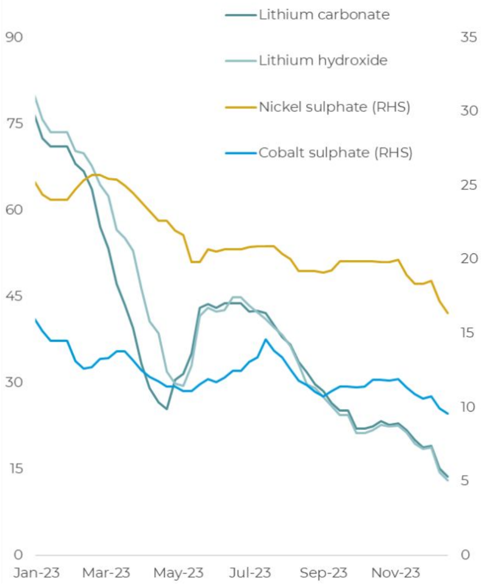


LFP

LFP prismatic cell – 2023 average production costs, $/kWh



Battery chemical prices, DAP China, $/kg



Source: CRU Group

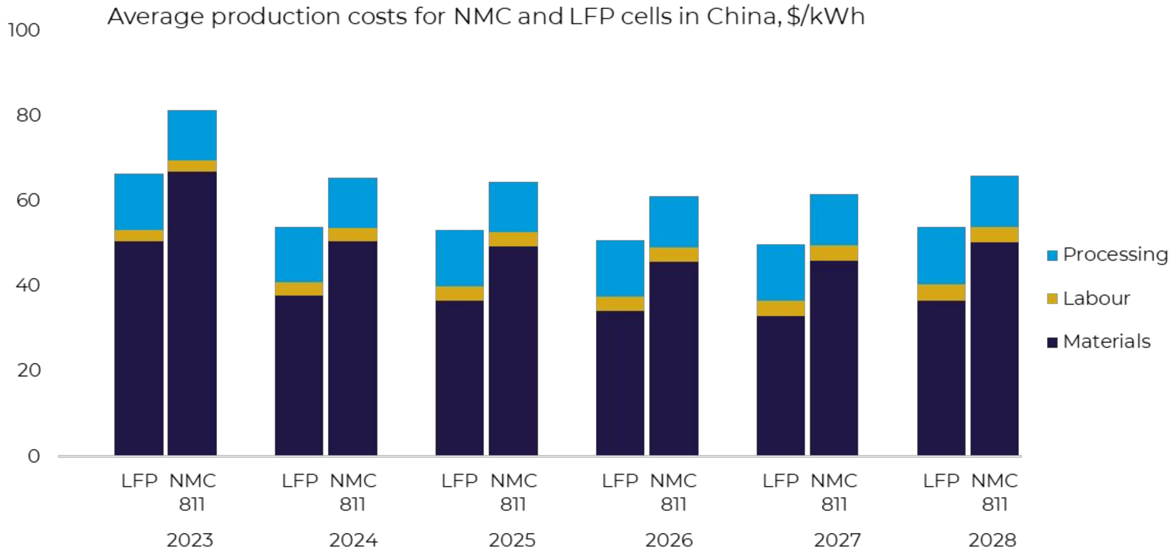
Cell costs

Cell Costs

| Future Of Cell Costs

Cell costs expected to continue to decline through the decade

Falling raw material prices result in average cell production costs in China dropping below $55/kWh for LFP and $65/kWh for NMC by 2028



- $65/kWh would enable <$100/kWh on pack level; cells typically account for 70% of combined pack + cell cost, with remaining 30% due to cost of pack mechanics
- The cost outlook is primarily influenced by lithium supply-demand-price dynamics
- Yield rates are already approaching practical limits in China (~99%)
- Processing (also including electricity), labour, and material costs outside China are generally higher. For example, the cost of manufacturing NMC 811 pouch cells in USA in 2023 was ~80% higher than in China
- Improving yield rates and economies of scale, along with subsidies, will help with cost-competitiveness for ex. China manufacturers

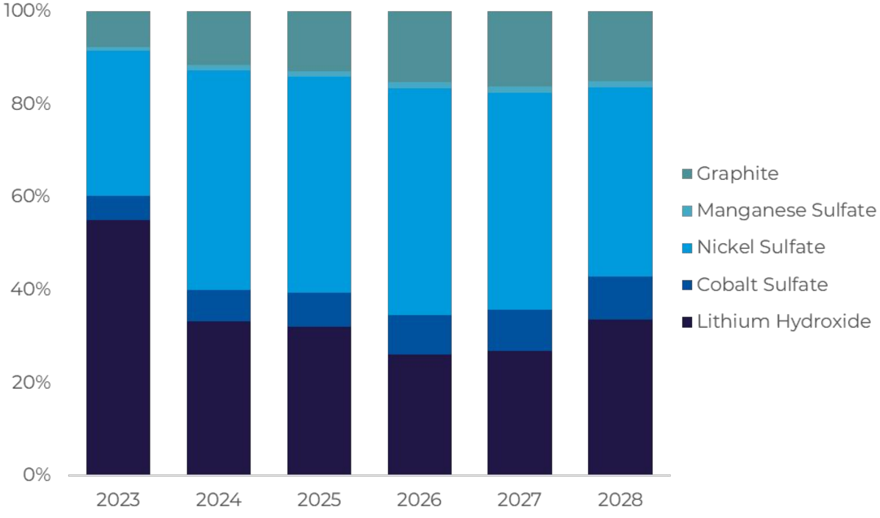
Source: [1] CRU Group [2] BloombergNEF

VF | VOLTA FOUNDATION

Cell Costs | # Cathode Cost Breakdown By Material

Nickel sulfate to become main cost driver for nickel-rich cathodes

Raw material cost makeup for NMC 811 electrode active materials, % $/kWh



Modelling NMC 811 pouch cell 35 Ah produced by a representative manufacturer in China.

NMC cell costs to be more sensitive to nickel prices

- Driven by imperative for higher energy density, manufacturers are shifting to increasingly high nickel content in new NMC/NCA chemistries
- The rise of inexpensive Indonesian MHP mitigates the nickel price risk for downstream buyers, but this also has its challenges, and sourcing nickel from other countries incurs an additional cost
- Lithium's relative influence on cell costs will decrease if lithium prices remain low. Resurgence of lithium's cost contribution towards the end of the decade represents the expectation of an eventual return to a supply-demand deficit, but this scenario carries risks, and assumes nickel prices do not also change

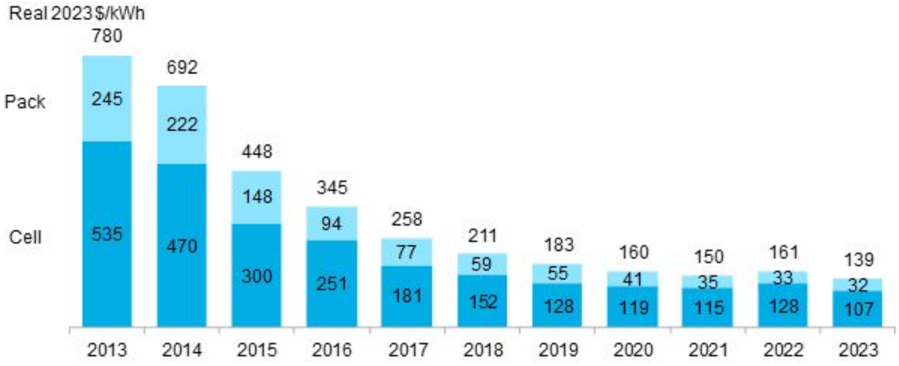
Source: CRU Group

Cell Costs | 2023 Battery Pack Prices

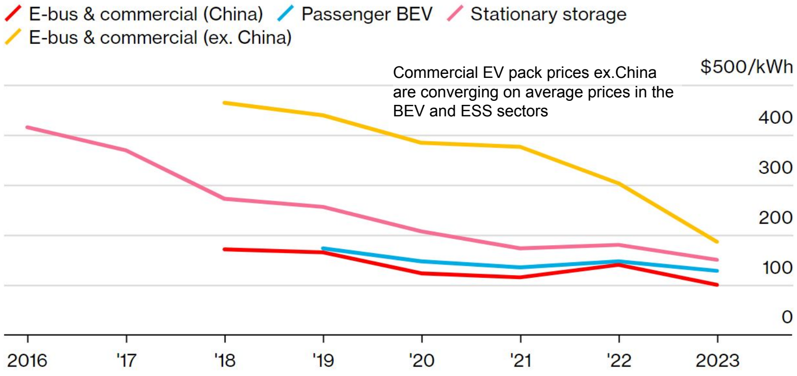
Battery prices resume long trend of decline after unprecedented increase in 2022

- Average pack price dropped 14% to a record low of $139/kWh
- This was driven by raw material and component prices falling while production capacity overshot demand
- Prices were lowest in China, followed by US and then Europe. There was intense price competition in a crowded market in China
- LFP cells were 32% cheaper than NMC cells

Pack-to-cell price ratio is recently plateauing at ~1:5



Prices are converging across sectors



Commercial EV pack prices ex.China are converging on average prices in the BEV and ESS sectors

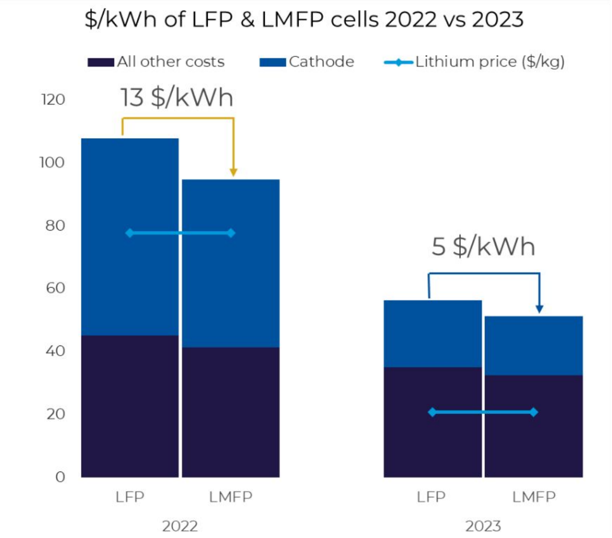
Source: Bloomberg NEF

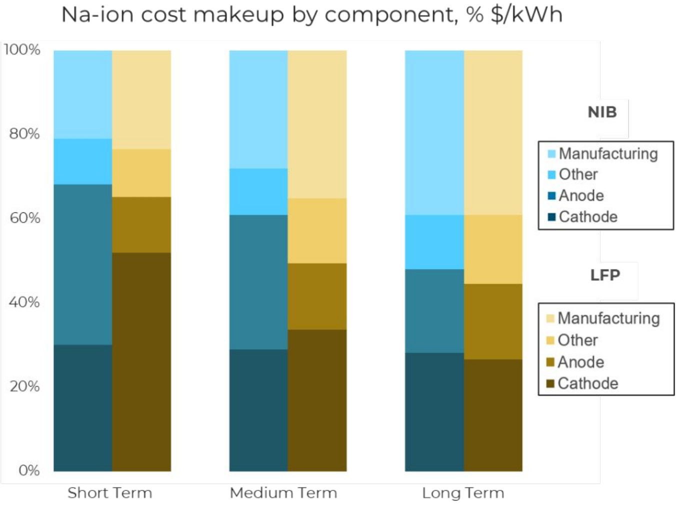
Cell Costs | LMFP & Na-Ion

LMFP cost advantage increases with lithium price. Na-ion cost structure is anode-heavy.

- The LMFP-LFP cost difference is more profound in a high lithium price scenario
- It is also more cost effective to use solid-phase rather than a liquid-phase production route

- Na-ion is not yet cost-competitive with Li-ion due to the immature supply chain for hard carbon. This drives up cost of the anode





Short term = 2023 - 2024 | Medium term = 2025 - 2028 | Long term = 2029+

Source: CRU Group [1], [2]

VF | VOLTA FOUNDATION

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

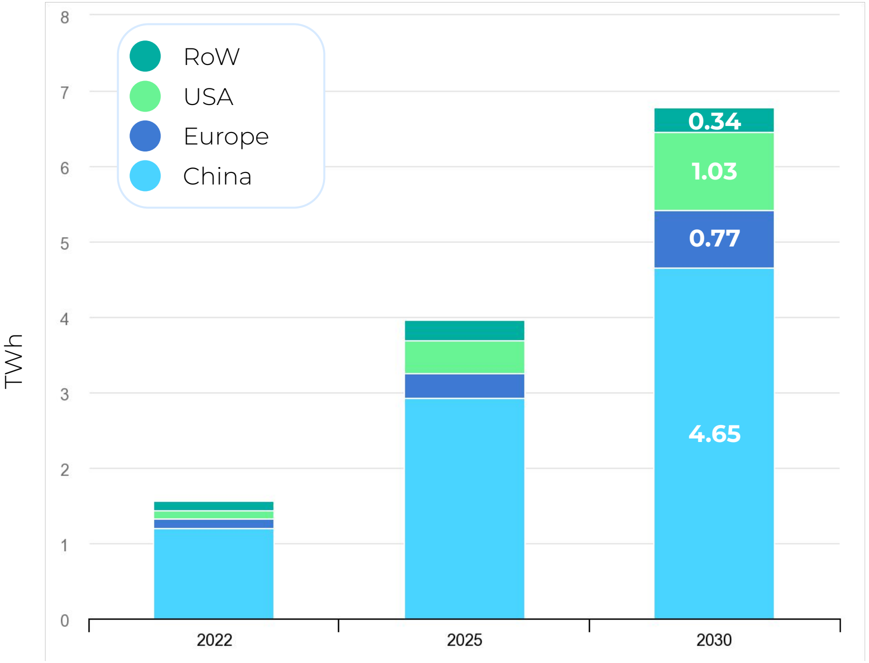
Recycling

Software & Analytics

Cell & Pack Manufacturing

| Future Li-Ion Battery Production Capacity

Geographic Distribution of Li-Ion Battery Production Capacity (Current & Future)



Lithium-ion battery capacity to grow steadily to 2030

EVs and ESS are the two main applications burgeoning li-ion battery capacity.

Investments in battery capacity at Northvolt are robust; recently raising $5B in financing to expand battery capacities.

Based on current announcements, manufacturing capacity is estimated to reach approximately 7 TWh in 2030, with China accounting for 68.5% of capacity.

Currently, the majority of the North American and European capacity is focused on NMC chemistries.

NA and EU have outlined official guidance over the past year to ensure greater security in the sourcing of these critical minerals and developing a more sustainable supply chain.

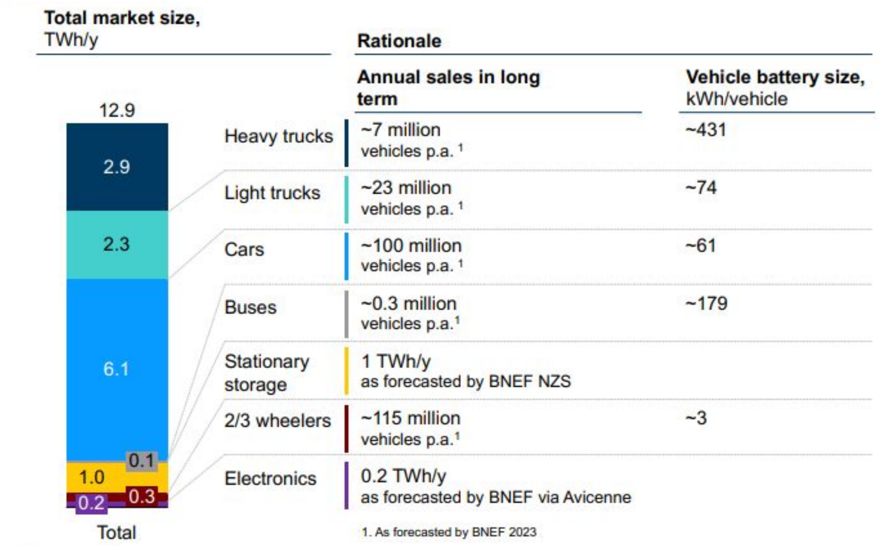
Source: IEA (Geographic Cell Production Capacity), S&P Global

Cell & Pack Manufacturing

Future Li-Ion Battery Production Capacity

Peak Demand & Production Capacity

Figure 33: Aggregate peak battery market size



Rationale	Annual sales in long term	Vehicle battery size, kWh/vehicle
Heavy trucks	~7 million vehicles p.a. [1]	~431
Light trucks	~23 million vehicles p.a. [1]	~74
Cars	~100 million vehicles p.a. [1]	~61
Buses	~0.3 million vehicles p.a.[1]	~179
Stationary storage	1 TWh/y as forecasted by BNEF NZS	
2/3 wheelers	~115 million vehicles p.a.[1]	~3
Electronics	0.2 TWh/y as forecasted by BNEF via Avicenne	

1. As forecasted by BNEF 2023

Source: BNEF,[197] RMI analysis

Net Zero Policy: The Gating Factor

The Net Zero Emissions by 2050 Scenario (NZE Scenario) is a normative scenario that shows a pathway for the global energy sector to achieve net zero CO2 emissions by 2050, with advanced economies reaching net zero emissions in advance of others. This scenario also meets key energy-related Sustainable Development Goals (SDGs), in particular universal energy access by 2030 and major improvements in air quality. It is consistent with limiting the global temperature rise to 1.5 °C (with at least a 50% probability), in line with emissions reductions assessed in the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report.

Sales of new internal combustion engine (ICE) automobiles are halted in 2035 in the Net Zero Emissions by 2050 Scenario (NZE Scenario).

It remains to be seen which governments will adopt and enforce the NZE Scenario and how that will ultimately determine the timing of peak battery demand and peak production capacity.

Source: RMI X-Change Batteries.

Cell & Pack Manufacturing

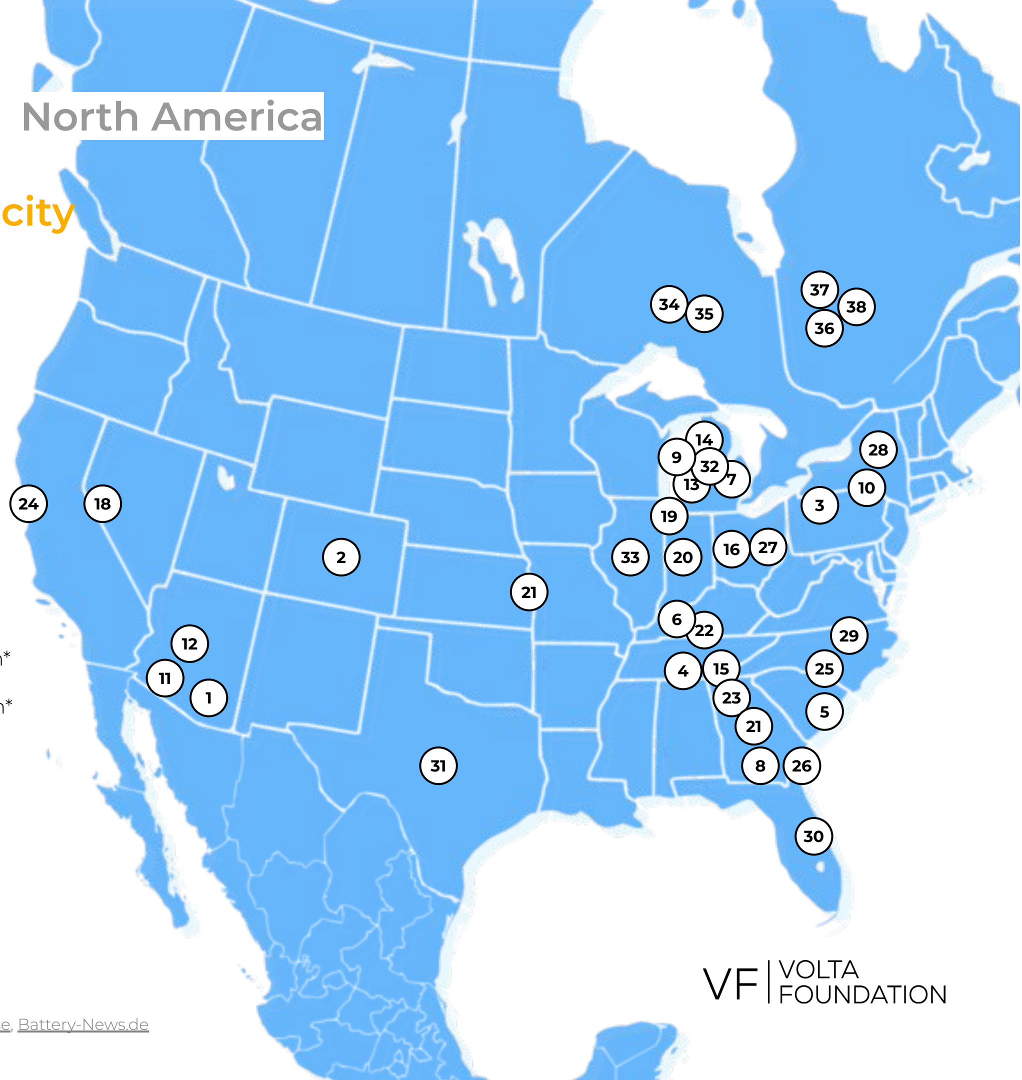
| Gigafactory Plants | North America

Gigafactory Tracker - 1,564 GWh of Capacity

USA
1 ABF, USA, 15 GWh*
2 Amprius Tech, USA, 10 GWh*
3 Electrovaya Tech, USA*
4 Envision AESC, USA, 3 GWh
5 Envision AESC, USA, 30 GWh*
6 Envision AESC/Mercedes-Benz, USA, 40 GWh*
7 Ford/CATL, USA, 20 GWh*
8 FREYR, USA, 34 GWh*
9 Gotion, USA*
10 IM3NY/MAGNIS, USA, 38 GWh*
11 KORE Power, USA, 12 GWh*
12 LGES, USA, 27 GWh*
13 LGES, USA, 25 GWh*
14 Ultium Cells, USA, 50 GWh*
15 Ultium Cells, USA, 70 GWh
16 LGES/Honda, USA, 40 GWh*
17 Panasonic, USA, 39 GWh*
18 Panasonic/Tesla, USA, 100 GWh*
19 Samsung SDI/GM, USA, 30 GWh*
20 Samsung SDI/Stellantis, USA, 67 GWh*
21 SK, USA, 31.3 GWh
22 SK/Ford, USA, 86 GWh*
23 SK/Hyundai, USA, 35 GWh*
24 Tesla, USA, 10 GWh
25 Toyota, USA, 30 GWh*
26 LGES/Hyundai, USA, 30 GWh*
27 Ultium Cells, USA, 41 GWh
28 Electrovaya, USA*
29 Forge Battery, USA* 1-3 GWh
30 SAFT, USA, 2 GWh*
31 Tesla, USA, 100 GWh
32 Our Next Energy, USA, 20 GWh*
33 Gotion, USA, 40 GWh*

Canada
34 LGES/Stellantis, CA, 45 GWh*
35 PowerCo, St. Thomas, CA, 90 GWh*
36 Lion Electric, Quebec, CA, 5 GWh
37 STORMVOLT, Quebec, CA, 10 GWh*
38 Northvolt, Montreal, CA, 60 GWh*

*Non-operational, slated for future date



VF | VOLTA FOUNDATION

Source: Charged: NA EV Battery Supply Chain, Benchmark Minerals, Felt: Global Battery Factory Database, Battery-News.de

Cell & Pack Manufacturing

| Gigafactory Plants | Europe

Gigafactory Tracker - 1,897 GWh of Capacity

France
1 ACC, 40 GWh*
2 Envision AESC/Renault, 30 GWh*
3 Verkor/Renault, 50 GWh*
4 Prologium, 48 GWh*

Germany
5 ACC, 40 GWh*
6 CATL, 14 GWh*
7 Leclanche, 2.5 GWh
8 Northvolt, 60 GWh*
9 SVOLT, 24 GWh
10 SVOLT, 16 GWh*
11 Tesla, 100 GWh*
12 PowerCo, 40 GWh*

Italy
13 ACC, 40 GWh*
14 ITALVOLT, 70 GWh*

Portugal
15 CALB, 45 GWh*

Netherlands
16 Eurocell, 1 GWh

Sweden
17 Northvolt, 60 GWh*
18 Volvo*
19 NOVO, 50 GWh*

Hungary
20 CATL, 100 GWh*
21 Cellforce Group, 10 GWh*
22 EVE Energy, 28 GWh*
23 Samsung SDI, 40 GWh*
24 SK, 47.3 GWh*

Norway
25 Elinor*
26 FREYR, 29 GWh*
27 Morrow, 43 GWh*
28 Beyonder, 10 GWh*

Spain
29 Envision AESC, 50 GWh*
30 PowerCo, 60 GWh*
31 Basquevolt, 10 GWh*

U.K.
32 Envision AESC, 35 GWh*
33 Tata, 40 GWh*
34 AMTE Power, 10 GWh

Slovakia
35 Inobat, 10 GWh

Poland
36 LGES, 115 GWh*

Czech Republic
37 MES, 15 GWh*

*Non-operational, slated for future date

Source: Felt: Global Battery Factory Database, Benchmark Minerals, Battery-News.de

VF | VOLTA FOUNDATION

Cell & Pack Manufacturing

| Gigafactory Plants | Greater Asia

Gigafactory Tracker - 2,691 GWh of Capacity

India
1 Reliance, Gujarat, 50 GWh*
2 Amara Raja, Telangana, 16 GWh*
3 Exide, Karnataka, 12 GWh*
4 Godi, Hyderabad, 12 GWh*
5 OLA, Tamil Nadu, 100 GWh*
6 TATA, Gujarat, 10 GWh*

Turkey
7 Aspilsan, 1 GWh*
8 Siro, Gemlik 20 GWh*

Vietnam
9 Gotion, Vung Ang, 5 GWh*

Thailand
10 EVE Energy, Thailand, 6 GWh*
11 GPSC, Map Ta Phut, 10 GWh*

Indonesia
12 CATL, Indonesia, 15 GWh*
13 LGES, Karawag, 10 GWh*

Malaysia
14 EVE Energy, Malaysia*
15 Samsung SDI, Seremban, 16 GWh*

South Korea
16 Samsung SDI, Cheonan, 12 GWh*
17 LGES, Ochang, 35 GWh*
18 SK, Seosan, 5 GWh

Japan
19 Prime Planet, Japan, 7 GWh*
20 Envision AESC, Kanagawa, 2.6 GWh
21 Envision AESC, Ibaraki, 18 GWh*
22 Panasonic, Osaka
23 Panasonic, Uchita, 10 GWh
24 Panasonic, Asonaka*

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

*Non-operational, slated for future date

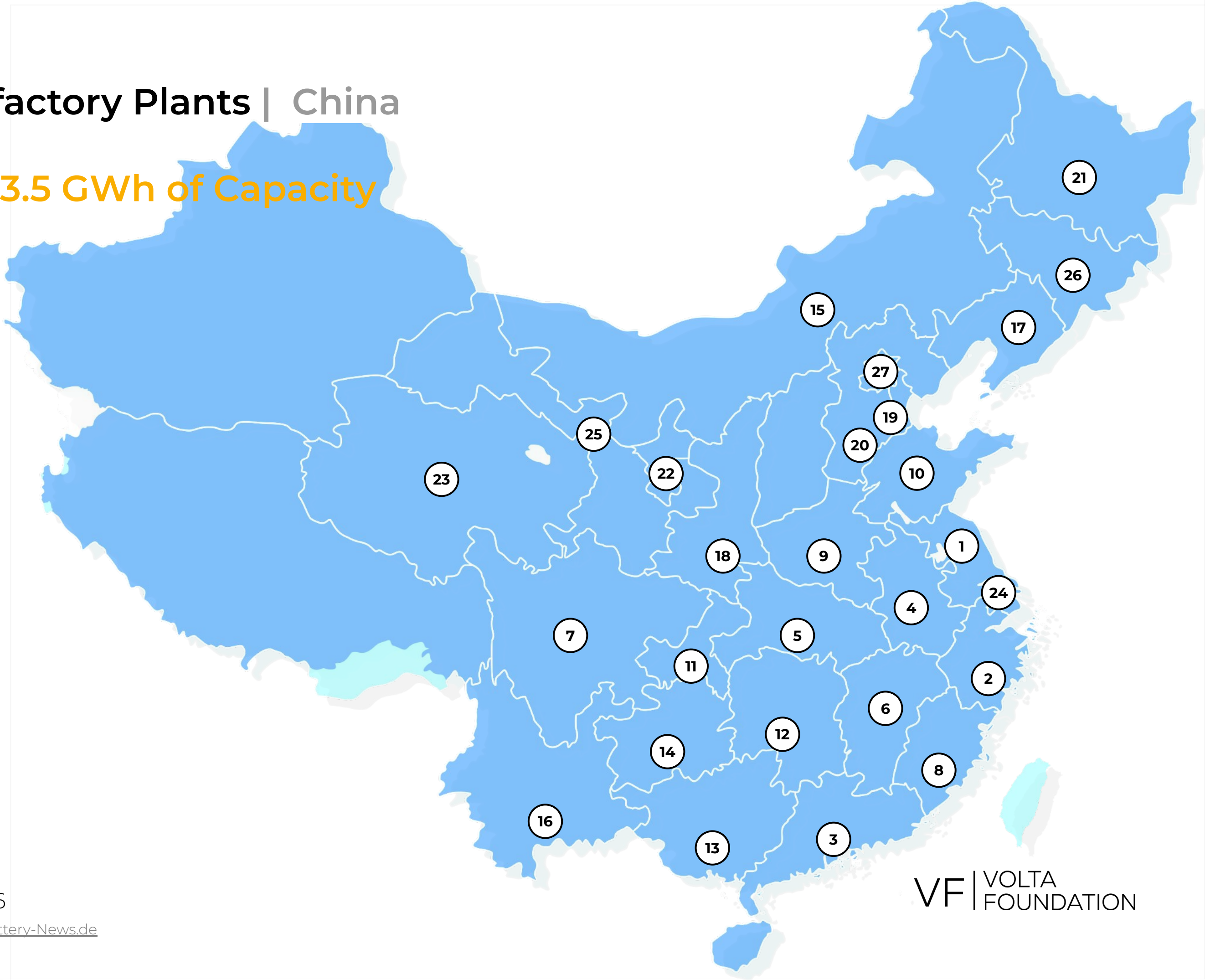
Source: Global Battery Factory Database, Benchmark Minerals, Battery-News.de

Cell & Pack Manufacturing

| Gigafactory Plants | China

Gigafactory Tracker - 2,293.5 GWh of Capacity

1 Jiangsu - 55
2 Zhejiang - 31
3 Guangdong - 28
4 Anhui - 24
5 Hubei - 24
6 Jiangxi - 21
7 Sichuan - 15
8 Fujian - 12
9 Henan - 12
10 Shandong - 10
11 Chongqing - 9
12 Hunan - 9
13 Guangxi - 8
14 Guizhou - 4
15 Inner Mongolia - 4
16 Yunnan - 4
17 Liaoning - 3
18 Shaanxi - 3
19 Tianjin - 3
20 Hebei - 2
21 Heilongjiang - 2
22 Ningxia - 2
23 Qinghai - 2
24 Shanghai - 2
25 Gansu - 1
26 Jilin - 1
27 Beijing - 1



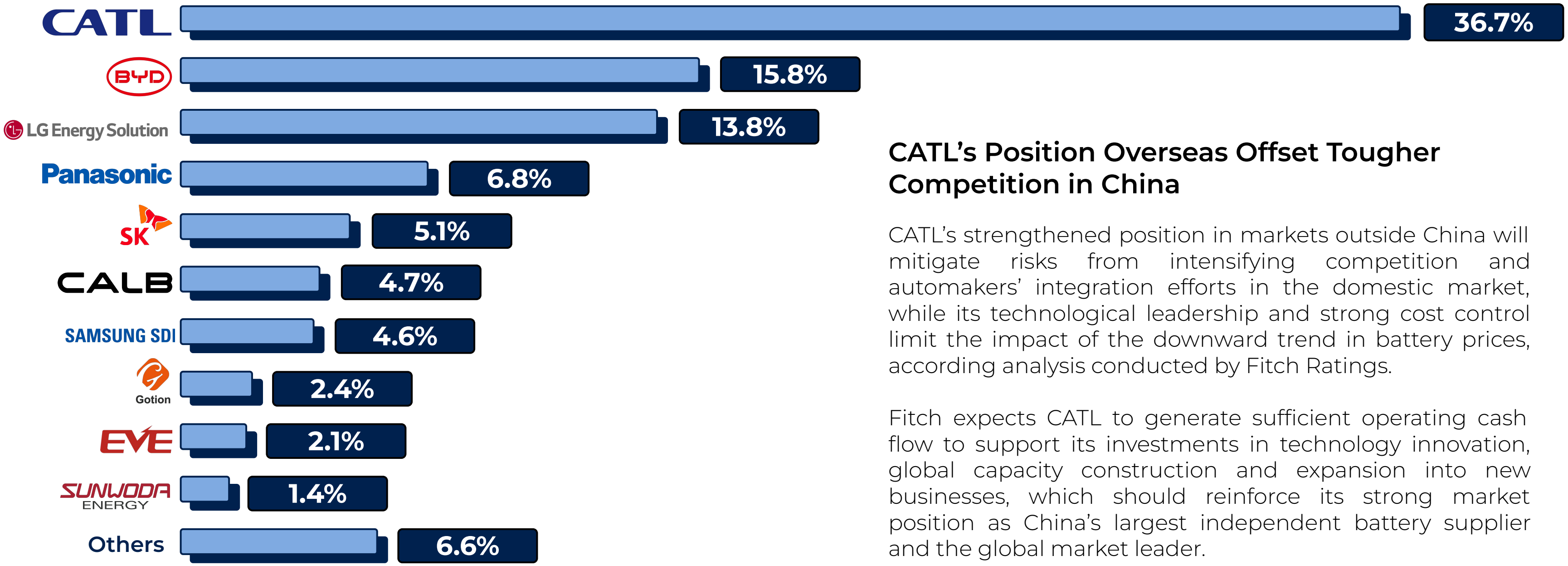
Note: Number of gigafactories is per province.

Source: Global Battery Factory Database, Benchmark Minerals, Battery-News.de

Cell & Pack Manufacturing

Cell & Pack Manufacturers' Market Share In 2023

CATL Leads Market Share Amongst Global Battery Cell Manufacturers



CATL's Position Overseas Offset Tougher Competition in China

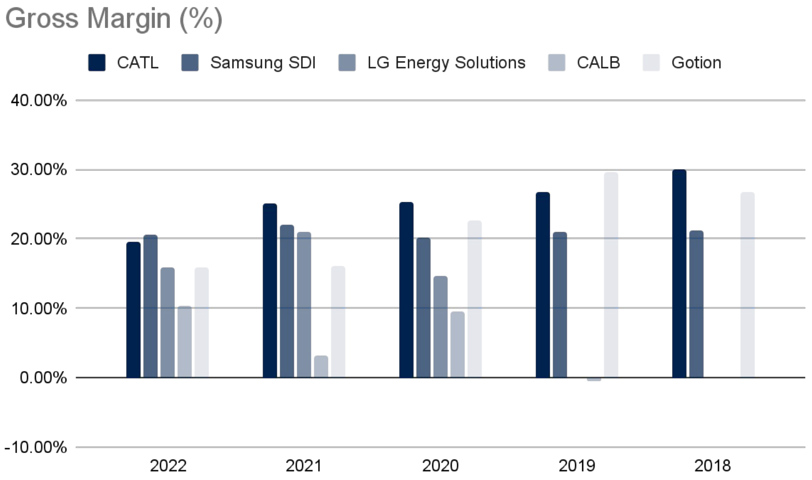
CATL's strengthened position in markets outside China will mitigate risks from intensifying competition and automakers' integration efforts in the domestic market, while its technological leadership and strong cost control limit the impact of the downward trend in battery prices, according analysis conducted by Fitch Ratings.

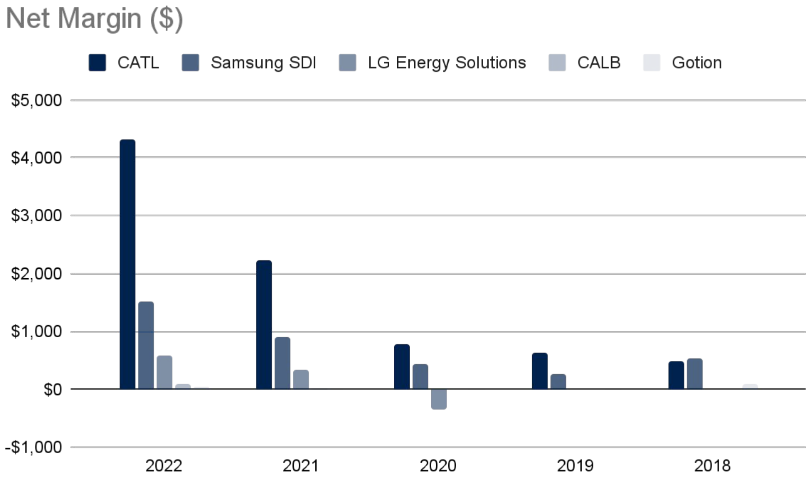
Fitch expects CATL to generate sufficient operating cash flow to support its investments in technology innovation, global capacity construction and expansion into new businesses, which should reinforce its strong market position as China's largest independent battery supplier and the global market leader.

Source: SNE Research, CATL Market Dominance

Cell & Pack Manufacturing

| Overview Of Cell & Pack Manufacturers' Margins



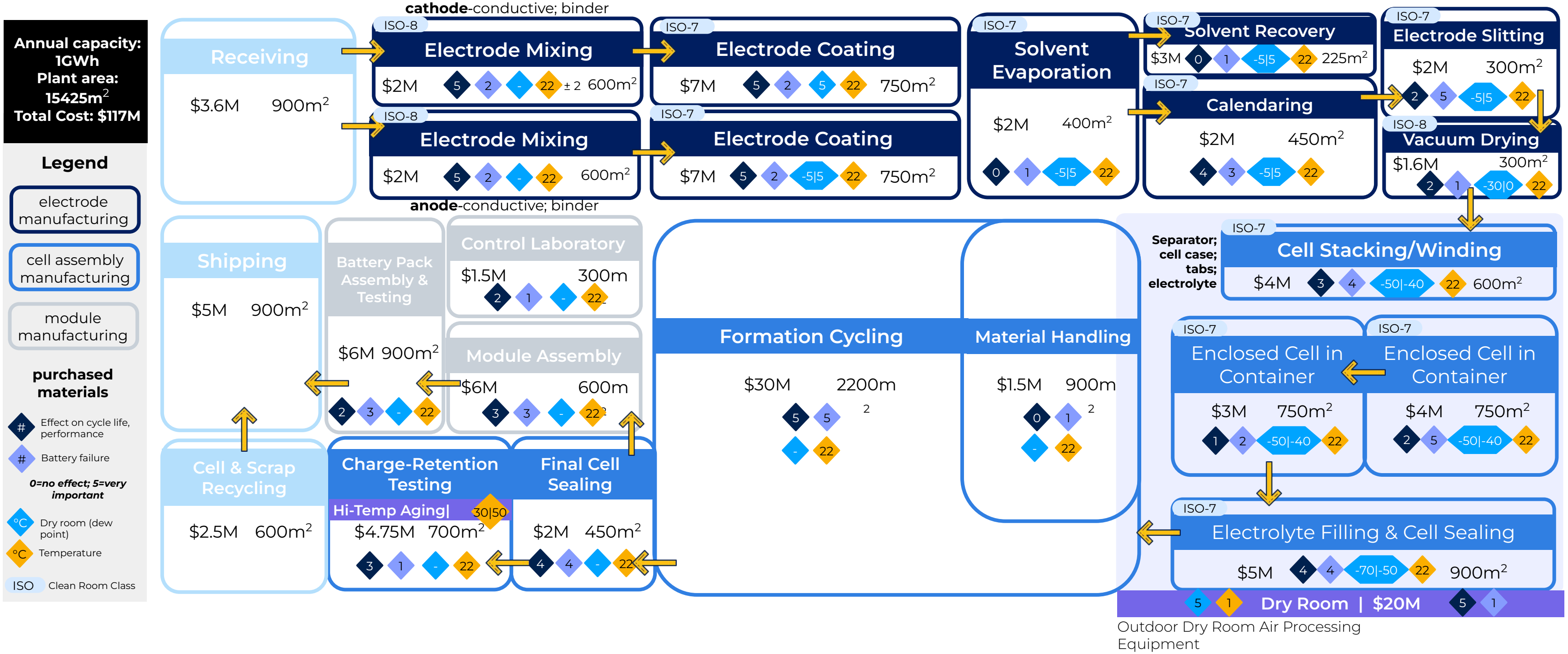


Margin Analysis

Gross margins steadily declined over the last 5 years as material prices pressured midstream suppliers like cathode and anode manufacturers, which in turn reduced cell & pack manufacturing margins. Notably, CATL exhibited a linear decline from 30% to sub-20% gross margins, while net margins expanded aggressively as non-cost of goods sold expenses plateaued as a direct result of an expansion in economies of scale.

Source: CATL, Samsung SDI, LG Energy Solutions, CALB, Gotion

| Typical Layout Of Li-Ion Manufacturing Plant



Annual capacity: 1GWh
Plant area: 15425m^2
Total Cost: $117M

Legend

electrode manufacturing

cell assembly manufacturing

module manufacturing

purchased materials

- # Effect on cycle life, performance
- # Battery failure

0=no effect; 5=very important

- °C Dry room (dew point)
- °C Temperature
- ISO Clean Room Class

Receiving
$3.6M 900m^2

cathode-conductive; binder

ISO-8 Electrode Mixing
$2M 5 2 - 22 ± 2 600m^2

ISO-8 Electrode Mixing
$2M 5 2 - 22 600m^2

anode-conductive; binder

ISO-7 Electrode Coating
$7M 5 2 5 22 750m^2

ISO-7 Electrode Coating
$7M 5 2 -5|5 22 750m^2

ISO-7 Solvent Evaporation
$2M 400m^2
0 1 -5|5 22

ISO-7 Solvent Recovery
$3M 0 1 -5|5 22 225m^2

ISO-7 Calendaring
$2M 450m^2
4 3 -5|5 22

ISO-7 Electrode Slitting
$2M 300m^2
2 5 -5|5 22

ISO-8 Vacuum Drying
$1.6M 300m^2
2 1 -30|0 22

Separator; cell case; tabs; electrolyte

ISO-7 Cell Stacking/Winding
$4M 3 4 -50|-40 22 600m^2

ISO-7 Enclosed Cell in Container
$3M 750m^2
1 2 -50|-40 22

ISO-7 Enclosed Cell in Container
$4M 750m^2
2 5 -50|-40 22

ISO-7 Electrolyte Filling & Cell Sealing
$5M 4 4 -70|-50 22 900m^2

5 1 **Dry Room | $20M** 5 1

Outdoor Dry Room Air Processing Equipment

Material Handling
$1.5M 900m^2
0 1
- 22

Formation Cycling
$30M 2200m^2
5 5
- 22

Final Cell Sealing
$2M 450m^2
4 4 - 22

Charge-Retention Testing
Hi-Temp Aging| 30|50
$4.75M 700m^2
3 1 - 22

Cell & Scrap Recycling
$2.5M 600m^2

Shipping
$5M 900m^2

Battery Pack Assembly & Testing
$6M 900m^2
2 3 - 22

Control Laboratory
$1.5M 300m^2
2 1 - 22

Module Assembly
$6M 600m^2
3 3 - 22

Source: ETN, RWTH-VDMA

Cell & Pack Manufacturing

Li-Ion Manufacturing Plant - CapEx By Region

Labor costs, vendor proximity, vertical integration, and policy all factor into CapEx costs of around 2x in NA and EU.

CapEx depreciation represents about 25% of cell cost which makes commercial viability difficult in NA & EU.

NA & EU have responded with favorable policies for manufacturers and a support for new manufacturing technologies which can lower CapEx and cost per kilowatt-hour produced.

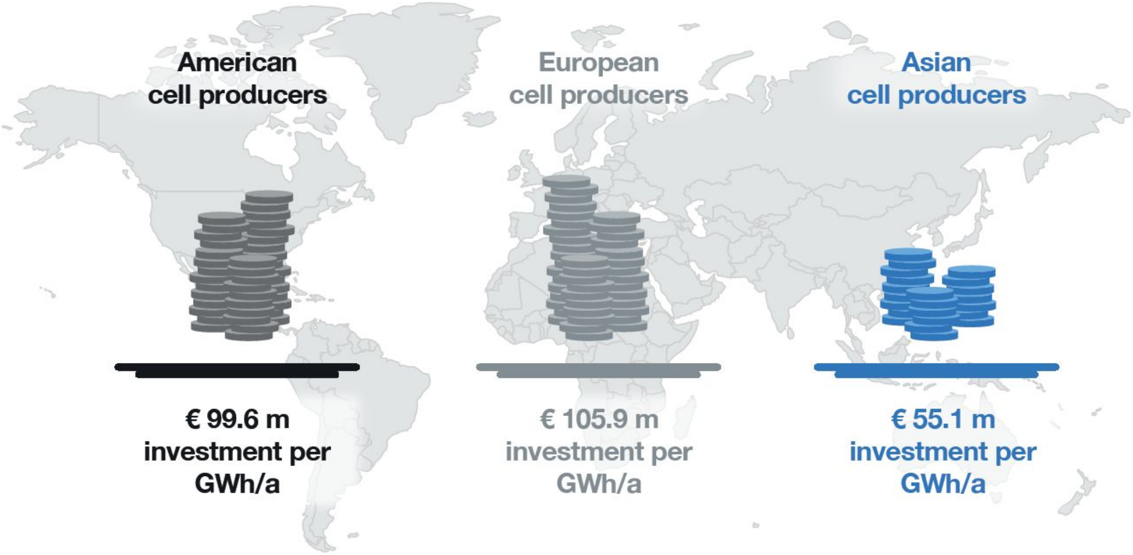


Fig. 17: *Estimated project costs for the setup of a gigafactory cell production by manufacturer origin; Source: PEM RWTH Aachen University*

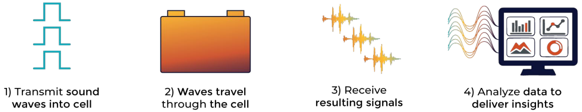
Source: Battery Monitor 2023

Cell & Pack Manufacturing

Manufacturing Challenges: 2023 Developments

Insufficient metrology of key quality characteristics poses a risk to cell reliability as manufacturing ramps up. In 2023, in-line measurement techniques continued to develop.

Ultrasound transducers & machine learning deployed to detect internal defects such as **electrolyte wetting quality**


1) Transmit sound waves into cell

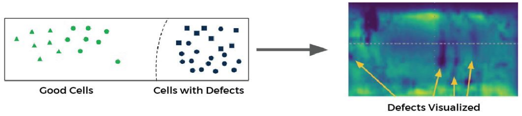
2) Waves travel through the cell

3) Receive resulting signals

4) Analyze data to deliver insights

During **In-line Primary Inspection**, Classify Good and "Suspect" Cells

Perform **Hi-res Secondary Inspection** on "Suspect" Cells to Locate and Identify Defects


Good Cells

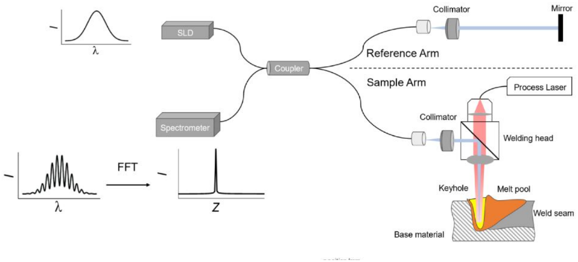
Cells with Defects

Defects Visualized

liminal

TITAN ADVANCED ENERGY SOLUTIONS

In-line measurement of **laser weld depth** is improved with optical coherence tomography (OCT)

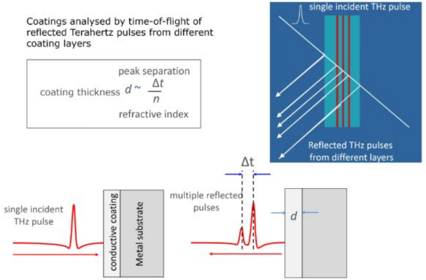


TRUMPF

IPG PHOTONICS

PRECITEC

Terahertz (THz) sensors deployed for concurrent **electrode thickness, loading, and conductivity** measurement



TeraView

LUNA

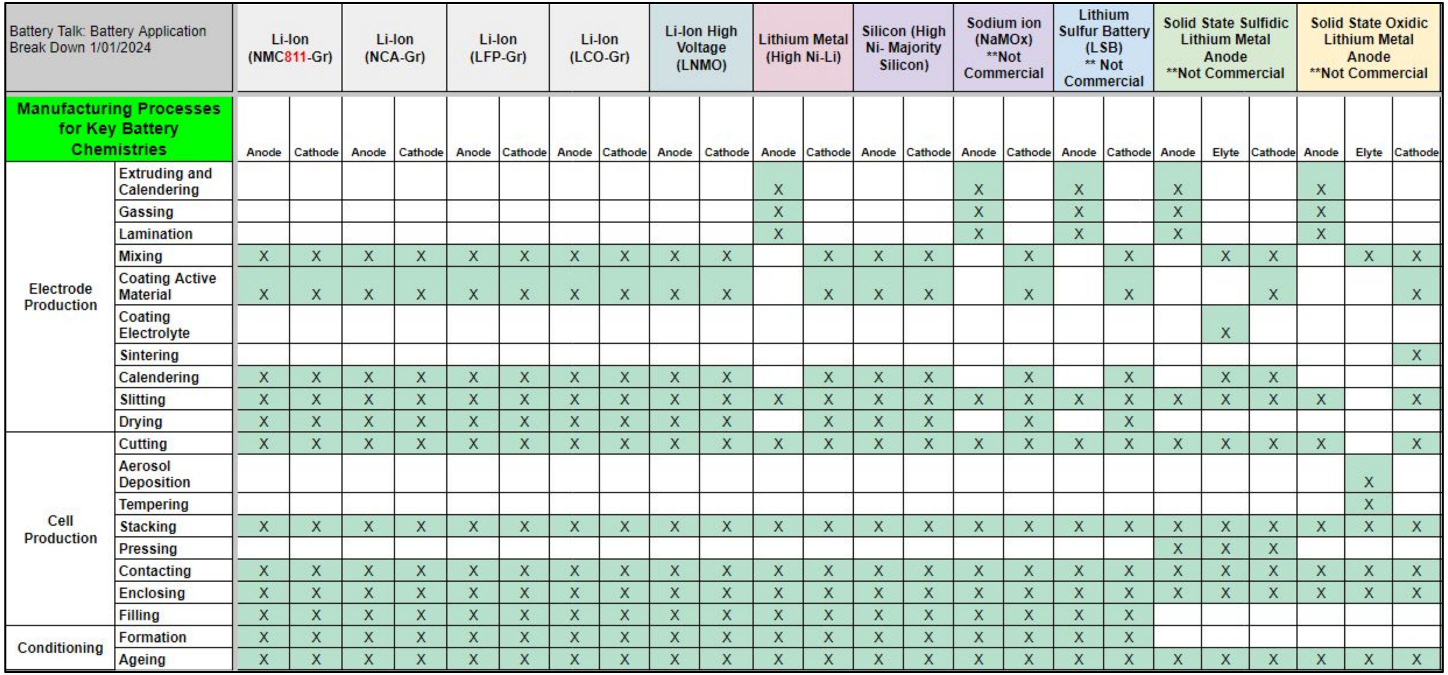
ThermoFisher SCIENTIFIC

Source: Liminal, OCT, Teraview, Luna

Cell & Pack Manufacturing

| Cell Chemistry Cathode Manufacturing Processes

Manufacturing Processes for Key Battery Chemistries



Battery Talk: Battery Application Break Down 1/01/2024		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	Elyte	Cathode	Anode	Elyte	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

VF | VOLTA FOUNDATION

Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

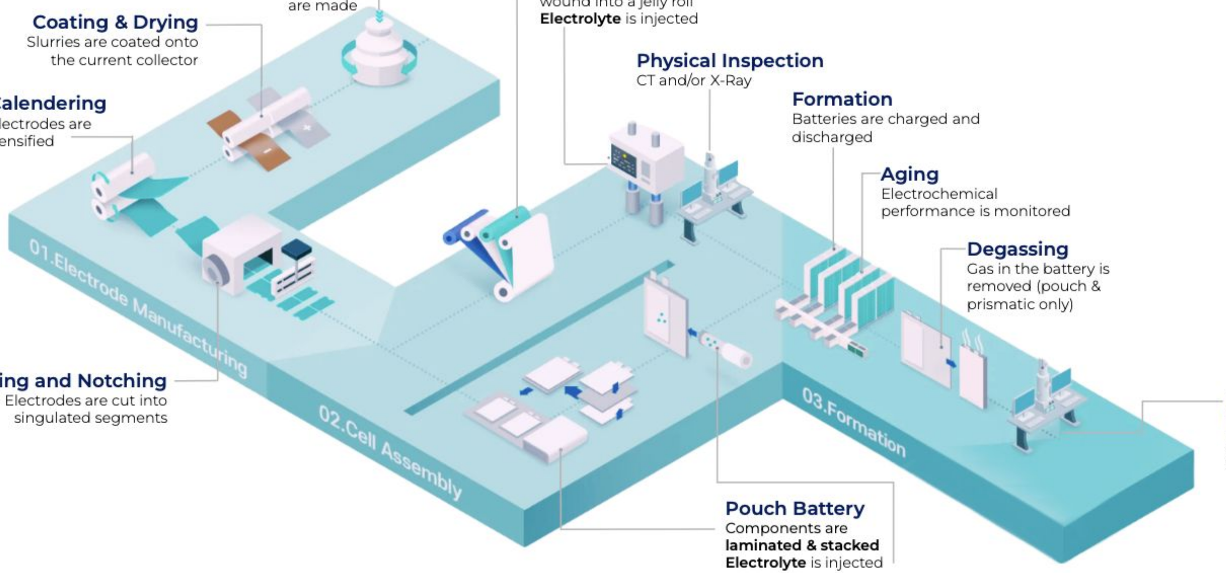
Cell & Pack Manufacturing

| Battery Equipment Manufacturers

Process Area	Wuxi Lead	Yinghe	Hangke	Chroma	Hanwha	PNE	mPLUS	Hana	Manz	Hitachi	Hirano	Toray	Kataoka
Mixing	✔	✔											
Coating	✔	✔			✔					✔	✔	✔	
Calendaring	✔	✔			✔					✔			
Slitting	✔	✔			✔	✔			✔	✔		✔	
Stack	✔	✔				✔	✔	✔	✔	✔		✔	
Wind	✔	✔				✔							
Packaging	✔	✔				✔	✔	✔	✔	✔			
Filling	✔	✔				✔	✔	✔	✔	✔			
Formation	✔	✔	✔	✔	✔	✔		✔					
Degassing	✔	✔	✔			✔		✔					
Aging	✔	✔	✔	✔		✔		✔					
Test / Grade	✔	✔	✔	✔		✔		✔					✔

Source: China Galaxy International, Chroma, Wonik PNE, mPLUS, Hana, Hanwha, Manz, Hitachi, Hirano, Toray, Kataoka - Non exhaustive list

| Manufacturing Process Map | Overview



Mixing
Cathode and anode slurries are made

Coating & Drying
Slurries are coated onto the current collector

Calendering
Electrodes are densified

Slitting and Notching
Electrodes are cut into singulated segments

Cylindrical Battery
Winding - components are wound into a jelly roll
Electrolyte is injected

Physical Inspection
CT and/or X-Ray

Pouch Battery
Components are **laminated & stacked**
Electrolyte is injected

Formation
Batteries are charged and discharged

Aging
Electrochemical performance is monitored

Degassing
Gas in the battery is removed (pouch & prismatic only)

Electrical Inspection
ACIR and/or voltage decay

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

Line Example Output
Prismatic: 1.4M cells / year
Cylindrical 70M cells / year

CAPEX
$55-127 million/GWh

Humans/GWh
175 jobs created per GWh

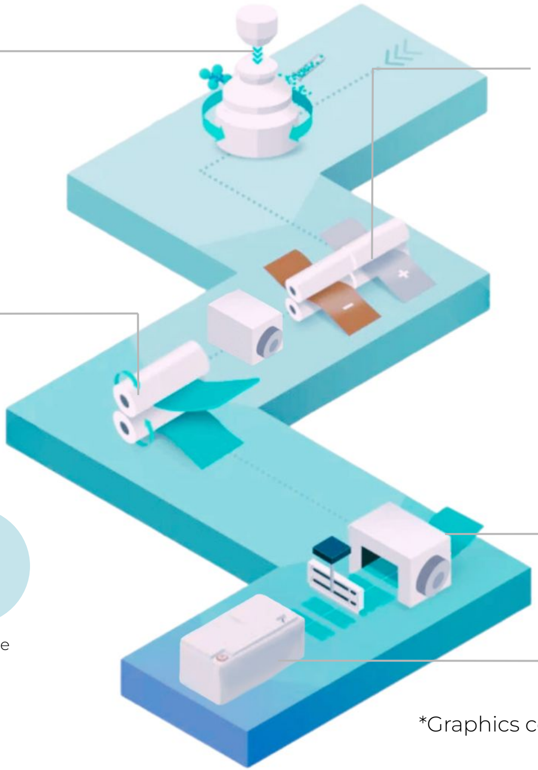
Scrap
20%
Scrap remains one of the **key issues** to overcome for battery production.

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

Source: LG Energy, VDMA, Faraday Institution,

Cell & Pack Manufacturing

| Manufacturing Process Map | 1. Electrode Production



Mixing

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

Challenges
slurry quality (uneven dispersion)

Coating & Drying

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

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

Calendaring

Electrodes are densified to a target value

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

Challenges
electrode waste; physical damage to material

Slitting & Notching

Electrodes are cut into singulated segments

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

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

Vacuum Drying

Removes leftover solvent

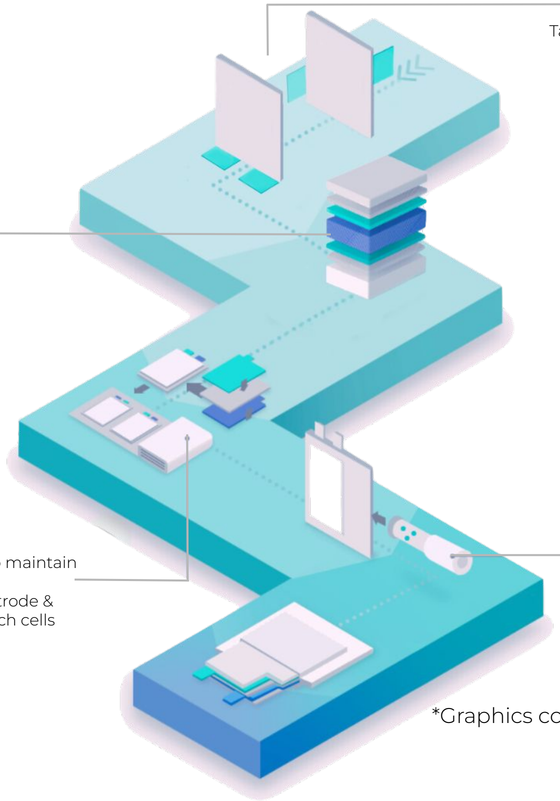
Challenges
processing time; footprint; takes 12-24 hours

39%	**50-80 m/min**	**20-30 m/min**	**5%**
of total manufacturing cost	pouch film speed	cylindrical film speed	scrap rate

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

Source: LG Energy; BCG

| Manufacturing Process Map | 2. Cell Assembly | Pouch



Tab Welding

Tabs are ultrasonically welded to the jelly rolli

Challenges
foil damage; coating adhesion

Challenges
corner cracking

Pouch Forming

Making a case by pressing a film

20% of total manufacturing cost

2-20 parts/min speed

5% scrap rate

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

Lamination & Stacking/Winding

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

Electrolyte Injection

Filling the electrode pocket with electrolyte through metered dispensing

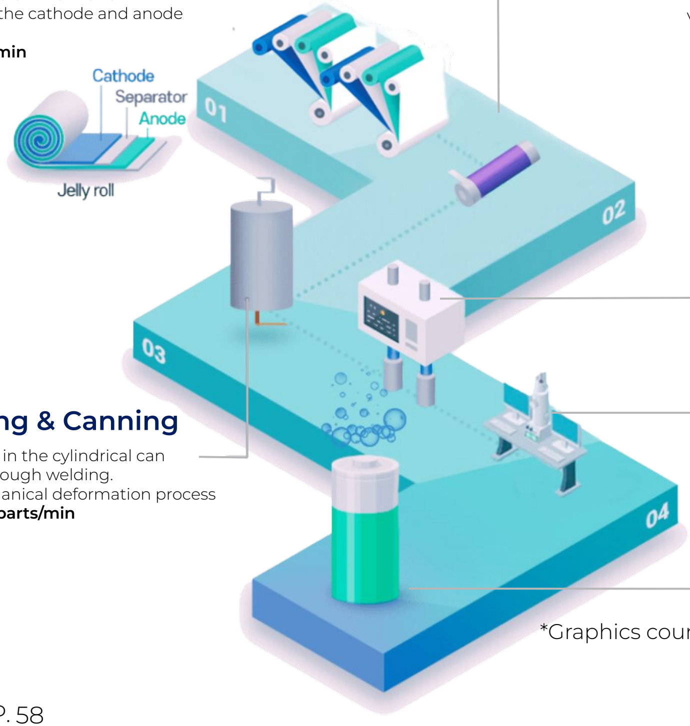
Challenges
dosing and distribution accuracy of the electrolyte in the cell; No electrolyte residues in the sealing seam; seal integrity

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

Source: LG Energy; BCG; RWTH PEM

Cell & Pack Manufacturing

| Manufacturing Process Map | 2. Cell Assembly | Cylindrical



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

Winding & Tab Welding

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

20%
of total manufacturing cost

5%
scrap rate

Challenges
metal contamination

Tab Shaping & Canning

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

Electrolyte Injection

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

Challenges
electrolyte absorption due to density; pooling of electrolyte

Physical Inspection

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

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

Degassing/ Pre-Charge

Optional process to remove gas

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

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

Source: LG Energy; BCG; RWTH PEM

GLIMPSE

The highest throughput X-ray powered platform to monitor your cell quality across factories, teams, and time

Automated Inspection Review

Metric: Electrode overhang - top of cell

Batch: Selected 1 of 5 batches

Samsung INR21700-50E
LH1T-356
Min: 0.4277

ENABLING BATTERY QUALITY AT SCALE

SCAN ON DEMAND

Glimpse is combining state-of-the-art hardware with cutting-edge software to turn cell computed tomography scanning into a fast and collaborative experience.

20-30X CHEAPER

TOP NOTCH IMAGE QUALITY

NO HEAVY FILES

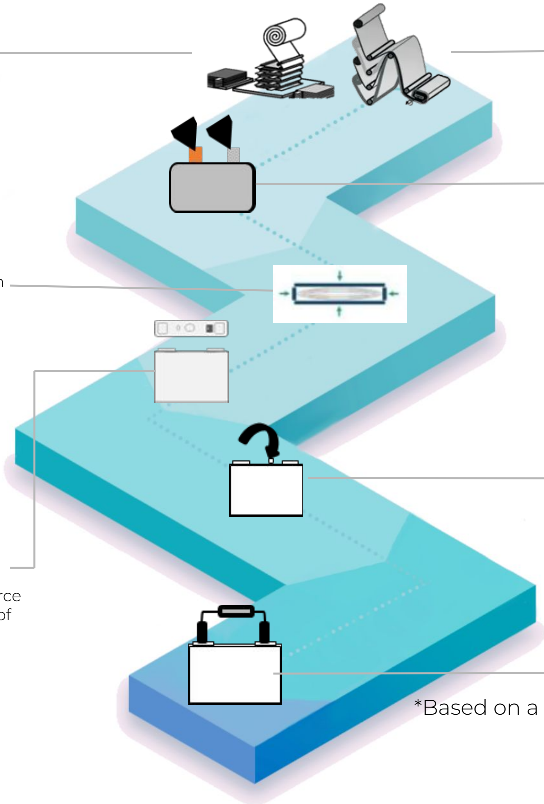
ON-PREMISE SCANNING

Whether you're a cell producer or a cell buyer, experience the full scale of Glimpse's end-to-end cell computed tomography scanning solution deployed on your premises.

Check out our 1000 cell demo

Learn more at glimp.se

Cell & Pack Manufacturing | Manufacturing Process Map | 2. Cell Assembly | Prismatic



Z-Stacking

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

SPEED: 30 parts/min

Challenges
anode, cathode, separator alignment

Wound Prismatic

Roll the slitted cathode, anode, and separator together by controlling speed, tension, etc.

SPEED: 30 parts/min

Challenges
Uneven stress, burr issues, and powder loss

Pre Welding & Trimming

The cathode and anode tab are aligned and U/S welded

SPEED: 18-20 parts/min

Challenges
anode, and cathode tab alignment

Hot Press

The hot press machine works on the principle of heat and pressure application to achieve a strong and reliable bond between battery components.

SPEED (DWELL TIME): >10 seconds/unit

Challenges
throughput

Electrolyte Injection

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

Challenges
electrolyte absorption due to density; pooling of electrolyte

20% of total manufacturing cost

5% scrap rate

Cap To Can Welding

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

Challenges
cap to can alignment, missed laser welding spot

Pre Charge & Formation

After the filling pre charge is performed and cell is kept for RT aging and followed by formation & grading process

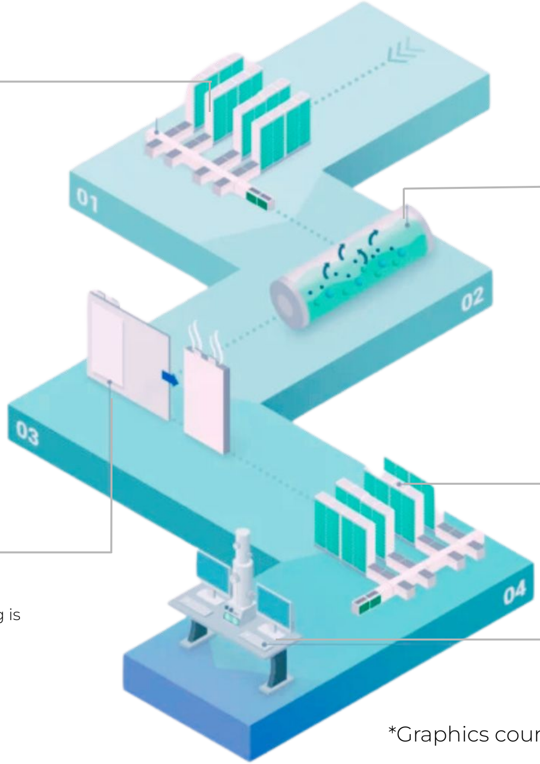
Challenges
throughput and quality

*Based on a graphics by LG Energy Solution, modified with permission.

Source: CATL, RWTH PEM

Cell & Pack Manufacturing

| Manufacturing Process Map | 3. Formation



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

Charging & Discharging

Electrochemical activation.
SEI is formed on the anode

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

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

Degassing

Pouch only.
Air pocket with gas (sacrificial gas bag) formed during aging is cut off inside of vacuum chamber.

Aging

Battery is stored at a certain temperature and humidity for an even electrolyte dispersion and SEI stabilization

Challenges
throughput; factory footprint

Charging, Discharging, & Aging

The previous processes are repeated

Challenges
throughput

Quality Control

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

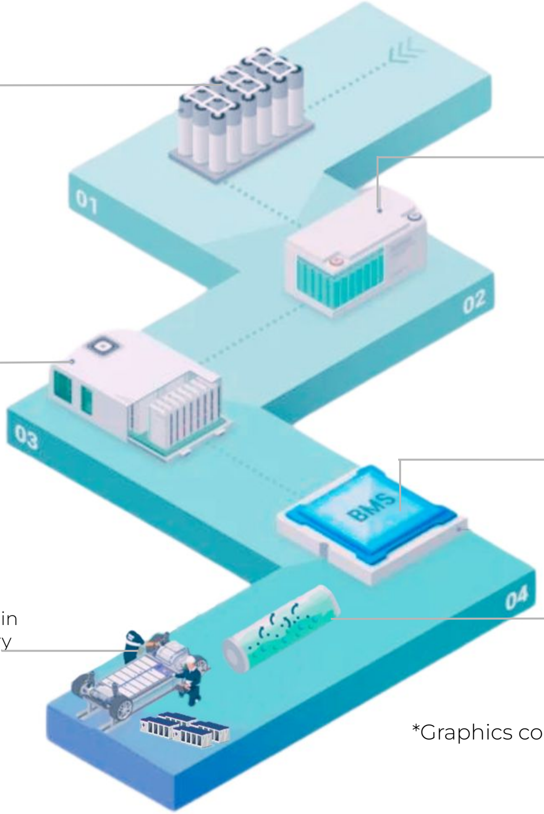
Challenges
cosmetic & variation in capacity; yield

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

Source: LG Energy; BCG; RWTH PEM

Cell & Pack Manufacturing

| Manufacturing Process Map | Pack Assembly



Challenges
surface cleaning; heat management

Connecting Battery Cells

Battery cells are connected after surface is cleaned

Modularization

The cells are attached to the module case

Challenges
ensuring cable flexibility, Battery cells handling

Challenges
avoidance of module short circuit and damages

Pack Assembly

The modules are put in the battery pack and connected

Applying BMS

A Battery Management System is applied to battery pack

Challenges
correct wiring and integration of the BMS

Challenges
battery pack integration with other components in EV or BESS. Extreme climate conditions and use cases during the battery life cycle

Final Integration

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

Final Test

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

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

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

Source: LG Energy; RWTH PEM, RWTH PEM,

Cell & Pack Manufacturing

Battery QA/QC Hardware Inspection Solutions

Lab

Waters™ | TA® Instruments

ZEISS

OXFORD INSTRUMENTS

KEYENCE

HITACHI

ThermoFisher SCIENTIFIC

Waygate Technologies
a Baker Hughes business

Manufacturing

liminal

TITAN

HAMAMATSU
PHOTON IS OUR BUSINESS

ISRA VISION

HITACHI

AVONIX IMAGING

Nikon

excillum

comet x-ray

COGNEX

Waygate Technologies
a Baker Hughes business

BECKHOFF

PDF/SOLUTIONS™

LUNA

SPEA

GLIMPSE

The highest throughput X-ray powered platform to monitor your cell quality across factories, teams, and time

Metric: Electrode overhang - top of cell

Batch: Selected 1 of 5 batches

ENABLING BATTERY QUALITY AT SCALE

SCAN ON DEMAND

Glimpse is combining state-of-the-art hardware with cutting-edge software to turn cell computed tomography scanning into a fast and collaborative experience.

20-30X CHEAPER

TOP NOTCH IMAGE QUALITY

NO HEAVY FILES

ON-PREMISE SCANNING

Whether you're a cell producer or a cell buyer, experience the full scale of Glimpse's end-to-end cell computed tomography scanning solution deployed on your premises.

Check out our 1000 cell demo

Learn more at glimp.se

pCAM-CAM Manufacturing

Analyzing the most expensive part of the battery bill of materials

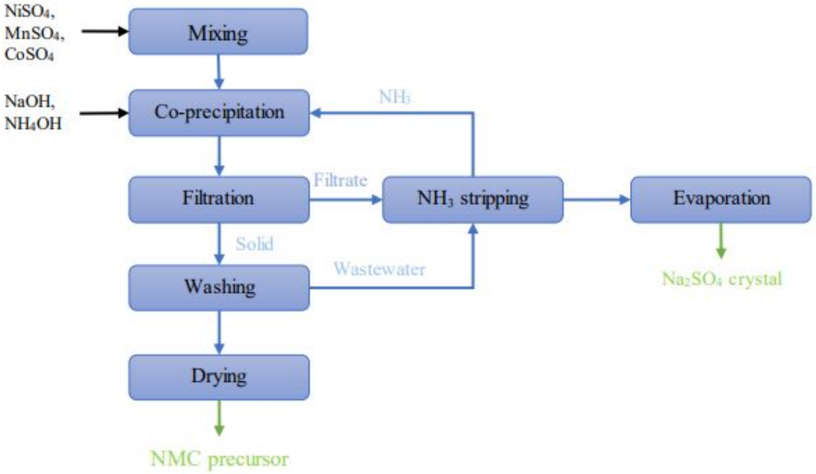


Figure 2. NMC Precursor Production via Co-precipitation

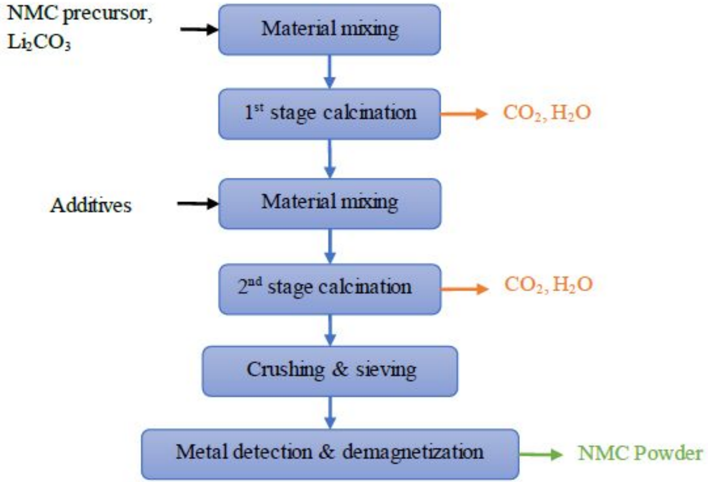


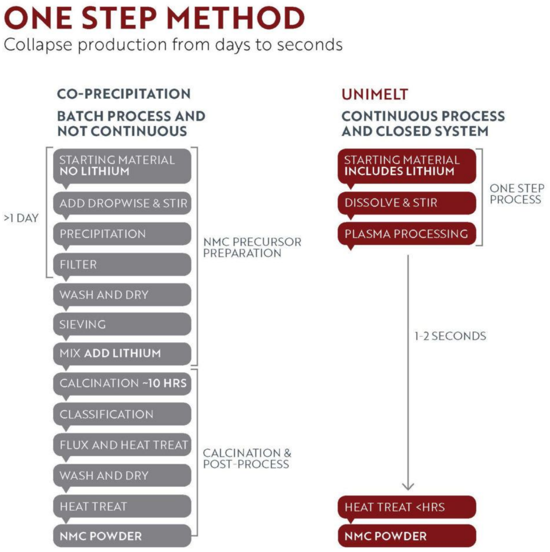
Figure 1. NMC Cathode Powder Production from Precursor via Calcination

Source: Argonne National Labs

Cell & Pack Manufacturing

pCAM-CAM Manufacturing Solutions

Innovations that are decreasing cost, complexity, and the environmental footprint of manufacturing CAM



ONE STEP METHOD

Collapse production from days to seconds

CO-PRECIPITATION

BATCH PROCESS AND NOT CONTINUOUS

>1 DAY

- STARTING MATERIAL **NO LITHIUM**
- ADD DROPWISE & STIR
- PRECIPITATION
- FILTER
- WASH AND DRY
- SIEVING
- MIX **ADD LITHIUM**
- CALCINATION **~10 HRS**
- CLASSIFICATION
- FLUX AND HEAT TREAT
- WASH AND DRY
- HEAT TREAT
- **NMC POWDER**

NMC PRECURSOR PREPARATION

CALCINATION & POST-PROCESS

UNIMELT

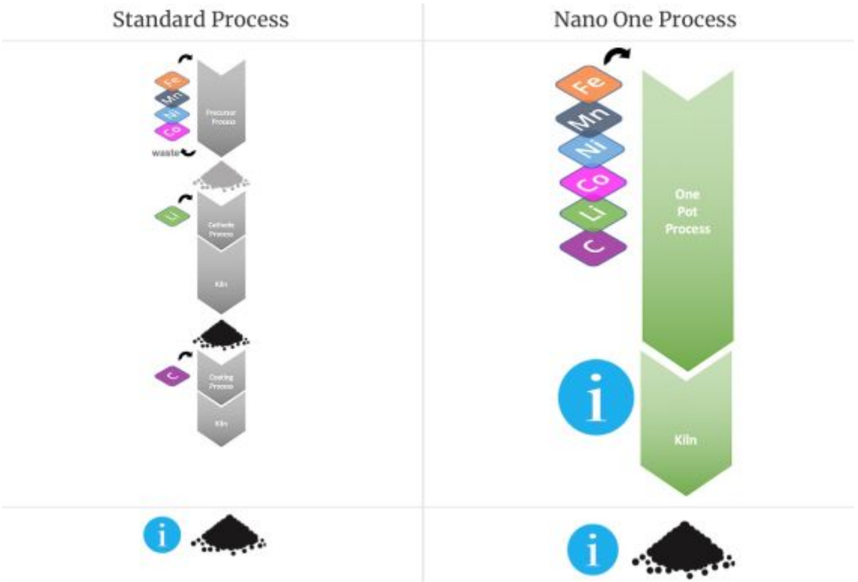
CONTINUOUS PROCESS AND CLOSED SYSTEM

ONE STEP PROCESS

- STARTING MATERIAL **INCLUDES LITHIUM**
- DISSOLVE & STIR
- PLASMA PROCESSING

1-2 SECONDS

- HEAT TREAT <HRS
- **NMC POWDER**



Nano One One-pot CAM Production Process

Source: 6K, Nano One

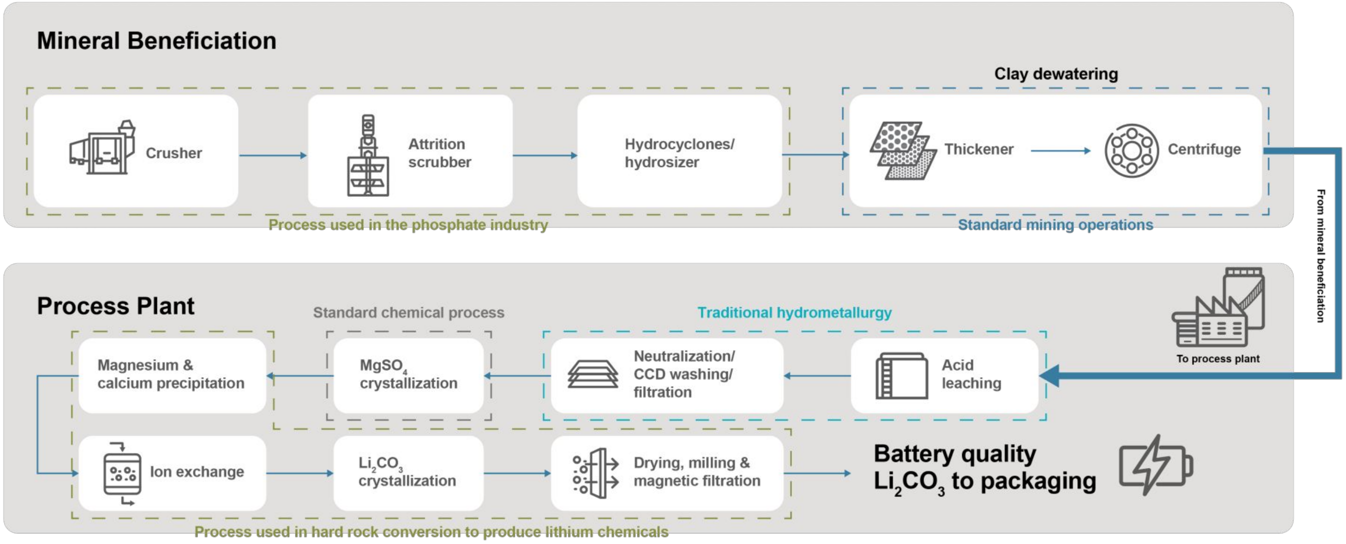
| Innovative Component Manufacturing Solutions

Lithium Extraction & Refining - Developing Battery Grade Li_2CO_3 From Sedimentary Lithium Economically & At Scale

Large scale lithium extraction from clay has been unsuccessful using traditional processes even from high concentration sources.

Processes from other mining industries were adapted for mineral benefaction.

Conversion process adapted from hard rock spodumene.



Mineral Beneficiation

Crusher → Attrition scrubber → Hydrocyclones/ hydrosizer

Process used in the phosphate industry

Clay dewatering

Thickener → Centrifuge

Standard mining operations

From mineral beneficiation

To process plant

Process Plant

Standard chemical process

Traditional hydrometallurgy

Acid leaching → Neutralization/ CCD washing/ filtration → $MgSO_4$ crystallization → Magnesium & calcium precipitation → Ion exchange → Li_2CO_3 crystallization → Drying, milling & magnetic filtration

Battery quality Li_2CO_3 to packaging

Process used in hard rock conversion to produce lithium chemicals

Source: Lithium Americas

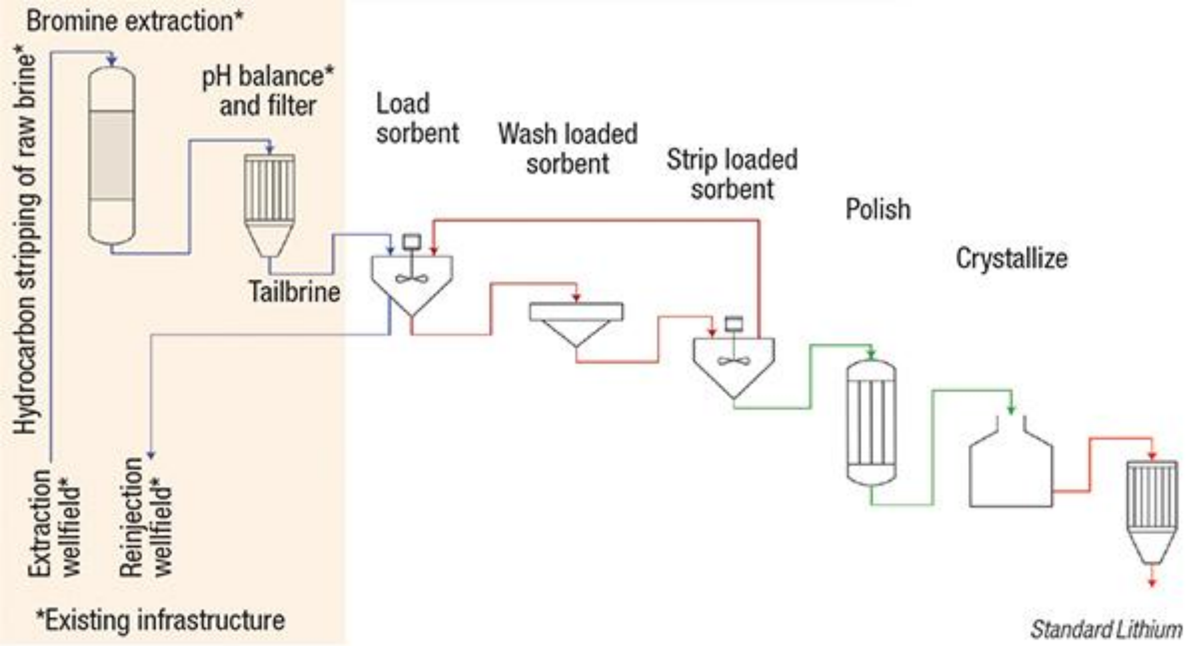
Cell & Pack Manufacturing | Innovative Component Manufacturing Solutions

Lithium Extraction & Refining - Direct Lithium Extraction

Standard Lithium has partnered with Lanxess to selectively extract lithium from oil field brine and produce battery quality lithium compounds.

In 2023 two feasibility studies were completed for separate projects in the Smackover Formation in Southwest Arkansas.

Preliminary feasibility study highlights indicate economic feasibility based in part on a reusable, custom-formulated lithium-selective sorbent.



Source: Chemical Engineering

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

Recycling

Software & Analytics

| Application Landscape | Part I

Applications Matched to Preferred Performance Metrics for Key Battery Chemistries Part I

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

Legend
Great
Good
Avg
Poor
Bad

Source: Battery Talk: Battery Application Break Down

| Application Landscape | Part II

Applications Matched to Preferred Performance Metrics for Key Battery Chemistries Part II

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
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

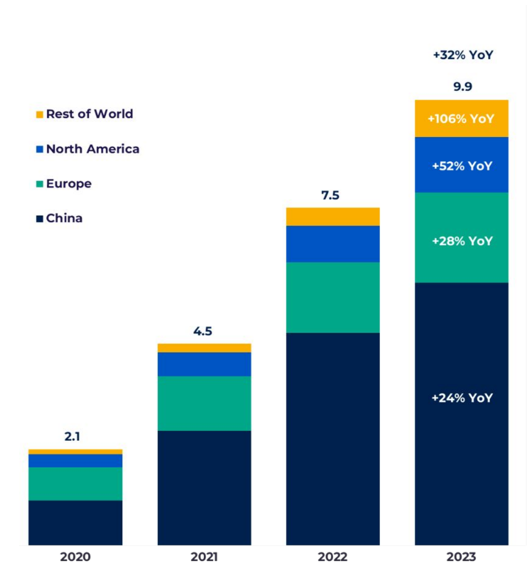
Source: Battery Talk: Battery Application Break Down

Applications

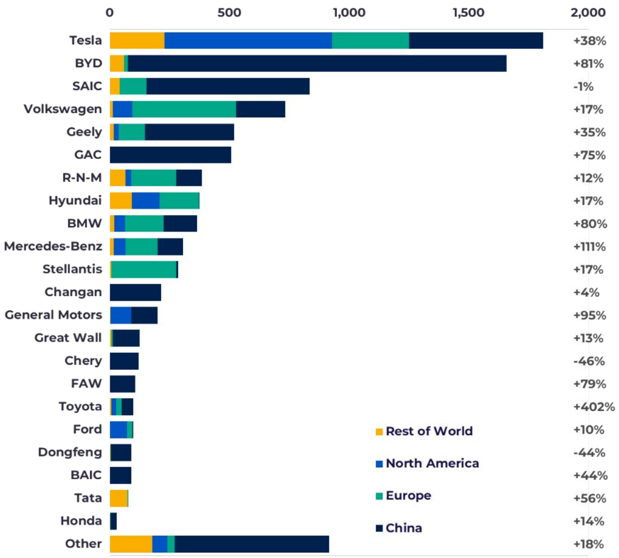
Applications | Electric Vehicles | Passenger BEVs

BEV sales growth trend remains fully intact

PV* BEV sales by region (mn vehicles)



PV* BEV sales by OEM in 2023 ('000 vehicles)



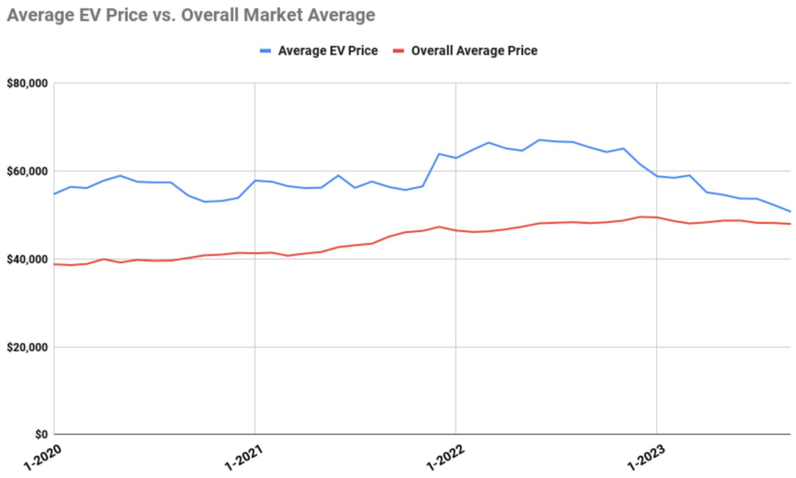
- Battery-electric vehicle sales reached 10 mn units for the first time in 2023.
- China remains the largest market with ~ 6 mn sales. All regions posted substantial growth.
- Tesla and BYD remain the largest manufacturers. The latter overtook the former in the last quarter.

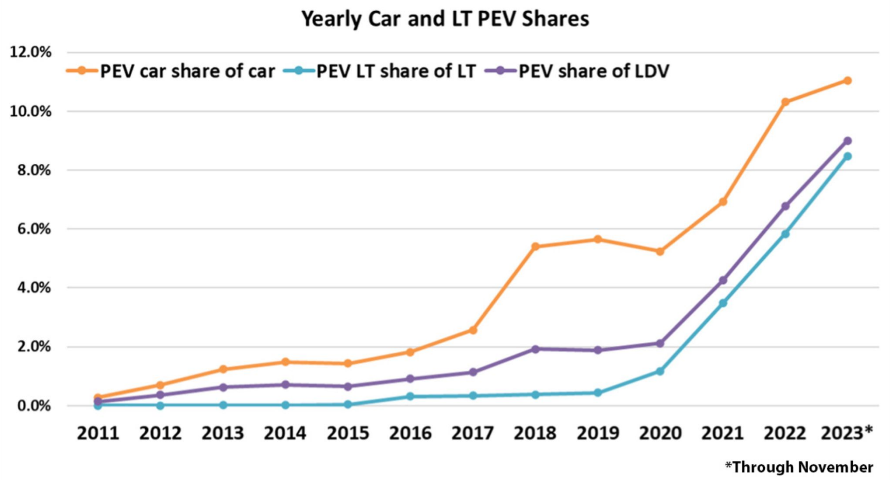
*Showing light duty vehicles registered for personal use only. Light commercial vehicles were an additional ~470k units in 2023. December 2023 is partially estimated.

Source: GlobalData

Electric vs ICE: Price Gap Decreases, Market Share Increases

The proportion of electric vehicle (EV) sales is experiencing a swift and steady increase in 2023. Concurrently, the average cost of an EV is on a downward trend, contrasting with the rising average price of conventional passenger vehicles during the pandemic period.



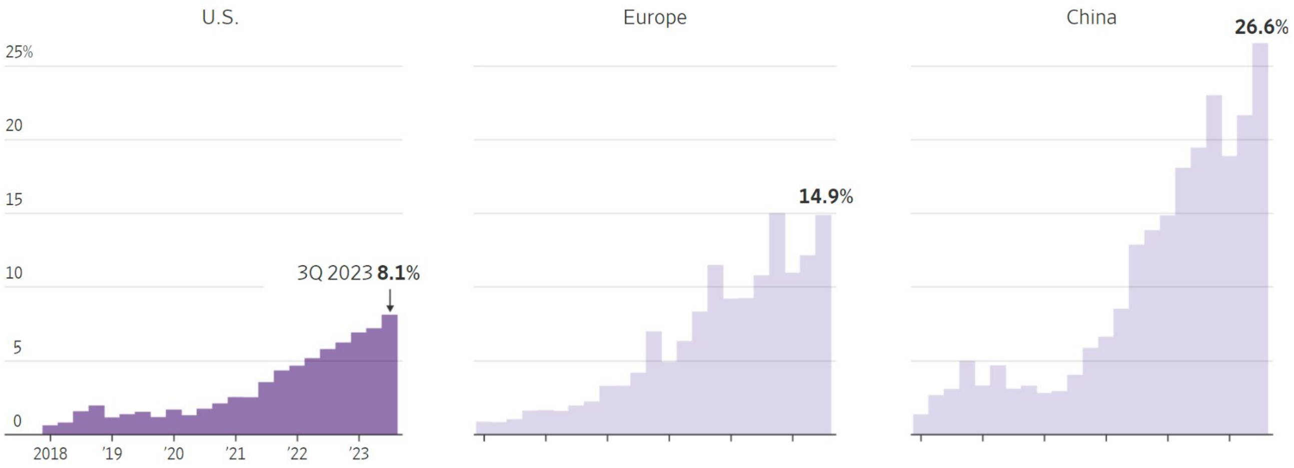


Source: Argonne National Lab, Caredge

Applications

China Continues To Be the Powerhouse of EV Adoption

Percentage of new vehicle sales that are EVs, quarterly



Note: 3Q 2023 figures are preliminary
Source: GlobalData

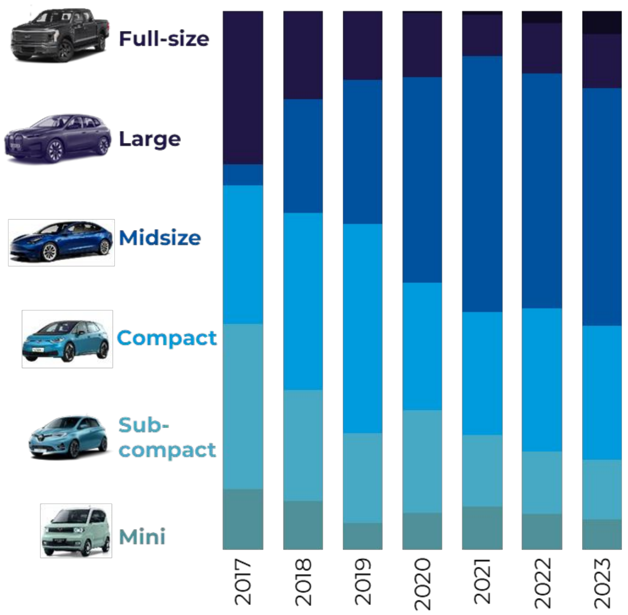
US & Europe

- Since the onset of the pandemic, China has experienced dramatic growth.
- In contrast, the growth trajectories in the US and Europe have been more gradual.
- Growth in China was in large part fuel by government incentives (similar to how the IRA could impact US growth).

Source: GlobalData

EV sizes & body types: market converging towards mid-size SUV segment

Vehicle segment trend based on battery demand, % GWh



Cost differential for EVs, consumer appetite for SUV body styles, and skateboard battery topologies are driving this trend.

Mini segment is disappearing in all markets, even China, but there are signs of an incoming resurgence:

Automotive News Europe

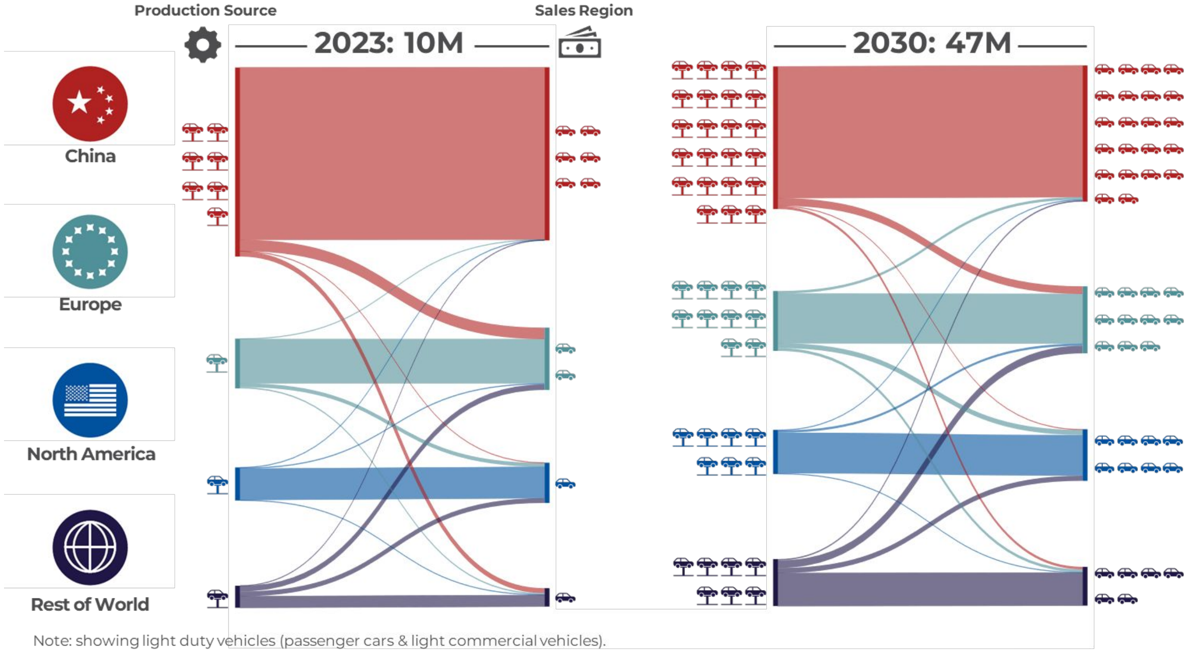
Automakers ready low-cost EVs for Europe to counter Chinese threat

Potential competition from China, inexpensive battery technology and concerns about consumer confidence have led to a wave of EVs for less than 25,000 euros.

Source: CRU Group, Autonews Europe

Applications | **Electric Vehicles** | Passenger BEVs

BEV trade flows: nations race to onshore BEV manufacturing, accelerated by policy



Note: showing light duty vehicles (passenger cars & light commercial vehicles).

'Build where you sell'

Decisions to localize vehicle production to where they are sold, or export from another country, are being made on a model-by-model basis and are driven by factors including:

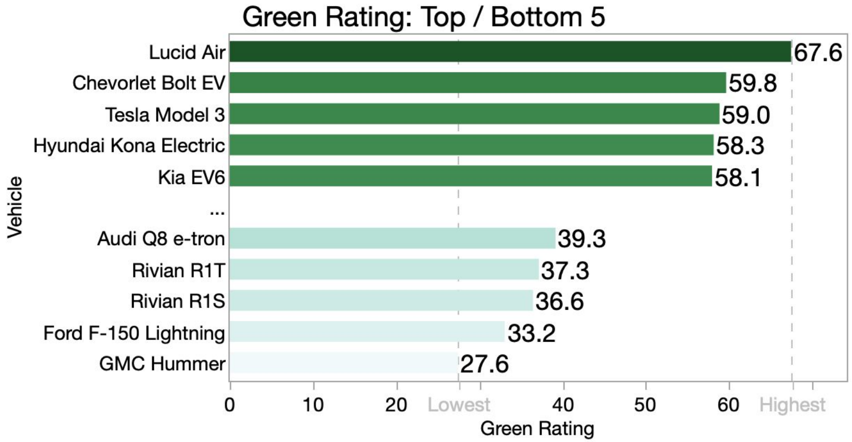
- Local demand
- Policy
- Cost
- Environmental

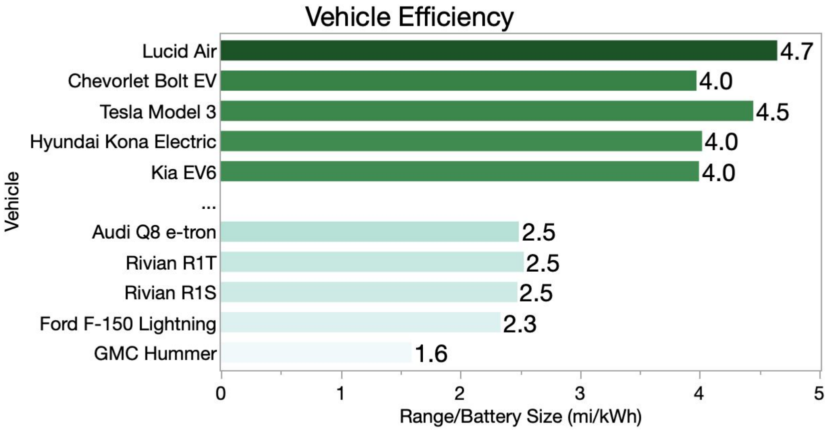
Source: CRU Group

Bloomberg Green Rating highlights inefficiencies of trucks/SUVs at the vehicle level

Bloomberg's Green Rating is a combined metric for a car's efficiency during travel and the resources required to manufacture the pack's battery. Compact cars and some premium EVs excel while crossovers, SUVs, and trucks rank the lowest in Green Rating, mapping well with vehicle efficiency ratings.

$$Green\ Rating = \left(\frac{miles\ of\ range / curb\ weight}{economy\ benchmark} \cdot 0.7\right) + \left(\frac{battery\ size\ benchmark}{battery\ size} \cdot 0.3\right)$$



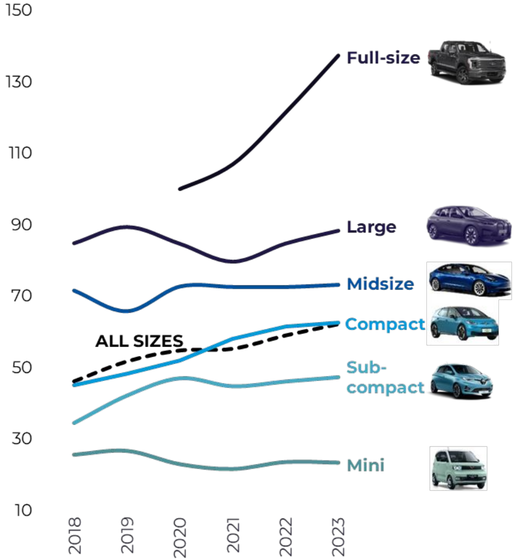


Source: Bloomberg

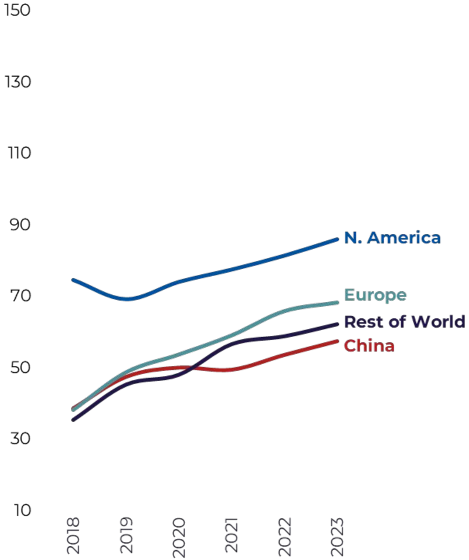
Applications | Electric Vehicles | Passenger BEVs

Battery pack capacities continue to increase but are starting to plateau

Weighted-average BEV battery pack capacity by vehicle segment, kWh



Weighted-average BEV battery pack capacity by region, kWh



Showing light duty vehicles (passenger cars and light commercial vehicles)

- Capacities primarily driven by range expectations
- Capacities also driven by chemistry selection and vice versa - small batteries more conducive to LFP & Na-ion
- But mini vehicles have small batteries and are small part of battery demand
- Rightsizing will contribute to thrifting of raw materials (less material being used per kWh of capacity)
- One scenario is that cost and legislative pressures and ubiquitous fast charging will encourage ‘rightsizing’ of batteries in the long term

Source: CRU Group

Applications

Applications | Electric Vehicles | Passenger BEVs

Mixed pullback in EV output; OEMs cite slow demand but reality is more complex

May-23

Polestar (China)
Lowers 2023 production guidance and will cut headcount by 10%, 'citing delayed production start for Polestar 3 and challenging industry environment'

Oct-23

Volkswagen (Germany)
Suspended production for ID.3 and Born in two plants for 2 weeks in October, 'due to weak demand'

Oct-23

Ford (USA)
Idling one of three shifts for F-150 Lightning, 'citing multiple constraints such as supply chain issues'. Also reducing output for Mustang Mach-E.

GM (USA)
Delayed production of Silverado and GM Sierra EVs to late 2025 'citing EV demand and engineering upgrades'

Oct-23

Honda/GM (USA)
Honda halting plans to develop smaller EVs with GM, 'citing cost and range challenges'

Mercedes-Benz (USA)
CFO says EV adoption rate lower than expected; US dealers complaining of slow-selling EVs piling up on lots

Oct-23

Tesla (USA, global)
CEO says high interest rates and macroeconomic situation making it difficult for consumers to afford new vehicles; Tesla is in no rush to build new Mexico assembly plant

Nov-23

Toyota (Global)
Cuts EV sales forecast for FY24 by 32%, from 202k down to 123k, citing profit drive

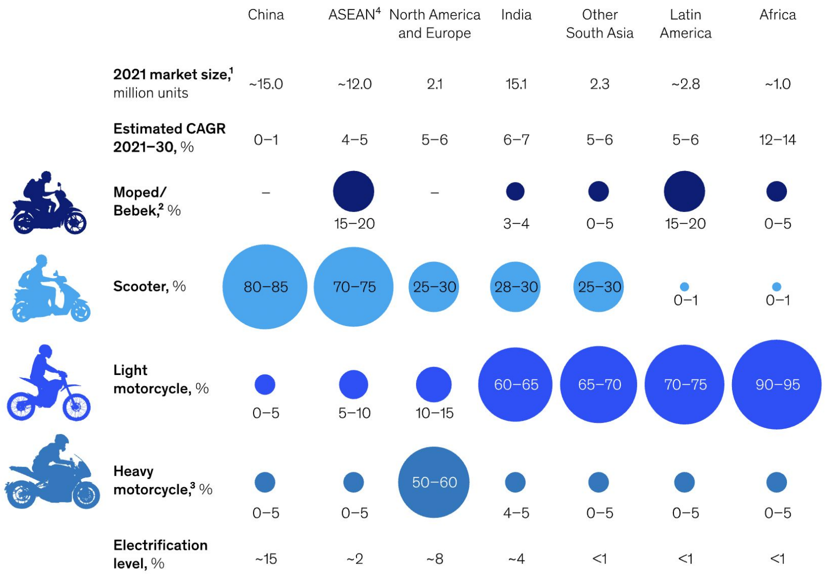
Dec-23

Ford (USA)
2024 production plan for F-150 Lightning cut by half (75k down from 150k)

- Wave of production cutbacks and watering down of EV targets cited from legacy automakers burdened with ongoing transition to EVs, large capex commitments and profitability concerns
- Industry is also dealing with interest rates, high inventories, workforce strikes (US), concerns over residual selling value, and competitive environment from continuous price cuts and stronger 'pure-play' manufacturers

2 Wheelers are the vehicle for decarbonization in several Asian markets

Electric-2-wheeler facts and product mix, by geography[1]



	China	ASEAN[4]	North America and Europe	India	Other South Asia	Latin America	Africa
2021 market size,[1] million units	~15.0	~12.0	2.1	15.1	2.3	~2.8	~1.0
Estimated CAGR 2021–30, %	0–1	4–5	5–6	6–7	5–6	5–6	12–14
Moped/ Bebek,[2] %	–	15–20	–	3–4	0–5	15–20	0–5
Scooter, %	80–85	70–75	25–30	28–30	25–30	0–1	0–1
Light motorcycle, %	0–5	5–10	10–15	60–65	65–70	70–75	90–95
Heavy motorcycle,[3] %	0–5	0–5	50–60	4–5	0–5	0–5	0–5
Electrification level, %	~15	~2	~8	~4	<1	<1	<1

Two wheelers (scooters,motorcycles, mopeds) are defined as vehicles capable of going at speeds greater than 25 kmph. An alternate definition is L-category vehicles with 2 wheels as defined by UNECE.

Two Wheelers are the primary mode of personal transport in China, South and South-East Asia but account for **<5% of global emissions**

But Indian and Chinese cities feature prominently in the list of **world's most polluted cities.** and ICE two wheelers are **a major contributor** to worsening air quality in these cities.

Two wheelers are also a major opportunity as the cumulative market size is 50 million units (if all two wheelers became electric). E2Ws are also on a **swifter path to zero emissions.**

The total cost of ownership (TCO) of electric two wheelers is already better than ICE in the largest market in **India,** aided by government incentives and in China the up front cost of a E2W is at par with ICE.

Countries like **Vietnam** and **Indonesia** have not achieved TCO parity yet but have a growing E2W market.

Source: McKinsey, TIME, BNEF, Blume, ICCT, BCG, IQAir

Applications | Electric Vehicles | Light Transport

2 Wheelers: Major players driving electrification across regions

China
- YADEA
- AIMA
- niu
- TAILG

ASEAN
- VINFAST
- gogoro
- ion MOBILITY
- GESITS

India
- OLA ELECTRIC
- TVS
- ATHER
- BAJAJ
- Hero

Africa
- ROAM
- AMPERSAND
- Zembo

North America and Europe
- ZERO MOTORCYCLES®
- Vespa
- LiveWire
- BMW MOTORRAD

Japan
- HONDA
- YAMAHA
- Kawasaki

Indian OEMs TVS and Hero are partnering with or investing in startups (**Indian** and **international**) and technology leaders such as **Zero** and **BMW**, to accelerate their electrification journey

ICE incumbents such as **Honda, Yamaha, Bajaj, Hero** and **TVS** have more EV products in development and are scaling up operations.

Partnerships/Investments of note

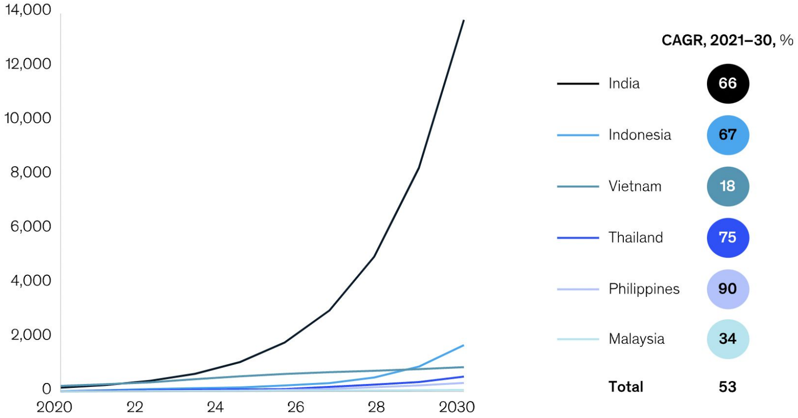
ATHER ZERO MOTORCYCLES® gogoro Hero	BMW MOTORRAD ion MOBILITY TVS ULTRAVIOLETTE

Source: Statista, McKinsey, Maybank, Business Standard, Autocar CNBC,, Company Announcements

Applications | Electric Vehicles | Light Transport

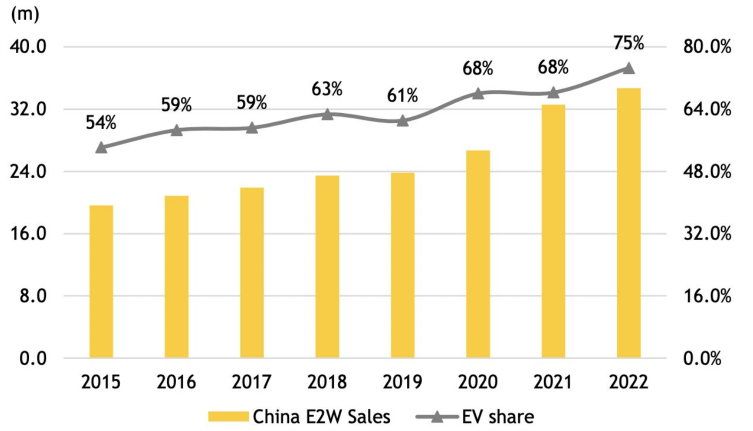
2 Wheelers: Countries driving electrification

E2W[1] sales in select countries, thousands of vehicles



[1] Includes e-scooter and e-motorcycles
Source: McKinsey EVOLVE tool; ASEAN Automotive Federation; expert interviews; International Clean Council on Transportation motorcycles data; Statista; WRI India

Fig 24: China's 2-wh EV market: EVs accounted for 75% of China's sales in 2022



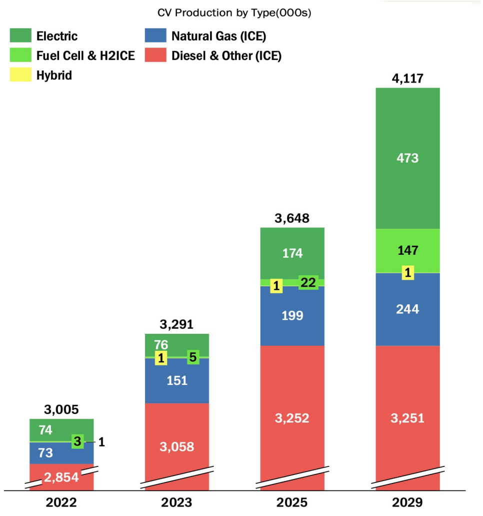
India and ASEAN poised for high growth over the next decade aided by government subsidies and support.

The Chinese market is almost fully electrified and saturating.

Source: Statista, Mckinsey, Maybank

Applications | Heavy Duty Vehicles (HDV) | Regulations & Market Size

Heavy Vehicles (>6t) will be increasingly electrified because of emissions legislation tightening and more favorable Total Cost of Ownership for non-diesel powertrains



KGP LMC Global Commercial Vehicle Powertrain Forecast GCVPTF Quarter 3 2023

Key Trends

Regulations

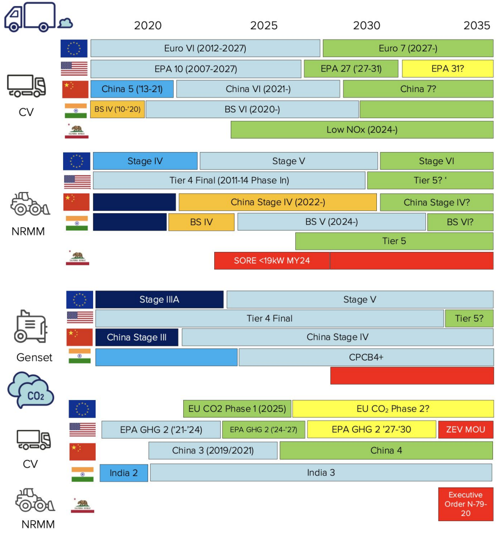
- Tightening of Heavy Vehicle CO_2 legislation in North America (California ACT, ACF), EPA GHG 3, European HDV CO_2 Regulation driving BEV and FCEV applications
- ESG/CSR, Zero Emission Pledges driving BEV construction and mining equipment
- There are no Off-Highway Machinery regulations in any major market globally, but California has a zero emission Executive Order and incentives driving BEVs

Longer Range

- Hydrogen investment to drive Fuel Cell Range Extended BEV post 2030
- Longer range BEV with larger batteries (Long-Haul Class 8) coming to market 2023

Total Cost of Ownership

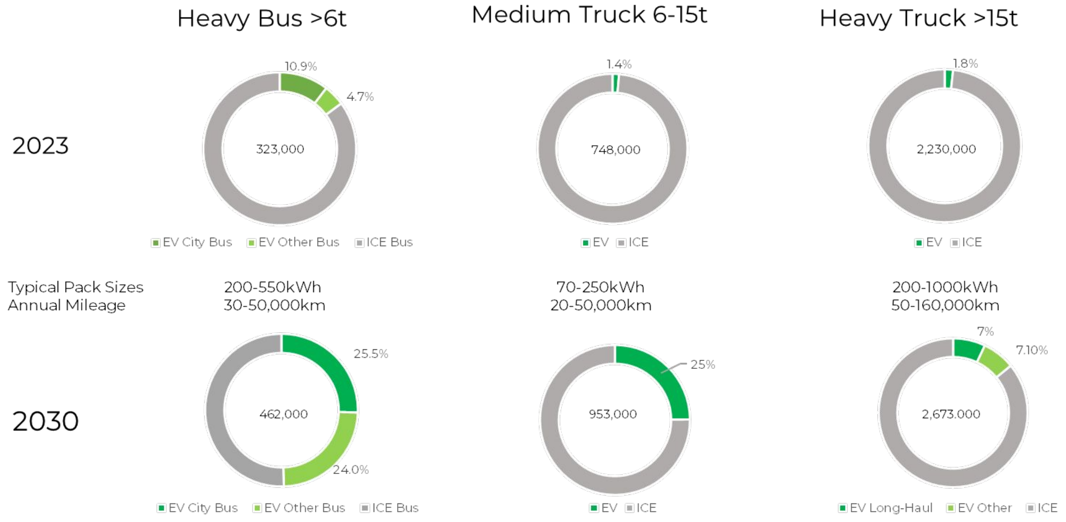
- The financial profile of BEV in HDV applications is very favorable because the biggest factor of the Total Cost of Ownership (TCO) is the cost to operate the vehicle, including the fuel costs.



Source: KGP

Applications | **Heavy Duty Vehicles (HDV)** | Pack Size & Durability

Battery sizes in heavy vehicles will depend mainly on usage cycle and gross vehicle weight



Unit Sales 2023/2030

Heavy Duty Battery Durability

Durability requirements for Heavy Duty will be considerably higher than for light duty, impacting chemistry, cooling, charging and warranty. High annual distances will require higher level (MCS) charging which will also impact durability.

A UN battery durability regulation for both light duty (legislation drafted GTR 22) and heavy duty (proposals being developed under WP 29) is being developed.

Heavy Duty battery durability starting point is GTR 22. Key metrics will included:

- % of SOCE (State-of Certified Energy) retained
- X years of Service (varies by weight category 8-15 years)
- Y Mileage (km)

HDV metrics also being considered:

- PTO Energy Throughput
- Total Energy Throughput
- Capacity Throughput Testing schedule
- Standardized Charging
- Cycle test method

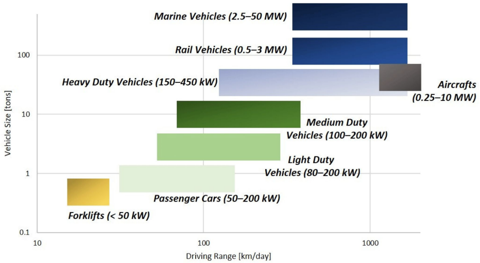
Source: KGP-GlobalData Commercial Vehicle Powertrain Forecast November 2023 , UNECE

VF | VOLTA FOUNDATION

Applications | Heavy Duty Vehicles (HDV) | Trends By Type Of Vehicle

Off Highway Vehicles growing adoption of electrified propulsion systems, with some technology transfer from Commercial Vehicles facilitating adoption

- Largest machines account for <1% of units but 20% fuel/energy demand
- Construction, Mining & Quarrying, Materials Handling and Agriculture make up majority of Non-Road Machinery globally. Total industry units are circa 4.4M in 2023
- Energy requirements dependent on size, application and hours used, with most vehicles housing >100kWh battery
- Batteries need high-cycle-life chemistries, with mix of energy/power for energy recovery
- Number of electric machine models available globally increased 50% between 2021 and 2023



Typical Battery Capacity & Equipment Size	Equipment Types (Examples)	Power/ Voltage	Technology Transfer	Model Availability
10-50 kWh Handheld/ Extra-Compact	Compaction, Dumpers, Lawn care	48V <19 kW	Passenger Car Forklift	AG - 16 CE - 43 MH - 2
50-100 kWh Compact	Mini-Excavators, Compact Wheel-Loaders, Compact Tractors, Asphalt Finishers, Forklift	48-90V 19-75 kW	Light Commercial Vehicle	AG - 40 CE - 110 MH - 11 Others - 9
100-300 kWh Mid-Sized	Wheeled, Crawler Excavators, Skid-Steer, Compact Tracked Loaders, Telehandlers, Wheel-Loaders	100-300V 75-225 kW	Medium Truck	AG - 14 CE - 86 MH - 19 Others - 4
0.3-1 MWh Large	Crawler Excavators, Wheel-Loaders, Crushers, Screens, Port-Handling, Mobile Cranes, Piling Rigs	400-1000V 225-560 kW	Heavy Truck Bespoke NRMM	AG - 6 CE - 34 MH - 8 Others - 35
>1 MWh Extra-Large	Mining Dump Trucks, Marine, Rail	>1000V >560 KW	Bespoke NRMM	CE/Mining - 32 Others - 3

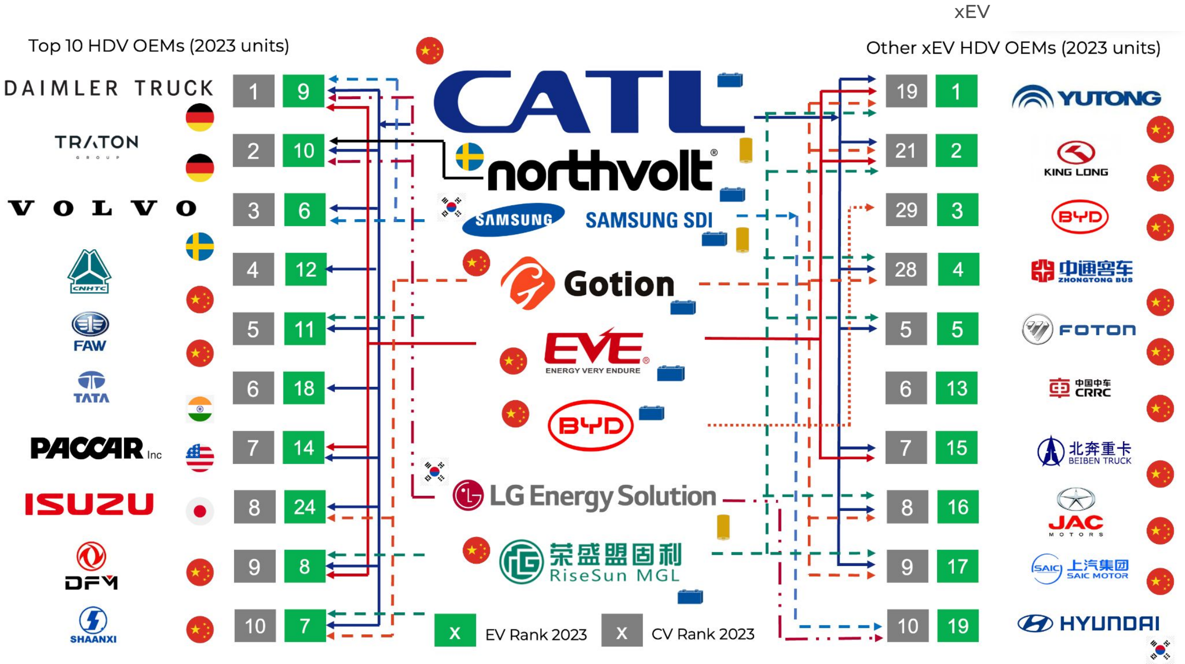
CE - Construction, AG - Agricultural, MH - Material Handling

VF | VOLTA FOUNDATION

Source: KGP-Off-Highway Research Global Non-Road Powertrain Forecast xEV Module November 2023, CECE Summit 2023

Applications | Heavy Duty Vehicles (HDV) | Suppliers, Chemistry, Form Factor

China dominates cell and vehicle supply in 2023 for Truck and Bus over 6t GVW



The HDV cell supply chain remains complex, with different suppliers for different platforms and end use applications.

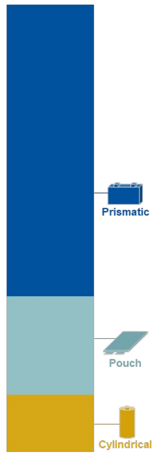
Chinese cell suppliers dominate currently with LFP prismatic cells used by many OEMs.

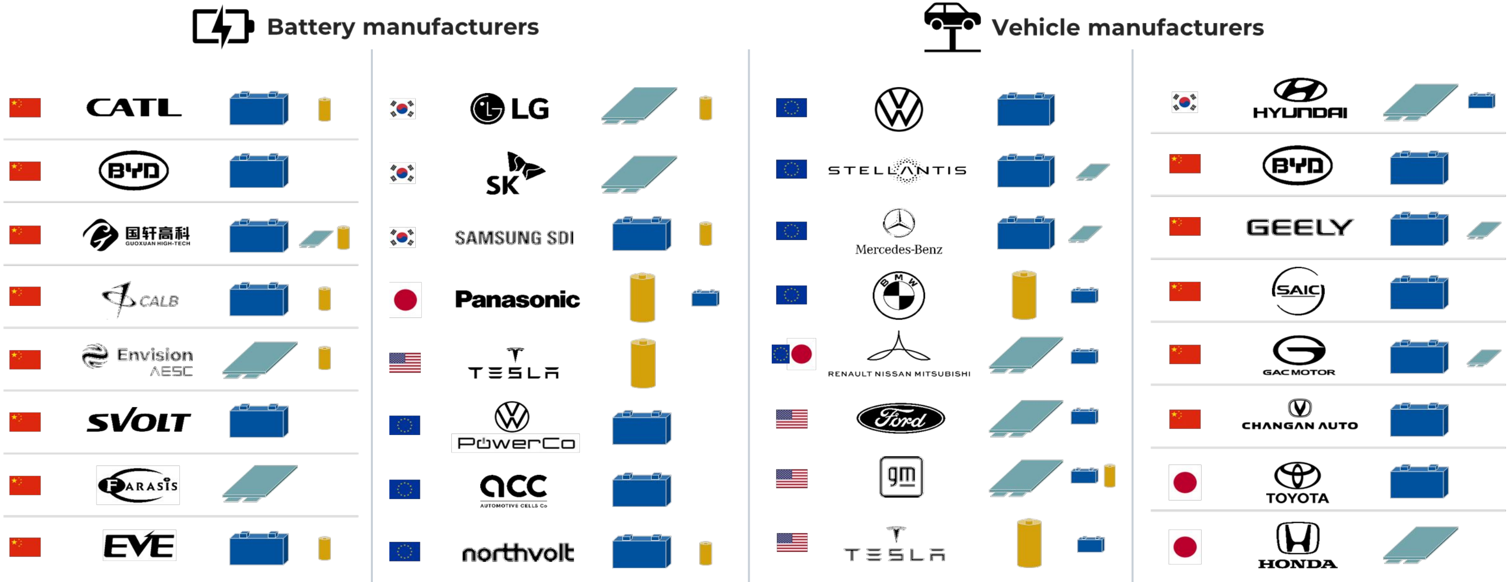
Cylindrical NMC used in a minority, mainly in Europe. EVE's joint venture with Daimler Truck, Paccar and Accelera (Cummins) is likely to be a major supplier towards 2030.

Source: KGP

Form Factors: mass market trending towards large-format cells, especially prismatic

Share of cell formats in BEVs, 2023, %
GWh basis





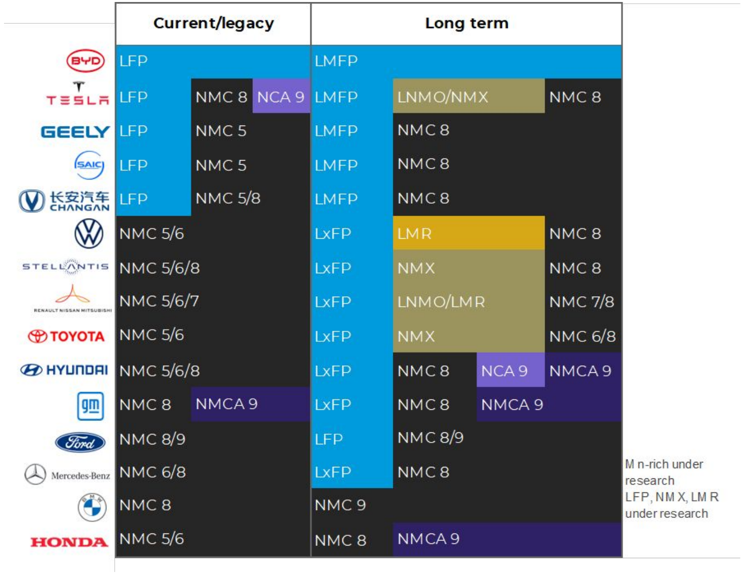
Large and small icons denote primary and secondary form factors respectively.

Source: CRU Group, company announcements

Applications | Electric Vehicles | Passenger BEVs

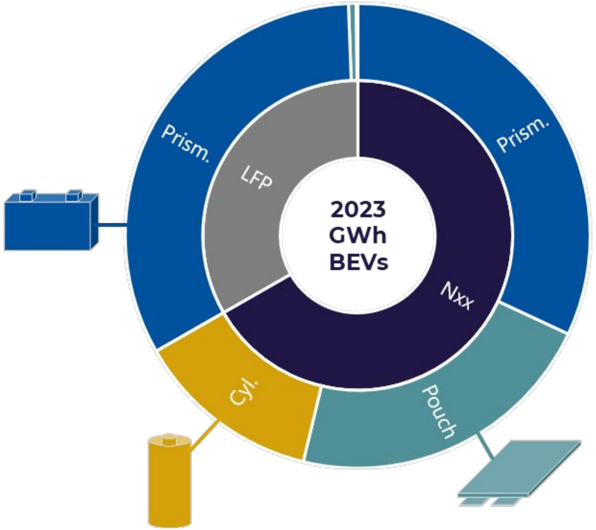
Chemistry & form factor selection of OEMs

OEMs increasingly adopting lower cost & energy-dense chemistries - impacting material usage and battery costs



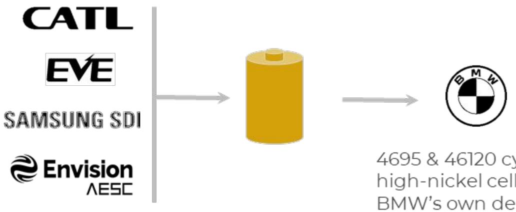
	Current/legacy			Long term				
BYD	LFP			LMFP				
TESLA	LFP	NMC 8	NCA 9	LMFP	LNMO/NMX		NMC 8	
GEELY	LFP	NMC 5		LMFP	NMC 8			
SAIC	LFP	NMC 5		LMFP	NMC 8			
长安汽车 CHANGAN	LFP	NMC 5/8		LMFP	NMC 8			
VW	NMC 5/6			LxFP	LMR		NMC 8	
STELLANTIS	NMC 5/6/8			LxFP	NMX		NMC 8	
RENAULT NISSAN MITSUBISHI	NMC 5/6/7			LxFP	LNMO/LMR		NMC 7/8	
TOYOTA	NMC 5/6			LxFP	NMX		NMC 6/8	
HYUNDAI	NMC 5/6/8			LxFP	NMC 8	NCA 9	NMCA 9	
gm	NMC 8	NMCA 9		LxFP	NMC 8	NMCA 9		
Ford	NMC 8/9			LFP	NMC 8/9			
Mercedes-Benz	NMC 6/8			LxFP	NMC 8			Mn-rich under research
BMW	NMC 8			NMC 9				LFP, NMX, LMR under research
HONDA	NMC 5/6			NMC 8	NMCA 9			

Chemistry influenced by cell format and vice versa LFP is driving trend towards prismatic

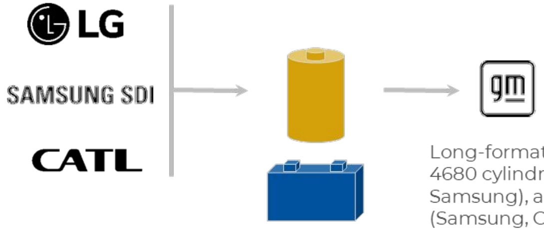


Source: CRU Group [1] [2]

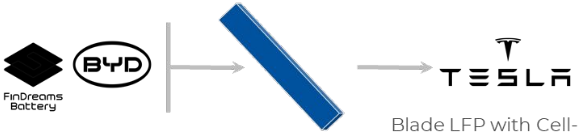
Form Factor Update: New & Emerging Partnerships



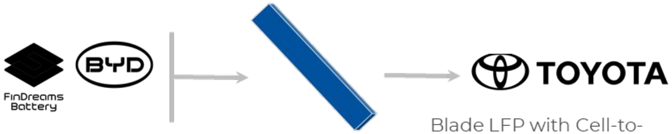
4695 & 46120 cylindrical high-nickel cells of BMW's own design



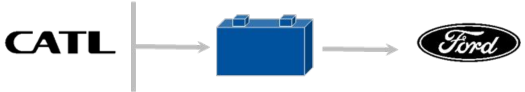
Long-format pouch (LG), 4680 cylindrical (LG, Samsung), and prismatic (Samsung, CATL)



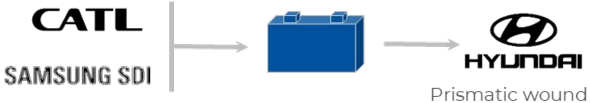
Blade LFP with Cell-to-Pack, currently for Made-in-Germany Model Y



Blade LFP with Cell-to-Pack, for specific Made-in-China models



Prismatic wound LFP, to be manufactured by Ford under license from CATL



Prismatic wound LFP with Cell-to-Pack (CATL), Prismatic NCA (Samsung)

Source: Company announcements: BMW [1], [2], [3], [4], Tesla [5], Ford [6], GM [7], [8], Toyota [9], Hyundai [10], [11]

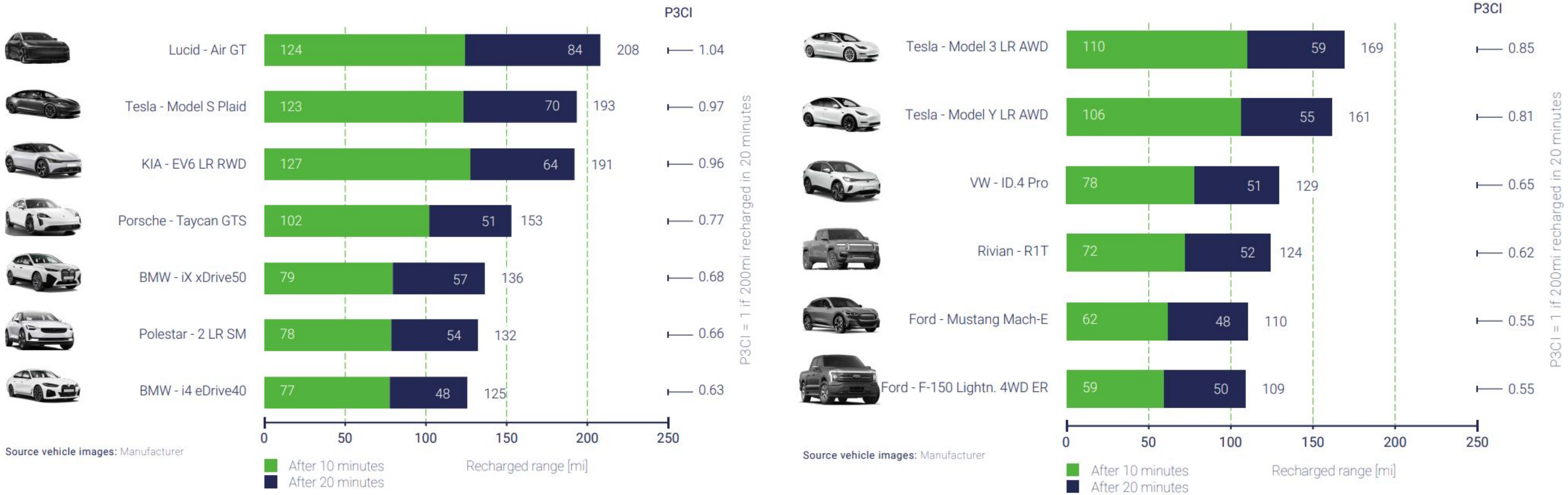
Applications | Electric Vehicles | Charging Performance

In the US, highest charging speeds have been limited to expensive premium models that are not eligible for IRA incentives.

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

Non-Tax Credit Eligible EVs

Tax Credit Eligible EVs

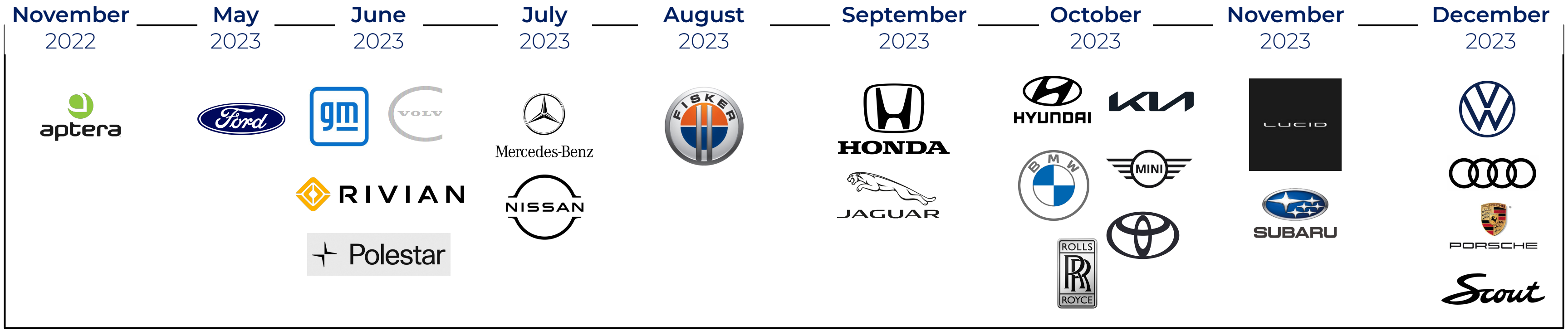


Definitions: P3CI - US = Real recharged range within 20 minutes / 200 mi

Source: P3 Charging Index 2023/06

NACS (North American Charging Standard) was adopted by nearly all major OEMs

- Unreliable charging infrastructure is the major reason OEMs have targeted access to the Tesla Supercharger network in NA beginning in 2025
- The charging system will be standardized as SAE J3400
- Major charging hardware manufacturers and CPOs have also signed on to offer charging stations with **NACS hardware**



November 2022

May 2023

June 2023

July 2023

August 2023

September 2023

October 2023

November 2023

December 2023

June 2023

Hardware manufacturers and CPOs:

Source: Reuters

Applications | Electric Vehicles | Charging Infrastructure

Europe’s Alternative Fuel Instructure Regulation defines charging infrastructure developments

EU Alternative Fuel Infrastructure Regulation (AFIR), adopted in September 2023, specifies mandatory infrastructure requirements for all EU member states along the international **TEN-T network.** The regulation covers both Light Vehicle and Heavy Vehicle electric charging and hydrogen refuelling requirements. The regulation is part of the EU’s Green Deal ‘Fit for 55’ program.

Light Duty Charging Pool Minimum requirements

Target Date	Scope	Capacity Requirement
December 31, 2025	TEN-T **core*** road network at 60km max	- Recharging pool ≥400kW and at least one point ≥150kW
December 31, 2027	TEN-T **core*** road network at 60km max TEN-T **comprehensive*** road network at 60km max	- Recharging pool ≥ 600kW and at least two points ≥ 150kW - Along at least 50% of the length of the comprehensive road network each pool offers ≥300kW and at least one point of ≥150kW
December 31, 2030	TEN-T **comprehensive*** road network at 60km max	- Recharging pool ≥ 300kW with at least one point ≥150kW
December 31, 2035	TEN-T **comprehensive*** road network at 60km max	- Recharging pool ≥600kW and at least two points ≥150kW

Heavy Duty Charging Pool Minimum Requirements

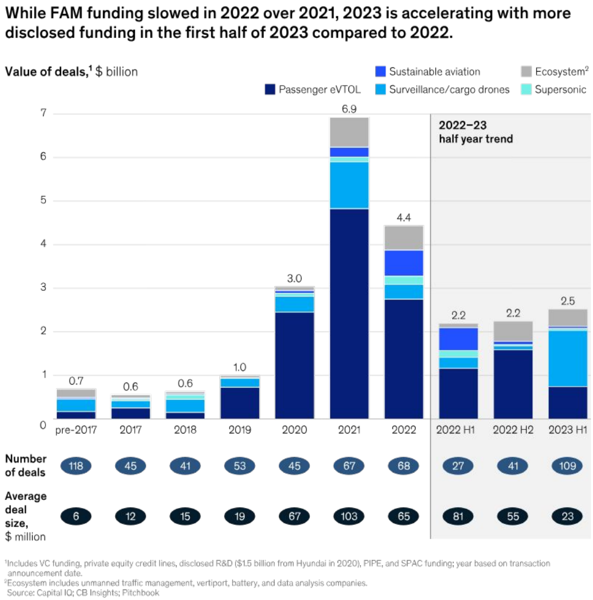
Target Date	Scope	Capacity requirement
December 31, 2025	TEN-T network In each Urban node	- Recharging pools for heavy-duty vehicles along >15% of the network, each direction, with minimum 1,400kW and one 350kW point - Accessible heavy-duty vehicle points totaling 900kW, with minimum 150kW each
December 31, 2027	TEN-T network TEN-T **core** network TEN-T **comprehensive** network Safe and secure parking areas	- Recharging pools for heavy-duty vehicles across 50% of the network length, each travel direction - Minimum 2,800kW power output with two points ≥350kW points - Minimum 1,400kW power output with one point ≥350kW - Two publicly accessible heavy-duty vehicle stations, each with ≥100kW
December 31, 2030	TEN-T core network TEN-T **comprehensive** network Safe and secure parking areas In each Urban node	- Pools with a maximum of 60km apart, ≥3,600kW, & two points ≥350kW - Publicly accessible heavy-duty vehicle pools in each direction, maximum 100km apart, with ≥1,500kW and one point ≥350kW - At least four publicly accessible heavy-duty vehicle stations, each with a minimum of 100kW. - Publicly accessible heavy-duty vehicle points totaling ≥1,800kW, with individual points ≥150kW

*The core network includes the most important connections linking major cities and nodes, and must be completed by 2030. It needs to meet the highest infrastructure quality standards. The comprehensive network connects all regions of the EU to the core network and needs to be completed by 2050

Source: Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure

Applications | Electrified Aviation | Funding

Funding towards passenger EVTOLs reduces significantly as incumbents progress towards certification; drones dominate investments in 2023



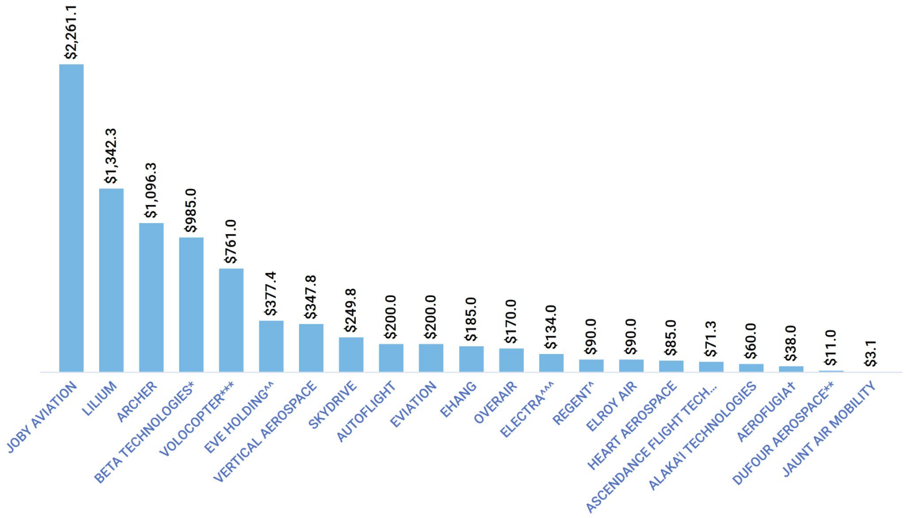
While FAM funding slowed in 2022 over 2021, 2023 is accelerating with more disclosed funding in the first half of 2023 compared to 2022.

[1] Includes VC funding, private equity credit lines, disclosed R&D ($1.5 billion from Hyundai in 2020), PIPE, and SPAC funding; year based on transaction announcement date.

[2] Ecosystem includes unmanned traffic management, vertiport, battery, and data analysis companies.

Source: Capital IQ; CB Insights; Pitchbook

Funding for Passenger EVTOLs



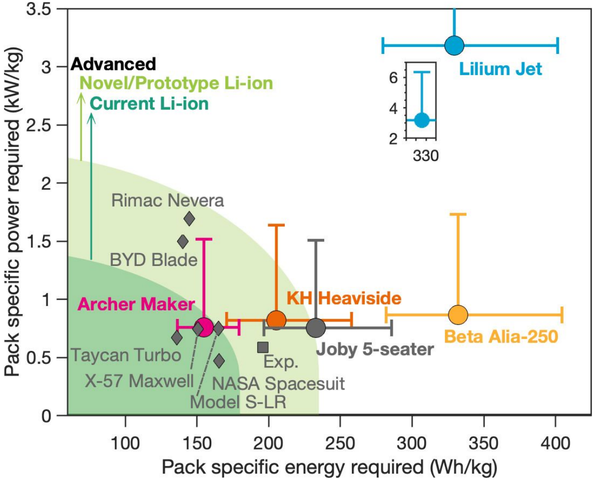
Source: McKinsey and Company, AAM Reality Index (SMG Consulting)

Applications | Electrified Aviation | EVTOLs

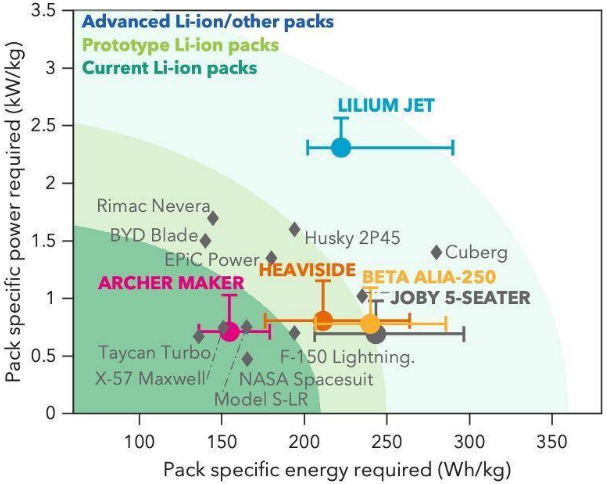
Battery system capabilities improve, and EVTOL companies continue aircraft development closer to existing battery technology

EVTOLs expected to go into production in the near future will use conventional Li-ion cells,with packs under 250 Wh/kg enabling aircraft certification and first-gen products

2021



2023



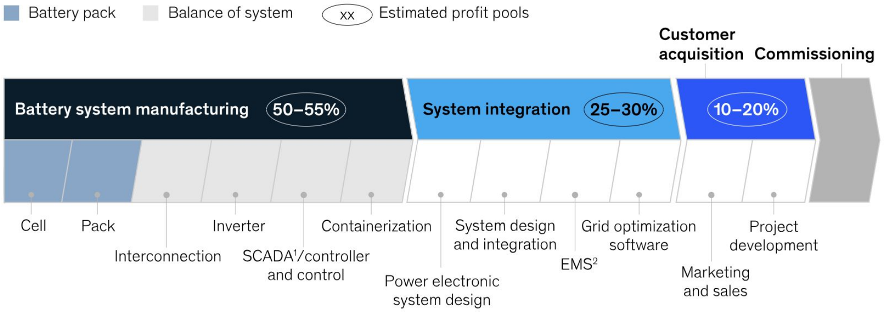
Source: S. Sripad et al., The promise of energy-efficient battery-powered urban aircraft

Applications | Battery Energy Stationary Storage (BESS)

BESS is a nascent yet rapidly growing market

Investment into battery energy stationary storage (BESS) has tripled to $5 billion in 2022 compared to 2021 with the global BESS market expected to reach ~**$120-$150 billion by 2030.** However, there is risk and uncertainty around financiers, integrators, and battery chemistries. From cell to commission, the ecosystem is complex, with 50%+ of the BESS value chain profit pool dominated by battery system manufacturing.

Value chain breakdown of battery energy storage systems (hardware only)



[1] Supervisory control and data acquisition.
[2] Energy management system.

Battery energy storage systems are used across the entire energy landscape.

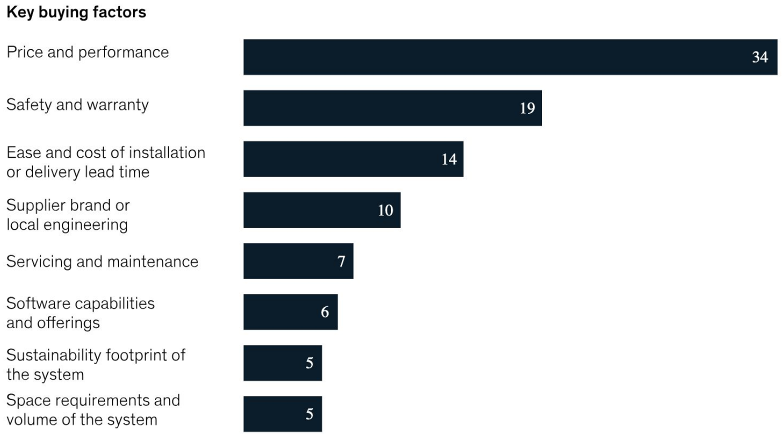
	Front of the meter (FTM)	Behind the meter (BTM)	
	Electricity generation and distribution (Utility)	**Commercial and industrial (C&I)**	**Residential**
Use cases	Price arbitrage Long-term capacity payments Ancillary service markets Derisking renewable generation Investment deferral	Renewable integration (rooftop photovoltaic) Uninterruptable power supply (UPS) Power cost optimization Electric-vehicle (EV) charging infrastructure	Home integration of: Renewable integration (rooftop photovoltaic) EV charging infrastructure

Source: McKinsey

Applications | BESS | Battery Technology

Residential energy storage products shifted towards LFP in 2023, consistent with top consumer preferences toward price, safety, & lifetime (warranty).

2023 BESS[1] Germany Customer Survey, perceived as most important, % of respondents



[1] Battery energy storage system.
Source: McKinsey BESS Customer Survey, 2023, German market (n = 300)

Table 2: Battery chemistry of major products by selected residential storage providers

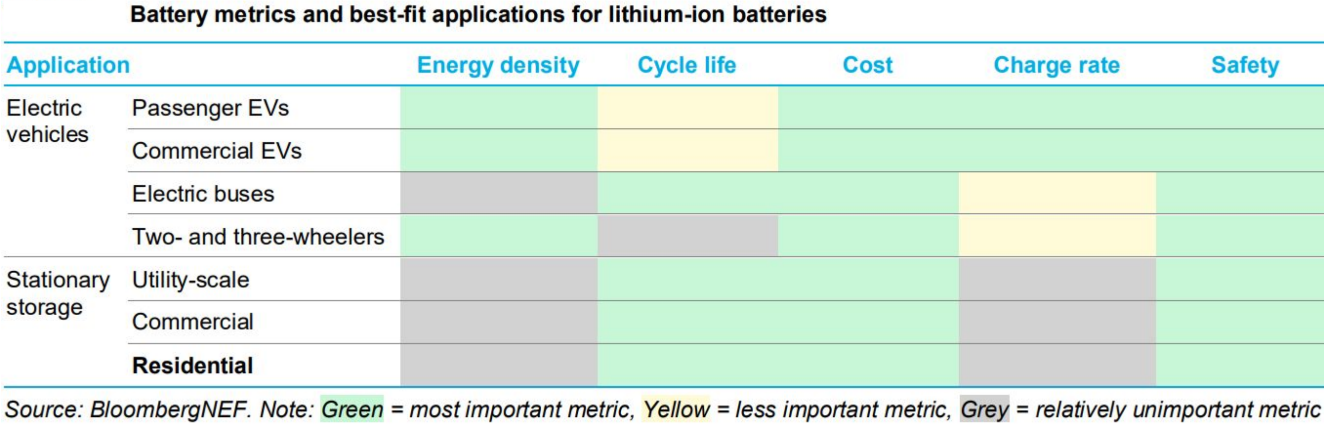
Company	2017	2021	2023
Pylontech	LFP	LFP	LFP
BYD	LFP	LFP	LFP
Panasonic	-	NMC	NMC / LFP
LG	NMC	NMC / LFP	NMC / LFP
Tesla	NMC	NMC / LFP	NMC / LFP
Enphase Energy	LFP	LFP	LFP
Sonnen	LFP	LFP	LFP
E3/DC	NMC / NCA	NMC / NCA / LFP	NMC / NCA / LFP
Senec	NMC	NMC	NMC
Powervault	NMC	NMC	LFP

Source: BloombergNEF. Note: NMC = nickel manganese cobalt, LFP = lithium iron phosphate, NCA = nickel cobalt aluminum oxide. Green entries refer to newly launched products or chemistry changes. Grey entries refer to newly announced or upcoming products or chemistry changes.

Source: BloombergNEF, McKinsey

Applications | BESS | Battery Requirements Comparison

Battery Energy Storage System (BESS) prioritize lifetime over energy density and charging rate compared to EV applications.



Battery metrics and best-fit applications for lithium-ion batteries

Application		Energy density	Cycle life	Cost	Charge rate	Safety
Electric vehicles	Passenger EVs	🟩	🟨	🟩	🟩	🟩
	Commercial EVs	🟩	🟨	🟩	🟩	🟩
	Electric buses	▨	🟩	🟩	🟨	🟩
	Two- and three-wheelers	🟩	▨	🟩	🟨	🟩
Stationary storage	Utility-scale	▨	🟩	🟩	▨	🟩
	Commercial	▨	🟩	🟩	▨	🟩
	Residential	▨	🟩	🟩	▨	🟩

Source: BloombergNEF. Note: Green = most important metric, Yellow = less important metric, Grey = relatively unimportant metric

Key Takeaways:

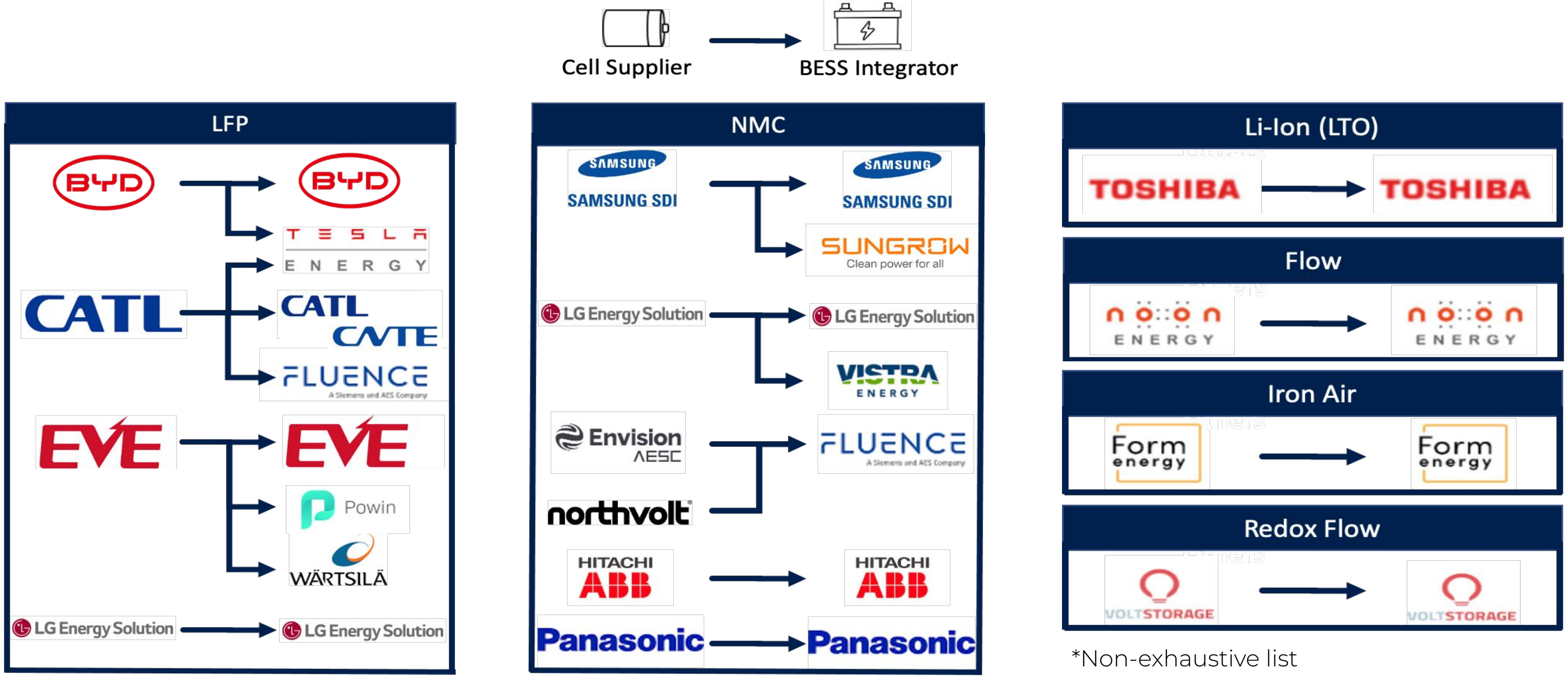
- Acceptance of lower charging rate (≤ 1C)
- Cycle life for BESS is crucial compared to EVs
- Acceptance of lower energy density (less constraints on footprint) versus EVs. Higher energy density is key for EVs, where the lighter the better. However, higher density batteries are unlikely to provide the long cycle life required for stationary storage

Source: BloombergNEF

Applications | BESS | Players: Cell Suppliers & Integrators

TESLA ENERGY
ENPHASE
Alpha·ESS
RIMAC ENERGY
WÄRTSILÄ
Nidec
HITHIUM
POWERVAULT
BYD
ENERGY STORAGE E3/DC
ABB
Trinasolar
Panasonic
ESS INC
VARTA
SENEC
SAMSUNG SAMSUNG SDI
Form energy
ENERGY VAULT®
CATL
LG Energy Solution
CATL
Envision AESC
NEXTera ENERGY
POWIN
Gotion
FLUENCE A Siemens and AES Company
northvolt
EVE®
PYLONTECH
noon ENERGY
SIEMENS
sunrun
SUNWODA
SK innovation
sonnen
SUNGROW Clean power for all
Bloomenergy®
VISTRA ENERGY
Highview Power
HYPER STRONG

Applications | BESS | Partnerships



Cell Supplier → BESS Integrator

LFP

Cell Supplier	BESS Integrator
BYD	BYD TESLA ENERGY
CATL	TESLA ENERGY CATL CATE FLUENCE A Siemens and AES Company
EVE	EVE Powin WÄRTSILÄ
LG Energy Solution	LG Energy Solution

NMC

Cell Supplier	BESS Integrator
SAMSUNG SDI	SAMSUNG SDI SUNGROW Clean power for all
LG Energy Solution	LG Energy Solution VISTRA ENERGY
Envision AESC northvolt	FLUENCE A Siemens and AES Company
HITACHI ABB	HITACHI ABB
Panasonic	Panasonic

Li-Ion (LTO)

Cell Supplier	BESS Integrator
TOSHIBA	TOSHIBA

Flow

Cell Supplier	BESS Integrator
noon ENERGY	noon ENERGY

Iron Air

Cell Supplier	BESS Integrator
Form energy	Form energy

Redox Flow

Cell Supplier	BESS Integrator
VOLTSTORAGE	VOLTSTORAGE

*Non-exhaustive list

Source: BYD, CATL, EVE- Powin, Wartsila, Panasonic, LG, Samsung SDI,, LG - Vistra, Fluence, Hitachi ABB, , Toshiba, Voltstorage,, Noon Energy, Form Energy ,

Applications | BESS | Commissioning

Over 6 GW of BESS commissioning delays in the US

US BESS sites by status in Q3 2023	Megawatt (MW)	Megawatt hours (MWh)
BESS in operation (Q3 23)	13,477 MW	38,337 MWh
BESS installations ((Q1-Q3 23)	4,393 MW	13,142 MWh
BESS installations Q3 23	2,142 MW	6,227 MWh
BESS under construction	8,134 MW	23,000 MWh^{e}
BESS under construction or in advanced development	21,445 MW	62,109 MWh
BESS project delays	**6,160 MW^{e}**	**17,500 MWh^{e}**

Commissioning phase is a critical step in the value chain of BESS

- Responsibilities and risks are transferred from contractor to client
- Substantial financial risk linked to the commissioning phase of BESS

Time pressure during commissioning causes errors

- Incentive for fast commission, due to high penalties for delays
- In ERCOT, 50% of revenue comes from the top 50 days according Modo Energy
- Commissioning reports lack of battery detail

Key Takeaway: Internal pressure is high to complete commissioning projects on time which can lead to compromises on performance and safety. Impact of commissioning delays is high on the project return-on-investments.

Source: Clean Power, Modo Energy

Applications | **BESS** | Commissioning

4 major challenges resulting in BESS commissioning delays

Challenges	Cell damages & connection issues	BMS failure & SoC estimation error	Thermal system malfunction	Water and heat damage
Issue	Manufacturing faults, transport damages, connection issues and power electronics failure	Deep discharge, overcharge, Underutilization and balancing problems	Overheating and leakage	Overtemperature and accelerated aging
Solution	Detect Cell quality and connection issues with data analytics	Recalibration and balancing, Check BMS data to reduce downtime and avoid warranty losses	Test HVAC functionality	Identify unexpected temperature deviations

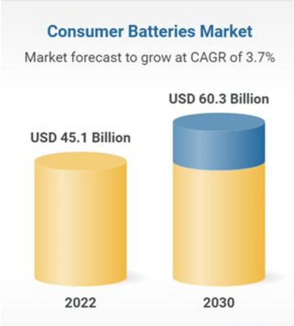
Key Takeaway: External factors and operational irregularities can lead to cell-to-cell imbalance. Additional cell-level instrumentation and robust real-time data visibility is critical to identify and proactive address these problems.

Source: Energy Storage News

Applications | Consumer Electronics - Smartphones

Battery capacities and charging capability of flagship phones from each smartphone manufacturer

- Phone battery capacities range from 2400 mAh to 5050 mAh
- Charging power for phones ranges from 25 W to 240 W, achieving full charge between ~60 minutes to as low as ~9 minutes.
- The global market for batteries in consumer electronics is estimated at US $45.1B in 2022, and projected to grow by ~30% to US $60.3B by 2030, at a CAGR of 3.7% over the analysis period.



Device manufacturer	Apple	Samsung	Google	Xiaomi	Sony	Huawei	Oppo	Vivo	Realme	OnePlus	Nothing
Product	iPhone 15 Pro Max	S23 Ultra	Pixel 8 pro	Redmi Note 12 Explorer	Xperia 1 IV	Mate XS	Find X5 Pro	iQ00 10 Pro	GT3	10T	Phone 2
Battery capacity [mAh]	4441	4855	5050	4300	5000	4500	5000	4700	4600	4800	4700
Max charging power [W]	25	45	27	210	30	55	80	200	240	150	45

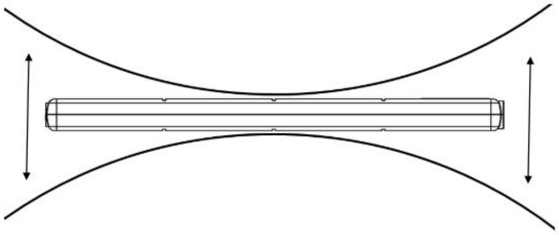
Source: Fast charging phones in 2023 - Phonearena

Applications | Military & Defense

Unique & Demanding Military Applications

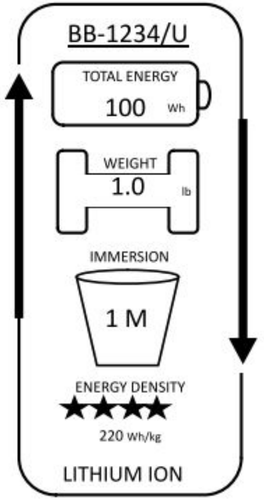
New Battery Technology Is Helping Battery Manufacturers Meet Mil Spec

- Military Specification ("MilSpec") for batteries is intended to ensure minimum capacity requirements in extreme operating conditions.
- Battery technology companies like **South 8 and NanoGraf** reduce or eliminate catastrophic failure when exposed to extreme temperatures or nail/projectile penetration.



Note: Figure not to scale

Conformability (flexibility) test fixture



Standardized simplified battery label

MIL-PRF-32383 Inspection & Test Requirements

- Visual and mechanical
- Dimensions and weight
- Battery open circuit voltage
- Insulation resistance
- Altitude
- *Explosive decompression*
- Charge acceptance
- Capacity discharge (initial)
- Cycle life
- Battery storage life
- Overcharge/electrical leakage
- Low temperature discharge
- High temperature discharge
- Projectile
- High rate discharge
- Retention of charge
- Pulse discharge
- Motor inrush current
- Thermal shock
- Mechanical shock
- Vibration (discharge)
- *Conformability*
- Connector insertion
- Flat terminal strength
- Immersion, shallow
- Transit drop, severe
- *Surface friction*
- *Salt Fog*
- *Chemical resistance*
- *Electrostatic Discharge*
- *Solar radiation*
- Immersion, shallow (post drop)
- State of charge
- SMBus
- Full capacity discharge
- Extreme low temp. discharge
- Extreme high temp. discharge
- Battery case vent
- Short circuit protection
- *Impact*
- High temperature temporary cut-off
- High temperature permanent cut-off
- Electromagnetic interference
- *Pulse magnetic field*
- Interchangeability
- Lithium Battery Safety Program (US Navy) Tests
- *Bullet Penetration*

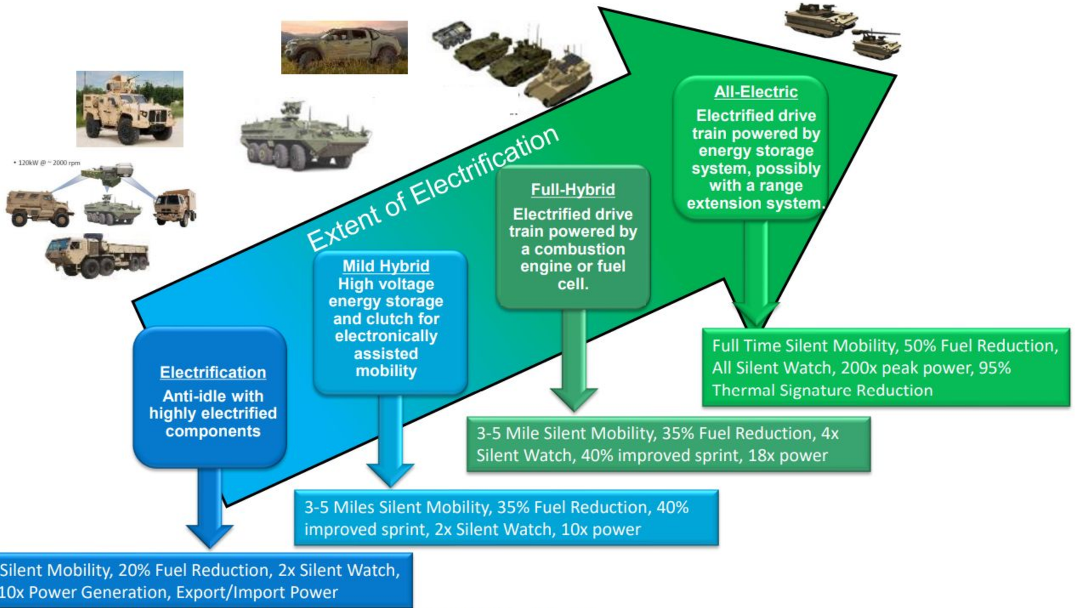
Source: US Department of Defense

Applications | Military & Defense

US Military Vehicle Fleet Electrification

Replacement strategies for tactical and non-tactical fleets

- **Executive Order 14057** requires all non-tactical U.S. military (and all other federal) vehicles to be zero-emission by 2035.
- The **US Defense Innovation Unit** is working with potential vendors on standardized battery systems for electrification of multiple end-use defense platforms.
- The non-tactical fleet is ~174,000 while the tactical fleet is ~250,000



Electrification
Anti-idle with highly electrified components

No Silent Mobility, 20% Fuel Reduction, 2x Silent Watch, 3x-10x Power Generation, Export/Import Power

Mild Hybrid
High voltage energy storage and clutch for electronically assisted mobility

3-5 Miles Silent Mobility, 35% Fuel Reduction, 40% improved sprint, 2x Silent Watch, 10x power

Full-Hybrid
Electrified drive train powered by a combustion engine or fuel cell.

3-5 Mile Silent Mobility, 35% Fuel Reduction, 4x Silent Watch, 40% improved sprint, 18x power

All-Electric
Electrified drive train powered by energy storage system, possibly with a range extension system.

Full Time Silent Mobility, 50% Fuel Reduction, All Silent Watch, 200x peak power, 95% Thermal Signature Reduction

Source: U.S. Army, National Academy of Sciences

Applications | Space Applications

Growing needs for energy storage in space exploration. Technology used depends on nature of mission profile.

- Crewed missions require additional design considerations to protect humans from potential toxic thermal runaway byproduct gasses.
- Space cells must tolerate wide temperature ranges which can impact electrolyte seal integrity due to thermal expansion rate differences.

Applications	Ambient Pressure	Mission example	Cell chemistry example	Avg. mission duration	Radiation	Avg. temperature	Design challenges
Earth	101.3 kPa	Electric vehicle	Graphite + NCM	8-12 years	H-3, Be-7, C-14,Na-22 0.21mSv/year	-30°C to +40°C	Corrosion
Upper atmosphere	200 Pa	Stratostats	Graphite + LCO	<100 days	He, Li- through Fe ions Neutrons 1-10 MeV 1.2 Neutrons/cm^2/s,	-20°C to -60°C	Low temperatures, icing, pressure variations
Low earth orbit (LEO)	10^{-6} - 10^{-9} Pa	ISP satellites	Graphite + NCA or LFP	<30 days (humans) 4 - 26 years (constellations)	1000-10 M Protons and Electrons/cm^2/s	-65°C to +125°C	Sealing under frequent temperature variation
Geosynchronous orbit (GEO)	10^{-12} Pa	Media broadcasting	Graphite + NCA or Nickel Hydrogen	>7 years (many operating past EOL)	400-500 km/s Protons & Electrons 30/cm^2/s	-196°C to +128°C	Calendar life, high cycle-life
Lunar	3 x 10^{-9} Pa	Lunar rover	Pu-238 RTG (radioisotope thermal generator)	3 months design, 31 months life (Jade Rabbit rover)	Protons, Electrons 10-10000 MeV, 1-10 Protons/cm^2/s	-130°C to +120°C	Extended duration of hot and cold/dark periods
Mars	560 Pa	Martian rover	Graphite + NCA	90 days NASA design (Opportunity lasted ~15 years)	Protons, Electrons 1-1000 MeV, 100-1000/s	-153°C to +20°C	Sealing under temperature variation, RTG radiation
Deep space	10^{-14} - 10^{-18} Pa	Deep space probes	Pu-238 RTG (radioisotope thermal generator)	45+ years (Voyager)	Protons, Electrons 1-10,000 MeV 100-10,000/s	-270°C	Calendar life, RTG radiation and decreasing heating

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

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

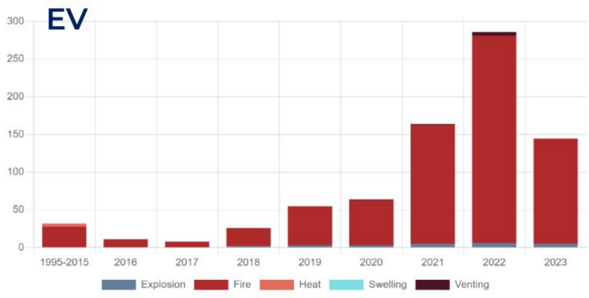
Recycling

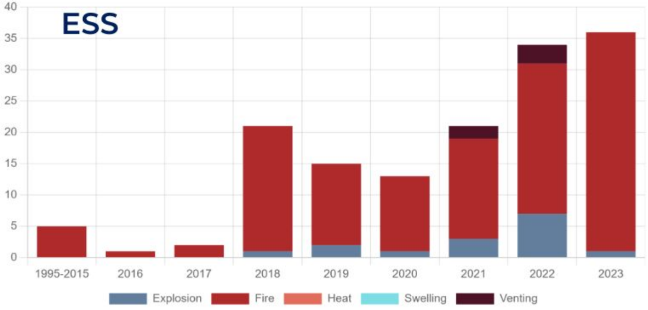
Software & Analytics

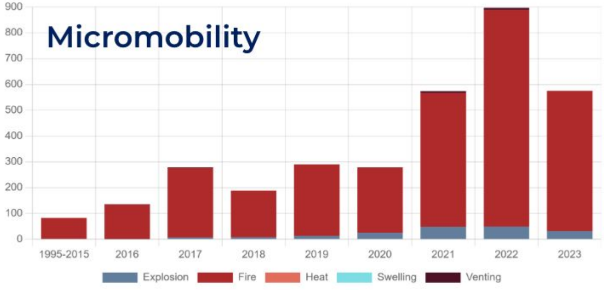
Safety | Incidents

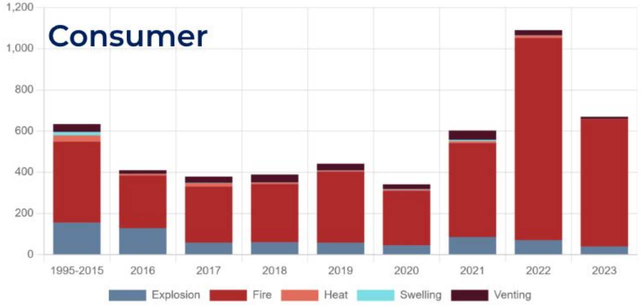
The total number of safety-related incidents decreased from 2022 to 2023

- Consumer products recorded the largest number of incidents, followed by micro-mobility products
- Most of the incidents were reported in the USA, Europe, and China
- Most of the incidents reported resulted in a fire, with a small fraction stopping at just swelling, venting, or excessive heating





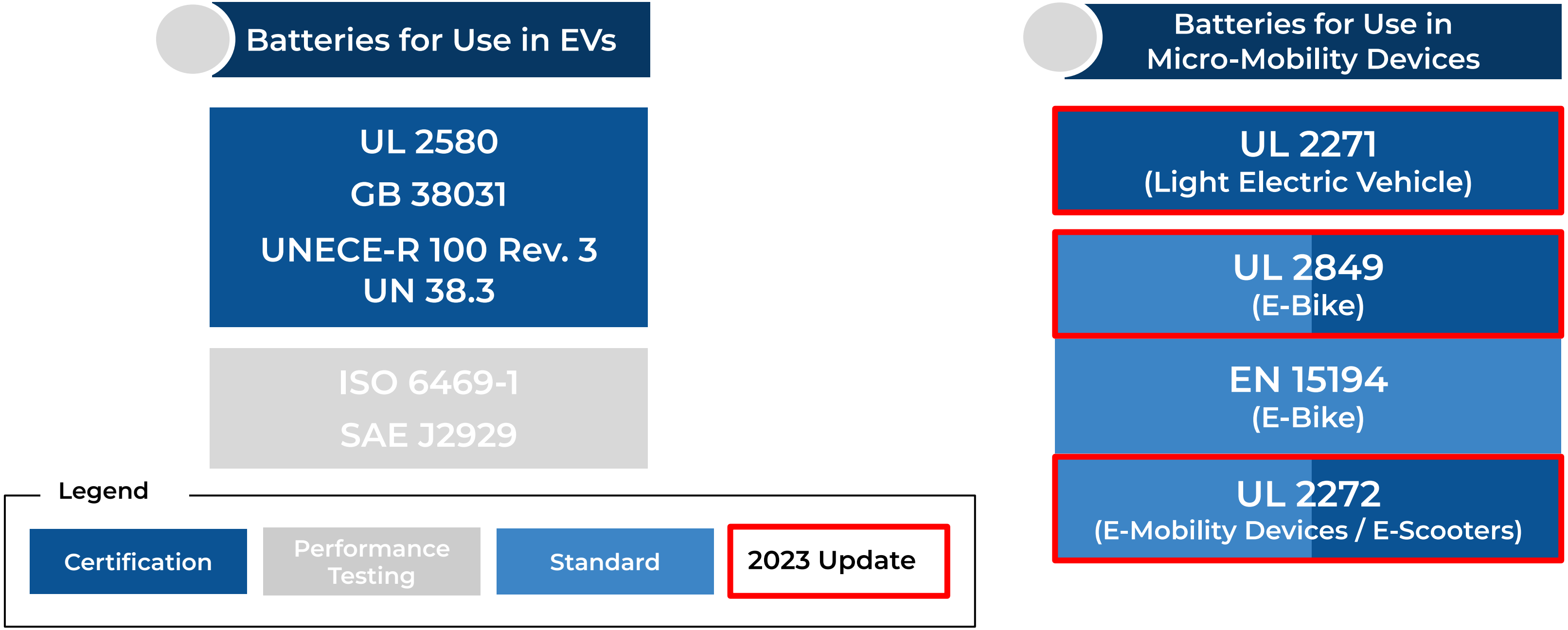




Source: UL Lithium-ion Battery Incident Reporting

Safety | EV Regulations & Standards

Certifications and standards for electric vehicles and micro-mobility devices



Batteries for Use in EVs

UL 2580
GB 38031
UNECE-R 100 Rev. 3
UN 38.3

ISO 6469-1
SAE J2929

Batteries for Use in Micro-Mobility Devices

UL 2271
(Light Electric Vehicle)

UL 2849
(E-Bike)

EN 15194
(E-Bike)

UL 2272
(E-Mobility Devices / E-Scooters)

Legend

Certification
Performance Testing
Standard
2023 Update

Source: (1) UL, (2) Cycling Weekly, (3) UL E-bike Standards

Safety | EV Recalls

Auto industry battery recalls for safety issues continued through 2023

January

Volkswagen ID4: 12V battery fire risk

March

Ford Lightning: battery defect fire risk

April

BMW: improper manufacturing of HV cell monitoring circuit in some hybrids

May

Mercedes: software recall related to battery safety

June

Cadillac Lyric and Hummer EV: improperly welded battery connections (previously water ingress in 2022)

Jaguar I-Pace: fire risk

Tesla: battery disconnect pyrofuse recall

August

Nikola: all BEV semi trucks recalled due to battery fires; Volvo/Mack: short circuit risk

September

Porsche and Audi: insufficient battery sealing

October

Ford Mach-E: power loss of HV battery

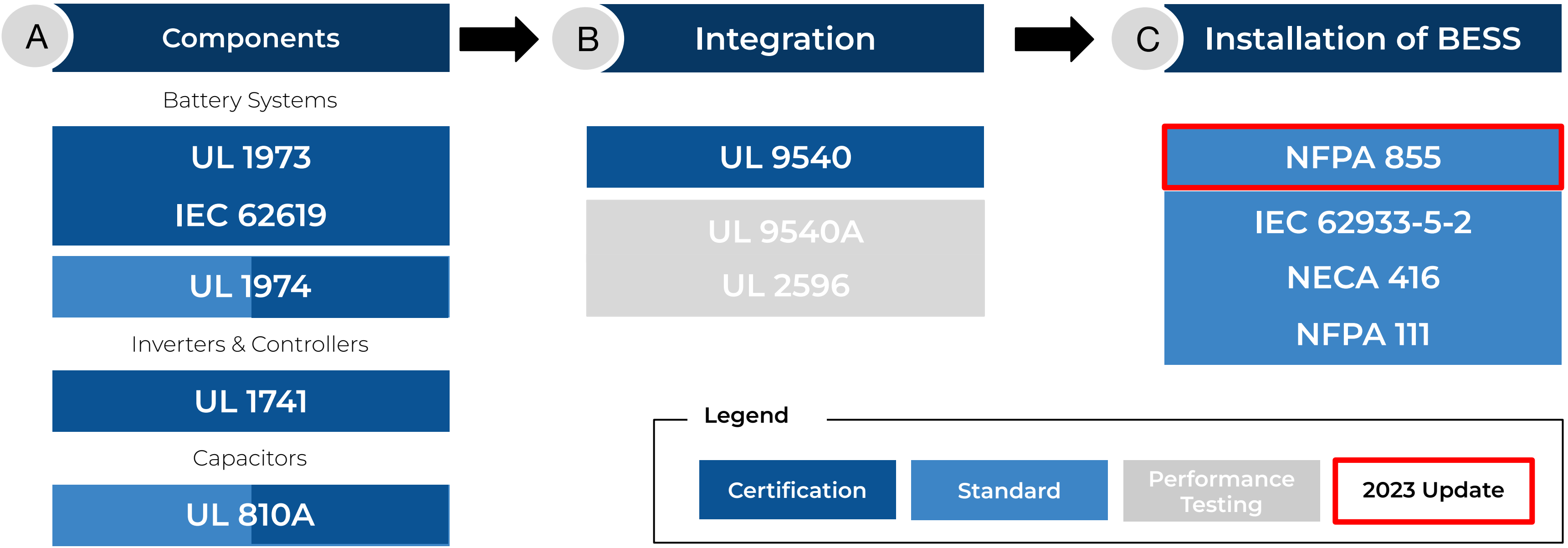
November

Toyota RAV4: batteries move during forceful turns

Detailed root cause analysis are not typically made public.
All batteries are assumed to have passed automotive industry mandated regulatory testing prior to shipment.

Safety | Stationary Storage | Regulations & Standards

Certifications and standards for grid-scale stationary storage systems



A Components

Battery Systems

UL 1973

IEC 62619

UL 1974

Inverters & Controllers

UL 1741

Capacitors

UL 810A

B Integration

UL 9540

UL 9540A

UL 2596

C Installation of BESS

NFPA 855

IEC 62933-5-2

NECA 416

NFPA 111

Legend

Certification

Standard

Performance Testing

2023 Update

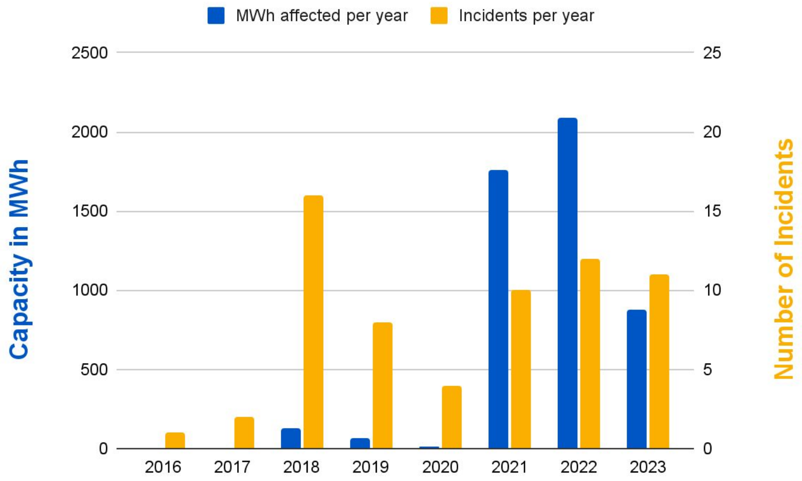
Source: Clean Power; ^{2} WoodMackenzie - Energy storage technology trends report II; UL

Safety | **Stationary Storage**

Safety incidents in grid-scale installations is trending down

- EPRI database shows 11 incidents in the US for grid scale systems, 9 of which occurred during the operational phase within the first 2 years [1]
- 7 incidents occurred in the US, 2 in France, 1 in Australia and 1 in Taiwan [1]
- The Inter-Agency Fire Safety Working Group was established in New York t ensure the safety and security of energy storage systems across the state o New York [2]
- The number of incidents per year has remained steady despite the commissioning of 99 GWh of energy storage in 2023, roughly double the amount added in 2022, but most of these systems are still relatively young [3]

Incident tracker (US)

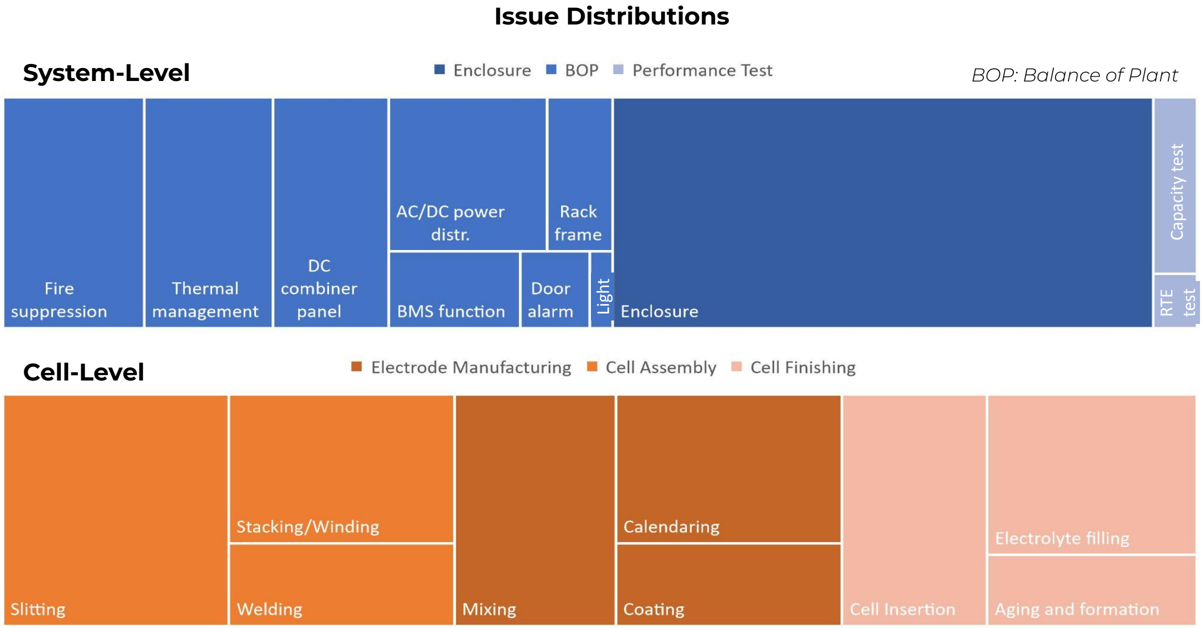


Source: EPRI; [2] PublicPower; [3] BNEF

Safety | Stationary Storage

Sources of safety Issues in grid-scale stationary storage systems

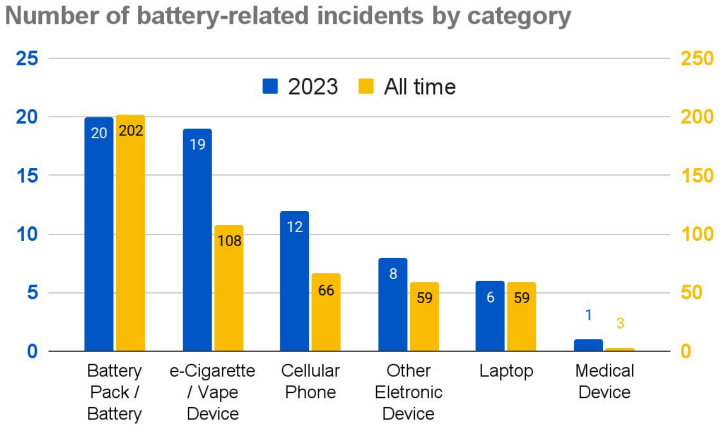
- System level issues are the greatest contributor (47%) to quality underperformance, followed by cell (30%) and module integration (23%).
- While battery cell manufacturing is highly automated, BESS system assembly still requires a large amount of manual work and is prone to error as a result.

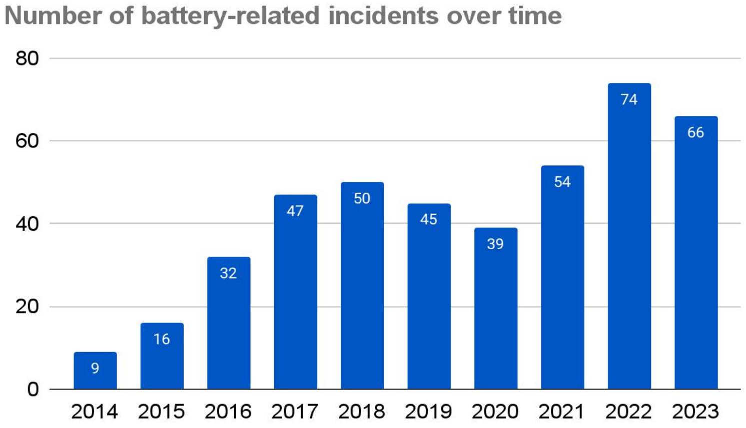


Source: CEA/PV-magazine

Safety | Aviation Incidents

Aviation safety incidents involving batteries in the US


Number of battery-related incidents by category


Number of battery-related incidents over time

- These incidents in the aviation industry were collected by the US Federal Aviation Administration (FAA) and consist of "events including smoke, fire or extreme heat" on flights to or from the US[1]
- Battery Pack / Battery is the category of the FAA with the highest number of recorded incidents[1]
- Most of the incidents in this category involve either a power bank or a battery charger leading to a thermal event[2]
- The large majority (80%) of these incidents occur on passenger aircraft[1]. Staff in these aircraft are equipped with thermal containment bags to secure faulty devices[2]

Source: FAA [1]; DOT [2]

Applications

Safety | Parking Garages

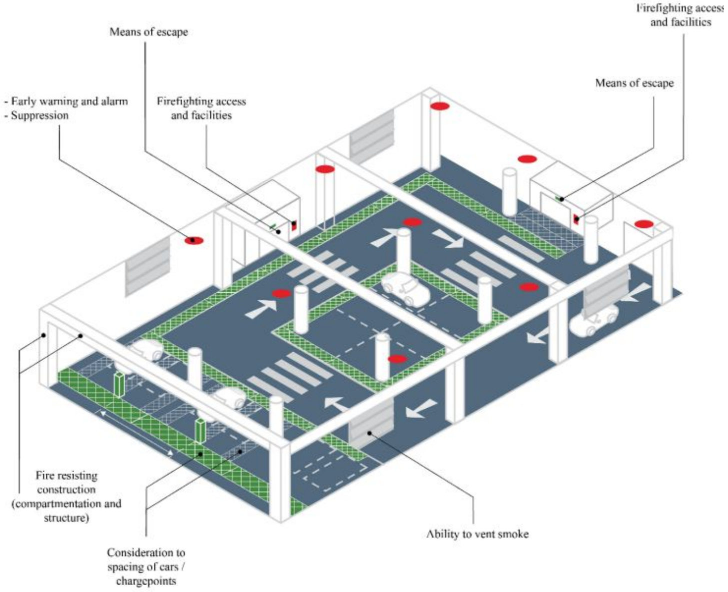
Codes and standards in adjacent sectors, such as parking garages, are trailing in development, giving rise to safety concerns. Ongoing research is addressing new safety challenges.

Despite similar fire sizes, EVs present additional fire suppression challenges compared to Internal Combustion Engine (ICE) vehicles:

- Battery re-ignition
- Explosion potential of flammable vent gases
- Toxicity potential from released gases
- Access to the interior of the battery enclosure for fire suppression

Current Research and Guidance on Mitigation Approaches

- **Existing structures**
  - Owner of structure should conduct a fire risk assessment to evaluate if introduction of EVs creates additional hazards
- **New structures**
  - Adequate spacing
  - Adequate fire detection (gas, smoke, heat detection)
  - Suitable water suppression system and ventilation
  - Trained and experienced fire responders with appropriate equipment



Example of Proposed EV Parking design.[3]

Source

Source: [1]NFPA; [2]Siemens, [3]ARUP

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

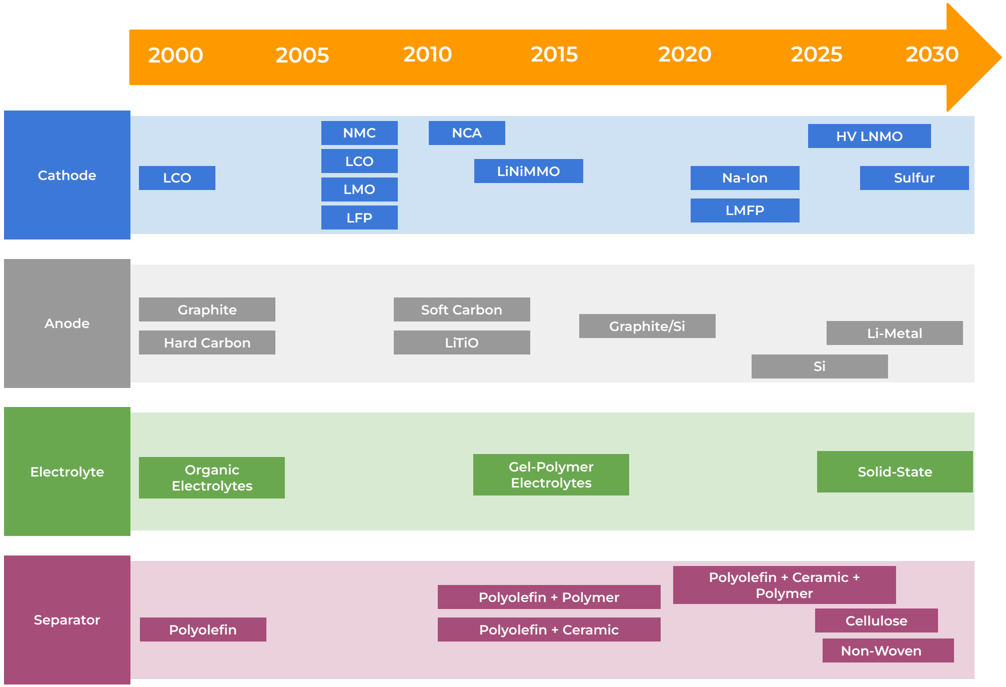
Recycling

Software & Analytics

Chemistry & Cell Components

| Cell Chemistry | Timeline Summary

Timeline of Battery Cell Chemistry Development



2000 2005 2010 2015 2020 2025 2030

Cathode
- LCO
- NMC
- LCO
- LMO
- LFP
- NCA
- LiNiMMO
- Na-Ion
- LMFP
- HV LNMO
- Sulfur

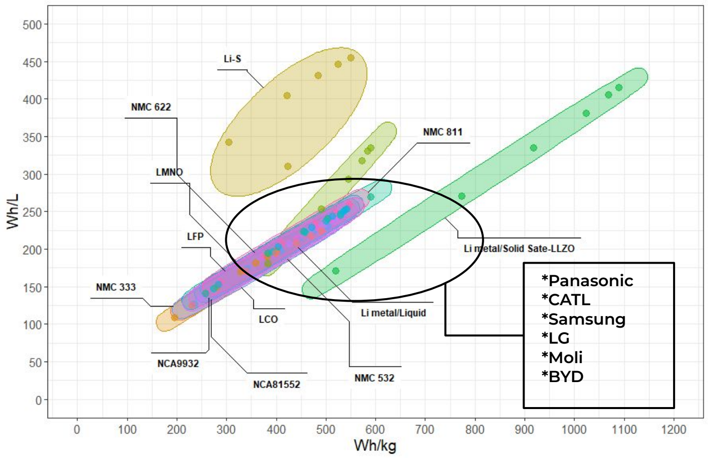
Anode
- Graphite
- Hard Carbon
- Soft Carbon
- LiTiO
- Graphite/Si
- Si
- Li-Metal

Electrolyte
- Organic Electrolytes
- Gel-Polymer Electrolytes
- Solid-State

Separator
- Polyolefin
- Polyolefin + Polymer
- Polyolefin + Ceramic
- Polyolefin + Ceramic + Polymer
- Cellulose
- Non-Woven

** 500 Wh/kg are the cells are the goal of government agencies in the US, EU, and Japan

<u>*USA Battery 500</u>
<u>*Japan Rising II (now Rising III)</u>
<u>*Battery 2030 EU</u>

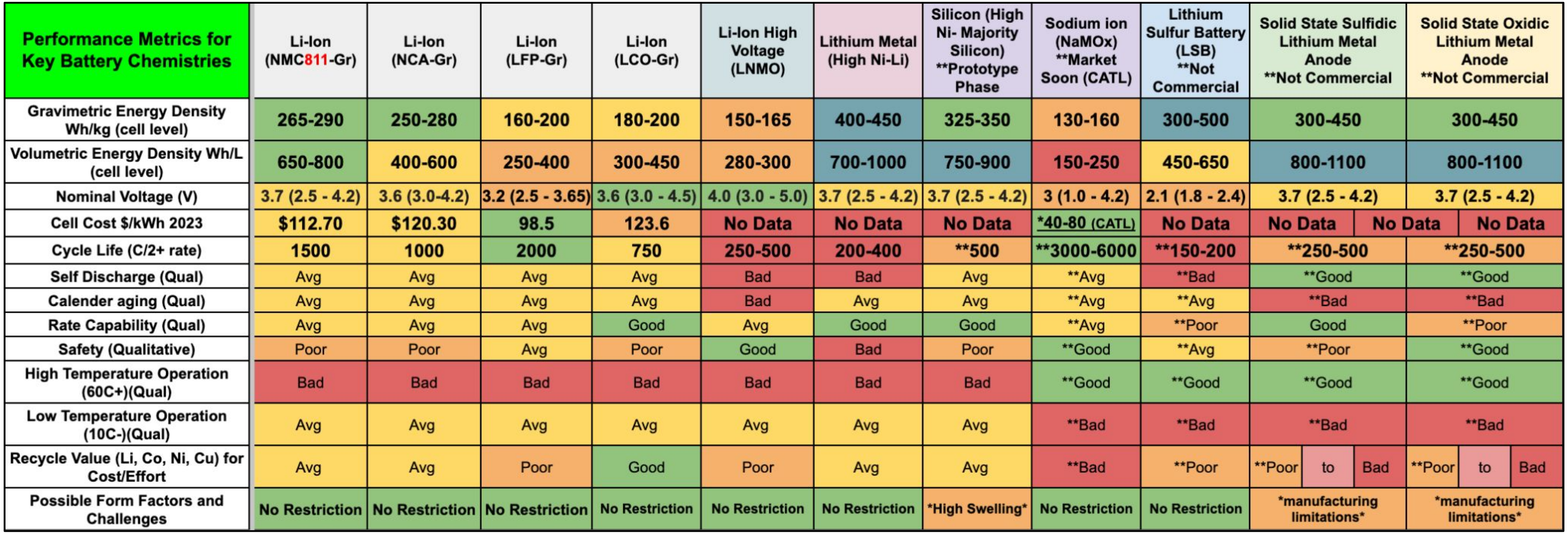


***Panasonic**
***CATL**
***Samsung**
***LG**
***Moli**
***BYD**

Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

| Cell Chemistry | Comparison

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) **Prototype Phase	Sodium ion (NaMOx) **Market Soon (CATL)	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	130-160	300-500	300-450	300-450
Volumetric Energy Density Wh/L (cell level)	650-800	400-600	250-400	300-450	280-300	700-1000	750-900	150-250	450-650	800-1100	800-1100
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 - 4.5)	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)
Cell Cost $/kWh 2023	$112.70	$120.30	98.5	123.6	No Data	No Data	No Data	*40-80 (CATL)	No Data	No Data	No Data
Cycle Life (C/2+ rate)	1500	1000	2000	750	250-500	200-400	**500	**3000-6000	**150-200	**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	Good	Poor	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

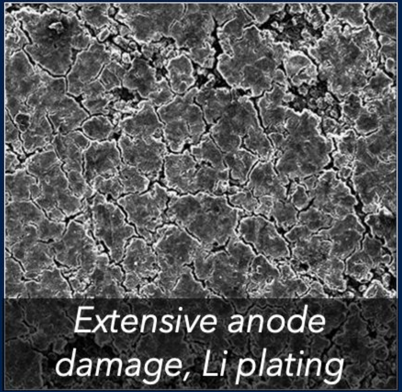
* Cell design and components other than the cathode can make a very large difference in cell performance metrics.
For more details, please visit: **Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)**

Today's batteries, next-gen performance

iontra

Example: **commercially popular** 18650 battery cell

Test conditions: 20-min charge, 10A discharge, 25°C temp, 100% depth of discharge

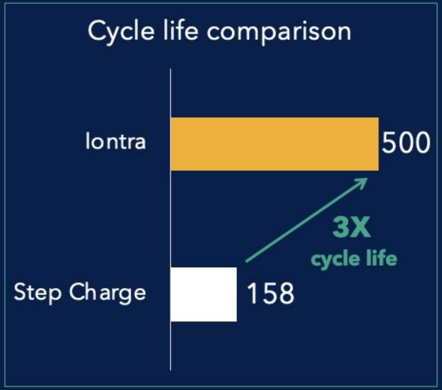


Best Step Charge

158 cycles @ 79% end of life

Iontra Charge*

500 cycles @ 79% end of life



* No hotspots – no dendrites – healthy anode for efficient lifetime intercalation

Over **6 million hours** of test data.
Independent validation studies.

NREL NATIONAL RENEWABLE ENERGY LABORATORY
UNIVERSITY OF MICHIGAN
NOVONIX
UL SOLUTIONS

Follow this link for more information or to set up a call.

Sensing and charging algorithm for all batteries and applications.

Unlocks dramatically faster charge speeds, longer cycle life, and charging at cold temperature.

Chemistry & Cell Components | Cathode | Overview

The importance of the cathode cannot be overstated for Lithium Ion Batteries.

Cathodes are responsible for storing and releasing lithium ions during charge and discharge cycles, enabling the flow of electrons and ensuring a stable and consistent energy supply. However, cathodes face several challenges including limited energy storage capacity , slow ion diffusion (particularly through thicker cathodes), and greater cost (**Nickel, Cobalt, Lithium Hydroxide/Carbonate**) compared to other battery components.

Key Trends & Areas of Development

High Ni Cathode

Researchers were working on cathode materials with higher nickel content, such as NMC (Nickel Manganese Cobalt) and NCA (Nickel Cobalt Aluminum). High-nickel cathodes aim to increase energy density and improve overall battery performance.

LFP/LMFP

Industry shifts towards high adoption of LFP and development in LMFP, which offers improved energy density compared to LFP while maintaining a low cost structure compared to high Ni & Co chemistries.

Cobalt Reduction

Efforts were being made to reduce or eliminate the use of Co in cathode materials due to its high cost, environmental concerns, and supply chain issues. This involved developing cobalt-free or low-cobalt cathodes.

Solid State Cathode

Solid-state battery technology, including solid-state cathodes, was a focus area for research. Solid-state batteries have the potential to offer higher energy density, improved safety, and longer cycle life compared to traditional liquid electrolyte lithium-ion batteries.

Coatings & Structures

Researchers were exploring advanced coatings and nanostructured cathode materials to enhance the stability of the cathode-electrolyte interface, mitigate side reactions, and improve overall battery performance.

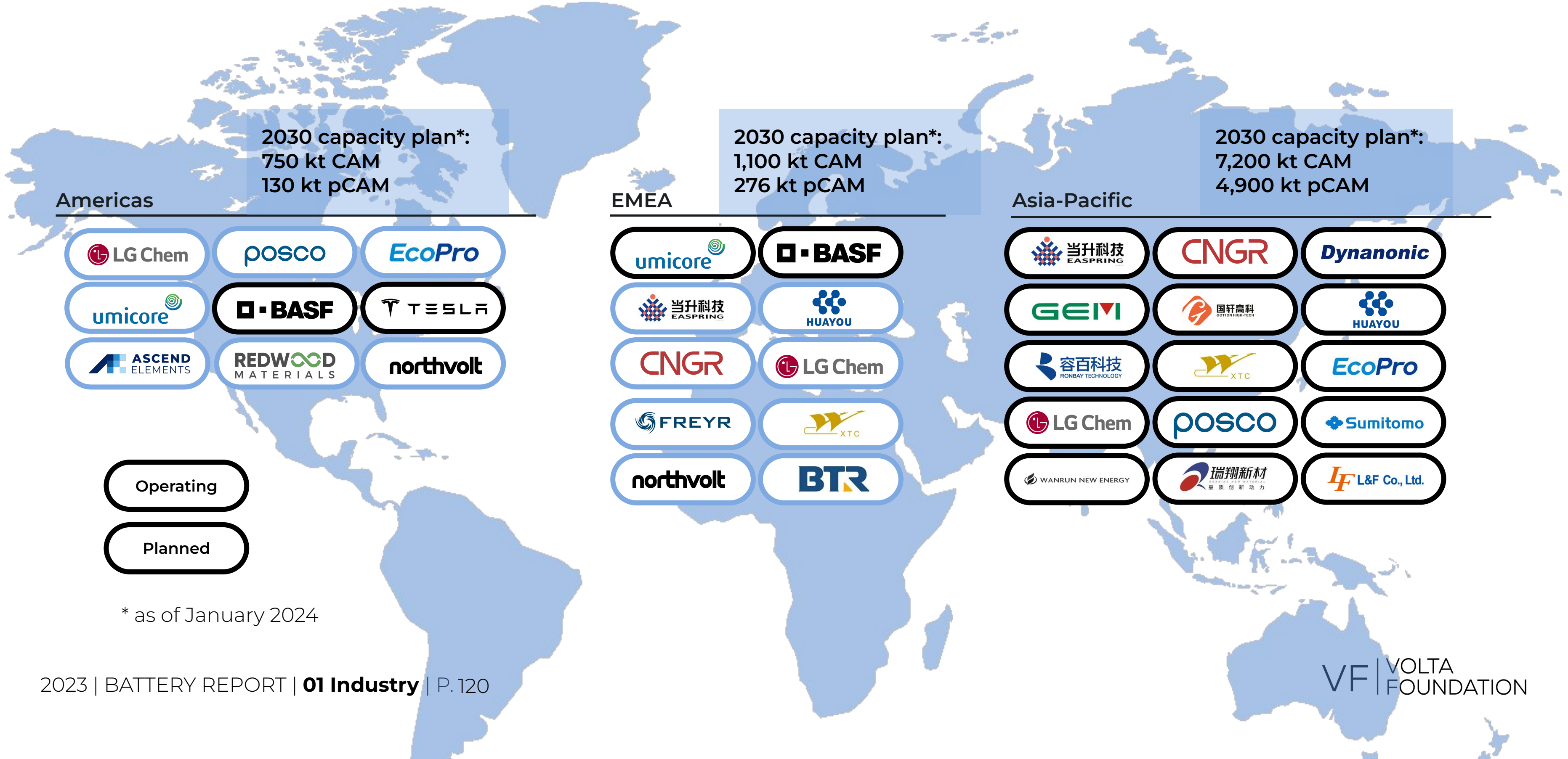
Recycling

Sustainable practices, including recycling technologies for cathode materials, were gaining attention to address the environmental impact of lithium-ion batteries.

Source: A Reflection on Lithium Ion - Nature, The Role of the Cathode in Lithium-Ion Batteries, Understanding Electrochemical Potentials of Cathode Material

Chemistry & Cell Components

| Cathode | Major Industry Players



Americas

2030 capacity plan*:
750 kt CAM
130 kt pCAM

LG Chem | posco | EcoPro
umicore | BASF | TESLA
ASCEND ELEMENTS | REDWOOD MATERIALS | northvolt

EMEA

2030 capacity plan*:
1,100 kt CAM
276 kt pCAM

umicore | BASF
当升科技 EASPRING | HUAYOU
CNGR | LG Chem
FREYR | XTC
northvolt | BTR

Asia-Pacific

2030 capacity plan*:
7,200 kt CAM
4,900 kt pCAM

当升科技 EASPRING | CNGR | Dynanonic
GEM | 国轩高科 GOTION HIGH-TECH | HUAYOU
容百科技 RONBAY TECHNOLOGY | XTC | EcoPro
LG Chem | posco | Sumitomo
WANRUN NEW ENERGY | 瑞翔新材 RESHINE NEW MATERIAL 品质创新动力 | L&F Co., Ltd.

Operating

Planned

* as of January 2024

Chemistry & Cell Components | NMC | Technology

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

S

LFP Strength

- Safety
- Good cycle life
- Abundance of iron
- Lower Costs

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
- Lowest recycle value

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
- 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 LNMO due to cost and thermal stability
- Increasing raw material cost

In 2023 Nickel Manganese Cobalt (NMC) battery technology saw progress in energy density, safety, and cost-effectiveness.

Ongoing research is aimed at optimizing cathode compositions, enhancing cycling stability, and exploring sustainable materials.

Cutting-edge NMC battery research in 2023 centered on advanced cathode formulations, incorporating super-high nickel content for increased energy density.

Overall, state-of-the-art NMC battery research is aimed at pushing the boundaries of performance, safety, and sustainability.

Leading the charge in NMC battery production in 2023 were major players like CATL, LG Energy Solution, SK On, and Samsung SDI.

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

Pros and Cons of Nickel Cobalt Aluminum (NCA) vs. Nickel Manganese Cobalt (NMC)

S

NCA Strength

- Safety
- Energy Density

NMC Strength

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

W

NCA Weakness

- Weight
- Cost
- Safety
- Ni/Co supply chain

NMC Weakness

- Cost
- Safety
- Ni/Co supply chain

O

NCA Opportunity

- Low/mid-range/ entry-level EVs
- Power Tools
- Portable electronics

NMC Opportunity

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

T

NCA Threat

- NMC
- High-voltage LNMO
- Increasing Ni and Co material cost

NMC Threat

- LFP
- High-voltage LNMO
- Increasing raw material cost

In 2023, Nickel Cobalt Aluminum (NCA) batteries continued to be a prominent technology in electric vehicles and portable electronics.

Development progress was made in optimizing electrode materials, enhancing energy density, and improving overall performance.

Major players like Panasonic and Samsung SDI, the first of which supplies batteries to Tesla, contributed to the advancement and widespread use of NCA batteries in various applications.

NCA batteries are primarily used for e-mobility applications, with power tools, e-bikes, and portable electronics making up the rest.

Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

Pros and Cons of Lithium Cobalt Oxide (LCO) vs. Nickel Manganese Cobalt (NMC)

S

LCO Strength

- Energy density
- Higher Voltage capability (up to 4.5)
- Power
- More Mature Technology than other cathode chemistries
- Highest recycle value

NMC Strength

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

W

LCO Weakness

- Lower Thermal Stability temperature
- Low discharge current can lead to pack overheat
- limited to a C rates due to overheating
- shorter life span
- Highest cobalt use
- Cobalt cost and scarcity

NMC Weakness

- Cost
- Safety
- Ni/Co supply chain

O

LCO Opportunity

- Portable and consumer electronics
- Industries that want 10+ years of reliability data
- High recycle Value in domestic industry

NMC Opportunity

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

T

LCO Threat

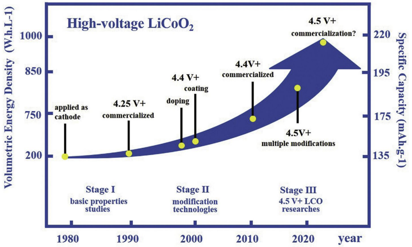
- High Energy NMC811 and NCA for high performance
- High-voltage LMNO
- Increasing material cost of cobalt

NMC Threat

- LFP
- High-voltage LNMO due to cost and thermal stability
- Increasing raw material cost

Lithium Cobalt Oxide batteries (LCO) have a relatively high cobalt content, which provides the high energy density and thermal stability for which they are known for.

LCO has a relatively high voltage capability. The EV industry has long since shifted away from LCO, due to the cost of cobalt in the past. However, smartphones, laptops, and other portable electronics depend heavily on LCO.



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

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
- Lowest 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
- Stationa
- 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 LNMO
- Increasing raw material cost

Lithium Iron Phosphate (LFP) batteries historically have been used in China for small and low-cost EVs. However, the past couple of years has seen LFP proliferate to the largest vehicles.

Almost all major automakers have now outlined plans to make use of LFP.

LFP is also the dominant chemistry used in energy storage systems.

Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

Chemistry & Cell Components

| LMFP | Technology

Pros and Cons of Lithium Manganese Iron Phosphate (LMFP) vs. Lithium Iron Phosphate (LFP)

S

LMFP Strength

- Energy density
- Cost per kWh
- Abundance and low cost of Mn
- Less raw materials used per kWh
- Easier SoC estimation

LFP Strength

- Better cycle life
- Existing supply chain in China
- No Mn needed

W

LMFP Weakness

- Cycle life (depending on Fe:Mn ratio)
- Immaturity of supply chain for LMFP CAM and new manganese chemicals

LFP Weakness

- Energy density
- Low temperature performance
- Absence of supply chain outside China
- Difficult to read state of charge

O

LMFP Opportunity

- Mid-to-Long range EVs
- Trucks and busses

LFP Opportunity

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

T

LMFP Threat

- High-nickel NMC in long-range applications
- High-voltage LNMO
- LMR
- Slower build-out of LMFP CAM
- Mn chemical production

LFP Threat

- NMC
- High-voltage LNMO
- Na-ion battery

Lithium manganese iron phosphate (LMFP) offers improved energy density compared to LFP while maintaining a low cost structure.

It is being pioneered primarily by Chinese manufacturers as an evolution of LFP. Initial variants are not pure LMFP but compounding with NMC.

Initial optimisation decisions being made involve the manganese:iron ratio, production route (solid vs. liquid phase), and manganese chemical feedstock.

Source: CRU Group, takomabattery,

Chemistry & Cell Components | LMFP | Notable Events

2023 Q1

Apr 2023

CALB launches new cell format with LMFP variant

CALB

2023 Q2

May 2023

Gotion launches long-format prismatic LMFP cell 'Astroinno L600' - 240 Wh/kg 525 Wh/L (190 Wh/kg on pack level). Gotion produces its own CAM.

Gotion

2023 Q3

Aug 2023

General Motors invests in Mitra Chem and plans to co-develop 'cathode materials like LMFP'

gm

Aug 2023

Ronbay plans LMFP CAM plant in South Korea

容百科技 RONBAY TECHNOLOGY

2023 Q3

Sept 2023

Samsung SDI unveils LMFP battery

SAMSUNG SDI

Sept 2023

NIO establishes in-house battery team to develop LMFP cells

NIO

2023 Q3

Oct 2023

Wanrun starts small batch trial stage for LMFP production

万润新能源 WANRUN NEW ENERGY

2023 Q4

Nov 2023

Renault plans to use LMFP

RENAULT

2023 Q4

Source: Company announcements (linked inline)

Chemistry & Cell Components | LMFP | Infrastructure / Supply Chain / Manufacturing

Manufacturers with announced or assumed plans to adopt LMFP

Cathode manufacturers

- 国轩高科 GOTION HIGH-TECH
- 容百科技 RONBAY TECHNOLOGY
- 当升科技 EASPRING
- WANRUN NEW ENERGY
- XTC
- Dynanonic
- CNGR
- Lithitech
- GHTECH 光华科技
- HENGTRON
- Lian Hui
- 乾运高科 ANYUN
- aleees
- Mitra Chem
- IBU tec

Battery manufacturers

- 国轩高科 GOTION HIGH-TECH
- CATL
- CALB
- BYD
- SVOLT
- SAMSUNG SDI
- TIANNENG
- SUNWODA
- 瑞浦能源 REPT

Automotive manufacturers

- BYD
- TESLA
- GROUPE RENAULT
- gm

Source: CRU Group, company announcements

Chemistry & Cell Components | LMO | Technology

Pros and Cons of Lithium Manganese Oxide (LMO) vs. Lithium Iron Phosphate (LFP)

S

LFP Strength

- Safety
- Good cycle life
- Abundance of iron

LMO Strength

- Cost
- Safety
- Power capability (Fast charge capability)

W

LFP Weakness

- Weight
- Energy density
- Low temperature performance
- Power
- Difficult to read state of charge
- Low recycle value
- Cost (*2022)

LMO Weakness

- Energy density
- Life span
- High temperature performance

O

LFP Opportunity

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

LMO Opportunity

- e-Bicycle, e-scooter
- Stationary storage
- Cost sensitive applications
- Long range/high-end EVs (NMC/LMO blends)

T

LFP Threat

- NMC
- High-voltage LNMO
- Na-ion battery
- Regulations on energy density
- Increasing material cost

LMO Threat

- LMFP
- High-voltage LNMO

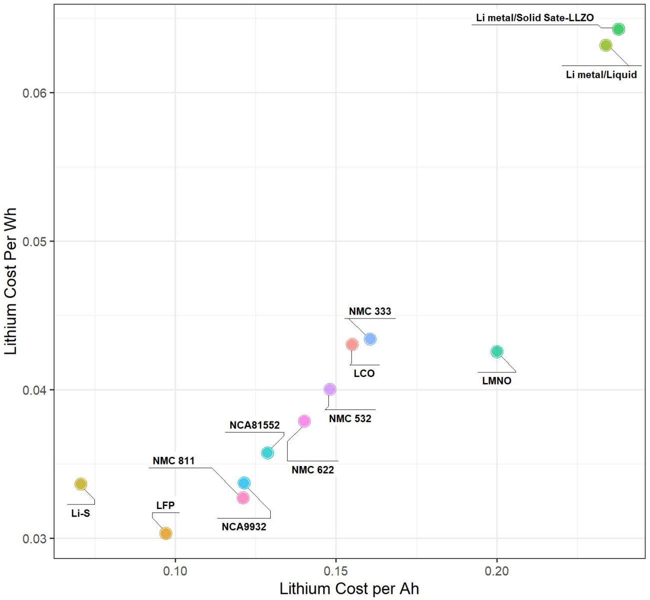
Lithium Manganese Oxide (LMO) was one of the earlier commercialized LIB technologies with its strength in cost effectiveness and high power output. However, LMO typically offers lower cycle life and thermal stability compared to LFP, which is known for its superior cycling stability and safety features.

Recent trend in LMO material development is NMC/LMO blend which leverages the high energy density of NMC with the enhanced power capability of LMO. This blend is suitable for applications that require both high capacity and good power delivery, such as in hybrid EV or certain portable electronics.

Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

Chemistry & Cell Components | Cathode | Lithium Tradeoffs

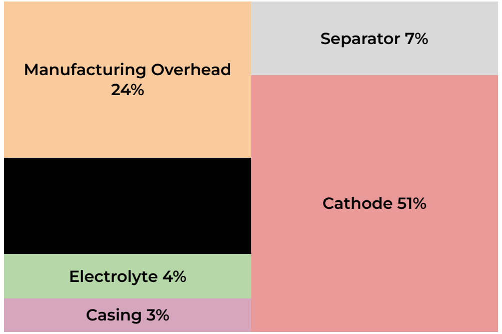
Chemistry Lithium Wh & Ah Cost Map: Drive Towards Cheaper Batteries



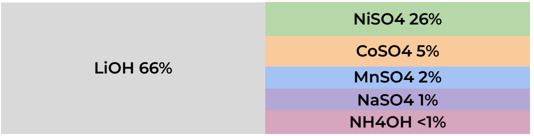
Current market conditions are demanding cheaper batteries for EV's at the same performance of modern day NMC811 batteries.

- CAM is major driver of cell cost accounting for >~50% of the cost
- Lithium Hydroxide (LiOH) or Lithium Carbonate (Li_2CO_3) account for > 50% of the CAM cost excluding processing/overhead
- To enable cheaper EV's, LFP is the near term solution to get the lowest lithium cost per kWh
- Beyond LFP, Manufacturers will need to turn to advanced chemistries, such as lithium-sulfur (LiS), to sustain downward trends on cost enhancing performance

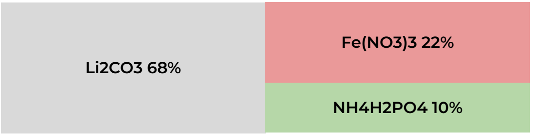
Cell Cost Breakdown



NMC811 Cost Breakdown



LFP Cost Breakdown

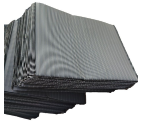


Source: Battery Talk: Lithium in Batteries Part 1, Battery Talk: Lithium in Batteries Part 2, Battery Talk: Lithium in Batteries Part 3

| Separator | Technology

Lithium-ion battery separators physically separate the positive and negative electrodes while allowing the transport of lithium ions. The most commonly used lithium-ion battery separators are typically made of polyolefin materials (typically PE or PP) coated with ceramic. There are many other different types of separators used in lithium-ion batteries with different performance traits and trade offs., and are broadly categorized below.

Separator Type	Material	Characteristics
Polyolefin	Polyethylene (PE) and/or polypropylene (PP)	Polyolefin separators are widely used due to their cost-effectiveness, chemical stability, and ease of manufacturing. They are commonly found in commercial lithium-ion batteries
Ceramic-Coated	Polyethylene or polypropylene separators with a ceramic coating	Ceramic-coated separators provide enhanced thermal stability and safety. The ceramic layer helps prevent thermal runaway by inhibiting the growth of internal shorts and dendrites
Composite	Combination of different polymers, ceramics, or other materials	Composite separators leverage the strengths of multiple materials to achieve a balance of properties, mainly to add electrochemical stability, prevent shorts, and inhibit growth of lithium dendrites.
Microporous	Often composed of polyethylene or polypropylene with added fillers or ceramic coatings	Microporous separators have a porous structure, allowing for efficient ion transport while maintaining good mechanical strength. The addition of fillers or ceramic coatings can enhance thermal stability and reduce the risk of thermal runaway
Glass Fiber	Glass fibers combined with a polymer matrix	Glass fiber separators offer good mechanical strength and can be used in high-temperature applications. They are known for their resistance to puncture and excellent thermal stability
Nonwoven Fabric	Nonwoven materials made of synthetic fibers	Nonwoven fabric separators provide good mechanical strength and are often used in flexible and lightweight battery designs. They can offer flexibility and conformability to different battery shapes
Composite Membrane	Combination of polymer and ceramic materials	Composite membrane separators aim to provide a balance between mechanical strength, thermal stability, and ion conductivity. They are designed to enhance safety and performance in lithium-ion batteries



Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

Anode | Overview

The choice of anode material in lithium-ion batteries is a critical decision that depends on the specific requirements of the application and significantly influences the overall performance, safety, and cost-effectiveness of the battery. Graphite is a reliable and cost-effective option, while silicon and lithium metal offer higher energy density but face challenges related to stability and safety. LTO, while lower in energy density, excels in terms of safety and cycle life. Several factors are considered when selecting an anode material:

Energy Density

Anode materials with higher energy density can store more lithium ions, resulting in batteries with greater overall energy storage capacity. Different materials, such as graphite, silicon, and lithium metal, offer varying energy densities, and the choice depends on the specific application requirements.

Cycle Life

The number of charge-discharge cycles a battery can undergo without significant degradation is crucial for long-lasting and reliable energy storage. Anode materials must exhibit stability and durability over multiple cycles to ensure the battery's longevity.

Cost

The cost of materials plays a crucial role in determining the overall cost-effectiveness of the battery. Anode materials should be economically viable for large-scale production while maintaining acceptable performance levels.

Safety

Safety is a paramount concern in battery design. Anode materials should minimize the risk of dendrite formation, which can lead to internal shorts, overheating, and potential safety hazards. Stable anode materials contribute to the overall safety of lithium-ion batteries.

Rate

Fast charging involves high charge and discharge rates, and the anode material must efficiently facilitate the rapid movement of lithium ions to and from the anode, which is an important metric in applications such as electric vehicles and consumer electronics.

Cathode Compatibility

Both the anode and cathode materials must be compatible to ensure efficient lithium-ion transport and maximize battery performance. The overall electrochemical compatibility of the materials contributes to the efficiency and reliability of the battery.

Manufacturability

The chosen anode material should be suitable for cost-effective and scalable manufacturing processes. Ease of processing and integration into battery production lines is a practical consideration for commercial viability.

Environmental Impact

There is increasing emphasis on choosing anode materials that are environmentally friendly and sustainable. The industry is exploring materials that minimize environmental impact during production, use, and disposal of lithium-ion batteries.

Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

| Anode | Overview

Common anode materials & performance tradeoffs

	Graphite	Silicon	LTO	Li Metal
Description	Graphite has been a traditional choice due to its stability, cost-effectiveness, and well-established manufacturing processes	Silicon offers higher energy density than graphite but comes with challenges related to volume expansion.	LTO offers lower energy density but longer cycle life	Lithium metal offers among the highest energy density but comes with challenges related to safety and cycle life, often due to dendrite formation.
Pro	Widely used in lithium-ion batteries, stable, low cost, and exhibits good cycling performance.	High theoretical capacity, leading to higher energy density compared to graphite.	Exceptional cycle life, high rate capability, and excellent safety characteristics.	Highest theoretical capacity, potentially leading to significantly increased energy density.
Con	Limited energy storage capacity, can hinder the development of high-energy-density batteries.	Higher cost than graphite (per kg) and experiences significant volume expansion during charge/discharge cycles, leading to mechanical degradation and reduced cycle life.	Lower energy density compared to graphite and silicon	Prone to dendrite formation during cycling, posing safety risks and reducing cycle life. Ongoing research focuses on addressing these challenges.

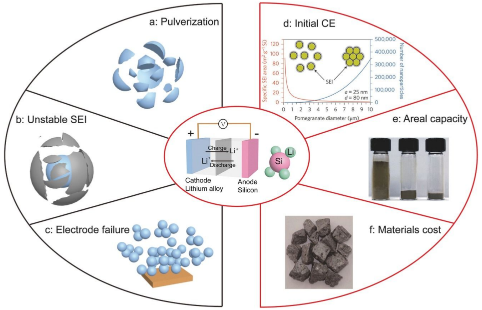
Source: Battery Talk: Battery Application Break Down 1/01/2024 (Version 2.0)

| Silicon Anode | Technology

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.

Silicon Anode Key Challenges



	Silicon Oxide	Silicon composite	Metallic Silicon
Composition	• Composed of silicon and oxygen • Common variants include: silicon monoxide (SiO) or silicon dioxide (SiO2)	• Metallic silicon or Silicon oxide embedded in carbon matrix • Other form factors include silicon nanowires, carbon coatings on silicon particles, or 3D structures	• Pure elemental silicon
Advantages	• Higher theoretical capacities than graphite • Less volume expansion compared to pure silicon, addressing some of the mechanical stress concerns	• Optimizes silicon/carbon matrix nanostructures to buffer the volume change of silicon • Composite carbon networks increase electrical conductivity, and add adhesion and higher chemical stability	• Lowest manufacturing cost • Highest energy density of silicon materials
Challenges	• Lower electrical conductivity compared to metallic silicon • Reversible capacity can be limited due to formation of SEI layers	• Substantial volume expansion and contraction during lithiation and delithiation cycles • Mechanical stress and electrode pulverization • Higher production costs than metallic silicon and most SiO	• Substantial volume expansion and contraction during lithiation and delithiation cycles • Mechanical stress and electrode pulverization • High capacity fade and reduced cycle life

Chemistry & Cell Components

| Silicon Anode | Notable Events

January

Group14/ Nexeon **lawsuit C**

March

Amprius **signs a letter of intent to acquire 775K sq ft facility in Colorado**

June

Enevate **partnership (production license) w/ JRES**

Amprius **walks away from DOE BIL $50M grant**

OneD **45M funding series C**

September

Enevate **signs partnership with NantG Power**

November

Storedot **Polestar to prototype vehicle with StoreDot material**

Sila **Moses Lake factory ribbon cutting**

February

Ionblox: **Silicon-sulfur batteries with Gelion**
Feb: **32M Series B**

Nanograf **65M fundraising**

April

Group 14 **begins construction of the world's largest commercial factory** for advanced silicon battery materials in Washington

July

Nexeon **signs Supply Agreement with Panasonic**

October

Enovix **closes facility in Bay area, building facility in Penang (Malaysia)**

China announces a new set of export restrictions on Battery graphite products.

December

CustomCells licenses Enervate technology

Sila **signs Supply Agreement with Panasonic**

Source: Company announcements (each linked in source)

Chemistry & Cell Components | Silicon Anode | Industry Players & Investments

Silicon Startups Continue Raising and Building Partnership with Industry Players

Company	Sila Nano	Enevate	Enovix	Amprius	Group14	IONBLOX	Nexeon	OneD	Storedot	Advano	Leydenjar	Coreshell	Ionic Mineral
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	CA, USA 2018	UT, USA 2020
Employees*	368	71	220	80	150	22	81	45	119	30	86	30	12
Money Raised/Valuation	$933M/3.3B	$202M/501M	$414M/1.8B	$622M/$441M	$683M/3B	$42M/80M	$262M/352M	$78/345M	$269M/1.27B	$40/Unknown	$43M/Unknown	$30M/Unknown	$20M/Unknown
Company Stage	Series F	Series E	PIPE, IPO	PIPE, IPO	Series C	Series B	Series D	Series C	Series D	Series A	Series A	Series A	Series B
Si %	50%	70-100%	100%	100%	50%		80%	5% to 50%		5-75%	100%	60-90%	80-100%
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	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 inside graphite using Cu catalyst to control size	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	Micron-sized Metallurgical Silicon. No Silane.	Continuous Metallothermic Reduction of Silica to Si nanotubes starting with Halloysite Feedstock
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	3250 mAh/g of Si Nanowires	5-min extreme fast charge	350 Wh/kg at $90/kWh	450 Wh/kg 1350 Wh/L	30% GED and VED Gain, 750+ cycles	All Si electrode 3200 mAh/g, 85% ICE 2500 mAh/g stable, Si/Gr Blend 15% Si substitution of Gr 750mAh/g 91% ICE 700 mAh/g Stable capacity
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	EV, Mobility	EV, Consumer Electronics, Military
Partnership/ Investment	Mercedes, Whoop, CATL, TDK, Samsung, Panasonic	RNM Alliance; LGES, Samsung	Intel, Qualcomm	Airbus, US Army	Porsche, 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	Zeon, Meyers Manx	Soon to be public

VF | VOLTA FOUNDATION

Source: Pitchbook, Intercalation Station Silicon Series (1, 2, 3, 4), Battery Talk Case Study on Group14

Pros and Cons of Lithium Titanate Oxide (LTO) vs. Graphite (C)

S

LTO Strength

- Power density
- Safety
- Cycle life
- Low temperature performance
- No SEI formation or Li-plating

Graphite Strength

- Energy density
- Cost
- Strong battery supply chain

W

LTO Weakness

- Cost
- Energy density
- High temperature performance
- Gassing side reactions

Graphite Weakness

- Cycle life
- Safety
- High/Low temperature performance

O

LTO Opportunity

- Mild hybrid EVs
- Electric buses
- Hybrid energy storage systems
- Applications with high-power demands and/or low environmental temperature

Graphite Opportunity

- EVs, Stationary storage systems

T

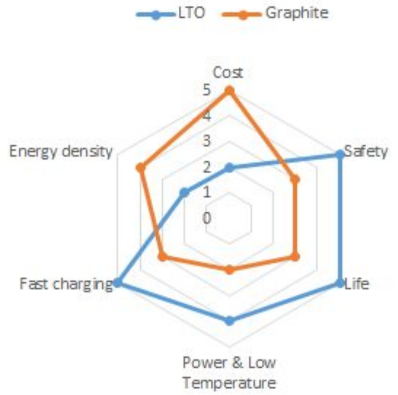
LTO Threat

- Na-ion battery
- Increasing material cost

Graphite Threat

- Improvements on silicon anodes
- Lithium metal
- Limited supply

While graphite anodes are widely used in lithium-ion batteries, LTO serves as an alternative, particularly in applications prioritizing safety, durability, fast charging, and power density over energy density. LTO is commonly used in mild hybrid vehicles for its high power density.



Source: Global LTO Battery Market

Chemistry & Cell Components | LTO | Industry Players

Toshiba Corporation: has been a prominent player in the development of LTO anodes for lithium-ion batteries. The company has been involved in manufacturing LTO cells and promoting their use in various applications, including electric vehicles and industrial energy storage.

NEC Energy Solutions: is known for its energy storage solutions, and they have utilized LTO technology in certain battery systems. The company focuses on providing grid energy storage solutions and has deployed LTO-based batteries for various projects.

Altairnano: now known as Energy Storage Systems (ESS), has been involved in the development of advanced energy storage technologies. They have worked on LTO anode materials for high-power and long-life applications.

NEI Corporation: is a materials science company that has been active in developing advanced materials for energy storage applications. They have worked on various types of anode materials, including LTO, and have been involved in research and development.

A123 Systems:, a subsidiary of Wanxiang Group, has been involved in the development of lithium-ion batteries for various applications. They have utilized LTO technology in certain battery products, particularly for high-power applications.

Kokam Co., Ltd.:, a South Korean company, has been involved in the development and manufacturing of advanced battery systems. They have utilized LTO anode technology in certain lithium-ion batteries for applications like electric vehicles and grid storage.

Leclanché:, a Swiss energy storage company, has worked on various energy storage solutions, including lithium-ion batteries. They have explored the use of LTO anodes in certain battery systems.

Amperex Technology Limited (ATL):, a major battery manufacturer based in China, has been involved in the production of lithium-ion batteries for various applications. While they are known for using different anode materials, they may explore or use LTO in certain battery configurations.

Source: Global LTO Battery Market

Pros and Cons of Lithium Metal (Li) vs. Graphite (Gr)

S

Li-Metal Strength

- Volumetric Energy
- Gravimetric Energy
- Supply Chain

Graphite Strength

- Cost
- Cycle Life
- Power
- Safety

W

Li Metal Weakness

- Cycle life
- Power Density
- Battery supply chain
- Difficult to determine state of health
- Manufacturing
- Safety

Graphite Weakness

- Supply Chain
- Energy

O

Li Metal Opportunity

- Aerospace
- Defense related applications
- Drones
- Cost incentive applications

Graphite Opportunity

- Low Cost EV's
- Stationary storage
- e-Bus, e-Bike, e-Motorcycle
- Power tools/performance sensitive applications

T

Li Metal Threat

- NMC/Silicon
- Na-ion battery
- Regulations on energy density and pack cycle life
- Increasing material cost

Graphite Threat

- Na-ion Battery
- Regulations

| Lithium Metal | Industry Players

Manufacturers who have announced or plan to work with Lithium Metal

Lithium Metal Producers

- ALBEMARLE®
- Li METAL
- TIANQI LITHIUM
- GanfengLithium
- CEL
- SQM
- arcadium lithium
- MINERAL RESOURCES
- Pilbara Minerals
- APPLIED MATERIALS®

Battery Manufacturers

- LYTEN
- CUBERG
- Zeta ENERGY
- solid energy
- Factorial
- NexTech Batteries
- QuantumScape
- BlueSolutions BOLLORÉ
- one our next energy
- Solid Power
- AMERICAN LITHIUM ENERGY
- SEPION TECHNOLOGIES

Automotive Manufacturers Interested

- gm
- BOLLORÉ
- STELLANTIS
- VW

Source: Battery Talk; Green Congress

| Lithium Metal | Industry Players & Investments

Company	Technology	No. of Employees	No. of Patents	Total Funding ($)	Remarks
QuantumScape	Metal Oxide - Solid State - Lithium Metal or Anodeless	850+	300+	800M +	Well funded startup with large headcount and patent portfolio, QuantumScape is one of the industry leaders for the field but has been overshadowed recently with lots of promise and no deliveries. It will be interesting to see where QuantumScape is in the next few year as it is the champion of solid state with Li-Metal
Cuberg	Metal Oxide - Liquid Electrolyte - Lithium Metal	150-200	26	Private	Originally a company focused on the development of liquid electrolytes for lithium metal batteries, Cuberg was acquired by Northvolt as a hedge against future battery developments. Northvolt has come out with some excellent 3rd party testing data but that too has been heavily scrutinized for rest times and asymmetrical rates.
Factorial Energy	Metal Oxide - Solid State - Lithium Metal or Anodeless	150-200	24	244+ M	Solid state battery company with a good patent portfolio and a lot of momentum behind it due to recent investments by OEM's. Till now factorial has has been relatively quiet until it released news of its manufacturing facility. It will be interesting to see the final destination of this company as it challenges the immense hurdles of solid state manufacturing.
SolidEnergy Systems	Metal Oxide - Liquid Electrolyte - Lithium Metal	130-160	27	597M	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.
Blue Solutions	Lithium Metal Polymer Batteries	200-300	5	Privately owned by Bollore	Blue Solutions, a Bolloré Group company, is the only manufacturer of all-solid-state batteries commercially available for transportation and stationary applications. They current sells solid-state lithium metal polymer (LMP®) batteries. Lithium metal polymer is not a new technology and has been around, it will be interesting to see where they land in the field of solid state.

Pros and Cons of Lithium Sulfur (LiS) vs. Lithium Nickel Manganese Cobalt Oxide (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

| Lithium Sulfur | Materials Selection

Active	Material Properties	Capacity (mAh/g)	Voltage Range (V)	Tap Density (g/cm^3)	Cycle Life	Prospects & Challenges
Cathodes	Sulfur Carbon	1100 - 1674	1.5-3.0	0.3 - 0.7	50-300	· Safety is better relative to conventional Li-ion · Voltage window prohibitive to pack design · Poor volumetric energy density due to tap density
	SPAN	300 - 600	1-2.5	0.4 - 0.6	100-600	· Poor volumetric and gravimetric energy · Limited power density due to nominal voltage
	Lithium Sulfide	1000 - 1166	1.5-3.0	0.3 - 0.7	50-300	· High moisture sensitivity leads to higher costs · Poor volumetric energy due to tap density
Anodes	Silicon	3000 - 4200	0.1-1	0.8-1.0	100-1000	· Poor volumetric energy due to tap density · Feedstock limits costs & quality
	Lithium/ Lithium Alloy	3200 - 3800	0-0.2	0.5-0.7	50-600	· Need to manage high volume change · Limited cycle life reported

Inactive	Material Properties	Description	Prospects & Challenges
Electrolyte	Ether based	LiTFSI salt in ethers / fluoro ethers	· Ethers solubility allows for a broad use of additives and salts for anode stability · Ethers dissolve active CAM material within the cell
	Carbonate based	$LiPF_6$ salt in Cyclic/Linear carbonate mixtures	· Good oxidative stability, but need to manage gas generation/accumulation
Current Collector	Aluminum Foil	Used at Cathode	· At < 1 V aluminum will react with Lithium · Weight of Al significant vs cathode loading
	Copper Foil	Used at Anode	· Copper weight is a significant impact on overall cell weight · Due to chemistry window - Copper should be ok at 0V

Chemistry & Cell Components

Lithium Sulfur | Notable Events

Q2

May 2023

Stellantis invests in US startup-up Lyten to develop lithium sulfur batteries.

May 2023

Zeta Energy **develops dry cathode process** for lithium sulfur

Q3

June 2023

Lyten opens **1st automated Pilot Line in U.S.** to produce lithium sulfur batteries

September 2023

Lyten **raises $200 million** in Series B

Q4

October 2023

Zeta announces **demonstration of a multilayer 300 Wh/kg pouch cell** with up to 20Ah.

November 2023

Gelion & Ionblox partner on sulfur silicon cells

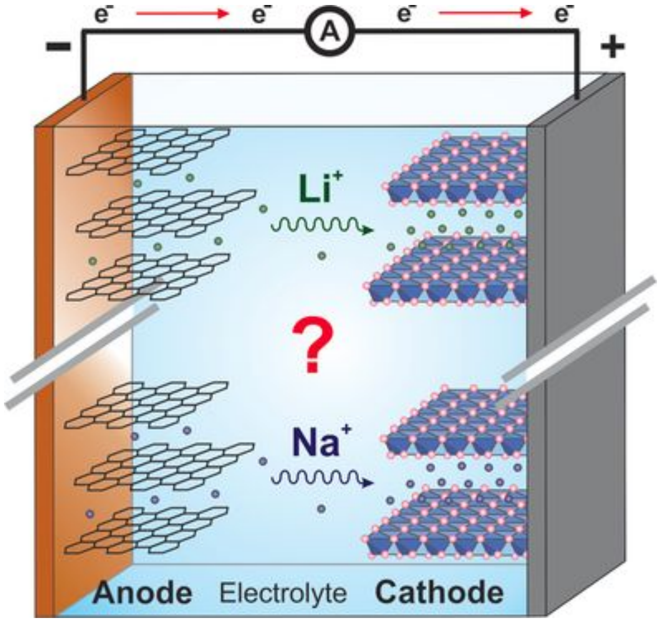
Chemistry & Cell Components

| Lithium Sulfur (LiS) | Industry Players & Investments

Company	Technology	No. of Employees	No. of Patents	Total Funding ($)	Remarks
Lyten	Sulfur Cathode-Li Metal Anode	250-300	350+	410M	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. At this point they've opened a pilot line and have been transparent about manufacturing activities. Based on employee count and recent boutique manufacturing capabilities they will be positioned to sample cells in the near future.
Gelion	Sulfur Cathode-Li-metal Anode Sulfur Cathode-Silicon Anode	30-40	450+	50M	Working on both silicon-sulfur and lithium-sulfur batteries. In 2023 Gelion acquired OXIS Energy's Lithium Sulfur technology and IP. Gelion also acquired OXLiD, developer of sulfur semi-solid state cathode materials. A partnership with Ionblox has been announced.
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 Carbon	11-50	1	102.4M (Market Cap as of 1/08/2024)	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	15-20	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	15-20	5	31.2M	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.
Coherent	Selenium Sulfur Cathode Lithium Anode	Unknown	NA	undisclosed	New player to the field of lithium sulfur and is already an established laser, networking, and optics company. At this point it's unclear why they jumped into the field but it's exciting to see another company investing in lithium sulfur.

Chemistry & Cell Components

| Sodium Ion | Technology



- Na-ion batteries, an alternative to Li-ion technology, operate on the same reversible cation intercalation 'rocking-chair' principle.
- Despite lower energy density and slower reaction kinetics, attributed to factors like Na's higher redox potential (−2.71 V vs. SHE for Na+/Na), and larger size (1.02 Å) compared to Li (with a redox potential of −3.01 V, and 0.76 Å ionic radius)., Na-ion batteries offer advantages.
- They are inert to aluminum, enabling its use as an anode current collector, and exhibit smooth Na intercalation with various 3d transition metals.
- Potentially suitable for stationary storage applications where cost-effectiveness and longevity are critical, Na-ion batteries capitalize on the abundance of sodium, faster charging capabilities, and a broader temperature range.
- Positioned as a potential solution for grid electricity storage, ongoing research aims to achieve a lower levelized cost of stored energy (LCOSE), targeting <$0.1/kWh,

Na-ion batteries emerge as an affordable and secure alternative to Li-ion for stationary storage applications, being an abundant and low cost technology.

Source: Polyanionic Cathode materials for Sodium ion batteries. Dissertation from Mr. Huang Zhang (KIT)

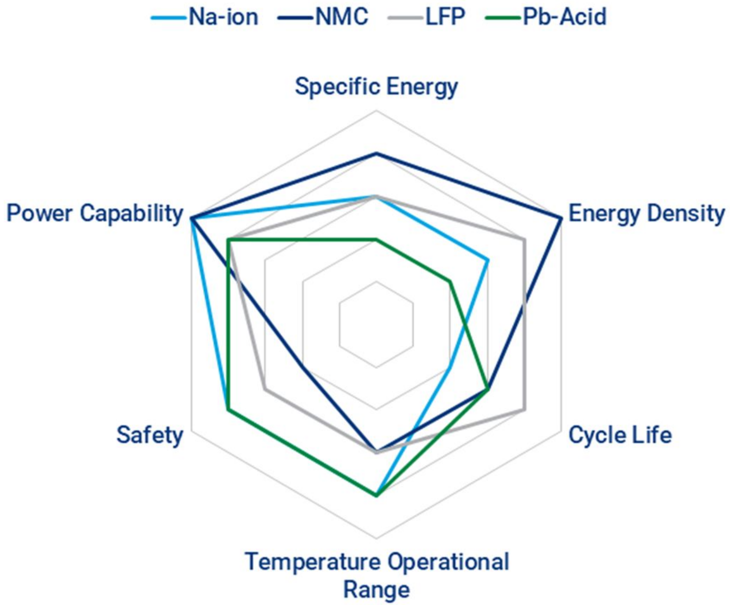
Chemistry & Cell Components | Sodium Ion | Materials Selection

Active	Material Properties	Capacity (mAh/g)	Voltage Range (V)	Tap Density (g/cm^3)	Cycle Life	Safety	Prospects & Challenges
Cathodes	Layered Oxide	120-150	2.0-4.0	2.2-3.2	2000-5000	Releases heat + O_2 during TR	· Thermal safety still unproven · Wide voltage range limits integration
	Polyanion	90-120	2.0-3.5* 4.2V in NVPF *	0.6-0.9	5000-10000	Limited heat release	· Poor volumetric energy due to tap density · Limited rate capability / power density
	Prussian Blue/White	150-170	2.0-4.0	0.6-0.9	5000-10000	Releases cyanide gas during TR	· High moisture sensitivity leads to higher costs · Poor volumetric energy due to tap density
Anodes	Hard Carbon	250-300	0-1.5	0.8-1.0	5000-10000	Releases energy rapidly, burns to CO_2	· Poor volumetric energy due to tap density · Feedstock limits costs & quality
	Alloys	650-850	0-0.8	6.6-7.3	1000-3000	Releases energy slowly, oxidizes to $M\text{-}O_2$	· Need to manage high volume change · Limited cycle life reported
	Sodium / Anodeless	1166	0	-	<1000	-	· Na foil processing challenges · Na-free cycle life limitations & volume change

Inactive	Material Properties	Description	Prospects & Challenges
Electrolyte	Ether based	$NaPF_6$ salt in Linear Glymes	· Ethers are compatible with Na anodes (incompatible with graphite), offers superior SEI stability · Limited oxidative stability, cannot be used with high voltage cathodes
	Carbonate based	$NaPF_6$ salt in Cyclic/Linear carbonate mixtures	· Good oxidative stability, but need to manage gas generation/accumulation at high voltage · Not compatible with metal-based anodes
Current Collector	Aluminum Foil	Used at both Anode and Cathode	· Aluminum does not react with sodium (unlike lithium), · Use on both electrodes reduces weight, cost and critical material needs of copper

| Sodium Ion | Comparison Against Lithium Ion

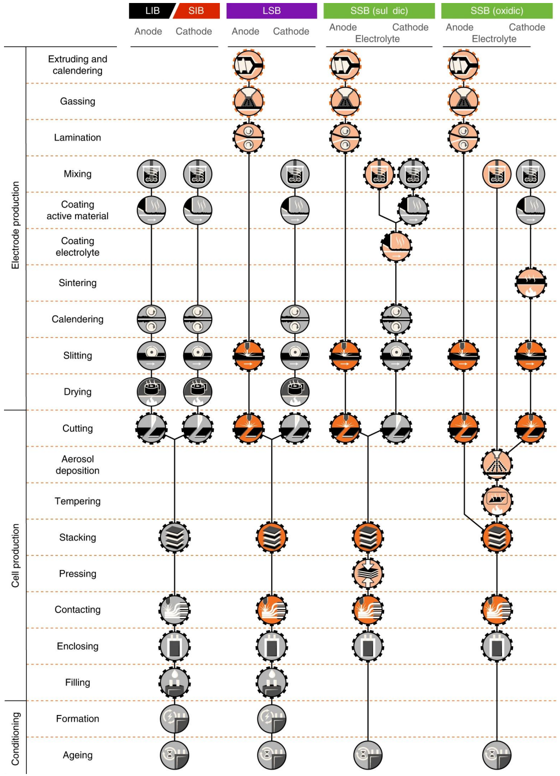
Na-ion battery		Li-ion battery
Elemental Abundance	~23000 ppm	20 ppm
Gravimetric Energy density	140-150 Wh/Kg	140-280 Wh/Kg depending on chemistry (NMC, LFP, LTO, NCA etc.)
Volumetric Energy Density	250-400 Wh/L	250-750 Wh/L depending on chemistry (NMC, LFP, LTO, NCA etc.)
Cycle Life	2000-20,000	2000-20,000
Fast Charging Capability	Demonstrated @ 4C for short period of time; R&D still ongoing	Depends on chemistry (NMC - <1C, LFP - <2C, LTO - <6C)
Operating Temperature	–20°C to 60°C	0°C – 45°C (For LTO, –30°C - 60°C
Safety	Safe to transport at 0V	Usually transported @ 50% SoC to avoid over-discharge



Source: Wood Mackenzie

| Sodium Ion | Production Process

- Sodium ion cell production process is **virtually identical** to Lithium ion
- Avoids need to reinvent manufacturing steps/protocols used in other next generation batteries (e.g. Li-S, Li-ASSB, SSE containing)
- Form factors are flexible, i.e. cylindrical cells, prismatic, pouch cells are manufacturable for both SIB and LIBs.
- Potential areas of production cost reductions: Reduced dry room requirements, eliminate need for SOC shipping



● LIB or identical production step

● New step compared to LIB

◌ Inert gas atmosphere (argon)

◌ Dry room atmosphere

● Same step and different manufacturing technology compared to LIB

Source: Duffner, F., Kronemeyer, N., Tübke, J. et al.

| Sodium Ion | Differentiating Properties

SIB Claims & prevailing areas of consideration

Claims	Reason	Prospects	Challenges
Lowering Costs	BOM of SIBs lower than LIBs (historical avg $200/MT for NCE vs $20,000/MT for LCE)	● Large abundance of NCE mitigates supply chain fluctuations ● Potential Cost reductions on anode/no copper/electrolyte	● Lower BOM not yet manifested in lower cell costs due to immature supply chain ● Reliance of Ni, V, other rare earth containing materials, or high moisture sensitivity for certain SIB cathodes
0 V storage & transport	Absence of Cu on anode allows for 0V discharge due to oxidative resistance on Al	● Avoids need for SOC shipping (UN38.3), and reduces handling / transport safety hazards ● Resistant to over discharge during long storage periods without access to charging	● No existing regulatory guidance on SIB transport standards yet, SIBs still classified in same category as LIB ● Sufficient BMS level protections against over discharge may negate needs
Wider temperature range	Use of low MP / high temp stable electrolytes (e.g. PC in SIB vs EC in LIBs.)	● High-capacity utilization at extreme low temperatures (-40°C). ● Reduced thermal cooling requirements at higher operating temps (60°C).	● Low temperature performance limited to discharge, charging still requires above -10°C ● Excessive gas formation at elevated temperatures when high voltage cathodes are used
Improved Safety	Lower heat released/rate of heat released for SIBs	● Reduced system level costs (safety/fire mitigation costs) ● Potential to serve indoor BTM markets if safety metrics can be met (meet NFPA 855)	● Limited ARC testing data available for reference ● Safety concerns for layered oxides (fire hazard/oxygen release), PBAs (cyanide gas hazard)
Integration Ease	Form factor compatibility with LIB at system level	● Use existing BMS/Power electronics during pack to system integration	● Some SIB cell chemistries uses wide voltage ranges that are not directly compatible

Chemistry & Cell Components

| Sodium Ion | Notable Events

Q1 2023

February

Hina-JAC launches first sodium-ion EV tests on roads (25 kWh pack)

March

Farasis Energy supplies JMEV Na-ion packs for EV3 small vehicle, in partnership with Renault

April

CATL's Sodium-ion Battery to Power Chery EV Models, new battery brand, ENER-Q, to supply multiple types of EVs

April

BYD Seagull version to include a sodium ion battery model for low cost EVs

August

Grid-scale Na ion battery project launched in China, between Great Power & partners

October

Peak Energy launches from stealth with Veteran execs to mass-produce sodium ion batteries

November

Northvolt develops state-of-the-art sodium-ion battery validated at 160 Wh/kg, PBA based

December

Volkswagen-Backed JAC Begins Mass Production For Sodium-Ion Battery-Powered EV In China

December

KPIT unveils sodium-ion battery with energy density of up to 170 Wh/kg

January 2024

BYD breaks ground on 30 GWh sodium battery plant in cooperation with Huaihai, making world largest sodium ion plant


JAC


BYD


JMEV

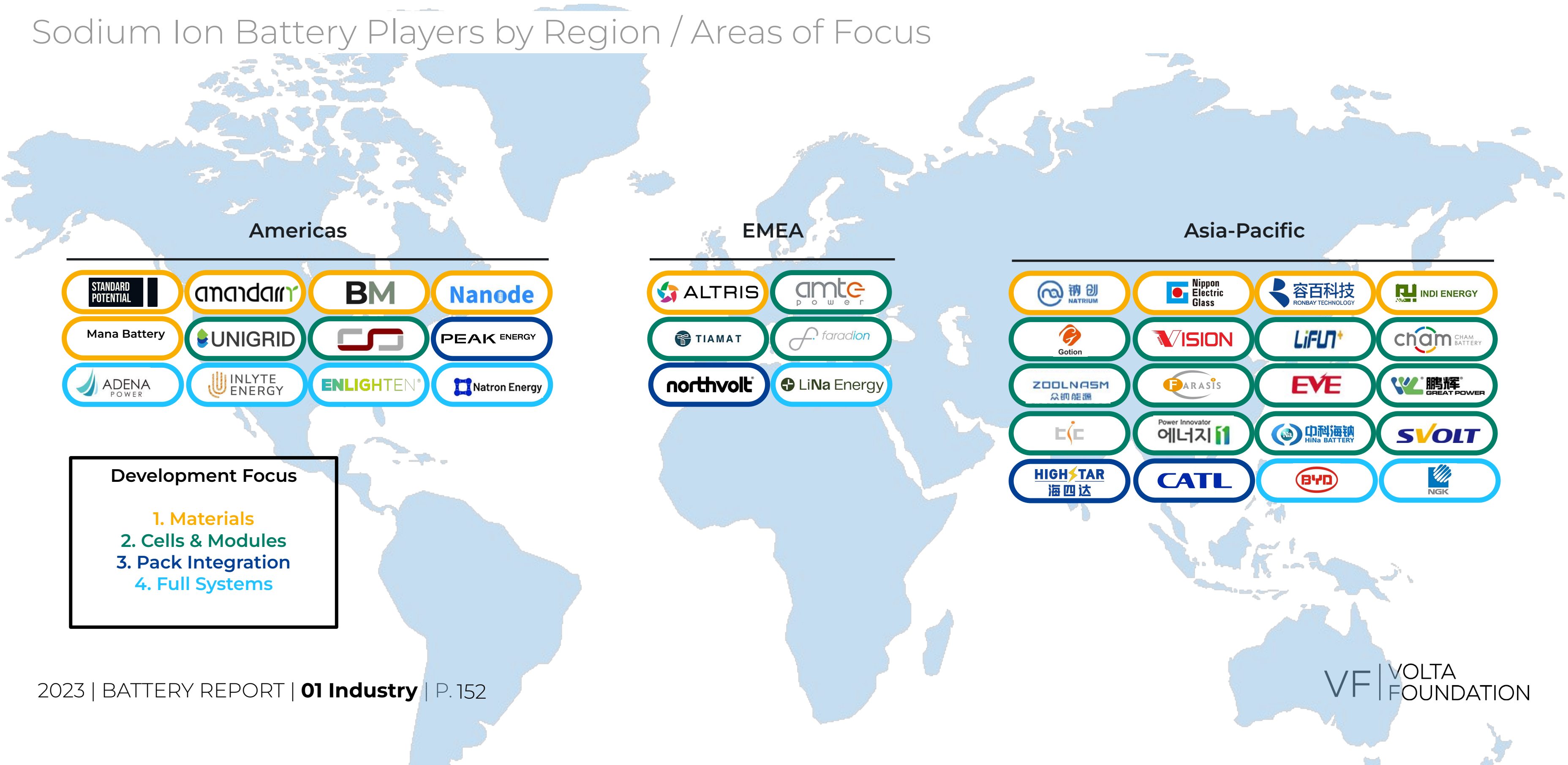

Yiwei


KPIT

Chemistry & Cell Components

| Sodium Ion | Industry Players

Sodium Ion Battery Players by Region / Areas of Focus



Americas

- STANDARD POTENTIAL
- amandarry
- BM
- Nanode
- Mana Battery
- UNIGRID
- PEAK ENERGY
- ADENA POWER
- INLYTE ENERGY
- ENLIGHTEN®
- Natron Energy

EMEA

- ALTRIS
- amte power
- TIAMAT
- faradion
- northvolt
- LiNa Energy

Asia-Pacific

- 钠创 NATRIUM
- Nippon Electric Glass
- 容百科技 RONBAY TECHNOLOGY
- INDI ENERGY
- Gotion
- VISION
- LiFUN
- cham CHAM BATTERY
- ZOOLNASM 众钠能源
- FARASIS
- EVE
- 鹏辉® GREAT POWER
- Power Innovator 에너지11
- 中科海钠 HiNa BATTERY
- SVOLT
- HIGHSTAR 海四达
- CATL
- BYD
- NGK

Development Focus

1. Materials
2. Cells & Modules
3. Pack Integration
4. Full Systems

VF | VOLTA FOUNDATION

| Sodium Ion | Industry Players Reported Metrics

Sodium Ion Battery Landscape	Origin	Founded	Cathode	Anode	Wh/kg	Wh/L	Cycle Life	Reference
Natron Energy	🇺🇸	2012	PBA	PBA	15-20	20-25	>50000	Link
TIAMAT	🇫🇷	2012	Polyanion	HC	65-85	135-150	>3000	Link
ALTRIS	🇸🇪	2012	PBA	HC	160	*Unreported*	*Unreported*	Link
中科海钠 HiNa BATTERY	🇨🇳	2012	Layered	HC	145	*Unreported*	>4500	Link
CATL	🇨🇳	2012	PBA/Layered	HC	160	*Unreported*	>3000	Link
EVE	🇨🇳	2012	Layered/Polyanion	HC	135	*Unreported*	>2500	Link
faradion	🇬🇧	2012	Layered	HC	160	*Unreported*	>4000	Link
FARASIS	🇨🇳	2012	Layered	HC	150-160	*Unreported*	>2000	Link
GREAT POWER	🇨🇳	2012	Layered	HC	125-145	240-270	>3000	Link

Note1: Significant variations between cylindrical vs pouch reported datapoints Note2: Metrics obtained from news reports, no verified datasets publicly available

Chemistry & Cell Components | Sodium Ion | EV Applications

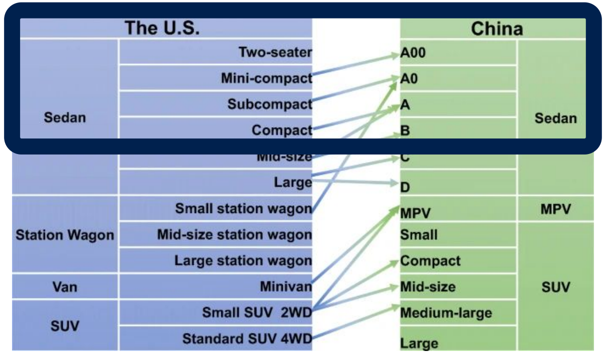
Volumetric energy density (Wh/L) of SIB is the bottleneck to higher range

A00 Class EV Reported Metrics

Pack Sizes : 20-40 kWh
Drive Ranges : 250-400 km


25 kWh Pack

OEM's Target EV Applications: Compact & Mini EVs



The U.S.

Sedan: Two-seater, Mini-compact, Subcompact, Compact, Mid-size, Large
Station Wagon: Small station wagon, Mid-size station wagon, Large station wagon
Van: Minivan
SUV: Small SUV 2WD, Standard SUV 4WD

China

Sedan: A00, A0, A, B, C, D
MPV: MPV
SUV: Small, Compact, Mid-size, Medium-large, Large

国内首次应用钠离子电芯开发蜂窝电池包，SOC30%-80%快充时长≤15min。

项目		基本参数
电芯	电芯类型	钠离子电池
	容量 Ah	12
	重量 g	256
	能量密度 Wh/kg	≥140
电池包	成组方式	6P110S
	总能量 kWh	25
	容量 Ah	72
	电压平台 V	341
	能量密度 Wh/kg	120
	快充时长SOC 10%-80% (min)	20
	快充时长SOC 30%-80% (min)	15
	-20℃容量保持率	≥90%

思皓E10X 花仙子（钠电版）配置表

整车基本参数		
外部尺寸（mm）		3650*1670*1540
轴距（mm）		2390
CLTC纯电续航里程(km)		252
最高车速（km/h）		≥120
最大爬坡度		25%
0-50km/h加速时间（s）		≤5.5
座位数		5座
整备质量(kg)		1130
电池系统		
电池类型		钠离子电池
电池容量（kWh）		25
充电时间	快充（SOC 30%-80%）（min）	15
	快充（SOC 10%-80%）（min）	20
电机系统		
电机类型		永磁同步
电机最大功率（kW）		45
电机最大扭矩（N.m）		150

Source: JAC-EV Publish day

Chemistry & Cell Components

| Sodium Ion | ESS Applications

Sodium's place in the ESS Market

Front-of-Meter Markets (larger deployment footprint)

Sodium-ion energy storage firm Peak Energy launches with US$10 million investment

By Cameron Murray

October 5, 2023

Alternatives: Li-LFP / Flow Batteries / Na-S / Zinc / Liq-metal / Metal-air
Key Metric: Levelized Costs ($/kWh/cycle) > Safety > Cycle life > Rate

Behind-the-Meter Markets (smaller deployment footprint)

Biwatt unveils new residential sodium-ion batteries

Biwatt Power, a Chinese manufacturer, has developed new residential sodium-ion batteries with an efficiency rate of 97% and a projected lifespan of more than 3,000 cycles.

AUGUST 11, 2023 EMILIANO BELLINI

Alternatives: Li-LFP / Lead-acid
Key Metric: Safety > Capital Costs ($/kWh) > Cycle life

Challenges:

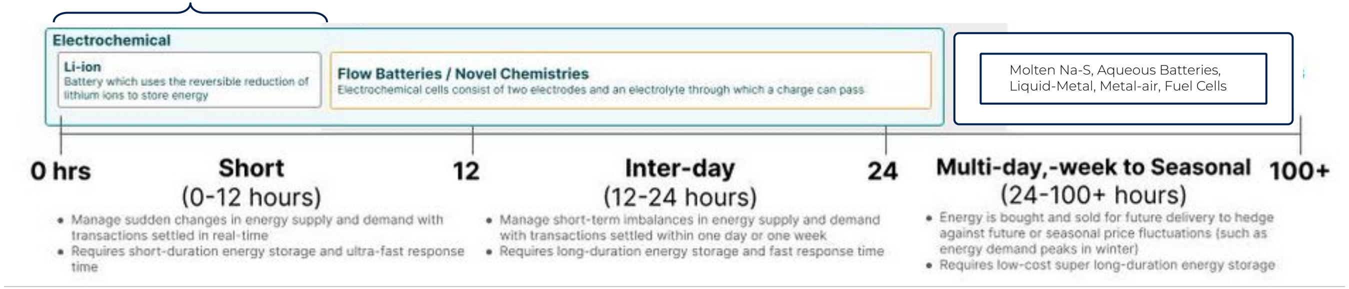
- Costs & Safety are still unproven.
- Cycle life yet to be demonstrated at scale

Loading Balancing
Cost/kWh/Cycle > Safety / Reliability > Cycle Life

Frequency Balancing
Cost/kWh/Cycle > Safety / Reliability > C-Rate

Residential Storage + Smart Grid
Safety / Reliability > Cost/kWh/Cycle > Cycle Life

Na Ion: 2-to-8-hour sweet spot



Electrochemical

Li-ion
Battery which uses the reversible reduction of lithium ions to store energy

Flow Batteries / Novel Chemistries
Electrochemical cells consist of two electrodes and an electrolyte through which a charge can pass

Molten Na-S, Aqueous Batteries, Liquid-Metal, Metal-air, Fuel Cells

0 hrs **12** **24** **100+**

Short
(0-12 hours)
- Manage sudden changes in energy supply and demand with transactions settled in real-time
- Requires short-duration energy storage and ultra-fast response time

Inter-day
(12-24 hours)
- Manage short-term imbalances in energy supply and demand with transactions settled within one day or one week
- Requires long-duration energy storage and fast response time

Multi-day,-week to Seasonal
(24-100+ hours)
- Energy is bought and sold for future delivery to hedge against future or seasonal price fluctuations (such as energy demand peaks in winter)
- Requires low-cost super long-duration energy storage

Source: DOE, CTVC

| Solid State | Industry Overview

Key trends of the current state of the solid-state battery industry

- **OEM Race:**
    - Almost all the automotive OEMs are actively participating in the solid-state battery race with varying strategies:
        - In-house research in SSB (e.g. Toyota)
        - Strategic partnerships with SSB companies (e.g. Nio with WeLion)
        - Direct investments in one (e.g. BMW, Ford, Stellantis) or multiple SSB companies (e.g. Mercedes, Hyundai, Kia)
        - Publicly disclosed mixed strategy, combining in-house development with investments in other companies (e.g. Honda)
- **Technology:**
    - There is no consensus on the electrolyte to be used, although polymers have achieved the highest level of maturity. Significantly, there is a growing trend towards employing semi-solid polymer electrolytes to enhance workability with the cathode
    - Notably, there is a substantial focus on Sulfide SSBs in the Asia-Pacific region
- **Timelines:**
    - The majority of startups in this sector were founded between 2010 and 2016 and are now either public or in the late stages of investments
    - The Start of Production (SOP) for most players is forecasted or announced to be between 2026 and 2029, with a few optimistic exceptions aiming for 2024

Chemistry & Cell Components

| Solid State | Technology

Types of Solid Electrolytes

Solid-state batteries differ from classical lithium-ion batteries due to their use of a solid electrolyte. However, a consensus on the preferred chemistry for the solid electrolyte has not been reached, as each type comes with distinct pros and cons.

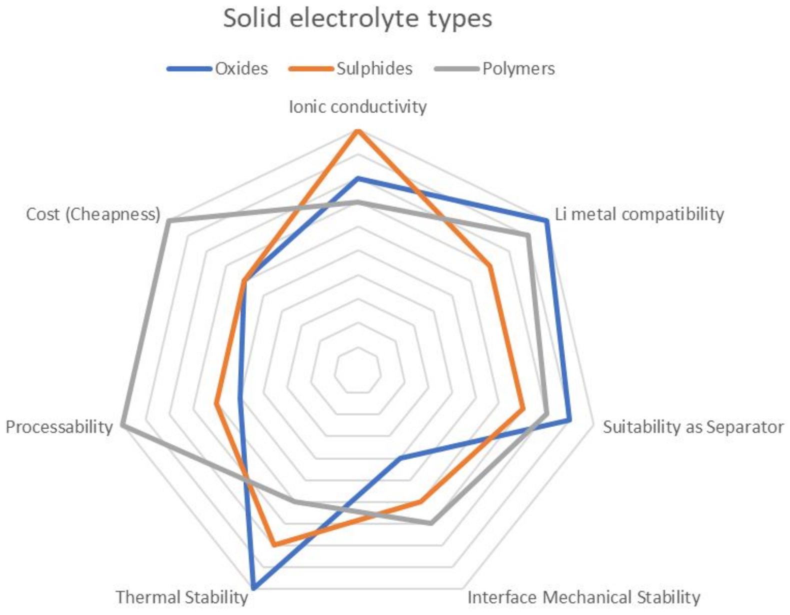
The two most common families of electrolyte used are:

- Ceramic (including Oxides and Sulphides)
- Polymers (solid, composite, or gel; the latter often referred to as a semi-solid electrolyte)

Key properties of a good solid-state electrolyte include high ionic conductivity, a robust electrode-electrolyte interface, high thermal and electrochemical stability, the ability to suppress dendrites, high processability, and low manufacturing cost.

Ceramic electrolytes exhibit high ionic conductivity and mechanical strength but suffer from poor interfacial properties. In contrast, organic polymers boast good interfacial properties but struggle with low ionic conductivity and mechanical strength.

So far, polymers have achieved a higher level of technology readiness owing to their superior processability.



Source: BatteryBits

| Solid State | Supply Chain & Manufacturing

Manufacturing differences with respect to traditional li-ion with liquid electrolyte

Chemistry	Anode Production	Cathode Production	Separator Production	Cell Assembly
Li-ion with Liquid Electrolyte	Anode slurry mixing and coating, drying, calendering	Cathode slurry mixing and coating, drying, calendering	Extrusion process, can be both dry and wet	Stacking, packaging, electrolyte filling and degassing, aging
Oxide Solid State Battery	Lithium foil extrusion, calendaring, lamination	Cathode slurry mixing and coating, drying, LT sintering	Slurry mixing and coating, HT sintering, lamination, LT sintering	Stack pressing, aging
Sulfide Solid State Battery	Lithium foil extrusion, calendaring, lamination	Cathode slurry mixing and coating, drying, calendering	Slurry mixing and coating, drying, calendering	Stack pressing, aging
Polymer Solid State Battery	Lithium foil extrusion, calendaring, lamination	Extrusion, calendaring	Extrusion, calendering	Stack pressing, aging
Key Manufacturing Differences	Remarkable difference in comparison to Li-ion, primarily attributed to the extrusion process of the lithium metal foil. Notably, the process for Si-based anodes is more akin to traditional Li-ion methods.	For Oxide and Sulfide, the cathode undergoes a process similar to traditional Li-ion, but solid electrolyte particles are mixed in the slurry. Additionally, Oxide SSBs need the expensive sintering step. On the other hand, Polymer SSBs necessitate extrusion.	In Oxide and Sulfide SSBs, the wet processing of the separator markedly differs from the traditional extrusion process employed in Li-ion batteries.	Unlike Li-ion batteries, SSBs do not require electrolyte filling and degassing, marking one of the distinctive advantages of SSBs.

Source: Fraunhofer ISI

| Solid State | Supply Chain & Manufacturing

Solid-state batteries share common components with liquid electrolyte-based ones but differ in resource demand due to the choice of solid electrolyte and anode materials. There are two main distinctions: the inclusion of new metals in the electrolyte and the increased lithium content.

Inclusion of New Metals

The **inclusion of new metals** like lanthanum, germanium, or zirconium in solid-state batteries sets them apart from traditional lithium-ion batteries:

- Zirconium is common and poses no significant supply chain issues. (present in oxide solid electrolyte)
- Lanthanum, while abundant among rare earth metals, could face increased demand with growing SSB adoption. (present in oxide solid electrolyte)
- Germanium, being relatively scarce and costly, may not be suitable for widespread use in batteries. (present in oxide and sulfide solid electrolyte)

Lithium Content

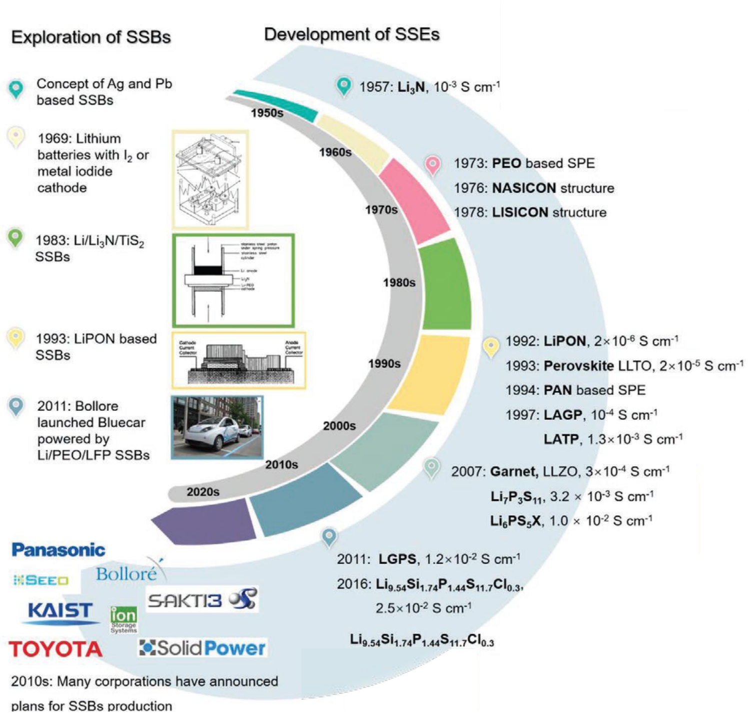
Regarding **lithium demand**:

- Cathode materials show no major changes compared to those in conventional lithium-ion batteries
- Noteworthy changes occur in the electrolyte, with a solid electrolyte resulting in an average additional demand for lithium ranging from 10 to 20 g/kWh compared to liquid organic electrolytes
- Lithium metal in the anode demands an additional lithium content, roughly equivalent to the transition from a liquid to solid electrolyte. The additional amount varies depending on the anode thickness and the excess lithium added to the cell to improve its performance

Source: Fraunhofer ISI

Chemistry & Cell Components

| Solid State | Notable Events



2023 was a lackluster year in terms of new investments and partnerships for solid state batteries compared to 2022. SSB companies consolidated existing partnerships and deployed previously raised capital on the path towards commercialization. For most, the start of production remains a moving target.

Q2

CATL

April: Battery giant CATL unveiled a condensed matter battery (semi-solid state) with energy density of 500 (Wh/kg).

ProLogium

May: ProLogium Announces €5.2b Gigafactory in Dunkirk France.

Q3

TOYOTA

June: Toyota announced a breakthrough in solid state batteries and expressed commitment for its commercialization in 2027-2028 (later rectified to "2030 and beyond").

WELION 卫蓝新能源 NIO

July: WeLion has delivered its first semi-solid-state battery cells to electric car manufacturer Nio.

Q4

Factorial

October: Factorial Energy has delivered A-samples of its lithium metal cells with more than 100 Ah to car manufacturers for testing.

Solid Power BMW

November: Solid Power has made first A-1 EV battery cell deliveries to BMW to formally enter automotive qualification.

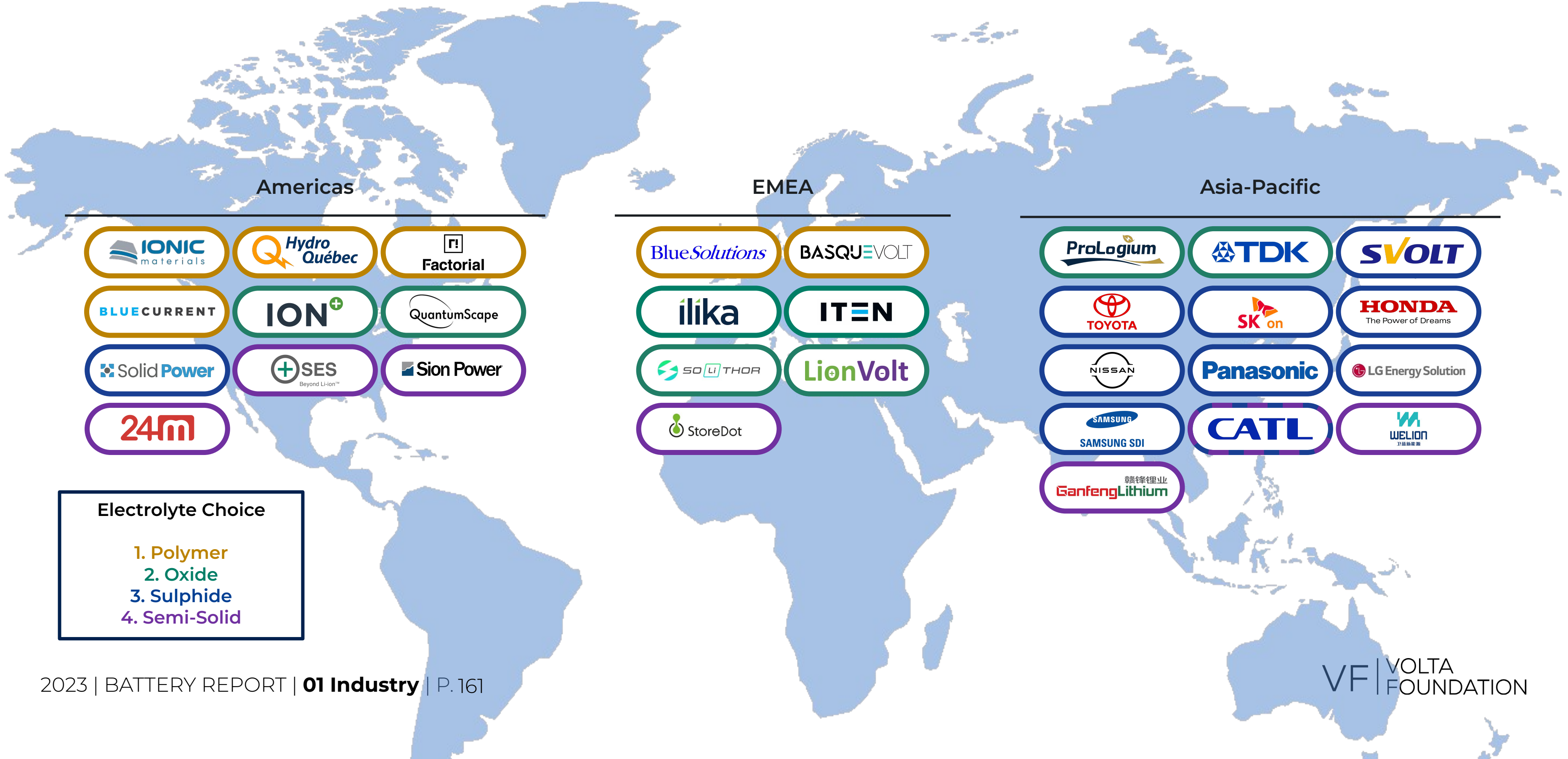
SES Beyond Li-ion™

November: SES has unveiled a new lithium metal battery cell with a capacity of 107 Ah.

Source: Xu, L., Lu, Y., Zhao, C.Z., Yuan, H., Zhu, G.L., Hou, L.P., Zhang, Q., & Huang, J.Q.

Chemistry & Cell Components

| Solid State | Industry Players



Americas

- IONIC materials
- Hydro Québec
- Factorial
- BLUECURRENT
- ION
- QuantumScape
- Solid Power
- SES Beyond Li-ion™
- Sion Power
- 24M

EMEA

- Blue Solutions
- BASQUEVOLT
- ilika
- ITEN
- SOLITHOR
- LionVolt
- StoreDot

Asia-Pacific

- ProLogium
- TDK
- SVOLT
- TOYOTA
- SK on
- HONDA The Power of Dreams
- NISSAN
- Panasonic
- LG Energy Solution
- SAMSUNG SAMSUNG SDI
- CATL
- WELION
- 赣锋锂业 GanfengLithium

Electrolyte Choice

1. Polymer
2. Oxide
3. Sulphide
4. Semi-Solid

Chemistry & Cell Components

| Solid State | Industry Players & Investments

Exploring Startups Post-2000

Company	Electrolyte Technology	Launch Date	Fund, Stage	Notable CVCs
Ilika	Oxide Solid Electrolyte	2004	$30M - Public	-
Ensurge	Oxide Solid Electrolyte	2005	$25M - Public	-
Prologium	Oxide Solid Electrolyte	2006	$538M - Series E	Mercedes-Benz
QuantumScape	Oxide Solid Electrolyte	2010	$1.5B - Public	VW
24m	Semi-Solid Electrolyte	2010	$107M - Series E	-
Solid Power	Sulfide Solid Electrolyte	2011	$387M - Public	BMW Ford SOLVAY SAMSUNG A123 SYSTEMS
Iten	Oxide Solid Electrolyte	2011	$110M - Series C	-
Ionic Materials	Polymer Solid Electrolyte	2012	$65M - Series C	NISSAN SAMSUNG MITSUBISHI MOTORS RENAULT HYUNDAI TotalEnergies
SES	Semi-Solid Electrolyte	2012	$600M - Public	HYUNDAI KIA HONDA The Power of Dreams gm LG SK GEELY
StoreDot	Semi-Solid Electrolyte	2012	$210M - Series D	Mercedes-Benz SAMSUNG bp VINFAST VOLVO OLA ELECTRIC

Source: Dealroom, Crunchbase

| Solid State | Industry Players & Investments

Exploring Startups Post-2000

Company	Electrolyte Technology	Launch Date	Fund, Stage	Notable CVCs
Factorial Energy	Polymer Solid Electrolyte	2014	$240M - Series D	HYUNDAI KIA Mercedes-Benz STELLANTIS
Blue Current	Polymer Solid Electrolyte (Composite)	2014	$46M - Series Unknown	umicore
Ion Storage Systems	Oxide Solid Electrolyte	2015	$53M - Series A	-
Sakuu	Unclear	2016	$16M - Series A	-
Svolt	Sulfide Solid Electrolyte	2016	$2.9B - Series B	xiaomi
Welion	Semi-Solid Electrolyte	2016	$275M - Series D	xiaomi HUAWEI
LionVolt	Oxide Solid Electrolyte	2020	$6.2M - Seed	-
Solithor	Oxide Solid Electrolyte	2021	$10M - Seed	-
BasqueVolt	Polymer Solid Electrolyte	2022	$30M - Seed	enagas Iberdrola

Source: Dealroom, Crunchbase

01 Industry | Overview

Notable Events
Industry Value Chain
Finance
Cell Costs
Cell & Pack Manufacturing
Applications
Safety
Chemistry & Cell Components
Raw Materials
Recycling
Software & Analytics

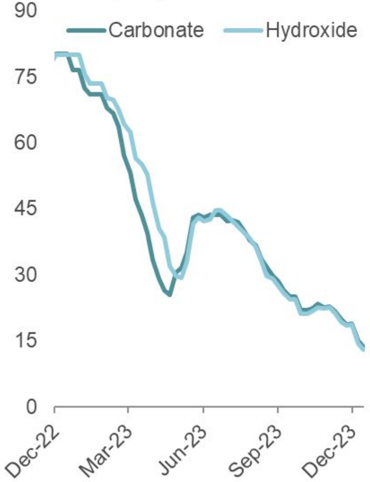
Raw Materials

Raw Materials

Battery Materials | 2023 Prices

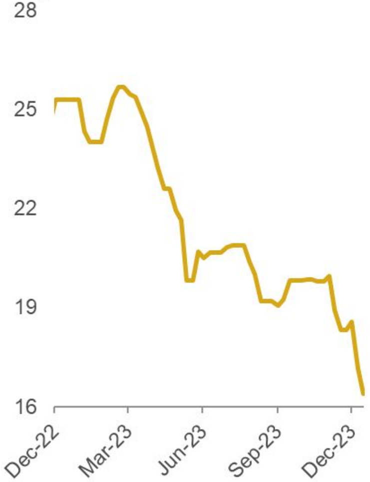
Battery chemical prices fall in 2023 as supply outpaces demand

Li



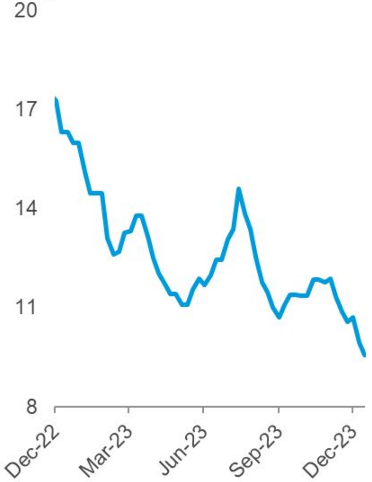
Lithium battery-grade chemical prices, DAP China, $/kg

Ni



Nickel sulphate price, DAP China, $/kg

Co



Cobalt sulphate price, DAP China, $/kg

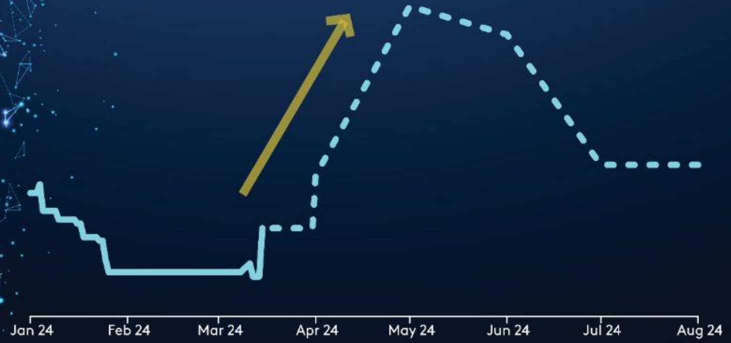
Factors Contributing to Price Declines

- Mining investments has increased supply of battery materials in the market
- Rate of growth in EV and battery demand has slowed relative to 2022
- China market has seen high inventories since start of the year
- Continued shift to LFP has softened demand for nickel and cobalt materials

Source: CRU Group

Fastmarkets

Did you know lithium prices are expected to increase over 20% in the next month?*



Source: Fastmarkets lithium hydroxide monohydrate LiOH.H2O 56.5% LiOH min, battery grade, spot price cif China, Japan & Korea, $/kg price. *Fastmarkets forecast data as of March 15, 2024 and is backed by 30+ analysts.

Will this price hike negatively impact your margins?

Could you gain a competitive advantage by purchasing key materials now or deferring until prices come down again?

Do you have access to detailed, market-reflective price data necessary to make informed decisions?

Subscribing to our battery raw material insights will give you access to market-reflective price data and forecasting to better manage your exposure.

Fastmarkets sets the benchmark for battery raw materials price data and analysis. Our price data underpins futures contracts on the LME, CME and SGX.

Speak to an analyst fastmarkets.com/analyst

Raw Materials

| Lithium 101 | Lithium Carbonate Equivalent (LCE)

With a wide variety of lithium compounds, it is commonplace to refer to the lithium content in terms of lithium carbonate equivalent ("LCE"). Lithium carbonate for technical use generally requires a grade of 99.0% and battery grade at least 99.5%.

- **Lithium Hydroxide:** used for high-nickel batteries would require 1.544 LCE
- **Lithium Carbonate:** used for LFP and low-nickel batteries would require 1 LCE
- **Lithium Metal:** used for Li Metal batteries would require 5.323 LCE

As more companies look to implement variable contracts to maximize margins, these multiples act as a multiplier based on cost changes to a given chemistry.

Conversion factors for lithium compounds and minerals

Convert from		Convert to Li	Convert to Li_2O	Convert to Li_2CO_3	Convert to LiOH
Lithium	Li	1.000	2.153	5.323	3.448
Lithium Oxide	Li_2O	0.464	1.000	2.473	1.601
Lithium Carbonate	Li_2CO_3	0.188	0.404	1.000	0.648
Lithium Hydroxide	LiOH	0.29	10.625	1.544	1.000

VF | VOLTA FOUNDATION

Source: Battery Talk: Lithium in Batteries Part 1, Battery Talk: Lithium in Batteries Part 2, Battery Talk: Lithium in Batteries Part 3

Raw Materials | Lithium 101 | Types & Sources

Lithium metal does not occur naturally in the environment, and lithium is most commonly found in lithium-bearing minerals such as spodumene ($LiAlSi_2O_6$) in pegmatite rocks or as dissolved salt such as lithium chloride (LiCl) in brines:

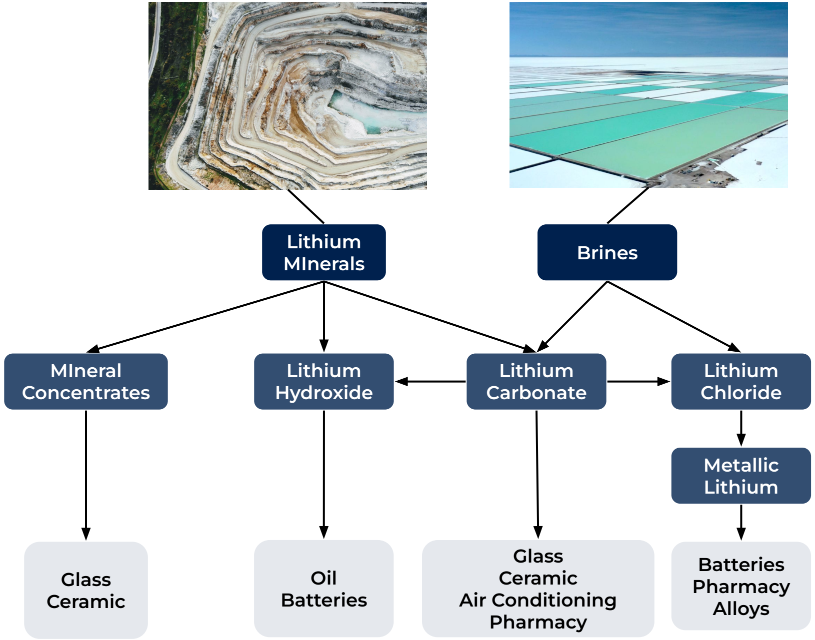
Hard rock mines - deposits are processed to a concentrate which is widely used in industry or may be converted to lithium carbonate or lithium hydroxide.

Lithium brines - typically derived from evaporative lakes and salars. The chemistry of saline brines is unique to each site and can change dramatically within the same salar.

Lithium clays - no production has yet been made from clays although a number of projects are studying their potential.

Main location of exploited deposits:
Australia, Brazil, Canada, China, United States, Zimbabwe

Main location of exploited deposits:
Chile, Argentina, China



Lithium MInerals

Brines

MIneral Concentrates

Lithium Hydroxide

Lithium Carbonate

Lithium Chloride

Metallic Lithium

Glass
Ceramic

Oil
Batteries

Glass
Ceramic
Air Conditioning
Pharmacy

Batteries
Pharmacy
Alloys

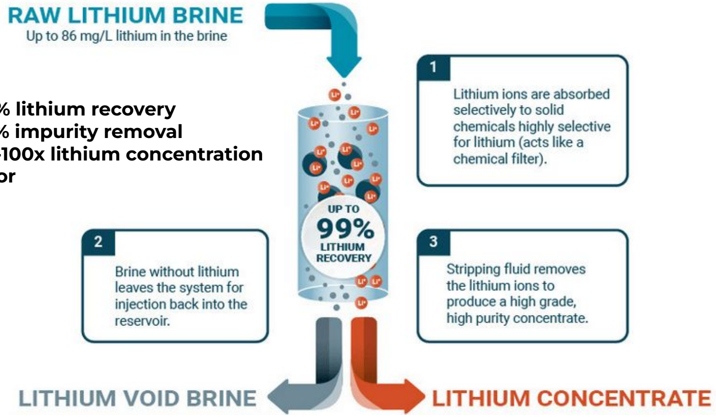
Source: Battery Talk: Lithium in Batteries Part 1, Battery Talk: Lithium in Batteries Part 2, Battery Talk: Lithium in Batteries Part 3

Raw Materials | Lithium 101 | Direct Lithium Extraction (DLE)

- Companies turn towards direct lithium extraction due to difficulties accessing hard rock minerals and the time/water intensity of brines

- DLE *should* be:
  - less impactful to the environment (less water intensive)
  - lower carbon production
  - lower water consumption
  - powered by renewable energy (although technically brines do this)
  - Reduce time spent getting a mine/refinery up and running
  - 70-80% efficient in terms of conversion

- **>90% lithium recovery**
- **>99% impurity removal**
- **200-100x lithium concentration factor**



RAW LITHIUM BRINE
Up to 86 mg/L lithium in the brine

1 Lithium ions are absorbed selectively to solid chemicals highly selective for lithium (acts like a chemical filter).

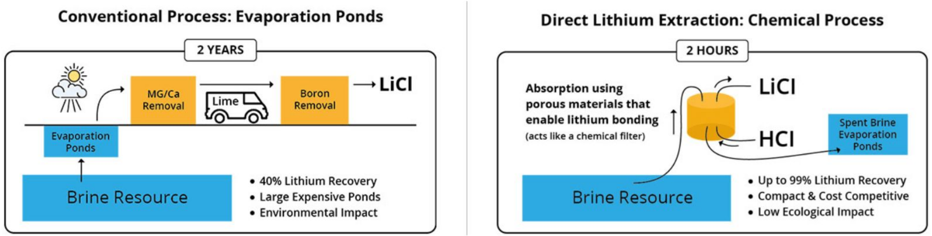
2 Brine without lithium leaves the system for injection back into the reservoir.

3 Stripping fluid removes the lithium ions to produce a high grade, high purity concentrate.

UP TO 99% LITHIUM RECOVERY

LITHIUM VOID BRINE

LITHIUM CONCENTRATE



Conventional Process: Evaporation Ponds

2 YEARS

- 40% Lithium Recovery
- Large Expensive Ponds
- Environmental Impact

Direct Lithium Extraction: Chemical Process

2 HOURS

Absorption using porous materials that enable lithium bonding (acts like a chemical filter)

- Up to 99% Lithium Recovery
- Compact & Cost Competitive
- Low Ecological Impact

Source: Battery Talk: Lithium in Batteries Part 1, Battery Talk: Lithium in Batteries Part 2, Battery Talk: Lithium in Batteries Part 3

Raw Materials | Lithium | Innovations In Extraction

Direct Lithium Extraction

Various processes for lithium extraction (DLE) encompass:

1. Adsorption (Sorption): Employing sorbents to selectively cling to lithium, this technique eliminates unwanted ions through a washing procedure.
Companies: *SunResin, IBM, Summit Nanotech, Vulcan Energy, Koch Technical*

2. Ion Exchange: Through a physicochemical process, ionic contaminants are separated as undesired ions are substituted with ions of similar electrical charge. The ion-exchange material acts as a selective sieve, permitting only lithium (and hydrogen) ions to traverse.
Companies: *Lilac Solutions*

3. Solvent Extraction: Using organic solutions containing solvent and extractant, lithium is extracted from brines, undergoing a transformation into LiCl (or ions) through chemical or physical means.
Companies: *Solvay, Adionics*

4. Membrane Separation: Employing membrane technologies like nanofiltration and reverse osmosis, this approach selectively removes hardness (Mg, Ca) and recovers lithium.
Companies: *EnergyX*

5. Electrochemical Separation: Utilizing electrochemical cells, this method directly converts LiCl to LiOH or Li2CO3, bypassing intermediates such as calcium hydroxide. Presently in its early stages, it has not yet reached commercialization.

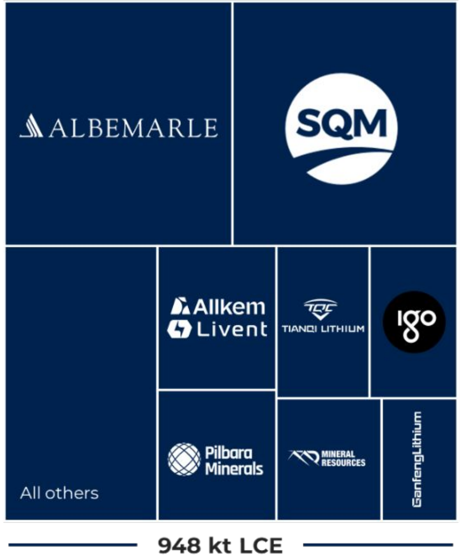
Characteristics	Hard rock	Brine	
	Mining	Evaporation	DLE
Production times (extraction to production)	Weeks to months	Months to years	Hours to days
Lithium recovery rates	~60-80% (processing)	~ 40-60%	~ 70-90%+
Capex cost	Vary with grade	~US$23-34,000/tpa LCE	~US$26-34,000/tpa LCE
Opex cost		~US$3,300-4,900/tpa LCE	~US$3,300-4,900/tpa LCE
Lithium product	Spodumene (~5-6% Li_2O)	Lithium carbonate (Li_2CO_3), Lithium Chloride (LiCl) Lithium hydroxide (LiOH)	Lithium carbonate (Li_2CO_3), Lithium Chloride (LiCl) Lithium hydroxide (LiOH)
Process	Heating, cooling, crushing & roasting	Atmospheric evaporation, plant processing	Different process like adsorption, ion exchange, solvent extraction, membrane separation, electrochemical separation
Water consumption	High	High	Low-Medium
Energy consumption	High	Low (solar evaporation)	Medium
Emissions	High	Low	Low

Source: Goldman Sachs report

Raw Materials | Lithium | Landscape In 2023

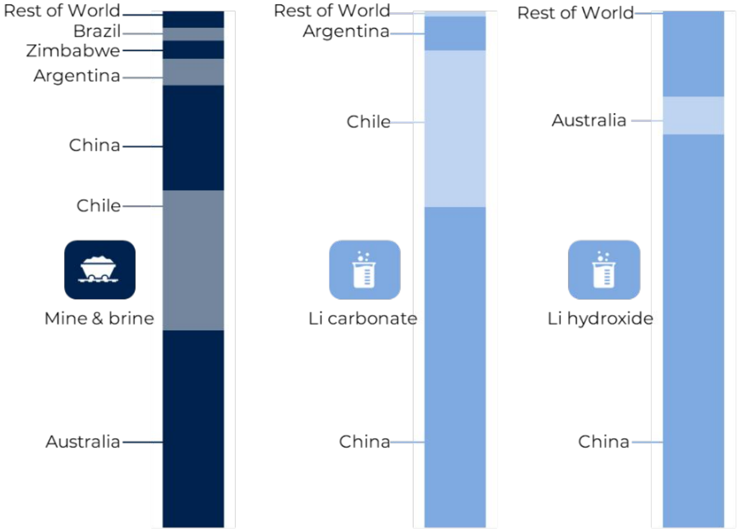
Supply is surging from new producers in China, Zimbabwe, Brazil

Top lithium miners in 2023



Top lithium refiners in 2023

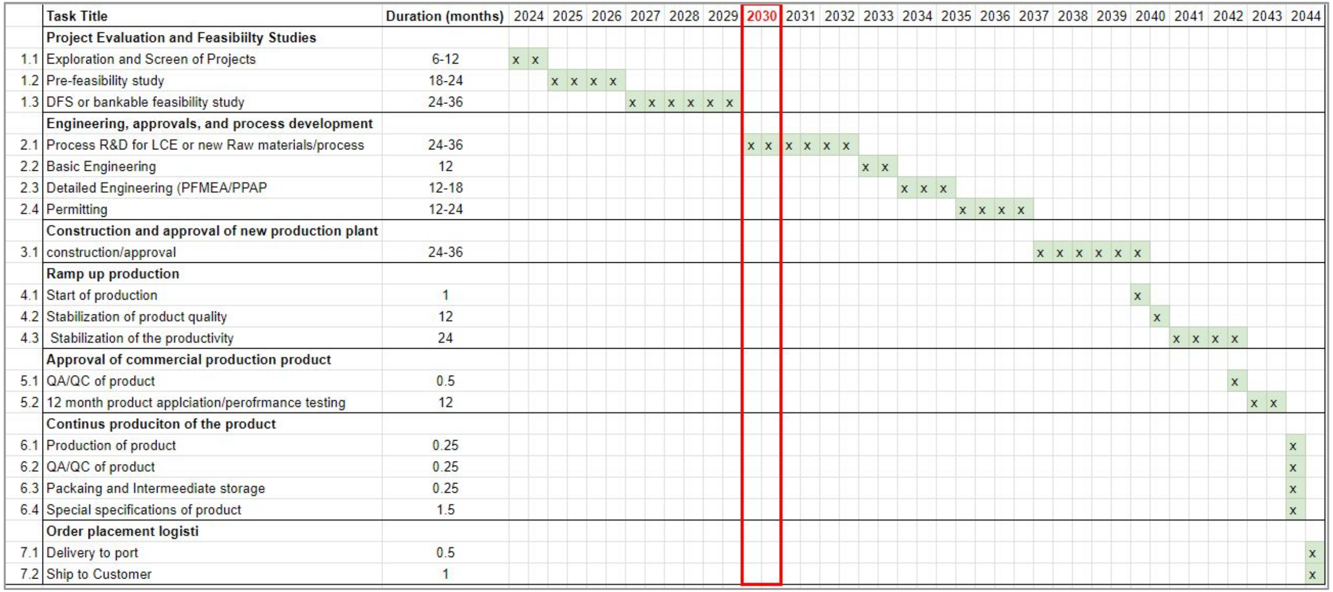
Top lithium producing countries in 2023, kt LCE



Source: CRU Group

Raw Materials | **Lithium** | Mining: Time To Market

Time model of starting a new mining/refining plant at the beginning of 2024



	Task Title	Duration (months)	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044
	Project Evaluation and Feasibiilty Studies																						
1.1	Exploration and Screen of Projects	6-12	x x																				
1.2	Pre-feasibility study	18-24		x x	x x																		
1.3	DFS or bankable feasibility study	24-36				x x	x x	x x															
	Engineering, approvals, and process development																						
2.1	Process R&D for LCE or new Raw materials/process	24-36							x x	x x	x x												
2.2	Basic Engineering	12										x x											
2.3	Detailed Engineering (PFMEA/PPAP	12-18											x x	x									
2.4	Permitting	12-24												x	x x	x							
	Construction and approval of new production plant																						
3.1	construction/approval	24-36														x	x x	x x	x				
	Ramp up production																						
4.1	Start of production	1																	x				
4.2	Stabilization of product quality	12																	x				
4.3	Stabilization of the productivity	24																		x x	x x		
	Approval of commercial production product																						
5.1	QA/QC of product	0.5																			x		
5.2	12 month product applciation/perofrmance testing	12																				x x	
	Continus produciton of the product																						
6.1	Production of product	0.25																					x
6.2	QA/QC of product	0.25																					x
6.3	Packaing and Intermeediate storage	0.25																					x
6.4	Special specifications of product	1.5																					x
	Order placement logisti																						
7.1	Delivery to port	0.5																					x
7.2	Ship to Customer	1																					x

Starting a mine today to meet 2030 CAGR demand of batteries is time prohibitive, given all the steps needed to bring on a site and qualify a new material.

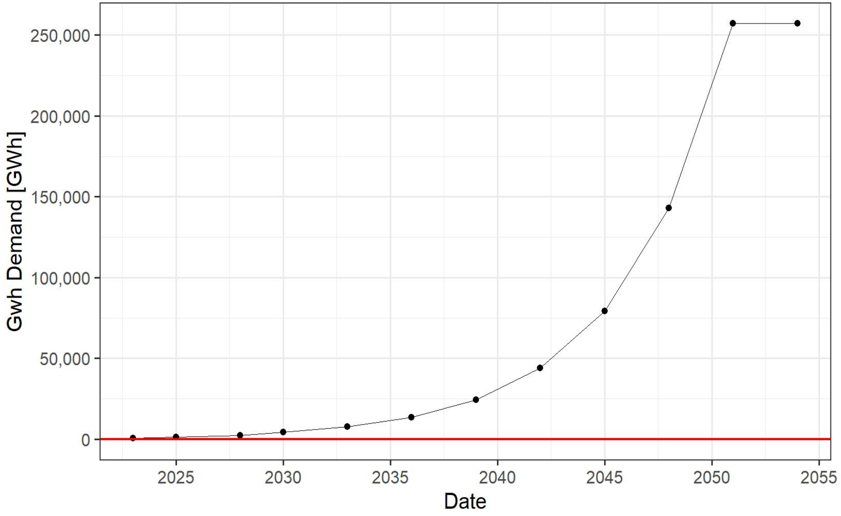
Worst case is 31 years to start a new mine from scratch; 16 years at best, unless new technologies such as Direct Lithium Extraction (DLE) come to fruition in the near future.

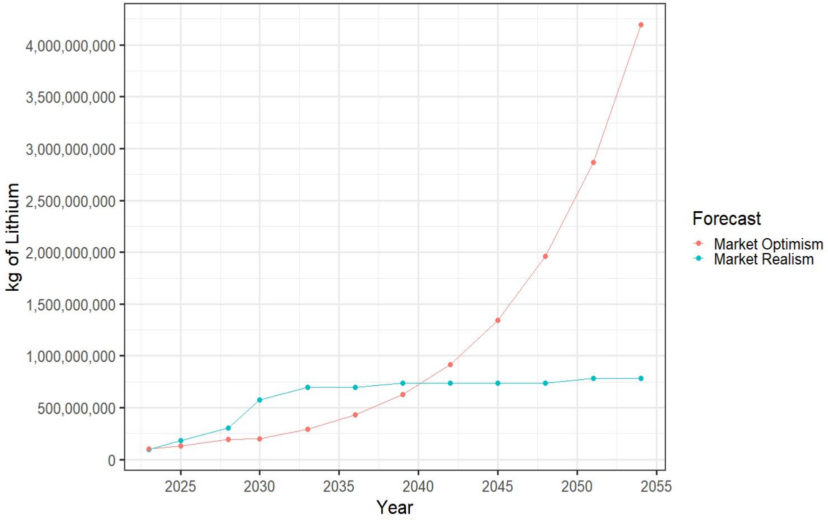
DLE would expand existing production of many brines while also allowing for quicker onboarding of new brines.

Source: Battery Talk: Lithium in Batteries Part 1, Battery Talk: Lithium in Batteries Part 2, Battery Talk: Lithium in Batteries Part 3

Raw Materials | Lithium | Market Growth

Lithium market realism vs optimism modeled Annual Growth Rate comparisons





Market Optimism

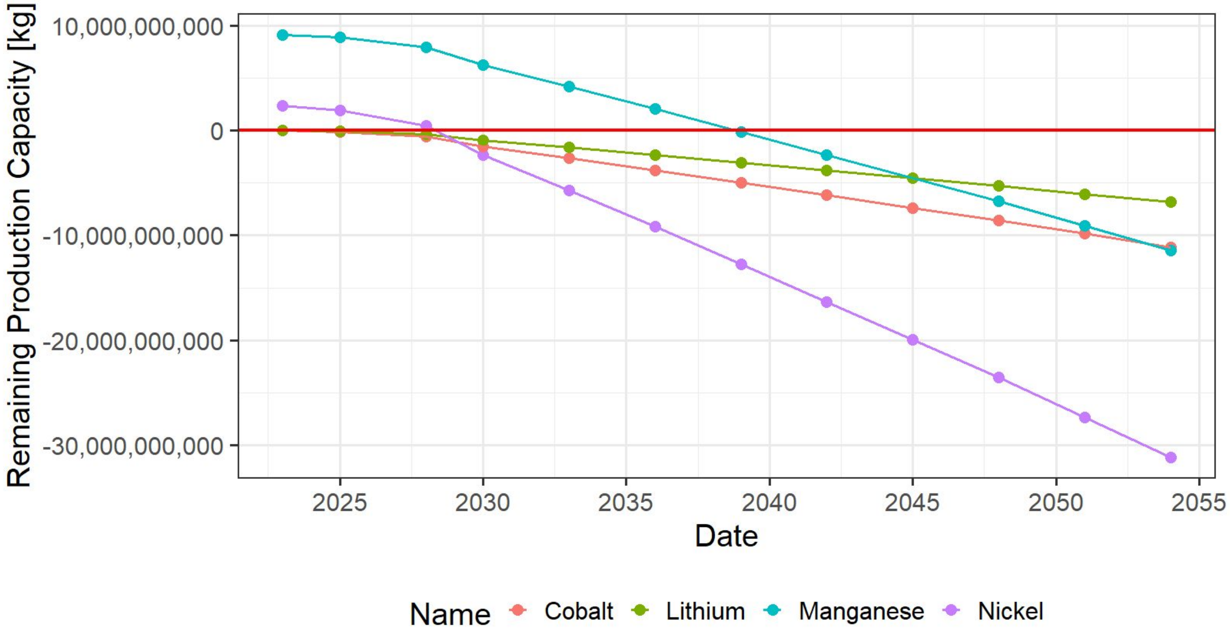
Market Realism

20.5% AGR Li (still Optimistic)
10% AGR Co (46% Congo)
5.1% AGR Ni
6.4% AGR Mn

Source: Battery Talk: Lithium in Batteries Part 1, Battery Talk: Lithium in Batteries Part 2, Battery Talk: Lithium in Batteries Part 3

Raw Materials | **Lithium Metal** | Market Growth

Lithium production data vs. market optimism for demand



Keeping up with expected CAGR of projected battery demand projected requires lithium operations to either launch several new projects by 2028 or companies need to dial back on scale.

Until recently, much of the recent annual production increases for lithium revolved around increasing output of existing mines rather than new sources.

VF | VOLTA FOUNDATION

Source: Battery Talk: Lithium in Batteries Part 1, Battery Talk: Lithium in Batteries Part 2, Battery Talk: Lithium in Batteries Part 3

Raw Materials

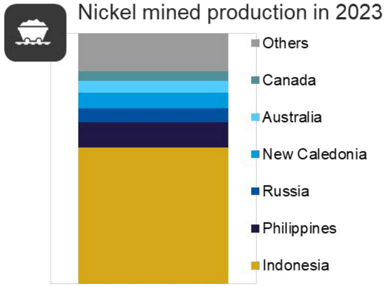
Raw Materials

| Nickel | Cost Vs. ESG Challenge

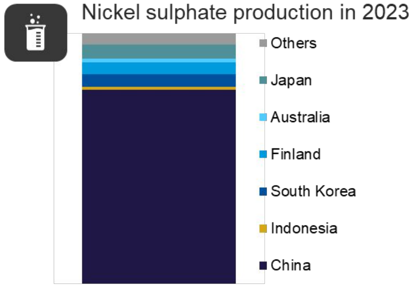
Indonesia produces the lowest cost nickel for batteries:

Nickel production, kt, versus cash costs, $/t, in 2025

NOTE: Extreme outliers have been removed from the nickel cost curve.



Nickel mined production in 2023



Nickel sulphate production in 2023

...but operations are linked to high carbon emissions, tailings, and deforestation:

Nickel miners linked to devastation of Indonesian forests

Vale (Blok Soroako) deforestation

Bintang Delapan deforestation

Sources: Mighty Earth, Planet Labs

Foreign investment in Indonesia battery-grade nickel operations, as of 2023

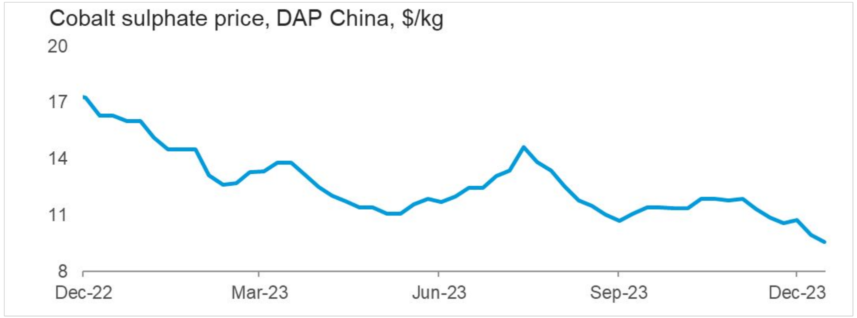
力勤资源 LYGEND RESOURCES
HUAYOU
GEM
青山控股 TSINGSHAN
CATL
EVE
CMOC

VALE
Ford
posco
EcoPro
LG Energy Solution
LX

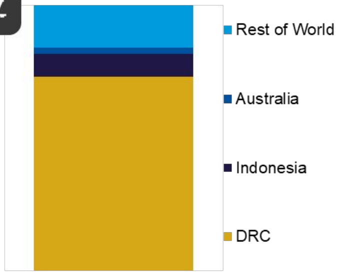
Source: CRU Group, Financial Times

Raw Materials | Cobalt | Market Surplus

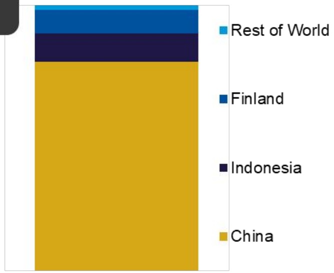
Cobalt market encountered record low prices


Cobalt sulphate price, DAP China, $/kg

Cobalt mined production in 2023



Cobalt chemical production in 2023



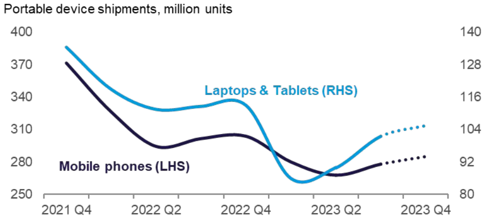
Large surplus driven by project ramp-ups:

Almost all Co is mined as a byproduct of Ni and Cu. As such, miners are not deterred by low Co prices and are expected to continue production as long as Ni and Cu markets incentivize production.

Cobalt is being thrifted and substituted:

Rise of Co-free LFP and increasingly high-nickel NMC chemistries are softening demand for Co in batteries.

Portable electronics market suffered waning demand; relies heavily on Co-rich LCO batteries:



Source: CRU Group

Raw Materials

Manganese Due For Great Influx Of Demand In Batteries

China dominates high purity Mn processing, and produces the cheapest product[1]

Mn chemicals used to make Li-ion and Na-ion CAM[2]:

Manganese sulphate
- for NMC, NMCA, LMFP, future LNMO, LMR

Manganese carbonate
- for LMFP and layered-oxide Na-ion

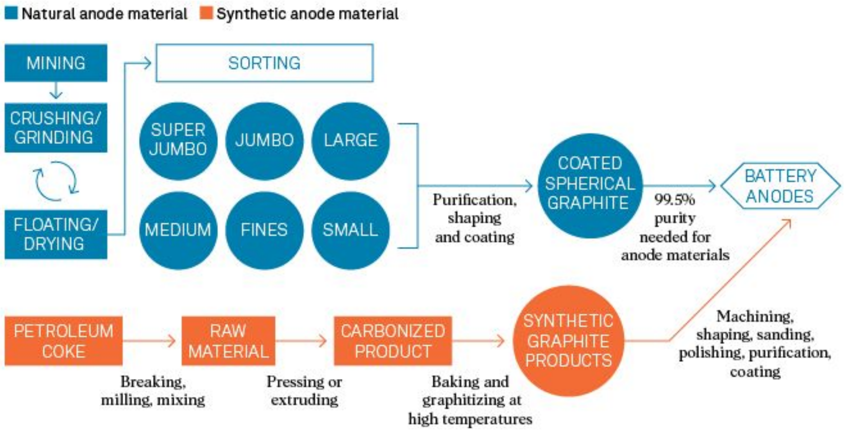
Manganese tretroxide
- for LMFP and layered-oxide Na-ion

Source: [1] Manganese Metals Company, [2] CRU Group

Raw Materials | **Graphite 101**

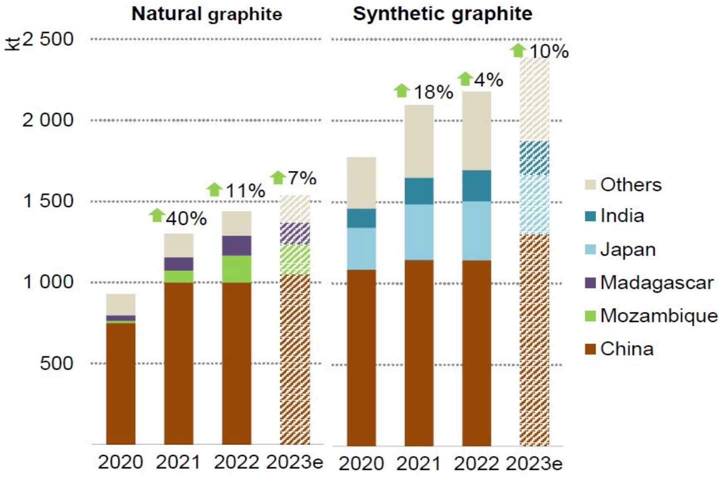
Natural vs. synthetic graphite

Natural graphite is mined from the earth
Synthetic graphite is derived from petroleum coke



Rules of thumb:
~0.45 kt of natural graphite consumed per kt of anode
~1 kt of synthetic graphite precursor consumed per kt of anode
~1.2 kt of graphite anode material per GWh of battery capacity

- Natural graphite is cheaper and much less carbon intensive to produce.
- Synthetic graphite is favored for its higher purity and predictable performance, and benefits of faster charging and longer cycle life. It also takes less time to build a synthetic graphite plant vs. bring a mine to production.

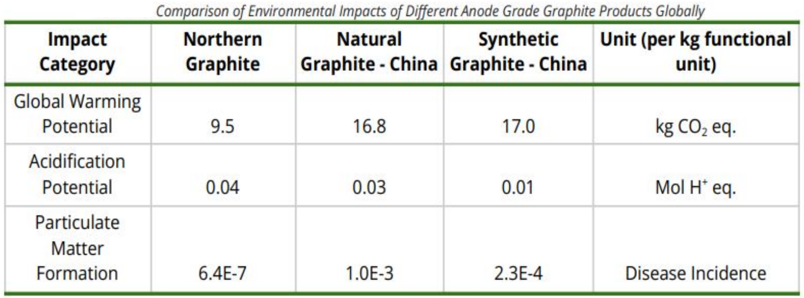


Source: S&P/Battery Materials Review, IEA, Nouveau Monde Graphite

Synthetic is the most commonly used graphite, but carbon intensity is a challenge

The high costs associated with synthetic graphite stem from its graphitization process, which requires prolonged high temperature heating to remove impurities.

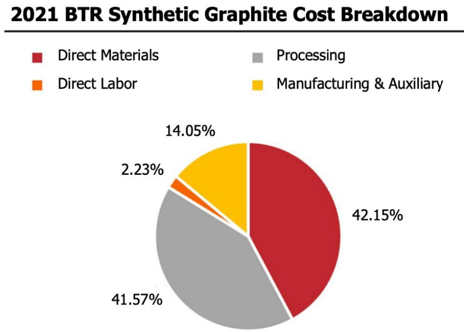
Production location plays a role in carbon intensity depending on energy source used

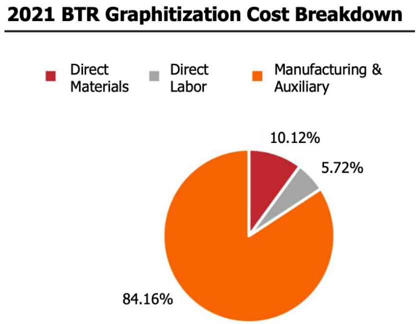


Comparison of Environmental Impacts of Different Anode Grade Graphite Products Globally

Impact Category	Northern Graphite	Natural Graphite - China	Synthetic Graphite - China	Unit (per kg functional unit)
Global Warming Potential	9.5	16.8	17.0	kg CO_2 eq.
Acidification Potential	0.04	0.03	0.01	Mol H^+ eq.
Particulate Matter Formation	6.4E-7	1.0E-3	2.3E-4	Disease Incidence

Electricity prices have large impact on manufacturing costs

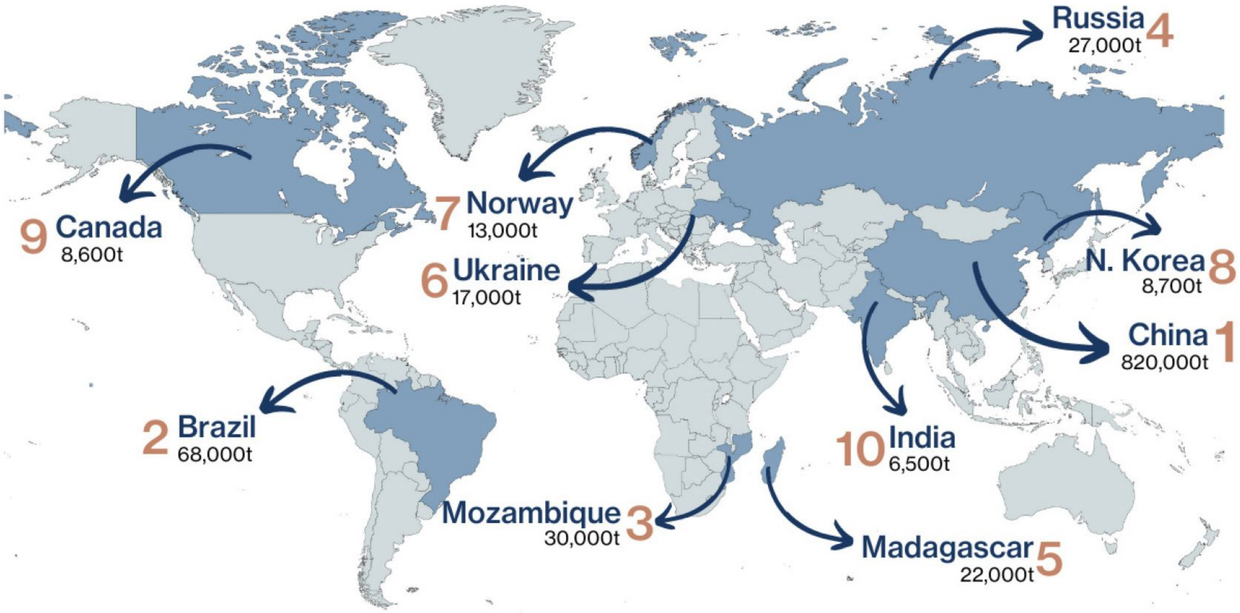




Source: Minviro for Northern Graphite, East Asia Qinghai Securities Co., Ltd.

Raw Materials | **Graphite** | Natural

Top producers of natural flake graphite production (tons)



China dominates natural flake graphite production and processing and holds a 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.

Source: Hague Centre for Strategic Studies

Developing Ex-China Graphite Projects

Chinese dominance is fueling search for alternative sources

Graphite anode active material facility plans (non-exhaustive)

	Manufacturer	Anode type	Country	Capacity plan	Integrated mine
SYRAH RESOURCES	**Syrah Resources**	Natural	USA	45 kt/y	Mozambique
MITSUBISHI CHEMICAL	**Mitsubishi Chemical**	BOTH	USA	10 kt/y	No
WESTWATER RESOURCES	**Westwater**	Natural	USA	40 kt/y	USA
NMG NOUVEAU MONDE GRAPHITE	**Nouveau Monde Graphite**	Natural	Canada	43 kt/y	Canada
RESONAC	**Resonac (Hitachi C.)**	BOTH	Japan	20 kt/y	No
talga	**Talga**	Natural	Sweden	20 kt/y	Sweden
Vianode	**Vianode**	Synthetic	Norway	1.5 kt/y	n/a
sgl carbon	**SGL Carbon**	Synthetic	Poland	Unknown	n/a
ANOVION	**Anovion**	Synthetic	USA	35 kt/y	n/a
NOVONIX	**NOVONIX**	Synthetic	USA	50 kt/y	n/a
posco	**POSCO**	Both	South Korea	90 kt/y	No
epsilon ADVANCED MATERIALS	**Epsilon Materials**	Both	USA	50 kt/y	No
SUPERIOR GRAPHITE	**Superior Graphite**	Both	USA	24 kt/y	No

In December 2023, China imposed further controls on graphite exports, prompting renewed interest in ex-China sources (More details in **Policy section**).

Financing and permitting is a major challenge for ex-China producers.

Combined plans amount to only ~6% of global capacity.

Source: company announcements

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

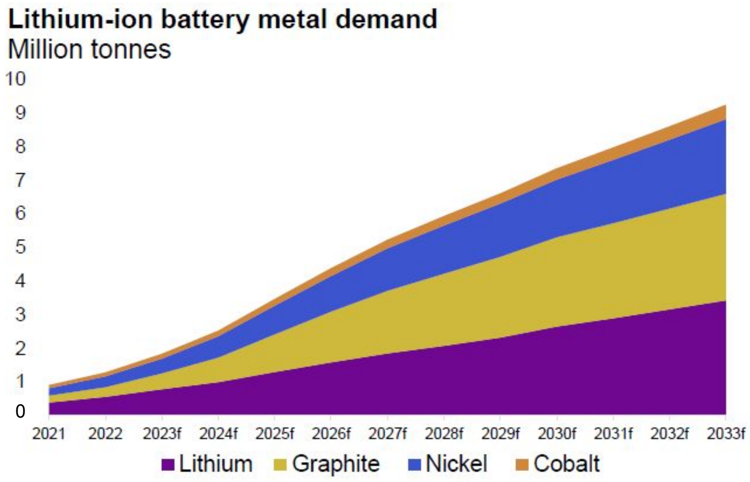
Recycling

Software & Analytics

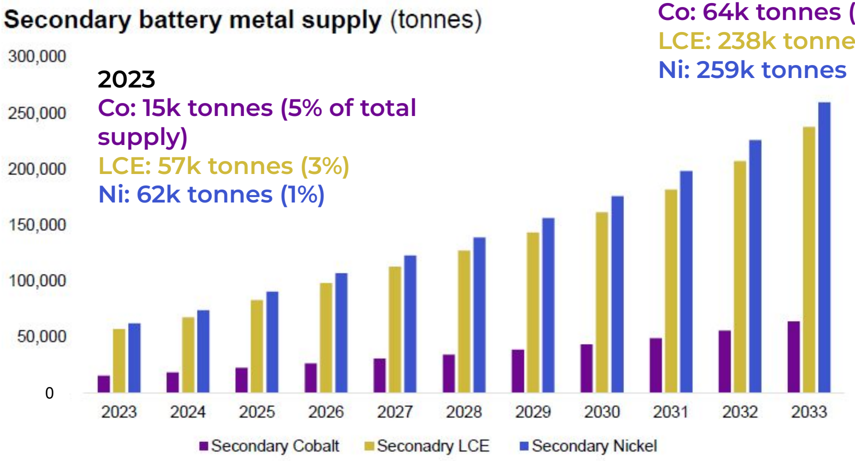
Recycling | **Market** | Secondary Metal Supply & Demand Forecast

Demand for lithium batteries expected to increase 5 fold by 2033 at 15% CAGR, which will translate to demand for battery metals.

The surge in electrification and cell production is set to escalate demand for battery metals. In the short-term, recycling can help to meet a part of this demand, providing marginal security of supply for regions with low primary metal production. Over the long term, recycling is going to play a key role in meeting market demand.



Source: Fastmarkets battery recycling and black mass outlook



2023
Co: 15k tonnes (5% of total supply)
LCE: 57k tonnes (3%)
Ni: 62k tonnes (1%)

2033
Co: 64k tonnes (12%)
LCE: 238k tonnes (6%)
Ni: 259k tonnes (5%)

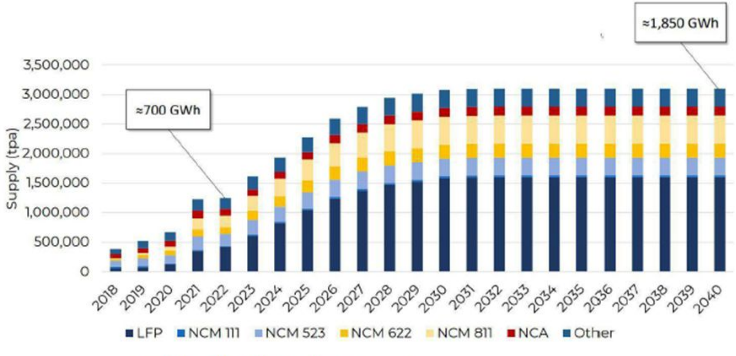
Source: Fastmarkets battery recycling and black mass outlook

Source: Fastmarkets Battery Recycling Forecast. Battery Raw Materials Global Outlook Webinar - November 2023, EU recycling market study Strategy& | PEM of RWTH Aachen University

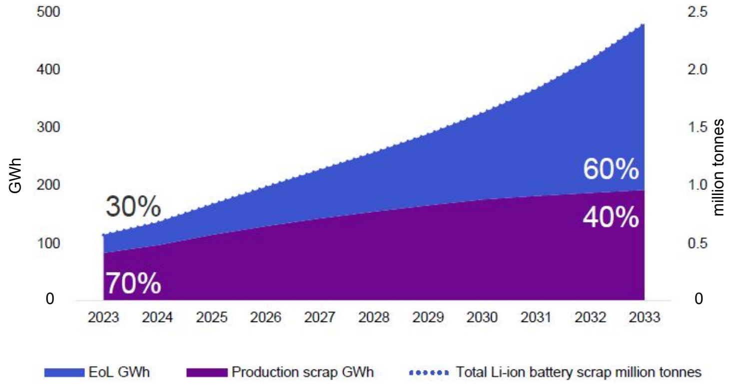
Recycling | Market | Battery Chemistry Forecast & Recycling Feedstock

By 2040, battery recycling market in Europe will be up ten-fold vs. 2030 –driven by gigafactory scrap initially, EoL batteries to ramp up from 2030+

Recycling addresses scarcity of raw materials and provides security of supply for regions with low primary metal production.



Source: Benchmark Mineral Intelligence 2022 | Q2 2022 Forecast



- Dominant battery chemistry in industry has significant implications for recycling feedstock
- Feedstock expected to shift from NCM to LFP with growing popularity, with LFP comprising more than 50% of feedstock supply by 2030.

- As the first wave of EVs reach end of life in 2030, recycling market is expected to grow substantially.
- 110GWh (≈ 5.5 million tonnes) of total battery scrap in 2023 and 480GWh (≈ 2.400 million tonnes) by 2033

Source: Benchmark Minerals, Fastmarkets Battery Recycling Forecast. Battery Raw Materials Global Outlook Webinar - November 2023, : EU recycling market study Strategy& | PEM of RWTH Aachen University

Recycling | Market | Regulatory Drivers

The European Commission's legislative minimum threshold targets encourages recycling. The US still has no obligation in place mandating battery recycling or recovery rates. However, China and Korea have advanced battery recycling regulations and efficiency mandates.

Asia leads way in regulation
With **initial regulations since 2013,** South Korea and China are leading the way in battery recycling. **Current battery recycling rates are ~90%.**

EU revised its legislation
The EU Battery Directive, stipulating **recycling rates of 55% since 2006**, required a new framework as the 2006 legislation was focused on consumer electronic batteries. With the **Battery Regulation 2023**, the EU set a relevant **milestone for an EU closed-loop battery value chain.**

Clear targets enabling a closed loop
With the **EU legislation taking effect in 2023**, it sets recycling efficiencies and rates for each critical material and defines a minimum target for use of recycled material for cell production.

Advanced battery recycling regulation and efficiency

- Since 2013, South Korea has established recycling rates of about 90% for batteries
- China has a battery recycling rate of ~90%, recycling rates for materials of lesser importance such as Mn above 85%, as well as regulations for wastewater handling

New regulatory environment for battery recycling adopted in August 2023

- Europe revised its Battery Directive from 2006 to expand the legislation to include EV batteries and to regulate the entire battery life cycle
- The updated regulatory framework introduces end-of-life requirements such as collection and recovery targets, as well as extended producer responsibility
- Revised EU Regulation sets recycling efficiencies of 70% from 2031 onwards and over 100% increase in recovery targets & minimum level of recycled material use by 2035

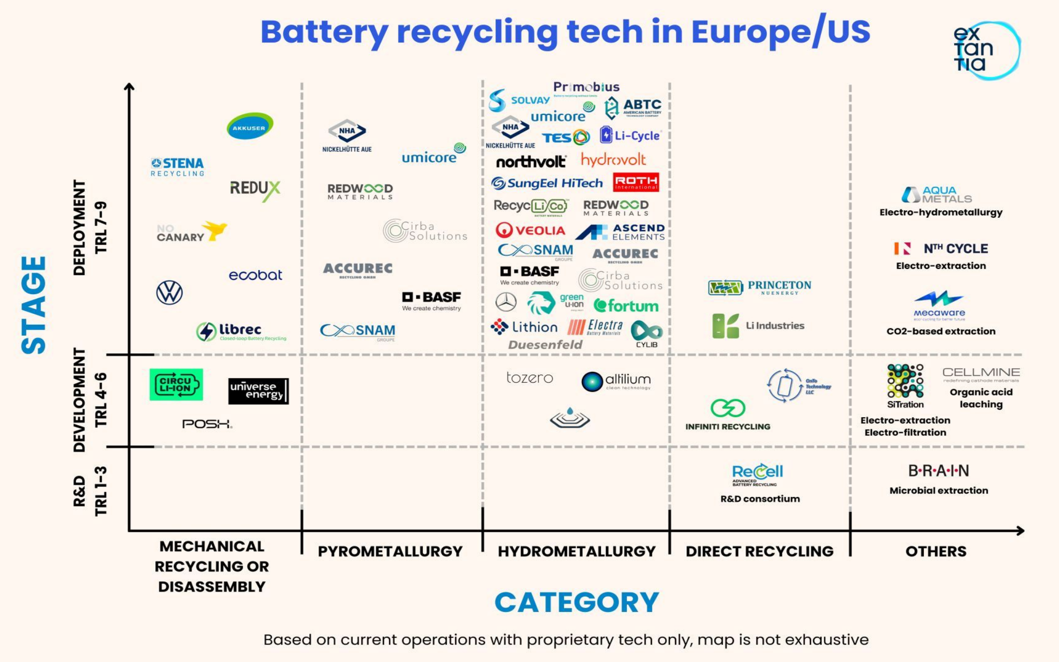
USA still has no general obligation in place for battery recycling

- Research projects, DOE's LiB Recycling Prize, and programs like "Call2Recycle" all exist to advance the battery recycling ecosystem
- The Critical Minerals and Materials Program indirectly impacts battery recycling by classifying materials for clean technology as critical

Source: EU recycling market study Strategy& | PEM of RWTH Aachen University

Recycling | Key Players | Landscape

Hydrometallurgy process gains most traction in the industry.



Based on current operations with proprietary tech only, map is not exhaustive

Pyrometallurgy

Pyrometallurgy was the 1st generation of recycling processes, but requires significant re-processing.

Key benefits: Lower waste generation, Production cost
Key challenges: High energy usage, capital cost, lower lithium recovery

Hydrometallurgy

Hydrometallurgy and direct recycling have higher probability of preserving material quality (structure, coatings, morphology), but require more capex investment to scale up.

Key benefits: Lower waste generation, energy consumption, and, modular capital cost structure
Key challenges: Feedstock consistency requirement and can be more expensive than Pyro for small scale

Direct recycling

Direct Cathode Recycling is in earlier stages of development and commercialization, but is of highest value for manufacturers.

Key benefits: Lower waste generation, energy consumption, higher recovery rates
Key challenges: Higher production cost and not commercially proven yet

Source: Max Werny, et al., Shruti Suriyakumar, et. al.

Recycling | Key Partnerships | Gigafactories And Their Recycling Partners

America

Battery Manufacturer	Battery Recycling Partner/ Plan
Panasonic ENERGY	REDWOOD MATERIALS
Envision AESC	
TOYOTA	
KOREPOWER	RENEWANCE STEWARDSHIP OPERATIONALIZED
SK innovation	ASCEND ELEMENTS
C4V	RecycLiCo™ BATTERY MATERIALS
Factorial	영풍 YOUNG POONG
LG Energy Solution	Li-Cycle®
ultium cells	
EVE	
TOYOTA	Cirba Solutions
HONDA	

Europe

Battery Manufacturer	Battery Recycling Partner/ Plan
ACC AUTOMOTIVE CELLS Co	umicore
PowerCo	
EVE	Li-Cycle®
MORROW	
ITALVOLT	AMERICAN MANGANESE INC.
InoBat	GIGAMINE™
SVOLT	BASF We create chemistry
CELLFORCE	
CATL	
ProLogium	elemental strategic metals
FREYR	STENA
northvolt	hydrovolt
ABB	REVOLT

Source: Li-Cycle Investor Presentation November 2023, ABB

Recycling | Investments

Technology start-ups and incumbents are racing to make recycling electric-vehicle batteries cleaner and more economical, with investors pouring billions of dollars into recycling facilities globally

Company	Investments Planned (in $Millions)	Remarks
REDWOOD MATERIALS	$1000	**Redwood** Materials raises over $1 billion to focus on collection of end-of-life batteries, increasing refining capability. Redwood receives conditional commitment for $2B Department of Energy loan for battery materials with recycled content
ASCEND ELEMENTS	$542	**Ascend Elements** (previously Battery Resourcers) raises $542 million to build North America's first cathode precursor (pCAM) facility, utilizing recycled material, on a 140-acre site in Hopkinsville, Kentucky
Li-Cycle	$375	**Li-Cycle** receives conditional commitment for $375 million loan from the U.S. Department of Energy ATVM Program
Cirba® Solutions	$282	**Cirba Solutions** & U.S. Department of Energy to expand Lithium-Ion Battery recycling operations in Ohio. The more than $200 million expansion is aided in part by an over $82 million Department of Energy (DOE) grant
AQUA METALS	$5	**Aqua Metals** and Yulho (a South Korean storage solution and battery materials company) form a strategic partnership. Yulho invests $5 million in Aqua Metals, and Aqua Metals grants Yulho a license to deploy Aqua Metals' AquaRefining technology in Asia and Europe
ABTC AMERICAN BATTERY TECHNOLOGY COMPANY	$60	ABTC receives $10 million DOE grant for the development of new lithium-ion battery recycling technologies. **ABTC** also secured up to $50 million investment to support commercial-scale battery material construction projects including Lithium-Ion battery recycling

Source: Li-Cycle Investor Presentation November 2023

Recycling | Investments

Technology start-ups and incumbents are racing to make recycling electric-vehicle batteries cleaner and more economical, with investors pouring billions of dollars into recycling facilities globally

Company	Investments Planned (in $Millions)	Remarks
Electra	$21.5	**Electra** closes private placements for gross proceeds of $21.5 million to advance its black mass recycling strategy and capabilities, and construction of its battery grade cobalt sulfate refinery in Canada
NTH CYCLE	$44	**Nth Cycle** closes $44 million in Series B and non-dilutive financing to scale Clean Critical Metal Refining Technology led by VoLo Earth Ventures, MassMutual, MM Catalyst Fund I, Caterpillar Venture Capital Inc.
mecaware eco-cycling for better future	$4.3	**Mecaware** secures $4.3 million to become the leader in battery recycling and production of strategic metals in France and Europe
PRINCETON NUENERGY	$20	**Princeton** NuEnergy secures $16 million in series A funding to advance Direct Recycling Technology. **Princeton NuEnergy** receives $4.375 million from DOE grant to drive advancements in cathode active materials manufacturing
CNGR 中伟	$2000	**CNGR** Advanced Material Co, is joining forces with African private investment fund Al Mada to build an industrial base in Morocco to develop precursor active materials for NCM batteries, production units for LFP cathodes and recycling facilities for battery materials **CNGR and CRONIMET** join forces to close the loop in battery recycling

Source: Li-Cycle Investor Presentation November 2023

Recycling | 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.

Bargaining Power Of Buyers

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

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

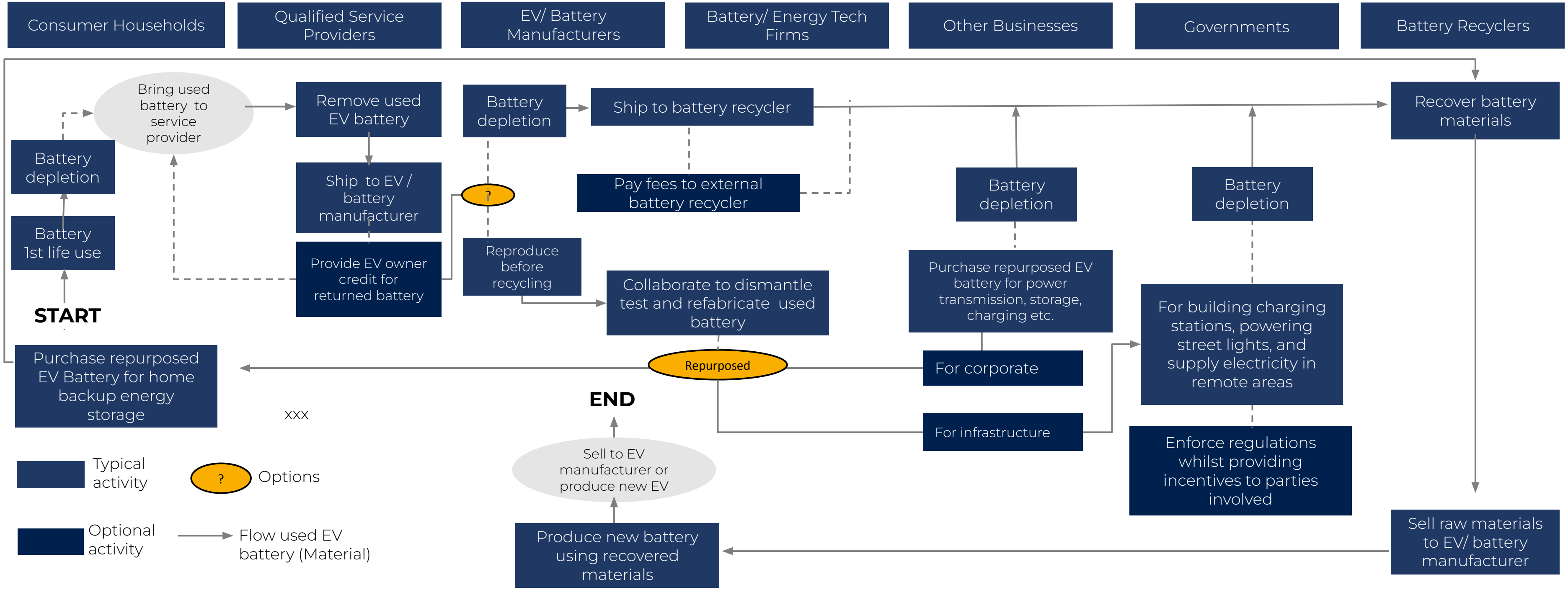
- Second life applications delay the time at which batteries can be recycled.
- Disparate hazardous waste regulations across markets can landfill disposal, especially for battery chemistries that use lower value materials.

Bargaining Power Of 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.

Recycling | **Challenges** | 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.



Consumer Households

Qualified Service Providers

EV/ Battery Manufacturers

Battery/ Energy Tech Firms

Other Businesses

Governments

Battery Recyclers

START

Battery 1st life use

Battery depletion

Bring used battery to service provider

Remove used EV battery

Ship to EV / battery manufacturer

Provide EV owner credit for returned battery

Battery depletion

?

Reproduce before recycling

Ship to battery recycler

Pay fees to external battery recycler

Collaborate to dismantle test and refabricate used battery

Repurposed

Purchase repurposed EV Battery for home backup energy storage

xxx

END

Sell to EV manufacturer or produce new EV

Produce new battery using recovered materials

Battery depletion

Purchase repurposed EV battery for power transmission, storage, charging etc.

For corporate

For infrastructure

Battery depletion

For building charging stations, powering street lights, and supply electricity in remote areas

Enforce regulations whilst providing incentives to parties involved

Recover battery materials

Sell raw materials to EV/ battery manufacturer

▬ Typical activity

? Options

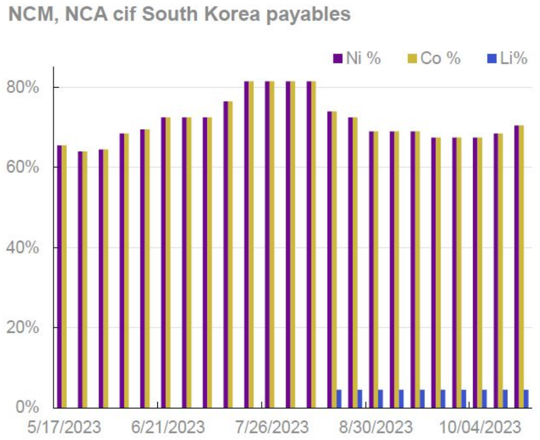
▬ Optional activity

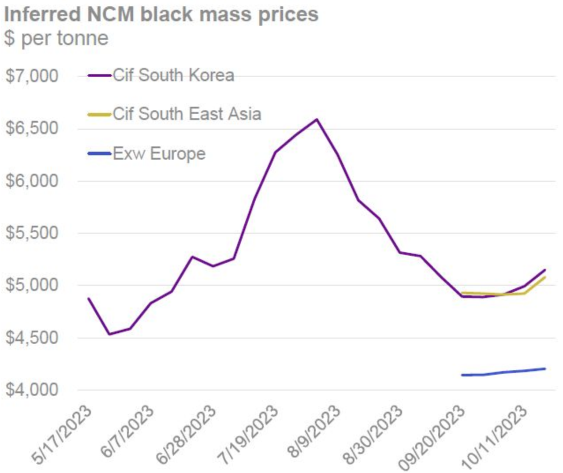
→ Flow used EV battery (Material)

Source: Benchmark Mineral Intelligence

Recycling | **Black Mass** | Payables & Prices

In 2023, about 0.5 million tonnes of black mass was produced globally. This figure is expected to increase up to 1 million tonnes of black mass in 2027. A major hurdle in this market is non-uniform payables and pricing mechanisms across various regions. It is unclear whether recyclers can command a 'green' price premium.





Payable:

Currently, black mass is typically priced based on a % payable of the nickel and cobalt content as there is no other way to determine black mass prices. In South Korea, the weekly payables are approximately 70% for Ni, 70% for Co, and 4.5% for Li.

Prices:

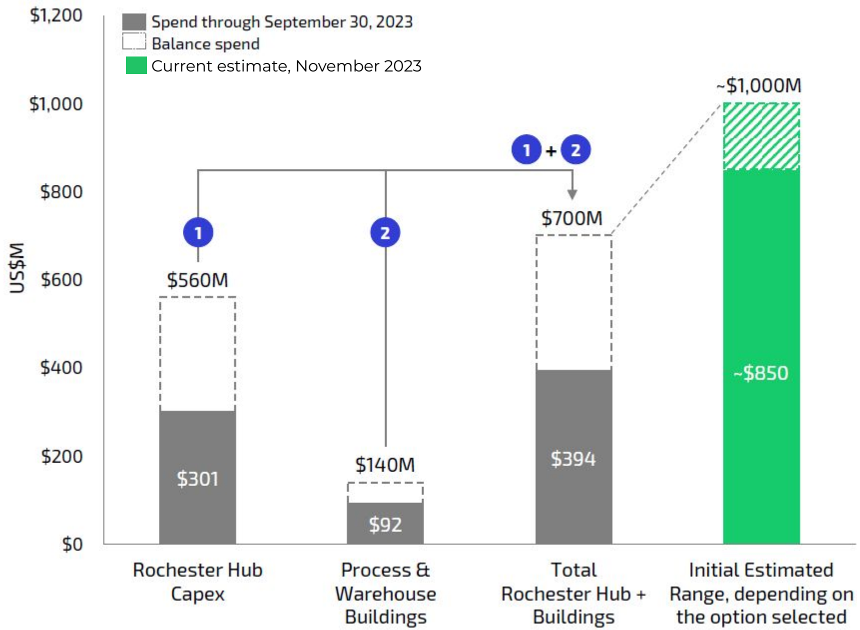
- In Asia, NCM, NCA black mass prices are 20% higher than black mass prices in Europe due to higher recovery rates in Asia.
- Europe black mass market supply is in surplus due to higher pre-processing capacity than refining capacity.
- Prices may also be impacted by black mass impurity %.

Source: Fastmarkets Battery Recycling Forecast. Battery Raw Materials Global Outlook Webinar - November 2023

Recycling | Challenges | CAPEX

Case Study: Li-Cycle Rochester Hub

Estimated Capital Investment



Key Learnings from Rochester Hub Project

- Rochester Hub CAPEX may exceed initial estimates given post-Covid inflation in labor, construction materials and other related areas
- Li-Cycle had to review the project, timeline and its contracting strategy
- Li-Cycle has also modified its process flow sheet to produce mixed hydroxide precipitate (MHP) rather than Ni, Co metal salts. This would help to reduce short-term capex and but would impact revenue as well
- In an effort to reduce OPEX, Li-cycle may look to reduce workforce. To fund its operation, it may also explore additional financing options

Takeaways

- Refining hub projects can often have high Engineering Procurement & Construction (EPC) and labor costs resulting in high CAPEX
- The recycling industry has little clarity and standards around cost structures, payables, feedstock inputs, recycling through-puts, process flows, and recovery rates

Source: Li-Cycle Investor Presentation November 2023

01 Industry | Overview

Notable Events

Industry Value Chain

Finance

Cell Costs

Cell & Pack Manufacturing

Applications

Safety

Chemistry & Cell Components

Raw Materials

Recycling

Software & Analytics

Software & Analytics

Software Solutions Across Battery Lifecycle

Design/ R&D Analytics

example: simulation, predictive modeling, cell design improvement

AIONICS
VOLTAIQ
TWAICE
iW
ionworks powered by PyBaMM
ABOUT:ENERGY
Ansys
MONOLITH
infyos
BATEMO UNDERSTANDING BATTERIES
GT AutoLion Lithium-ion Battery Simulation
ELECTRODER
MINVIRO
N NOBLEAI
Chemix
ENERGSOFT
Julia SIM
Byterat
PyBaMM

Process Control

example: equipment data, MES

ABB
BECKHOFF
camLine elisa company
Honeywell
INFICON
MITSUBISHI ELECTRIC
PDF/SOLUTIONS™
RA Rockwell Automation
SIEMENS
Schneider Electric

Manufacturing Analytics

example: FDC, yield improvement

PDF/SOLUTIONS™
VOLTAIQ
SIEMENS
APPLIED MATERIALS®
AmpLabs
E7
eyelit7 Optimize manufacturing performance

In-field Analytics

example: MES, in-field data

TWAICE
Honeywell
VOLTAIQ
Brill Power
BattGenie.
eatron TECHNOLOGIES
novo™
volytica diagnostics
zitara
ACCURE Battery Intelligence
Coulomb AI

Software & Analytics

| Predictive Battery Analytics Platforms

Cloud-Based Algorithms Overcome BMS Limitations

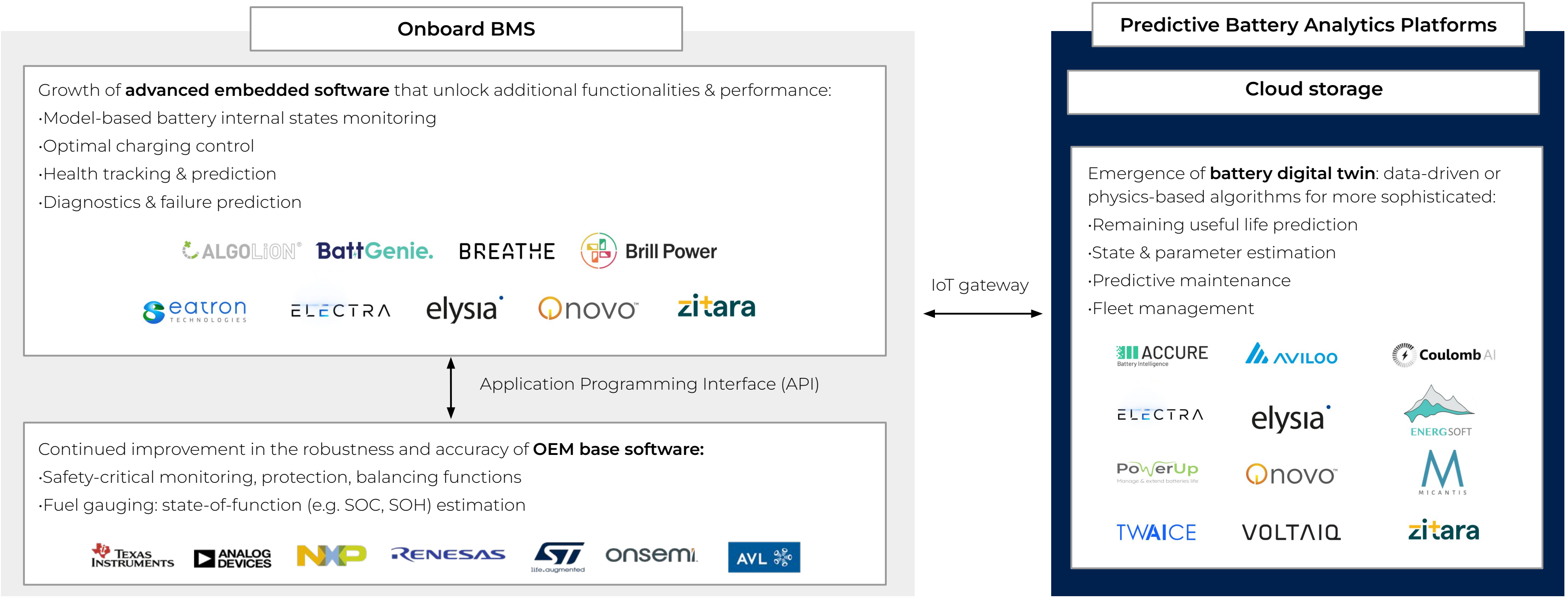
	BMS Limitation	How Cloud-Based Algorithms Overcome BMS Limitations
Short-sighted	Focused on reacting to acute issues, the BMS has limited capacity to learn from other batteries in the system and in the field.	Statistical Anomaly Detection: Cloud analytics can compare data from millions of cells, enabling statistical anomaly detection and trend analysis. This allows for the early identification of deviations from normal behavior, helping prevent potential issues.
Limited Computational Power	Inconsistencies with Aging Model Updates: It may not adapt its algorithms as the battery ages or operates under varying conditions, leading to inaccuracies, Inaccurate SoC and SoH estimation, impacting overall system performance.	Cloud solutions offer scalable computational power. This scalability ensures that data from external systems can be efficiently processed and analyzed, maintaining system reliability and accuracy.
Limited Access to Historical Data	The BMS typically lacks robust historical data analysis capabilities, hindering trend monitoring and long-term performance analysis.	Cloud-based solutions can investigate historical data, identifying long-term trends and potential problems that may not be apparent to a BMS relying on real-time data alone.
Not 100% Fail-Safe	The BMS itself can experience problems. For example, if a BMS doesn't recognize a sensor error, it can result in a battery fault.	Cloud analytics provide continuous monitoring of the BMS and sensor functionality. It can detect BMS malfunctions and sensor issues, preventing potentially significant problems.
Lacks Ability to Foresee Incidents	The BMS cannot predict unexpected incidents, such as incorrect current data due to loose plugs.	Cloud-based platforms leverage advanced forecasting models to predict battery performance more accurately. This enables proactive maintenance and optimization, ensuring the battery system operates efficiently.

Source: https://www.accure.net/battery-knowledge/battery-management-systems-and-predictive-analytics-overview

Software & Analytics

BMS Software

Enhancing safety, cycle life, charge time, and run time via advanced BMS algorithms



Onboard BMS

Growth of **advanced embedded software** that unlock additional functionalities & performance:
- Model-based battery internal states monitoring
- Optimal charging control
- Health tracking & prediction
- Diagnostics & failure prediction

ALGOLiON BattGenie. BREATHE Brill Power
eatron TECHNOLOGIES ELECTRA elysia novo zitara

Application Programming Interface (API)

Continued improvement in the robustness and accuracy of **OEM base software:**
- Safety-critical monitoring, protection, balancing functions
- Fuel gauging: state-of-function (e.g. SOC, SOH) estimation

Texas Instruments Analog Devices NXP Renesas ST life.augmented onsemi AVL

IoT gateway

Predictive Battery Analytics Platforms

Cloud storage

Emergence of **battery digital twin**: data-driven or physics-based algorithms for more sophisticated:
- Remaining useful life prediction
- State & parameter estimation
- Predictive maintenance
- Fleet management

ACCURE Battery Intelligence AVILOO Coulomb AI
ELECTRA elysia ENERGSOFT
PowerUp Manage & extend batteries life novo MICANTIS
TWAICE VOLTAIQ zitara

Source: Concept Review of a Cloud-Based Smart Battery Management System for Lithium-Ion Batteries: Feasibility, Logistics, and Functionality

02 Academia

The Volta Foundation is an independent non-profit professional association dedicated to supporting the growth of the Battery Industry.

02 Academia | Overview

Research Overview

Cathode

Anode

Electrolyte

Machine Learning

Other

02 Academia | Overview

Research Overview

Cathode

Anode

Electrolyte

Machine Learning

Other

Research Overview | Research Trends

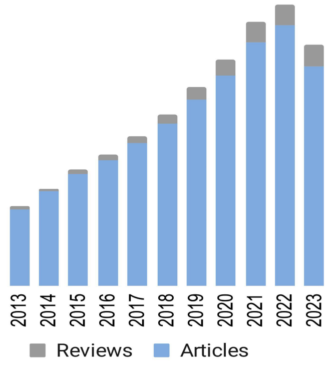
Research publications level off, sodium-ion gains popularity, China maintains lead

Tentative overall easing in research publications for 2023, with reviews making up 8% of volume compared to original research.

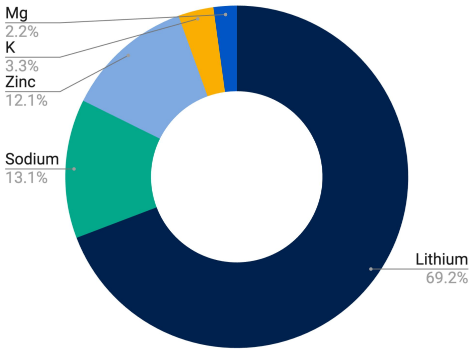
Lithium-ion batteries continue to dominate research attention, although sodium-ion gains ground at 13% of publications.

China maintains sizeable lead in quantity of battery papers published and citation impact (H-index), followed by the USA and India.

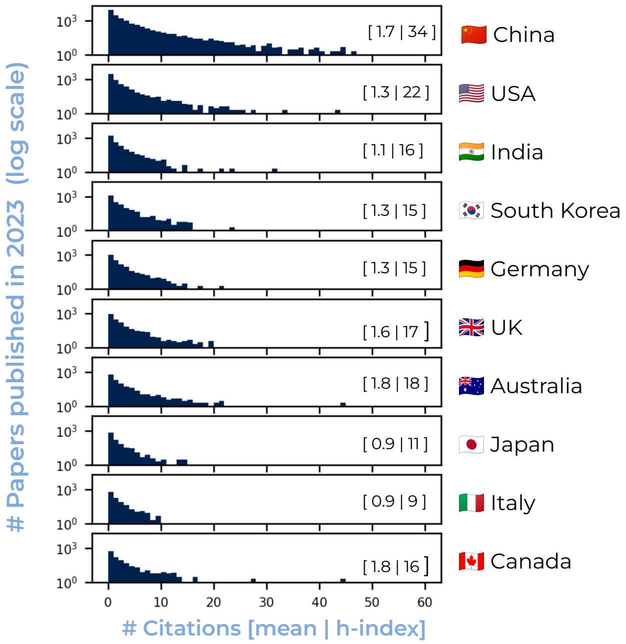
Relative Publication Volumes



Battery Chemistry Focus



2023 Publication vs Citation Leaderboard



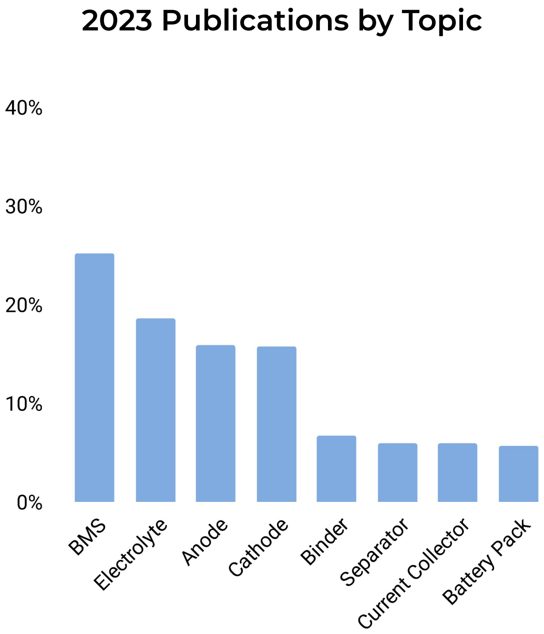
Source: (accessed 2023-12-10): (1) Web of Science Query: "ALL=(battery)" Date: 20XX-01-01 to 20XX-12-31 (2) Web of Science Query: "ALL=(X battery)" Date: 2023-01-01 to 2023-12-31

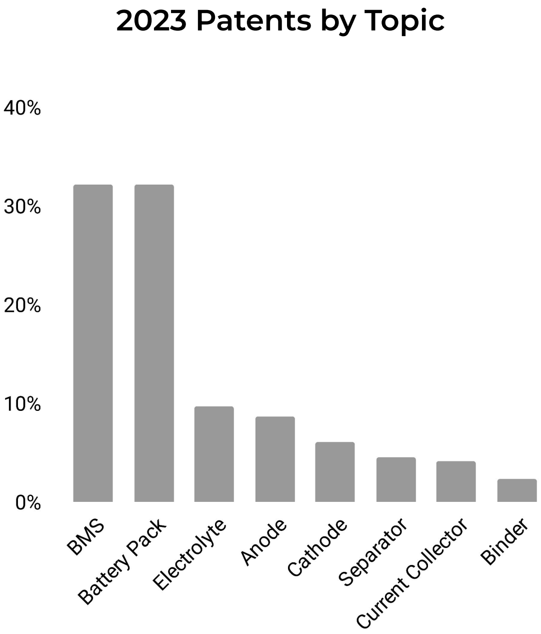
Research Overview | **Publication & Patent Breakdown**

Battery management systems maintain attention of researchers in 2023

Summary:

- Battery management systems and algorithms maintain attention of researchers in 2023.
- Electrolytes overtake electrode materials in publication count. Similar increase for electrolytes observed with industry patents.
- Overall focus in commercial space continues to skew towards system-level innovations for battery pack and management, as observed previously in 2022.



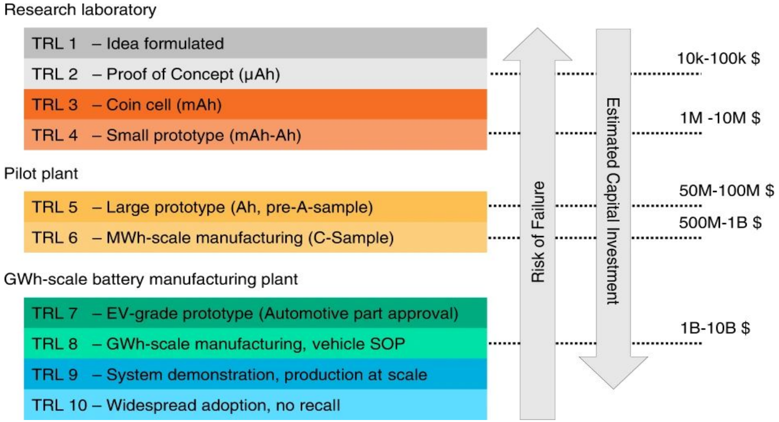


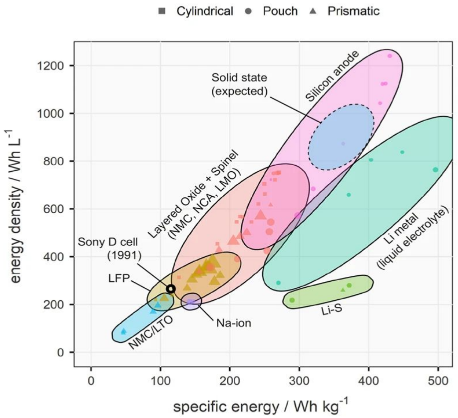
Source: (accessed 2023-12-10): Google Scholar/Patents Query: “X Battery” Date: 2023-01-01 to 2023-12-31

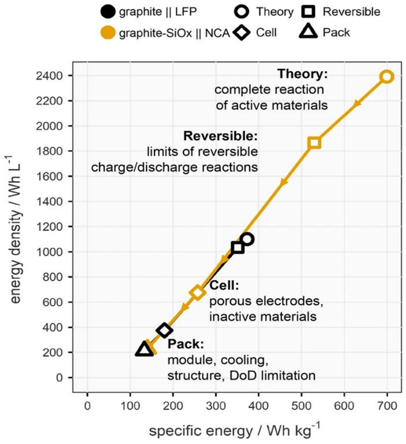
A Non-Academic Perspective On The Future Of Lithium-Based Batteries

A call to action for transparent, adequate, impartial, and exhaustive communication to reduce the gap between academia and industry.

- Collaboration across disciplines, with advisory from industry on customer requirements is needed for academic research to provide large benefits to the battery industry.
- Key Performance Metrics must be considered at multiple system levels. Material level KPI may not translate to the pack level (e.g. pack level LFP and NCA cells have similar pack energy density despite material level differences)
- Battery researchers should be cognizant of practical challenges of material integration into the battery supply chain such as cost considerations, and that performance targets can be achieved with incremental improvements at various levels of the battery system







Source: Frith, J.T., Lacey, M.J. & Ulissi, U.

02 Academia | Overview

Research Overview

Cathode

Anode

Electrolyte

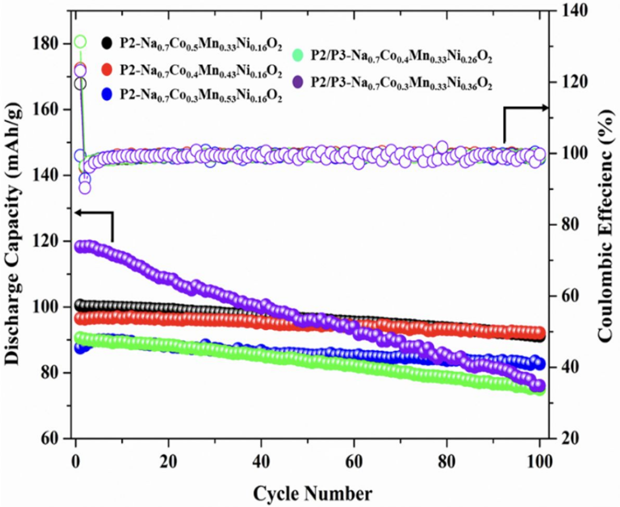
Machine Learning

Other

Cathode | **Controlling Ni And Mn Content In Cathode Materials For Sodium-Ion Batteries**

Effect of Mn/Ni content on the SIB cathode material performance

C. Hakim and coworkers synthesized five variations of the layered oxide $Na_{0.7}Co_xMn_yNi_zO_2$ (x+y+z=1) to investigate the influence of altering transition metal (TM) compositions and reducing cobalt on electrochemical characteristics and performance.



Cycling performance of the different electrode materials at C/10.

An increase in Mn content led to a decrease in initial discharge capacity. However, after 100 cycles, capacity retention exhibited higher values (~94-95% as compared to 90-91% retention in materials with lower Mn and higher Co).

Increased Ni content led to a mixed-phase material (P2 and P3) and showed elevated discharge capacity near 120 mAh/g but reduced rate capability.

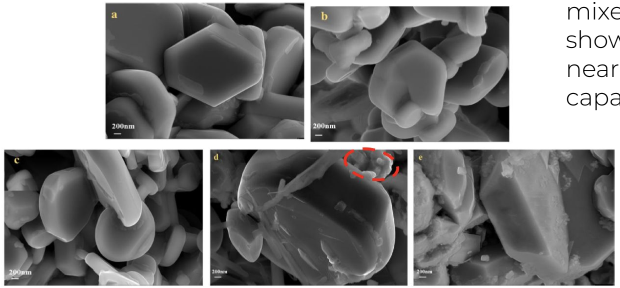


Fig. 2) SEM images of
a) $P2\text{-}Na_{0.7}Co_{0.5}Mn_{0.33}Ni_{0.16}O_2$,
b) $P2\text{-}Na_{0.7}Co_{0.4}Mn_{0.43}Ni_{0.16}O_2$,
c) $P2\text{-}Na_{0.7}Co_{0.3}Mn_{0.53}Ni_{0.16}O_2$,
d) $P2/P3\text{-}Na_{0.7}Co_{0.4}Mn_{0.33}Ni_{0.26}O_2$ and
e) P2/P3- $Na_{0.7}Co_{0.3}Mn_{0.33}Ni_{0.36}O_2$.

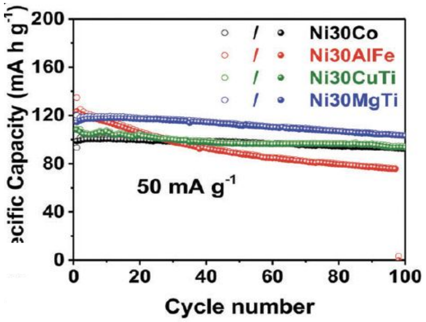
The content of Mn and Ni in Na_xTMO_2 (T = transition metal) layered oxide cathode materials affects battery performance: Increased Mn content produces better cycle life performance while higher Ni helps achieve higher discharge capacities..

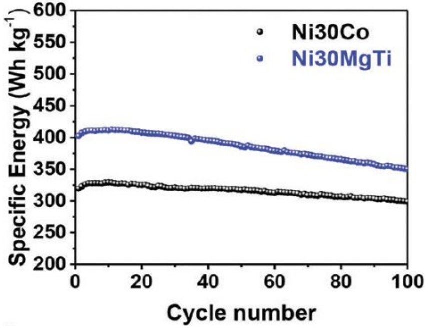
Source: C. Hakim, H. D. Asfaw, R. Younesi, D. Brandell, K. Edström, I. Saadoune

Cathode

Co-Free Layered Oxide Cathode Material For Sodium-ion Batteries

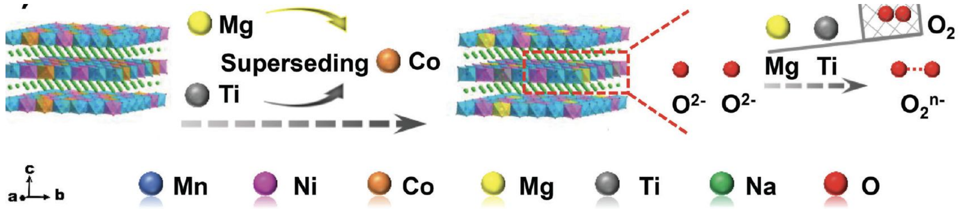
Synthesis of a new SIB cathode material: Replacing Co with Mg and Ti





Liu, et al. developed a cost-effective method to synthesise high-performance cathode materials for sodium-ion batteries (SIBs), replacing expensive cobalt (Co) with magnesium (Mg) and titanium (Ti). The material was synthesized using a solid sintering method. Metal oxides and sodium carbonate were mixed together and then ball-milled at 300 rpm followed by calcination at 900°C.

The optimized Co-free cathode, $Na_{0.67}Mn_{0.53}Ni_{0.3}Mg_{0.085}Ti_{0.085}O_2$, demonstrated a reversible specific capacity of 118 mAh/g at a current density of 50 mA/g in the voltage range of 2.0–4.25 V. This capacity surpasses that of its Co-containing counterpart. The inclusion of Mg and Ti also raises the median discharge voltage (from 3.21 V to 3.59 V), increasing the energy density from 325 to 410 Wh/Kg.



A solid-sintering technique has been demonstrated as a cost-effective method for synthesizing Co-free high performance sodium ion battery cathode materials. Replacing Co with Mg and Ti increased the discharge voltage and energy density of the cell.

Source: Z. Liu, J. Wu, J. Zeng, F. Li, C. Peng, D. Xue, M. Zhu, J. Liu

Cathode | Synthesis Sensitivities Of Lithium-Rich Layered Oxides

Lithium carbonate particle size is critical to the synthesis of lithium-rich layered oxides

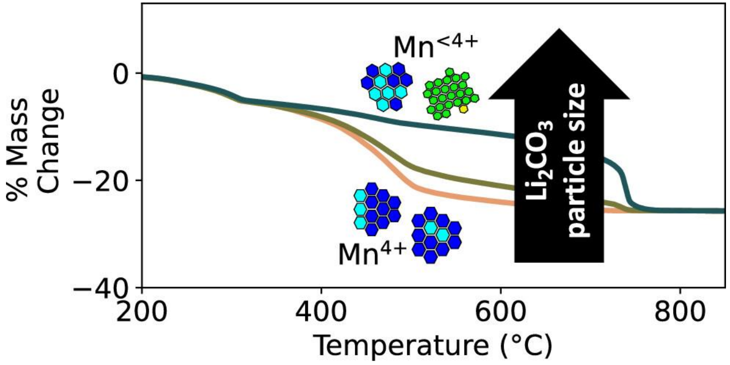
Busse and co-authors studied the impact of lithium carbonate particle size on the calcination process of lithium-rich layered oxides.

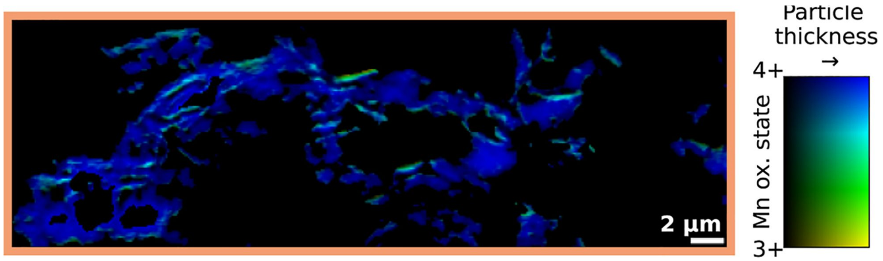
Previous studies had suggested that Li_2CO_3 melting was key to the synthesis. Intermediate phases and reaction inhomogeneity are frequently observed, which this work has attributed to mismatched precursor particle sizes.

Cation ordering occurs in lithium-rich cathode materials and affects the voltage profile and charge storage capacity. This cation ordering is strongly influenced by the synthesis protocol and particle characteristics.

Careful control of these parameters is often implicit in industrial processes but may not be understood as the source of batch-to-batch differences. Particle size and morphology should be reported in academic papers.

Lithium carbonate melting is not required to synthesize homogeneous lithium-rich cathode materials, if the lithium and transition metal precursors are of similar particle size.





Source: G. Busse, Csernica, P.M., Lim, K., Lee, J., Jiang, Z., Rivera, D.F., Kim, Y.J., Shapiro, D.A., Gent, W.E., Chueh, W.C.

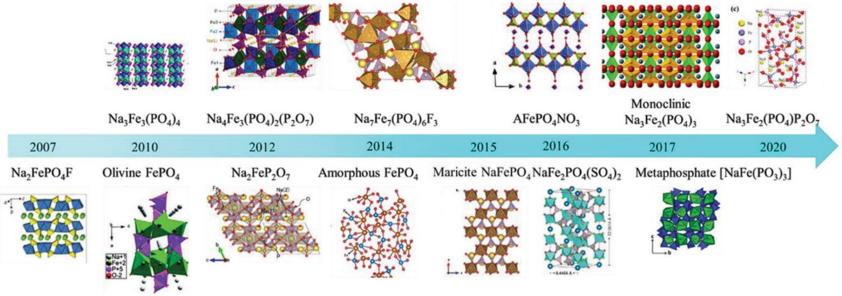
Cathode

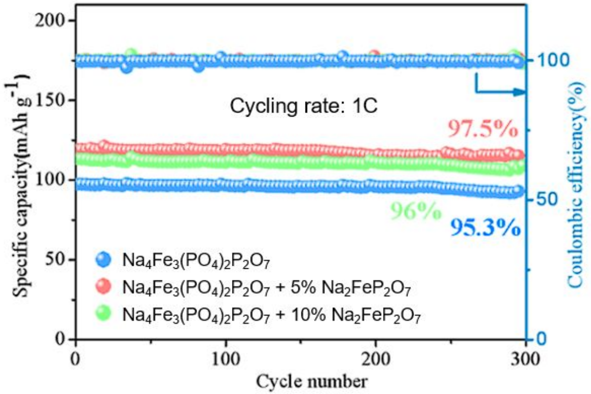
| Iron-Based Phosphate Cathodes For Practical Na-Ion Batteries

Progress in sustainable sodium iron phosphates makes them a contender among Na-ion cathodes

The high chemical and cycling stability of polyanionic cathodes makes them attractive candidates for Na-ion batteries over layered oxide and Prussian blue analogue alternatives. In particular, iron-based phosphates comprised of abundant and sustainable elements stand out as cost-effective materials. A review by Liu et. al. summarizes the research progress on this class of cathodes, highlighting improvements in energy density through new compositions.

Mixed iron phosphate-pyrophosphate chemistries are currently the most promising cathodes in this materials class, with $Na_4Fe_3(PO_4)P_2O_7$ and $Na_3Fe_2(PO_4)P_2O_7$ compositions reaching 110-125 mAh/g capacities, and showing operational lifetimes in the thousands of cycles. However, further improvements in energy density, conductive coatings, and presodiation techniques are needed for this class of cathodes to match the performance of lith





Mixed sodium iron phosphate polyanionic cathodes are cheap and abundant with decent capacities and high stability, allowing them to compete with layered oxides and Prussian blue analogues.

Source: Y. Liu, X. Cui, Y. Liu, Y. Xia, and Liu, Z., Cao, Y., Zhang, H., Xu, J., Wang, N., Zhao, D., Li X., Liu, Y., Zhang J.

02 Academia | Overview

Research Overview

Cathode

Anode

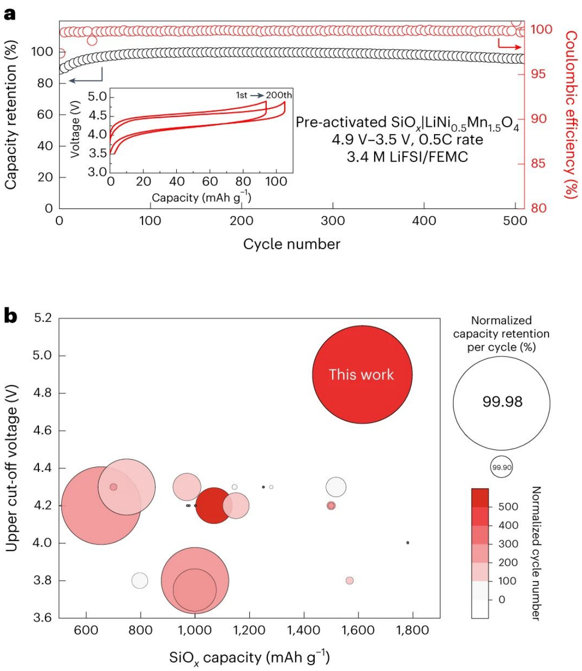
Electrolyte

Machine Learning

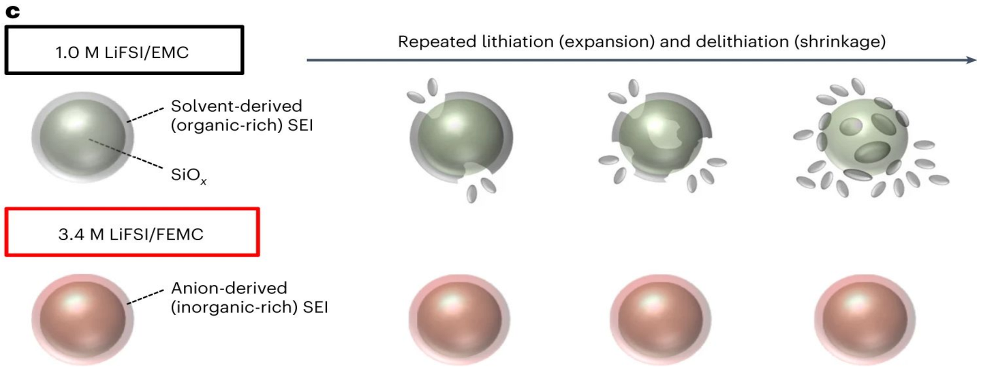
Other

Anode | Silicon Anodes

Electrolyte design enables high energy-density SiOx/LNMO cell



Researchers from the University of Tokyo and SKKU Korea demonstrated stable cycling of a $SiO_x/LiNi_{0.5}Mn_{1.5}O_4$ battery (Fig. a) to an upper cut-off voltage of 4.9 V and reported a very high capacity for the silicon oxide (Fig. b). This was achieved with the selection of the $LiN(SO_2F)_2$ (LiFSI) salt, which forms a robust SEI, and methyl (2,2,2-trifluoroethyl) carbonate FEMC electrolyte, which has a high oxidation potential.



Long-term cycling of a $SiO_x/LiNi_{0.5}Mn_{1.5}O_4$ battery with a 4.9 V cut-off was enabled by a 3.4 M LiFSI/FEMC electrolyte.

Source: Ko, S., Han, X., Shimada, T., Norio, T., Yamada, Y., Yamada, A.

Anode | Prelithiated Si/C Anodes

A new transfer-printing prelithiation process applied to graphite and Si/C anodes demonstrates higher initial coulombic efficiency and energy density

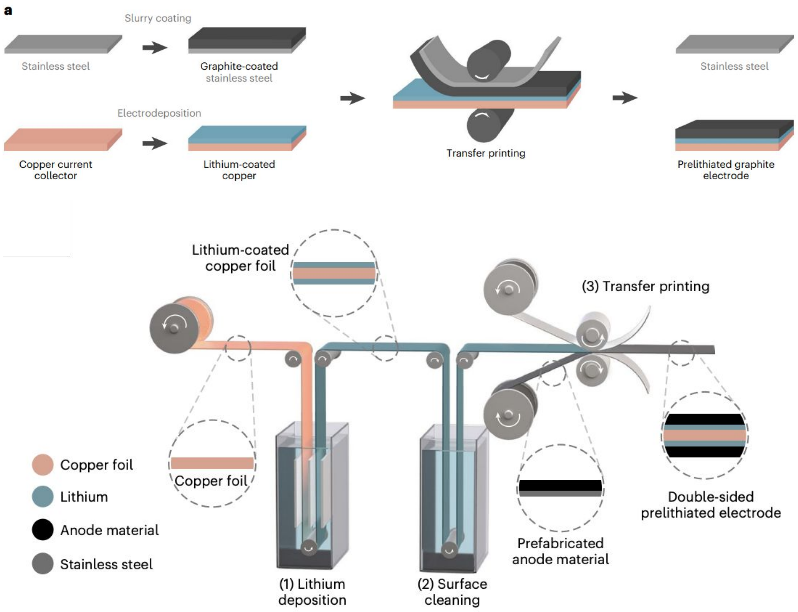
Lithium loss during cell formation results in a decreased initial Coulombic efficiency and energy density. Lithium loss is even worse in Si-based anodes due to volumetric changes and defect sites. Different prelithiation methods are commonly used to embed extra Li in the anode material to replenish the loss of lithium from the cathode.

Researchers at Tsinghua University developed a roll-to-roll electrodeposition and transfer-printing system to produce pre lithiated graphite and Si/C anodes. The system includes:

1. Lithium electrodeposition on copper foil
2. Surface cleaning
3. Transfer-printing of prefabricated anodes
4. Continuous production of prelithiated electrodes

This method resulted in high initial Coulombic efficiencies of 99.99% for graphite anode and 99.05% for Si/C anode half cells and improved the initial Coulombic efficiency and energy density of full cells.

A fast and low-cost prelithiation process that is compatible with roll-to-roll manufacturing can unlock the full potential of silicon-based anodes.



Source: C. Yang, H. Ma, R. Yuan, K. Wang, K. Liu, Y. Long, F. Xu, L. Li, H. Zhang, Y. Zhang, X. Li and H. Wu

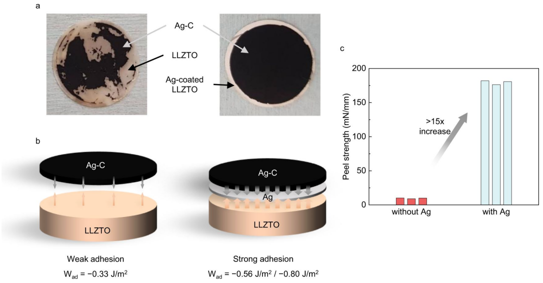
Anode | Lithium Metal

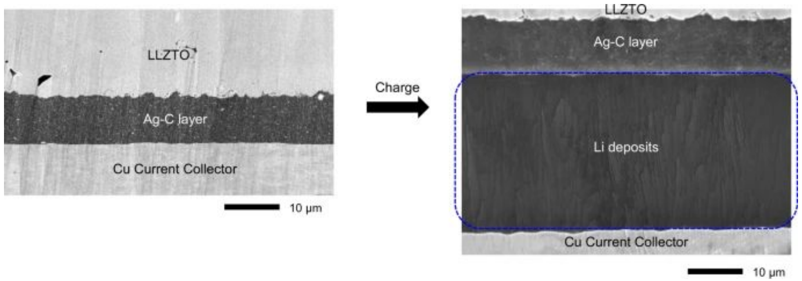
Surface engineering of inorganic solid-state electrolytes

This study aimed to improve the performance of quasi-all-solid-state lithium batteries using Ag coated inorganic solid-state electrolytes (LLZTO). The hypothesis was that employing a Ag coating on LLZTO along with a Ag-C composite interlayer would prevent dendrite penetration, enhance stability, and facilitate higher current density operation.

LLZTO solid electrolyte films were prepared via tape casting, and various interlayers, including Ag-C, were coated on the LLZTO surface. Cells with Ag-C interlayers demonstrated enhanced stability and avoided short-circuiting at higher current densities compared those without. The Li|Ag-C/Ag/LLZTO/IL|NCM 333 cell exhibited an impressive initial discharge capacity and retained about 85% capacity after 800 cycles at 1.6 mA/cm^2 and 25 °C. The study showed that the interlayers effectively shielded the solid electrolyte, preventing dendrite penetration and allowing substantial capacity retention even after multiple charge-discharge cycles.

Surface engineering of solid-state electrolyte LLZTO significantly improves cycling performance of a lithium-metal battery without the need to apply external pressure.



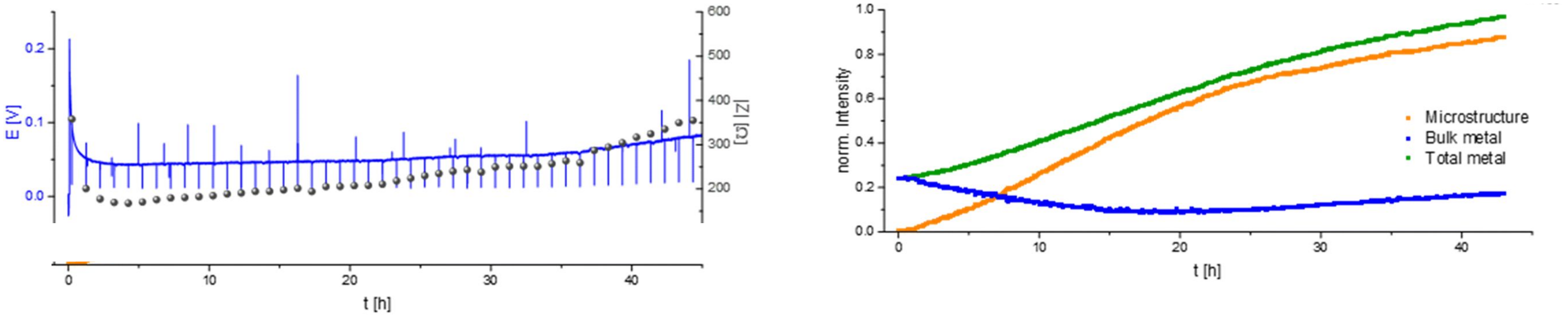


Source: Kim, JS., Yoon, G., Kim, S., Sugata, S., Yashiro, N., Suzuki, S., Lee, M.J., Kim, R., Badding, M., Song, Z., CHang, J., Im, D.

Anode | Lithium Metal

Insights into soft short circuit-based degradation of lithium metal batteries

Research by S. Menkin, et al. extensively explored the detection of soft shorts during lithium plating. The paper seeks a more nuanced understanding of voltage traces and impedance variations in lithium metal batteries, which has historically correlated squarelike waveforms with uniform plating and stripping. The authors propose redefining the critical current density based on reversible soft shorts observed in symmetric cell polarization experiments across both ether and carbonate based liquid electrolytes.



Operando Li NMR and impedance (GEIS) measured at 8 Hz intensities measured during unidirectional Li plating at 1 mA cm-2 in an NMR in situ cylindrical symmetrical Li cell with LP30 electrolyte.

Combining EIS and NMR experimental approaches, reversibility of soft shorts and their evolution into hard shorts can be characterized and predicted.

Soft short-circuits exhibit resistances in the tens to hundreds of ohms, compared to hard short-circuits, whose resistance typically falls in the milli-ohm range.

Source: S. Menkin, J. Fritzke, R. Larner, C. de Leeuw, Y. Choi, A. B. Gunnarsdottir, and C. P. Grey

Anode | Anode Free

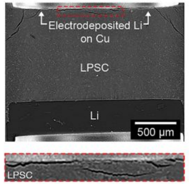
Alloy interfacial layers are confirmed as necessary to improve coulombic efficiency

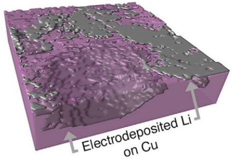
Researchers at the Georgia Institute of Technology and Purdue University have studied the evolution during cell cycling of 100-nm silver and gold interface layers between the Cu current collector and sulfide-based solid electrolyte in an "anode-free" configuration.

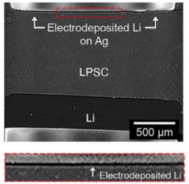
The Ag and Au alloy layers form alloys with Li during plating (cell charging). This allows for uniform Li growth across the current collector, improving the coulombic efficiency and resistance to short circuiting of the cell, even though the alloys form solute regions or particulates that detach from the current collector during plating.

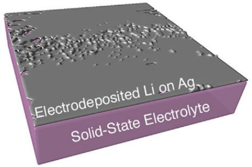
A key feature of both the Au and Ag interlayers is that, despite morphological evolution, they remain relatively uniformly dispersed after Li deposition (either as particles for Li-Au or dissolved for Li-Ag). Therefore, at the end of stripping (discharging), the alloys return to the interface and mitigate contact loss between the Cu current collector and the solid electrolyte, avoiding a critical vulnerability of anode-free solid-state cells. Other alloys with different reaction behavior, electrode potential, and/or mechanical properties may not be as effective as the costly Ag and Au metals.

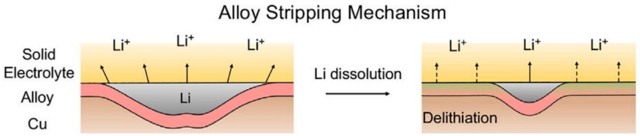
A thorough morphological and electrochemical characterization helps to understand the already-known beneficial effect of Ag and Au anode interfacial layers in improving the cycling behavior of solid-state cells.









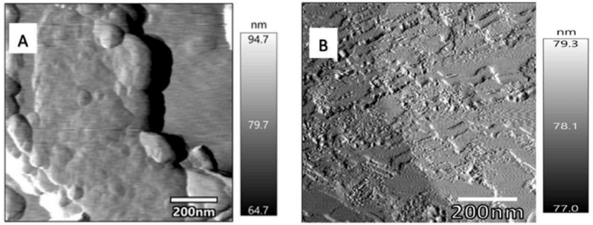


Source: S. E. Sandoval, J. A. Lewis, P. P. Mukherjee, M. T. McDowell, et al.

Anode | Graphite

Engineering microstructure and defects to enhance electrochemical performance in graphite anodes

Researchers at North Carolina State University and Oak Ridge National Laboratory used nanosecond pulsed laser annealing (PLA) to alter the structure of graphite and improve electrochemical performance. Carbon vacancies created during the PLA process provide sites for Li$^+$ during charging, while increasing the current density that can be achieved during discharge by 20 percent. In addition, steps and grooves generated on the surface of the graphite improve Li+ diffusion transport. Inactive or ineffective disordered carbon and PVDF binder that may otherwise hinder lithium transport is also removed from the graphite surfaces. However, PLA must be optimized; if the vacancy concentration is too high, crowding of Li$^+$ can cause electron trapping and result in lithium plating.



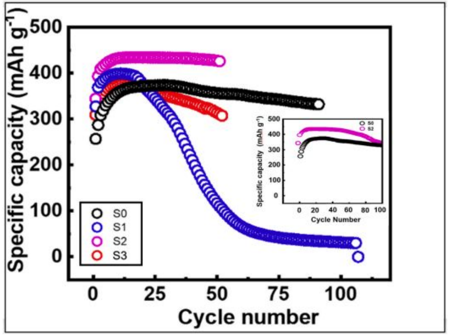
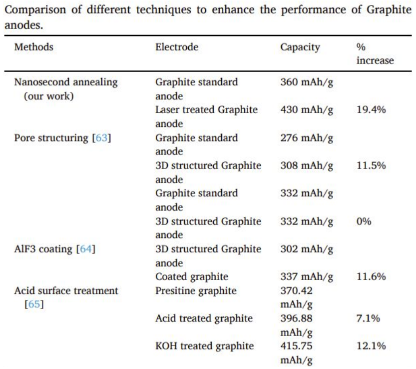


Figure A-B: AFM images of a (A) reference graphite without PLA treatment and (B) optimised PLA treatment graphite sample. Figure C shows a reference sample (**S0**) compared to under-annealed and unoptimised (**S1**), optimised (**S2**), and over-annealed and unoptimised (**S3**) PLA-treated graphite.



Comparison of different techniques to enhance the performance of Graphite anodes.

Methods	Electrode	Capacity	% increase
Nanosecond annealing (our work)	Graphite standard anode	360 mAh/g	
	Laser treated Graphite anode	430 mAh/g	19.4%
Pore structuring [63]	Graphite standard anode	276 mAh/g	
	3D structured Graphite anode	308 mAh/g	11.5%
	Graphite standard anode	332 mAh/g	
	3D structured Graphite anode	332 mAh/g	0%
AlF3 coating [64]	3D structured Graphite anode	302 mAh/g	
	Coated graphite	337 mAh/g	11.6%
Acid surface treatment [65]	Presitine graphite	370.42 mAh/g	
	Acid treated graphite	396.88 mAh/g	7.1%
	KOH treated graphite	415.75 mAh/g	12.1%

Pulsed laser annealing (PLA) alters graphite structure for increased rate capability in lithium ion cells, owing to increased vacancies within the structure and surface steps and grooves.

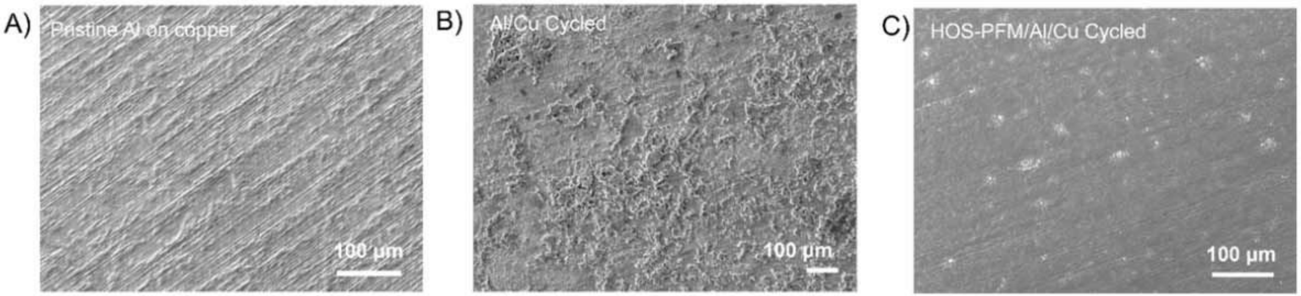
Source: N. Khosla, J. Narayan, R. Narayan, X Sun, M P Paranthaman

High Energy Density Anodes Enabled By Functional Polymer Coating

Conductive polymer as a functional surface coating layer for anode materials

Researchers at Lawrence Berkeley National Laboratory have developed a conductive polymer coating, dubbed HOS-PFM. Combining this polymer with silicon or aluminium increases the life cycle and power of lithium-ion batteries. The elasticity of the polymer combined with the ion and electron conducting properties helps to maintain electric contact when the silicon or aluminium material cracks during cycling. Additionally, this coating shows improved adhesion between the anode material and the current collector throughout its cycle life.. Remarkably, HOS-PFM delivers high battery capacity and energy density as well as extended cycle life, matching the performance of the most advanced electrodes currently available.

A functional polymer coating that enhances mixed ionic-electronic conduction could serve as an effective approach for anode protection, thereby improving cycling efficiency.



Pristine anode **Without anode coating** **With anode coating**

Source: Zhu, Sternlicht, Ha, Fang, Liu, Savitzky, Zhao, Lu, Fu, Ophus, Zhu, Yang, Minor, Liu and Berkeley Lab News Release

02 Academia | Overview

Research Overview
Cathode
Anode
Electrolyte
Machine Learning
Other

Electrolyte | High-Entropy (He) Electrolytes Improve Stability And Performance

Increasing entropy of electrolytes improves ionic conductivity and rate capability

Increasing the entropy of liquid electrolytes by introducing multiple salts was shown to alter the solvation structure, enhance the solubility and improve the ion mobility and electrochemical stability at the electrolyte-electrode interface. In this case, increasing the entropy results in a more negative Gibbs free energy of mixing, allowing for stably homogeneous electrolytes at previously inaccessible compositions (Fig. 1).

Wang et. al. used $LiNO_3$ (lithium oxonitrate), a common additive insoluble in the commercial EC/DMC electrolyte, to showcase that introducing a mixture of LiTFSI, LiFSI, and LiDFOB result in HE electrolytes with higher ionic conductivity, diffusivity, lithium ion transference number, and higher $LiNO_3$ solubility. More stable cycling was also observed due to the denser and more uniform stripping/depositing on lithium metal (Fig. 2).

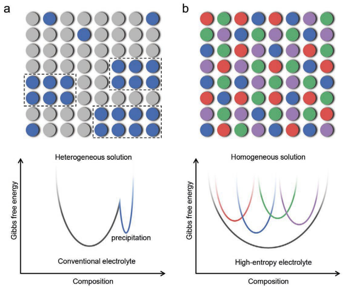


Figure 1.

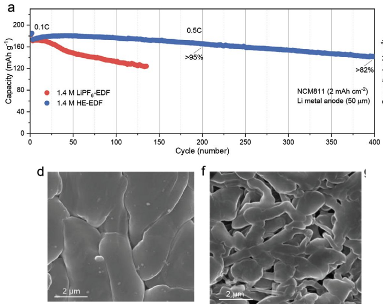


Figure 2.

Kim et. al. showed a similarly weakened solvation and ion clustering by increasing the electrolyte entropy (although here by introducing more co-solvents), and demonstrated improved ionic conductivity and cycling stability of lithium metal at high current densities for both ether and carbonate-based electrolytes (Fig. 3), where EL2, EL4, and EL5 correspond to electrolytes with 2, 4, and 5 solvents, respectively.

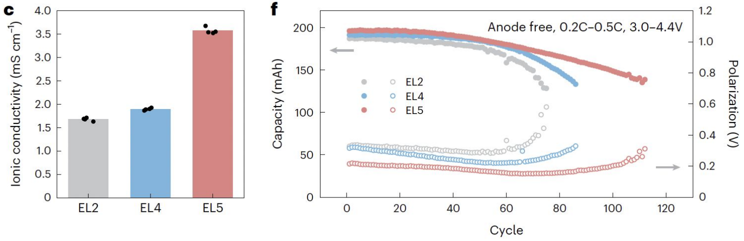


Figure 3.

High-entropy electrolytes alter solvation structure, enhancing solubility, ion mobility, ionic conductivity, diffusivity, and electrochemical stability.

VF | VOLTA FOUNDATION

Source: Q. Wang, C. Zhao, Z. Yao, J. Wang, F. Wu, S. G. H. Kumar, S. Ganapathy, S. Eustace, X. Bai, B. Li, J. Lu, M. Wagemaker, and Kim, S.C., Wang, J., Xu, R. et al.

Additives in aqueous electrolytes increase performance in Zn batteries

Aqueous electrolytes continue to attract attention, especially for post-lithium ion chemistries. Zinc-ion batteries have a high energy density, but parasitic side-reactions and non-uniform dendrite growth on Zn anodes limit their usage.

Zhang et al. used a $NH_4H_2PO_4$ additive to regulate the Zn^+ deposition and avoid dendrite formation. In this case, the NH_4^+ is preferentially absorbed on the Zn to block free water molecules, in what the authors call “shielding effect”, while the $H_2PO_4^-$ forms a buffer that maintains a favorable pH (Figure 1). This results in more uniform and stable deposition/stripping of the Zn ion, resulting in improved capacity retention in Zn//Zn and Zn//Cu cells. Highly reversible Zn plating/stripping behaviors were observed; the Zn//Zn symmetric cell stably cycled 2100h at 1 mA cm^{-2}, 1900 h at 4 mA cm^{-2} and 930 h at 10 mA cm^{-2}.

A Zn//Cu asymmetric cell displayed a high average coloumbic efficiency of 99.4% over 1000 cycles. The NHP additive also boosted teh electric chemical performance of Zn//MnO_2 full cells and Zn//activated carbon capacitors.

Additives such as $NH_4H_2PO_4$ (NHP) can reduce dendrite growth and parasitic side reactions in aqueous zinc batteries.

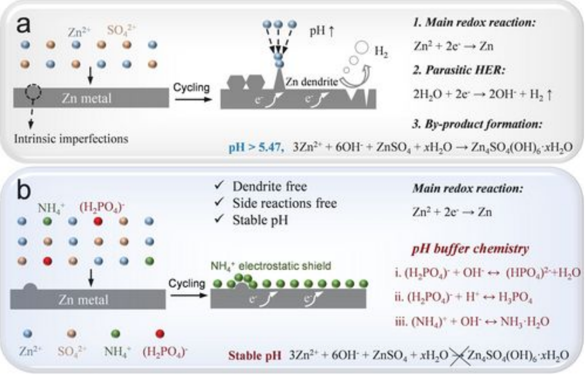


Figure 1.

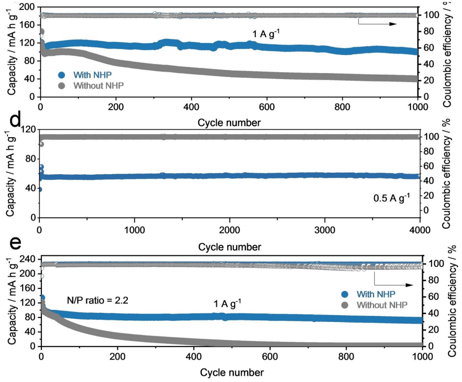


Figure 2.

Source: W. Zhang, Y. Dai, R. Chen, Z. Xu, J. Li, W. Zong, H. Li, Z. Li, Z. Zhang, J. Zhu, F. Guo, X. Gao, Z. Du, J. Chen, T. Wang, G. He, I. P. Parkin

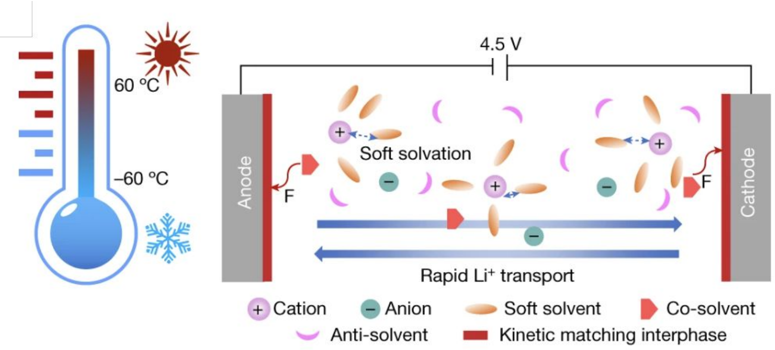
Electrolyte | Designing Electrolytes For Extreme Operating Conditions

A design principle for electrolytes paves the way for high-voltage, fast-charging, wide-temperature range batteries

Lithium ion batteries used in extreme applications require novel electrolytes. Ideally these electrolytes need to be non-flammable, operate over a wide voltage and temperature range range, and enable fast charging while reducing the risk of lithium plating.

Xu et al developed and validated an electrolyte design strategy for high energy batteries operating under extreme conditions (±60°C). The primary criteria for solvent selection are: a low freezing point, moderate boiling point, and wide electrochemical stability. A secondary criteria is the solvating ability; the appropriate solvent system ensures low Li-ion desolvation energy while maintaining Li salt dissociation. In order to maintain ionic conductivity, soft solvents are paired with a highly dissociating lithium salt.

Researchers applied their design criteria to create NMC811||graphite full cells with 1 M LiTFSI MDFA/MDFSA–TTE electrolytes. The coin cells (areal capacity >2.5 mAh cm^{-2}) were able to operate over a wide temperature range (−60 °C to +60 °C), and the pouch cells retained >83% room-temperature capacity over 300 cycles with an average CE of more than 99.9% at −30 °C.

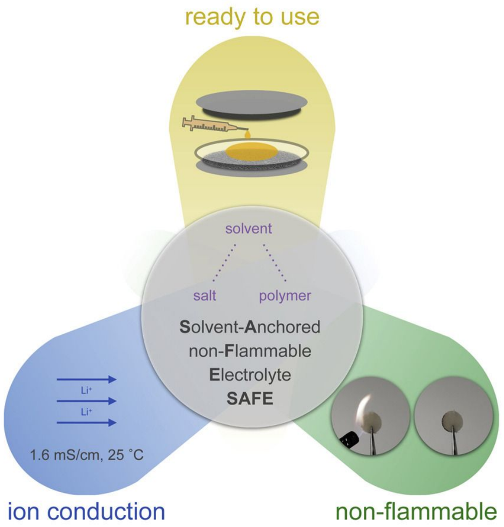


The electrolyte design principle for extreme Li-ion batteries involves identifying solvents with relatively low DN (<10) and high dielectric constant (>5) which minimizes Li$^+$/solvent binding energy while still dissociating Li salt. Adding a component with high reduction potential enables the formation of LiF-rich interphases on both electrodes, which facilitates similar lithiation/delithiation kinetics.

Source: Xu, J., Zhang, J., Pollard, T.P. et al.

Electrolyte | Solvent-Anchored, Non-Flammable Electrolytes (SAFE)

SAFE paired with NMC and graphite achieved >400 cycles without capacity decay



Battery electrolytes containing organic solvents are often flammable, which poses safety concerns. Non-flammable, solvent-free polymer electrolytes have been developed, but due to limited ionic conductivity at room temperature, are limited to elevated temperature operation. Gel electrolytes have higher ionic conductivity at room temperature, but their safety is compromised without anchored solvent molecules.

Researchers at Stanford and UC Berkeley created solvent-anchored, non-flammable electrolytes (SAFE). This SAFE has increased ionic conductivity at room temperature without undermining its non-flammability. When paired with commercially-available NMC and graphite electrodes, SAFE achieved >400 cycles at room temperature with no significant capacity decay.

SAFE is comprised of lithium bis(trifluoromethanesulfonyl)imide [LiFSI], dimethoxyethane [DME] and polysiloxane tethered with ion-solvating functional groups. The solvent coordinates with both salt and polymer, which plasticizes the polymer and increases ionic conductivity.

Solvent-anchored polymer electrolyte addresses two challenges of polymer and gel electrolytes: low conductivity at room temperature and flammability concerns. SAFE has a room temperature ionic conductivity of 1.6 mS/cm and an operating window of 25°C - 100°C.

VF | VOLTA FOUNDATION

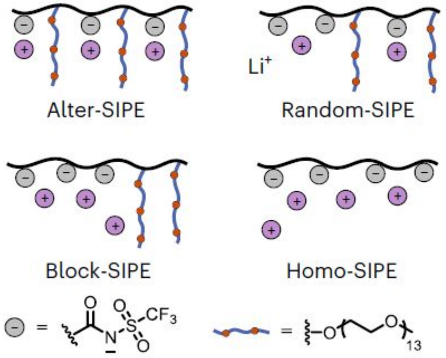
Source: Huang, Z. Lai, J.C., Kong, X., Rajkovic I., Xiao X., Celik H., Yan H., Gong H., Rudnicki P., Lin Y., Ye Y., Li Y., Chen Y., Gao X., Jiang Y., Choudhury S., Qin J., Tok J.B.H., Cui Y., Bao Z.

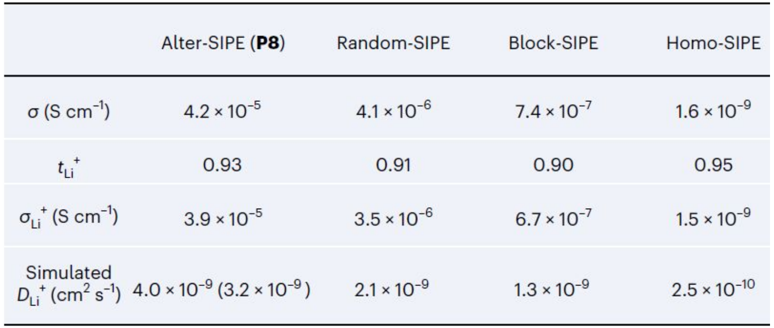
Electrolyte | Topological Solid Polymer Electrolytes

Molecular engineering creates highly ion-conductive polymers for solid-state lithium batteries

Current polymer electrolytes exhibit significantly lower ionic conductivity compared to their liquid and ceramic counterparts at room temperature, which hinders their widespread adoption in practical battery applications. Recent research demonstrates that strategic positioning of specific repeating units within alternating polymer sequences can dramatically enhance lithium ion (Li+) conductivity—by as much as three orders of magnitude under the room temperature. This study reveals that an alternating arrangement of fluorinated lithium salts and polyethylene oxide (PEO) side chains can increase the uniformity of ion distribution on a molecular level. This arrangement facilitates modulated complexation between anions and Li+, leading to enhanced Li+ dissociation. It also promotes a novel migration mechanism aided by the sequence of PEO, Li+, and anions. The construction of all-solid-state batteries incorporating this design exhibits stable, dendrite-mitigated performance.

Single-Ion Polymer Electrolytes (SIPE)





	Alter-SIPE (**P8**)	Random-SIPE	Block-SIPE	Homo-SIPE
σ (S cm^{-1})	4.2×10^{-5}	4.1×10^{-6}	7.4×10^{-7}	1.6×10^{-9}
t_{Li}^{+}	0.93	0.91	0.90	0.95
σ_{Li}^{+} (S cm^{-1})	3.9×10^{-5}	3.5×10^{-6}	6.7×10^{-7}	1.5×10^{-9}
Simulated D_{Li}^{+} (cm^{2} s^{-1})	4.0×10^{-9} (3.2×10^{-9})	2.1×10^{-9}	1.3×10^{-9}	2.5×10^{-10}

Molecular engineering through topology control of polymer electrolytes can influence Li^{+} dissociation and conduction, which endows desirable chain mobility and overcomes the inherent limitation of ion conductivity.

Source: Han, S., Wen, P., Wang, H. Zhou, Y., Gu, Y., Zhang, L., Shao-Horn Y., Lin, X., Chen, M.

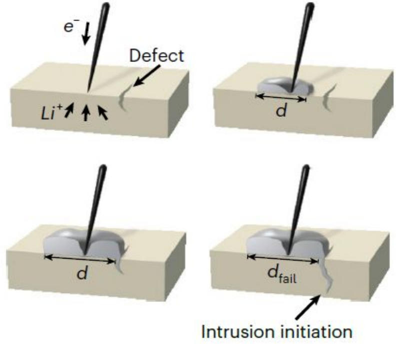
Electrolyte | Lithium Intrusion In Garnet (LLZO) Solid Electrolytes

Mechanical forces can propagate nanoscale cracks and lithium intrusion in LLZO electrolytes

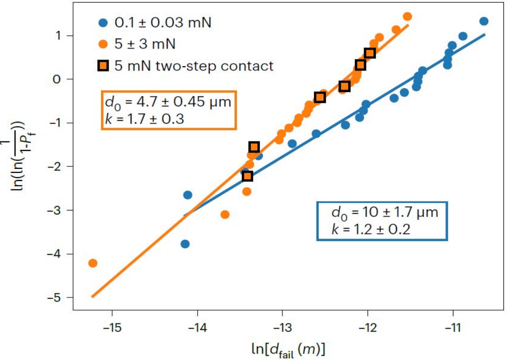
Lithium-metal batteries with solid electrolytes are at risk of short-circuiting due to lithium-metal plating. A detailed investigation by Stanford University researchers, involving 56 lithium plating tests on unblemished LLZO (lithium lanthanum zirconium oxide) surfaces, provides new insights into this issue (Fig A below). The team's findings suggest that the primary causes of lithium intrusion into garnet-type electrolytes are current focusing effects and the existence of nanoscale surface cracks. These factors contribute more to the problem than previously theorized causes like electronic leakage or electrochemical reduction. The study also reveals that the likelihood of intrusion is statistically related to the size of the lithium-metal (diameter), following a Weibull distribution (Fig B below). This indicates that initiation of intrusion tends to occur at sites with more focused current or concentrated microstructural defects within the LLZO.

Nano-cracks (pre-existing or generated via external load) are the root cause of lithium-metal intrusions in lithium garnet electrolytes, the propagation of these nanocracks can be controlled mechanically. A fundamental understanding of this intrusion process will enable the development and manufacturing of next-generation solid-state batteries that can remain stable over higher charge rates.

A



B



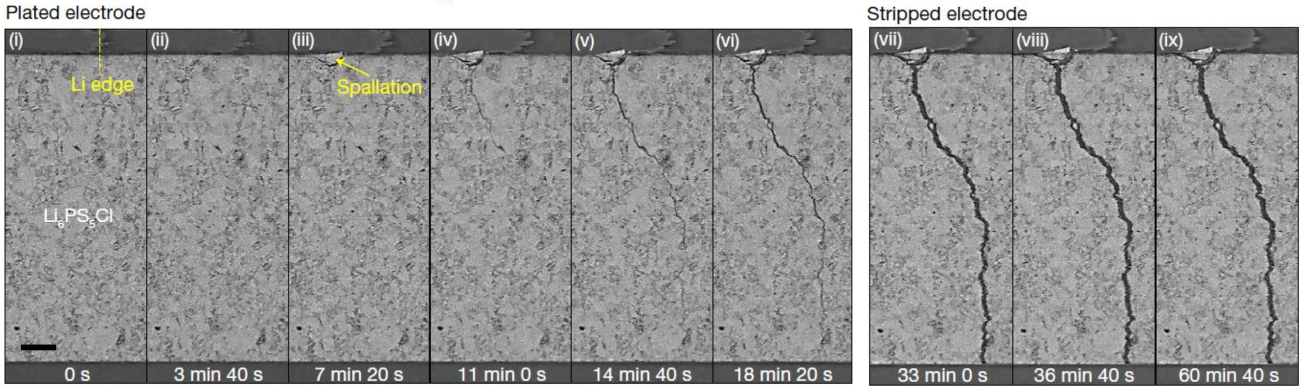
Similarly, the team led by Yet-Ming Chiang at MIT previously demonstrated that lithium dendrites form due to the mechanical failure of electrolytes (LLZTO). Their research further revealed that controlling mechanical stresses can effectively guide the trajectory of these dendrites.

Source: McConohy, Xu, Cui, Barks, Wang, Kaeli, Melamed, Gu, Chueh and Fincher, Athanasiou, Gilgenbach, Wang, Sheldon, Carter, Chiang

Electrolyte | Dendrite Growth In Argyrodite Solid Electrolytes

Dendrite initiation and propagation are separate processes in Li metal/SE solid-state batteries

Li dendrite formation poses a significant risk, leading to short circuits and cell failure during charging at practical rates. Research conducted by the University of Oxford has shed light on this issue, demonstrating that dendrite initiation and growth are distinct processes influenced by different factors. For Li_6PS_5Cl solid electrolytes, the occurrence of dendrites is largely influenced by local conditions such as the fracture strength at grain boundaries, pore size and density, and current density. Dendrite growth is driven by broader factors, including the material's overall fracture toughness, the physical characteristics of the dendrite, and operational parameters such as current density, stack pressure, and charge capacity utilized per cycle. Experimental observations revealed that battery systems with these electrolytes exhibit varying lifespans based on pressure conditions, with significantly longer life at lower pressures (around 0.1 MPa) compared to moderate pressures (around 7 MPa).



Low pressures can help to suppress dendrite propagation in argyrodite during charging, but might not be beneficial during discharging. Controlling the dynamics of lithium-metal charging and discharging remains a grand challenge.

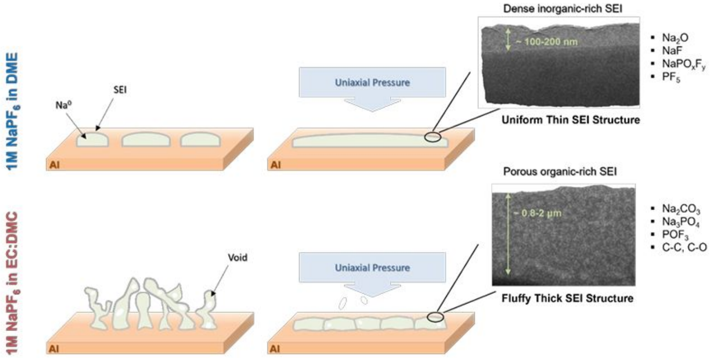
Source: Ning, Li, Melvin, Chen, Bu, Spencer-Jolly, Liu, Hu, Gao, Perera, Gong, Pu, Zhang, Liu, Hartley, Bodey, Todd, Grant, Armstrong, Marrow, Monroe, Bruce

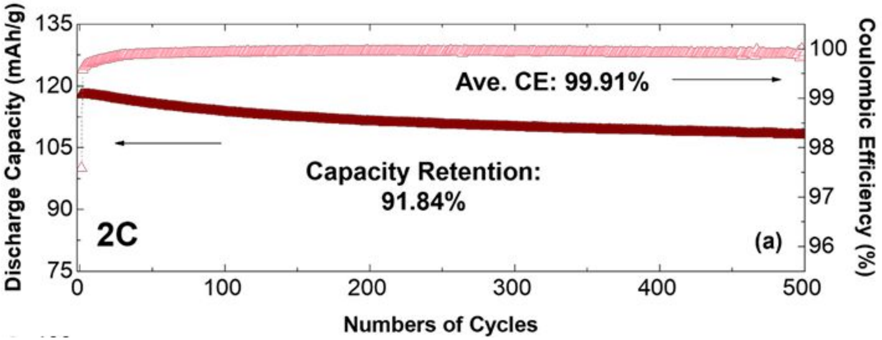
Electrolyte | High-Energy Sodium-Ion Batteries (Sibs) Using A Na Metal Anode

Sodium metal batteries with ether based electrolyte achieved >90% capacity retention at @ 2C rate

Sayahpour et al. developed a full cell utilizing a controlled electroplated sodium metal in ether-based electrolyte that achieved > 90% capacity retention after 500 cycles at 2C. The study focuses on the development of high-energy sodium-ion batteries (SIBs) using a Na metal anode. The application of stack pressure and the chemical composition of the SEI layer are crucial factors in enabling a sodium anode. Higher uniaxial pressure controls the uniformity and thickness of the electroplated Na layer, enabling high initial coulombic efficiencies.

Authors report, SEI thickness and its chemical compositions depend strongly on the type of electrolyte, with ether-based electrolyte enabling a thin and dense SEI, while a fluffy and porous SEI is formed in carbonate-based electrolyte. The group achieved a capacity retention of 91.84% after 500 cycles at a current rate of 2C.





VF | VOLTA FOUNDATION

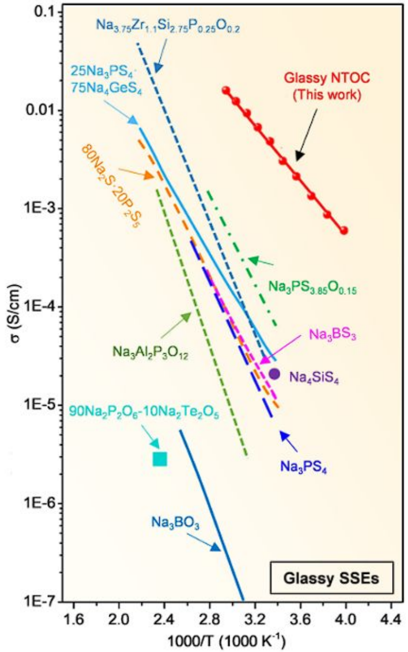
Source: Sayahpour B., Li W., Bai, S., Lu, B., Han, B., Chen, Y., Deysher, G., Parab, S., Ridley, P., Raghavendran, G., Nguyen, L.H.B., Zhang, M., & Meng, Y.S.

Electrolyte | Glassy Solid Electrolytes For Sodium-Ion Batteries

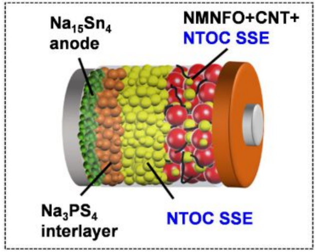
Soft superionic glasses demonstrate high conductivities and excellent formability

In addition to high ionic conductivities, good formability of solid-state electrolytes is crucial for practical application, as the compressive step required to enable sufficient interfacial contact in a solid-state battery is a key manufacturing bottleneck due to the high pressures and temperatures often required. While amorphous glasses are an interesting subset of solid-state electrolytes due to their high deformability and absence of grain boundaries detrimental to ion diffusion, most glassy materials to date show restrictively low ion conductivities.

Lin and Zhao et. al. report a new superionic oxychloride glass electrolyte, $0.5Na_2O_2\text{-}TaCl_5$ (NTOC), which demonstrates an ultrahigh ionic conductivity of 4.6 mS cm^{-1}, more than 20 times higher than the previous record for glassy electrolytes. This impressive performance is attributed to unique local structures generated by the dual anion chemistry of chlorine and oxygen. Importantly, high structural formability is observed in NTOC, along with good chemical stability in dry air. When incorporated into an solid-state Na-ion battery, superior cycling stability over 500 cycles is observed, highlighting the potential of glassy NTOC electrolytes.



Dual anion chemistry in glassy electrolytes can drastically improve ionic conductivities. The $0.5Na_2O_2\text{-}TaCl_5$ composition shows promise as a practical Na-ion solid electrolyte due to its high conductivity, formability, and stability.



Source: Lin, Zhao, Wang, Luo, Fu, Xiao, Gao, Li, Zhang, Xu, Yang, Hao, Duan, Sun, Guo, Huang, Sun

02 Academia | Overview

Research Overview

Cathode

Anode

Electrolyte

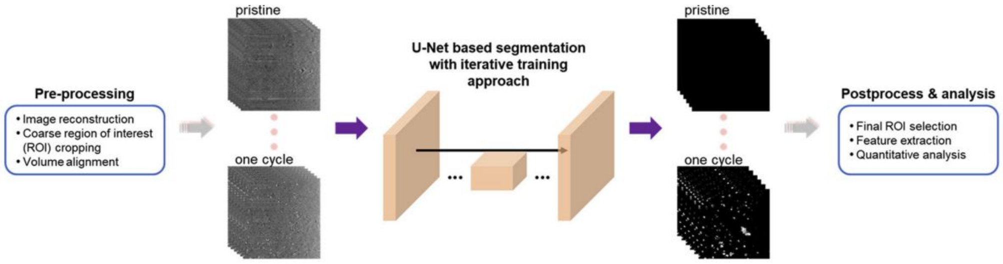
Machine Learning

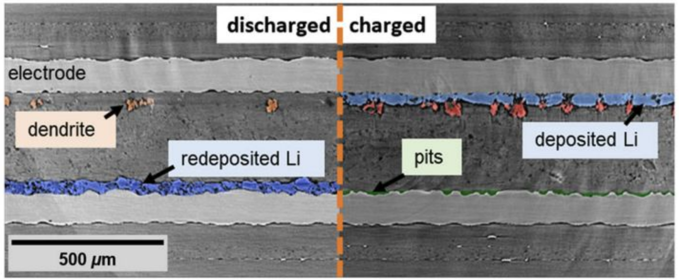
Other

Machine Learning | Solid-State Battery Li-Plating Dynamics Detection

A deep learning computer vision model for dynamic analysis of Li metal structures

Researchers proposed and trained a machine learning (ML) computer vision-based auto-segmentation method ("batteryNET"), analyzing micro-computed tomography (µCT) datasets to study the dynamics of Li structures in Li-metal/polymer electrolyte batteries. The ML model semantic segmentation result demonstrates singular Li-related component changes, addressing diverse morphologies in the dataset. The visualizations of the cycled Li morphologies are provided below, including calculations about the volume and effective thickness of electrodes, deposited Li, and redeposited Li. This study discusses the spatial relationships between these components. The approach focuses on developing a computer vision ML model to detect and analyze the dynamics of lithium metal/polymer electrolyte battery cycling.





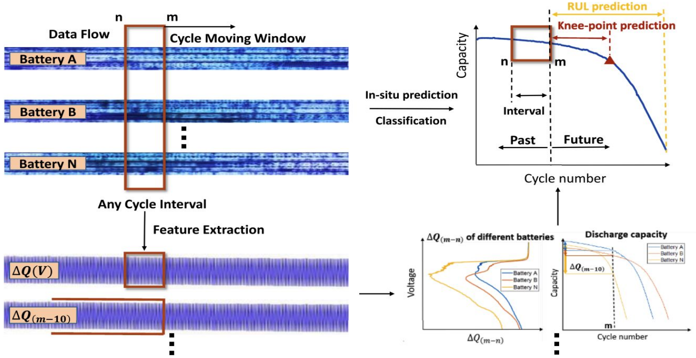
BatteryNET, a machine learning computer vision auto-segmentation system, was used to quantify dead Li, deposited, Li, and redeposited Li relative to the volume of the electrodes, allowing for quick and accurate analysis of lithium-metal battery datasets.

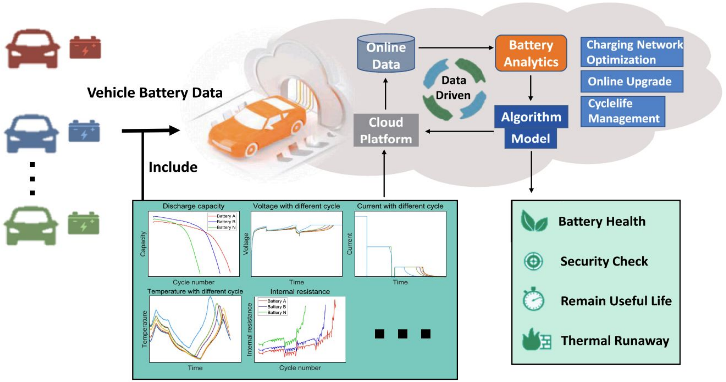
Source: Huang, Y., Perlmutter, D., Fei-Huei Su, A. et al.

Machine Learning | Cloud-Based Battery Prognostics And Health Management

Developing a cloud computing pipeline with ML for accurate in-situ battery life prediction

In-situ battery life prediction and classification are important to lithium-ion battery prognostics and health management (PHM). This research proposes a cloud-based PHM pipeline with a novel physical features-driven moving-window ML model, which can be used to predict the battery remaining useful life and knee-point. The proposed ML model is validated based on experimental data from a batch of 124 LFP/graphite cells from A123. The results show that the method predicts remaining useful life and knee-point accurately (with extremely small prediction error.





Machine learning is used to capture the relationship between physical features and battery life, demonstrating high accuracy in remaining useful life and knee-point prediction, with low errors of 55 cycles and 3.55% respectively.

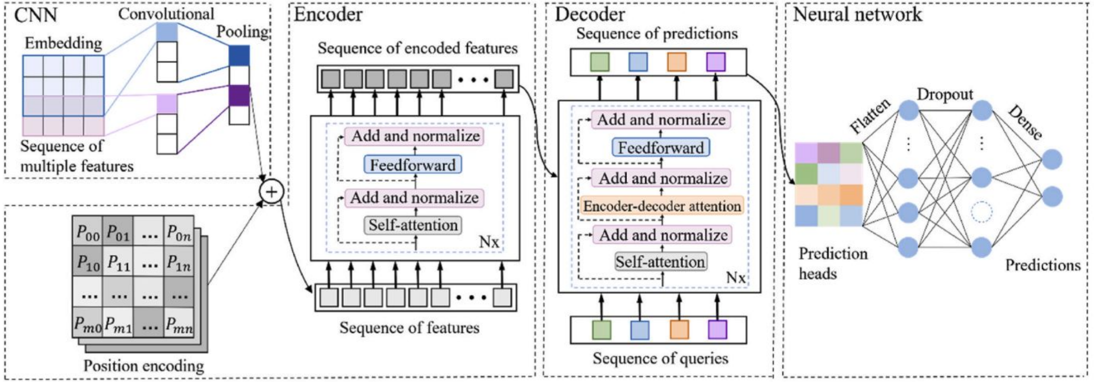
Source: Zhang, Yongzhi, and Mingyuan Zhao

Machine Learning

| Transformer-Based Battery Prognostic And SoH Prediction

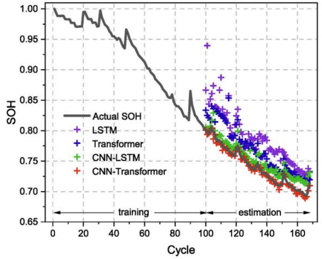
The deep learning transformer model can provide accurate and stable battery SoH prediction

SoH estimation of lithium-ion batteries is crucial for ensuring the reliability and safety of battery operation while keeping maintenance and service costs down in the long run. This research proposed a novel ML prognostic model based on a convolutional neural network (CNN)-Transformer framework. The Pearson correlation coefficient (PCC) and Principal correlation analysis (PCA) are used in pre-processing for feature selection. The NASA battery dataset is used as a training and testing dataset. The testing results show this CNN-Transformer model can predict the battery SoH with high accuracy and stability.

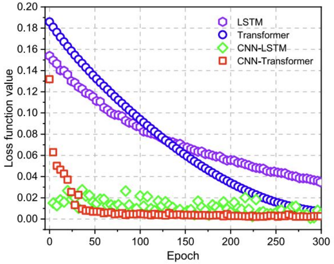


A convolutional neural network predicts battery SoH from the NASA dataset to within 1%.

Accuracy:



Efficiency:



Source: Gu, Xinyu, K. W. See, Penghua Li, Kangheng Shan, Yunpeng Wang, Liang Zhao, Kai Chin Lim, and Neng Zhang

Machine Learning | **AI-Driven A-Lab: Synthesizing Inorganic Materials With Robotics And ML**

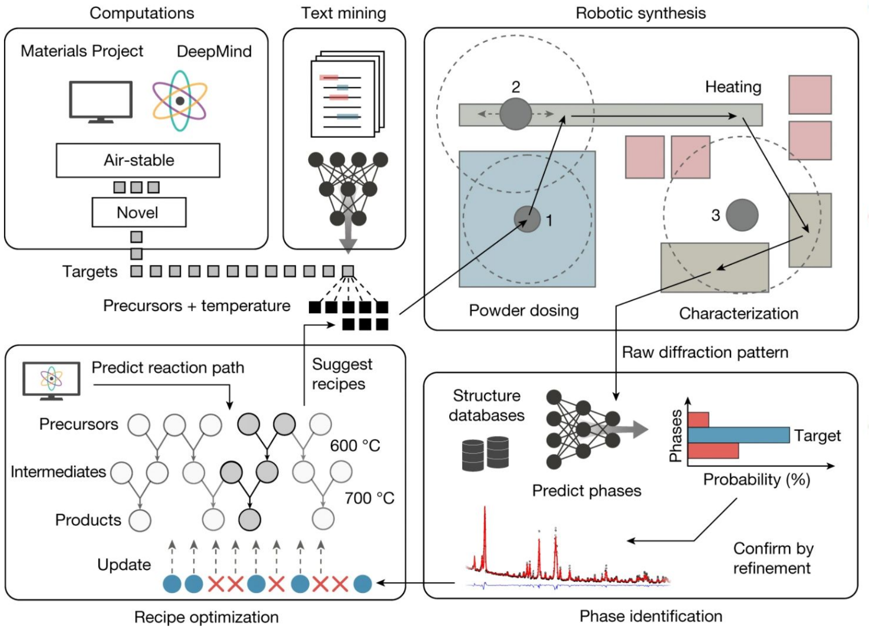
An autonomous laboratory for the accelerated synthesis of novel materials

UC Berkeley and Berkeley Lab established A-Lab, which merges robotics, databases, machine learning, and literature data for autonomous optimization of inorganic powder synthesis. The A-Lab planned and interpreted the outcomes of experiments performed by robots.

The Materials Project identified novel, air-stable targets. Machine learning natural-language models trained on scientific literature proposed synthesis recipes. A fully-automated robotic laboratory tested the recipes by performing 1) powder dosing, 2) sample heating, and 3) product characterization via XRD. The sample purity was assessed via XRD and analyzed by ML models. When samples were impure (< 50% target yield), the A-Lab proposed novel synthesis recipes based on a thermodynamics-based active-learning algorithm.

A-Lab's success highlights AI's potential in material discovery, bridging computational and experimental approaches.

The A-Lab, an autonomous laboratory, synthesized 41 novel inorganic compounds out of 58 targets over only 17 days.



Source: N.J. Szymanski, B. Rendy, Y. Fei, R.E. Kumar, T. He, D. Milsted, M.J. McDermott, M. Gallant, E. Dogus Cubuk, A. Merchant, H. Kim, A. Jain, C.J. Bartel, K. Persson, Y. Zeng & G. Ceder

Overview

Research Overview

Cathode

Anode

Electrolyte

Machine Learning

Other

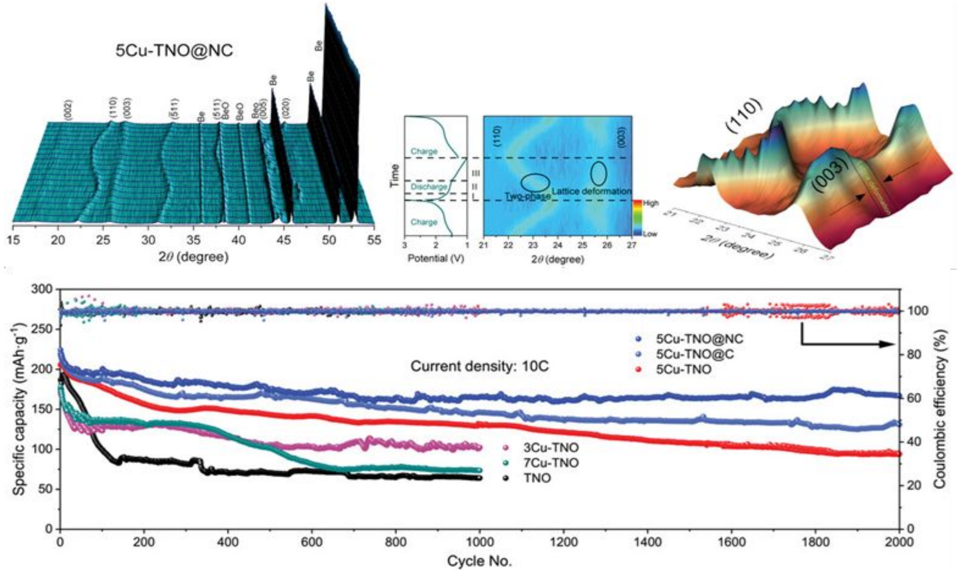
Fast-Charge

| Advanced Tinb$_2$o$_7$ Anode: Fast-Charging And Long-Cycling Alternative

Enhancing fast-charge and long-cycling in mesoporous Cu^{2+}-doped TiNb$_2$O$_7$ microspheres

$TiNb_2O_7$ is one of several promising anode materials, but suffers from volumetric change during the charge/discharge process as well as slow ion/electron kinetics. Yang, et al created a 5% Cu^{2+}-doped $TiNb_2O_7$ microsphere anode material with a surface coating of N-doped carbon, which demonstrates enhanced specific capacity and cyclic performance.

Uniform $TiNb_2O_7$ microspheres were quickly synthesized using microwave-based synthesis. To enhance Li$^+$ ion storage, the researchers added Cu^{2+} and a carbon coating. Cu^{2+} increased lattice volume and ion/electron conductivity. Density functional theory demonstrated that Cu^{2+} dopants substitute Ti^{4+} ions, reducing Li$^+$ diffusion barrier and increasing ionic conductivity. The microspheres were coated with N-doped carbon and maintain a stable capacity of 167.0 mAh g^{-1} after 2000 cycles at a high rate of 10 C.



Optimized Cu^{2+}-doped $TiNb_2O_7$ microspheres with N-doped carbon coating exhibit enhanced fast-charging and cycling performance.

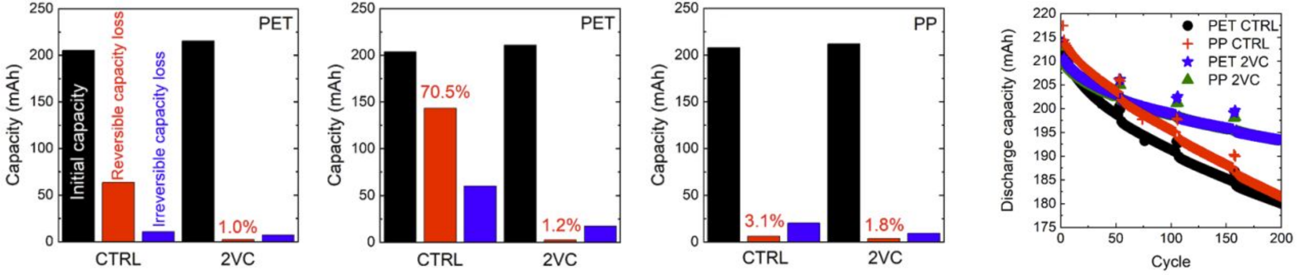
Source: C. Yang, D. Ma, J. Yang, M. Manawan, T. Zhao, Y. Feng, J. Li, Z. Liu, Y.-W. Zhang, R. B. Von Dreele, B. H. Toby, C. P. de L. Albarrán, J. H. Pan

Cell Design | Inactive Cell Component Material Optimization

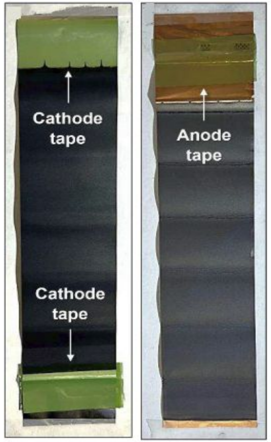
Replacing PET tape with PP tape to avoid degradation

Researchers at Dalhousie University analyzed the chemical stability of materials of various common tapes used in lithium ion batteries: polyethylene terephthalate (PET) and polypropylene (PP). Chemical degradation products of the tape were investigated with FTIR throughout cycling of LFP/graphite pouch cells under various conditions.

PET tape exhibited significant degradation, leading to the generation of dimethyl terephthalate (DMT). This byproduct from PET decomposition was identified as a redox shuttle, contributing to substantial self-discharge within LIBs. PP tape demonstrated robust chemical stability, exhibiting negligible degradation products under similar stress conditions. The authors mention that polyimide (PI/Kapton) tape is also chemically stable, but it is of substantially higher cost than PP tape.



Capacity losses of cells using PET and PP tape formed at 70°C and stored at 40°C (where 2VC refers to 2% vinylene carbonate in EC:DMC)



PET Tape is used to contain windings and cover aluminum in a cylindrical cell

Transitioning from PET to PP tape in LIB assembly will help mitigate the adverse effects of PET degradation.

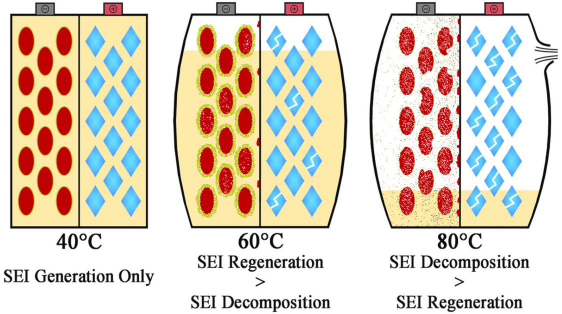
Source: Adamson, A., Tuul, K., Bötticher, T. et al.

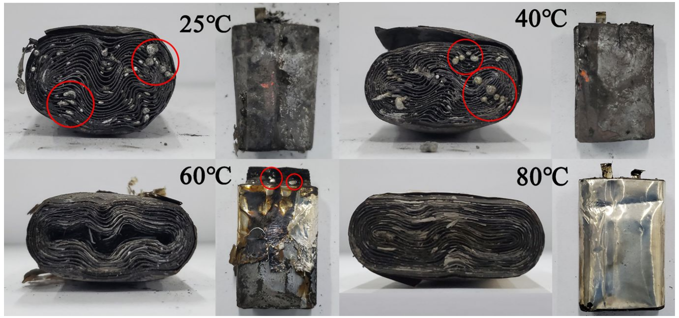
Safety | **Li-ion Thermal Stability**

Aging temperature impact on thermal stability of lithium-ion batteries

Researchers cycled commercial pouch cells (NCM622+LMO||graphite) at different temperatures. Cells at 25 °C and 40 °C showed slower capacity loss, but 40 °C experienced faster decay due to SEI overgrowth. At 60 °C, capacity decayed after 30 cycles, attributed to repeated SEI regeneration. Cells at 80 °C rapidly lost capacity after 7 cycles due to SEI growth. Post-ARC test, cells at 25 °C released the most heat, indicating significant aging.

Aluminum beads in wreckage at 25 °C and 40 °C suggested internal temperatures exceeded aluminum's melting point. The 80 °C cell had intact aluminum due to film rupture and electrolyte evaporation, reducing heat release. The study provides insights into temperature-dependent effects on pouch cell performance and safety.



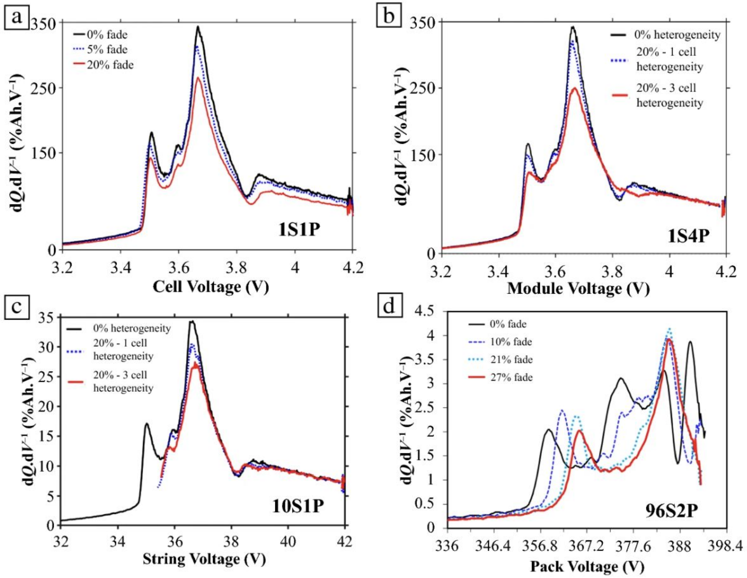


The transformation of SEI layer decomposition products at high temperature is the main reason for the difference in electrical performance and thermal runaway behavior due to the cycling of LIBs at high temperatures.

Source: Gao T., Bai J., Ouyang D., Wang Z., Bai W., Mao N., & Zhu Y.

Applications | Stationary Storage

Challenges of Scaling from a Single Cell to a Module/Enclosure



Slow rate dQ dV^{-1} (IC) plots for multicell configurations at different aging states: (a) single gr/NMC cell, calendar aged,[17] (b) 1S4P gr/NMC module, calendar aged,[17] (c) 10S1P gr/NMC string, calendar aged,[17] (d) 96S2P gr/LMO Nissan Leaf pack aged with a practical duty cycle (DST discharge and 2C DCFC charged).[28]

Challenges to implementing single-cell diagnostics to multicells include:

- Transient nature of detection signals
- Sensitivity of a detection signal with string configuration and size
- Time required for signal detection
- Issues separating the cell-to-cell heterogeneity from overall aging
- Need for additional, more accurate sensors
- More onboard computational power
- Large sets of baselining data specific to design and chemistry

Reconfigurable test setups and rapid validation platforms are needed to accelerate the development of advanced management and diagnostics technologies from single-cell to multi-cell configurations.

Source: Tanim, T.R., Dufek, E.J. & Sazhin S.V.

STEER

Guiding “What to build” by quantitatively predicting techno-economic viability

A SLAC-Stanford partnership working backwards from TWh-deployment to guide R&D directions, investment decisions, and policy agendas.

5 Pillars of STEER

- Technology Learning Curves
- Market Growth Analysis
- Minerals & Materials Supply Chain
- Device & Systems Modeling
- Energy Systems Modeling

Sally Benson
Co-PI

Will Chueh
Co-PI

Adrian Yao
Founder & Team Lead

Inaugural Industry STEER Launch Workshop | November 1, 2023

By the Numbers

180+ attendees

100+ companies (**20+** startups, **20+** VCs)

4 panels, covering:

- Na-ion vs. Li-ion in short-duration storage
- Storage durations for a decarbonizing grid
- Minerals constraints on energy transition
- Realistic pathways to break into EV market

A partnership between

SLAC-Stanford Battery Center & **Precourt Institute for Energy**

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford | ENERGY

For info, contact ayao2@stanford.edu

VF | VOLTA FOUNDATION

03 Talent

The Volta Foundation is an independent non-profit professional association dedicated to supporting the growth of the Battery Industry.

03 Talent | Overview

Headlines

H-1B Survey

Compensation

Workforce Development

Community

03 Talent | Overview

Headlines

H-1B Survey

Compensation

Workforce Development

Community

Headlines | Snapshot Of Battery Industry Talent Dynamics In 2023

Industry across every continent still looking for talent

Japan is **training teenagers** to fill the talent gap in its EV battery industry

Quartz

GM, Ford **partner with state and universities** to recruit future EV workforce

Detroit Free Press

Layoffs happening simultaneously as industry recalibrates focus

The Electric: A **Layoff Surge** in EV Batteries

The Information

EV battery startup **Our Next Energy** cuts workforce by 25%

Reuters

Government efforts to increase battery workforce pick up steam

US DoE & Stellantis Announce The **Battery Workforce Challenge**

CleanTechnica

EU battery skills program touts 50,000 course completion milestone

Smart Energy International

Salaries continue to rise but have not kept up with inflation

Median salaries are rising but have not kept up with **inflation**

H-1B Survey

Salaries vary widely. **Negotiate your salary.**

H-1B Survey

03 Talent | Overview

Headlines

H-1B Survey

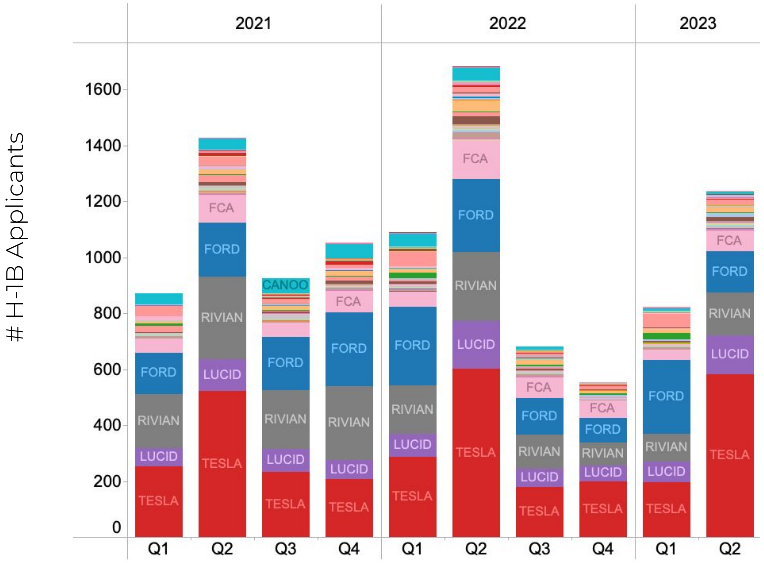
Compensation

Workforce Development

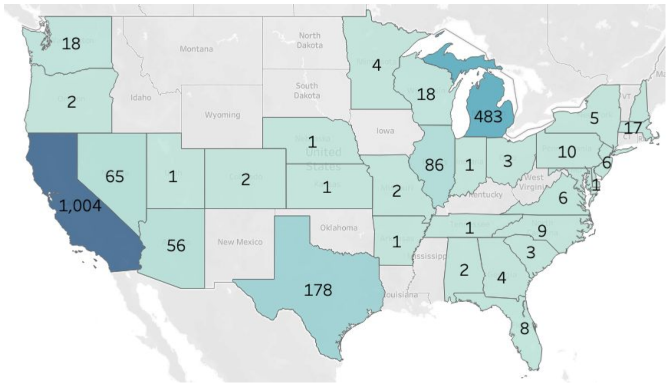
Community

H-1B Survey | Which Companies Are Sponsoring Battery Related Visas?

The H-1B is a **visa** in the U.S. under the Immigration and Nationality Act 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. Salary figures indicate base pay.



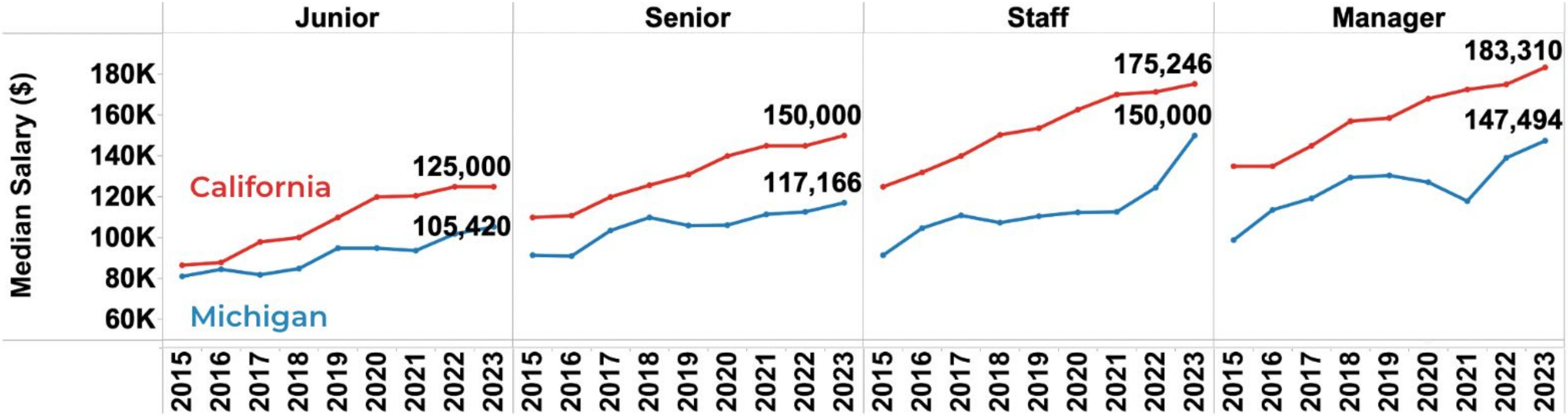
H-1B sponsorships declined during mid-2022 but picked back up again in first half of 2023. The vast majority of H-1B applications continue to be sponsored by automakers based in California and Michigan.



Map shows number of H-1B applicants by state. Data covers first two quarters of 2023 only.

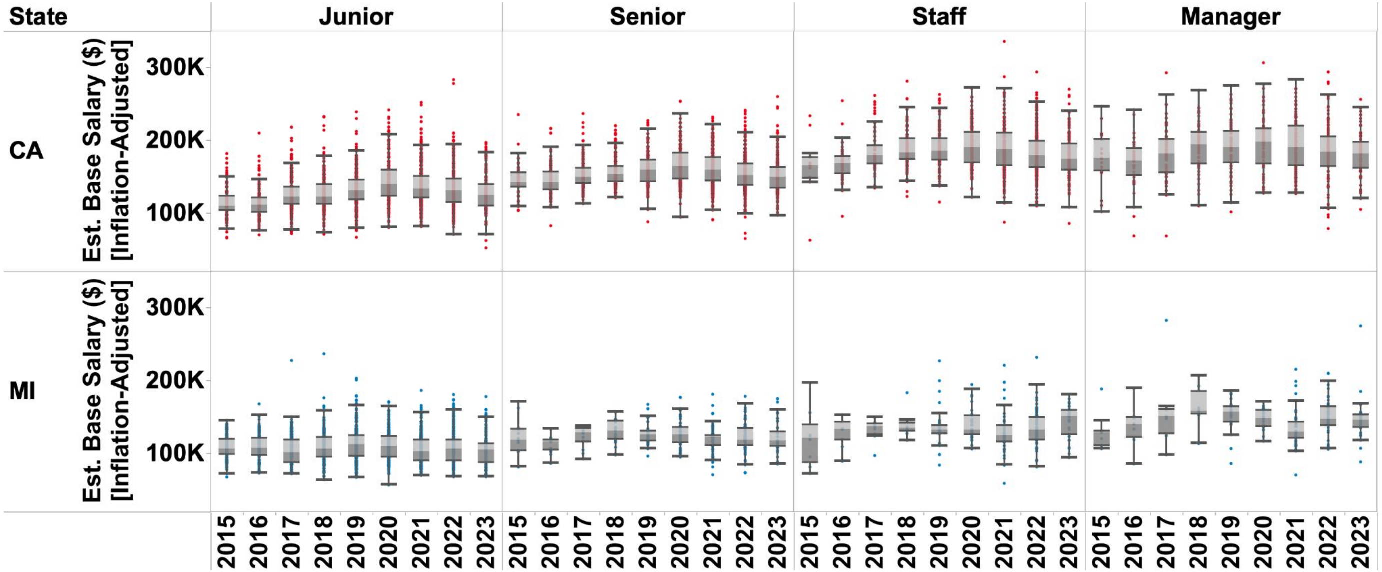
H-1B Survey | Battery Industry Salaries Surged In 2023

The H-1B is a **visa** in the U.S. under the Immigration and Nationality Act 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. Salary figures indicate base pay.



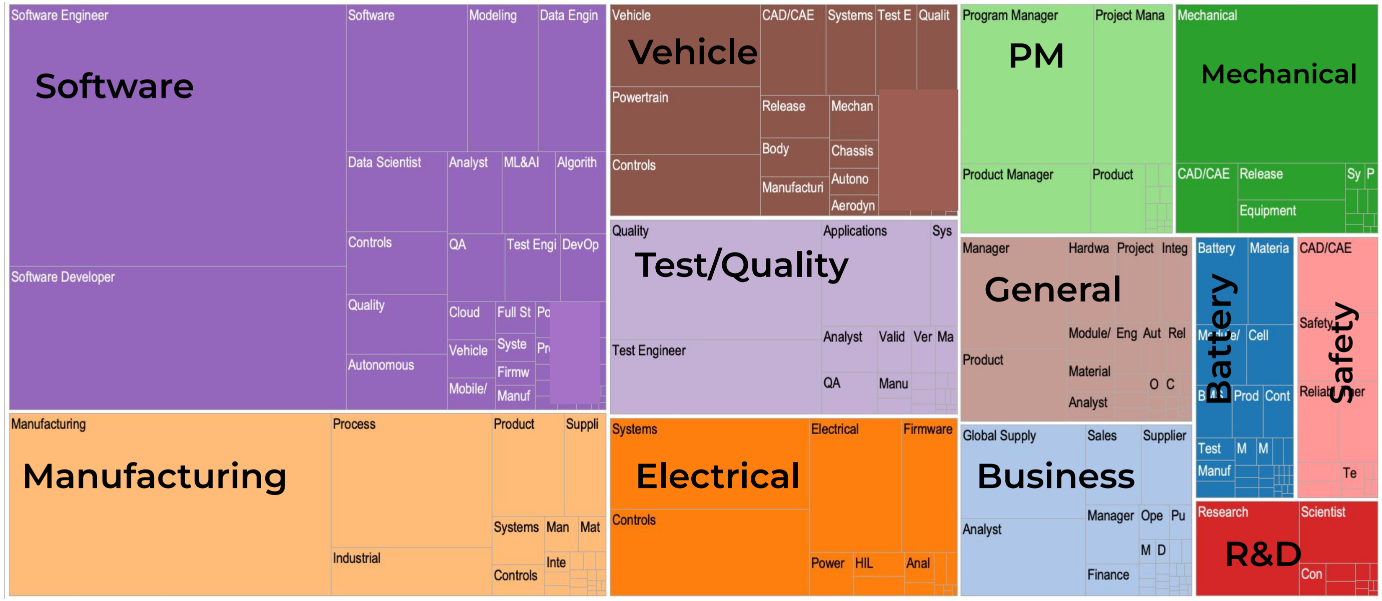
H-1B Survey | Salaries Vary Widely. Negotiate Your Salary.

The H-1B is a **visa** in the U.S. under the Immigration and Nationality Act 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. Salary figures indicate base pay.



H-1B Survey | What Roles Are Companies Hiring For? | Including Auto Companies

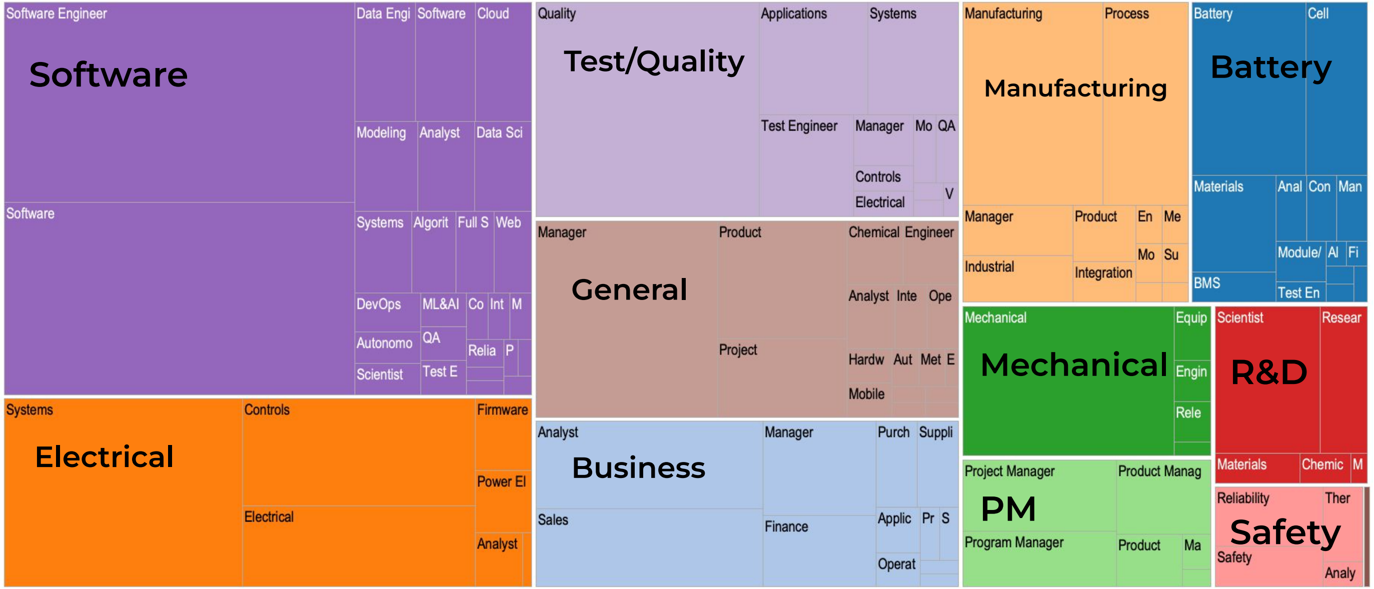
We analyzed job titles from over 20,000 H-1B applications from 2012 to 2023 which cover several dozen battery companies across the value chain (see the full list **here**). We grouped job titles into different job categories. The size of each box shown below corresponds to the number of job applications that match the job title.



VF | VOLTA FOUNDATION

H-1B Survey | What Roles Are Companies Hiring For? | Excluding Auto Companies

We analyzed job titles from over 20,000 H-1B applications from 2012 to 2023 which cover several dozen battery companies across the value chain (see the full list **here**). We grouped job titles into different job categories. The size of each box shown below corresponds to the number of job applications that match the job title.



03 Talent | Overview

Headlines

H-1B Survey

Compensation

Workforce Development

Community

Compensation | Getting Paid: What Compensation Databases Say

In the upcoming tables, we have compiled base salaries from **Pave,** a compensation database.

The ranges take into account base pay only, and are formulated based on job titles and level for individual contributors alone.

The provided ranges may not fully capture nuances related to the full scope of responsibilities, company stage, or one's tenure, and adjustments may be warranted based on these factors.

pave

Location

Pave created location tiers by listing out the pay differentials for all cities, ranking the pay differentials, and then running a clustering algorithm to determine which cities should be grouped together.

Experience Level

- **Entry**: Contributes to small or function-specific projects. Receives regular guidance and check-ins within each project.
- **Mid**: Owns small or function-specific projects. Provides updates and receives input at key milestones within each project.
- **Experienced**: Identifies, defines, and translates company vision and goals into functional projects/direction for lower levels. Identifies objectives for team leaders according to business needs. Receives regular updates at key milestones on each project.

Inputs Used & Definitions

Source: https://www.pave.com/

Compensation | Entry Level

pave	High Cost of Living (e.g., SF, Seattle, NYC)			Mid Cost of Living (e.g., Chicago, Austin, Denver, Boston)			Low Cost of Living (e.g., Minneapolis, RTP, Atlanta)		
Title	**50th Percentile**	**75th Percentile**	**90th Percentile**	**50th Percentile**	**75th Percentile**	**90th Percentile**	**50th Percentile**	**75th Percentile**	**90th Percentile**
Hardware Engineer	---	---	---	---	---	---	$57k	$60k	$99k
Applications Engineer	$65k	$71k	$79k	$56k	$65k	$76k	$50k	$60k	$67k
Program Manager	$75k	$90k	$135k	$70k	$80k	$90k	$67k	$80k	$108k
Product Manager	$99k	$132k	$148k	$87k	$116k	$130k	$82k	$109k	$123k

Base Salary

** Insufficient data for some levels and locations for Hardware Engineer*

Source: https://www.pave.com/ :

Compensation | Mid Career

pave	High Cost of Living (e.g., SF, Seattle, NYC)			Mid Cost of Living (e.g., Chicago, Austin, Denver, Boston)			Low Cost of Living (e.g., Minneapolis, RTP, Atlanta)		
Title	**50th Percentile**	**75th Percentile**	**90th Percentile**	**50th Percentile**	**75th Percentile**	**90th Percentile**	**50th Percentile**	**75th Percentile**	**90th Percentile**
Hardware Engineer	$157k	$187k	$215k	$130k	$164k	$190k	$125k	$153k	$188k
Applications Engineer	---	$125k	$153k	$113k	$130k	$155k	$83k	$120k	$143k
Program Manager	$150k	$182k	$223k	$125k	$150k	$180k	$115k	$138k	$160k
Product Manager	$171k	$200k	$230k	$145k	$165k	$190k	$138k	$155k	$177k

Base Salary

Source: https://www.pave.com/

Compensation | Experienced

pave	High Cost of Living (e.g., SF, Seattle, NYC)			Mid Cost of Living (e.g., Chicago, Austin, Denver, Boston)			Low Cost of Living (e.g., Minneapolis, RTP, Atlanta)		
Title	**50th Percentile**	**75th Percentile**	**90th Percentile**	**50th Percentile**	**75th Percentile**	**90th Percentile**	**50th Percentile**	**75th Percentile**	**90th Percentile**
Hardware Engineer	$230k	$241k	$305k	$224k	$241k	$319k	$208k	$223k	$296k
Applications Engineer	$197k	$217k	$273k	$187k	$207k	$260k	$182k	$201k	$252k
Program Manager	$267k	$302k	$339k	$237k	$267k	$300k	$220k	$249k	$279k
Product Manager	$279k	$325k	$347k	$270k	$312k	$331k	$255k	$294k	$311k

Base Salary

Source: https://www.pave.com/

03 Talent | Overview

Headlines

H-1B Survey

Compensation

Workforce Development

Community

Workforce Development

| Top US Schools Powering The Battery Workforce

This map highlights the complete list of institutions recognized as top in the "**Fuels and Energy**" category according to the US News Ranking as well as the top 15 institutions highlighted in the QS World University Rankings in both "**Material Science**" and "**Chemistry.**"

Workforce Development

A Snapshot Of Institutions Powering The Future Of Batteries

Institution	Description	What It Means For Workforce Development
UTD THE UNIVERSITY OF TEXAS AT DALLAS	• DOD allocation of $30 million over 3 years. • Funding supports the development and commercialization of innovative battery technologies and manufacturing processes.	**UTD will work with community colleges in North Texas to provide training for skilled workers**. According to the **DOE's National Renewable Energy Laboratory 2020 report,** the battery energy storage sector is projected to require a minimum of 130,000 additional workers in the U.S. by 2030, with at least 12,000 of those workers needed in Texas.
N University of Nevada, Reno	• A group of researchers are working together through the Nevada Institute for Sustainability, a virtual organization at the University. • Focused on batteries research, and education and workforce training.	They **created a Batteries and Energy Storage Technologies Minor, the first of its type in the US**. Centerpiece of the minor is a hands-on laboratory in which students make and test their own lithium-ion batteries, starting with raw chemicals.
O THE OHIO STATE UNIVERSITY	• Plans underway to build a battery cell R&D center slated to open in April 2025. • The lab will accelerate domestic development of battery cell materials and manufacturing.	The **new facility will be used to train the next-generation workforce** in advanced manufacturing technologies.
TENNESSEE COLLEGES OF APPLIED TECHNOLOGY	• TCAT experiments with a free technical school to meet industry's demand for trained workers. • The campus in Smyrna opened in 2017, in partnership with Nissan Motor Co., which makes its electric cars nearby.	**Students "split their time between lectures and the shop – learning the theory and practice of welding pipes, troubleshooting hydraulic power systems, or programming robots to move battery parts."**

Source: UT Dallas; University of Nevada, Reno; Ohio State;; Tennessee College of Applied Technology

Workforce Development

2023 Battery Workforce Challenge

The Battery Workforce Challenge is a program put on by the DOE, Stellantis, and Argonne National Laboratory. This unique challenge **invites universities and vocational schools to collaboratively design, build, test, and integrate an advanced EV battery pack into a Stellantis vehicle.**

12 universities have joined forces with community colleges, trade schools, or other vocational partners to fulfill the competition requirements. The overarching objective is to equip a diverse workforce with the necessary skills for upcoming careers in battery engineering and manufacturing.

The Challenge kicked off Fall 2023. The winning team will receive a $100,000 award.

U.S. DEPARTMENT OF ENERGY

STELLANTIS

Managed by Argonne NATIONAL LABORATORY

Selected Universities & Vocational Partners

CAL STATE LA	↔	CERRITOS COLLEGE
CLEMSON UNIVERSITY	↔	Greenville Technical College
COLORADO SCHOOL OF MINES	↔	ACC ARAPAHOE COMMUNITY COLLEGE
JSU JACKSON STATE UNIVERSITY	↔	HINDS COMMUNITY COLLEGE
McMaster University	↔	MOHAWK COLLEGE
THE OHIO STATE UNIVERSITY	↔	COLUMBUS STATE COMMUNITY COLLEGE
ROSE-HULMAN INSTITUTE OF TECHNOLOGY	↔	IVY TECH COMMUNITY COLLEGE
THE UNIVERSITY OF ALABAMA	↔	SHELTON STATE COMMUNITY COLLEGE
UNIVERSITY OF CALIFORNIA MERCED	↔	MERCED COLLEGE
M DEARBORN	↔	HENRY FORD COLLEGE
UNLV	↔	CSN COLLEGE OF SOUTHERN NEVADA
UNIVERSITY OF WATERLOO	↔	Lambton College

Source: https://battchallenge.org/

UK Battery Workforce Development Programs

UK Increases Support for Battery Workforce Development, from Lab to Shop Floor

Skills Level	Initiative	Description
Level 2-4	Battery Workforce Training Initiative	£1.2m for the **Digital Enhanced Battery Ubiquitous Training-West Midlands** led by University College Birmingham with consortium partners Warwick Manufacturing Group (WMG), Cranfield University, RAVMAC and JLR. £1.3m for the **National Battery Training and Skills Academy** led by Newcastle University with consortium partner New College Durham.
Level 2-5	UKBIC Battery Manufacturing Training Program	UK Battery Industrialisation Centre (UKBIC) now offers **courses** including introduction to battery manufacturing and design courses. Funding provided by the Faraday Battery Challenge to develop **6 free training courses** to develop skills for the UK battery sector.
Level 2-8	UK Electrification Skills - National Electrification Skills Framework and Forum	**£700k to Coventry University** to deliver vision for coordinated and national approach to re-skilling, up-skilling and new-skilling the workforce at the **National Electrification Skills Framework and Forum** via new initiative called UK Electrification Skills
Level 3	Battery Manufacturing Technician Apprenticeship	Cogent skills facilitated a **Battery Manufacturing Technician Apprenticeship** which will enable learners to train as an electrode technician, cell assembly technician, formation, ageing & testing technician, or module & pack technician.
Level 8	Faraday Institution PhD Training Program	The Faraday Institution continues their **PhD training program** which provides enhanced training for top doctoral talent across disciplines aligned with the Faraday Institution research projects. **Recruitment** for October 2024 will open in March 2024.

Source: UKRI; UCB; Newcastle Uni; UKBIC; Eventbrite; InsiderMedia; HVMC; IFATE; FI - PhD; FI - Cohort 7

Workforce Development

| How Many Factory Jobs Will Battery Manufacturing Create?

The number of jobs created by battery factories depends on (1) **how are the jobs counted** (e.g. is module/pack assembly included?), (2) **process technology** employed by the manufacturer (e.g. level of automation, equipment outsourcing) and (3) **process maturity** (e.g. how many years have they had to refine their manufacturing processes?).

60 to 125 jobs per GWh
- McKinsey, 2022

(Consulting Firm)

McKinsey reported that, on average, new battery factories add approximately 80 jobs for every GWh of capacity. This number carries some uncertainty since differences in value-chain coverage, e.g. battery-cell production only versus local module and pack production or co-location of R&D facilities, are unclear.

65 to 162 jobs per GWh
- Electrek, 2018

(News Report)

The Electrek investigated a state audit report showing that the Tesla Gigafactory 1 reportedly employed 3,249 people when the factory was producing 20 GWh of annual output, including 1,201 Panasonic employees, 1,955 Tesla employees, and 93 employees from Heitkamp & Thumann Group a battery cell can supplier. The equivalent "jobs per GWh" depends on whether Tesla employees are included in the count.

35 jobs per GWh
- BatPaC v5.0, 2022

(Factory Model)

The BatPaC v5.0 baseline factory model reported an annual labor of 3,876,000 hours per year to produce 50 GWh of output. Assuming each worker works 2,236 hours per year (with a 43-hour work-week), this amounts to 35 workers per GWh.

44 to 119 jobs per GWh
- Cotterman et al., 2022

(Research Paper)

Cotterman et al. reported labor intensity (LI) per EV powertrain assuming a 60 kWh pack. LI varied by data source and whether pack/module assembly was included. For the available data, LI ranged between 11-16 hours with industry sources and 6-15 hours with public sources. With 2,236 hours worked per year, this translates to 44 to 119 workers per GWh.

Workforce Development

UAW: A New Driver Of The Battery Workforce

The 2023 United Auto Workers (UAW) strike and resulting deal signals the first collective acknowledgement from traditional auto workers in the U.S. that the **future of auto manufacturing and battery manufacturing are intertwined.** It is the latest in a series of negotiations and changing sentiments since the Great Recession.

*The Big 3's **profits rose 92%** while workers' inflation-adjusted **pay fell 19%***

2007-08

Concessions Amid Crisis

- **The Big 3 (Chrysler/Stellantis, Ford, GM) faced major losses**
- To prop up them up, UAW **conceded pay raises, cost-of-living protections, retiree healthcare**

2019

First Negotiation to Involve Batteries

- After 40-day strike against GM, **workers won 3% pay raise** but **conceded Lordstown, OH car plant closure**
- During negotiations, **GM had proposed new battery plant in Lordstown**
- **UAW rejected battery plant because it offered fewer jobs, lower pay under separate contract**

2023

Beginning of a Battery-Aligned UAW

- Historic strike against all of Big 3 yielded **25% pay raise, return of cost-of-living protections**
- **UAW can now organize GM/Ultium and Ford workers at new MI and TN battery plants and BlueOval EV campus in TN**
- **ICEV workers can transfer to EV plants**

What could the future look like?

U.S. battery manufacturing jobs may pay more. In turn, companies may slow construction of U.S. battery plants and reconsider their non-U.S. options.

More ICEV workers may be open to switch to battery/EV plants. Companies, educators, and policymakers should increase support for skills retraining.

Source: Peoplesdispatch.org

Workforce Development

Layoffs Happening Simultaneously As Industry Recalibrates Focus

	Company	Workforce Reduction	Reason
Startup	one our next energy	25%	The company said the decision was “in response to market conditions,” without elaborating. (**Bloomberg**)
	Lucid	18%	Lucid cuts approximately 1,300 employees, 18% of its workforce, to lower operating expenses and preserve cash ahead of releasing a second model this year. (**WSJ**)
	RIVIAN	6%	Rivian is focusing resources on ramping up vehicle production and reaching profitability. (**Reuters**)
	ENOVIX	185 workers	Enovix lays off employees as it shifts most of its operations to Malaysia (**The Information**)
Established	gm	1300 workers	GM plans to lay off about 1,300 workers in Michigan due to vehicles they produce ending production. (**CNBC**)
	Ford	700 workers	Ford cited "multiple constraints, including the supply chain and working through processing and delivering vehicles held for quality checks after restarting production in August” for the layoffs (**Motley Fool**)
	LG Energy Solution	170 workers from MI plant (10% of workforce)	Layoffs due to a “production gap and automakers realigning the speed of the EV transition.” (**Automotive Dive**)
	SK on	100+ workers from Georgia plants	SK On slowing expansion in response to sluggish demand. (**Financial Times**)

03 Talent | Overview

Headlines

H-1B Survey

Compensation

Workforce Development

Community

Community | Popular Content In 2023

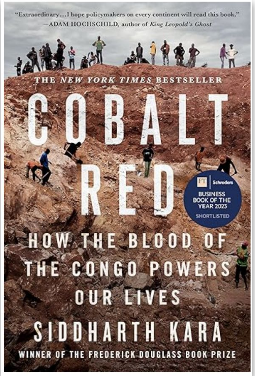
Newsletters

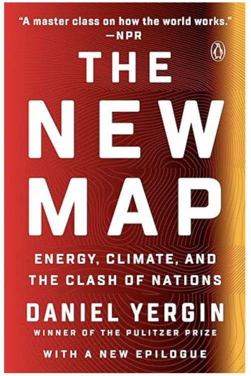
- This Week in Batteries (TWIB)
- Intercalation Station Newsletter
- The Electric by Steve LeVine
- Better Batteries Newsletter
- Lithium Valle Newsletter
- Green Rocks Newsletter

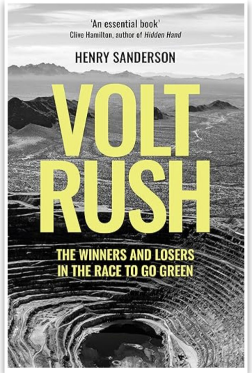
Content

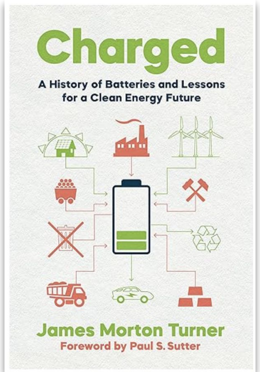
- The Limiting Factor YouTube
- The Global Lithium Podcast
- Recharge by Battery Materials Review
- Battery Generation Podcast
- Battery + Storage Podcast
- Redefining Energy

Books









04 Policy

The Volta Foundation is an independent non-profit professional association dedicated to supporting the growth of the Battery Industry.

04 Policy | Overview

In 2023, a sweeping global transition is evident as nations prioritize sustainable practices and actively pursue the safeguarding of critical mineral supplies.

In North America, strides are made with updates to IRA EV tax credits, reflecting a commitment to incentivize electric vehicle adoption. Meanwhile, in Europe, significant regulatory frameworks come into play with the introduction of the Battery Regulation and the implementation of the Critical Raw Materials Act, signaling a strategic move toward securing a stable domestic supply of essential battery materials. Simultaneously, China responds to global dynamics by enacting graphite export controls. India takes a bold step forward with the launch of the national Advanced Cell Chemistry program. Mineral rich nations seek to protect and leverage their strategic natural resources: Australia unveils the Critical Mineral Strategy, and Emerging Markets and Developing Economies make proposals for critical mineral strategies.

Beyond regional boundaries, nations worldwide are actively pursuing financial incentives to catalyze innovation, bolster local battery manufacturing capabilities, and fortify supply chains.

Policy Summary **North America** **Europe**
Asia **Rest Of World**

04 Policy | Overview

Policy Summary

North America

Europe

Asia

Rest Of World

Policy Summary | A Year In Battery Policy

2023: The year of more policy incentives, regulation for sustainability and securing critical mineral supply

Global policy takeaway/trends

North America:
- IRA EV tax credit updates.
- Initiatives to promote onshoring and EV sales including introduction of 'Foreign Entity of Concern' rules.

Europe:
- Europe favours introduction of new battery regulation to stimulate sustainability.
- Announcement of Critical Raw Materials Act to secure domestic battery material supply.
- Late 2023 announcements for additional financial incentives to boost innovation, local manufacturing and supply chain.

Asia:
- China introduces graphite export controls in response to US and EU preventing Chinese manufactured BEV access to incentives.
- China invests in non-domestic upstream supply.
- India launches national Advanced Cell Chemistry program..

Rest of World:
- Emerging Market and Development Economy nations seek to strategically leverage critical mineral resources but fall behind in EV policy.
- Australia introduces Critical Mineral Strategy.

04 Policy | Overview

Policy Summary
North America
Europe
Asia
Rest Of World

North America | US IRA Tax Credit | Summary

US seeks to grow EV sales and onshore manufacturing

Incentive for consumers and OEMs:
Clean Vehicle Tax Credit (30D)

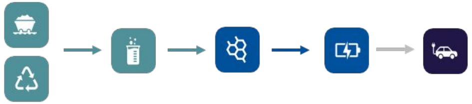
New vehicles[4] must satisfy two conditions to qualify for a purchase tax credit up to $7,500:

①  Assembled in North America

+

② **Foreign Entity of Concern (FEOC) compliant:** Vehicles may not contain any critical minerals (from 2025) or battery components (from 2024) that were extracted, processed, or manufactured by a FEOC.

Vehicles must also meet **critical mineral** and **battery component** requirements, each accounting for 50% of the total credit:



Part 1: Critical Mineral Requirement $3,750
Minimum % value of critical minerals[1] in the battery must be extracted OR processed[2] in the US or Free Trade Agreement country.

Part 2: Battery Component Requirement $3,750
Minimum % value of components[3] in the battery must be manufactured OR assembled in North America.

	2023	2024	2025	2026	2027	2028	2029
Minerals	40%	50%	60%	70%	80%	80%	80%
Component	50%	60%	60%	70%	80%	90%	100%

Incentive for suppliers:
Advanced Manufacturing Production Tax Credit (45X)

Battery components[3] and critical minerals[5] produced in the US may qualify for tax credits under certain requirements.

	2023 Full credit	2030 75% credit	2031 50% credit	2032 25% credit
Battery modules ($/kWh)	**10.00**	**7.50**	**5.00**	**2.50**
Battery cells ($/kWh)	**35.00**	**26.30**	**17.50**	**8.80**
Electrode active materials (% of production cost)	**10.0**	**7.5**	**5.0**	**2.5**
Critical minerals (% of production cost)[5]	**10.0**	**7.5**	**5.0**	**2.5**

Notes:
1- Critical minerals applicable to batteries include: Li, Ni, Co, Mn, graphite, among trace minerals
2- Processing means the refining of minerals into constituent materials include powder of CAM and AAM, foils, electrolyte sales and additives etc.
3- Battery Components include: electrode, electrolyte, separator, battery module
4- Selling price must not exceed $80k for vans, SUVs, and pickup trucks, and $55k for other vehicles
5- As per latest guidance, the cost of raw material extraction of acquisition used to produce the critical mineral or active material is excluded from the tax credit

Source: US Treasury, US Treasury, CRU Group

North America | US IRA EV Tax Credit (30D) | Update

Proposed guidance issued on Foreign Entity of Concern (FEOC) rule

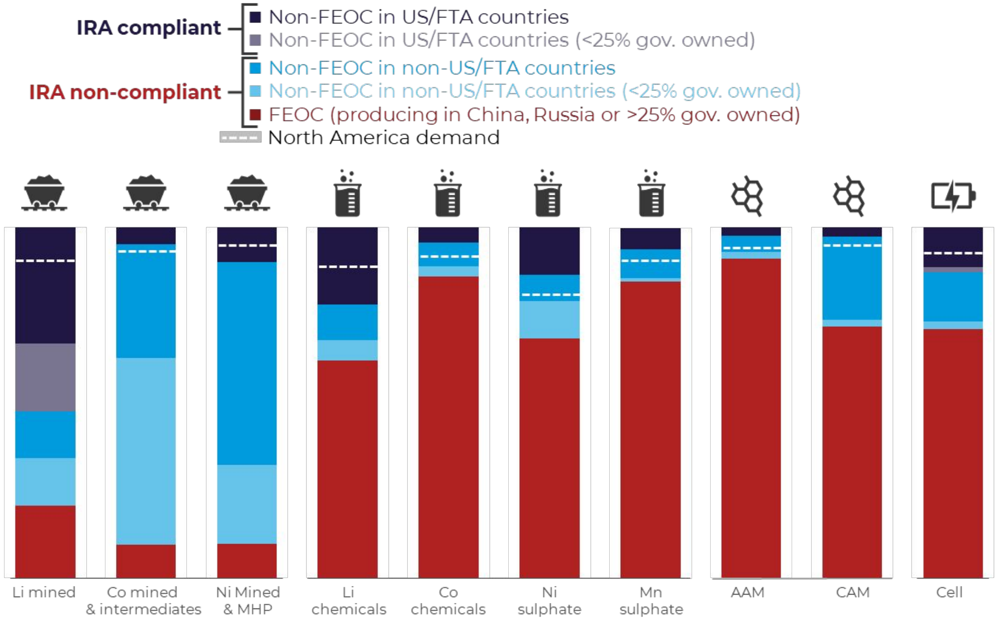
To qualify for tax credits, vehicles may not contain any critical minerals (from 2025) or battery components (from 2024) that were extracted, processed, or manufactured by an FEOC.

In December 2023, officials used further proposed guidance on this rule.

Most common interpretation:
FEOC applies to all production within China and Russia, and any company that has greater than __25% ownership by the governments__ of those countries.*

**Specifically, the government, military, and family members of senior officials.*

Battery supply chain production by IRA 30D tax credit eligibility in 2025, %



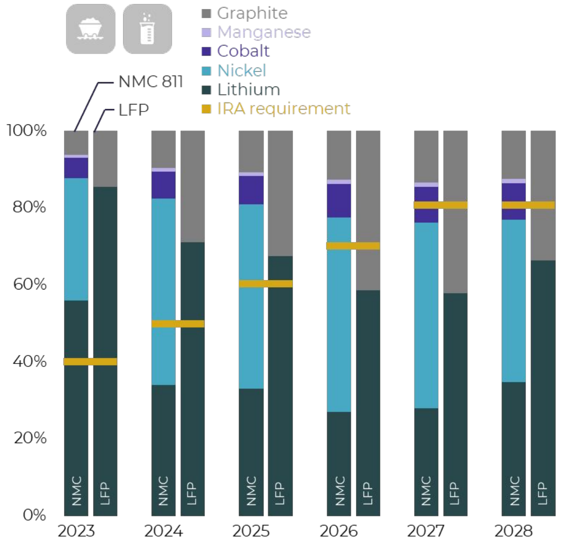
Source: US Treasury, CRU Group

VF | VOLTA FOUNDATION

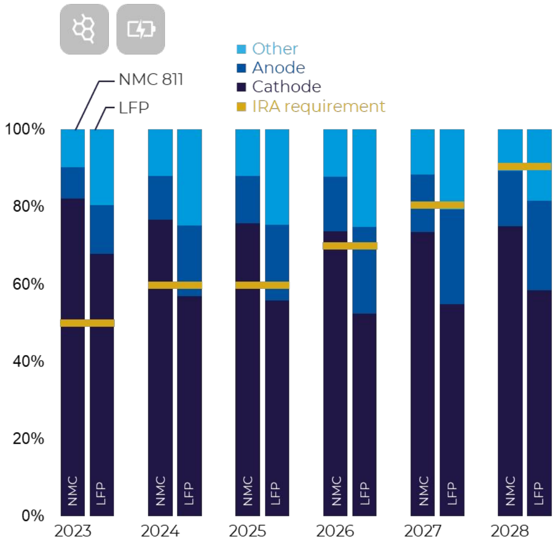
North America | US IRA EV Tax Credit (30D) | Update

Manufacturers face increasingly stringent criteria for mineral and component sourcing to receive tax credits

Critical mineral value makeup of battery cells built in US vs. IRA requirement, % $/kWh



Battery component value makeup of battery cells built in US vs. IRA requirement, % $/kWh



NOTE: Data based on modelling a 35 Ah pouch cell produced in the US, excluding processing and labour costs. Aluminium and copper are assumed to be excluded from value calculation. There will be differences in costs of critical minerals and battery components between the US and other countries, which will affect the value makeup.

As thresholds become more stringent over time, automakers will need to source supply for more components that are dominated either by a non-FTA country or by China. The latter would fall under the FEOC rule.

Cobalt from DRC, nickel from Indonesia, LFP cathode, graphite anode, and high purity manganese from China are the most profound examples.

Source: US Treasury, CRU Group

04 Policy | Overview

Policy Summary

North America

Europe

Asia

Rest Of World

Europe | The Green Deal Industrial Plan

EU steps up to de-risk investment, increase supply chain resilience and energy independence

The Green Deal Industrial Plan (GDIP) was announced in 2023 to enhance the competitiveness of Europe's net-zero industry and accelerate the transition to climate neutrality. It is designed to create a more supportive environment for scaling up the EU's manufacturing capacity for the net-zero technologies and products required to meet Europe's climate targets. GDIP is broad and covers many different technologies, including batteries.

The Green Deal Industrial Plan is comprised of 4 pillars:

Predictable and simplified regulatory environment

Battery relevant initiatives:

- Critical Raw Materials Act

Faster access to funding

Battery relevant initiatives:

- InvestEU €372bn between 2021-27
- Innovation Fund €40bn over next decade of which **€3bn announced in 2023** dedicated to cell production
- Strategic Technology for Europe Platform (clean technologies)

Enhancing skills

Battery relevant initiatives:

- European Skills Agenda
- Partnership for Skills

Open trade for resilient supply chains

Battery relevant initiatives:

- Free Trade Agreements
- Critical Raw Materials Club
- Clean Tech/Net-Zero Industrial Partnerships

Source: GDIP; GDIP explainer;InvestEU; Dedicated instrument for battery value chain

Europe | EU Critical Raw Materials Act

EU provisionally approved Act to secure domestic supply of raw materials

In **March 2023**, the European Commission put forward a proposal for establishing a framework for ensuring a secure and sustainable supply of critical raw materials.

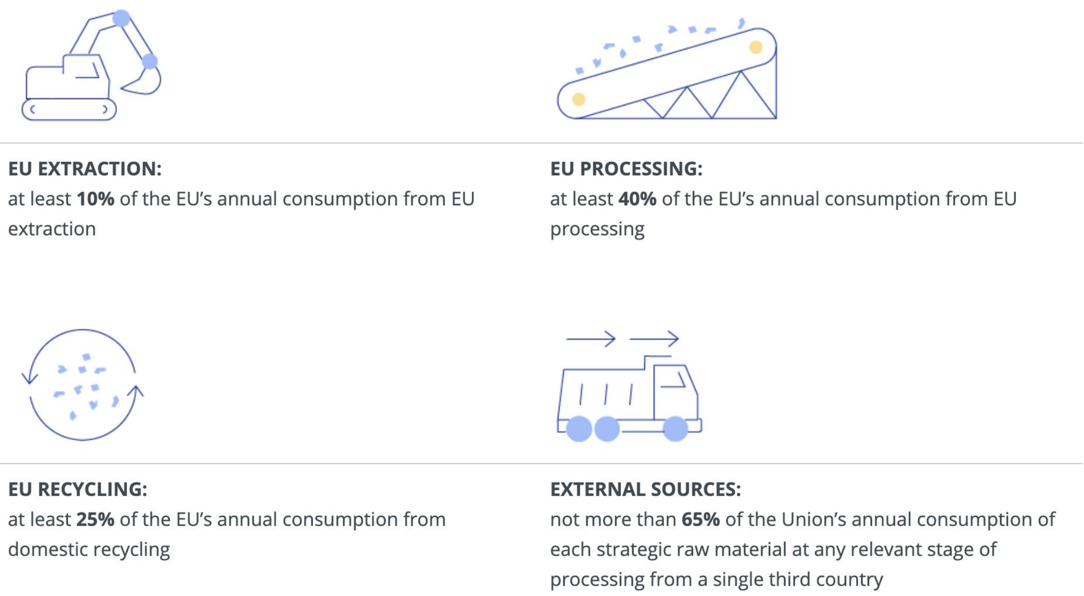
A provisional agreement was reached in **November 2023**.

The act aims to:

- increase and diversify the EU's critical raw materials supply
- strengthen circularity, including recycling
- support research and innovation on resource efficiency and the development of substitutes

The Critical Raw Materials Act is part of the European Green Deal and EU Industrial Strategy.

2030 targets for the Critical Raw Materials Act:



EU EXTRACTION:
at least **10%** of the EU's annual consumption from EU extraction

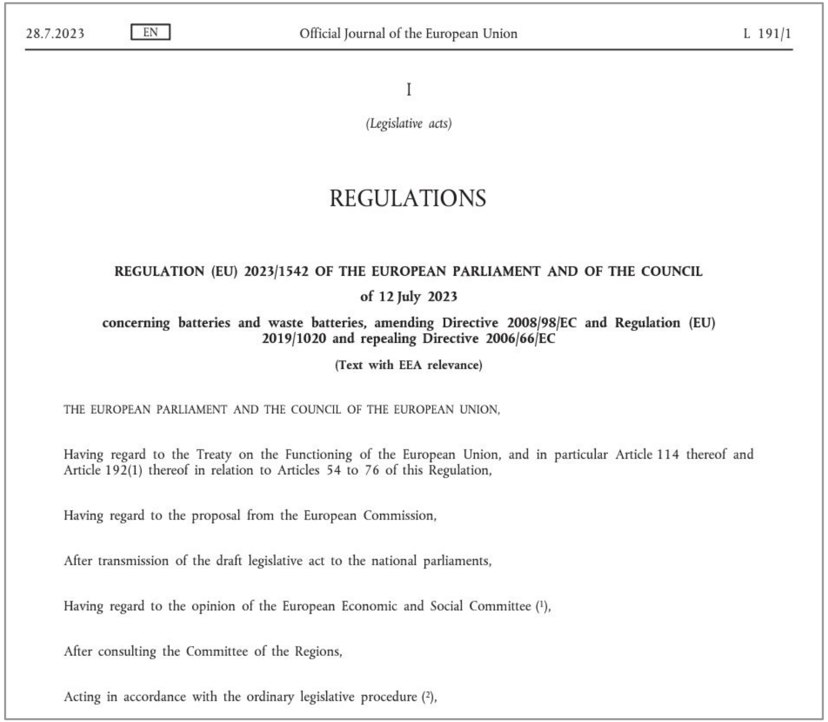
EU PROCESSING:
at least **40%** of the EU's annual consumption from EU processing

EU RECYCLING:
at least **25%** of the EU's annual consumption from domestic recycling

EXTERNAL SOURCES:
not more than **65%** of the Union's annual consumption of each strategic raw material at any relevant stage of processing from a single third country

Source: Proposal; Provisional Agreement; CRM Act Infographic;

Europe | The EU Battery Regulation



28.7.2023 EN Official Journal of the European Union L 191/1

I

(Legislative acts)

REGULATIONS

REGULATION (EU) 2023/1542 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 12 July 2023

concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC

(Text with EEA relevance)

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty on the Functioning of the European Union, and in particular Article 114 thereof and Article 192(1) thereof in relation to Articles 54 to 76 of this Regulation,

Having regard to the proposal from the European Commission,

After transmission of the draft legislative act to the national parliaments,

Having regard to the opinion of the European Economic and Social Committee (1),

After consulting the Committee of the Regions,

Acting in accordance with the ordinary legislative procedure (2),

The European regulation on batteries and waste batteries was approved by the European Parliament on July 12, 2023, and will come into effect on February 18, 2024.

The document is part of the EU Green Deal. It constitutes the regulatory framework for the battery sector in the European market for the next decades.

The macro areas that the regulation affects include:

- **Sustainability** (battery carbon footprint declaration and supply chain due diligence)
- **Circularity** (Well-defined extended producer responsibility and recycling targets)
- **Digitalization** (labelling and battery digital product passport)

Source: EU Batteries Regulation

Europe

| The EU Battery Regulation

The Battery Regulation chapters, articles, and paragraphs will not be applied simultaneously but will follow a time interval from 2024 to 2037. Moreover, within the regulation, several Delegated Acts and Implementing Acts are foreseen, which will be crucial to fill gaps in regulation, standardize its implementation, and adapt it to future technical and market developments. The publication of these acts is expected between 2024 and 2031.

2023

Approval of the Regulation

2024

Access to SOH data for battery owners and operators

2025

- Due diligence policies
- Carbon footprint declaration for EV batteries
- 65% target for recycling efficiency

2026

Methodology for calculation and verification of recycled content

2027

- Battery passport requirements
- Mineral recovery targets:
  - 50% Li
  - 90% Co, Ni, Cu

2028

- Performance and durability requirements
- Recycled content declaration
- Maximum carbon footprint threshold for EV batteries

2029

2030

- 70% target for recycling efficiency

2031

- Recycled content targets for new batteries:
  - 16% cobalt
  - 85% lead
  - 6% lithium
  - 6% nickel
- Mineral recovery targets:
  - 80% Li
  - 95% Co, Ni, Cu

2036

Recycled content for new batteries:

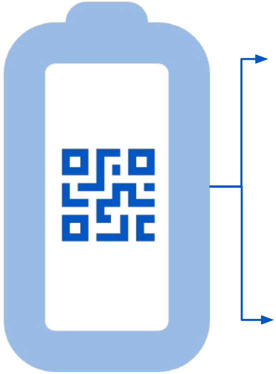
- 26% cobalt
- 85% lead
- 12% lithium
- 15% nickel

Source: EU Batteries Regulation, EU recycling market study Strategy& | PEM of RWTH Aachen University

Europe | The Framework Of The EU Battery Passport

The battery passport will introduce new data sharing obligations

Beginning in February 2027, the European Union will mandate an electronic "battery passport" (an example of Digital Product Passport - DPP) for mobility and stationary batteries.



Battery model information (‘static’ data)

- **Accessible publicly**: e.g., material composition, carbon footprint, recycled content, expected lifetime in cycles, rated capacity, weight, manufacturer, place of manufacture;
- **Accessible to persons with ‘legitimate interest’**: detailed composition, part numbers for components, dismantling info and safety measures;
- **Accessible to notified bodies, market surveillance authorities and the Commission**: results of test reports proving compliance with the Regulation.

Individual battery information (‘dynamic’ data):

- **Accessible to persons with ‘legitimate interest’:**
  - Performance and durability parameters;
  - State of health information;
  - Status of the battery (‘original’, ‘repurposed’, ‘re-used’, ‘remanufactured’ or ‘waste’);
  - Usage data: number of cycles, accident, operating conditions and state of charge.

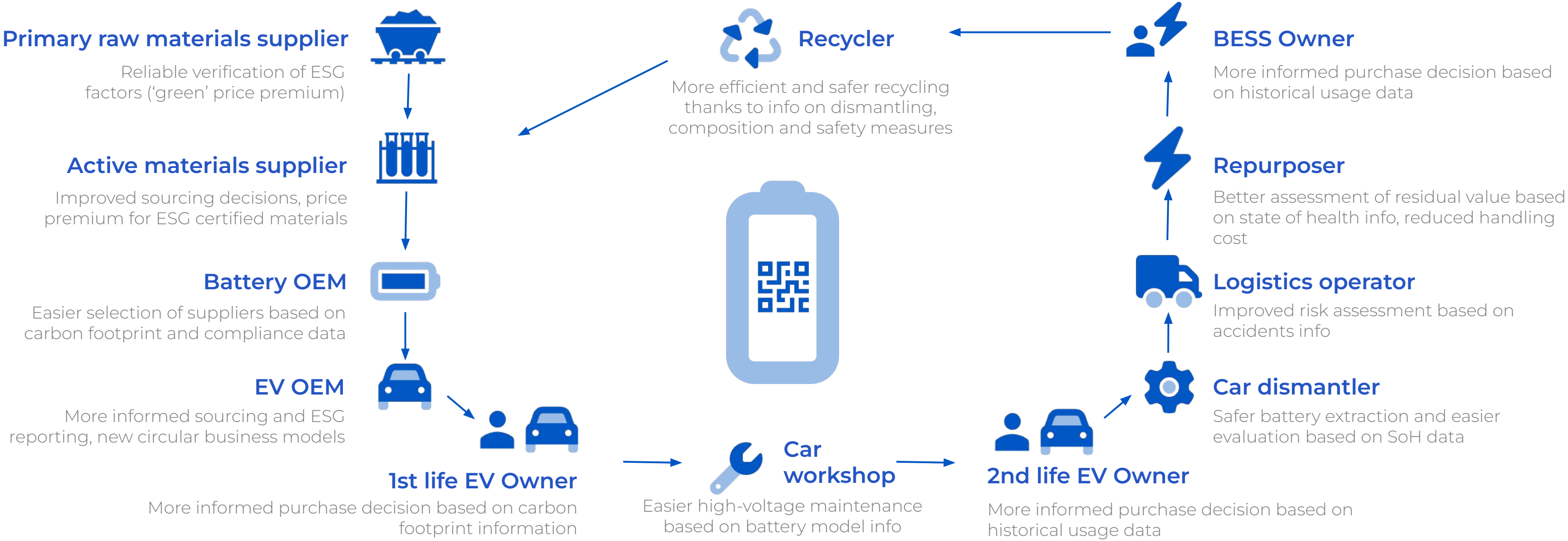
Beginning in August 2026, the Commission will provide guidance on which person(s) constitute a ‘legitimate interest’. Detailed information from the battery management system shall be provided respecting the intellectual property rights of the battery manufacturers.

Source: EU Batteries Regulation

Europe | The Impact Of The Battery Passport

The whole battery value chain to be affected by the new data sharing rules

The information sharing mechanism introduced by the Battery Regulation will impose new reporting obligations and significantly influence operations throughout the battery value chain, generating value across various use cases.



Primary raw materials supplier
Reliable verification of ESG factors ('green' price premium)

Active materials supplier
Improved sourcing decisions, price premium for ESG certified materials

Battery OEM
Easier selection of suppliers based on carbon footprint and compliance data

EV OEM
More informed sourcing and ESG reporting, new circular business models

1st life EV Owner
More informed purchase decision based on carbon footprint information

Car workshop
Easier high-voltage maintenance based on battery model info

2nd life EV Owner
More informed purchase decision based on historical usage data

Car dismantler
Safer battery extraction and easier evaluation based on SoH data

Logistics operator
Improved risk assessment based on accidents info

Repurposer
Better assessment of residual value based on state of health info, reduced handling cost

BESS Owner
More informed purchase decision based on historical usage data

Recycler
More efficient and safer recycling thanks to info on dismantling, composition and safety measures

Source: EU Batteries Regulation, Battery Pass, COBRA Market Intelligence Report

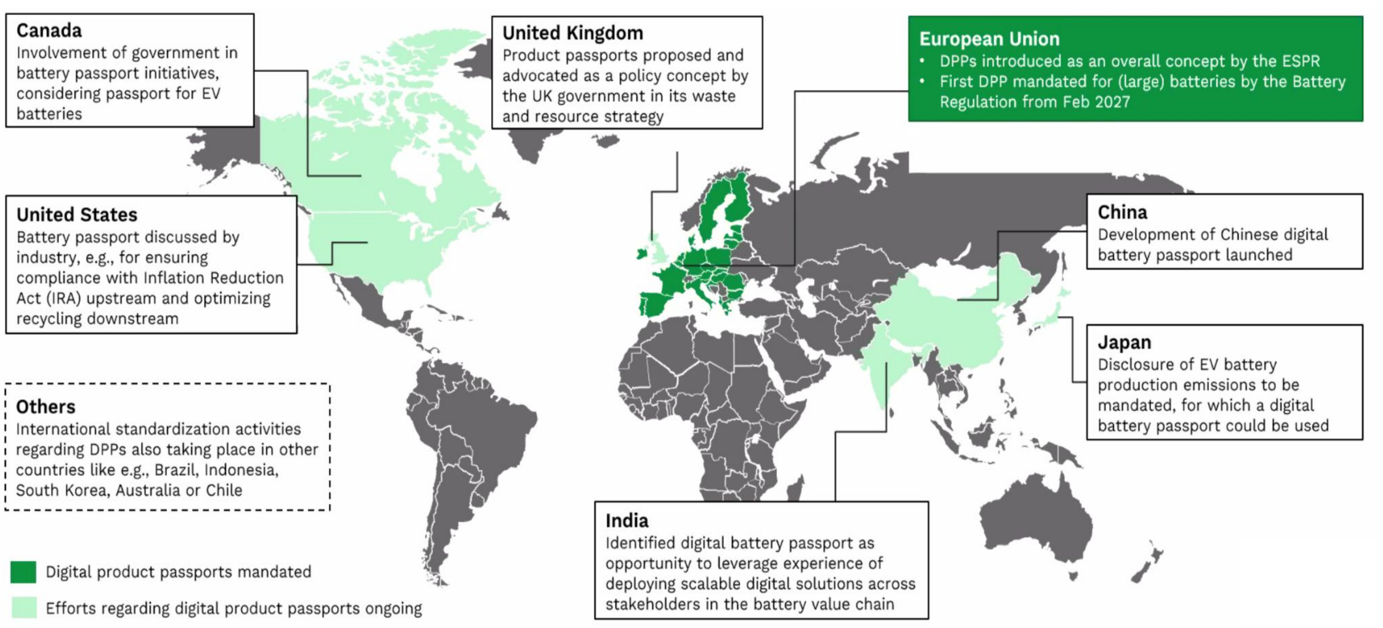
Europe | The Battery Passports

Comparison with other regional regulations

The European Battery Passport is a Digital Product Passport (DPP) that is a digitization initiative to ensure transparency and promote sustainability in the battery value chain.

Currently, numerous other countries are exploring comparable regulations.

An essential consideration lies in understanding how these diverse frameworks could effectively operate with each other.



Canada
Involvement of government in battery passport initiatives, considering passport for EV batteries

United States
Battery passport discussed by industry, e.g., for ensuring compliance with Inflation Reduction Act (IRA) upstream and optimizing recycling downstream

Others
International standardization activities regarding DPPs also taking place in other countries like e.g., Brazil, Indonesia, South Korea, Australia or Chile

United Kingdom
Product passports proposed and advocated as a policy concept by the UK government in its waste and resource strategy

European Union
- DPPs introduced as an overall concept by the ESPR
- First DPP mandated for (large) batteries by the Battery Regulation from Feb 2027

China
Development of Chinese digital battery passport launched

Japan
Disclosure of EV battery production emissions to be mandated, for which a digital battery passport could be used

India
Identified digital battery passport as opportunity to leverage experience of deploying scalable digital solutions across stakeholders in the battery value chain

🟩 Digital product passports mandated

▨ Efforts regarding digital product passports ongoing

Source: thebatterypass.eu

Europe | UK Strategy Update

UK responds to industry demands for a coordinated approach to batteries


Department for Business & Trade

Advanced Manufacturing Plan


Department for Business & Trade

UK Battery Strategy

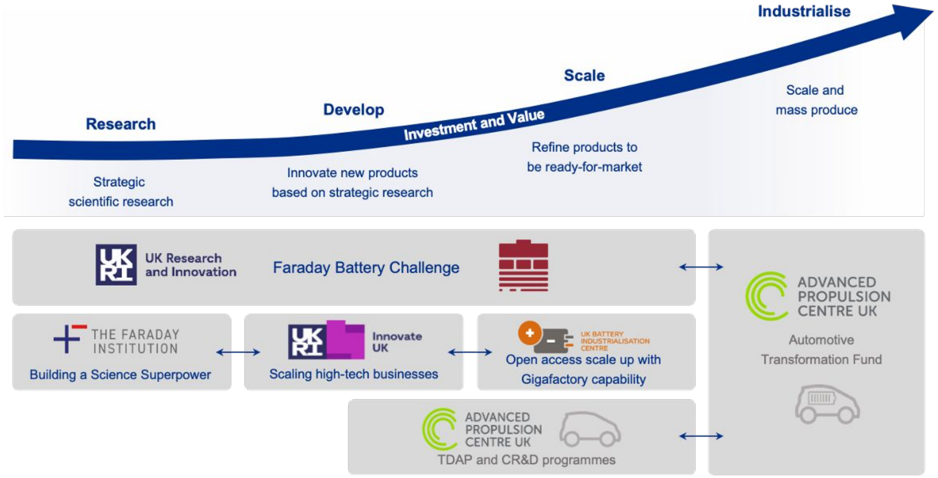
UK Government published the UK Battery Strategy, focusing on 3 key pillars: **Design | Build | Sustain.**

With £2bn of financial support for the Auto2030 program, as part of the Advanced Manufacturing Plan which provides £4.5bn of public funding to support the UK's manufacturing ambitions.

The Critical Mineral Strategy, published in 2022, was refreshed with more details on how it will be delivered and includes commitments to international partnerships to secure material supply.

The strategies also commit to enabling a favorable regulatory environment and new financial instruments for crowding in private funding with public money.

Grant funding available in the UK to support research, development, scale-up and industrialization of batteries:



Research

Strategic scientific research

Develop

Innovate new products based on strategic research

Investment and Value

Scale

Refine products to be ready-for-market

Industrialise

Scale and mass produce

UK Research and Innovation — Faraday Battery Challenge

The Faraday Institution — Building a Science Superpower

Innovate UK — Scaling high-tech businesses

UK Battery Industrialisation Centre — Open access scale up with Gigafactory capability

Advanced Propulsion Centre UK — TDAP and CR&D programmes

Advanced Propulsion Centre UK — Automotive Transformation Fund

Source: UK Battery Strategy; Advanced Manufacturing Plan; Critical Mineral Strategy Refresh

Europe | European Innovation Funding

Europe continues to provide strong incentives to support battery innovation

EU Commission launches **€4bn** 2023 Innovation Fund for innovative decarbonization technologies including energy storage (alongside **€3bn** for batteries):

	Budget	Min. CAPEX	Summary
Large scale general decarbonization	€1.7bn	€100m	Construction and operation of innovative energy storage technologies
Medium scale general decarbonization	€500m	€20m to €100m	
Small scale general decarbonization	€200m	€2.5m to €20m	
Cleantech manufacturing	€1.4bn	€2.5m	Includes improving scale-up, supply chain resilience and strategic autonomy in Europe
Pilot	€200m	€2.5m	A higher degree of innovation is expected than the other topics

Faraday Battery Challenge

Delivered by Innovate UK

£11m awarded to battery innovation projects.

£36m and **£38m** to upgrade the UK Battery Industrialisation Centre.

£12m to create the Advanced Materials Battery Industrialisation Centre.

ADVANCED PROPULSION CENTRE UK

£86.9m to 16 projects for scale-up and R&D of net-zero vehicle technology (of which 12 are focused on batteries for EVs and their supply chains).

Source: Innovation Fund; Battery Supply Chain Fund; Innovate UK KTN; UKBIC-£36m; UKBIC-£38m; InnovateUK KTN-AMBIC; APC

Europe | Major EV Policy Changes In 2023

European nations revise EV incentives and ICE phase out policies

European Commission:

- Approves **extension** of the current rules of origin for electric vehicles and batteries under the Trade and Cooperation Agreement with the UK until 31st December 2026. Also confirms that it will be it legally impossible for the Council to extend this period.
- A guide to the **tax benefits and purchase incentives** available for EVs for the EU member states in 2023.

France:

- Introduces **'Bonus Écologique'** which will favor vehicles produced in France and Europe over models made in China. The subsidy is dependent on the vehicle production and transportation CO2 emissions
- Launches **EUR100** per month EV leasing scheme.

Germany:

- Reaches agreement with EU commission to **amend 2035 internal combustion engine ban** to allow sale and registration of ICE vehicles after 2035, as long as they are powered with 'carbon neutral' e-fuels.

United Kingdom:

- **Revised plans around the phase out of ICE vehicle sales.** The new rules state that in 2030 80% of all new car sales and 70% of all new van sales must be zero emission (at the tailpipe). In 2035 100% of these sales must be zero emission.

Source: RoO extension; ACEA incentives list; Rho Motion - France updates; SAE - German agreement with EU; UK Gov - ICE sales

04 Policy | Overview

Policy Summary

North America

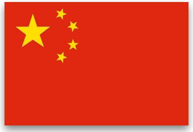
Europe

Asia

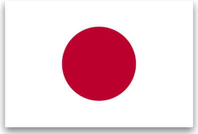
Rest Of World

Asia | Incumbents Battery Policy Objectives & 2023 Updates

Proactive policies and incentives to maintain industry leadership



- Policy objectives to **2025**:
    - Improve supply of Li, Ni and Co
    - Achieve breakthrough of new power battery systems (e.g. Li-S), targeting 500Wh/kg at cell level
    - Global leader in recycling with >98% rate for Ni, Co and Mn and 85% for Li.
- **Millions in CNY** available for battery innovation funding incentives.
- Support for EVs shifts from purchase subsidy to **tax exemption**. New EVs purchased by 31/12/25 are exempt from vehicle purchase tax.
- **Guideline** on the trial work of the comprehensive electrification of vehicles in the public domain issued, focusing on public transport, service vehicles and charging infrastructure.



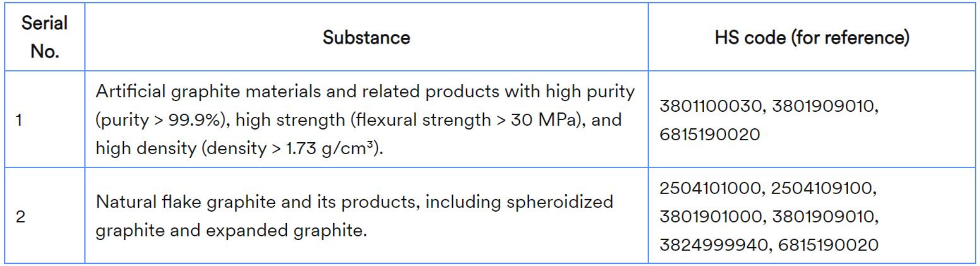
- Policy objectives to **2030**:
    - Increase domestic secondary battery production to 150GWh/year
    - Commercialize all-solid-state-batteries at scale
    - Reduce GHG by 46% from 2013
    - 30k trained battery and supply chain workers
    - In-vehicle battery pack price max of 10k yen/kWh, household BESS price max of 70k yen/kWh
- Up to **$2.2bn** in new support for production of batteries in Japan.
- **Deal struck with US** to secure **supply of EV battery minerals** and enable Japanese OEM access to US $7,500 EV tax credit.

- 2023 Battery industry roadmap proposal with following aims:
    - Increase domestic production capacity of CAM to **1.58mt**
    - Increase export of battery equipment to KRW 3.5bn over next 5 years
    - 100% of all secondary batteries to be recycled
    - 40% global market share by 2030
- **2023-2030 public-private joint R&D** innovation fund launched and > KRW 20 trillion to be committed to commercializing advanced battery technologies by 2030.

Source: China Policy Explainer; China Dialogue; Gov.cn; Japan Policy Explainer; Reuters-$2.2bn; Reuters-US Trade Deal; US-Japan Trade Deal; South Korea Policy Explainer; Korea Herald

Asia | Chinese Graphite Export Restrictions

From Dec 2023, operators must apply for special licenses to export graphite products outside China



Serial No.	Substance	HS code (for reference)
1	Artificial graphite materials and related products with high purity (purity > 99.9%), high strength (flexural strength > 30 MPa), and high density (density > 1.73 g/cm³).	3801100030, 3801909010, 6815190020
2	Natural flake graphite and its products, including spheroidized graphite and expanded graphite.	2504101000, 2504109100, 3801901000, 3801909010, 3824999940, 6815190020

China dominates the supply of natural and synthetic graphite and anode active material

China exports over:

- 100kt per annum natural graphite, principally to Japan, South Korea, USA, India and Europe;
- 60kt per annum spherical graphite, principally to Japan, South Korea and USA
- 80kt per annum AAM (principally to Japan, South Korea and USA).

Chinese dominance in graphite supply is fuelling search for alternative sources (see Raw Materials Section in Industry for further background).

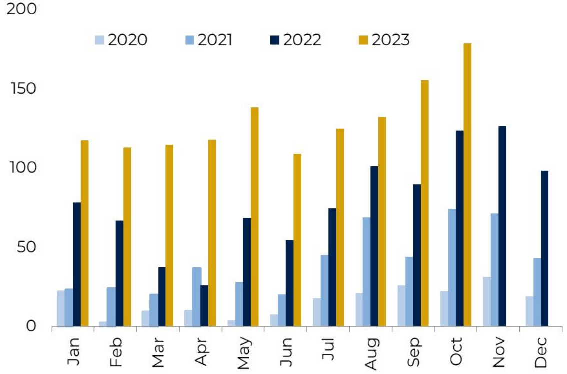
Source: CIRS, Syrah Resources

Asia | How Governments Are Responding To Chinese BEV Imports

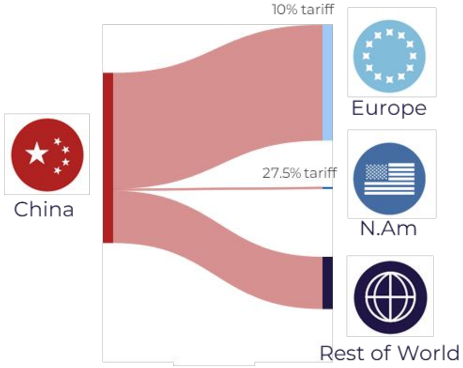
EU anti-subsidy probe

4th October 2023: European Commission launches **investigation into Chinese EV subsidies** claiming that "the global market is flooded with cheaper electric vehicles, the price of which is kept artificially low owing to huge state subsidies" . *"It may result in the Commission levying countervailing tariffs on EU imports of BEVs from China"*

Chinese BEV exports grew 123%



Almost 30% of EU BEV sales in 2023 were imported



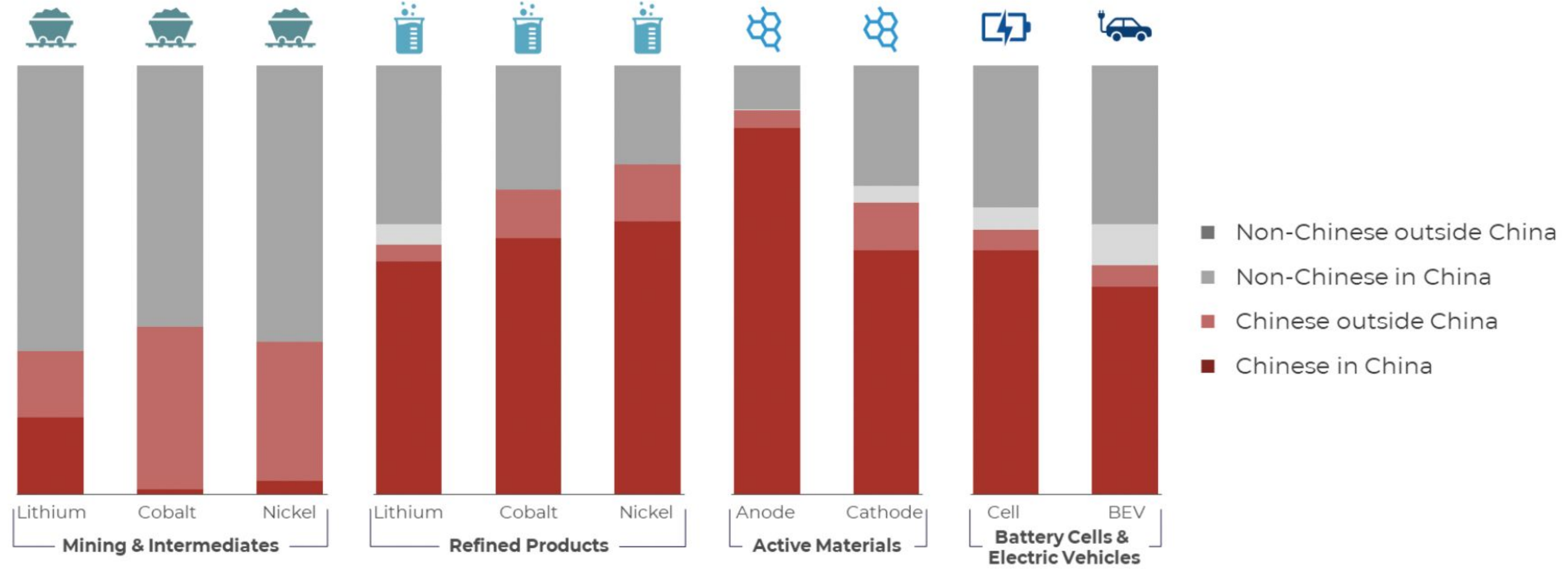
Most exports from China are western OEMs, but Chinese are growing in share

Source: European Commission, CRU Group, CRU Group

Asia | **Geopolitics Of Batteries**

Chinese battery investments go global

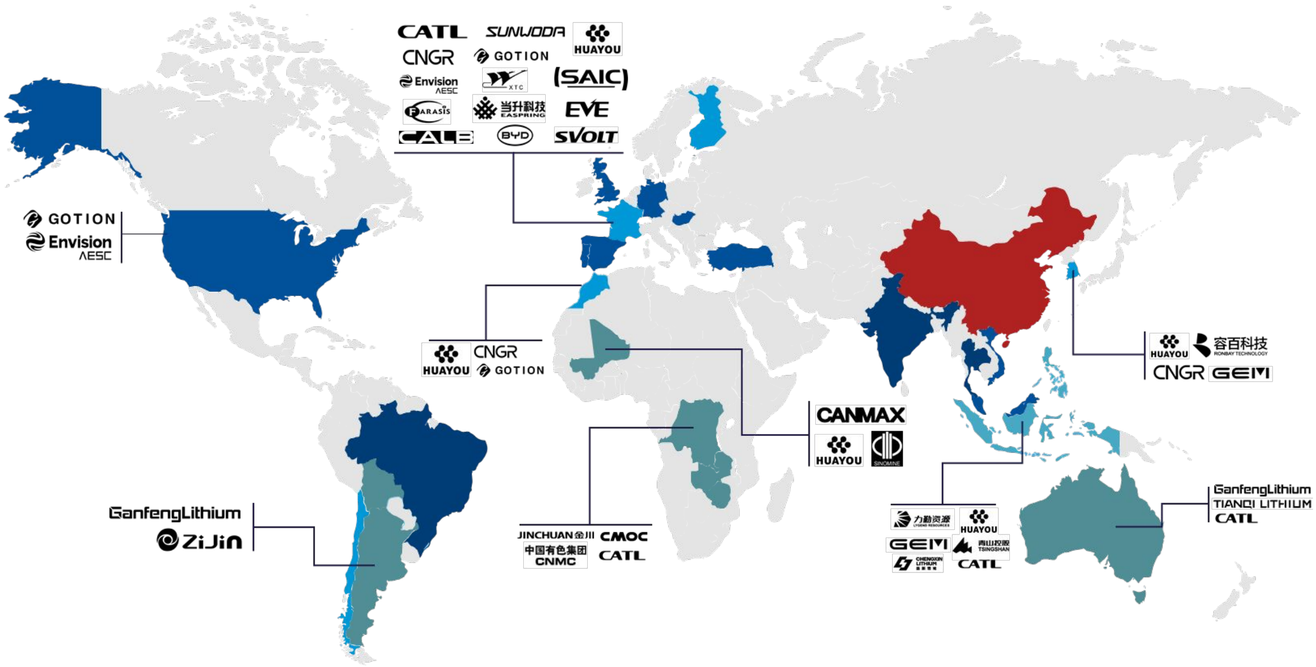
Battery supply chain production by equity ownership, 2028 forecast, %



Source: CRU Group

Asia | # Geopolitics Of Batteries

Chinese Battery Investments Go Global



Raw & Refined Materials

Spurred on by state support, Chinese mining companies are acquiring stakes in assets on all continents to secure a cheap and stable supply.

Active Materials & Battery Cells

Chinese battery cell and cathode manufacturers are establishing partnerships and a production presence in other regions.

Electric Vehicles

Chinese automakers are aggressively expanding exports and are planning to localise production to bypass trade tariffs.

Source: CRU Group

Asia | **India** | Energy Storage Sector Review 2023

Top Developments In Energy Storage Sector Across Policies, Regulations, Announcements in India in 2023

1. **Framework** for ESS and Guidelines for promoting Pumped Hydro, Guidelines issued for competitive bidding of RE+ESS projects
2. Viability Gap Funding (VGF) for 4 GWh of Standalone BESS projects (**INR 3,760 Crores**) approved by Government
3. Central Electricity Regulatory Commission **(CERC)** allowed ESS to participate in High Price – Day Ahead Market (HP-DAM) segment
4. Government identified **30 critical minerals** for India, also **20 blocks** of critical raw minerals were put to auction during the year
5. In 2022, Government set a target of **4%** Energy Storage Obligation (ESO), till date 10 states has aligned the same in state RE Policies
6. Rajasthan became the first state to declare Energy Storage target for **2030**, the state has put forward a target for 10 GWh by 2030
7. CEA revised India's ESS Demand to **61 GW/336 GWh by 29-30**. A total Investment of INR 368K will be required between 27-32
8. Lithium Reserves were discovered in the states of **Jharkhand** & **Rajasthan**
9. 50 GWh of battery **manufacturing** capacity related announcement were done in 2023
10. A total of 25 **Energy Storage Linked Tenders** were released during the year associated with a capacity of 40 GWh ESS Capacity

VF | VOLTA FOUNDATION

Source; Economic Times; PIB.gov - Cabinet; PIB.gov - CERC; Critical Minerals; Economic Times - Mineral Blocks; MNRE.gov - Energy Storage Obligation; Mercom India- Rajasthan Energy Storage Target; Solarquarter - CEA; Jharkhand; CNBC - Rajasthan; Economic Times - 50GWh; JMK - ESS tenders

Asia | India | Policy Targets & Drivers

Policy Drivers

- **Energy independence**
- **Improvement of air quality**
- **Localization of value chain**
- **Improving manufacturing capability**

Policy Targets

- **50GWh** of local cell production by 2030
- 30% of Cars and 80% of 2/3Ws to be EVs by 2030
- 500 GW renewable energy by 2030

Policy Instruments

- **Production Linked Incentive Schemes** for Cell Manufacturing,
- Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME)
- Viability Gap Funding for Energy Storage

2015

FAME 1 introduced

2019

FAME 2 introduced with subsidy outlay of Rs 10000 Crores

2020

2021

FAME 2 subsidies increased by 50% for two wheelers.

PLI scheme for advanced cell chemistries announced.

2022

Draft Battery Swapping Policy released

Battery Waste Management rules published

2023

FAME 2 subsidies decreased by 33% for two wheelers.

Controversy surrounding localization and rules around chargers.

2024

FAME 3 expected

Source: Niti Manufacturing Strategy; Switch Delhi; RMI; Niti-Advanced Cell Chemistry; Ministry of Heavy Industries

Asia | India | Policy Push & Incentive Support

Battery Energy Storage System policy updates in 2023

Feb 2023
VGF Support for 4 GWh of BESS

May 2023
National Electricity Plan – Capacity requirement & duration mix

June 2023
Indian Electricity Grid Code identifies ESS as reserves

Aug 2023
National Framework for ESS

In Union Budget 2023, Government of India announced Battery Energy Storage Systems (BESS) with capacity of 4,000 MWh will be supported with Viability Gap Funding. In September 2023, Cabinet approved a budgetary support of **Rs.3,760 crore**.

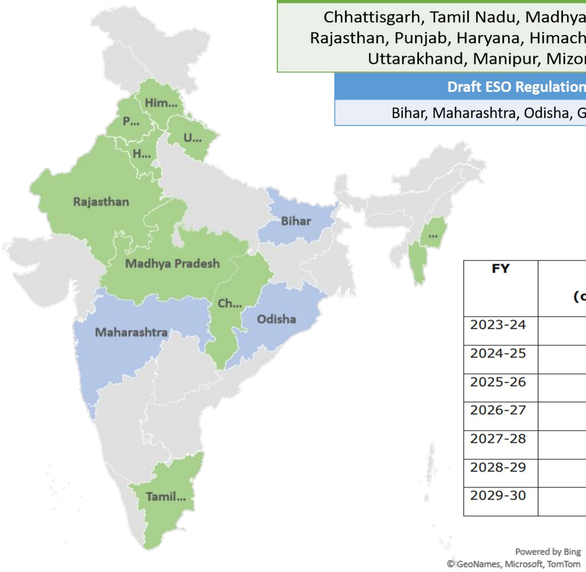
National Electricity Plan requires a BESS capacity of 8.68 GW/34.72 GWh may be required to fulfill the storage requirement of the grid by 2026-27. However, Battery energy storage requirements increase to 47.24 GW/236.22 GWh in addition to 26.68 GW of PSS based installed capacity for the year 2031-32.

Indian Electricity Grid Code (IEGC) Regulation, 2023 identified one of the eligible resources to participate in the ancillary markets of India, the service necessary to support the grid operation in maintaining power quality, reliability and security of the grid.

National Framework for ESS was notified by Indian government with an objective to have 24X7 dispatchable RE-RTC power, to reduce overall cost of energy and reduce greenhouse gas emission, redesign energy markets to incentivize participation of ESS in market, to improve grid stability and reliability through deployment of ESS and to monitor and evaluate performance and impact of ESS and giving feedback for making policy and investment decision. Several measures were proposed to strengthen the present status of ESS deployment in India vide this **framework**.

Source: India Energy Storage Alliance- Annual Market Assessment Report – 2023; Cabinet; vision report; Central Electricity Regulatory Commission;

| India | End Use Incentives & Regulations



Final ESO Regulations

Chhattisgarh, Tamil Nadu, Madhya Pradesh, Rajasthan, Punjab, Haryana, Himachal Pradesh, Uttarakhand, Manipur, Mizoram

Draft ESO Regulations

Bihar, Maharashtra, Odisha, Goa & UTs,

FY	Storage (on Energy basis)
2023-24	1.0%
2024-25	1.5%
2025-26	2.0%
2026-27	2.5%
2027-28	3.0%
2028-29	3.5%
2029-30	4.0%

*Punjab: PSERC has notified "Total RPO" and have not provided source wise break up of RPO to fulfill including ESO too.

Renewable Purchase Obligations (**RPOs**): The Ministry of Power has introduced Uniform Renewable Purchase Obligations (RPO) wherein all electricity distribution licensees have to consume a specified minimum quantity of their total requirements from Renewable Energy Sources. This is under implementation since 2016.

Energy Storage Obligation (**ESO**): the Ministry of Power in the year 2022, issued updated RPO and Energy Storage obligation trajectory till 2029-30. ESO shall be calculated in energy terms as a percentage of total consumption of electricity shall be treated as fulfilled only when 85% of the total energy stored in the ESS on an annual basis is procured from RE source.

RPO shall be calculated in energy terms as a percentage of total consumption of electricity. Wind RPO shall be met only by energy produced by Wind Power Projects (WPPs), commissioned after 31st March 2022.

HPO shall be met from Large or Small Hydro projects including Pumped Storage Projects (PSPs), commissioned after 8th March 2019. Other RPO may be met by energy produced from any RE power project except wind and hydro.

Energy Storage Obligation (ESO) shall be met from Solar/Wind energy along with/through storage and shall be treated as fulfilled only when at least 85% of energy stored in ESS on an annual basis is procured from RE sources.

Source: India Energy Storage Alliance- Annual Market Assessment Report – 2023; Cabinet; vision report; Central Electricity Regulatory Commission;

Asia | India | Tender Health Check: Status Of Ess Tenders As Of December 2023

50 **Tenders** | 46 GWh ESS Capacity (31 GWh PSP, 3 GWh BESS, 12 GWh tech. agnostic) with 23.4 GW of associated RE Capacity (9 under execution (2 GWh) | 19 open tenders (29 GWh) | 3 Operational)

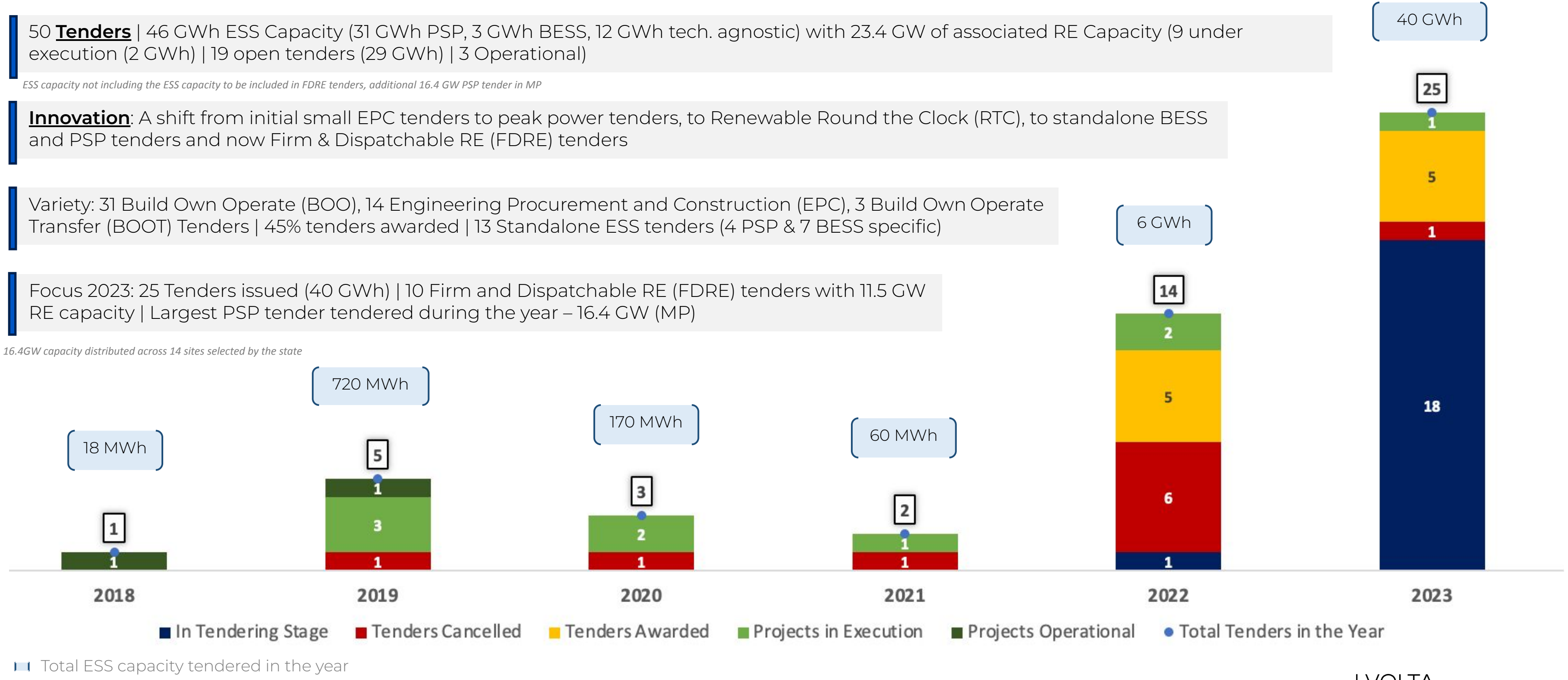
ESS capacity not including the ESS capacity to be included in FDRE tenders, additional 16.4 GW PSP tender in MP

Innovation: A shift from initial small EPC tenders to peak power tenders, to Renewable Round the Clock (RTC), to standalone BESS and PSP tenders and now Firm & Dispatchable RE (FDRE) tenders

Variety: 31 Build Own Operate (BOO), 14 Engineering Procurement and Construction (EPC), 3 Build Own Operate Transfer (BOOT) Tenders | 45% tenders awarded | 13 Standalone ESS tenders (4 PSP & 7 BESS specific)

Focus 2023: 25 Tenders issued (40 GWh) | 10 Firm and Dispatchable RE (FDRE) tenders with 11.5 GW RE capacity | Largest PSP tender tendered during the year – 16.4 GW (MP)

16.4GW capacity distributed across 14 sites selected by the state



VF | VOLTA FOUNDATION

Source: Analyzed and Compiled from public announcements by SECI, MNRE, MoP and Organization Announcements; Tender Results

04 Policy | Overview

Policy Summary

North America

Europe

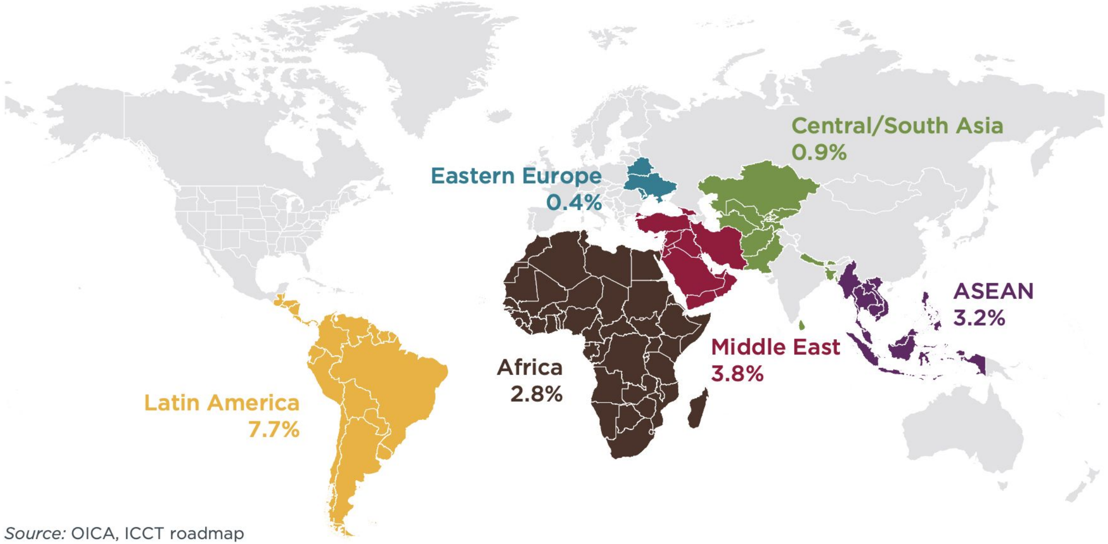
Asia

Rest Of World

Rest Of World

| Share Of Global On-Road Vehicle Market By EMDE Region

EMDE market share of on-road vehicles* is approximately 19% global total but greater policy support is needed to support the BEV transition



Source: OICA, ICCT roadmap

*on-road means passenger cars, vans, buses and trucks and excludes 2-3 wheelers in this analysis

Emerging Markets and Developing Economies (EMDE) market share of on-road vehicles (excluding 2-3 wheelers) is approximately 19% global total.

This represents a decarbonization opportunity of 4,739m tons CO2e per annum by 2050. The global EMDE target is 1,157m tons CO2e per annum by 2050.

BEV market share across all EMDEs is approximately 1% total market.

Available grant to support BEV transition from 2017-2021 across all EMDE regions was $84.4m.

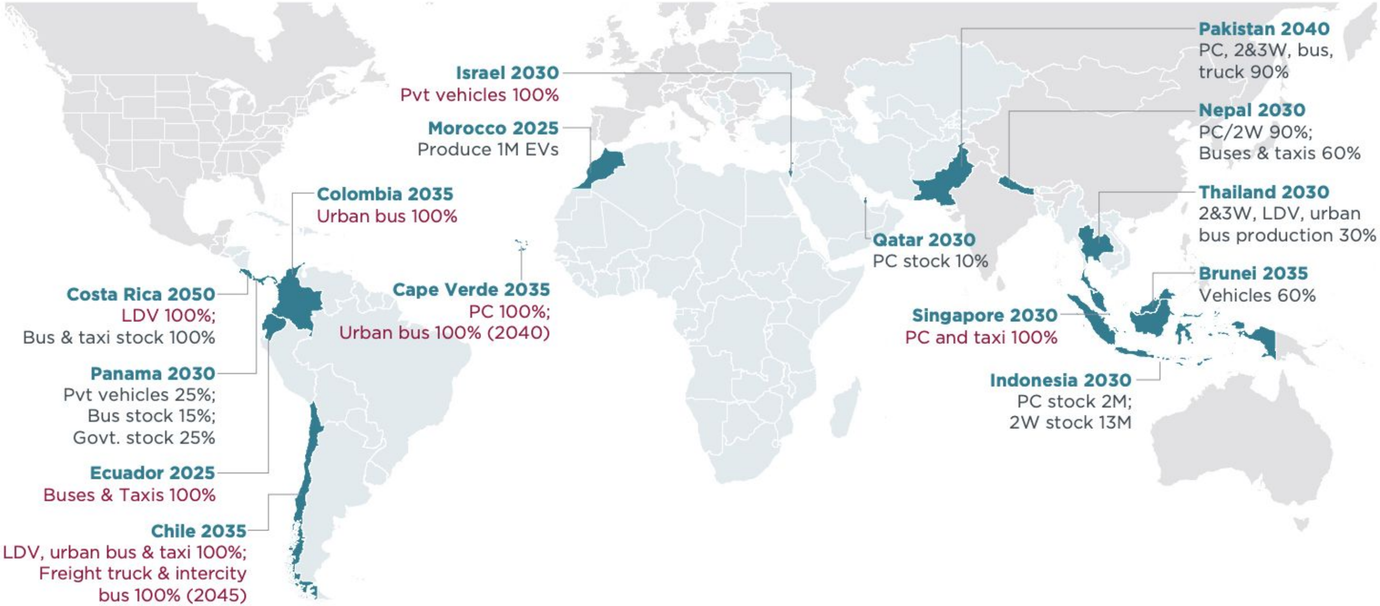
The estimated level of financial support required to enable the BEV transition is $4,960m.

Greater financial support is required to meet the deficit.

Source: ICCT Briefing Paper

Rest Of World | EMDE ICE Phase Out Dates

Some Emerging Market and Development Economy nations have sale of new ICE vehicle phase out dates which promotes positive BEV uptake. However, the majority of EMDE nations do not, including the majority of Africa, Eastern Europe, Central/South Asia and Latin America which represent 16% of the global on-road vehicle market. ASEAN is the most progressive in terms of implementation of ICE phase out dates.



Israel 2030
Pvt vehicles 100%

Morocco 2025
Produce 1M EVs

Colombia 2035
Urban bus 100%

Cape Verde 2035
PC 100%;
Urban bus 100% (2040)

Costa Rica 2050
LDV 100%;
Bus & taxi stock 100%

Panama 2030
Pvt vehicles 25%;
Bus stock 15%;
Govt. stock 25%

Ecuador 2025
Buses & Taxis 100%

Chile 2035
LDV, urban bus & taxi 100%;
Freight truck & intercity
bus 100% (2045)

Pakistan 2040
PC, 2&3W, bus,
truck 90%

Nepal 2030
PC/2W 90%;
Buses & taxis 60%

Thailand 2030
2&3W, LDV, urban
bus production 30%

Qatar 2030
PC stock 10%

Brunei 2035
Vehicles 60%

Singapore 2030
PC and taxi 100%

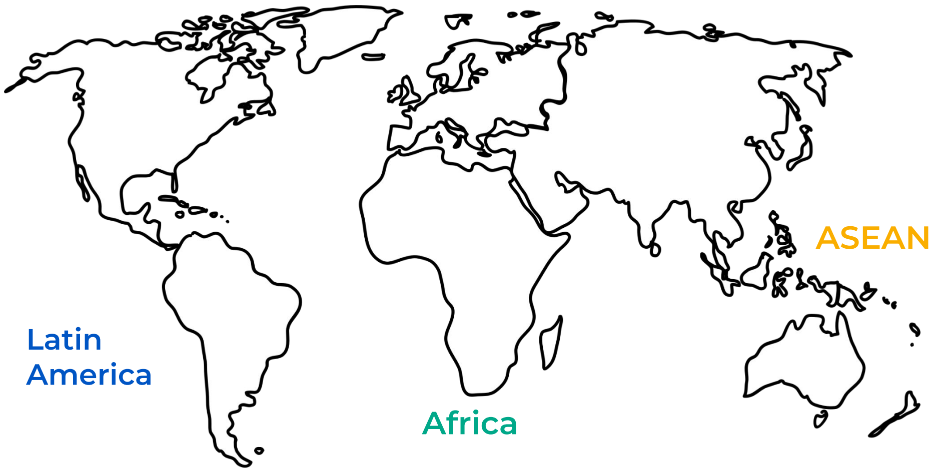
Indonesia 2030
PC stock 2M;
2W stock 13M

Source: ICCT Briefing Paper

Rest Of World

| EMDE Critical Mineral Policies

EMDE nations are developing policies to strategically leverage their position as the global suppliers of battery minerals



Africa:

The African Development Bank Group put forward the **Approach Paper towards preparation of an African Green Minerals Strategy**. The Paper outlines how the green transition and Africa's rich mineral resources will be leveraged to industrialize and achieve economic diversification. The full African Green Minerals Strategy is to follow.

ASEAN:

The ASEAN-IGF Minerals Cooperation: **Scoping study on critical minerals supply chains in ASEAN** appraises how ASEAN can take advantage of and expand its mineral and industrial value chains without becoming "sacrifice zones for the energy and digital transitions happening elsewhere."

Latin America:

The Economic Commission for Latin America and the Caribbean published a **report** which appraises the opportunity for Latin America to strategically exploit its rich Lithium reserves to promote economic growth and the challenges associated with this.

Source: African Development Bank Group; ASEAN-IGF Minerals Cooperation; Economic Commission for Latin America and the Caribbean

Rest Of World | Australia

A focus on critical material supply with ESG emphasis

Australian battery policy is centered around the global contribution they can make to mining of the minerals critical in the battery supply chain, with a strong emphasis on positive environmental, social and governance. The strategy is supported by billions of Australian dollars through the National Reconstruction Fund and Northern Australian Infrastructure Facility.

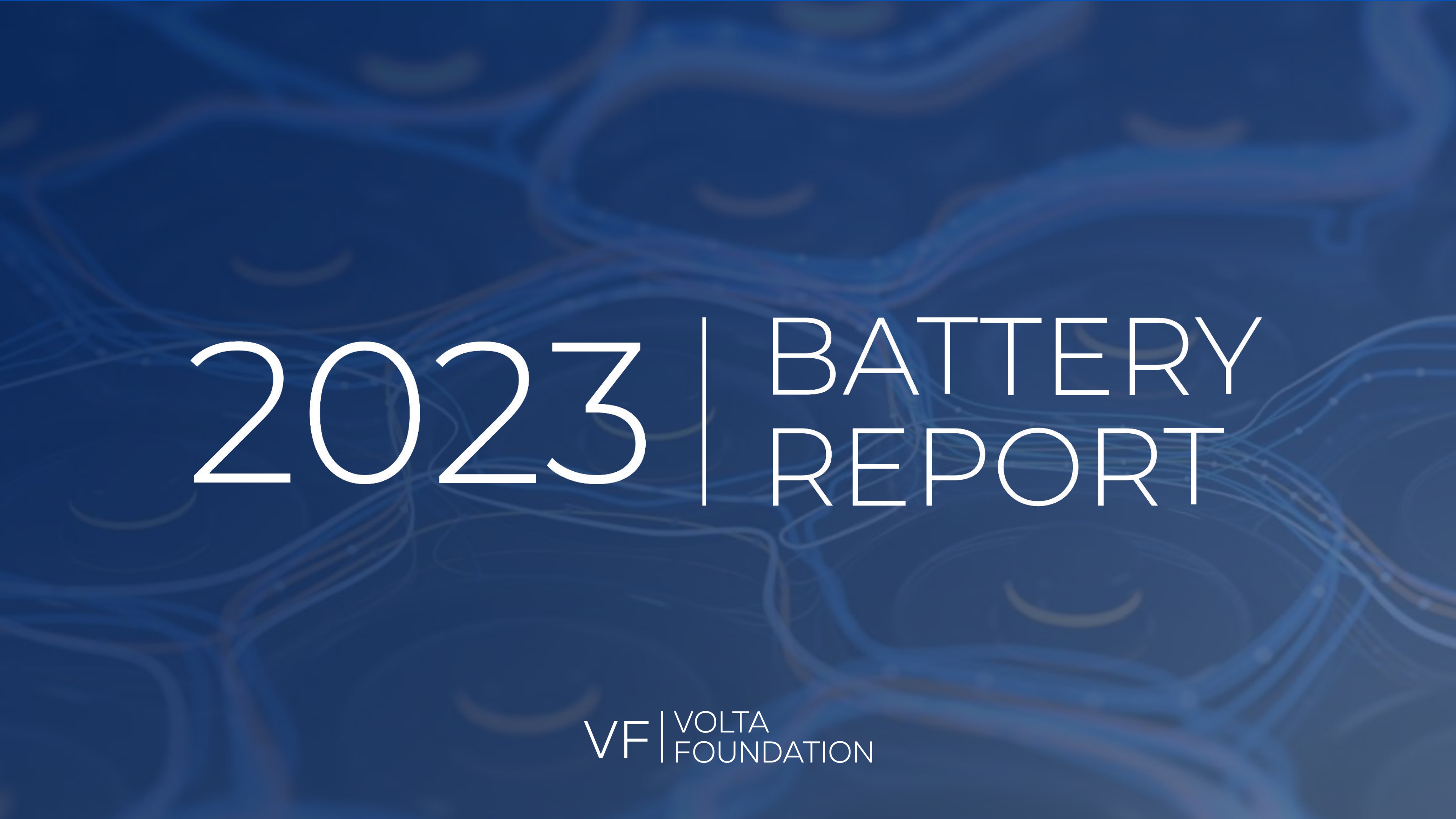
Australia published their **Critical Mineral Strategy** with a focus on 6 key areas:

- Developing strategically important projects
- Attracting investment and building international partnerships
- First Nations engagement and benefit sharing
- Promoting Australia as a world-leader in ESG performance
- Unlocking investment in enabling infrastructure and services
- Growing a skilled workforce

Also in 2023:

- The **Critical Mineral list** was **updated** and a Strategic Mineral list was created to include battery-relevant minerals such as Nickel, Copper, Fluorine, Phosphorus and Aluminium.
- A consultation was held concerning the development of a **National Battery Strategy**.
- A proposal for an **Australian Made Battery Plan** was also published and comprises two main aspects: 1) Battery Precinct Equity Investment and 2) Powering Australia Growth Centre, representing $123m Australian dollars.

Source: Australian Battery Policy Explainer; Critical Mineral Strategy; Critical Mineral List; Critical Mineral List Update 23; National Battery Strategy Consultation; Australian Made Battery Plan



2023 | BATTERY REPORT

VF | VOLTA FOUNDATION

Outro | Authors


Linda Jing
Volta Foundation


Yen T. Yeh
Volta Foundation


Aubert Demaray
SpectraPower


Jeffrey Bell
Lyten


Michael Liu
Sila


Sam Adham
CRU


Aaron Wade
CRU


Jennifer Channell
Anaphite


Alex Cipolla
Anxer


Charlie Parker
Ratel Consulting


Nika Ptushkina
PDF Solutions


Sriram Bharath
UC Berkeley


Dhevathi Kannan
UL Research


Mouda Abusukheila
Sylvatex, Inc.


Wendy Papakostandini
Anzu Partners


Andrew Weng
University of Michigan


Darren Tan
UNIGRID


Pooja Vadhva
Rimac Energy


Katherine He
TDK Ventures


Rohit Kumar
Standard Chartered Bank


Jhalak Sharma
Cognizant


Nanette Jarenwattananon
Lucid Motors


Eric Zheng
Rivian


Kent Griffith
UC San Diego


Sneha Solanki
Liminal


Lara Dienemann
Exponent

Disclaimer: The views expressed herein are solely those of the authors, and have not been reviewed or approved by any other organization, agency, employer or company. The primary purpose of this work is to educate and inform. The Content is for entertainment and informational purposes only and you should not construe any such information as investment, financial, or other advice. Data and information is from publicly available sources and often self-reported by the companies. The authors declare no conflicts of interest in producing this report.

Outro | Authors & Contributors

Thank you to our Contributors for their input and their subject matter expertise.

Authors

Industry

Notable Events
Eric Zheng, Rivian
Mouda Abu-Sukheila, Sylvatex
Value Chain & Finance
Katherine He, TDK Ventures
Sam Adham, CRU
Costs
Sam Adham, CRU
Aaron Wade, CRU
Cell & Pack
Charlie Parker, Ratel Consulting
Mouda Abu-Sukheila, Sylvatex
Nika Ptushkina, PDF Solutions
Applications
Michael Liu, Sila Nanotechnologies
Sriram Bharath, UC Berkeley
Sam Adham, CRU
Pooja Vadhva, Rimac Energy
Cell Chemistry
Aubert Demaray, SpectraPower
Jeffrey Bell, Lyten, Battery Talk
Alex Cipolla, Anxer
Darren Tan, UNIGRID
Raw Materials
Sam Adham, CRU
Aaron Wade, CRU
Aubert Demaray, SpectraPower, Battery Talk
Jeffrey Bell, Lyten, Battery Talk
Recycling
Rohit Kumar, Standard Chartered
Jhalak Sharma, Business Consulting
Software
Sneha Solanki, Liminal

Academia

Dhevathi Kannan, UL Research Institute
Lara Dienemann, Exponent
Nanette Jarenwattananon, Lucid Motors
Kent Griffith, UCSD

Talent

Andrew Weng, Volta Foundation
Wendy Papakostandini, Anzu Partners

Policy

Jennifer Channell, Anaphite Ltd.
Alex Cipolla, Anxer, Volta Foundation

Contributors

Industry

Adrian Yao, Stanford
Ahmed Chahbaz, RWTH Aachen University
Alex Woodrow, Knibb Gormezano (KGP)
Arthur Claire, Sinovoltaics
Chirag Bansal, Log 9 Materials
Crystal Jain, Form Energy
Darren H. S. Tan, UNIGRID Battery
Digital Comm Team (SANG BOK LEE), LG Energy Solution
Erika Guerrero, Electric Goddess
Faith Kileo, WAGA Tanzania
Gayatri Dadheech, Exide Energy
Georg Angenendt, ACCURE
Gibson Kawago, WAGA Tanzania
Hubert Biteau, Code Red Consultants
Jason You, CATL
Jon Fold von Bülow, Morrow Batteries
Luke Workman, Electric Goddess
Matthew Chistolini, Mizuho
Matthias Simolka, TWAICE
Nicholas Yiu, Intercalation, Voltaiq
Piotr Grudzień, Bax & Company
Pranav Nagaveykar, FEV Group
Raul Arredondo, Defining Humanity
Sam Adham, CRU
Saheem Absar, ADVANO
Shashank Sripad, And Battery Aero
Shiying Wang, Cornell
Shreyas Seethapathy, Ather Energy
Siddharth Kurwa, Natron Energy
Solid State Battery
Teng Zhang, Breathe Battery Technologies
Yixuan Li, UCSD
Yan Zhao, Breathe Battery Technologies
Vincent Pluvinage, OneD Battery Sciences

Academia

Andrew Wang, Intercalation, Columbia
Chirag Bansal, Log 9 Materials
Cassius Clark, Nyobolt
Fan Yu, McGill University, McISCE
Gayatri Dadheech, Exide Energy
Marco Siniscalchi
Mahmoud Reda, University of Vienna
Omar Alshangiti, University of Oxford
Siddharth Tiwari, Panasonic
Tianyu Zhu, Clemson University
Vincent Wu, UC Santa Barbara
Zhaoyi Xu, Pull Data

Talent

Jennifer Channell, Anaphite Ltd.
Omar Ahmed, University of Michigan

Policy

Bindu Madhavi, Customized Energy Solutions
Debmalya Sen, World Economic Forum
Gayatri Dadheech, Exide Energy
Piotr Grudzień, Bax & Company
Rahul Walawalkar, Customized Energy Solutions
Raul Arredondo, Defining Humanity
Sam Adham, CRU
Shreyas Seethapathy, Ather Energy

Supporters

Tim Suen, Form Energy
Gabe Hege, NVIDIA
Paul Sinclair, Volta Foundation
Myra S. Dyer, Volta Foundation

Design

Milena Cywińska

Outro | Advisors

Thank you to our Advisors for providing feedback to this report.

Bob Galyen
Principal,
Galyen Energy LLC

Shirley Meng
Professor, University of Chicago
Chief Scientist, Argonne National Laboratory

James Frith
Principal,
Volta Energy Technologies

Steve LeVine
Editor,
The Electric

Dee Strand
Chief Scientific Officer,
Wildcat Discovery Technologies

Venkat Viswanathan
Professor, University of Michigan,
Co-Founder, Aionics, Chement, & Battery Aero

Anna Stefanopoulou
Professor,
University of Michigan

Outro | Citations & More

"The Battery Report 2023." ***Volta Foundation,*** **X January 2024. Web. [Date accessed].**

Please cite the report appropriately.

Feedback Form

To submit suggestions and error corrections, please fill out this form: **https://forms.gle/CQmCjS2CXyq8Q397A**

License

Sponsorship

For sponsored slides, partnerships, and speaking engagements, please reach out to us at **sponsorship@volta.foundation**

Sponsor the BR23

2023 | BATTERY REPORT

Sponsor The
Battery Report

www.volta.foundation

VF | VOLTA FOUNDATION