LITHIUM-ION RECYCLING CENTER OVERVIEW

Project ID: bat377 and bat378

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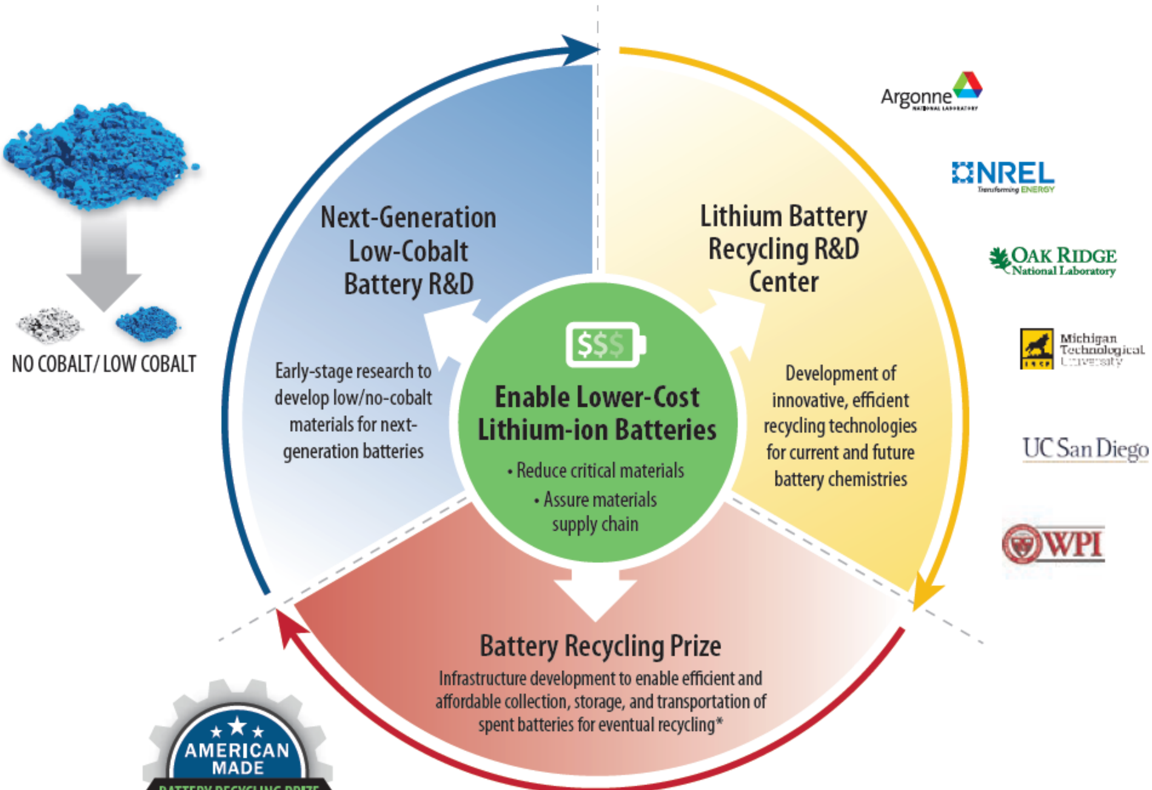
PRESENTATION OVERVIEW

- DOE's perspective
- Relevance (Why recycle lithium-ion batteries)
- Introduction to ReCell
- ReCell focus areas and capabilities

- The following four presentations expand on each focus area
  - Direct Cathode-to-Cathode Recycling Efforts: bat379
  - Other Materials Separation: bat380
  - Design for Recycle: bat381
  - Modeling and Analysis for Recycling: bat382



AMERICAN MADE BATTERY RECYCLING PRIZE
U.S. DEPARTMENT OF ENERGY

* Funded by the U.S. Department of Energy Vehicle Technologies Office, in collaboration with the Advanced Manufacturing Office, and administered by the National Renewable Energy Laboratory

OVERVIEW

Timeline

- Project start: October 2018
- Project end: September 2021
- Percent complete: ~15%

Barriers

- Recycling and Sustainability
  - Cost to recycle is currently 5-15% of battery cost
  - Material shortage (Li, Co, and Ni)
  - Varying chemistries result in variable backend value

Budget

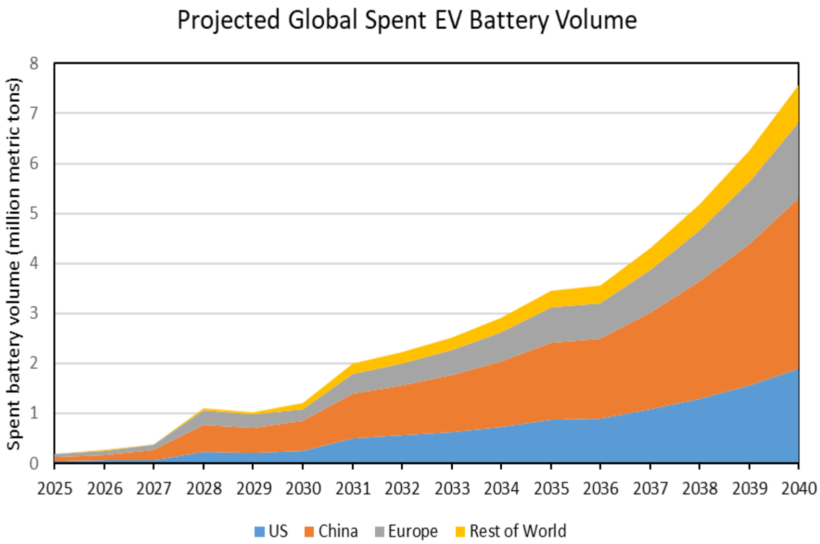
Year 1	$4,615k
Argonne	*$2650k*
NREL	*$965k*
ORNL	*$550k*
UCSD	*$150k*
WPI	*$150k*
MTU	*$150k*

Partners

- Argonne National Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory
- University of California, San Diego
- Worcester Polytechnic Institute
- Michigan Technological University

WHY RECYCLE?

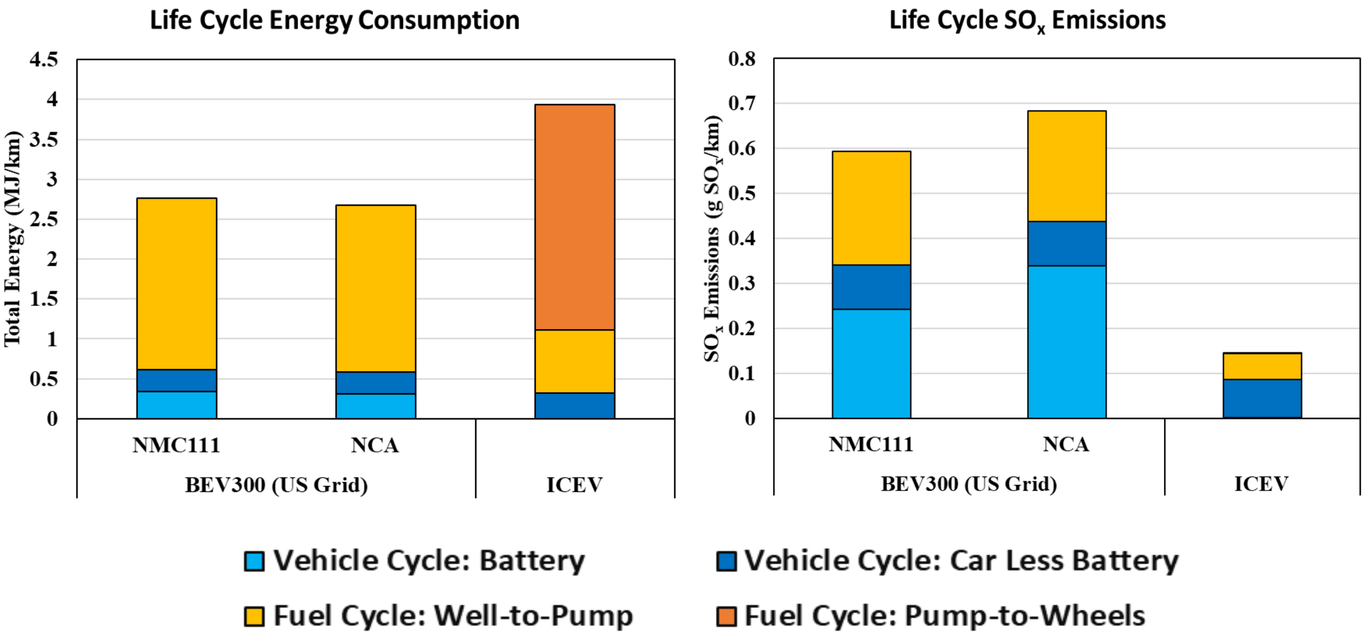
- 8 million tons of EV lithium-ion battery scrap could require disposition by 2040
- Treatment of EV battery at end-of-life is costly
- Objective is to provide batteries with minimum lifecycle impacts:
  - Energy use/emissions
  - Resource depletion
  - Cost
  - Waste generation



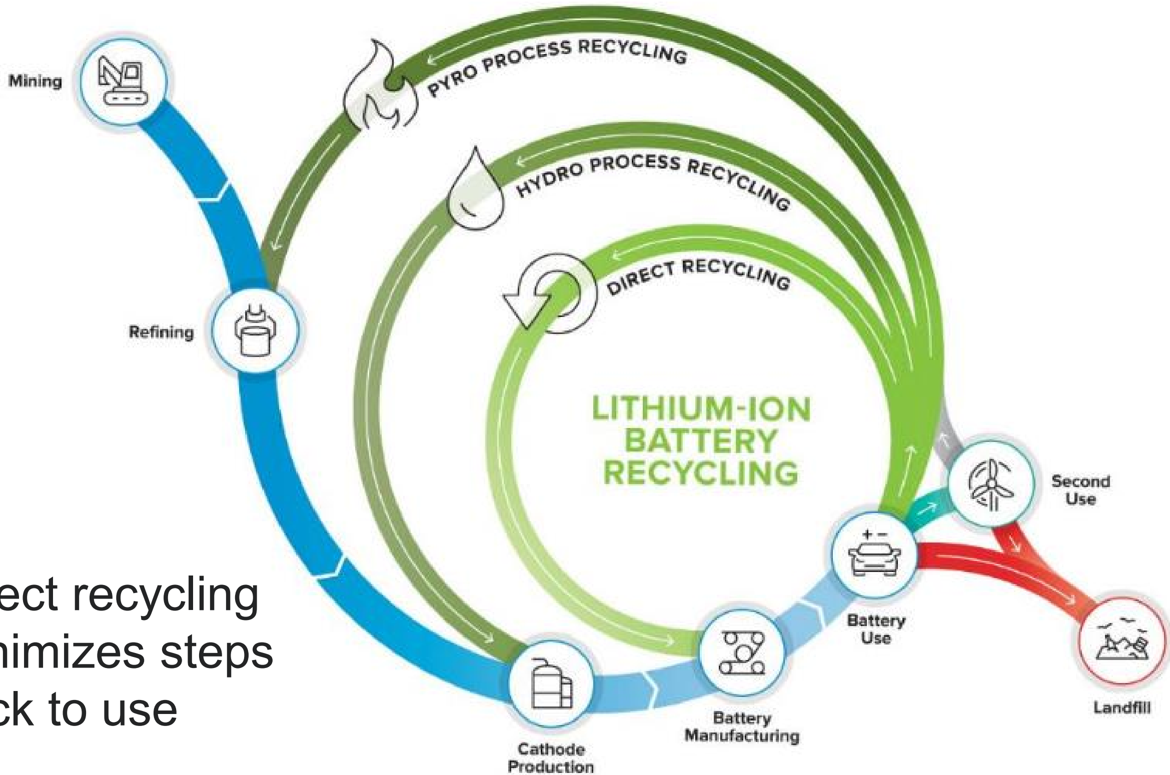
ANL projection (based on IEA global PEV projection)

BATTERY PRODUCTION ENERGY USE SMALL, BUT NOT SOX

Recycling reduces all emissions and energy use



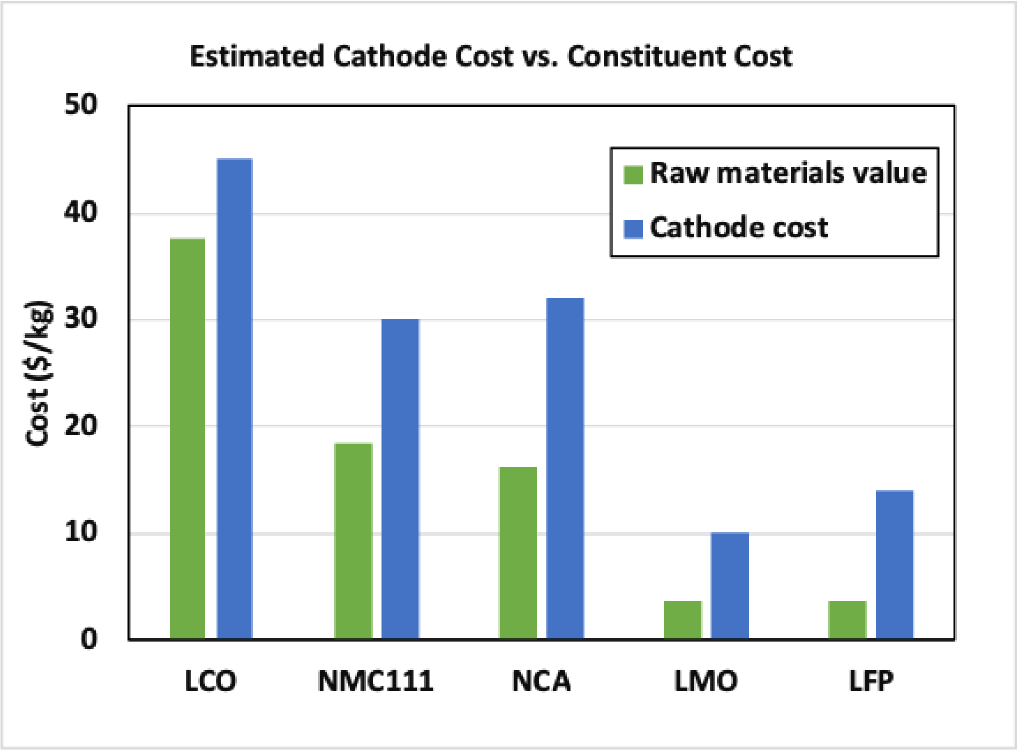
BATTERY LIFECYCLE



Direct recycling minimizes steps back to use

CATHODE VIABILITY IS KEY

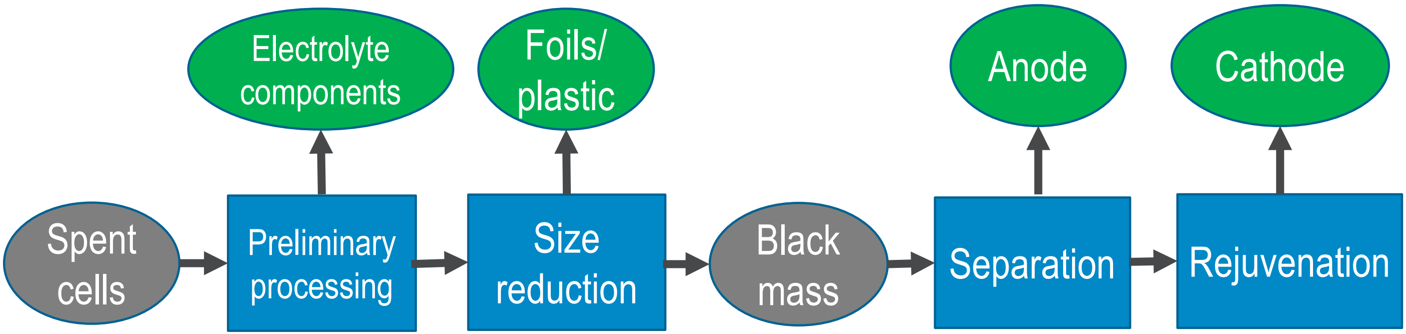
Cathodes are valuable, even if constituent elements are not



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

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

SEVERAL REVENUE STREAMS SOUGHT

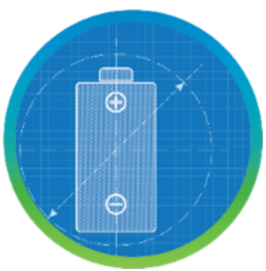


RECELL MISSION

Decrease the cost of recycling lithium-ion batteries to ensure future supply of critical materials and decrease energy usage compared to raw material production

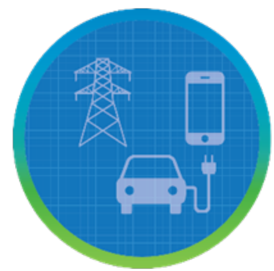
DIRECT CATHODE RECYCLING

OTHER MATERIAL RECOVERY



DESIGN FOR RECYCLING

MODELING AND ANALYSIS



DIRECT CATHODE RECYCLING

CHALLENGE

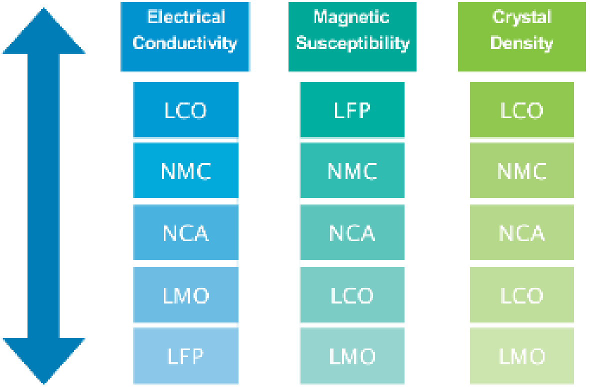
- Contaminants from processing
- Mixtures of cathode chemistries
- Old chemistry

SOLUTION

- Binder removal
- Cathode separation
- Compositional change
- Relithiation

IMPACT

- Increased product value (even w/out Co)
- Decreased processing and waste
- Decrease dependence on raw materials



Many different aspects of the cathode material can be exploited to separate cathode powders. Electrical conductivity, magnetic susceptibility, and crystal density are just a few. *Courtesy of Argonne*

OTHER MATERIALS RECOVERY

CHALLENGE

- Low value materials
- Cost effective processes

SOLUTION

- Cost effective recovery of electrolyte components
- Direct recycling of anode

IMPACT

- Increased revenue potential
- Decreased waste treatment

A laboratory scale froth flotation unit is used to separated anode powders from cathode powders.
Courtesy of Michigan Technological University

DESIGN FOR RECYCLING

CHALLENGE

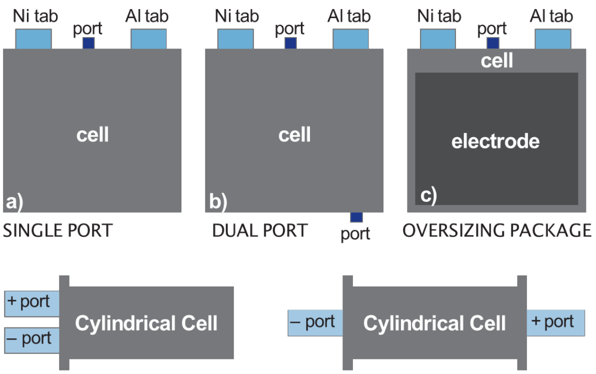
- Minimizing cost and performance impacts

SOLUTION

- New cell designs
- New cell component design
- Enabling cell flushing for rejuvenation

IMPACT

- Reduced cost of recycling
- Overall cost reduction
- Reduced number of cells reaching end of life
- Extended cell life



Initial pouch and cylindrical cell designs that will be used to determine the pressures and flows needed to "rinse" used cells.

MODELING AND ANALYSIS

CHALLENGE

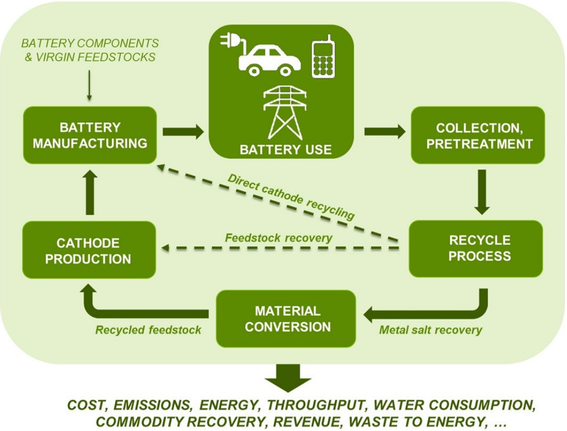
- Myriad of recycling pathways
- Need for preliminary review of new technologies to streamline work
- Need for research validation

SOLUTION

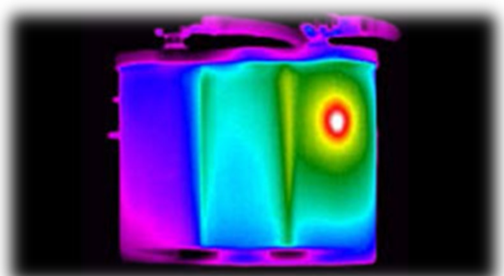
- Supply chain modeling (LIBRA)
- TEA/LCA modeling (EverBatt)
- Material Analysis at end of life
- Thermal analysis at end of life

IMPACT

- Cost/time efficient work plan to achieve the Center's objectives



Process flow of EverBatt model. *Courtesy of Argonne*

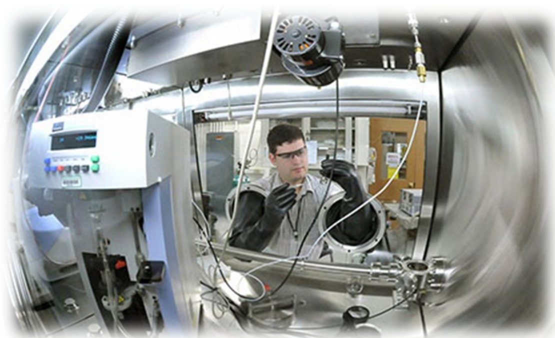


Infrared thermal image of a lithium-ion battery cell with poor terminal design. *Courtesy of NREL*

CROSSCUTTING

Assembly of 18650 cell at the CAMP facility
Courtesy of Argonne

Each of the collaborating labs brings crosscutting capabilities with it. The Center has a broad range of capabilities to enable creation of an efficient pathway to commercialization.



Post-test cell inspection inside a glovebox
Courtesy of Argonne

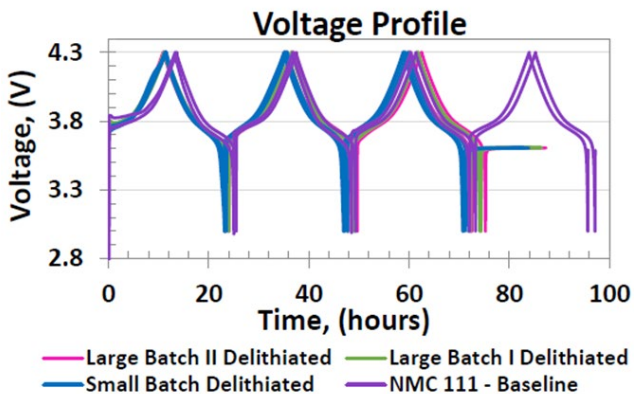
Process scale-up research in the MERF
Courtesy of Argonne

METHODOLOGY

Consistency is key

The ReCell Center uses consistent materials and methods that provide common and comparable results among researchers.

- Powders (NMC111, LMO, Graphite, etc.) and electrodes generated and distributed for early testing
  - Chemically delithiated (10%) NMC 111 cathode powder
- Standardized cell cycling protocols
- Analysis is performed using SOPs



ReCell Formation Protocol at 30°C, 3.0-4.3V:
3 Cycles of C/10 Charge, C/10 Discharge

MILESTONES

Q1 (Center) Establish the battery recycling center's mission and include its targets and goals

✓ COMPLETED 12/21/18:

"Decrease the cost of recycling lithium ion batteries to ensure future supply of critical materials and decrease energy usage compared to raw material production"

Q2 (NREL) Provide an initial progress report on roll-to-roll relithiation

✓ COMPLETED 3/29/19: Roll-to-roll relithiation work is progressing and the concept is currently being testing using coin cells

Q3 (ORNL) Provide an initial progress report on design for recycle initiative

In progress

Q4 (ANL) Establish the ReCell Center's Battery Recycling Laboratory and Scale-up Facility

In progress

TECHNICAL ACCOMPLISHMENTS

ReCell Facility Ribbon Cutting Ceremony

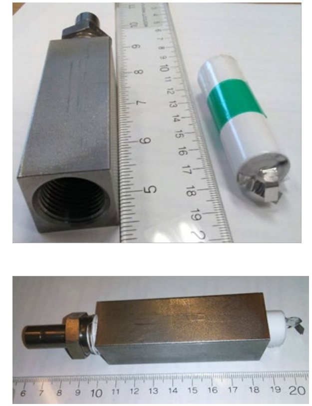
Facility ribbon cutting at Argonne National Laboratory

Asst. Secretary of EERE, Daniel Simmons, speaking

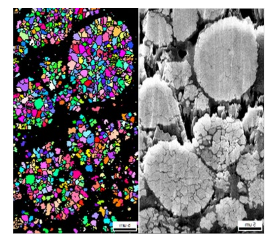
Demonstration of potentially recyclable battery materials

TECHNICAL ACCOMPLISHMENTS

- Removed binder by thermal treatment without significantly altering the initial electrochemical performance.
- Achieved hydrothermal delamination of graphite anodes; work continues on optimization of cathode electrode delamination.
- Designed, fabricated, and tested prismatic cells with ports. Data were used to model flow patterns in the cells.
- An updated version of EverBatt was developed and is available for download.
- Established methodology to obtain grain orientation from cathode samples via electron backscatter diffraction.



Cylindrical cell test unit with flushing ports



Grain orientation via EBSD

REMAINING CHALLENGES AND BARRIERS

- Front-end processing needs to be determined to identify contamination and purity challenges for downstream processing.
- A robust recycling process is needed that works for all lithium-ion battery chemistries (including non-EV).
- Projects need to be evaluated for technical and economic viability and a down-select process is needed.
- Industry buy-in for commercialization is needed
- The use of lithium metal anodes and solid state electrolytes will require new recycling processes.
- Future battery chemistries (sulfur, sodium, magnesium, etc.) may introduce even more recycling challenges.

PROPOSED FUTURE WORK

- Battery pre-treatment to enable direct recycling and maximum material recovery
- Research using new technologies that become available
- Analytical techniques for processing/quality control testing
- Improvement of EverBatt and LIBRA models
- Demonstration of batteries made with recycled content in real applications
- Demonstration of a continuous battery recycling line to prove feasibility to industry
- Joint projects with industry to ensure relevant work scope

Any proposed future work is subject to change based on funding levels

SUMMARY

- Volume of lithium-ion batteries reaching end of life will increase dramatically
- It currently costs money to treat EV lithium-ion batteries
- The US needs an effective battery recycling system to capture critical materials for national security
- ReCell is working to make recycling profitable, even as cobalt is removed
- This will be done by
  - Direct cathode recycling
  - Recovery of additional materials
  - Having designs that enable big picture cost reduction
  - Using modeling and analysis to direct and validate work

RESPONSE TO REVIEWERS

- **New Project FY19**

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ADVANCED BATTERY RECYCLING

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