ENERGY EXECS SUMMIT

MATERIALS RESEARCH FOR BATTERY RECYCLING

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NREL

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

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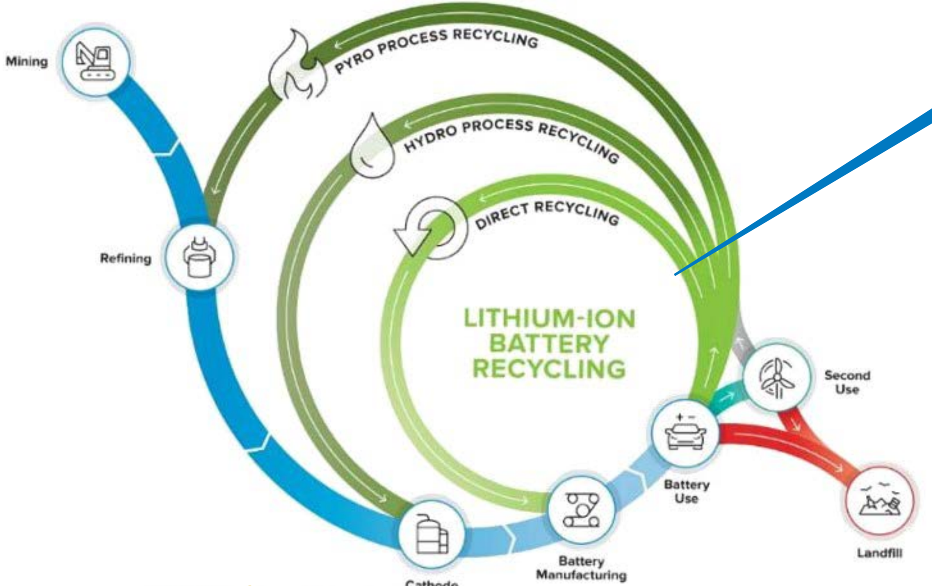
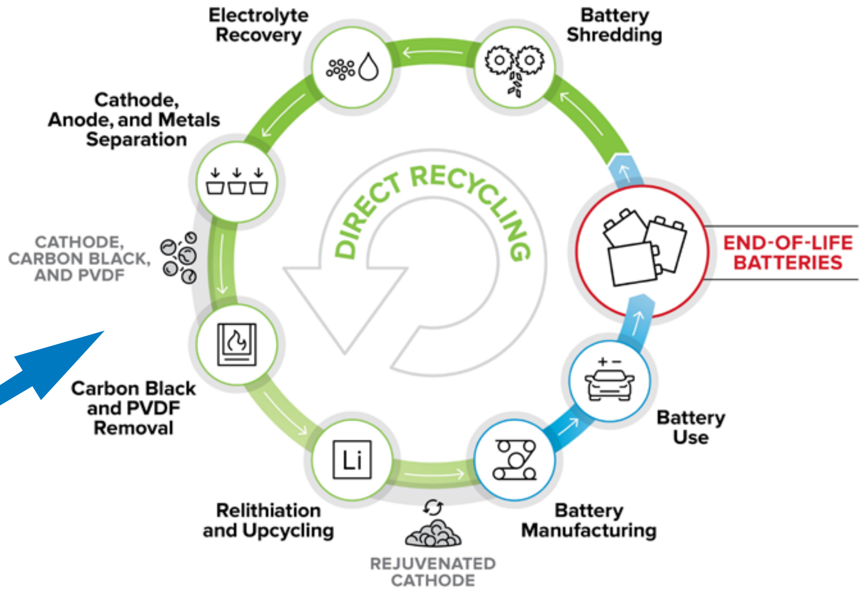
Direct Recycling of Li-Ion Batteries

DOE goal: "Reduce the cost of electric vehicle battery packs to <$150/kWh with technologies that significantly reduce or eliminate **dependency on critical materials** and utilize **recycled material feedstocks**"





Direct recycling retains the engineered value of battery materials and minimizes processing steps.

Developing viable direct recycling techniques is a high-risk/high-reward materials research challenge.

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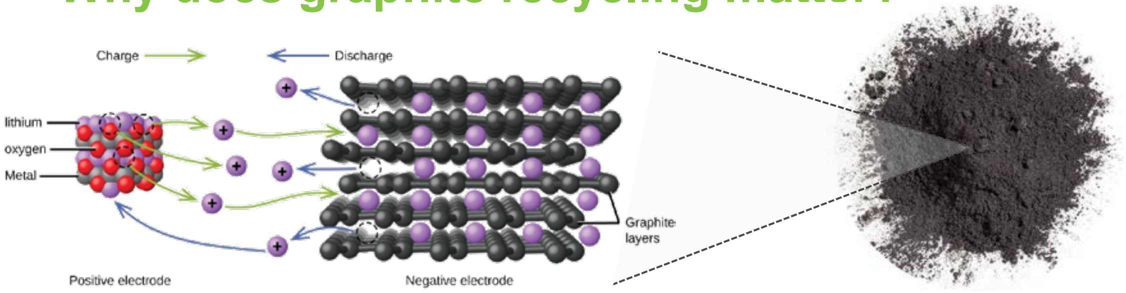
Introduction to Graphite Recycling

Why does graphite recycling matter?



- Graphite (Gr) traditionally viewed as a waste product or simple reductant in Li-ion battery recycling processes.
- Battery-grade Gr is now being recognized as a critical and potentially high-value material.
- Materials circularity & supply chain considerations warrant the development of *effective*, *low-cost*, and *energy-efficient* Gr recycling.

DEPARTMENT OF THE INTERIOR

Geological Survey

2022 Final List of Critical Minerals

AGENCY: U.S. Geological Survey, Department of the Interior.

ACTION: Notice.

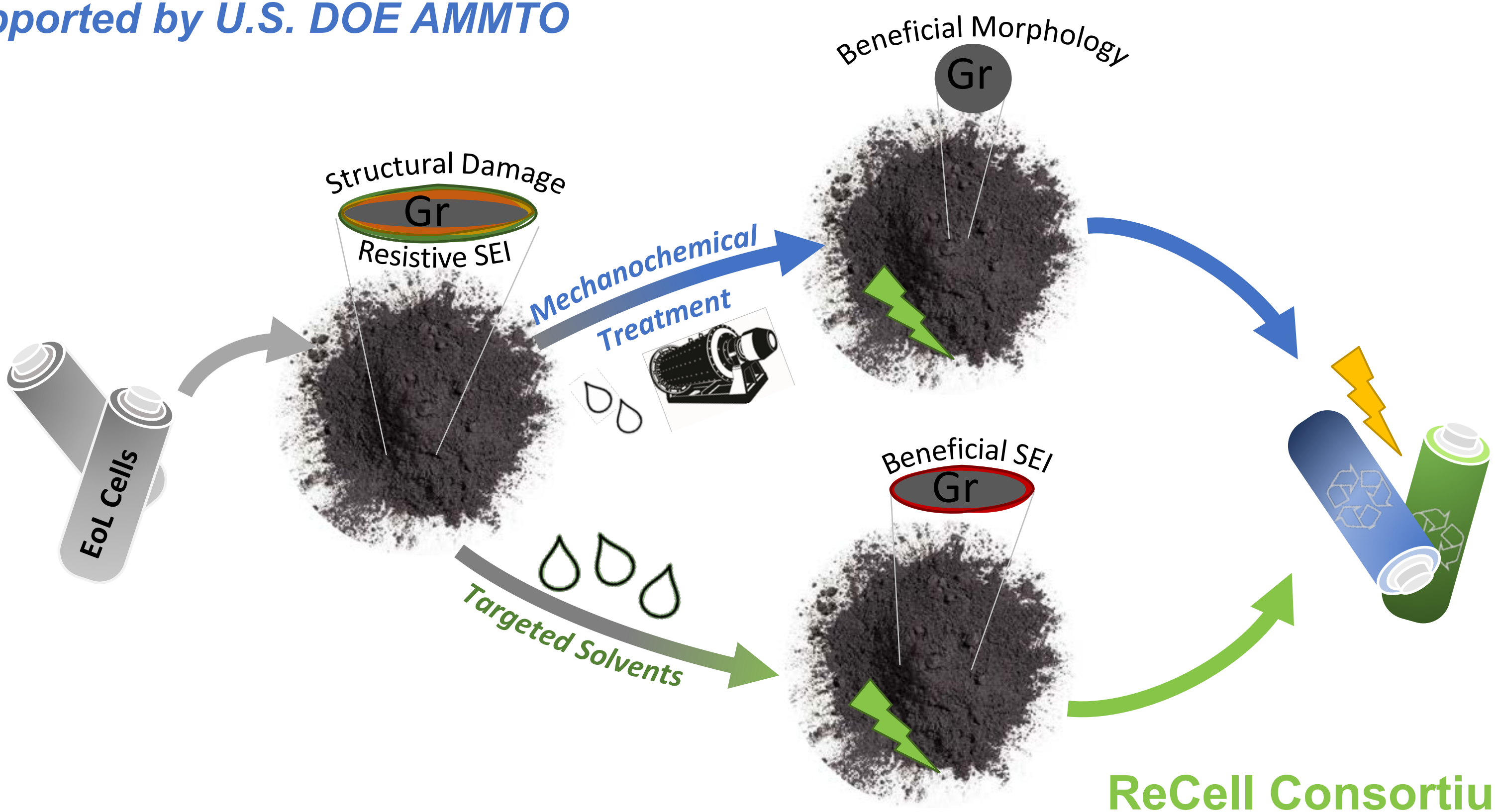
SUMMARY: By this notice, the Secretary of the Interior, acting through the Director of the U.S. Geological Survey (USGS), presents the 2022 final list of critical minerals and the methodology used to develop the list. The 2022 final list of critical minerals, which revises the final list published by the Secretary in 2018, includes the following 50 minerals: Aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium.

Battery Schematic: Lumen Learning, Module 17: Electrochemistry

U.S. Geological Survey, 2022 Final List of Critical Minerals, 87 FR 10381 (Document Number 2022-04027), 10381-10382.

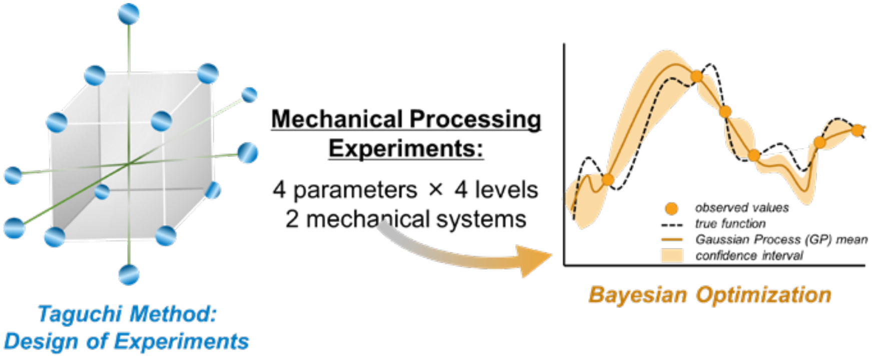
Exploring Various Approaches to Gr Recycling

NREL + Industry Cooperative Research & Development Agreement (CRADA)
Supported by U.S. DOE AMMTO



ReCell Consortium
Supported by U.S. DOE VTO

“Anode Upcycling” via Mechanical Treatment



We are using a ML-based experimental design framework to identify mechanical treatment process optima for end-of-life Gr.

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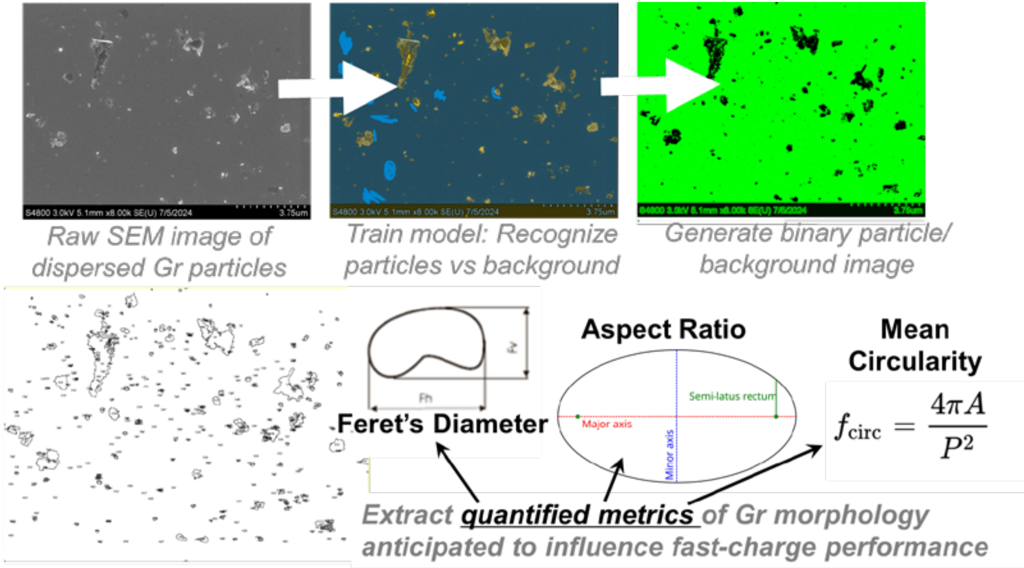
We are developing advanced characterization and image segmentation tools to characterize Gr morphology.



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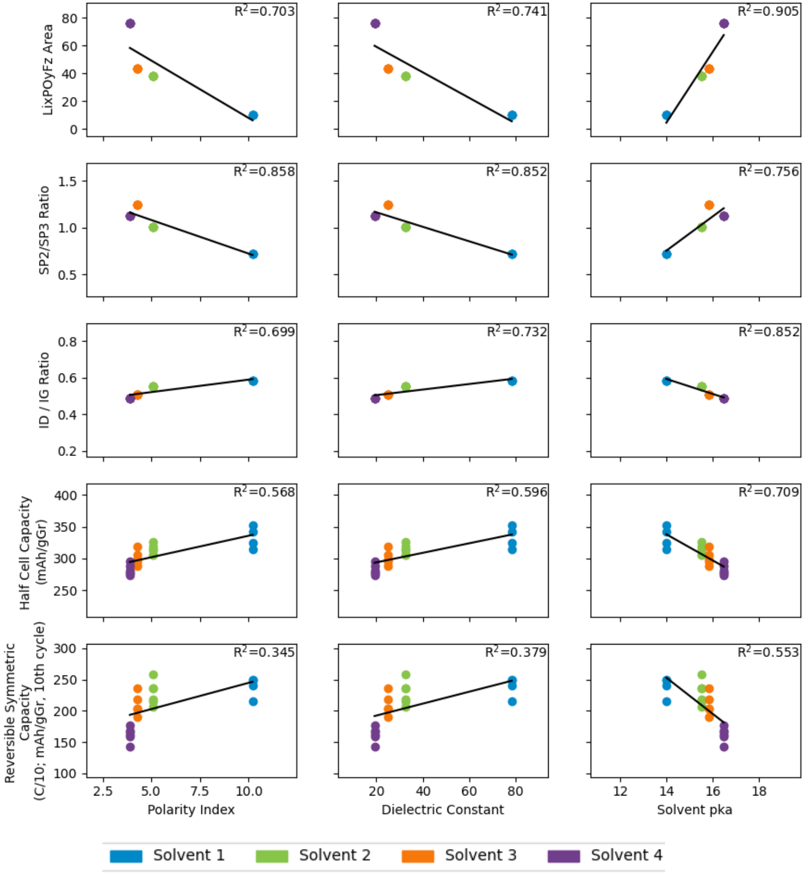
“Anode Upcycling” via Solvent Treatment



We are optimizing a tailored solvent-treatment process to selectively surface-purify end-of-life Gr anodes.

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The goal is to remove resistive surface species while retaining beneficially passivating species.

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The result is an “upcycled” anode product that can reduce remanufacturing requirements and offer added value to battery producers.

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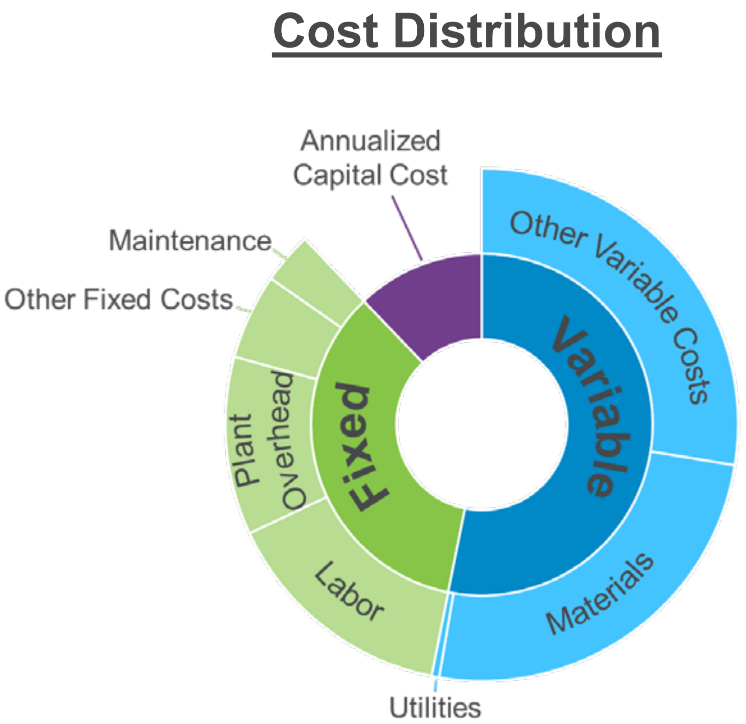
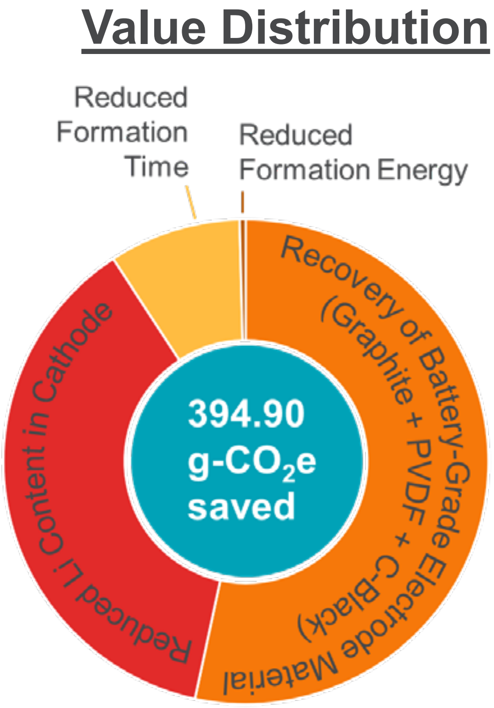
“Anode Upcycling” via Solvent Treatment





We are pairing our experimental method development with technoeconomic analysis to identify areas for process cost reduction and quantify the added value that a successfully upcycled anode could offer to the battery market.

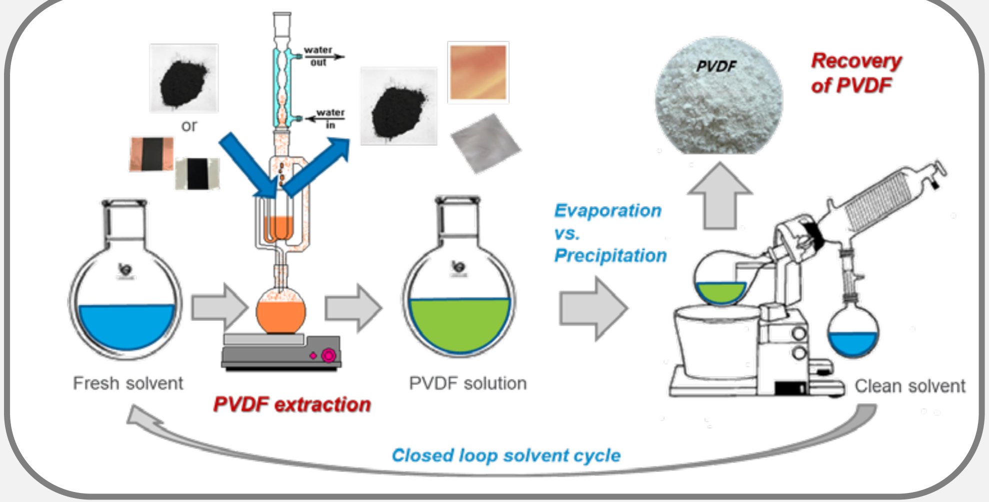
Additional Materials Research: Relithiation, Upcycling & Recovery

Microwave-Assisted Extraction of Metals (*J. Coyle*)

Use MAE as process intensification technique for hydrometallurgical recycling

Binder Extraction & Recovery (*J. Coyle*)

Removal & recovery of electrode binder via chemical extraction

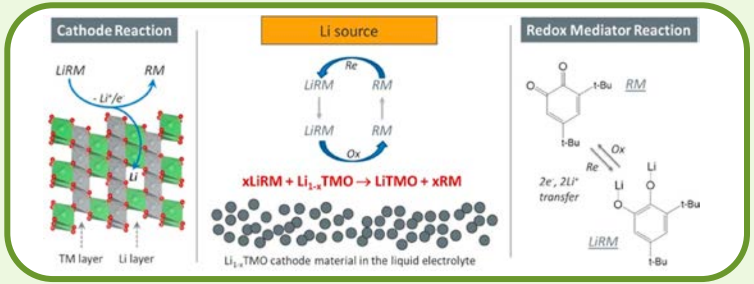


PV Si Recovery (*J. Coyle*)

Recover Si from end-of-life solar panels for reuse in Si-based anodes

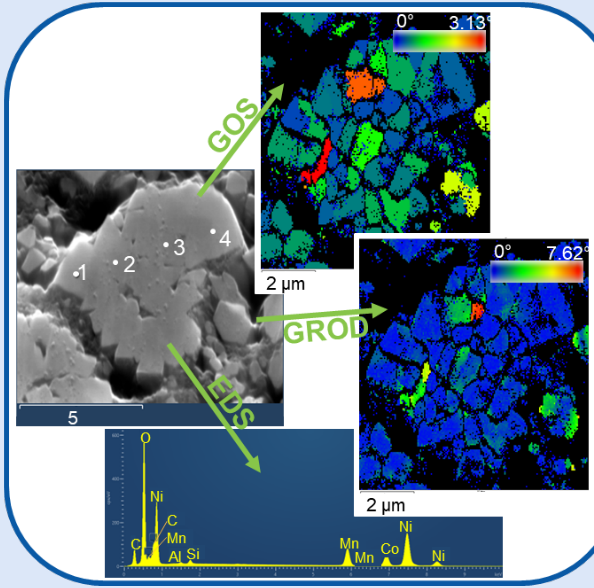
Redox Chemistry Relithiation (*J. Coyle*)

Developing tailored redox mediator chemistry to recover capacity in end-of-life batteries

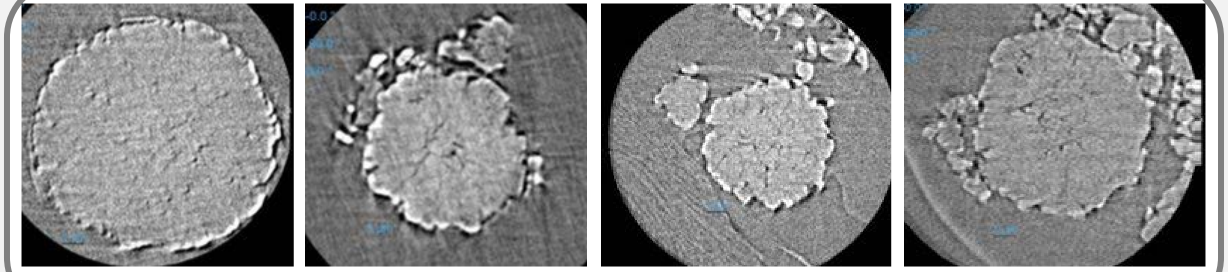


Additional Materials Research: Characterization & Diagnostics

Electron Backscatter Diffraction (EBSD) (*K. Fink*)
Novel diagnostic techniques and analysis to evaluate micro-structure of recycled materials

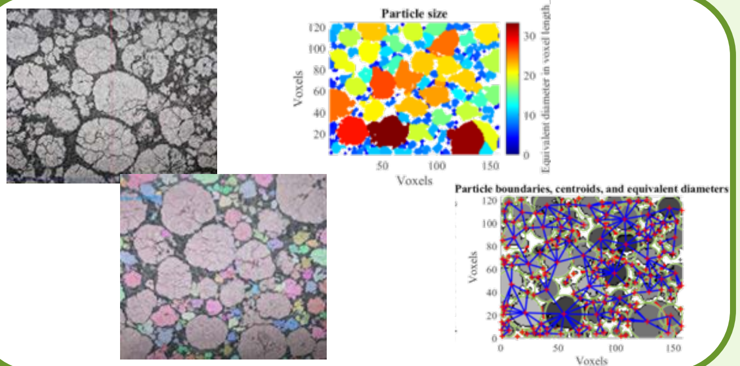


Mechanical Strength Enhancement of End-of-Life Cathode Particles (*J. Coyle*)
Characterize mechanical stability & cracking in end-of-life and recycled cathodes; optimize annealing processes for crack healing



Pristine | End-of-Life | Relithiated | Relithiated + Annealed

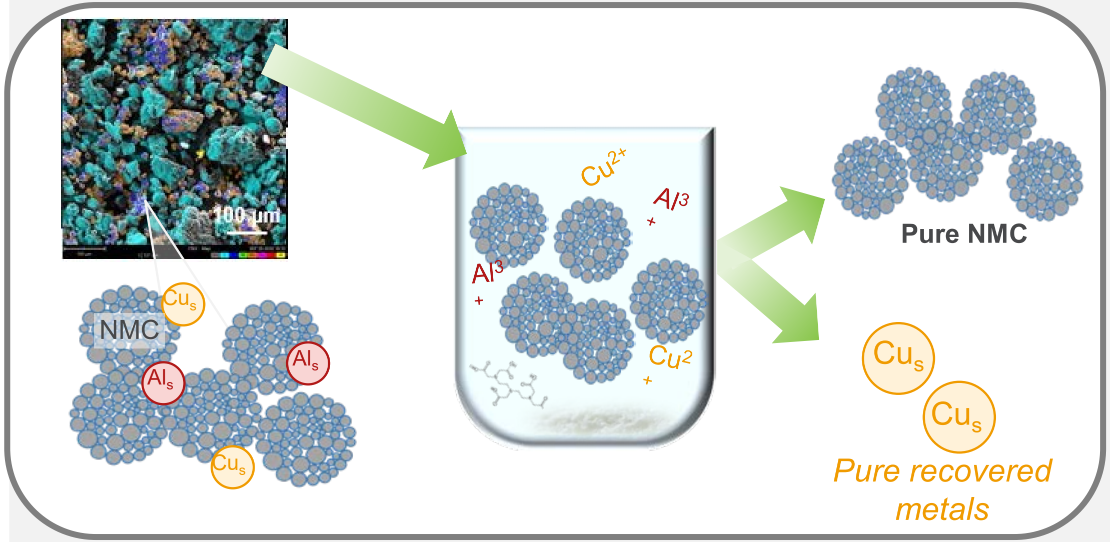
End of Life Cathode Characterization (*D. Finegan*)
Characterize distribution of material properties within EoL cathodes to determine viability for reuse vs recycling



Additional Materials Research: Contamination & Safety

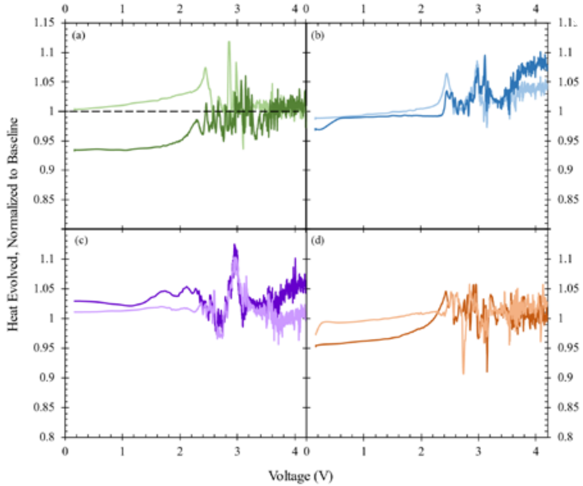
Black Mass Purification (*K. Fink*)

Selectively remove metallic contaminants from shredded end-of-life material (black mass) without impacting NMC performance



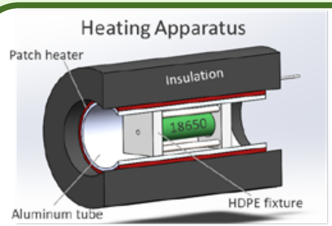
Contamination Studies (*M. Keyser*)

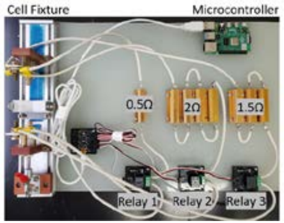
Thermal & electrochemical analysis to identify contaminants in recycled materials



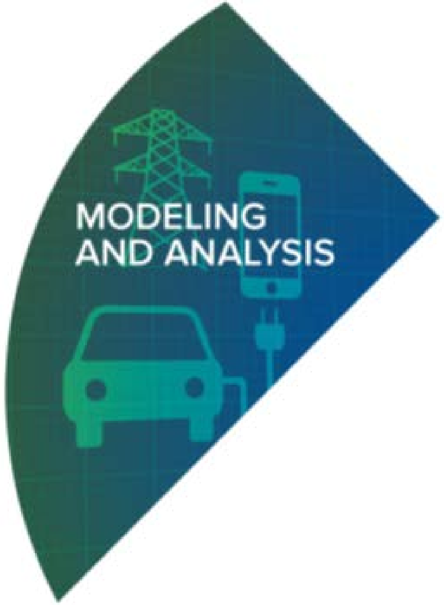
End-of-Life Cell Passivation (*A. Colclasure*)

Evaluating approaches to safely passivate end-of-life batteries for storage and transport

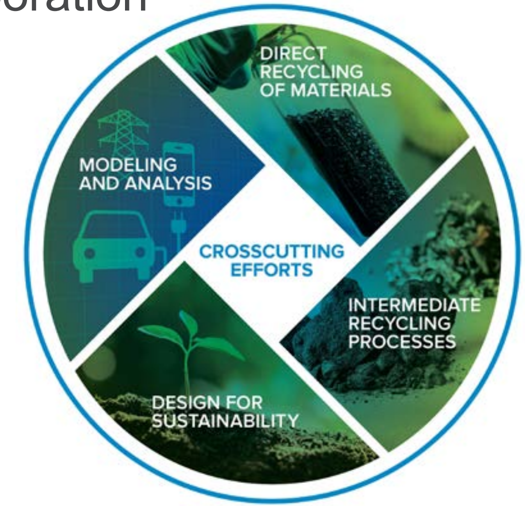




Complementary to Materials Research: Modeling & Analysis



- **Separation requirements** for high-performing recycled materials ***(A. Colclasure)***
- **Battery Lifetime as a Service**: New business model for battery ownership throughout 1st/2nd life + recycling ***(K. Smith)***
- **Machine learning** (ML) for remaining usable lifetime (RUL) and state-of-health (SOH) of 2nd life batteries ***(P. Gasper)***
- **Grid-scale impacts** of reused pack incorporation on complex future grid, utilizing NREL's ARIES platform ***(P. Gasper)***
- **LIBRA:** Systems dynamics model evaluating battery manufacturing, reuse, and recycling across dynamic global conditions ***(M. Mann)***



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