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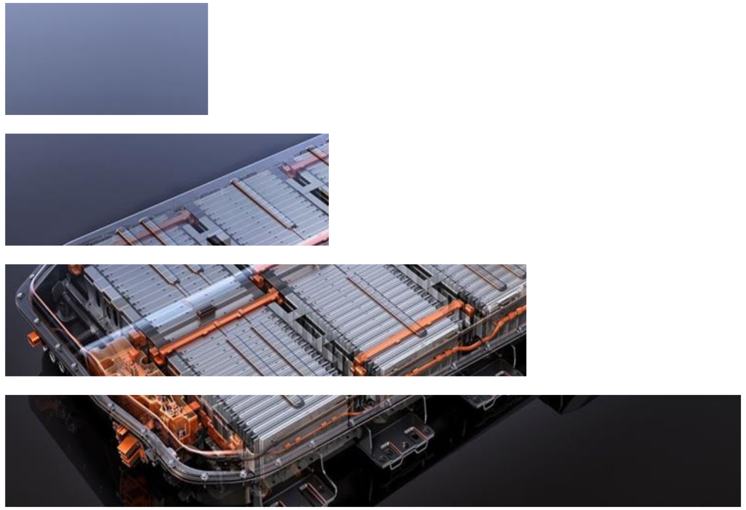

Li-ion Battery Recycling

Deep Dive | 8th September 2023

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Executive Summary

Set to experience significant growth riding the wave of the booming EV market

Li-ion Battery Recycling

The collection and reprocessing of used lithium-ion batteries to **recover valuable materials** while mitigating hazardous environmental impact.

Key Drivers

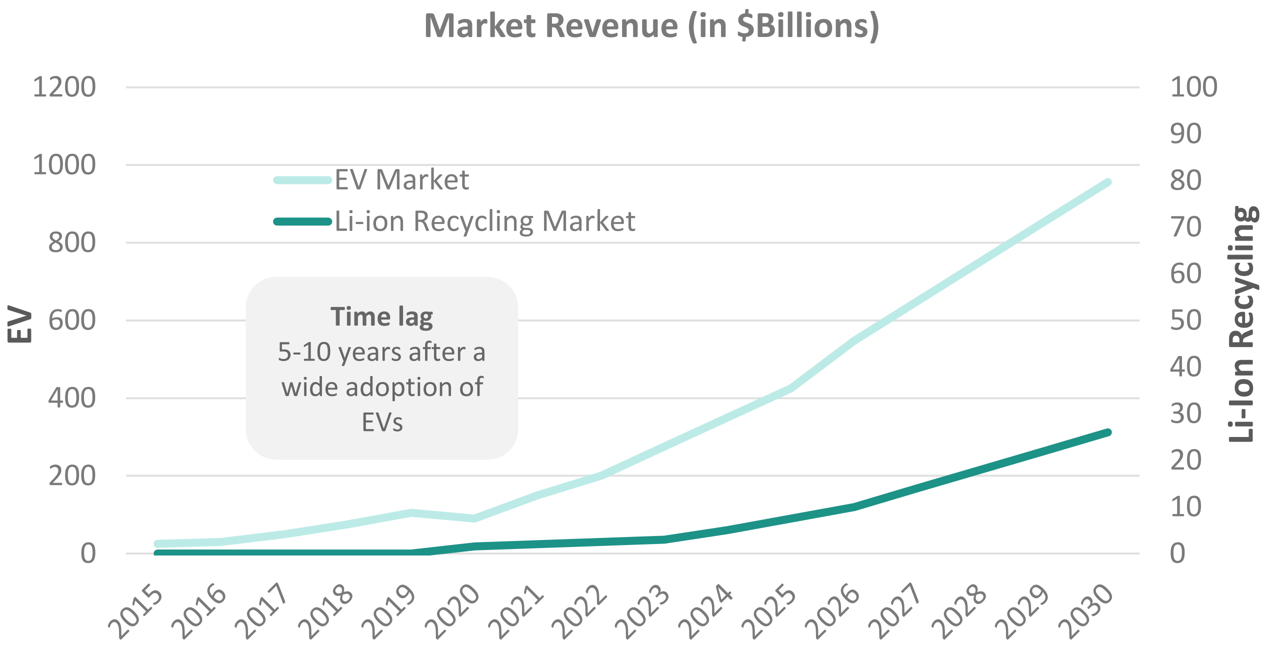
The global Li-ion battery market is projected to grow at **~34%** in the next 10 years driven **by supply and demand for electric vehicle batteries**, **regulatory support, circular economy, and technological advancements.**

Industry Maturity and Investments

In terms of maturity, the industry is in its **nascency.** Starting 2021, the space has seen an influx of capital (~$4b), enabling several startups and companies to achieve premium valuations.
Widespread profitability has yet to be established; projected gross margins stand at **13-31%.**

Technology

The battery recycling procedures encompass four primary methods**:** **Mechanical, Pyrometallurgy, Hydrometallurgy,** and **Direct**. Among these, **Hydrometallurgy** stands out as **the preferred approach** for recycling due to its optimal balance between **metal recovery rate, process intricacy, technological advancement**, and **environmental implications.**



Challenges

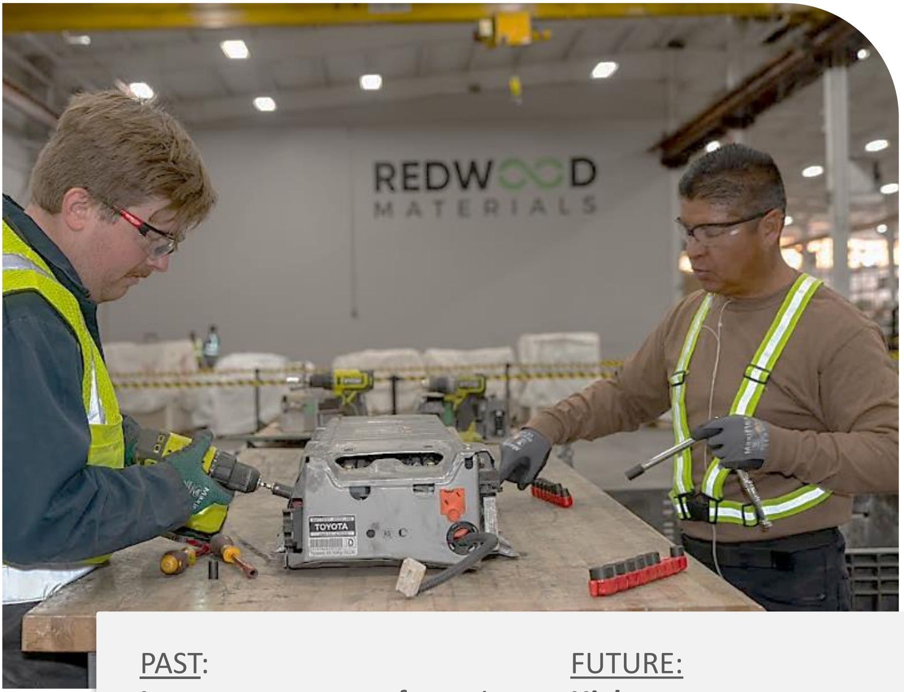
Some headwinds seen faced in the industry include battery **collection**, **transport, battery lifespan standardization, manual processes**, **scaling up operations,** and **mineral composition**.

Source: Pitchbook, IEA, McKinsey

Overview

Battery Recycling

The collection and reprocessing of used Lithium-ion ("Li-ion") batteries to **recover valuable materials** while mitigating hazardous environmental impact

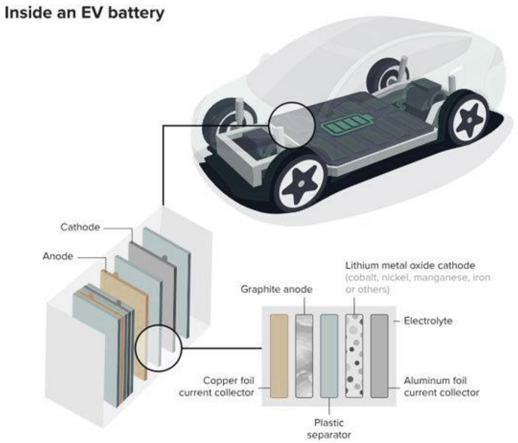


PAST:
Low recovery rates for active materials
Unsustainable amounts of energy and chemicals

FUTURE:
Higher recovery rates
Cleaner process for large-scale recycling

Lithium-Ion Battery

Rechargeable
High energy density
Low self-discharge
Predominantly used **in consumer electronics, electric vehicles, grid-scale energy storage,** and **aerospace applications**



Lead Acid

Alkaline

Lithium-Ion Battery Value Chain (EV)

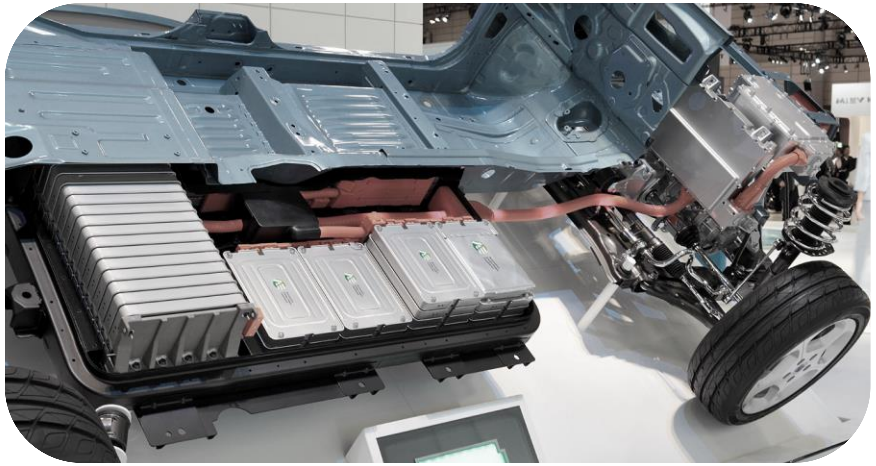
Extraction & Processing	Cell Production	EV Integration	End-User	End of Life
Cathode Precursor: • Lithium • Cobalt • Nickel • Manganese Anode Precursor Graphite Precursor	Anode Cathode Electrolytes Separator Packaging	Module Production Battery Management Systems Battery Pack Integration	Automakers	Landfill Recycling

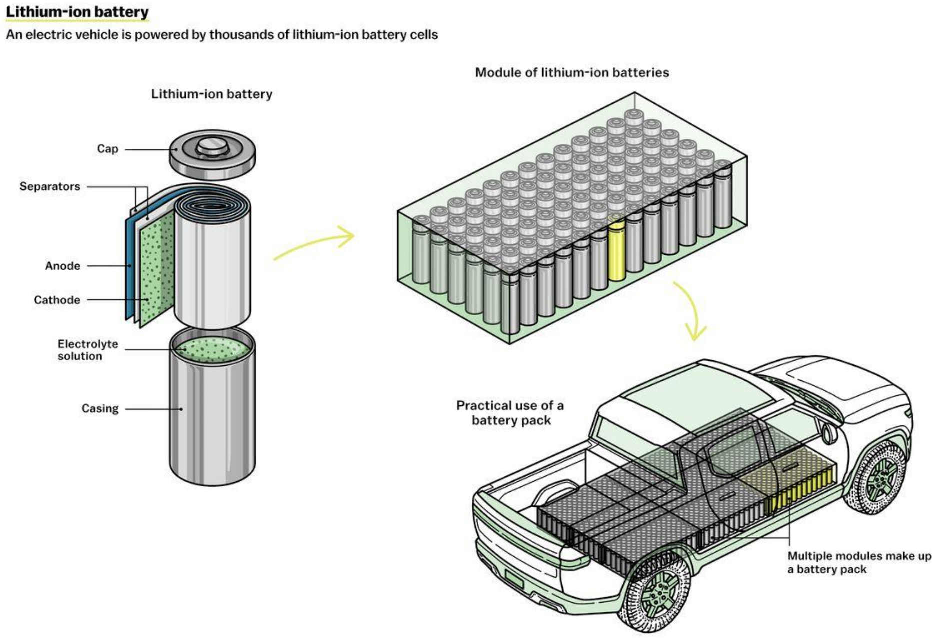
Battery Recycling

Source: Pitchbook

Overview

Lithium ("Li-ion") Batteries
Most important part of an electric vehicle is the battery cells.
About ~**40% of the cost of a vehicle**.





2 Dominant Cathode Chemistries:

1. Lithium Nickel Manganese Cobalt (NMC)
- Higher energy capacity, higher range
- Expensive
- Generally seen in the West, where EVs are a "luxury."

2. Lithium Iron Phosphate (LFP)
- Lower energy capacity, lower range
- Less expensive (~30% cheaper)
- Generally seen in the East where EVs are more "mass market."

Source: Pitchbook

Global Landscape

The battery recycling arena is comprised of three main markets

APAC | 1st | 45%

The value chain holds strong roots in China as the **first country to enact supportive policy for the industry**, with almost a decade-long head start

Trailing the EV Boom

Starting in **2011** as part of China's 12th Five-Year Plan, the Chinese government set targets for electric vehicle (EV) sales and supported them through government subsidies

Those incentives made China the earliest and largest EV market in the world, creating a momentum that other governments are left chasing

With a decade long head start, they have encountered the first wave of EV end-of-life batteries

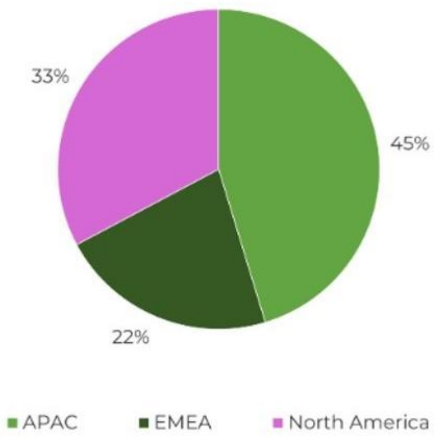
North America| 2nd | 33%

Presence in EV battery recycling is more recent, more SMEs headquartered in the US are seen emerging

2021

Battery materials have become part of the national strategy; the U.S. has funded several battery recycling projects as part of the **Bipartisan Infrastructure Law**

Battery Recycling Players by Region

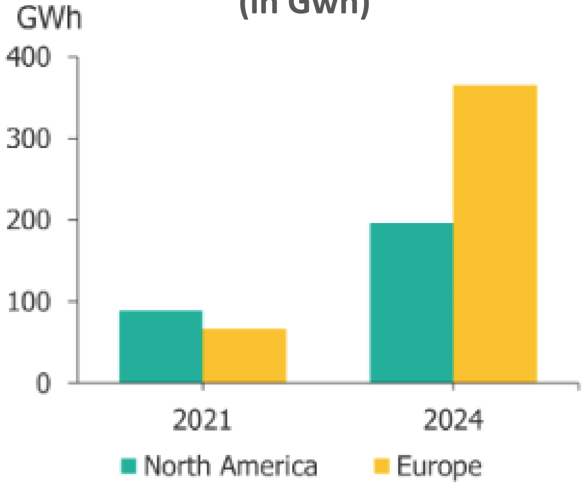


Europe | 3rd | 22%

The EU proposed comprehensive policies to manage battery end of life, requiring high recycling rates

The quota calls for a recovery level of **95% for cobalt, copper, lead, and nickel, as well as 70% for lithium**

Planned Manufacturing Capacities, 2024 (in Gwh)



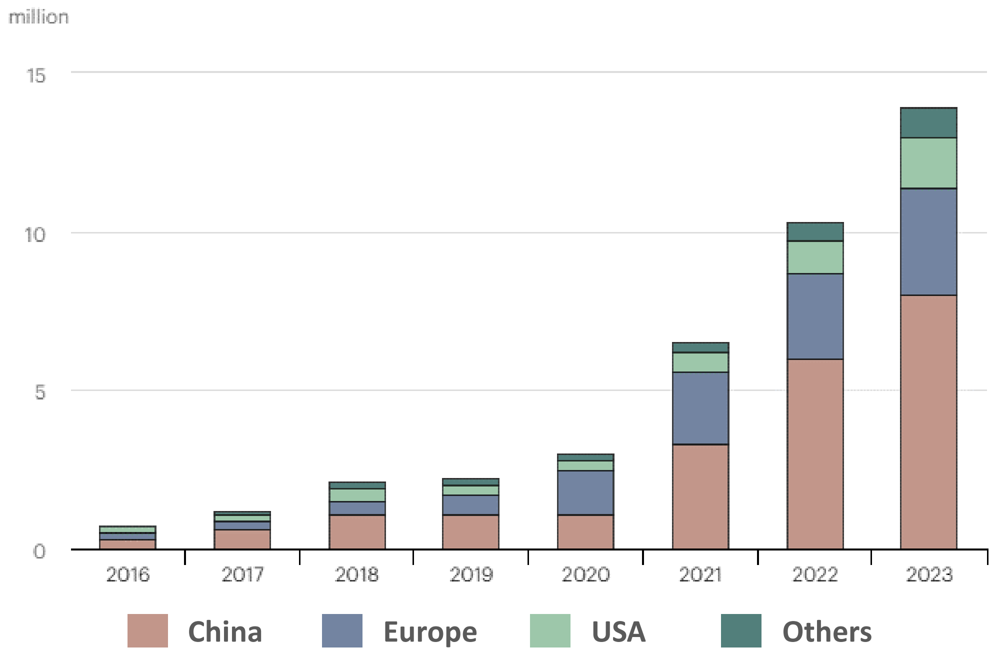
Source: Lux Research, EU Regulatory Framework, European Parliamentary Research Service

2021 Exponential Lift-Off

Lithium-Ion battery demand surges due to the rise of electric vehicles

Historical

The Number of EVs Sold Globally, 2016-2023E (in millions)

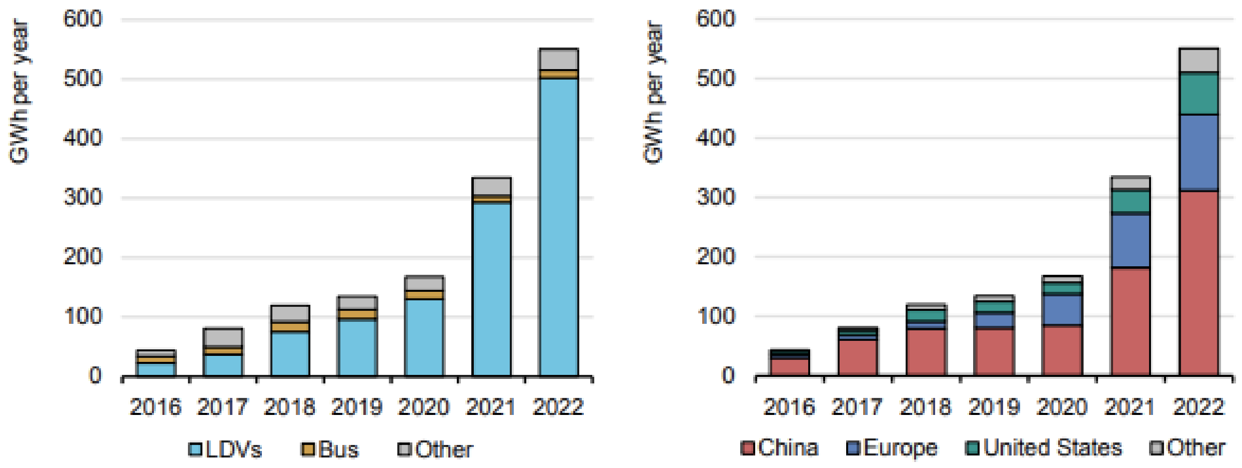


Historically, the EV market has seen exponential growth
Units sold exceeded ~**10 million** in FY2022.

EV % of all new cars sold	<5%	9%	14%	18%
	2020	2021	2022	2023E

Historical

Battery demand by mode and region, 2016-2022



65% increase YoY, 2022
Global Battery Demand
mainly as a result of LDV electrical vehicles

Source: IEA

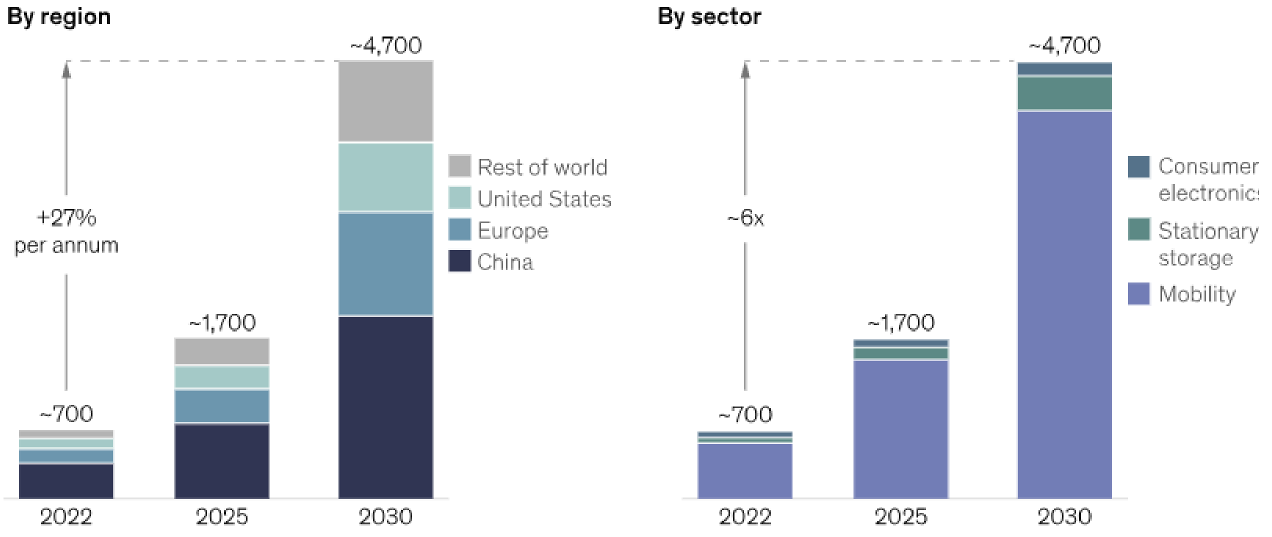
Recycling Revenue 34% Growth for the Next 8 Years

Li-ion demand and recycling revenue expected to grow 27% and 34% annually, for the next 8 years

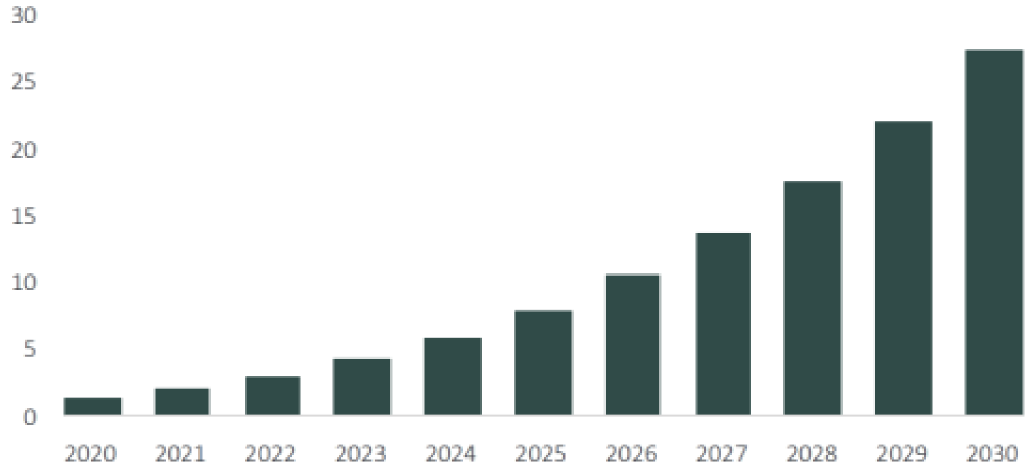
Projected

Projected

Global Li-ion Battery Cell Demand
(in GWh)



Lithium-ion Battery Recycling Revenue
(in USD billions)



~27% 8-yr CAGR

6.7x

From ~700 Gwh to ~4,700 Gwh (2022 to 2030); driven by the mobility sector from China, Europe, the US, and the rest of the world respectively

~90 KwH
1 Tesla Car Battery Charge, 400km

~34% 8-yr CAGR

$2.5B - $27B (2022 to 2030)

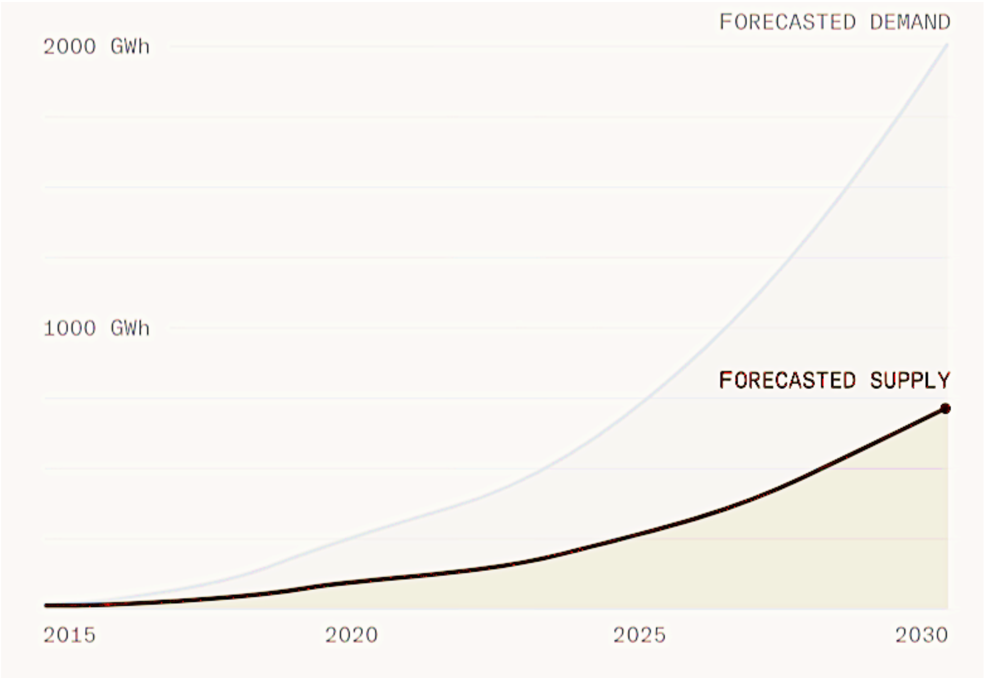
Source: McKinsey & Company, PitchBook

Demand Outstrips Supply

Bottleneck in the lack of Lithium supply

Li-ion Battery Supply and Demand (USA only)

Lithium-Ion Battery Supply and Demand (in GWh)

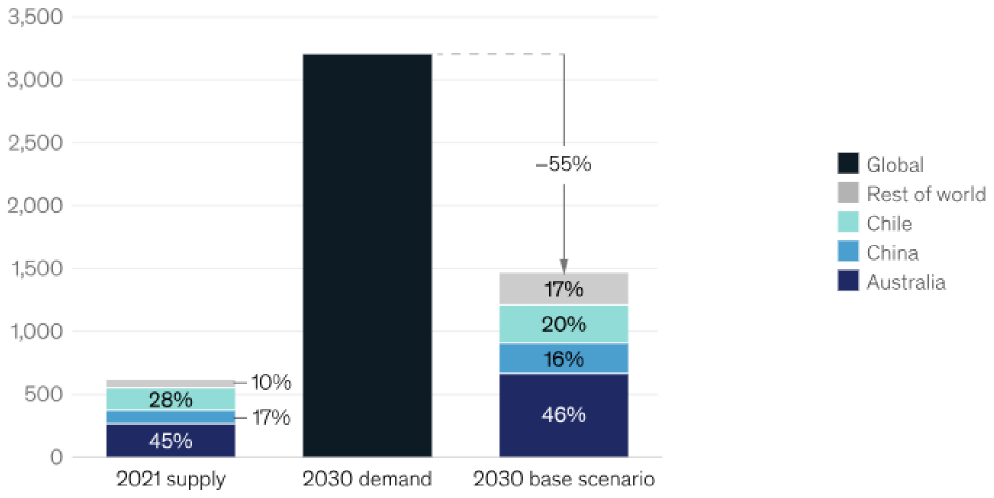


800 Gwh
Supply, 2030

2000 Gwh
Demand, 2030

Lithium Supply and Demand

Lithium Carbonate Supply and Demand (in kt)



1500 kt
Supply, 2030

3200 kt
Demand, 2030

95-98% of batteries end up in a landfill and new battery production depends on environmentally costly lithium mining

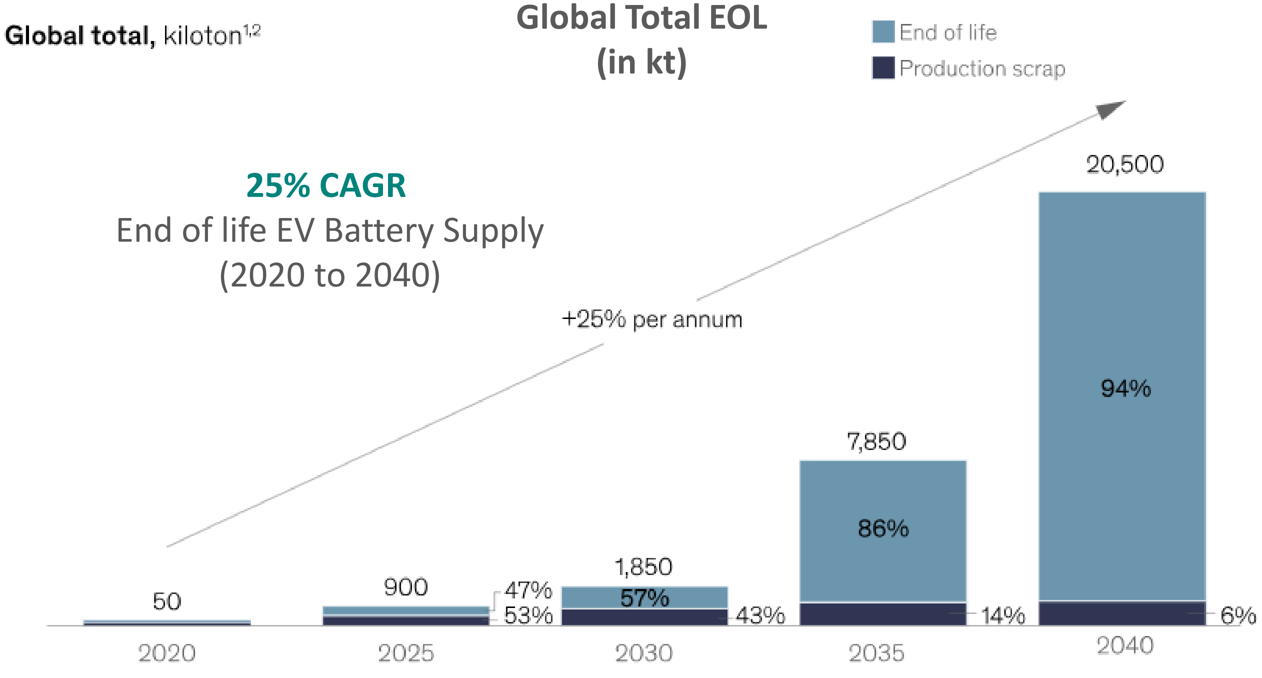
Source: McKinsey & Company, IEA

Alternate Supply: EOL Batteries as Highly Enriched Ores

Supply wave: EOL batteries coming off the road by 2030

Li-ion End of Life Battery Supply

25% CAGR
End of life EV Battery Supply
(2020 to 2040)

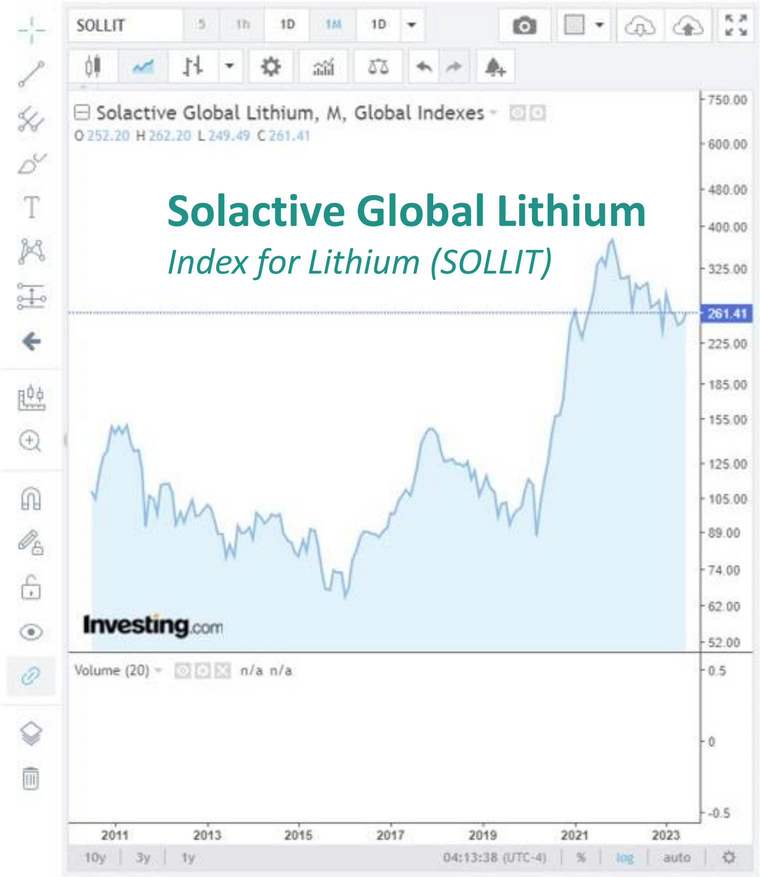


[1]Numbers are rounded.

After 2030, battery recycling supply will be rapidly accelerating
The recycling segment is still expected to be relatively small in 2030.

It is projected to grow more than three-fold in the following decade, when more batteries reach their end-of-life

Solactive Global Lithium Chart



Index Components:
SAYONA MINING LIMITED
Pilbara Minerals
BYD
赣锋锂业 GanfengLithium
RIVIAN

Lithium surges in price
First wave – 2016 (L: 65; H: 140)
Second wave – 2021 (L: 90; H: 360)

Source: McKinsey & Company 2023

Regulations as Crucial Tailwinds

As similarly observed with EV adoption, initial push comes from regulatory support

Battery and Critical Mineral Recycling Act of 2021

Supports R&D on innovative battery recycling
Establishment of a national collection system*

Aims to decrease U.S. dependence on critical mineral imports that are crucial to clean energy technology

EU Battery Regulation

50% of a battery's weight must be recycled

From 2025, this requirement will increase to 65% for lithium-ion batteries and to 70% from 2030

US Department of Energy announces new funding for lithium-ion battery recycling

The US Department of Energy announced on Monday June 12 that it was allocating more than $192 million in new funding for recycling batteries from consumer products

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Charged

U.S. set to loan Redwood Materials $2 bln for EV materials plant

By Paul Lienert and David Shepardson

February 10, 2023 6:31 AM GMT+8 · Updated 4 months ago

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Sustainable Business

U.S. to loan Li-Cycle $375 million for New York recycling plant

By Ernest Scheyder

February 27, 2023 8:55 PM GMT+8 · Updated 3 months ago

EU Battery Regulation make new demands on industry

BATTERIES

The EU is preparing tougher battery regulations, which are expected to come into force in 2022-2023. Once passed, these regulations will require new circular partnerships between battery manufacturers and recyclers.

European Parliament

New EU rules for more sustainable and ethical batteries

Economy Updated: 14-06-2023 - 13:49
Created: 03-03-2022 - 14:05

As batteries become a strategic market, the European Parliament has adopted new rules to tackle related environmental, ethical and social issues.

At least 30 million zero-emission electric vehicles are forecast to be on EU roads by 2030. While electric cars are expected to significantly decrease greenhouse gas emissions, they have an environmentally damaging downside: their batteries.

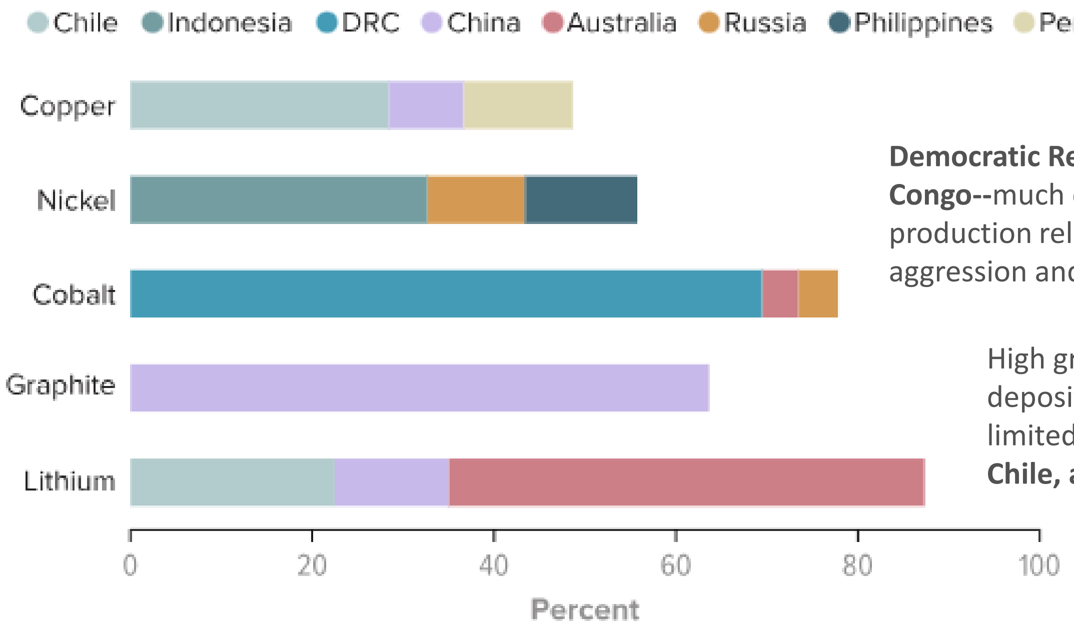
Source: Reuters, STENA, European Parliament, European Commission 2023

Nations Aiming to Secure the Supply Chain

Optimized cross-border import and export economics

Battery Recycling offers **buffers against global supply chain volatility**, reduce dependence on foreign resources, and would allow regions to capture and **retain imported materials**

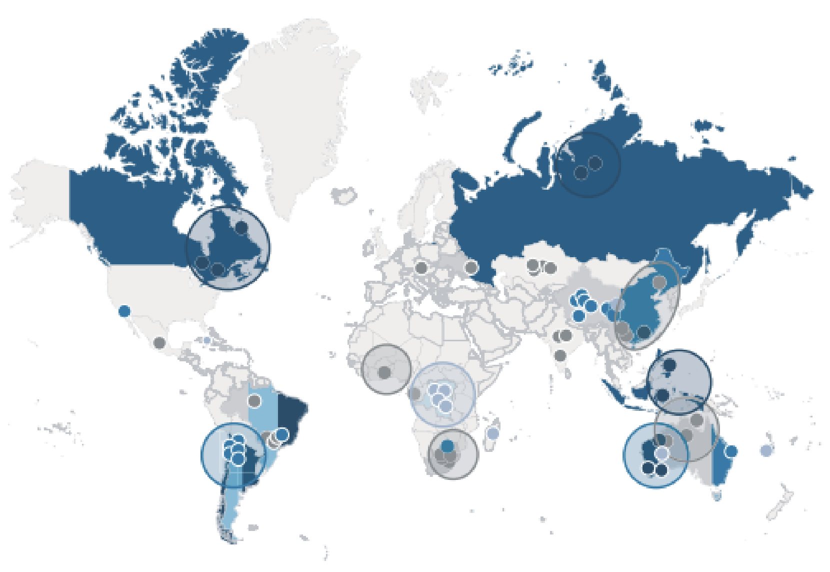
Top Countries Mining Lithium-Ion Battery Minerals

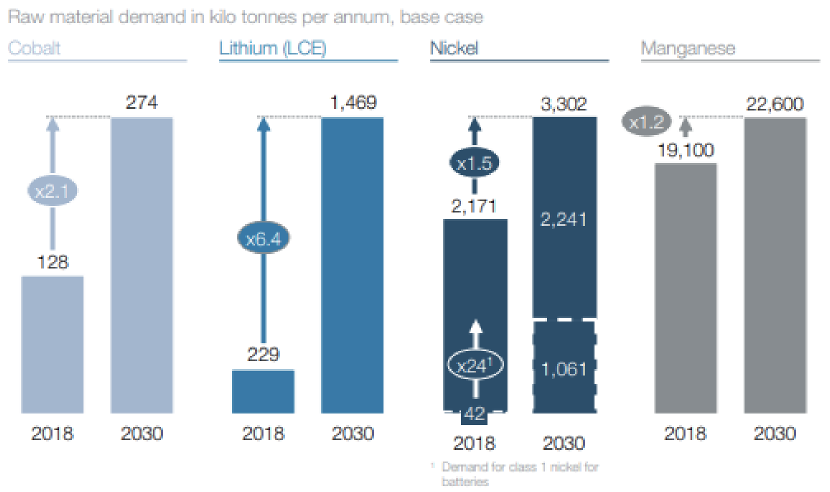


Democratic Republic of the Congo--much cobalt production relies on armed aggression and child labor

High grade lithium deposits are mainly limited to **Australia, Chile, and China**

Major Mining Locations for Cobalt, Lithium, Nickel, and Manganese





Source: IEA 2023

Circular Economy

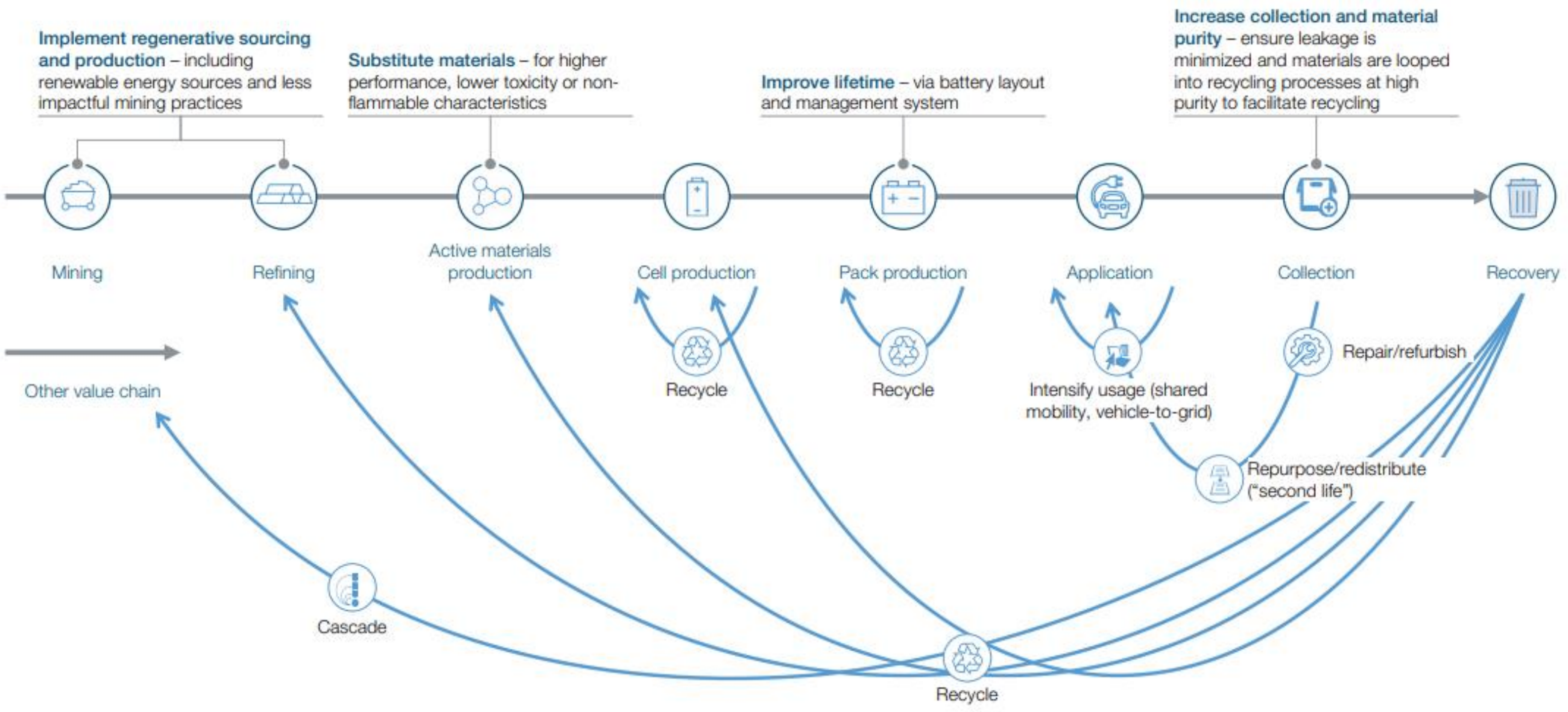
For a Circular Economy to emerge, batteries must ultimately be recycled

Stockpiling of waste batteries is **unsafe and environmentally undesirable**

Batteries can leak **toxic chemicals** into the soil and groundwater, polluting the surrounding ecosystem

As the world increasingly relies on lithium-ion batteries, **it's essential that we consider their impact on the environment**

Overview of Circular Economy Levers for Batteries (kgCO2e per kWh)

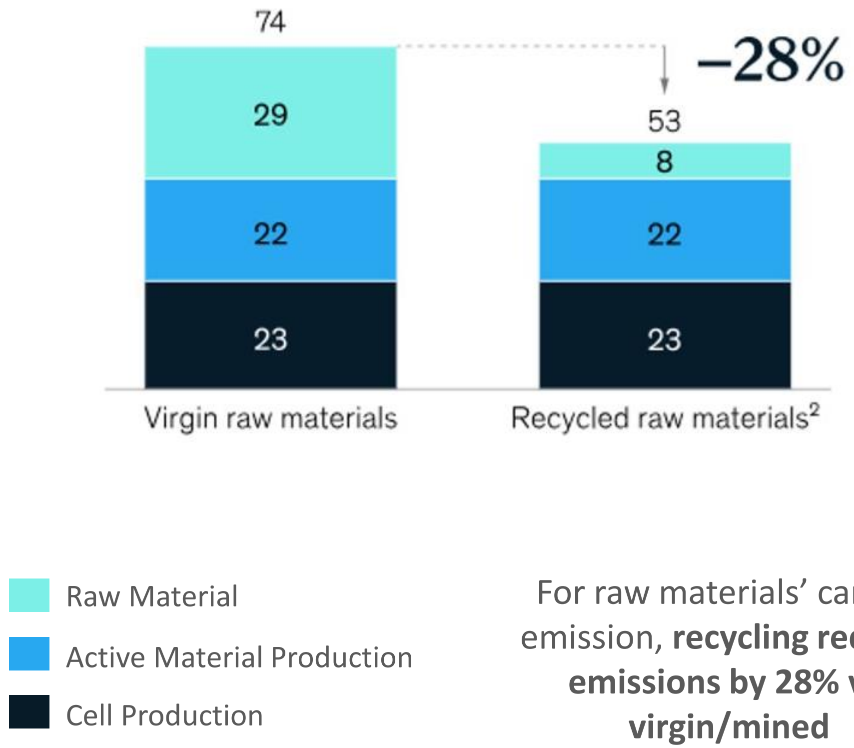


Source: World Economic Forum

Carbon Emissions Reduction through Recycling

The entire recycled process reduces emissions by -28% compared to the mined process

Battery Cell Production Emissions Comparison of Virgin Raw Materials vs. Recycled Raw Materials (kgCO2e per kWh)



For raw materials' carbon emission, **recycling reduces emissions by 28% vs. virgin/mined**

TTV Fit Perspective

PETRONAS

"A Progressive energy and solutions partner, enriching lives for a sustainable future"

2022: Announced Net Zero Carbon Emissions by 2050

Circular Economy through recycling
"For PETRONAS, circular economy is integral to our sustainability efforts, and we are in the process of embedding the mindset of circular economy into our activities to enable a low waste future, steward natural resources, and minimise our carbon footprint while creating value."

- Petronas Pathway to NZCE 2050

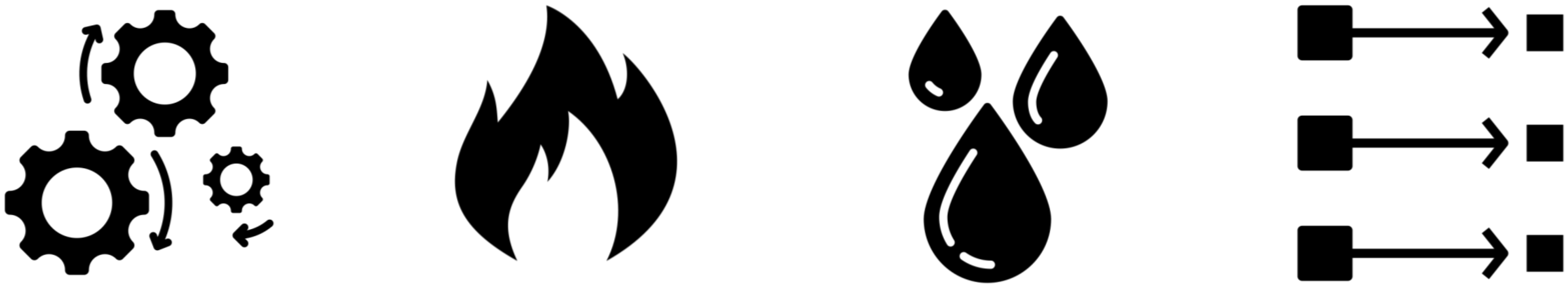
Source: McKinsey & Company 2023

Diverse Methods in Battery Recycling

Key factor for evaluating battery recycling companies

Maturity

Hi → Lo



Mechanical | **Pyrometallurgy** | **Hydrometallurgy** | **Direct**

The process used in recycling is one of the key factors for evaluating battery recycling companies, focusing on key differentiators--**cost efficiency, moats, and innovations**

Some companies use hybrid method combinations.

Source: Lux Research

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Diverse Methods in Battery Recycling

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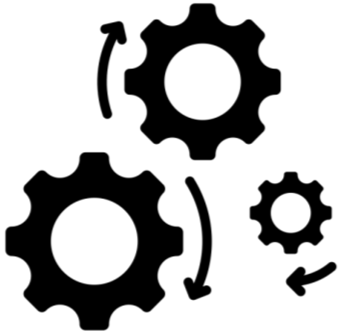


Mechanical

Pyrometallurgy

Hydrometallurgy

Direct

- Physical process
- Cell deactivation, separation of cells, external housing, wiring, and circuitry
- Crushing and shredding for "**black mass**"

Black Mass

- Industry term of the e-waste of crushed and shredded battery cells
- Contains mixtures of valuable metals: **lithium, manganese, cobalt and nickel** which are further processed to be extracted
- Has varying qualities which are influenced by the valuable mineral content

Source: Lux Research

Diverse Methods in Battery Recycling

Key factor for evaluating battery recycling companies

Maturity

Hi → Lo

Mechanical | **Pyrometallurgy** | Hydrometallurgy | Direct

- Thermal treatment - smelting and pyrolysis methods to produce **alloy** and **slag**
- **Primarily** used in other battery types
- Low cost

Alloy Mix
Copper
Cobalt
Nickel
Iron

Slag Fraction
Lithium
Manganese
Aluminum
Silicon

Challenges

- Requires fossil fuels
- High energy cost
- Lower-grade output
- **Li and Mn are trapped in the slag**
- As chemistries move toward lower metal content, the value for pyrometallurgical recycling deteriorates
- Innovation is low

Source: Lux Research

Diverse Methods in Battery Recycling

Key factor for evaluating battery recycling companies

Maturity

Hi → Lo

Mechanical | Pyrometallurgy | **Hydrometallurgy** | Direct

- Growing alternative to Pyrometallurgy
- Dissolves **black mass** into different constituents
- Chemical precipitation and acidic reagents
- Lower energy footprint
- Higher cathode material recovery rates as high as **98%**
- Significant patent activity, **most active area of innovation**:
  - Recovery rate
  - Material use
  - Energy consumption

Challenges

- Process complexity
- Trade secrets and engineering expertise are key success factors
- High costs
- Differentiated technology

Source: Lux Research

Diverse Methods in Battery Recycling

Key factor for evaluating battery recycling companies

Maturity

Hi → Lo

Mechanical | Pyrometallurgy | Hydrometallurgy | **Direct**

- **Least mature** technology segment
- Recovery, regeneration, and reuse **without chemical structure breakdown**
- Involves methods outside of Pyrometallurgy and Hydrometallurgy:
    - Electro-wiring
    - Mechanical separation and relithiation
    - Membrane separation

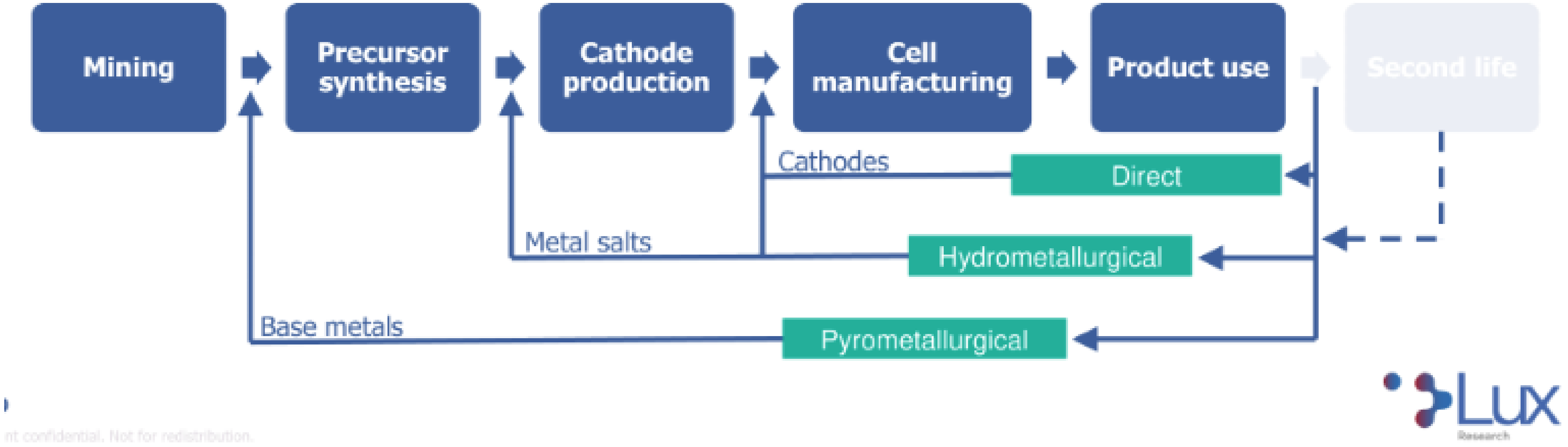
Challenges

- Highest costs
- Sorting costs – specific process per kind of battery specification
- Hard to scale
- **Esoteric**

Source: Lux Research

Efficiency in the Big Picture

Key factor for evaluating battery recycling companies



For each recycling technology, the process used is correlated with how many steps of the Li-ion battery chain it can bypass

Direct: closest to cell manufacturing

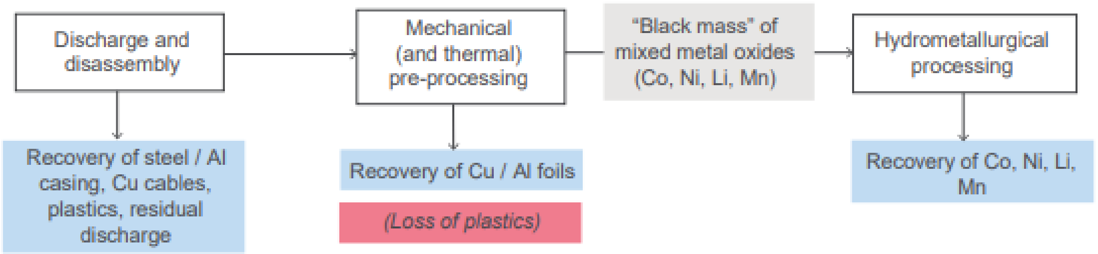
Pyrometallurgy: requires the most refinement to be replanted

Source: Lux Research

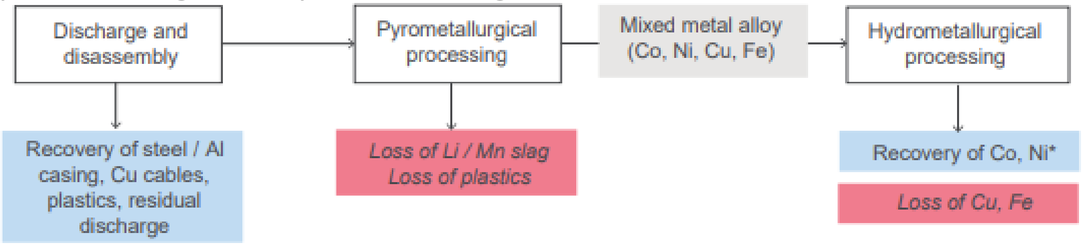
Hybrid Methods

Sample typical combination routes taken that involve the technological processes in battery recycling

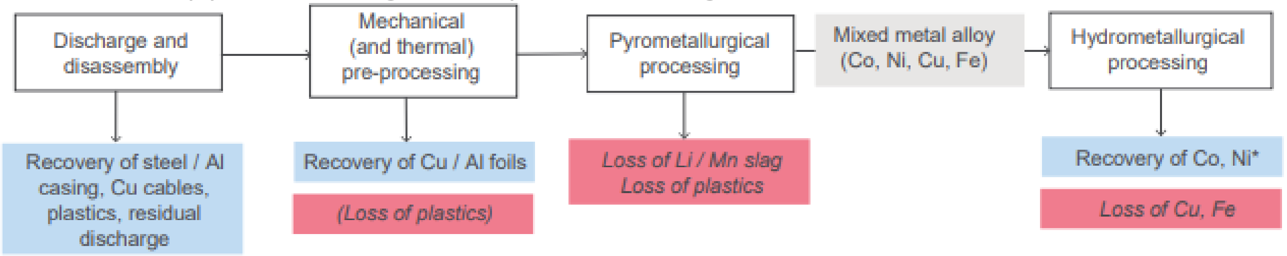
Mechanical + hydrometallurgical



Pyrometallurgical + hydrometallurgical



Mechanical + pyrometallurgical + hydrometallurgical

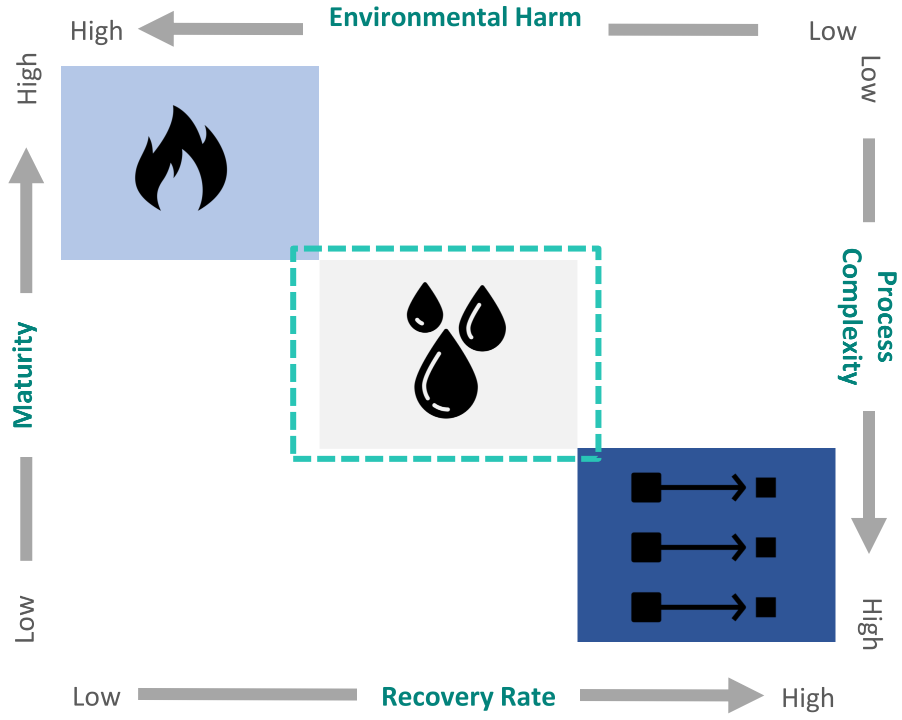


*note Li can also be recovered from the slag through the hydrometallurgical process but it is not typica lly recovered

Source: Nature

Hydro: Emerging Popular Process, Highest Potential

The sweet spot for Li-ion battery recycling

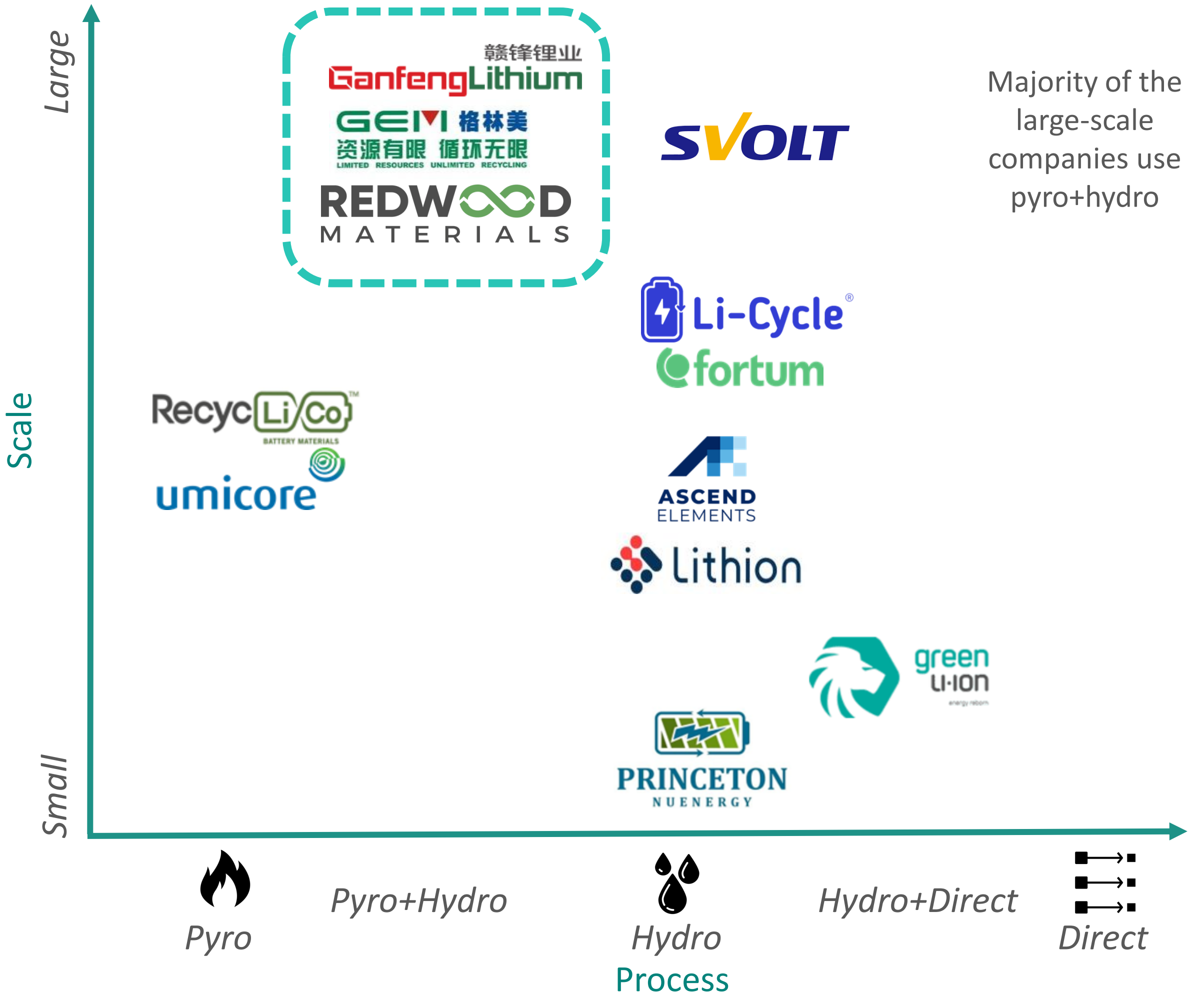


Hydrometallurgy as the mode that balances mineral extraction and economics

Names in the Space

Nascent: few big players, concentrated market

Competitive Landscape



	SVOLT	REDWOOD MATERIALS	Li-Cycle
Total raised (USD millions)	3,231	2,978	774
Year founded	2018	2017	2016
First financing date	2020	2017	2017
HQ	Changzhou, China	Nevada, USA	Toronto, Canada

Solution to a Problem

Founded by **Tesla Co-Founder JB Straubel**, Redwood Materials was established in 2017 to help create a circular battery supply chain.

Source: PitchBook

Business Models

Sales or service

Revenue models

Revenue from Sales of Recovered Materials
OEM may sell battery scrap to recyclers whereby value of **raw material content** is above the recycling cost plus margin

Recycling Service Fee
OEM maintains control over recovered raw materials and instead pays fee for recycling

Significant cost considerations

Collection and logistics
Transportation including hazardous goods surcharge

Processing
Shredding, pyro/hydrometallurgical processing, labor, and energy

Testing and disassembly
Labor and energy costs

Capital expenditures
Buildings and equipment

Source: Indonesia's Electric Vehicle Outlook 2023

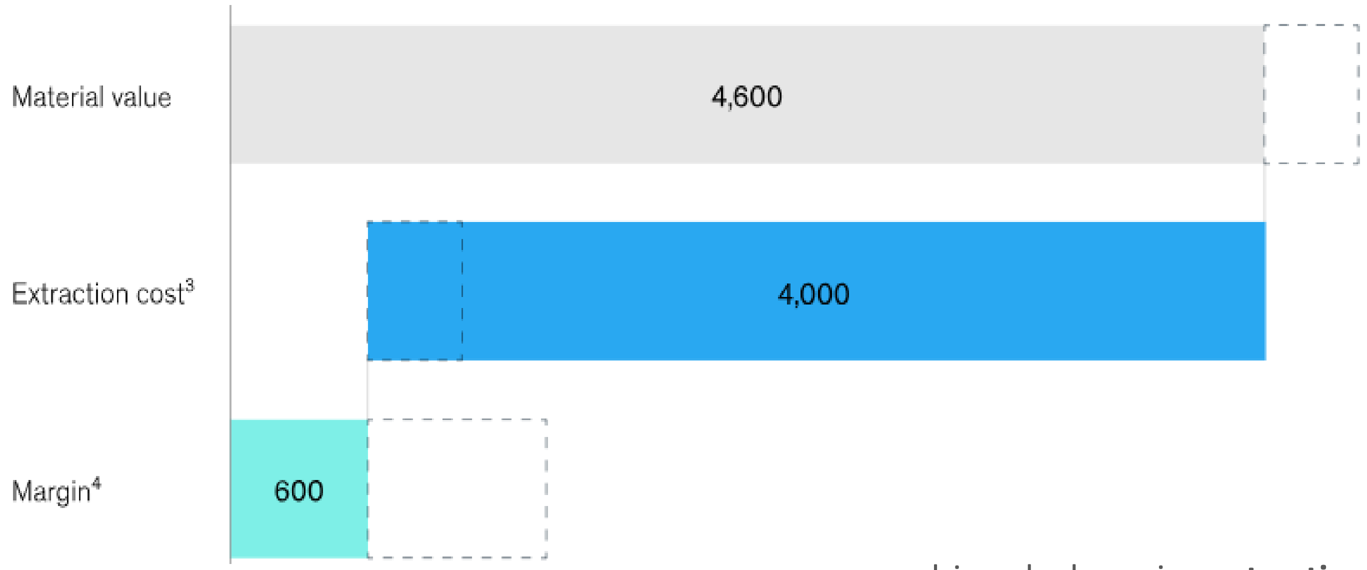
Economics Still a Question Mark

Profitability has yet to be established but projections are promising

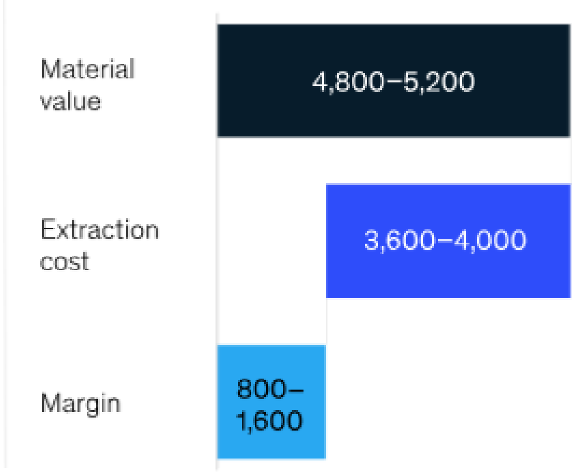
Projected

EV Battery Recycling Economics (USD/ton)

2025



2030



...driven by lowering **extraction costs,** and **increase in material value**

13% Margin (Gross)
$600/ton

Up to 31% Margin (Gross)
$800-$1,600/ton

Source: McKinsey & Company 2023

Challenges

Collection and Logistics

Battery Collection

Mechanisms to enable battery collection at EoL are currently limited across jurisdictions.

There needs to be improved traceability of batteries and incentives for users to return EVs and batteries to battery recycling facilities.

Transport and Logistics

These add significant costs to recycling especially over large distances or internationally.

In addition, batteries may be considered hazardous goods which may mean further fees for import and export.

Source: LuxResearch

Challenges

Myriad Designs and Manual Disassembly

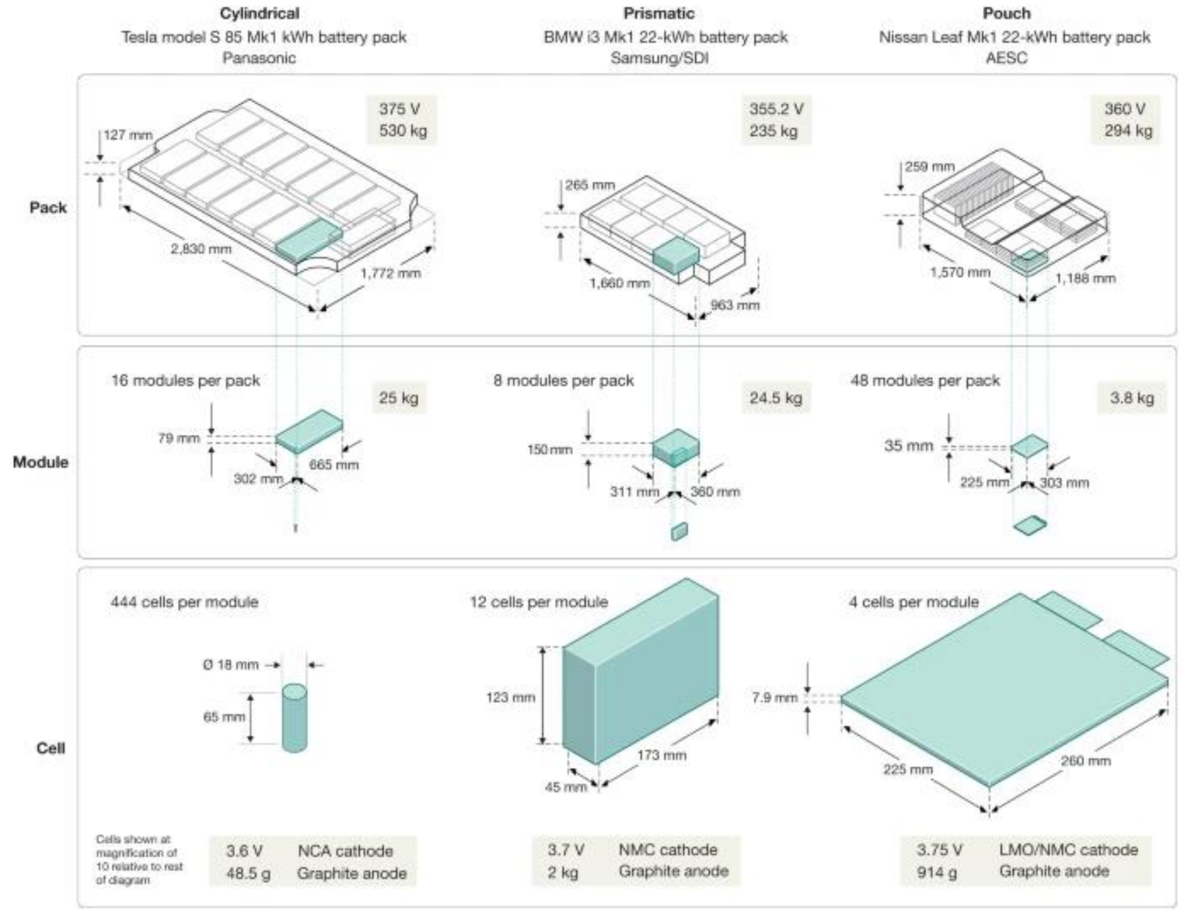
Myriad Designs

Different chemistries and divergent designs (LDVs, Buses, Trucks) may call for different SOPs in battery recycling processes.

Manual Disassembly

With numerous designs available in the market, most initial stages rely on **human sorting and disassembling** batteries.

Fig. 2: Examples of three different battery packs and modules (cylindrical, prismatic and pouch cells) in use in current electric cars.



Source: LuxResearch

Challenges

Scale, Lifespan, and CAM

Economies of Scale

Due to collection and transportation challenges, a recurring supply of Feedstock may be difficult to secure which may prevent companies to prove out its processes and technologies at scale.

Standards on Lifespan

Current lifespans are between 8-15 years. Several OEMs are working on developing batteries with longer lifetimes, which could reach ~20 years.

However, consumers are more likely to upgrade vehicles before batteries reach end-of-life.

Cathode Active Material (CAM) Composition

Battery manufacturers may explore other cathode compositions that lower costly CAM contents (i.e., Lithium-ion to Sodium-ion). This shift could impact the viability of cost-efficient recycling.

Source: Bloomberg NEF

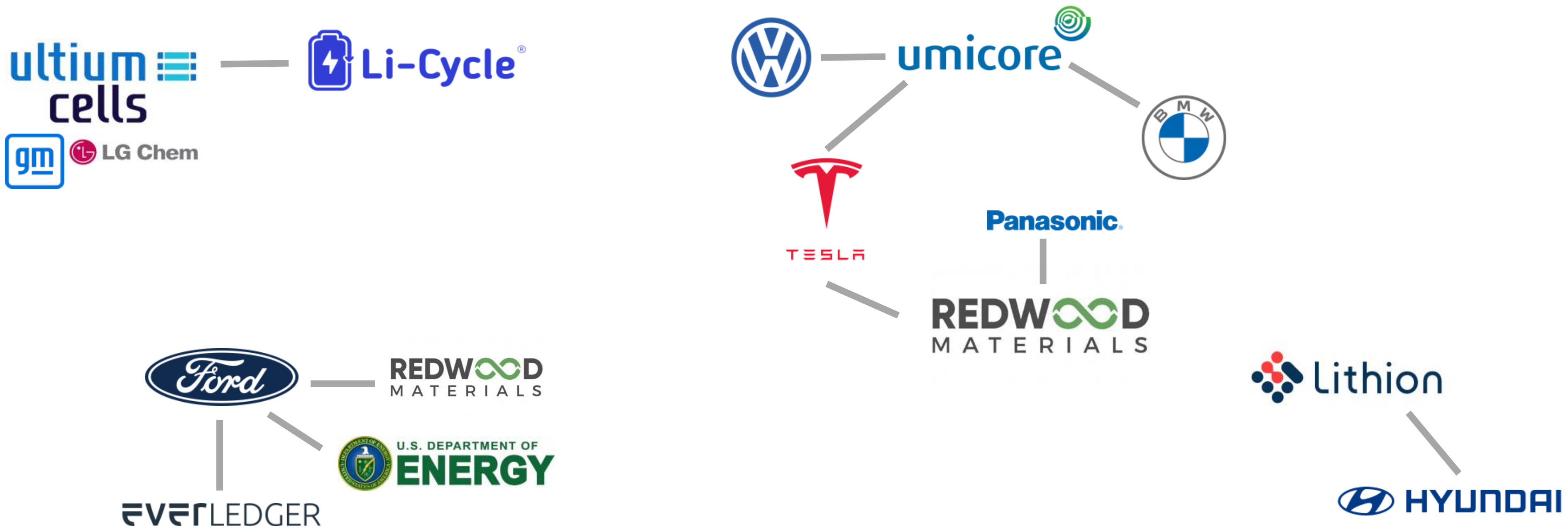
TTV
TWIN TOWERS VENTURES

De-risking

Observed collaborations between players to minimize risk

The necessity of partnerships in battery recycling is illustrated by the **networks** that larger companies have built. This better secures the feedstock stream and the eventual sale of products.

Automaker, Cell Manufacturer, Recycler

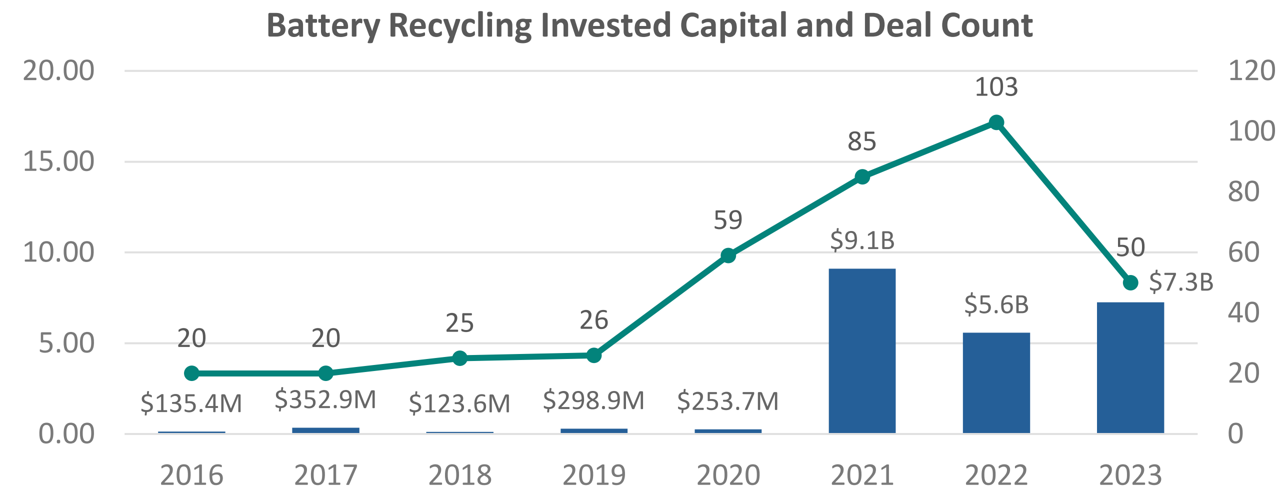


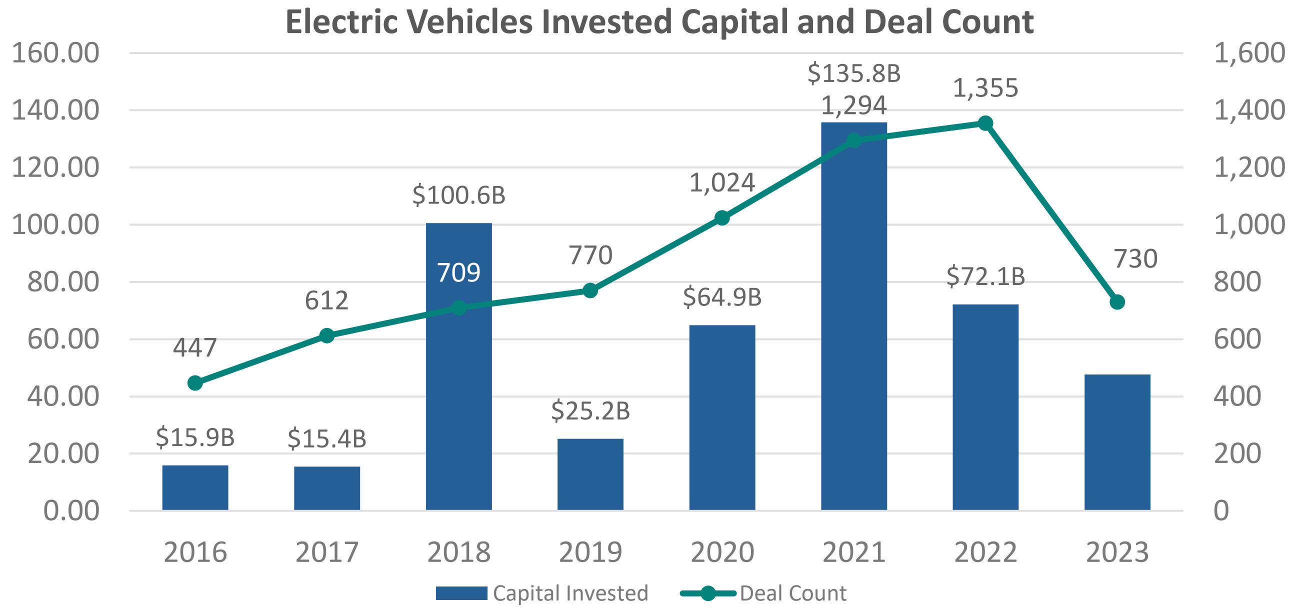
Everledger
Blockchain company that will assign digital identities to batteries for monitoring

Source: Lux Research 2023, Pitchbook 2021

Investment Space (I of II)

Spikes in investment starting 2021





Source: PitchBook Data, Inc. 2023

Nascency, Opportunity, and Potential

On an absolute level, **significant capital inflow started in 2021**.

Investments in the higher single-digit billions are becoming evident.

However, when viewed comparatively, these amounts **remain relatively modest when contrasted with the entirety of the electric vehicle industry**.

Investment Space (II of II)

Example of investment activities by VC / CVC investors in the space

APAC

METASTABLE MATERIALS™ – WASTE AS ORES
- SEQUOIA
- SPECIALE INVEST
- THEIA VENTURES

SVOLT
- 四川能投 SICHUAN ENERGY INVESTMENT
- 九至资本 JIU ZHI ZI BEN
- CDH INVESTMENTS 鼎晖投资

green li-ion energy reborn
- equinor
- BANPUNEXT
- trirec RENEWABLES / ENVIRONMENTAL / CLEANTECH

North America

REDWOOD MATERIALS
- Tesla
- United States Department of Energy
- VALOR EQUITY PARTNERS
- Goldman Sachs Asset Management
- Fidelity Investments

Li Industries
- khosla ventures
- Shell Ventures

RecycLiCo™ BATTERY MATERIALS
- Canada NRC·CNRC

Li-Cycle®
- Bloomberg NEW ENERGY FINANCE
- MUBADALA
- NEUBERGER BERMAN

PRINCETON NUENERGY
- Shell Ventures
- United States Department of Energy
- NJEDA ECONOMIC DEVELOPMENT AUTHORITY

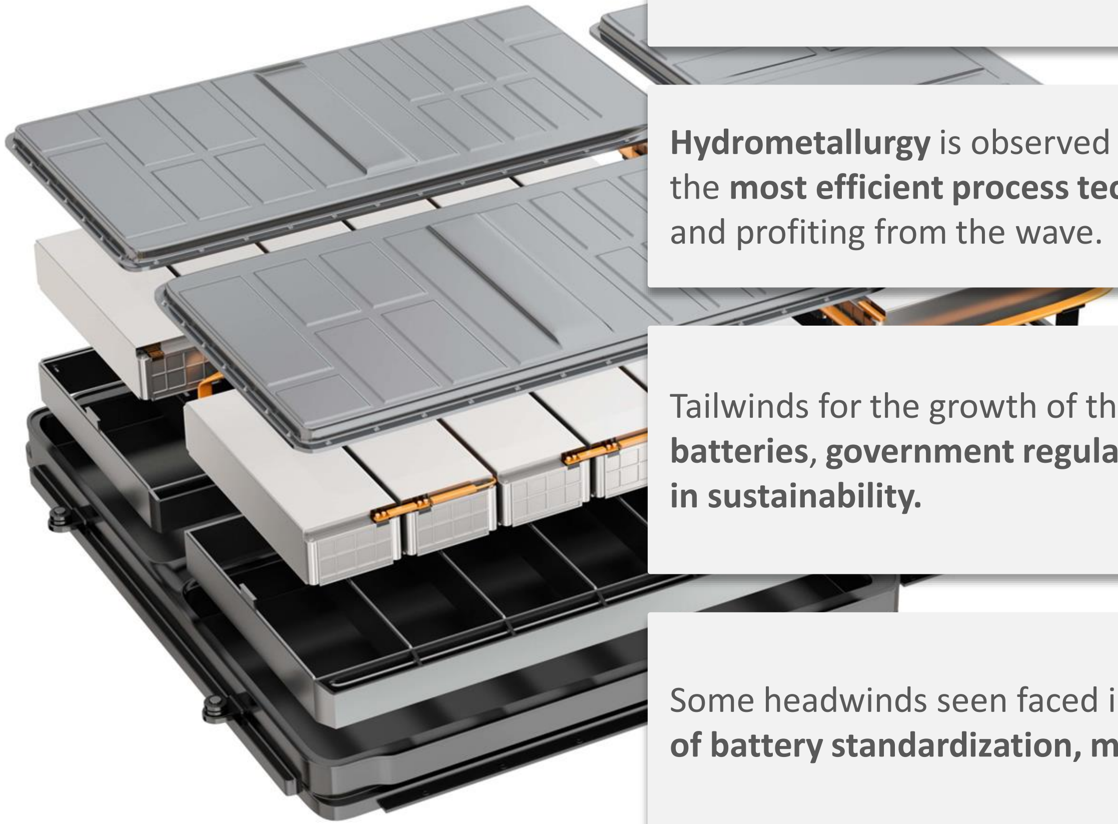
Europe

CYLIB
- WORLDFUND
- vsquared ventures

Source: PitchBook 2023

Takeaways

The rising tide of EVs lifts the battery recycling boat



The battery recycling industry is **nascent and poised to see growth (~34% annually)** following the exponential rise of Electric Vehicles as the global market looks to sustainability and a circular economy with end-of-life batteries.

Hydrometallurgy is observed to be the emerging popular technique. Battery recycling companies with the **most efficient process technologies** and streamlined value chains will have an advantage in riding and profiting from the wave.

Tailwinds for the growth of the industry include **process innovations**, **surging demand for Li-ion batteries**, **government regulatory suppor**t for reduction in foreign resource dependence and; a **push in sustainability.**

Some headwinds seen faced in the industry include **profitability, battery collection & transport, lack of battery standardization, manual processes,** and **scaling operations.**

Thank You