ReCell
ADVANCED
BATTERY RECYCLING

RECELL: WORKING TO ADVANCE BATTERY RECYCLING

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ReCell Center Director

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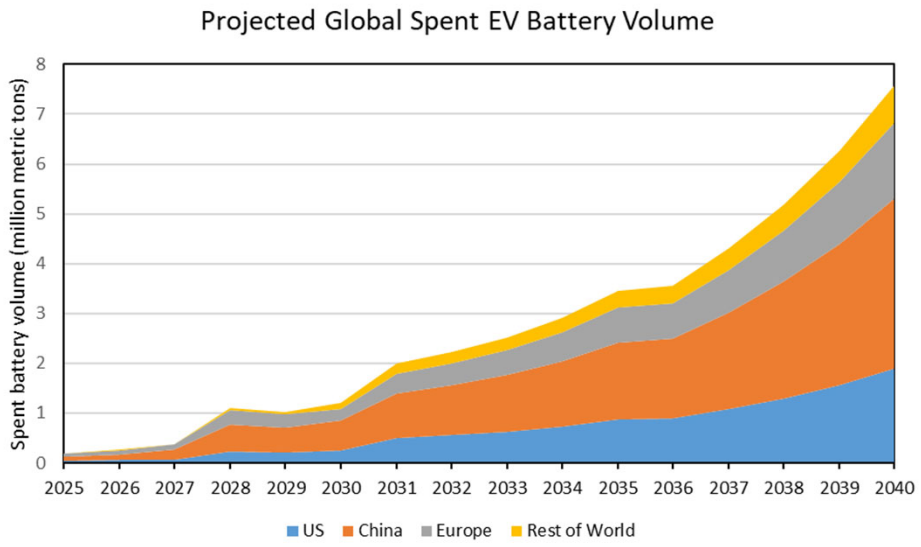
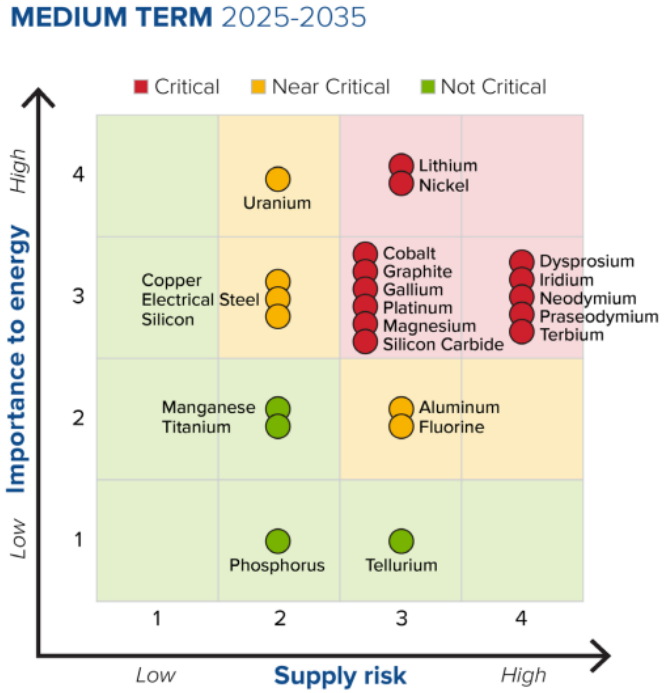
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

October 24th, 2023

WHY RECYCLE BATTERIES?

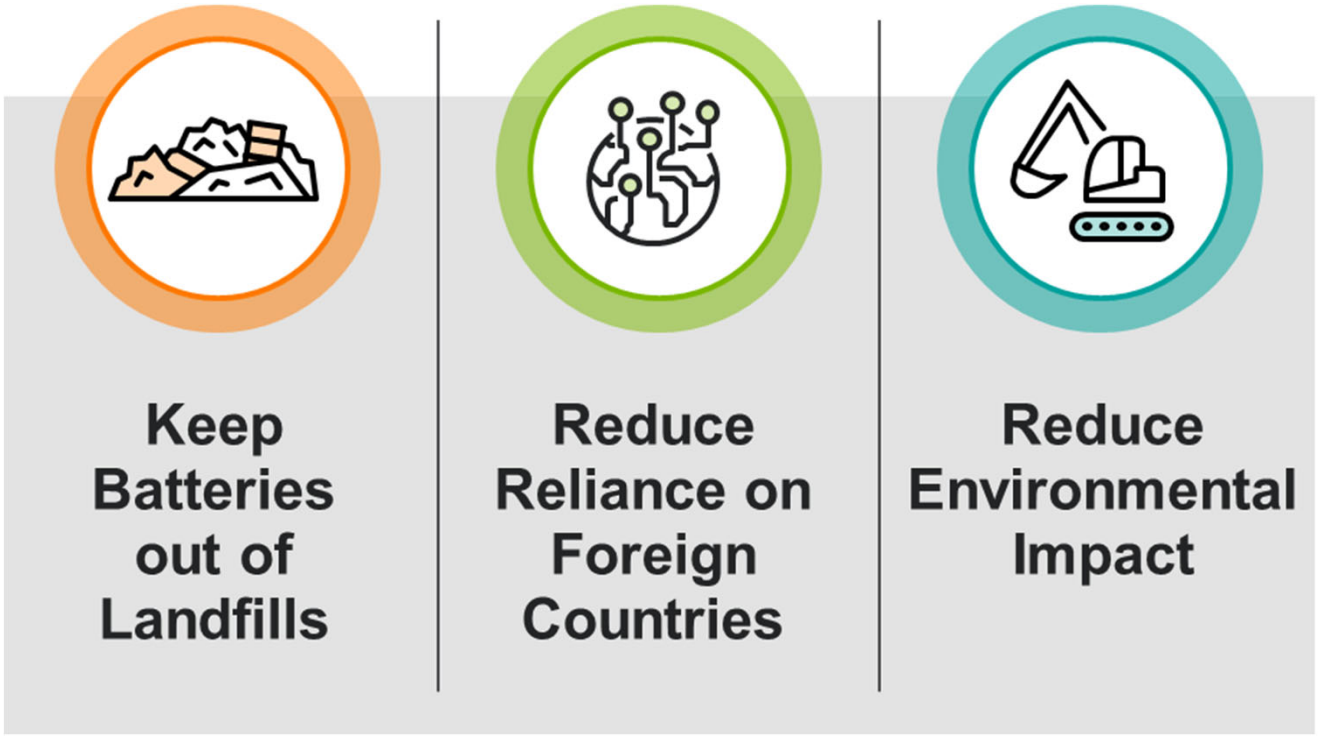


(ANL projection based on IEA global PEV projection)



www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf

WHY RECYCLE BATTERIES?



WHERE WILL BATTERY MATERIALS FOR RECYCLING COME FROM?

ELECTRONIC DEVICES

Nearly 152 million cell phones are thrown away in the U.S. every year, with the rest ending up in drawers

Source: USA Today

MANUFACTURING SCRAP

Waste from the battery industry is expected to supply nearly 80% of the material for recycling by 2025

Source: Benchmark Minerals

ELECTRIC VEHICLES EVs

Over 1 million vehicles on the road today will become 8 million tons of battery scrap by 2040

Source: Reuters

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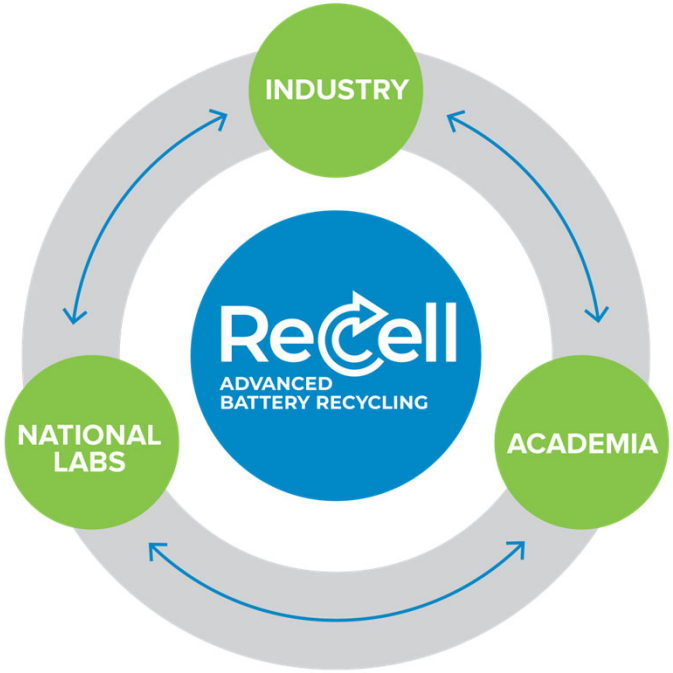
ARGONNE AND BATTERY RECYCLING

- Argonne brings together battery development, process optimization, scale-up, recycling, and modeling expertise
- Argonne leads DOE's ReCell Center for Advanced Battery Recycling
- We work in other areas of recycling:
  - Critical materials
  - Plastics
  - Electronics waste
- We work closely with industry and our goal is to help industry succeed



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THE RECELL CENTER

The center develops cost-effective, flexible processing techniques to extract as much value as possible from current and future batteries chemistries making recycling economically viable.

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THE RECELL CENTER'S FOCUS AREAS

Overview

DIRECT RECYCLING

Recycling materials back to their original purpose without destroying their chemical structure.

26 Projects

ADVANCED RESOURCE RECOVERY

Recapturing materials for reuse in batteries or other applications through chemical conversion.

13 Projects

DESIGN FOR SUSTAINABILITY

Working toward more sustainable batteries by improving material choice, battery design, and second life opportunities.

8 Projects

MODELING AND ANALYSIS

Developing tools to provide a deep materials/ process understanding and evaluate economic and environmental impacts.

11 Projects

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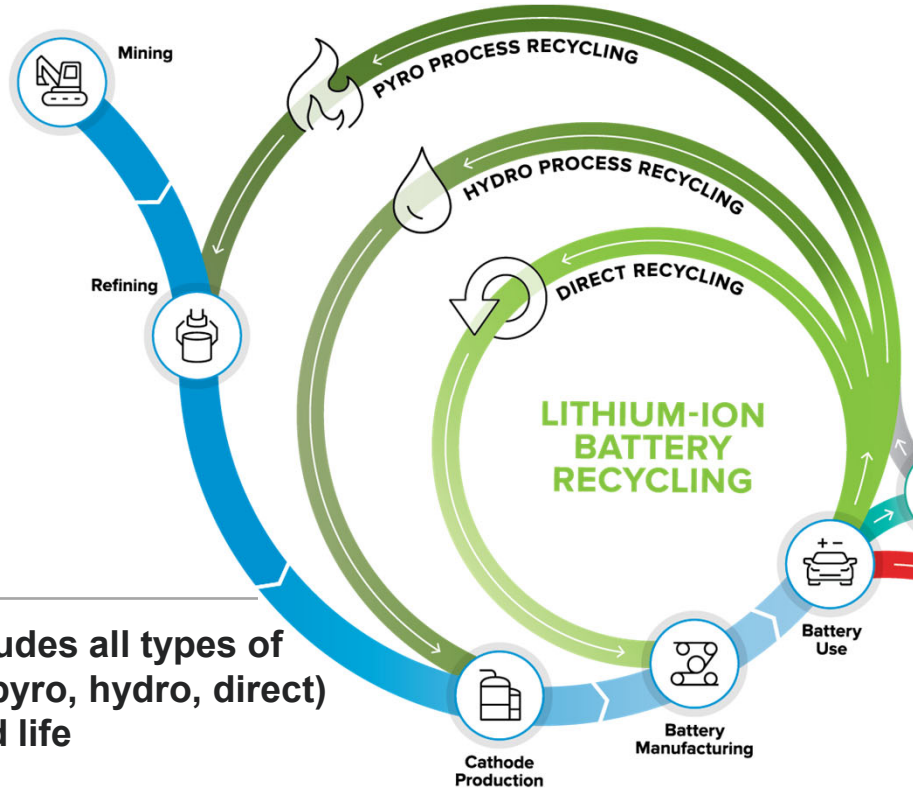
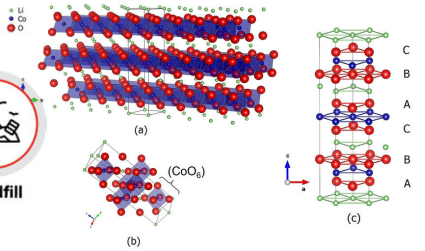
LITHIUM-ION BATTERY RECYCLING



Pyrometallurgical Processing

Hydrometallurgical Processing



Direct Recycling

ReCell includes all types of recycling (pyro, hydro, direct) and second life

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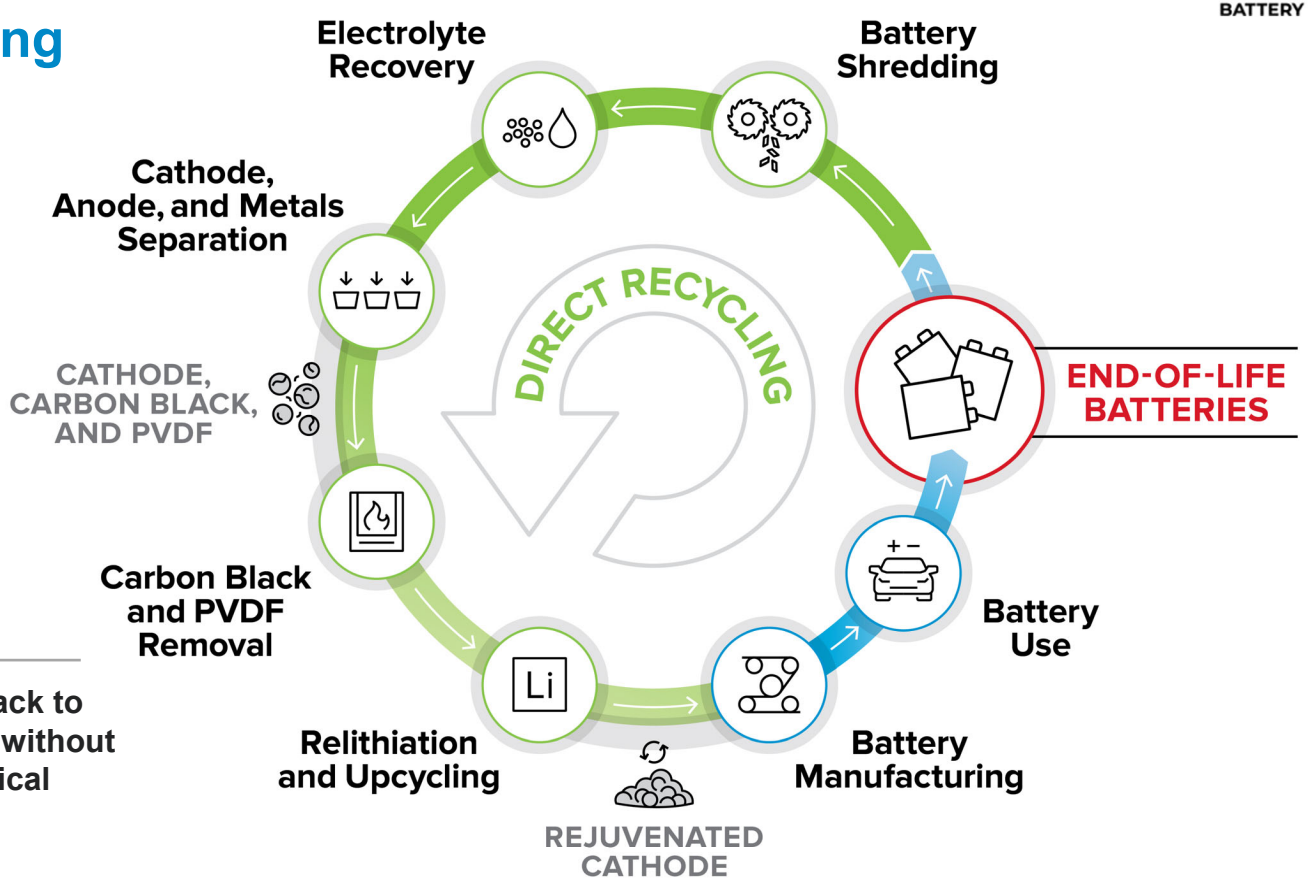
LITHIUM-ION BATTERY RECYCLING

Direct Recycling



Recycling materials back to their original purpose without destroying their chemical structure

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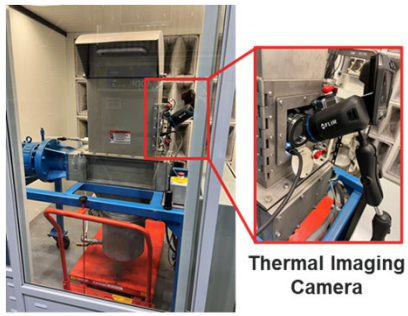
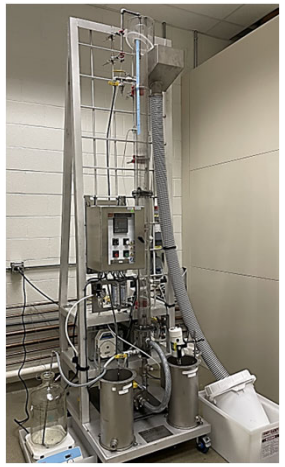
BATTERY RECYCLING FACILITIES

- ReCell currently occupies:
  - 3,000 ft^2 of highbay space
  - Bench and pilot scale labs in the MERF
- Equipment includes:
  - Shredding
  - Size separation
  - Magnetic separators
  - Froth columns
  - High-temperature furnaces
  - Rotary kiln
  - Optical sorter
  - Sink/float separation
  - Electrochemical separation
  - Aspirator
  - Sheer mixers



Shredding
Safely break down lithium-ion batteries



Froth Flotation
Separation of battery materials (anode and cathode powders)

Optical Sorter
Color, shape, and size separation

Rotary Kiln
Thermal binder removal and relithiation

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OTHER MATERIALS RECYCLING CAPABILITIES

MATERIALS SEPARATION

Large Wet Separation System

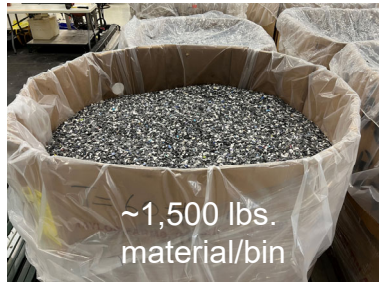
Wet Separation Systems	Processing Capability
Small (55 gallons)	100 lbs/hr
Medium (250 gallons)	500 lbs/hr
Large (1,000 gallons)	4,000 lbs/hr (~2 tons/hr)

Rare-Earth Magnetic Drum
Remove and separate ferrous metals

Eddy Current
Remove and separate non-ferrous metals

Aspirator/Cyclone
Remove light materials (foam, thin plastics)

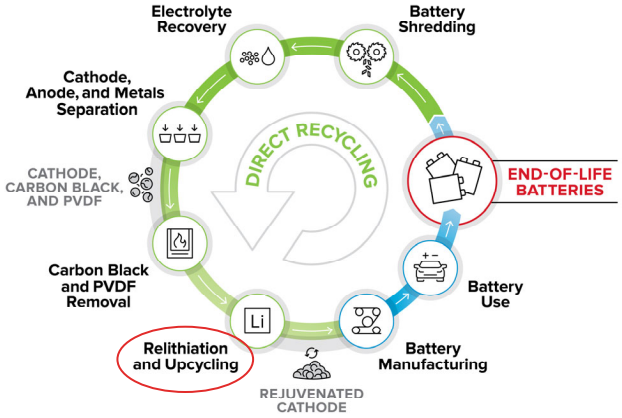
- Process and separate plastics and metals from various sources (electronics waste, toner cartridges, vehicles, household appliances, etc.)
- Produce clean feedstocks for plastics or metals recycling processes
- FY22 ANL Lab-to-Market (L2M) funding
  - E-waste material from 2 companies
  - Processed 10-15 tons material each

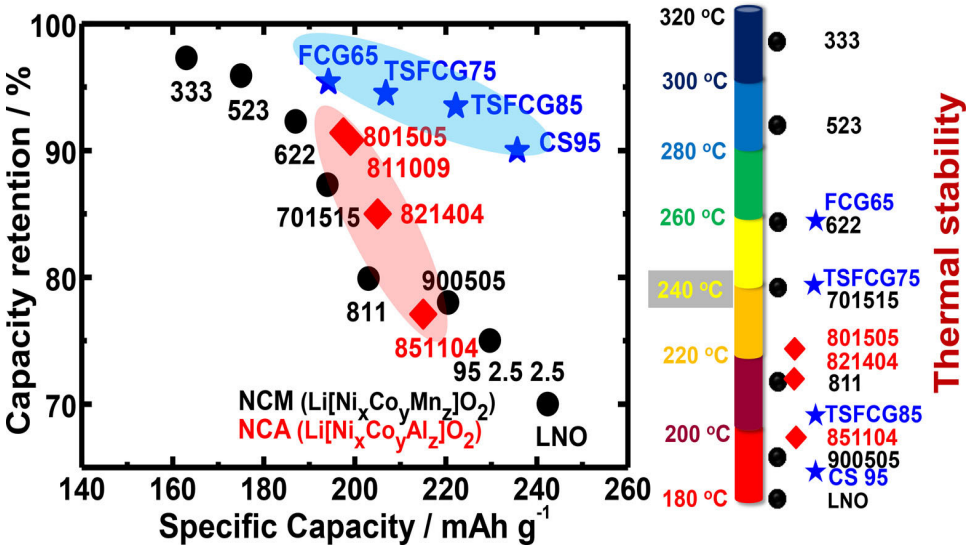


RELITHIATION AND UPCYCLING

NEED FOR UPCYCLING PROCESSES

- Cathode materials recovered from vehicles that are about 15 years old are likely to be of lower nickel composition
  - Lower capacity
- Adding nickel to these compositions can increase capacity





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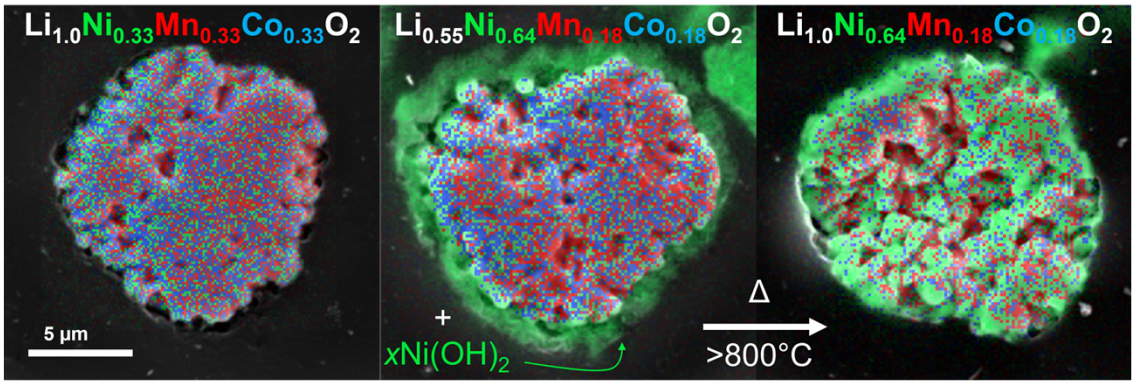
COPRECIPITATION UPCYCLING

Rapid Coprecipitation:

ACS Appl. Energy Mater. 2021, 4, 2, 1972–1977

Advantages:

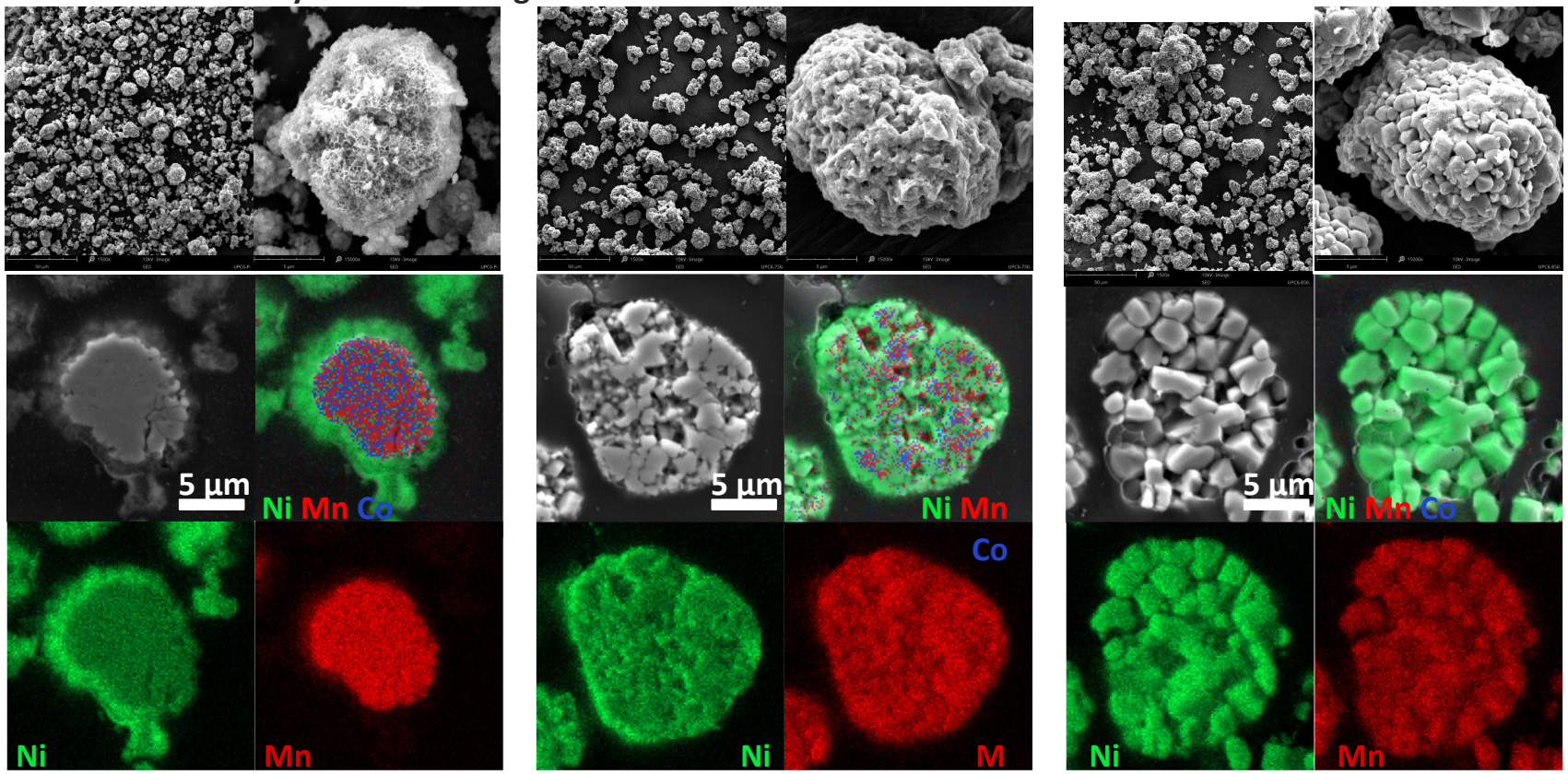
- Low capital cost:
  - Minimal inputs of additional chemicals and equipment
- Fast reaction: ~1.5 h
- Ambient pressure and aqueous environment



WHOLE AND CROSS-SECTIONAL SEM EDS

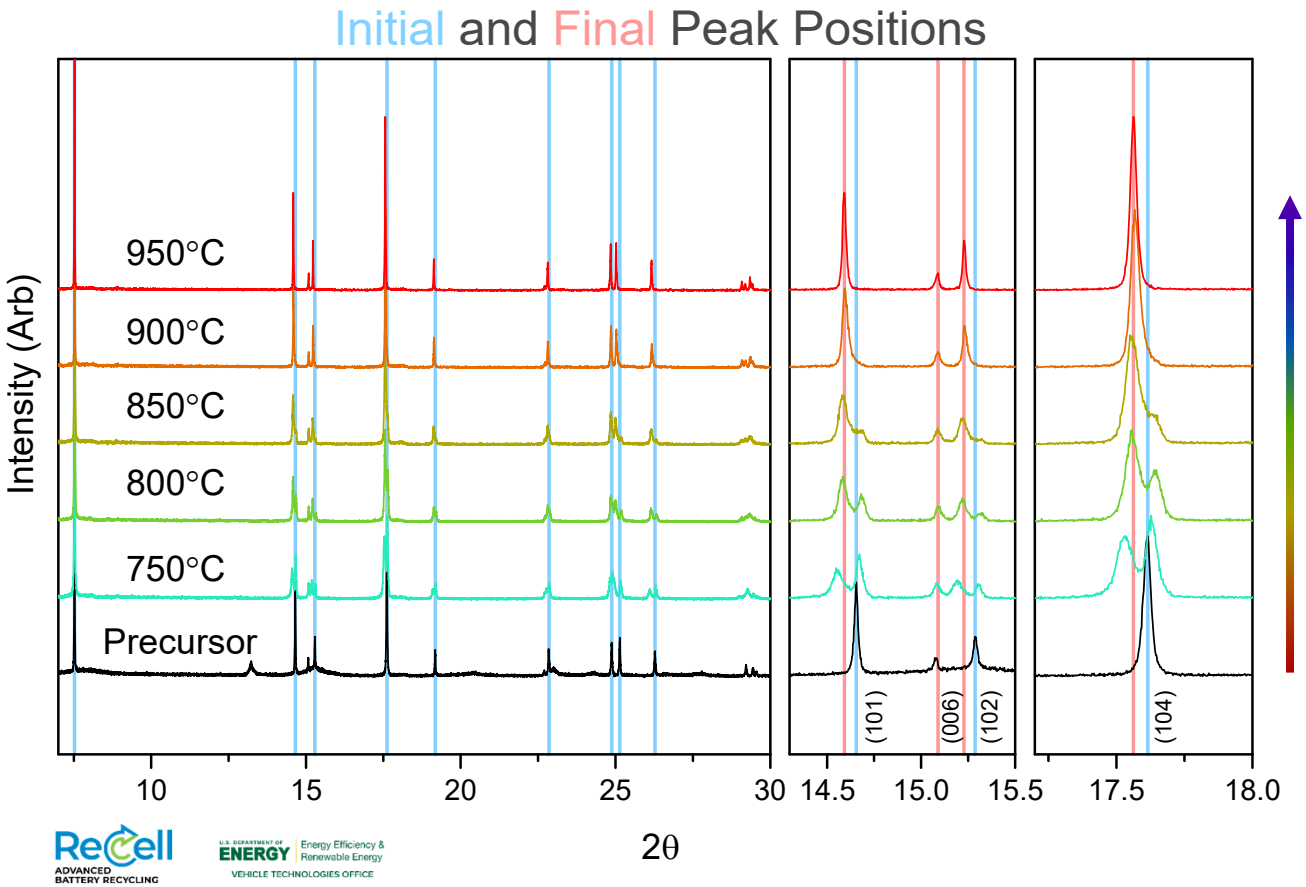
ICP ratio of Ni : Mn : Co after upcycling → 0.64 : 0.18 : 0.18

NMC111 with Ni-rich Hydroxide Coating **NMC622 Cathode - 750°C** **NMC622 Cathode - 900°C**



EX-SITU HIGH-RESOLUTION XRD OF CALCINATION

Collected at 5-BMC at the APS



As calcination temperature is increased, pXRD peaks combine and shift to lower 2θ positions indicative of NMC622

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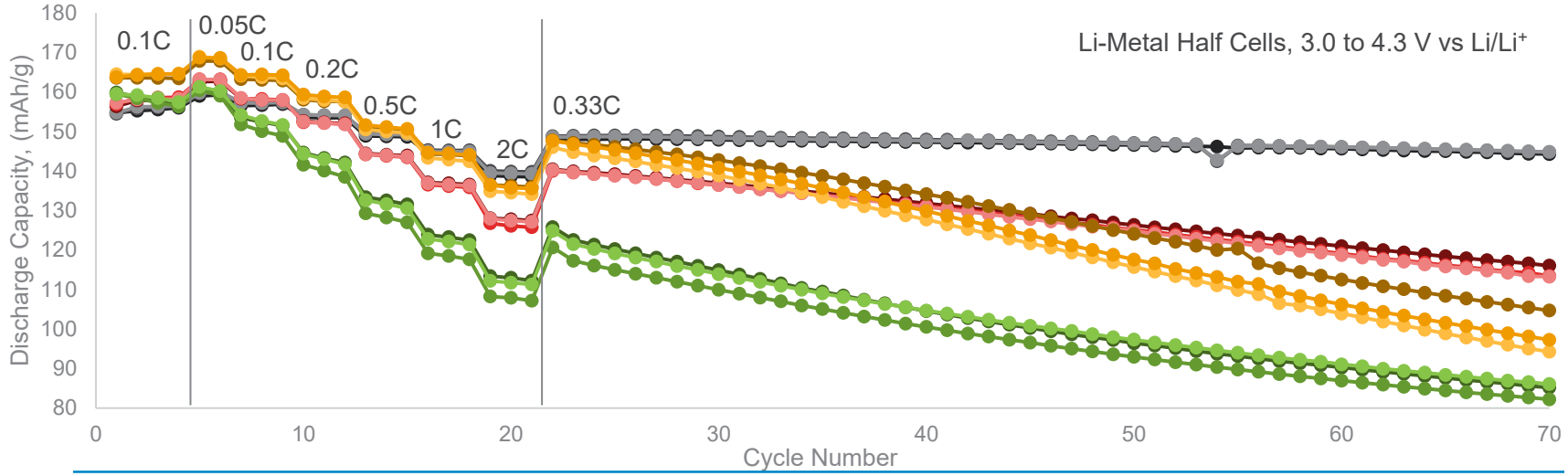
ELECTROCHEMICAL PERFORMANCE OF UPCYCLED NMC622



Sample	First Charge Capacity, C/10 (mAh/g)	First Discharge Capacity, C/10 (mAh/g)	First Cycle Efficiency (%)	Capacity Retention (%)
TODA NMC111	171.9±0.1	154.7±0.2	90.0±0.1	97.5
UPC-NMC622-850°C	179.0±0.9	156.8±0.4	87.6±0.1	82.0
UPC-NMC622-900°C	184.5±1	163.9±0.5	88.8±0.6	67.8
UPC-NMC622-950°C	184.8±0.5	159.6±0.2	86.4±0.1	70.2

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TOMOGRAPHIC TRANSMISSION X-RAY MICROSCOPY (TXM)

Argonne NATIONAL LABORATORY

X-Ray Light source

Rotation Stage

Detector Array

2D Projection Images Collected across 180°

Reconstructed with GPU assisted SIRT algorithm (TomoPY-ASTRA)

Reconstructed slices assembled as a 3D volume

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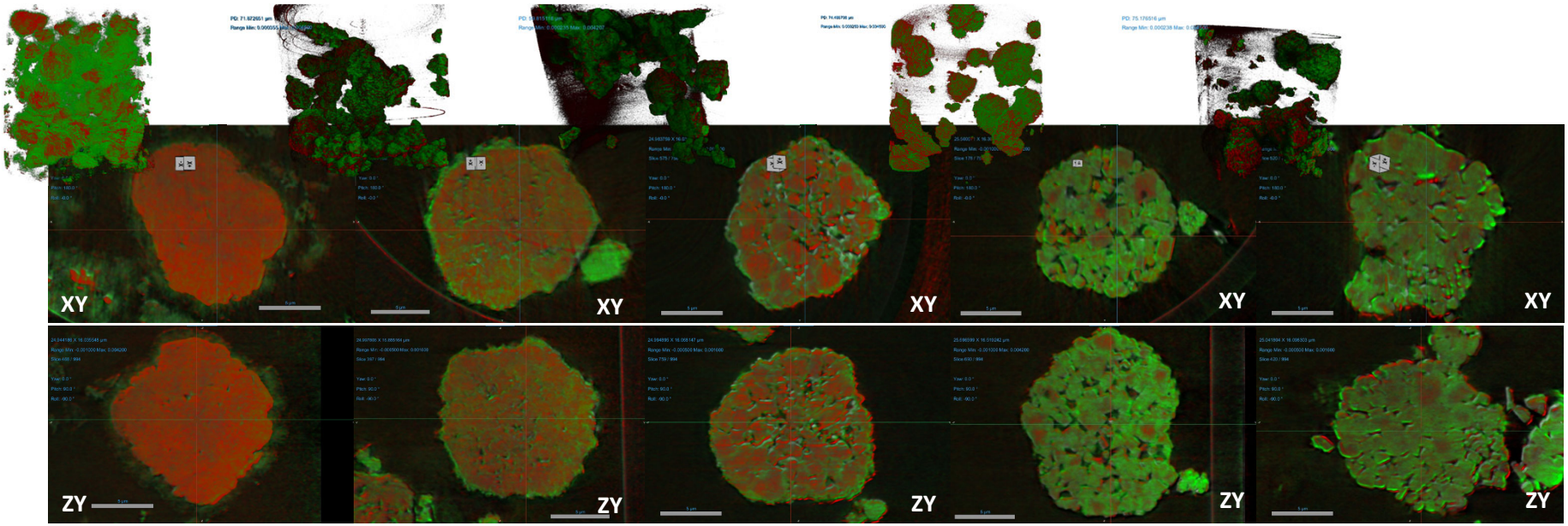
ELEMENTAL SPECIFIC TOMOGRAPHIC TRANSMISSION X-RAY MICROSCOPY (TXM)

Pixel color representative of relative Ni and Co concentration

Differential absorption between above and below K-edge for Ni and Co



Precursor → 750°C → 800°C → 850°C → 900°C

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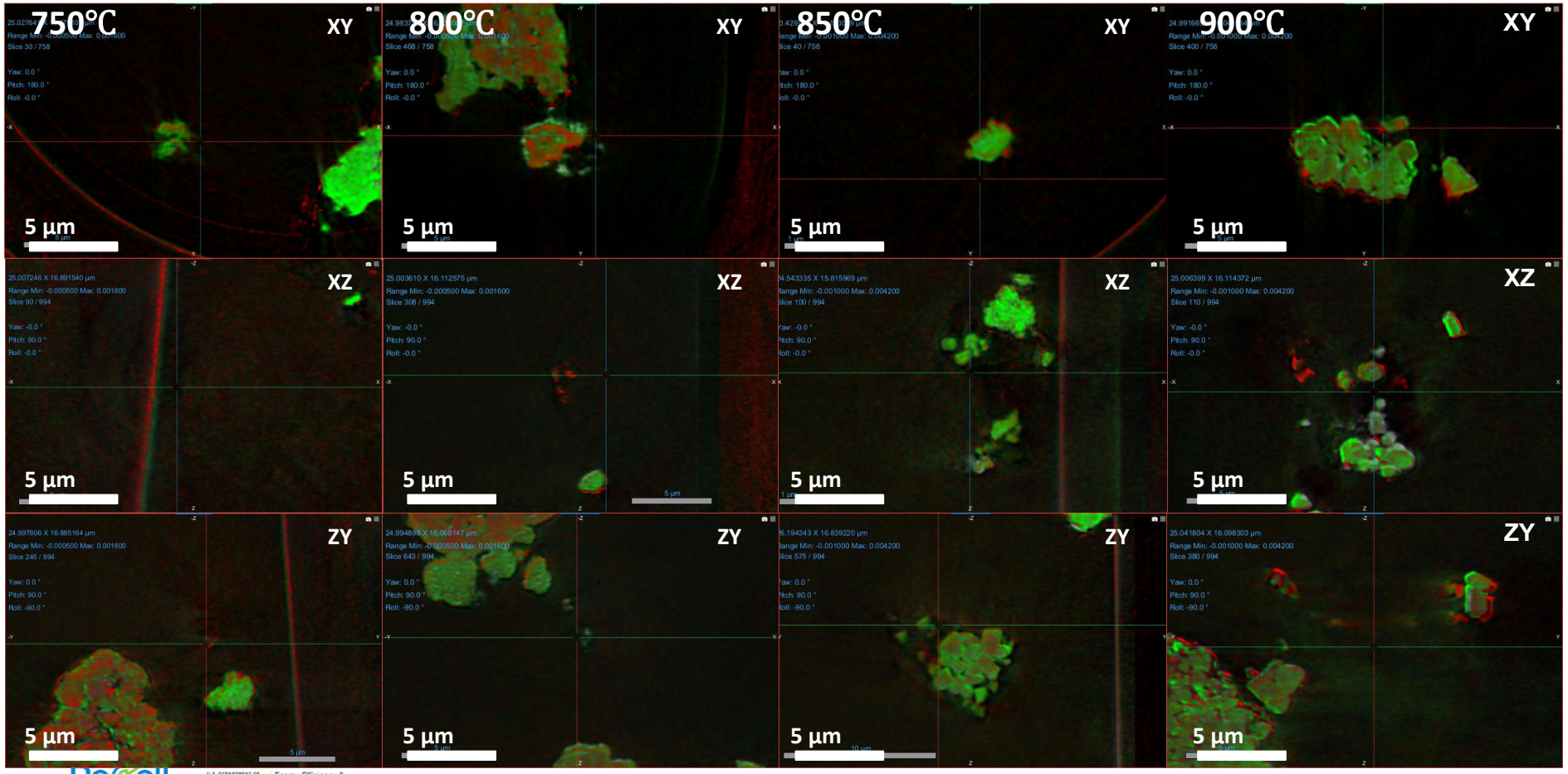
ENTIRE 3D VOLUMES FROM ELEMENTAL TXM



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SUMMARY

- A fast (~1.5 hr) and effective method to convert low-capacity cathode material into higher capacity by introducing higher Ni compositions.
- This conversion improved the initial capacity (C/10, 3.0 to 4.3 V vs. Li/Li^+) from 154.7±0.2 mAh/g to 163.9±0.5 mAh/g

Tackling battery recycling from separations to advanced characterization to gain fundamental knowledge of what is required to provide recycled cathodes for reuse

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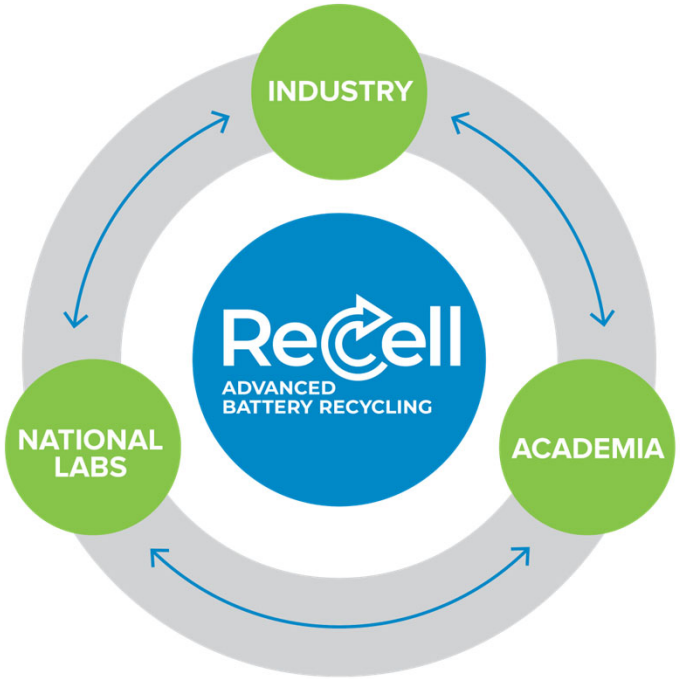
WRAP UP

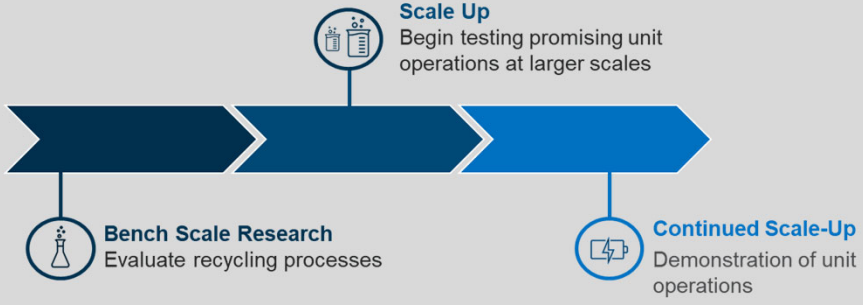
RECELL CENTER COLLABORATION

Working Together to Solve Recycling Challenges



Bringing together battery recycling expertise from national laboratories, universities, and industry to bridge the gaps that are keeping us from realizing the most successfully advanced battery recycling infrastructure

Typical Process Workflow



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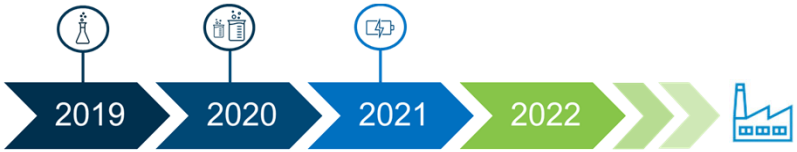
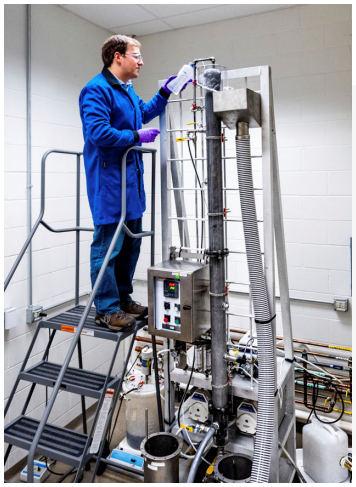
BEYOND THE BENCH: DIRECT RECYCLING AT SCALE

Expansion of ReCell Center into Large Highbay Space

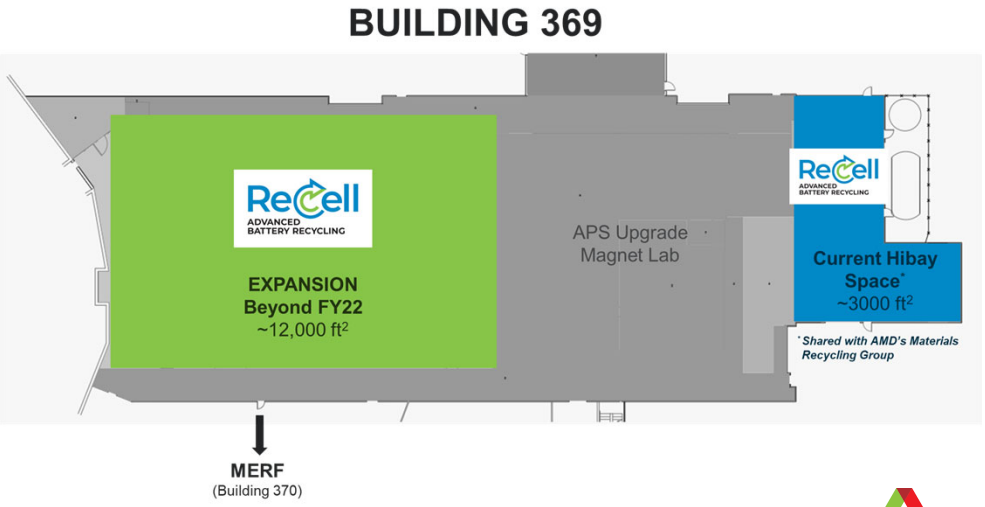
- Provide space for pilot scale equipment capable of handling 10 kg/day (~2.5 tons/year)
- Transfer new recycling technologies to industry



Battery Shredding



Froth Flotation



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BATTERY RECYCLING PILOT PLANT

Beyond the Bench: Direct Recycling at Scale

- Renovation of 12,000 ft^2 of highbay space (expected completion Spring 2024)
- Provide space for pilot scale equipment capable of handling 10 kg/day (~2.5 tons/year)
- Transfer new recycling technologies to industry

Pilot-Scale Electrodialysis
Remove ions from solution

Pilot-Scale Aspirator
Remove light materials (foam, thin plastics)

Pilot-Scale Magnetic Separation
Separate magnetic materials

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RECELL INDUSTRY COLLABORATION MEETING

Hosted at Argonne

- Provided an opportunity for ReCell and industry stakeholders to exchange challenges and ideas
- Meeting included stakeholders from every corner of the vehicle battery value chain
- Another meeting will be hosted in Spring 2024

November 2019 *(134 people, 76 organizations)*
April 2023 *(146 people, 81 organizations)*

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RECELL PARTNERSHIPS, SPONSORS, AND COLLABORATORS

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NREL NATIONAL RENEWABLE ENERGY LABORATORY

OAK RIDGE National Laboratory

INL Idaho National Laboratory

UNIVERSITY COLLABORATIONS

Michigan Technological University

WPI

UC San Diego

TENNESSEE STATE UNIVERSITY

INDUSTRY COLLABORATIONS

24M

ALBEMARLE

BATTERY RESOURCERS

BLUEWHALE

EASTPENN

FARASIS

FCA FIAT CHRYSLER AUTOMOBILES

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COLLABORATION AND ACKNOWLEDGEMENTS

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NREL NATIONAL RENEWABLE ENERGY LABORATORY

OAK RIDGE National Laboratory

INL Idaho National Laboratory

Michigan Technological University

WPI

UC San Diego

TENNESSEE STATE UNIVERSITY

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