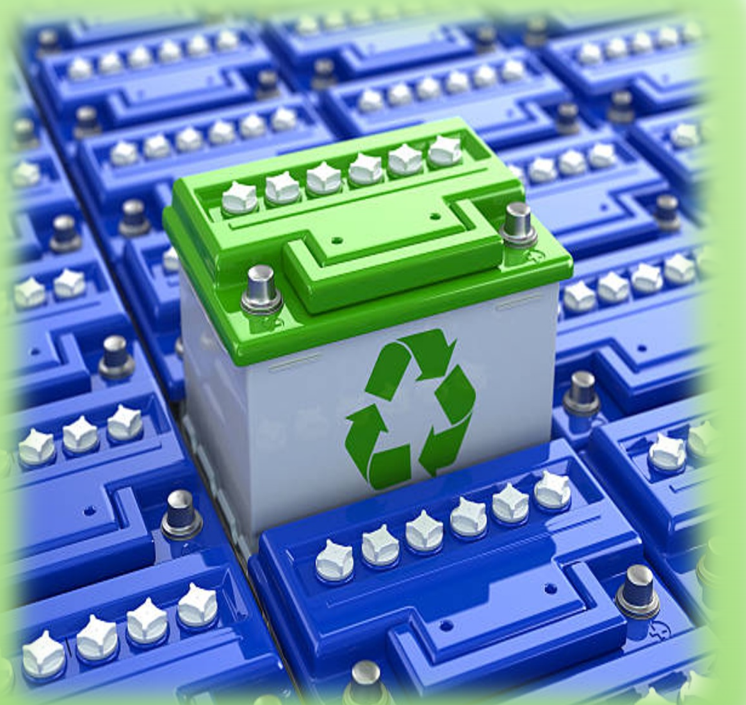

Can we Make US Battery Supply Chain Sustainable?

Lithium Ion Battery (LiB) Recycling-

Current Practices and New Innovations

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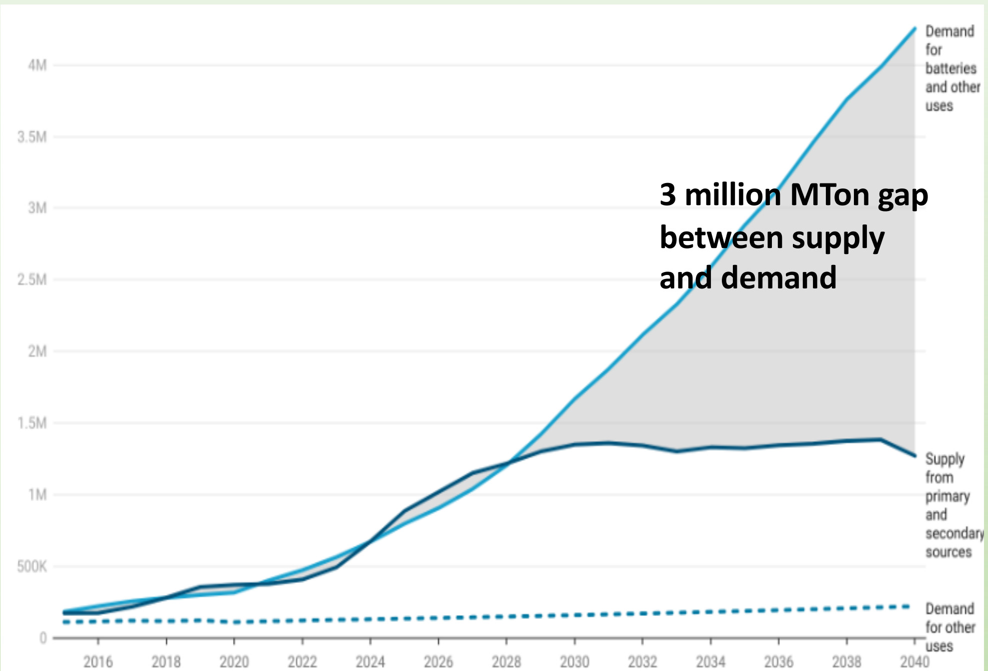
Critical Materials Institute

Availability and Cost of Minerals for Electrification Drives Lithium Demand

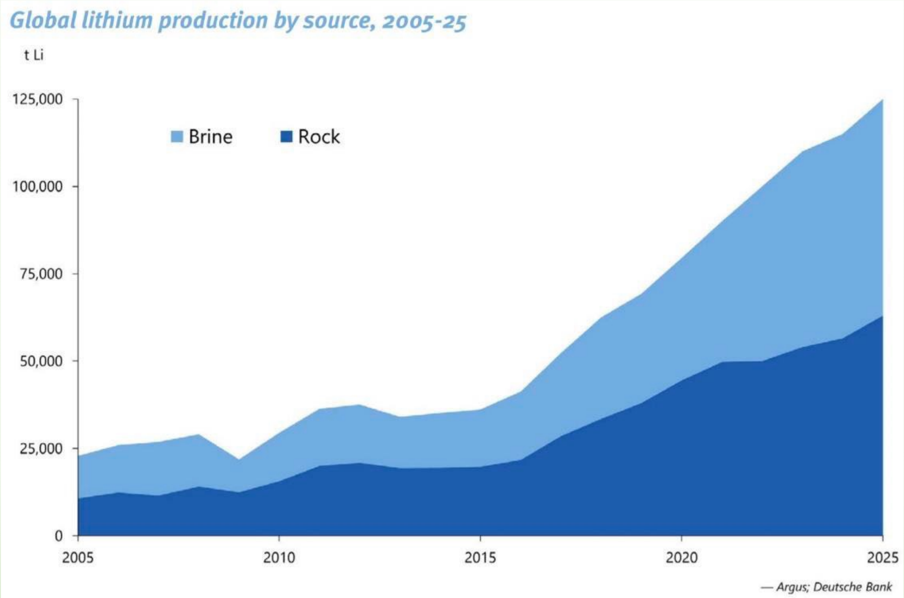
Forecast of global Supply-Demand balance for lithium [t LCE]



Source: INL, 2023.

- Lithium(Li), Nickel(Ni) and Cobalt (CO) and other critical minerals are key to electrification
- Lithium is expensive and critical for many batteries
- Conventional processing techniques require long processing, are energy intensive and generate waste

Lithium Supply Sources



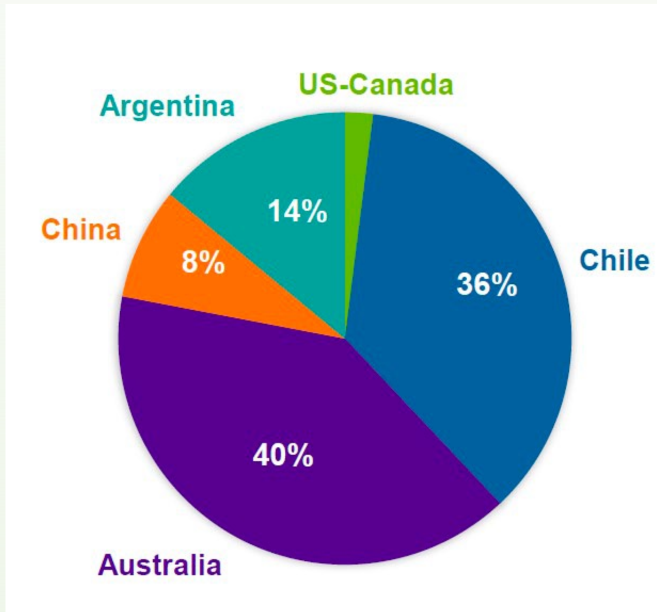
- Minerals (2,300 –18,000 ppm)
- Sedimentary clays (2,000 –3,000 ppm)
- Sea water (0.17 ppm)
- Recycling of lithium-ion batteries – Lithium, Nickel, Cobalt and Graphite

Global lithium production by source

AUSTRALIA
Greenbushes
Mt. Cattlin
Mt. Marion
Wodgina (starting)

CHINA
Sichuan (Jiajika, Maekang, Lijiagu)
Jiangxi (Yichun, Heynan)
Xinjiang (Koktokay)

CHINA
Taijinar (Citic, QLL)
Zhabuye (Tibet)
Chaerhan (QSLG)

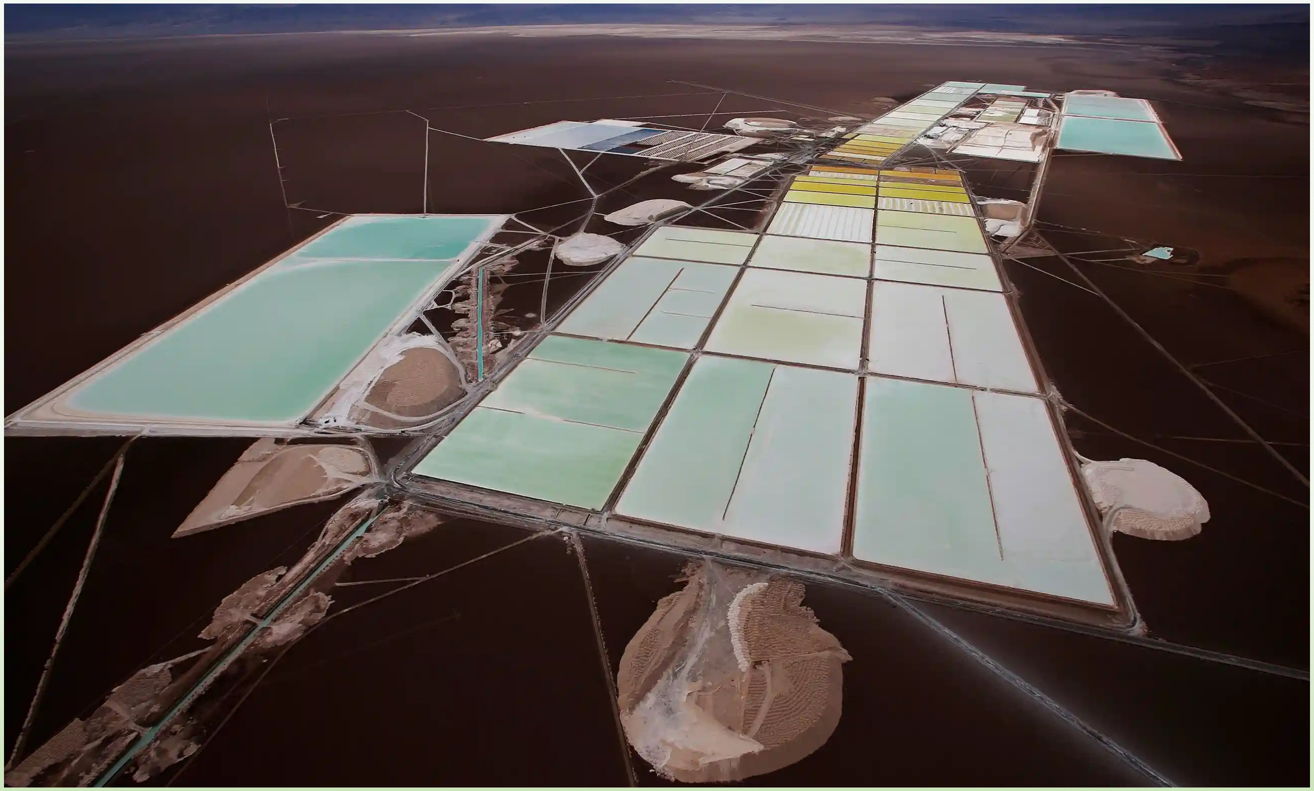


ARGENTINA
Salar de Hombre Muerto (FMC)
Olaroz (ORE)

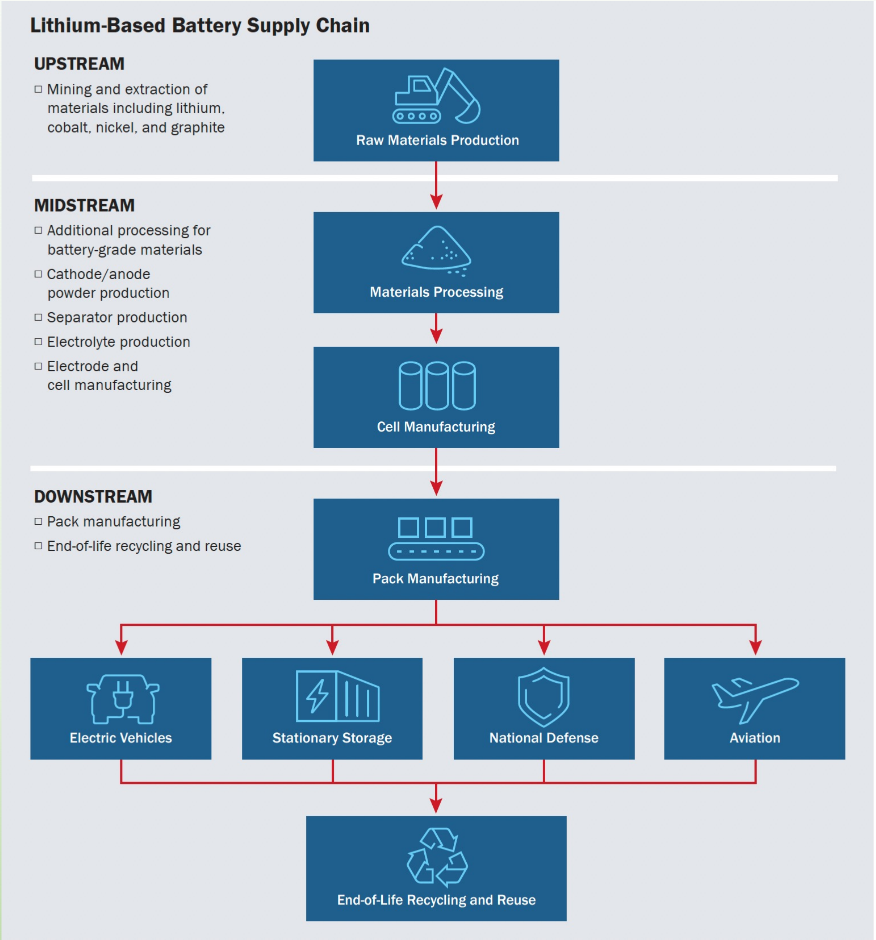
CHILE
Salar de Atacama (SQM, ALB)

Source: Stringfellow, et al, 2021.

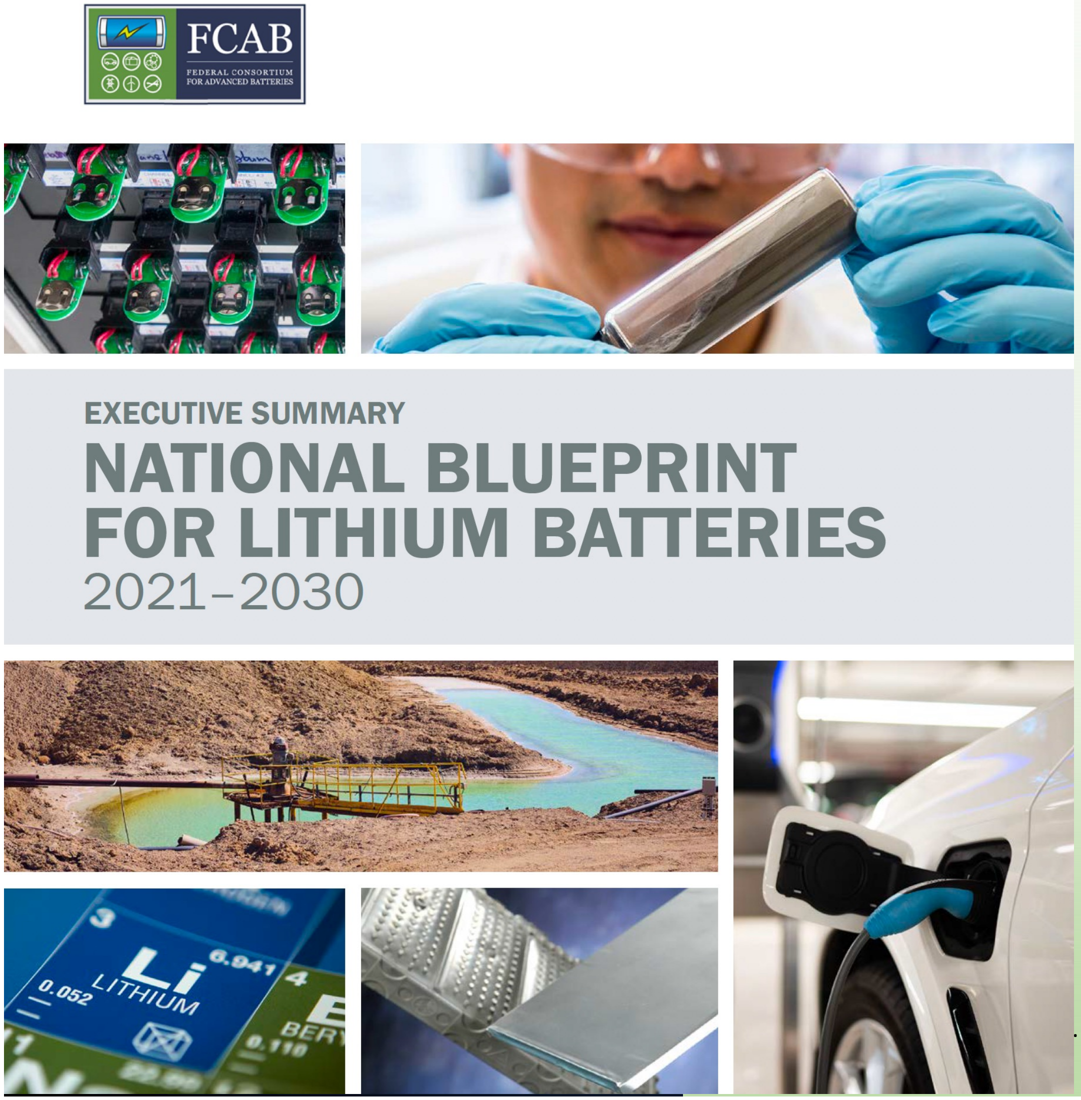
Lithium Mining: Practices, Environmental Impacts and Processing time



Lithium-Ion Batteries (LiB) Supply Chain



Source: US DOE, 2022.



GOAL 1 - Secure access to raw and refined materials and discover alternatives for critical minerals for commercial and defense applications

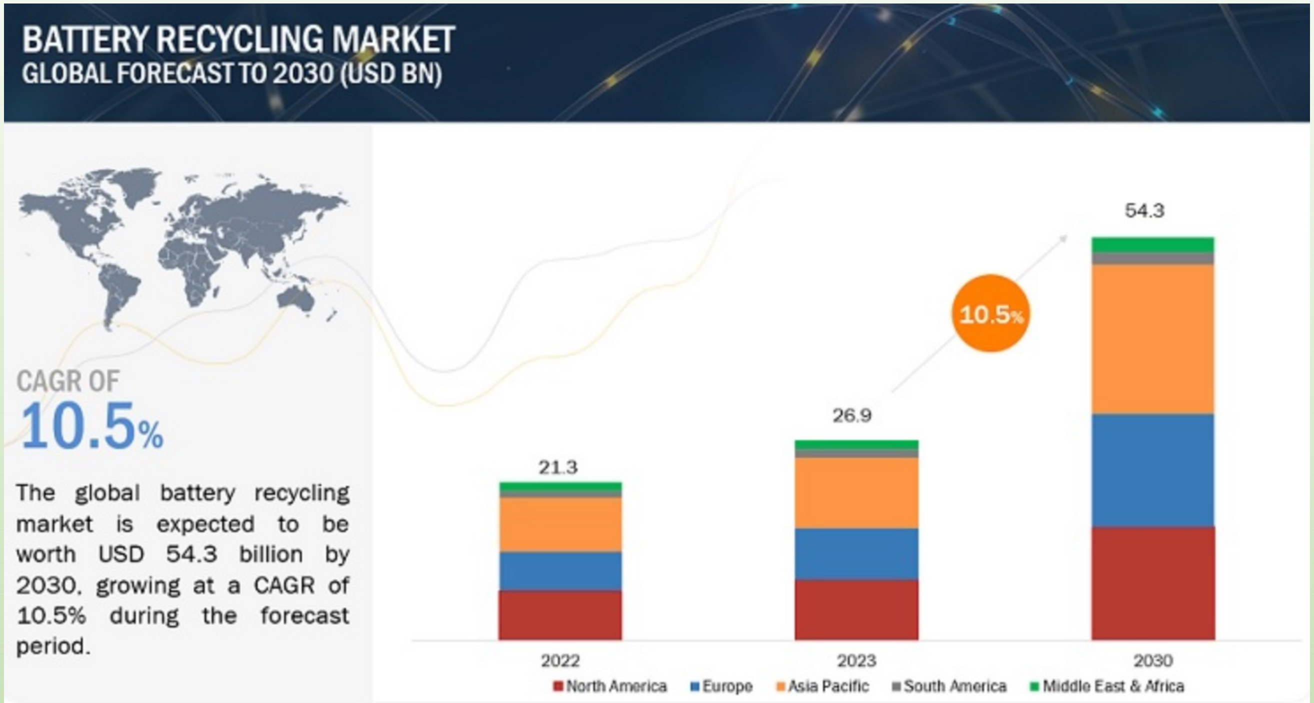
GOAL 2 Support the growth of a U.S. materials-processing base able to meet domestic battery manufacturing demand

GOAL 3 Stimulate the U.S. electrode, cell, and pack manufacturing sectors

GOAL 4 Enable U.S. end-of-life reuse and critical materials recycling at scale and a full competitive value chain in the United States

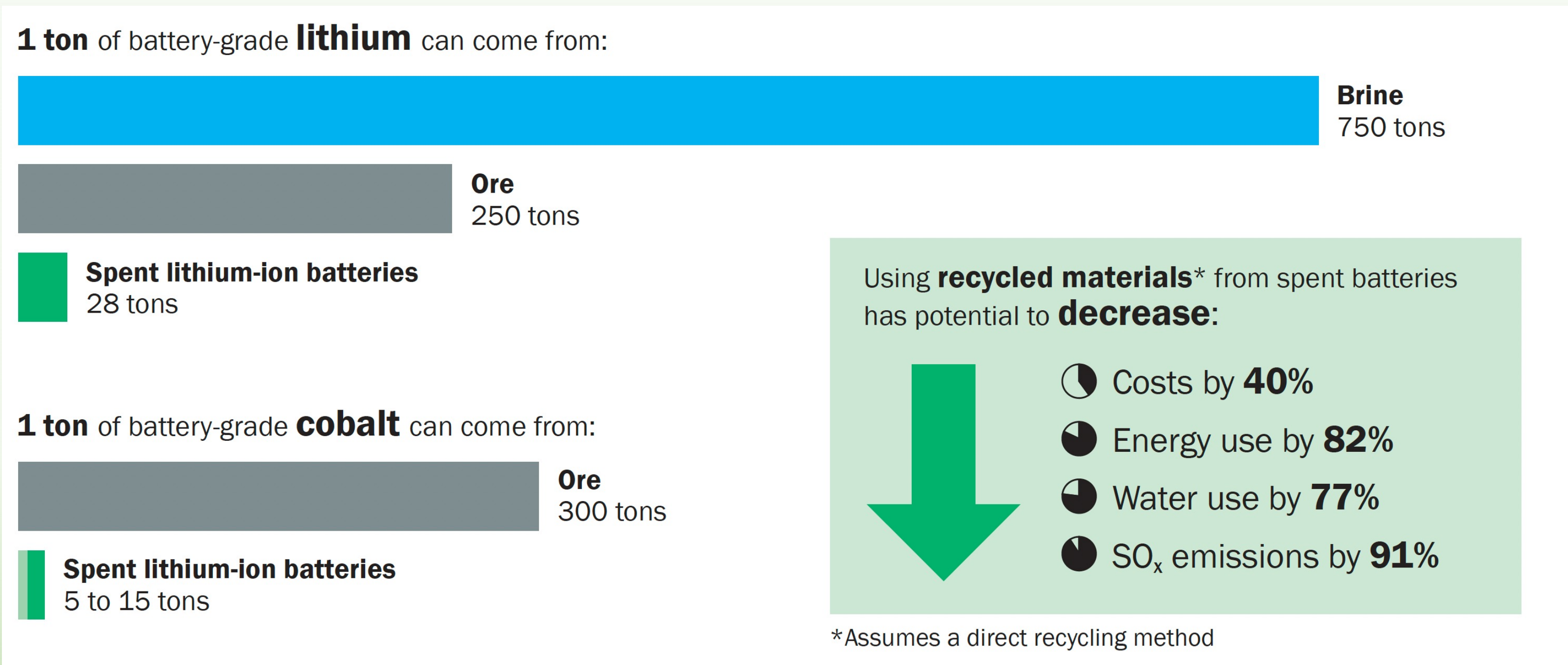
GOAL 5 - Maintain and advance U.S. battery technology leadership by strongly supporting scientific R&D, STEM education, and workforce development

Li-B Recycling Market in US Expected to Grow from $21.3B in 2022 to $54B in 2030

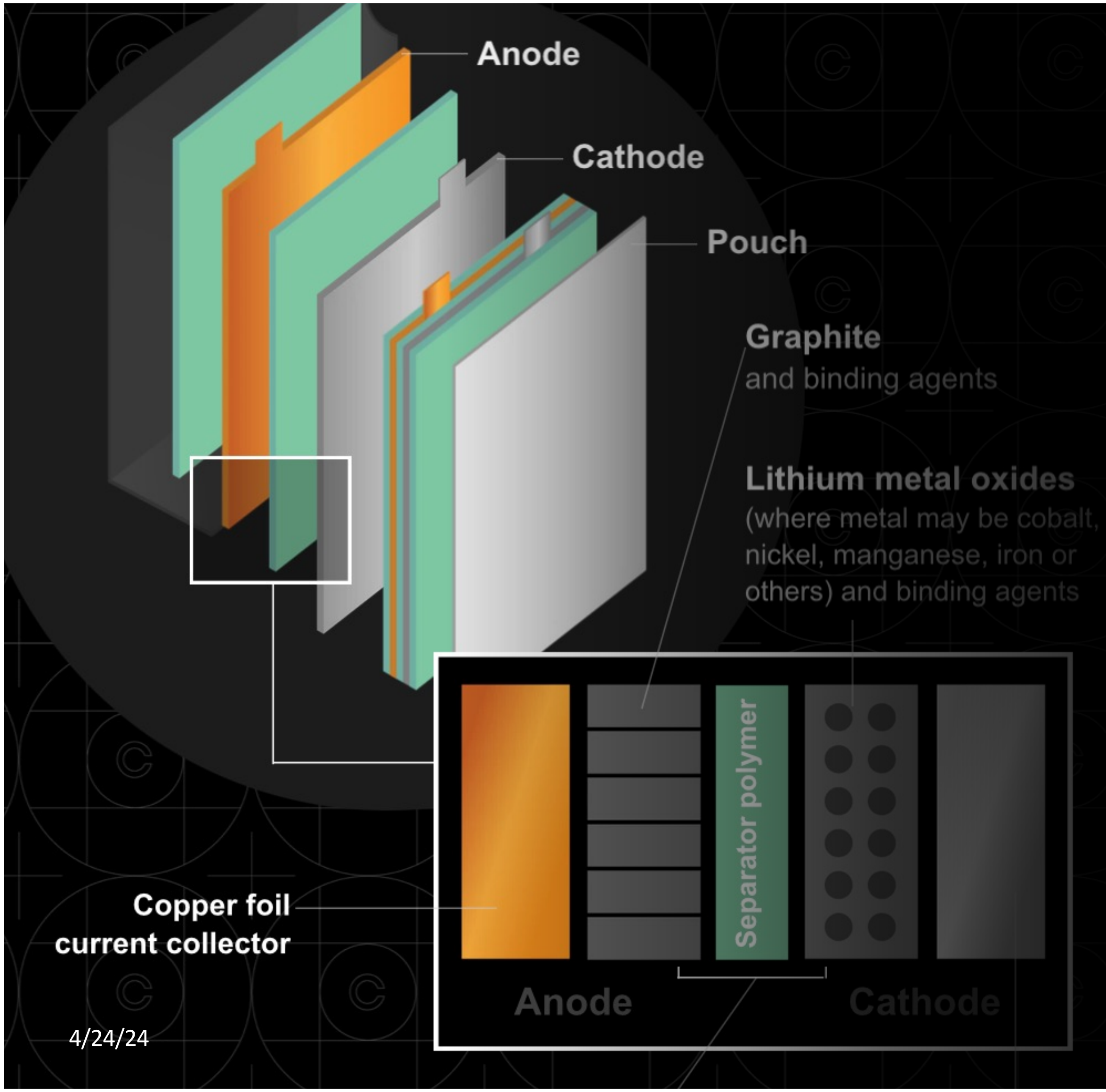


Source: Markets & Markets, 2023.

Benefits of Recycling for Lithium-ion Batteries

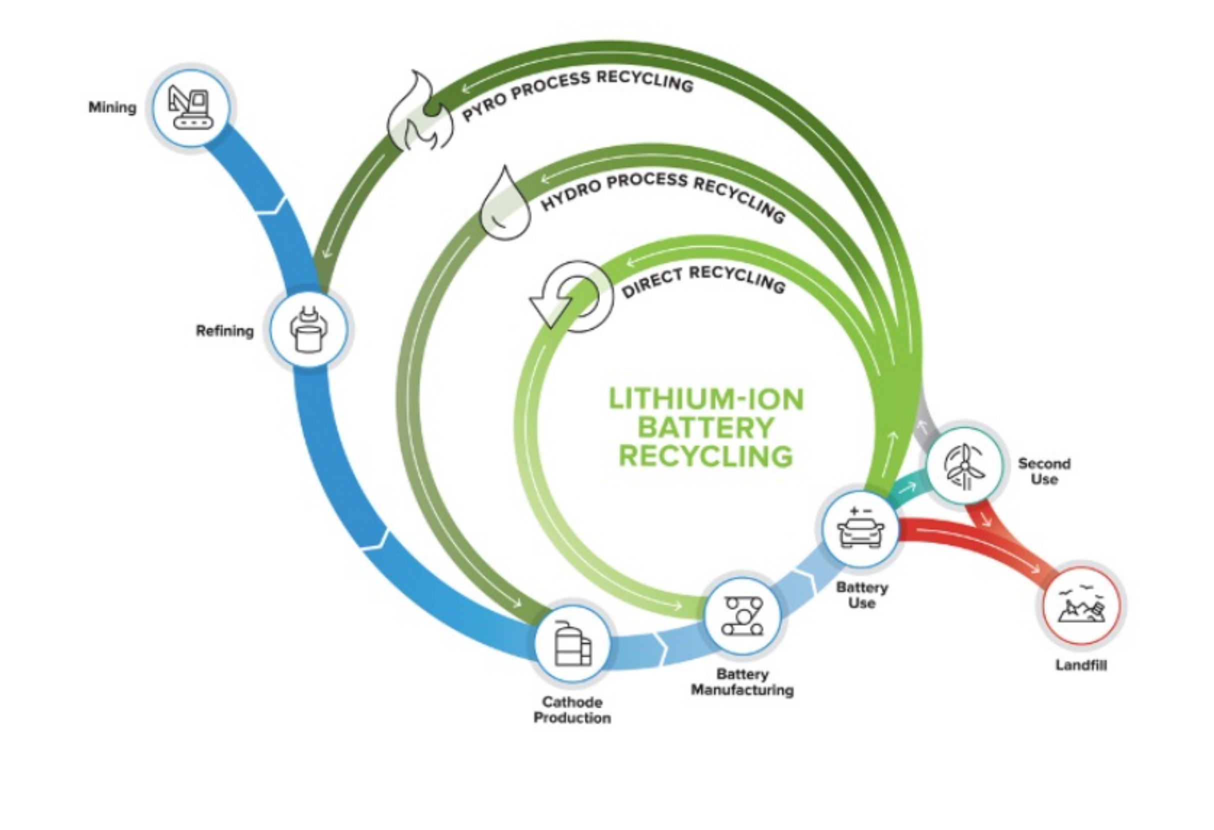


Source: Argonne National Lab, 2019.



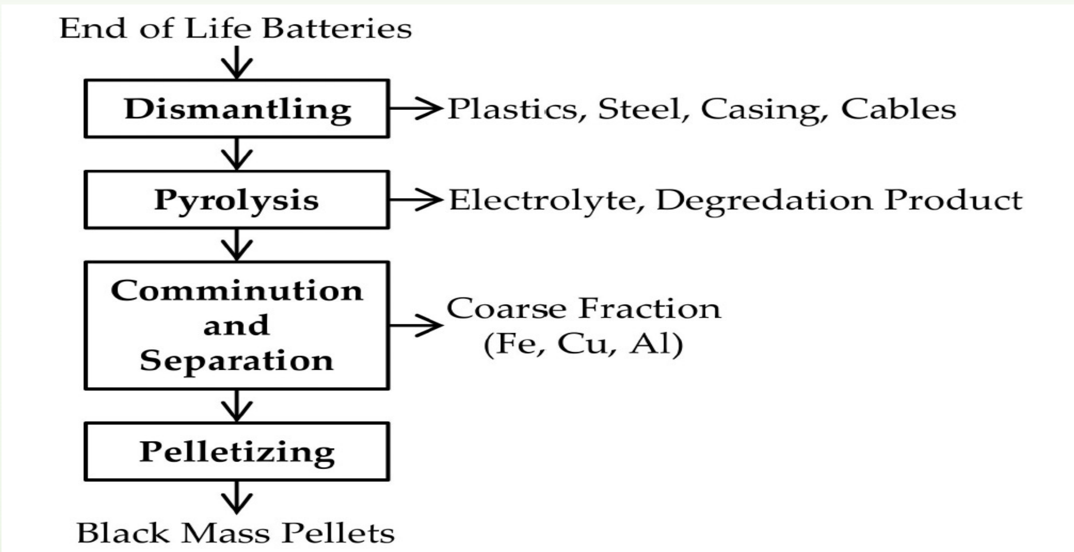
What is inside a lithium Ion Battery?

Common LiB Battery Recycling Processes



Schematic: Argonne National Lab

Process Flow Diagram for Blackmass Process

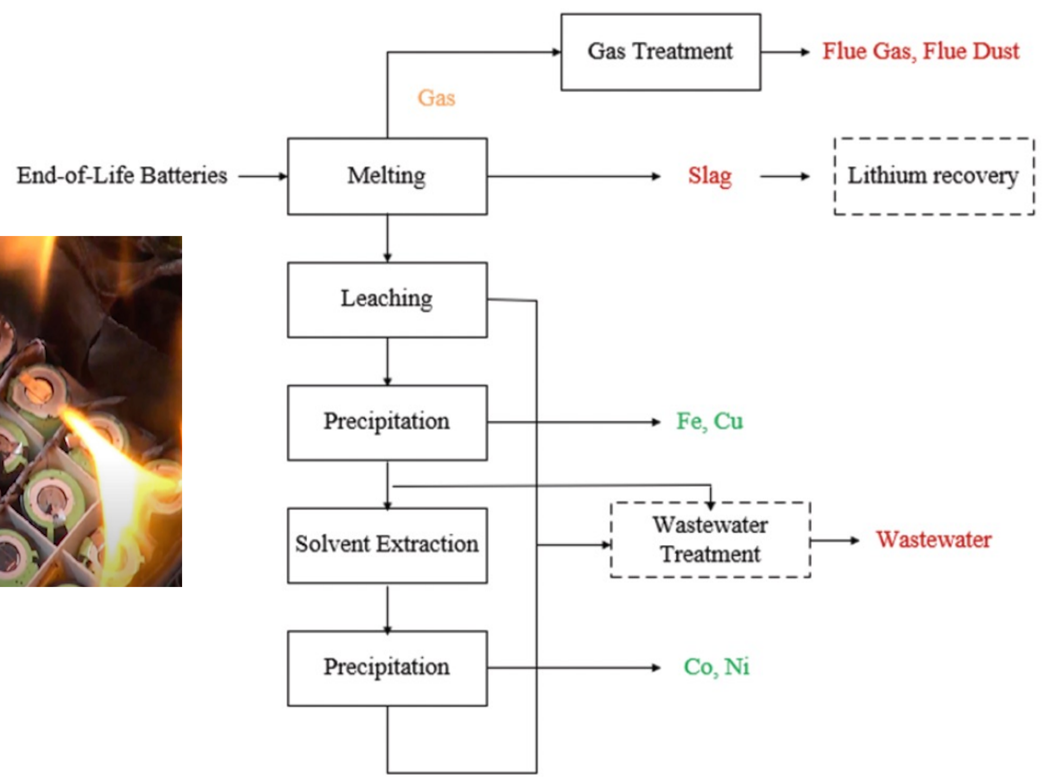


Compound	Co	Fe	Mn	Al	Cu	Si	Zn	Ni	Ag	Li	C
Mean	22.0	6.51	0.75	3.88	4.69	0.37	0.11	2.71	0.32	2.24	20.5
Std. Dev.	0.14	0.12	0.00	0.05	0.02	0.07	0.00	0.04	0.01	0.02	0.27

Source: Ozturk, M, et al, 2023

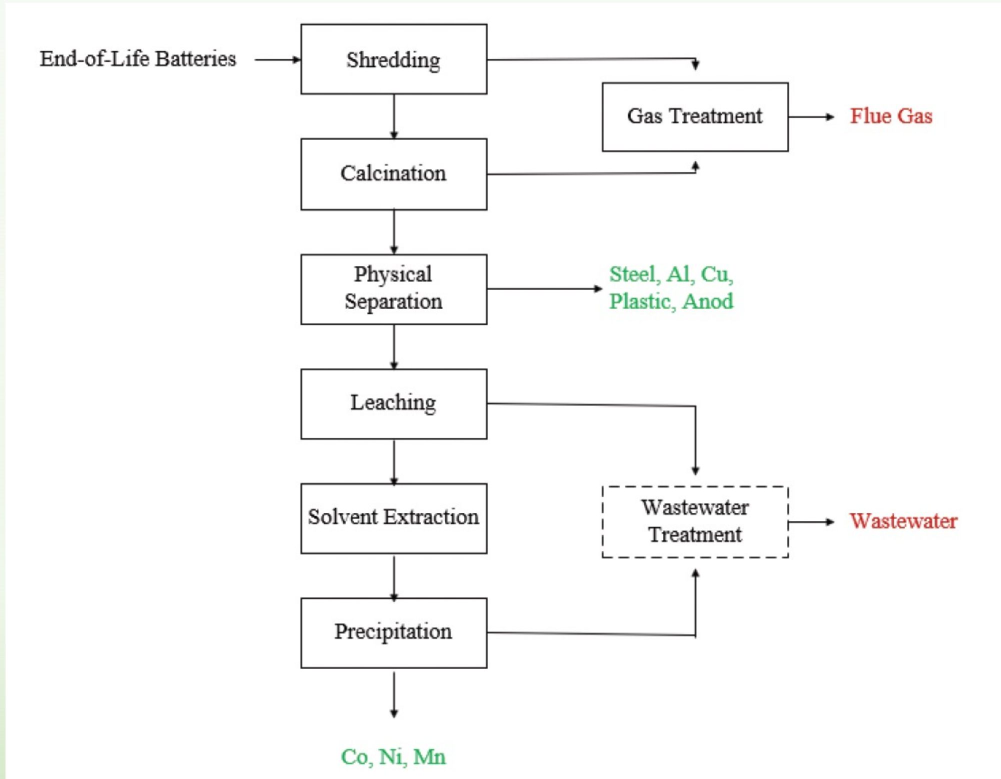
Composition of the black mass in wt.%

Pyrometallurgical LiB Recycling Process

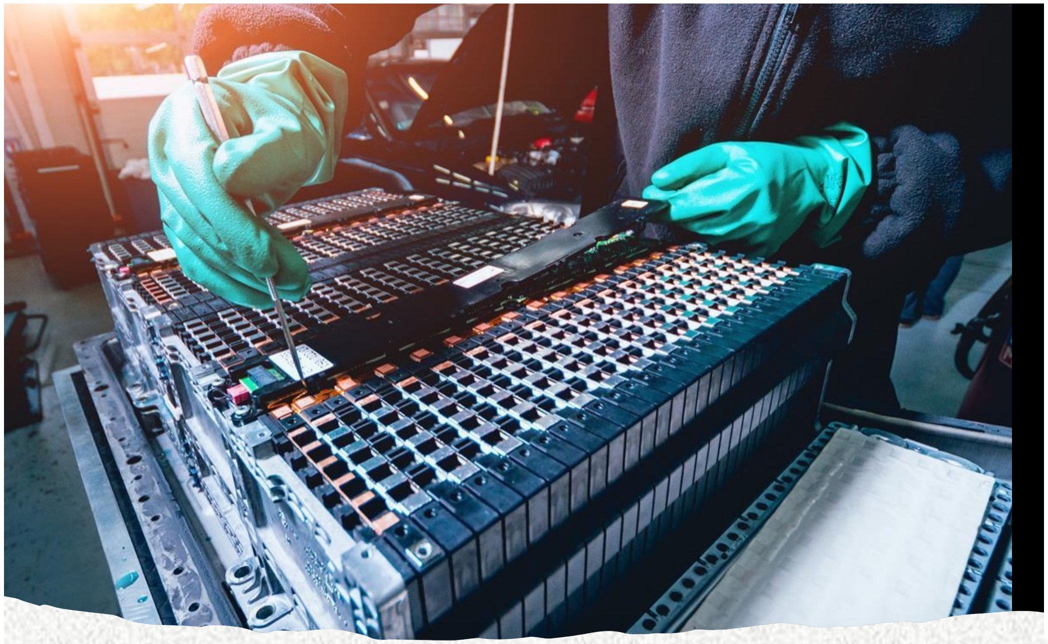


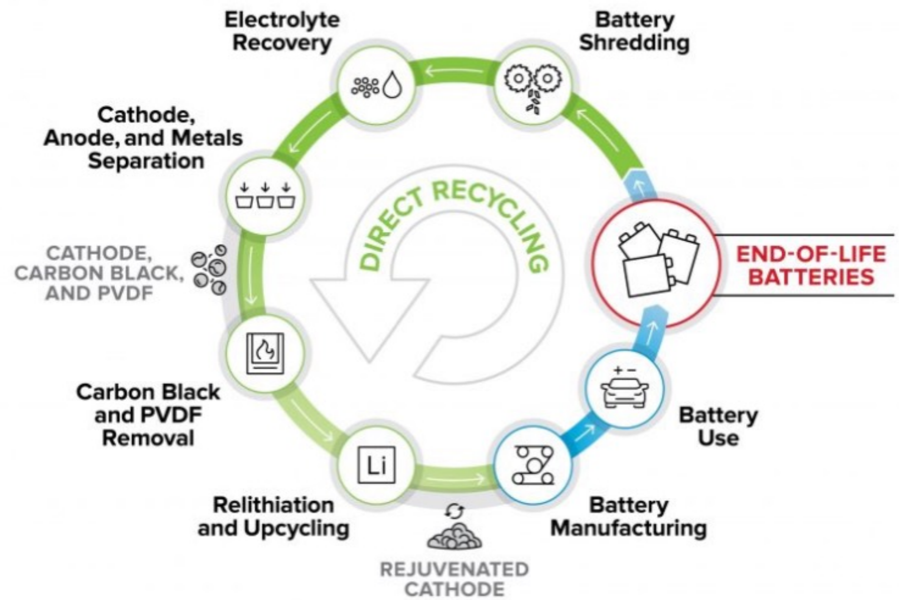
Source: Ozturk, M, et al, 2023

Hydrometallurgical LiB Recycling Process



Source: Ozturk, M, et al, 2023





Direct LiB Recycling

Schematic: Argonne National Lab

Comparison of Maximum Efficiencies for LIB recycling

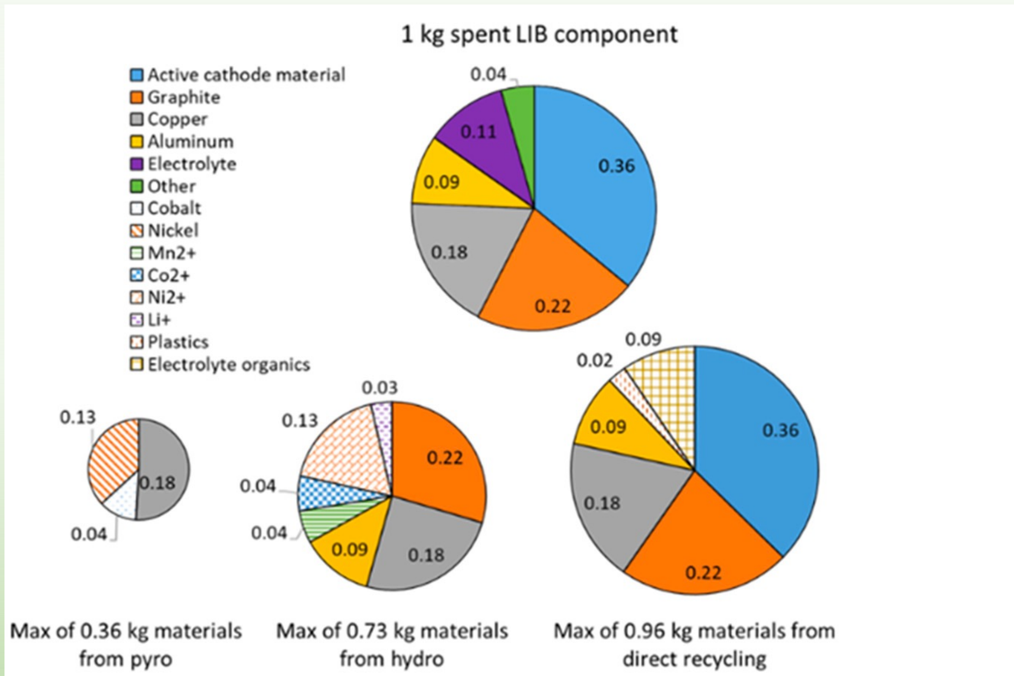
Process	Cathode	Li	Co, Ni, Mn	CU	Al	Anode	Electrolyte	Separator
Pyro								
Hydro								
Direct			N/A					

red = not recovered

green = up to 100%

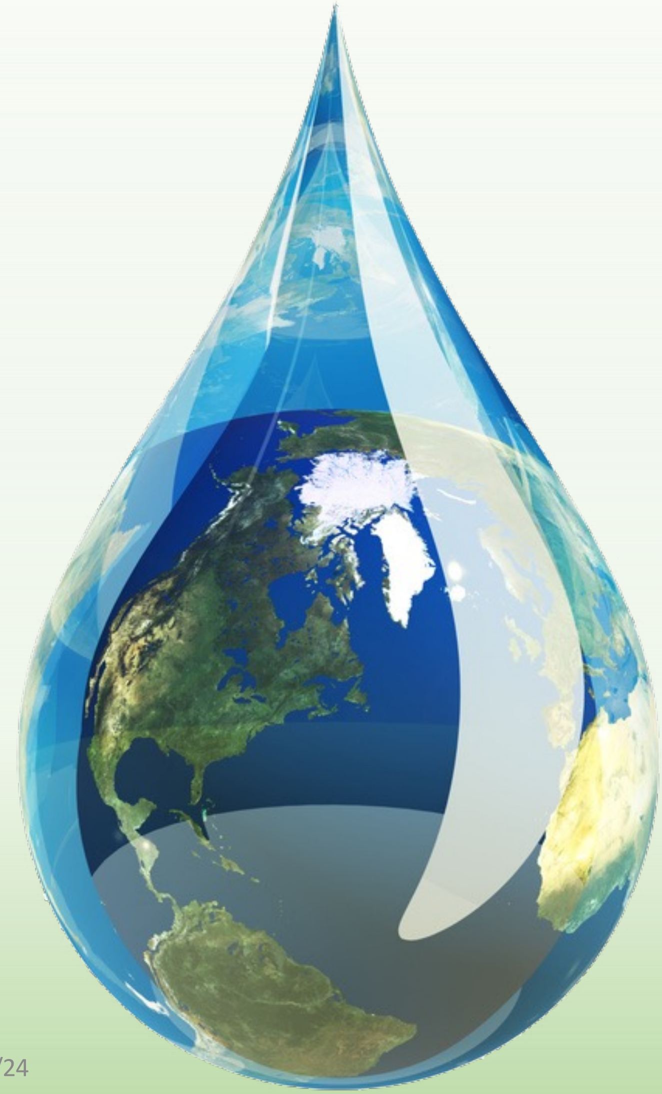
yellow = possible but generally not economical

Source: Gaines, et al, 2023.



EXERGY

Advanced Technologies for Circular Production



Role of Innovative Technologies in LiB and Critical Materials Recovery

4/24/24

Membrane and Electro-Separation

- Unique electrochemical and advanced membrane separation technologies can help in recycling and recovery of resources from brine/mining and LiB recycling
- Various membrane technologies can be combined to provide complete solutions
- Can meet high material quality/purity requirements

Why Membrane Electro-separation?

Conventional treatment techniques including Ion Exchange (IX) and conventional membrane creates wastewater, rejects and wastes:

- **Waste treated or hauled off site for waste treatment**

- Contaminated with various undesired compounds
- High volumes of brines is generated in many cases
- High costs for treatment and/or disposal
- No technology exists today to effectively manage Brine on-site

Electro-Membrane Processes
General Overview

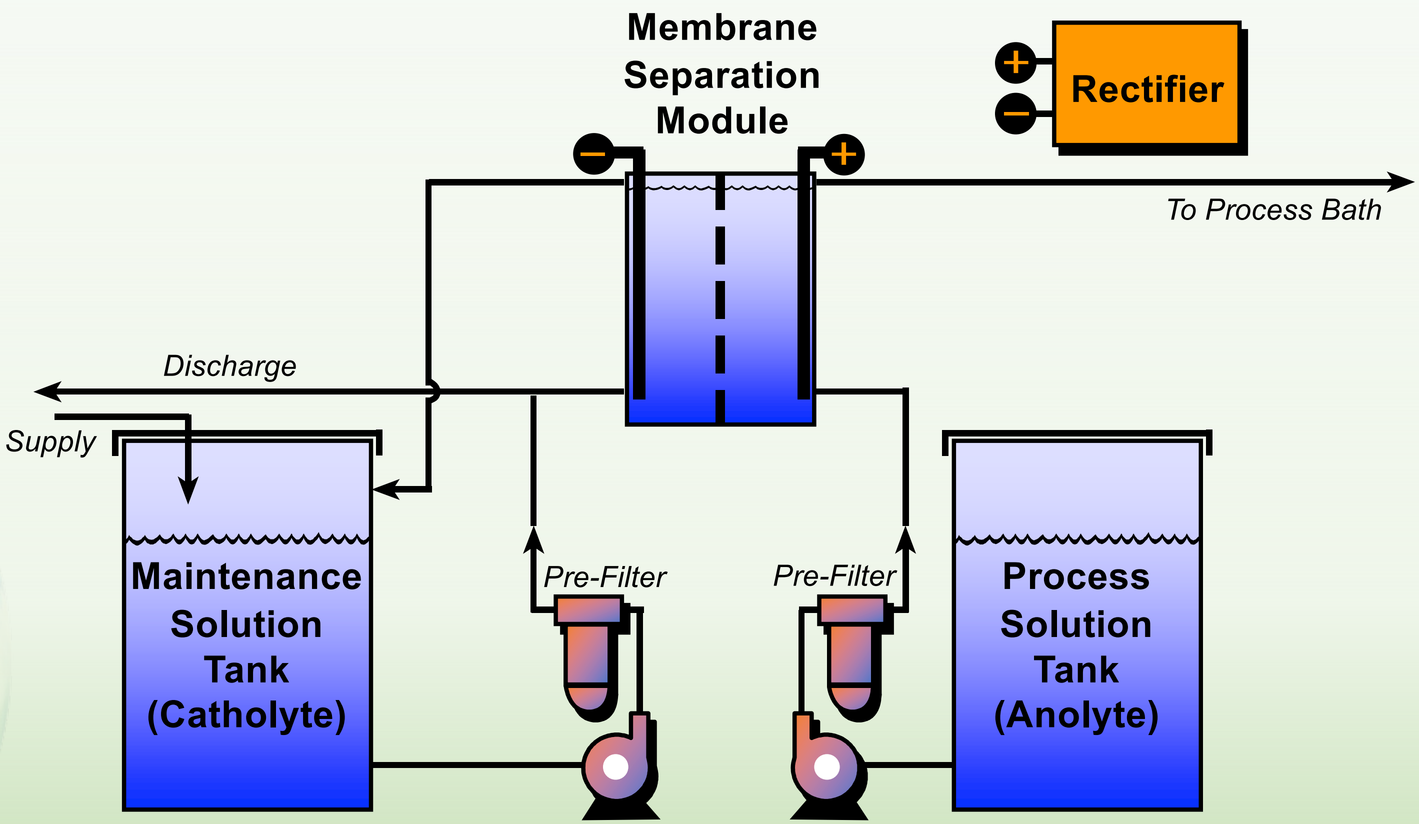
- **Membrane separation processes are driven by an electrical potential**
- **Removal of selective metallic/ionic impurities from process solutions**
- **Regeneration/recovery system has been deployed in industrial applications such as etching, deoxidizing and stripping solutions**

EXERGY

General Overview (Cont'd)

- Eletro-separation technologies utilize ion exchange membranes for each select application and ionic separation
- The membranes are ion-permeable and selective to allow ions of a given electrical charge to pass through
- Cation exchange membranes allow metal ions to pass through
- Anion exchange membranes allow only anions, such as chloride and sulfate to pass through

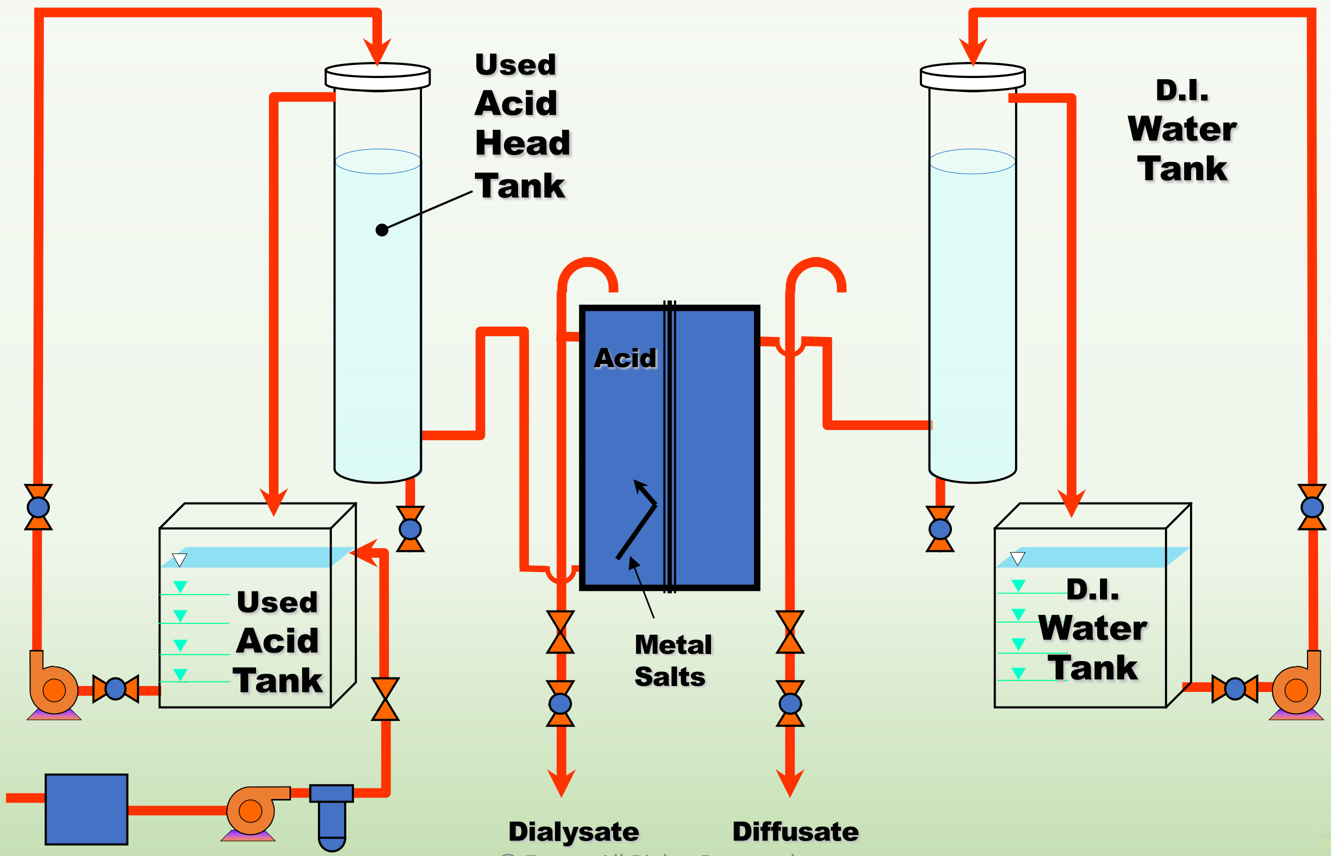
Schematic for Membrane Electro-Separation Process



Acid Leach Chemistry Purification and Recovery

- Typical application is maintenance and purification of acids in process application
- Anion exchange membranes are used to achieve separation
- Gravity operation driven by Donnan diffusion as the separation mechanism (concentration difference)

Acid Recovery Configuration



Closing Remarks

- Today: technologies utilized in battery material mining and recovery are dated, inefficient and costly to operate
- Major inefficiencies in LiB reprocessing leads to high energy use, large waste and wastewater generation
- Innovative technologies have the opportunity to reduce costs, improve processing, and lower the climate impact of LiB recycling
- The chemical structure of batteries shifts from year to year so the recovery processes have to be adaptable — Panasonic slashed the cobalt content in Tesla batteries by 60% between 2012 and 2018, for instance.
- Tomorrow: US is well positioned to embrace new technologies in this segment

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Discussion and Q&A