ReCell
ADVANCED
BATTERY RECYCLING

LI-ION BATTERY RECYCLING AND THE RECELL CENTER

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NASEM
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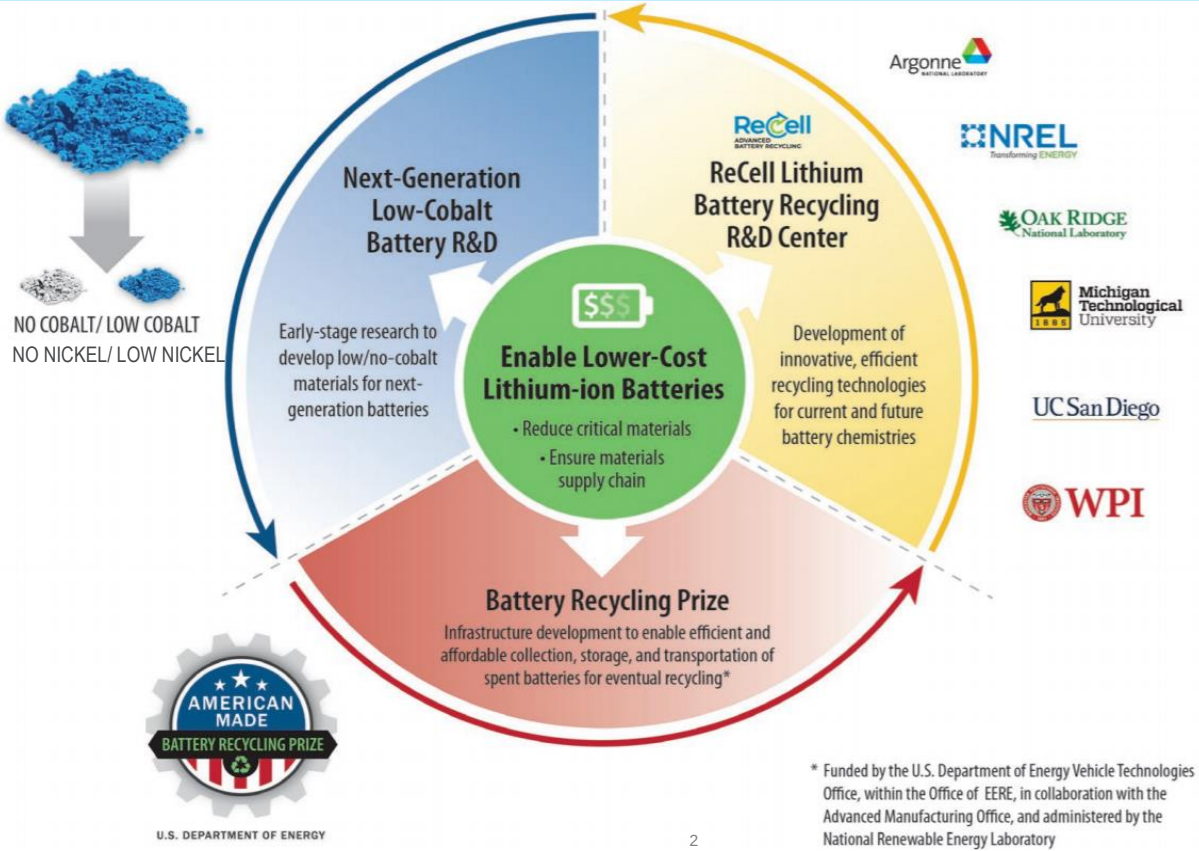
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

RECELL IS PART OF DOE'S CRITICAL MATERIALS PLAN

to reduce the cost of EV batteries while significantly reducing or eliminating dependency on critical materials (such as Co and Ni) and using recycled material feedstocks.



Argonne leads ReCell's $5+ million/y collaboration of 3 national labs and 3 universities, funded in 2019 by Vehicle Technology Office to develop a viable recycling process.

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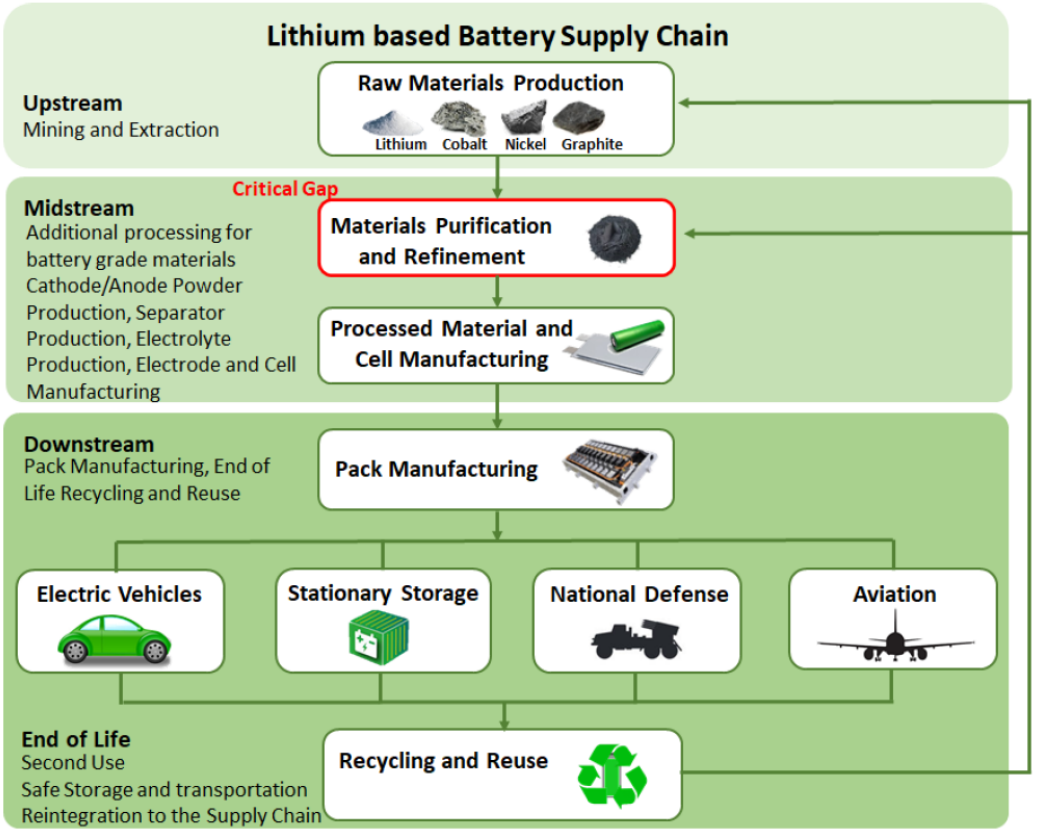

Source: DOE Vehicle Technologies Office (VTO)

White House, BUILDING RESILIENT SUPPLY CHAINS, REVITALIZING AMERICAN MANUFACTURING, AND FOSTERING BROAD-BASED GROWTH 100-Day Reviews under Executive Order 14017 (June 2021) https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf?utm_source=sfmc%E2%80%8B&utm_medium=email%E2%80%8B&utm_campaign=20210610_Global_Manufacturing_Economic_Update_June_Members

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HOW MUCH MATERIAL IS THERE IN US?

How many NMC811 car batteries could you make using reserves?

Element	kg/kWh*	kg per car @85 kwh/car	US reserves (kT)**	World reserves (KT)**	number for US (millions)	global number (billions)
Cobalt	0.08	6.8	53	7100	7.8	1.0
Nickel	0.6	51	100	94,000	2.0	1.8
Lithium	0.1	8.5	750	21,000	89	2.5
Manganese	0.07	5.95	230,000	1,300,000	38,656	219

* from Shabbir Ahmed 2/8/21;
NMC811-Graphite System from BatPaC 4.0 1Oct2020.

** USGS Mineral Commodity Summaries 2021

Not enough, but recycling can help… eventually.

THE US ALSO LACKS PROCESSING CAPACITY

There is some under construction.

TABLE 2. Midstream Lithium-ion Battery Manufacturing: Percentage of Total Manufacturing Capacity by Country for Various Battery Components.

Country	Cathodes Manufacturing (3 M tons)	Anode Manufacturing (1.2 M tons)	Electrolyte Solution Manufacturing (339,000 tons)	Separator Manufacturing (1,987 M sq. m)
United States	—	10%	2%	6%
China	42%	65%	65%	43%
Japan	33%	19%	12%	21%
Korea	15%	6%	4%	28%
Rest of World	10%	—	17%	2%

Source: BloombergNEF, Battery Components Manufacturing Asset Map 2019, Accessed March 15, 2021.

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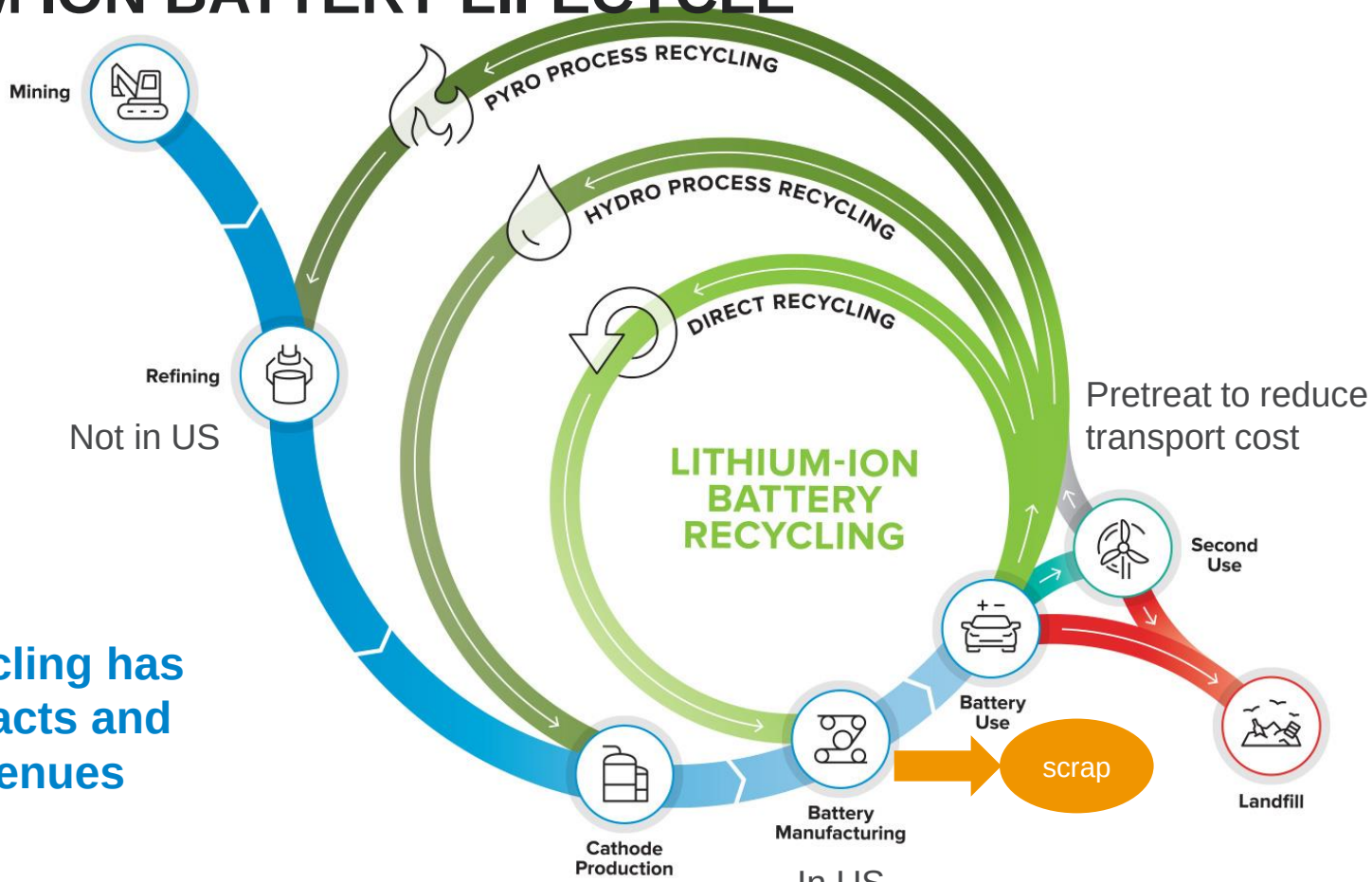
J. Granholm, Executive Summary: NATIONAL BLUEPRINT FOR LITHIUM BATTERIES 2021–2030 (June 2021) https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf

A KEY FINDING

Increased recycling can decrease the need for new raw material extraction and production. Different recycling processes reintroduce that material at different stages of the supply chain. A more robust domestic recycling industry will be most effective at securing material supply chains if paired with growth at various stages of manufacturing. Without a footprint in the earlier stages of manufacturing (including materials processing, as well as electrode, cell, and pack manufacturing), intermediate recycled products will be exported to markets/countries that have these capabilities.

White House, BUILDING RESILIENT SUPPLY CHAINS, REVITALIZING AMERICAN MANUFACTURING, AND FOSTERING BROAD-BASED GROWTH 100-Day Reviews under Executive Order 14017 (June 2021) https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf?utm_source=sfmc%E2%80%8B&utm_medium=email%E2%80%8B&utm_campaign=20210610_Global_Manufacturing_Economic_Update_June_Members

LITHIUM ION BATTERY LIFECYCLE



Direct recycling has lowest impacts and highest revenues

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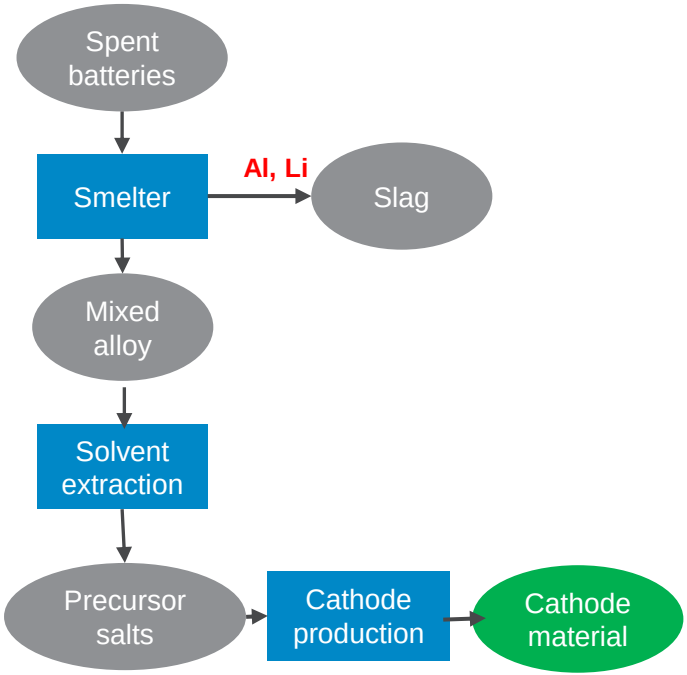
PYROMETALLURGICAL PROCESSING IS HIGH TEMPERATURE AND LARGE SCALE

Umicore pilot plant is designed to process 7,000 tonnes per year



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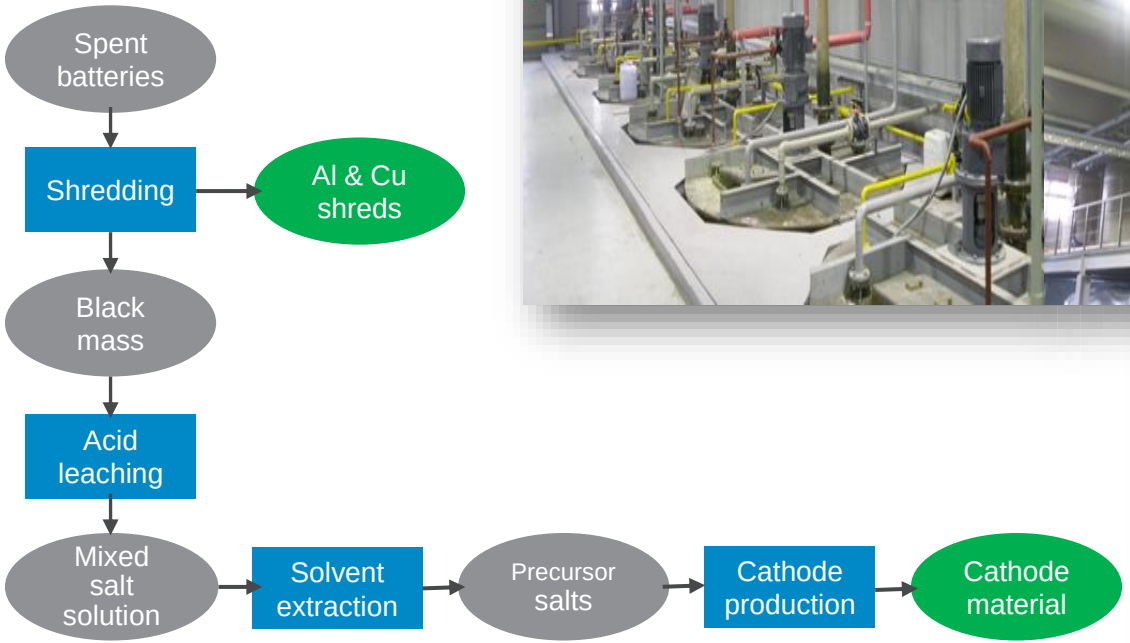
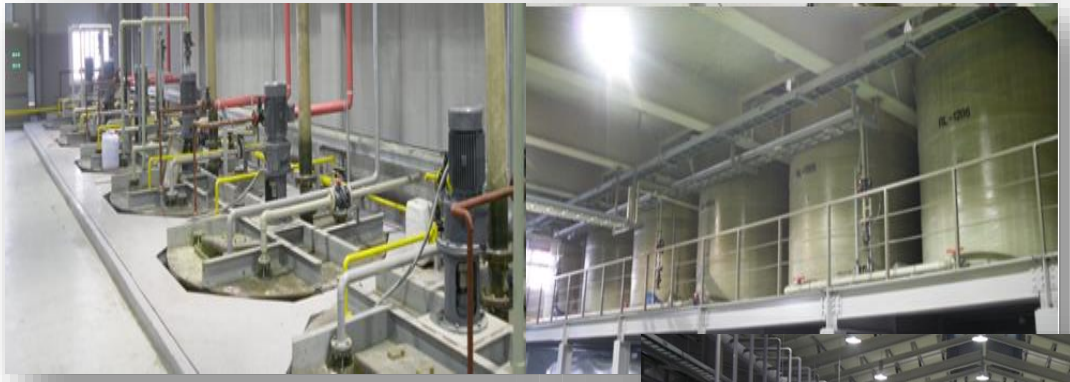
HYDROMETALLURGY

Materials are dissolved in acid and components are separated





Courtesy of SMCC

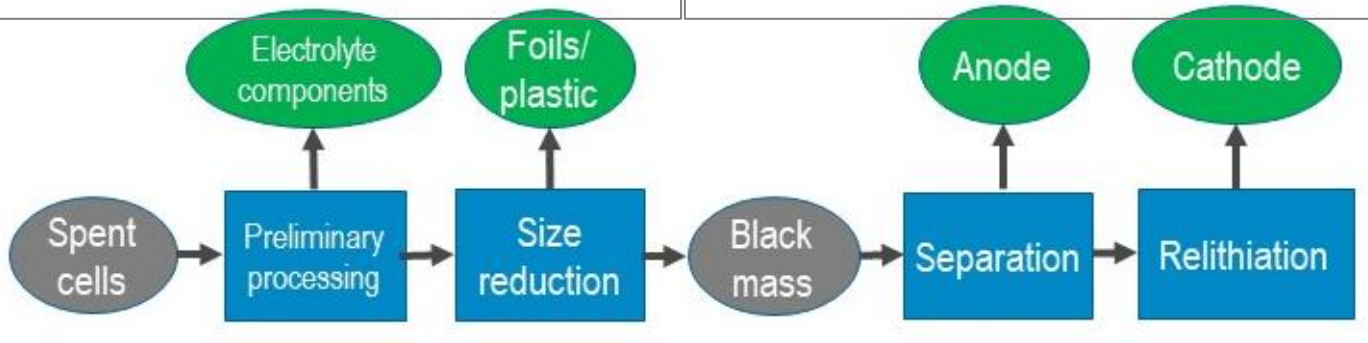
DIRECT RECYCLING is the recovery, regeneration, and reuse of battery components directly without breaking down the chemical structure.

BENEFITS

- **Retains valuable chemical structure**
- Enables economic recovery of more materials
- Could be used now for manufacturing scrap
- Low temperature, low energy
- Avoids most impacts of virgin material production

CHALLENGES

- Separating multiple cathode chemistry particles
- Product may be obsolete formulation
- Degradation may limit repeats
- Buyer must be assured of quality
- Not demonstrated on industrial scale



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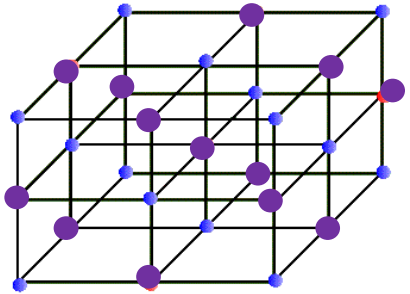
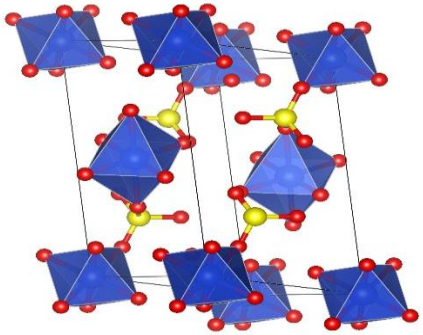
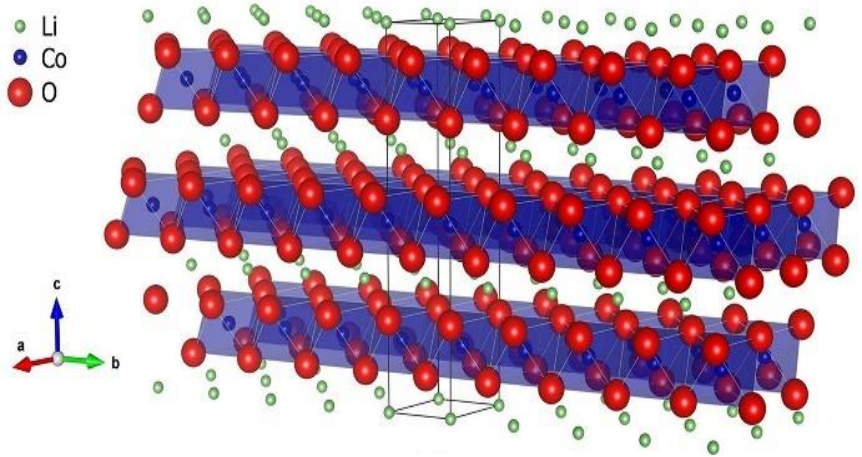
DIRECT RECYCLING RECOVERS HIGHLY STRUCTURED MATERIAL



Cobalt has a simple cubic structure; nickel impurities can substitute



Cobalt sulfate is octahedral

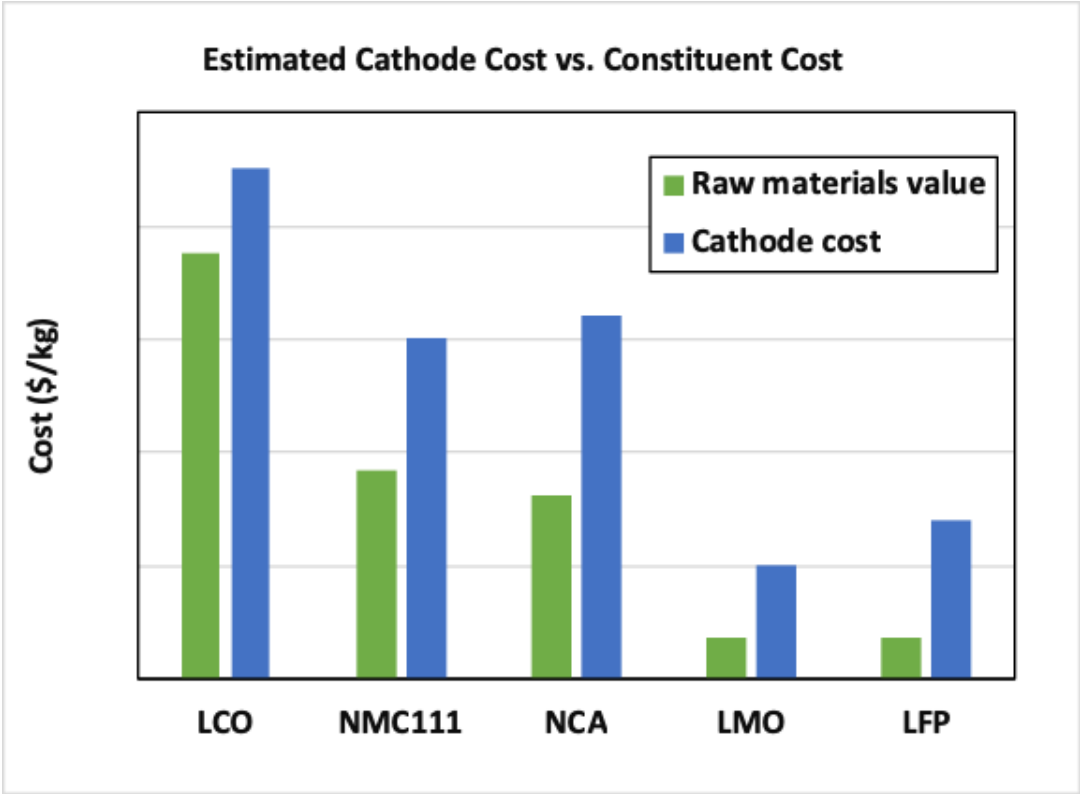


LCO has an ordered layered structure

CATHODE VIABILITY IS KEY TO ECONOMICS

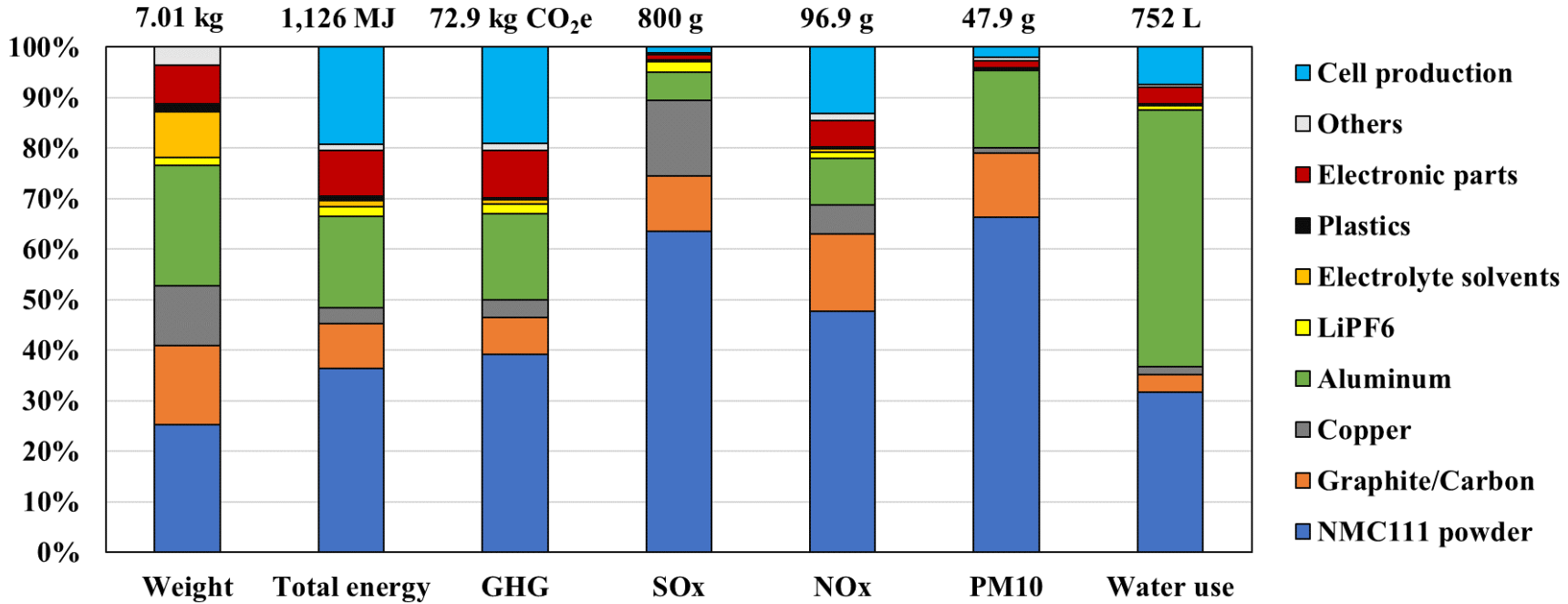
FOR CATHODES WITH REDUCED COBALT CONTENT

Cathode materials are valuable, even if constituent elements aren't

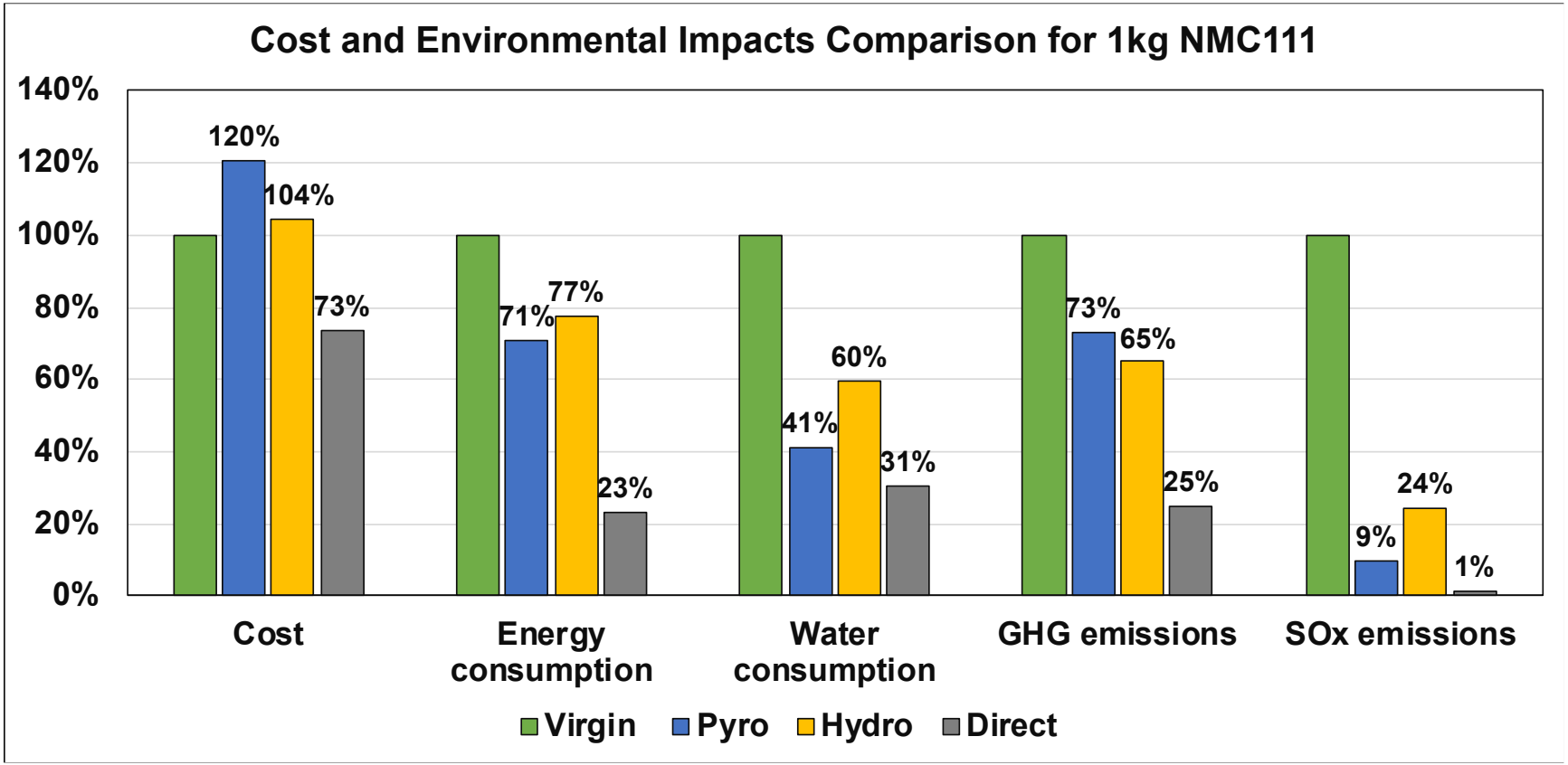


CRADLE-TO-GATE ENVIRONMENTAL IMPACTS: 1KWH NMC111 CELLS

Cathode, production energy, and aluminum are notable contributors



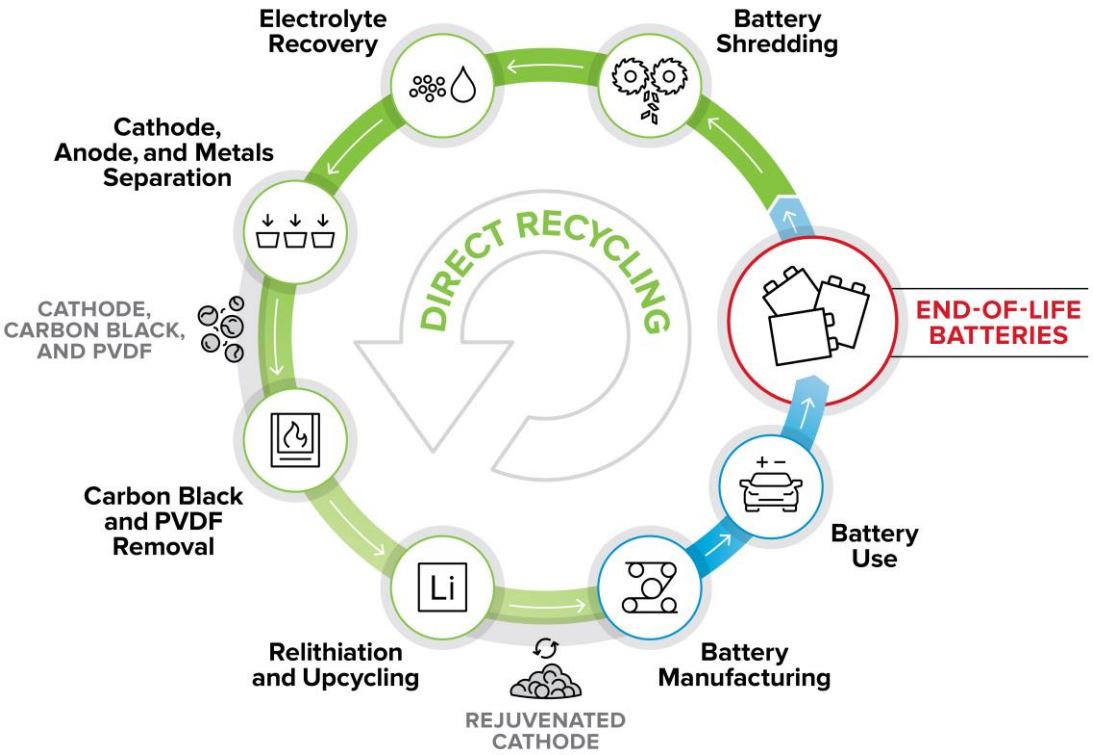
DIRECT RECYCLING HAS LOWEST IMPACTS



UNIT PROCESS ORDER WILL BE OPTIMIZED

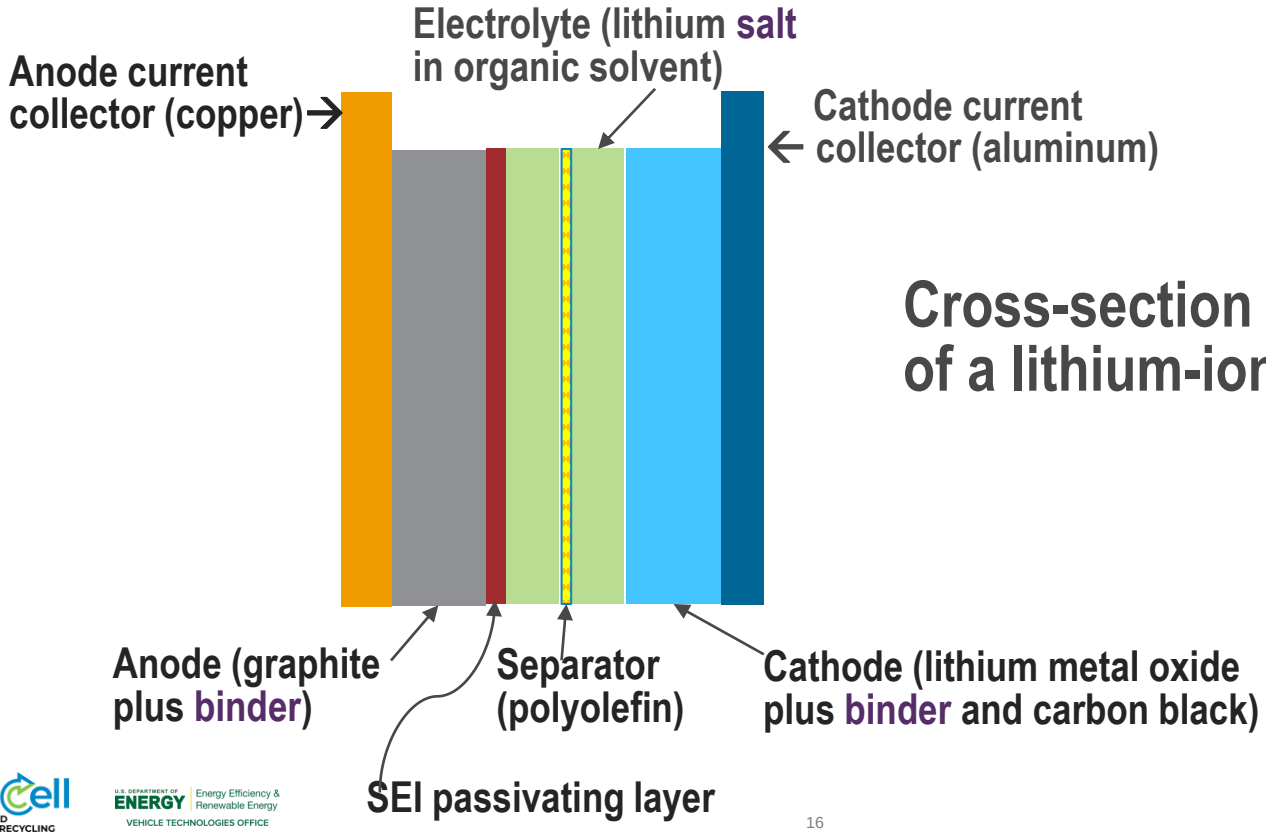
- Multiple processes investigated to mitigate risk
- Continual review of new project ideas
- End projects that are not showing promise in cost and performance
- These unit operations can benefit other recycling processes

Typical Direct Recycling Process Flow



PROCESSING REQUIRES MANY SEPARATIONS

Commercial technologies lose some of the materials



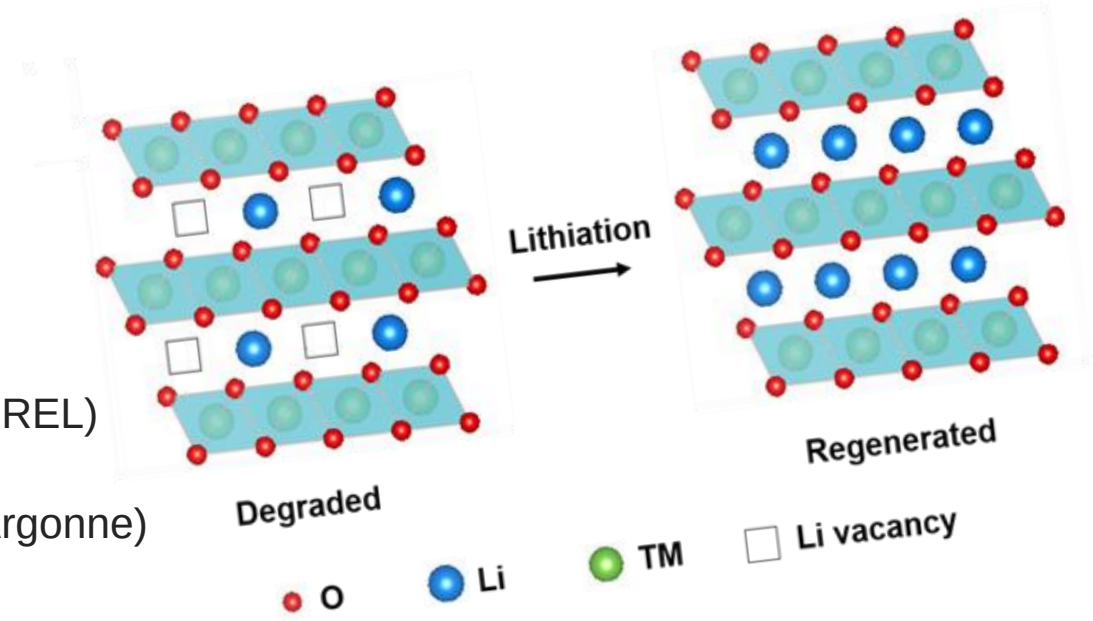
Cross-section of one layer of a lithium-ion cell

DIRECT RECYCLING UPGRADES CATHODE

Product must be as good as new… or better

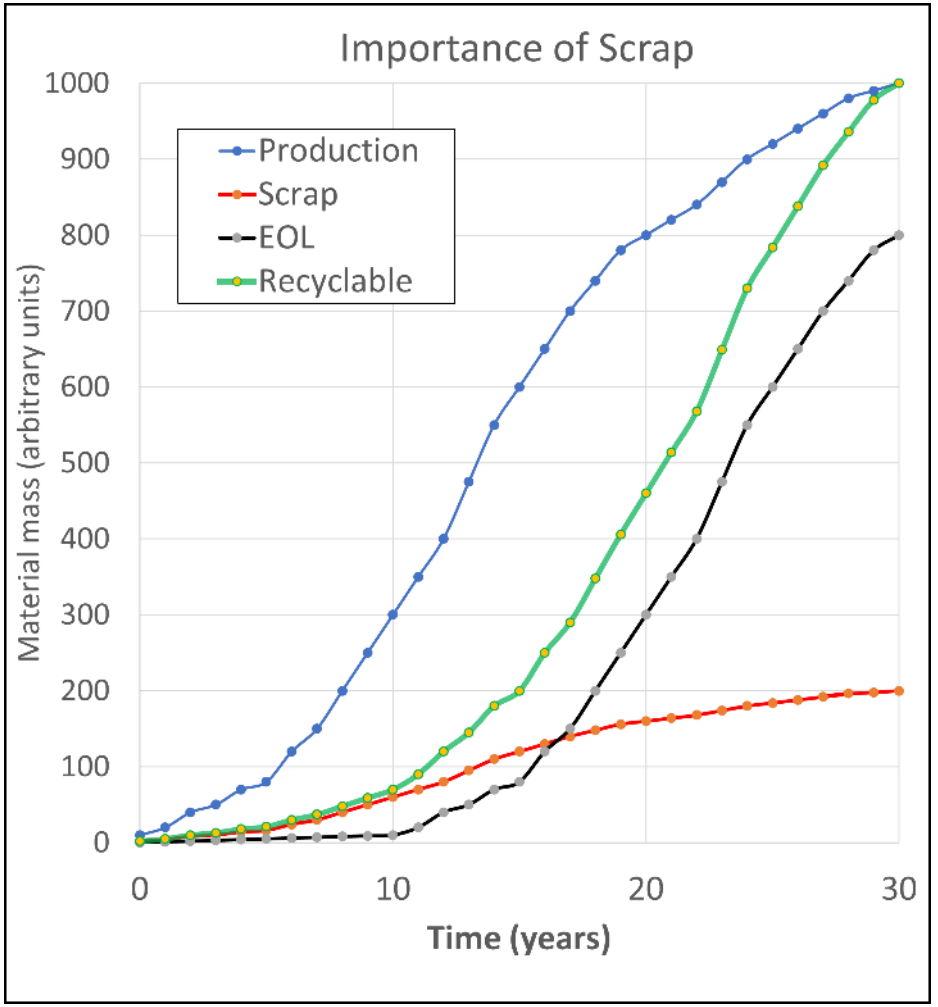
Several phenomena contribute to the gradual drop in lithium-ion battery performance, including surface degradation, cathode instability, reactivity with organic electrolyte components, and surface films. These phenomena need to be reversed and performance restored.

- **Relithiation**
  - Electrochemical (NREL)
  - Solid State (Argonne)
  - Hydrothermal (UCSD)
  - Ionothermal (ORNL)
  - Redox Mediated NREL)
  - Roll to Roll Processing (NREL)
- **Upcycling**
  - Compositional Change (Argonne)



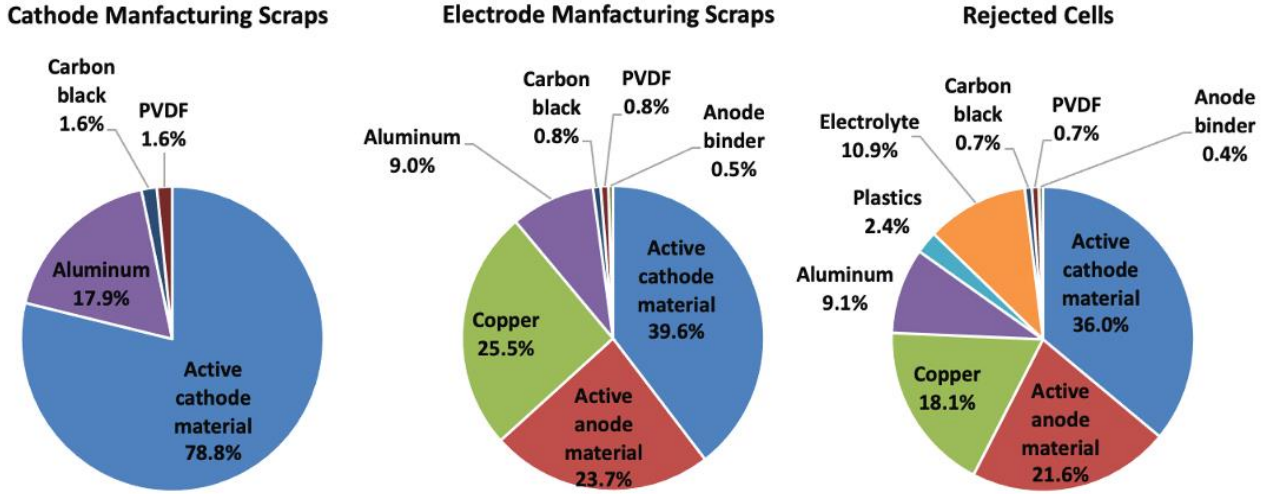
NEW RECYCLING PLANTS' MAIN FEED IS PRODUCTION SCRAP

Artifact of rapid growth

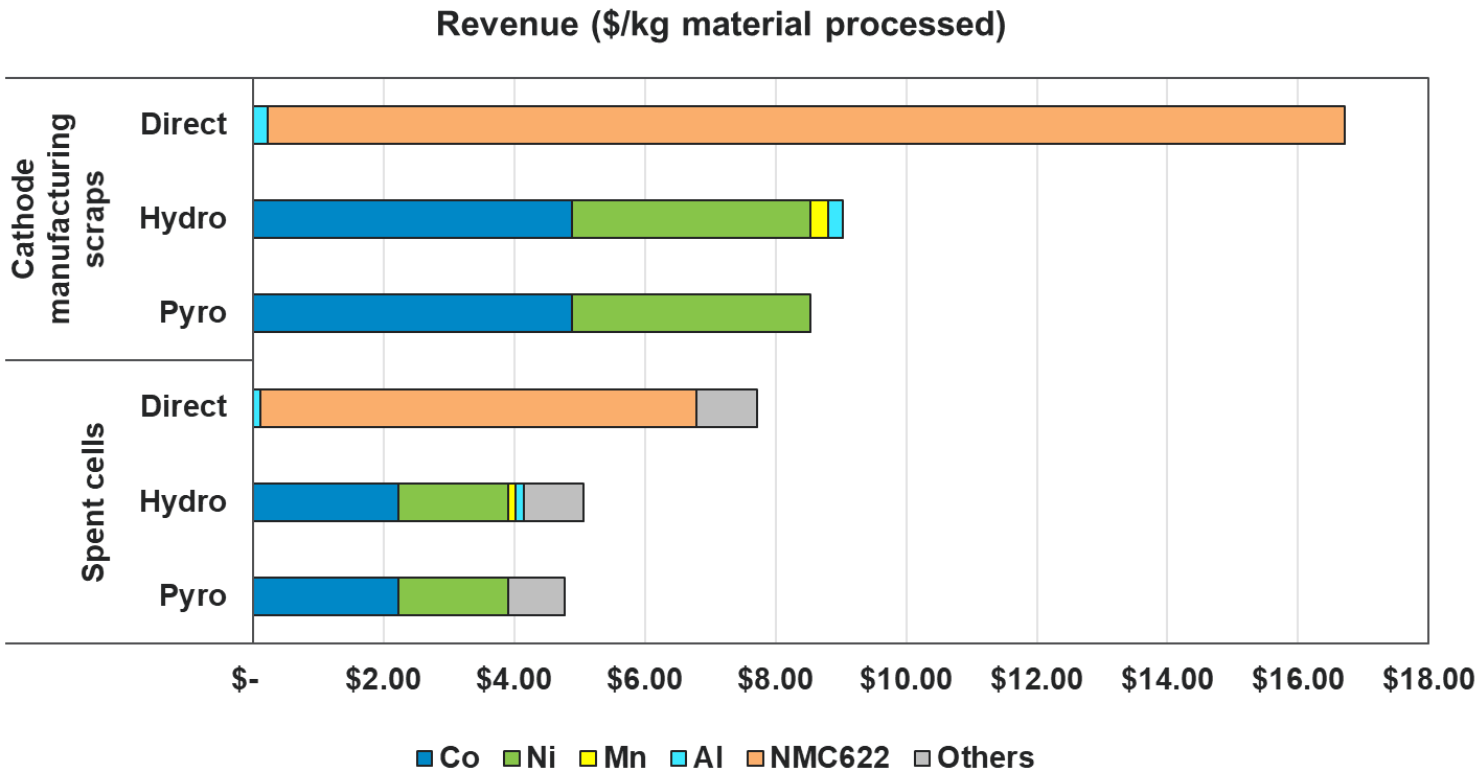


MANUFACTURING SCRAP IS PREMIUM FEED

- Available in large quantities
- Material is new and uncycled
- Does not require many purification and upgrading processes
- Composition is known, can go back into production line
- Highly concentrated: few additional components



EVERBATT SHOWS SCRAP RECOVERY IS PROMISING



Results based on plants processing 10,000 t materials per year.

REMAINING CHALLENGES AND BARRIERS

- Getting the most life out of batteries
- Keeping used batteries in the US for material recovery
- Recovering materials that perform as well as new ones
- Getting industry buy-in for commercialization
- Developing new recycling processes for future batteries
  - Sodium or magnesium-based cathodes
  - Lithium metal anodes and solid-state electrolytes

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Thanks to:
Samm Gillard and Dave Howell

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BACKUP SLIDES

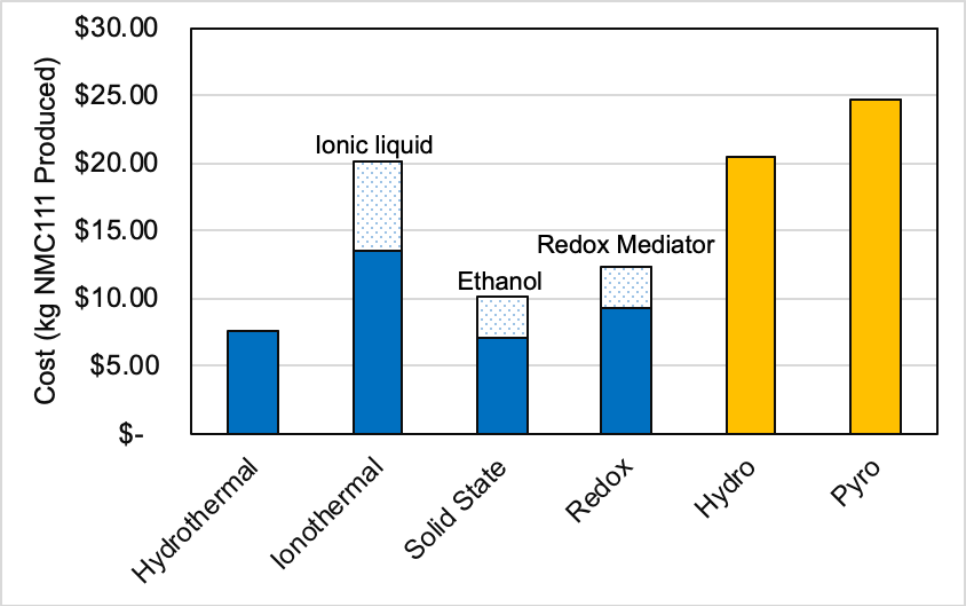
TECHNICAL ACCOMPLISHMENTS

- Recovered usable cathode from spent cells and scrap
- ~40 papers, ~20 patents in process
- Dedicated ReCell laboratory space ready for collaboration
- Industry meeting provided an opportunity for ReCell and industry stakeholders to exchange challenges and ideas.

MATERIALS ARE KEY TO RELITHIATION COSTS

Further research targeted at reducing high material costs

- Replace or reduce use:
  - Ionic liquid (ionothermal)
  - Redox mediator (redox)
  - Ethanol (solid state)
- Hydrothermal lowest cost
- Solid state could potentially be lower
- Results for commercial-scale plant; scaling will not change ordering



Dashed bars represent potential cost reductions by closed-loop recycling of key materials; blue bars represent other costs for 10,000 T/y direct recycling plants; yellow bars represent costs for 10,000 T/y pyrometallurgical (pyro)/hydrometallurgical (hydro) recycling plants plus costs to convert recovered materials into cathode powder.

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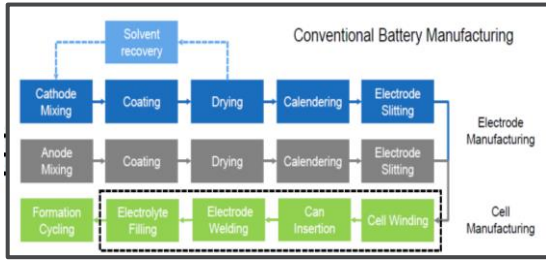
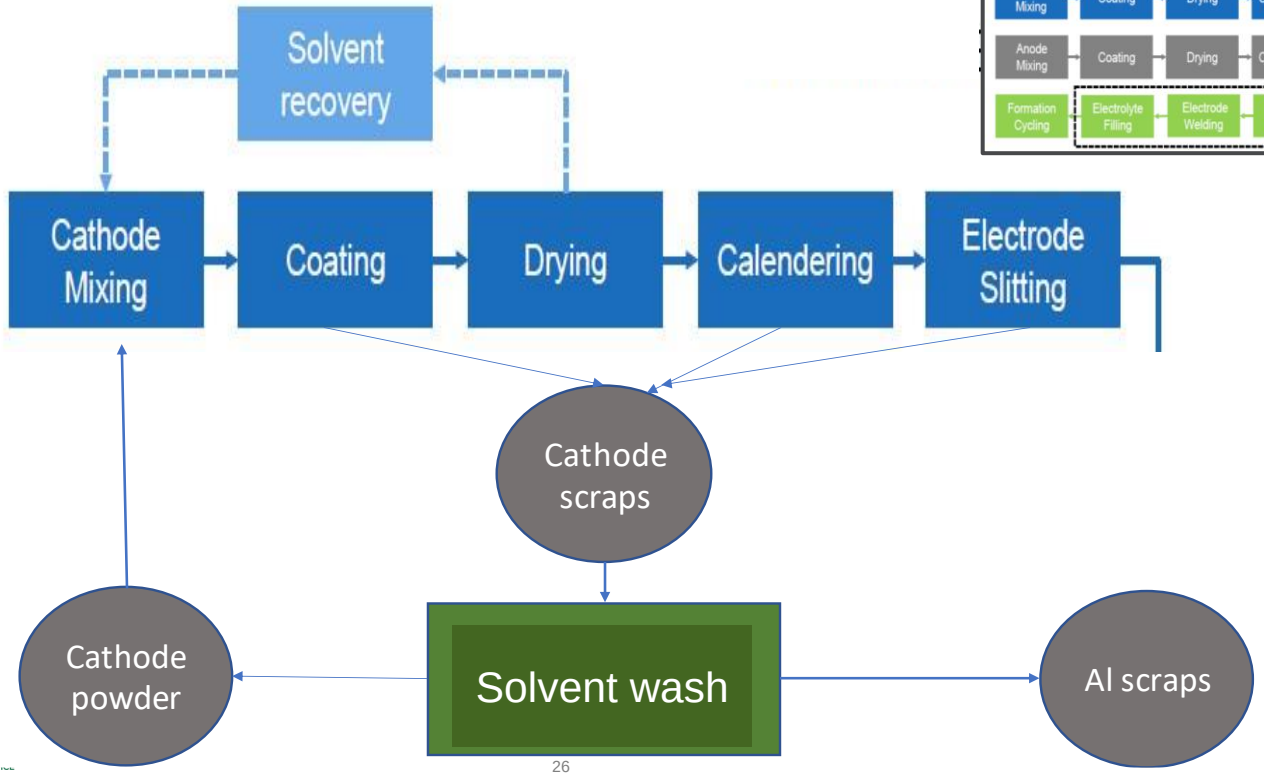
AFTER SIMPLE PROCESSING, SCRAP CAN RETURN TO MANUFACTURING

Need to compare to full recycle loop





BUILDING RESILIENT SUPPLY CHAINS, REVITALIZING AMERICAN MANUFACTURING, AND FOSTERING BROAD-BASED GROWTH

100-Day Reviews under
Executive Order 14017

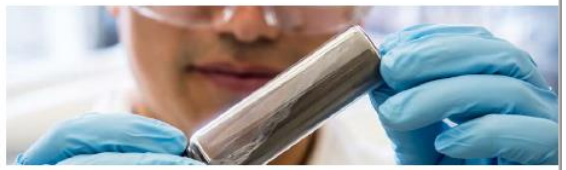
June 2021

A Report by
The White House

Including Reviews by
Department of Commerce
Department of Energy
Department of Defense
Department of Health and Human Services

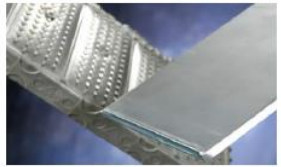
THE WHITE HOUSE
WASHINGTON

FCAB
FEDERAL CONSORTIUM FOR ADVANCED BATTERIES



EXECUTIVE SUMMARY

NATIONAL BLUEPRINT FOR LITHIUM BATTERIES
2021–2030



June 2021

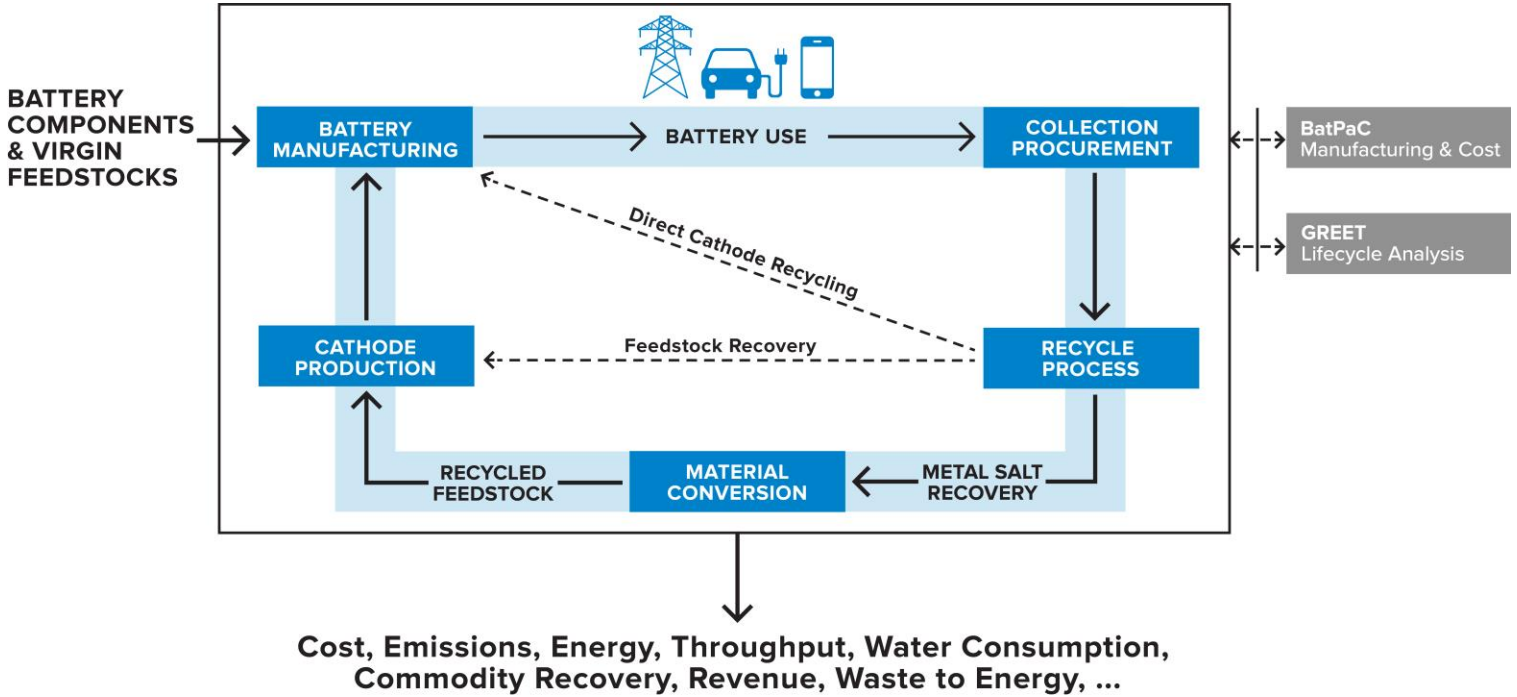
GOAL 4 Enable U.S. end-of-life reuse and critical materials recycling at scale and a full competitive value chain in the United States

- Establish and support U.S. industry to implement a blueprint that will **enable a secure domestic lithium-battery recycling ecosystem** to reduce constraints imposed by materials scarcity, enhance environmental sustainability, and support a U.S.-based circular materials supply chain

J. Granholm, Executive Summary: NATIONAL BLUEPRINT FOR LITHIUM BATTERIES 2021–2030 (June 2021)
https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf

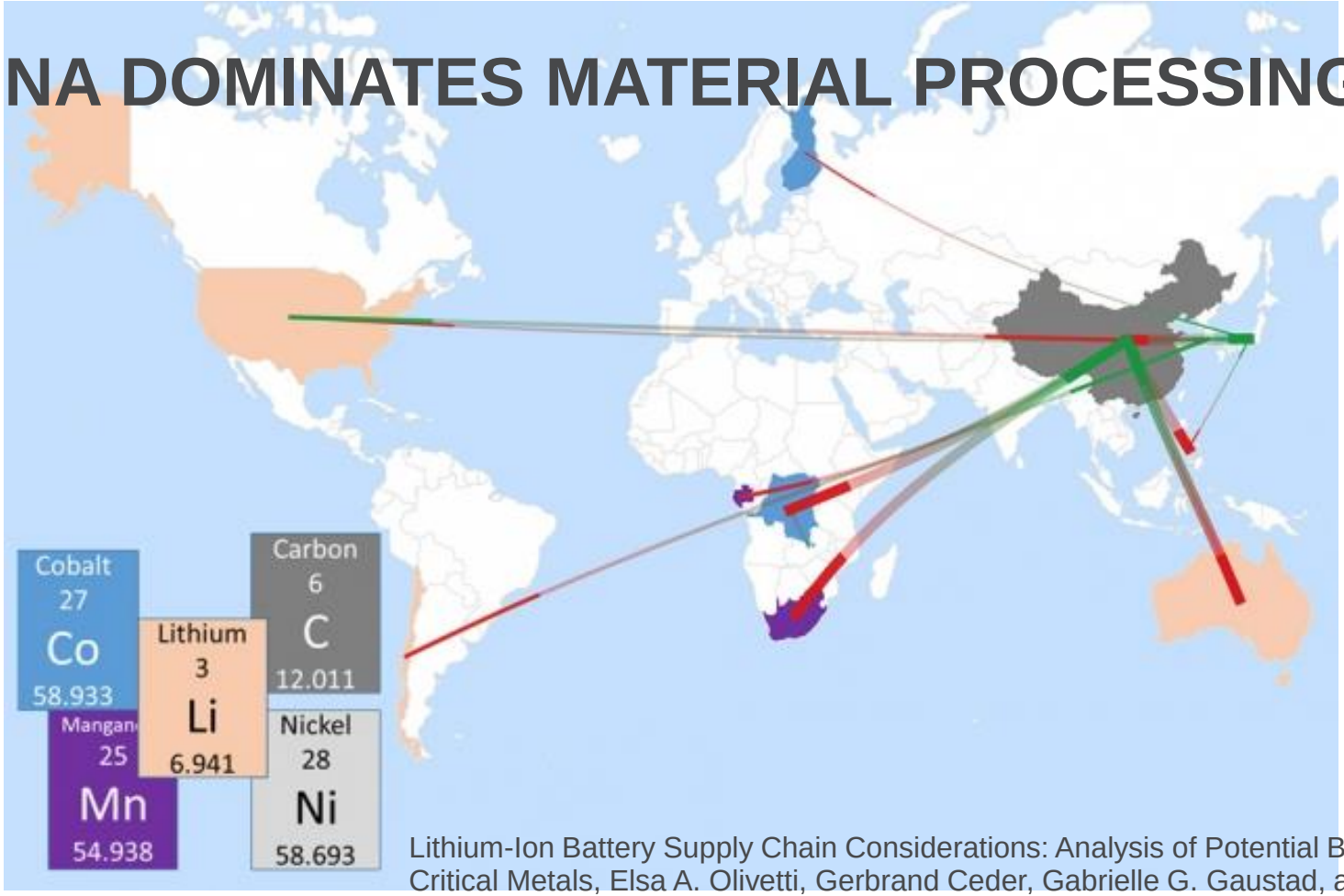
EVERBATT MODEL IDENTIFIES THE MOST EFFICIENT AND ECONOMIC PROCESSES

There are many potential recycling pathways for batteries. Modeling and analysis can guide process development without the need to actually try all options.



EverBatt received a 2019 R&D100 award.

CHINA DOMINATES MATERIAL PROCESSING



Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals, Elsa A. Olivetti, Gerbrand Ceder, Gabrielle G. Gaustad, and Xinkai Fu, Joule 1, 229–243, October 11, 2017