U.S. DEPARTMENT OF ENERGY'S (DOE)
VEHICLE TECHNOLOGIES OFFICE (VTO)
2020 ANNUAL MERIT REVIEW (AMR)

ReCell
ADVANCED BATTERY RECYCLING

MODELING AND ANALYSIS OF BATTERY RECYCLING

RECELL CENTER FOR ADVANCED BATTERY RECYCLING

LINDA GAINES
Argonne National Laboratory

bat468
Virtual Poster
June 1-4, 2020

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

This presentation does not contain any proprietary, confidential, or otherwise restricted information

PROJECT OVERVIEW

Timeline

- Project start: October 2018
- Project end: September 2021
- Percent complete: ~50%

Budget

FY19	$4,615k
FY20	$5,150k

Barriers

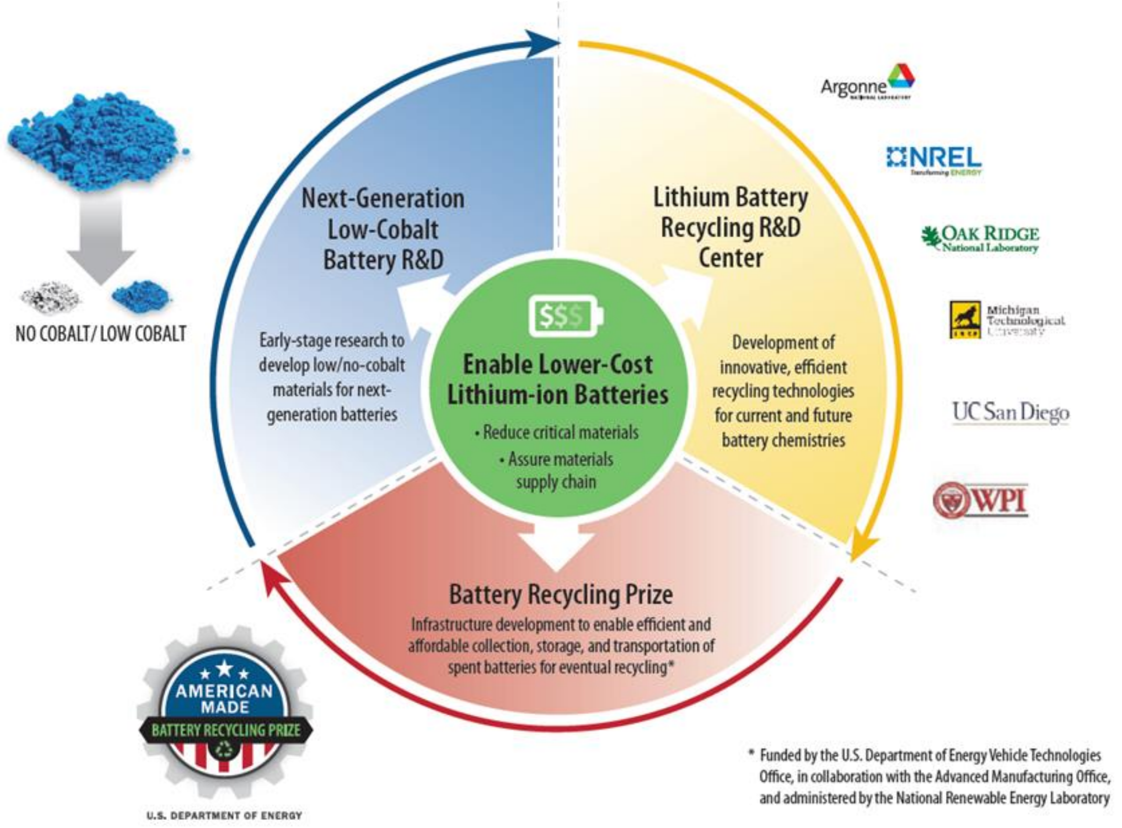
- Recycling and Sustainability
  - Cost to recycle is currently 5-15% of battery cost
  - Material shortage (Li, Co, and Ni)
  - Varying chemistries result in variable backend value

Partners

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

RELEVANCE

- Lower cost of batteries
- Enable lower environmental impacts
- Increase our country's energy security

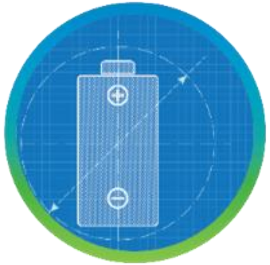


APPROACH

Year 1 – Bench scale testing: Powder-to-Cell → Year 2 – Start to scale up unit operations → Year 3 – Finish scale up and show cell-to-cell recycling

DIRECT CATHODE RECYCLING

OTHER MATERIAL RECOVERY



DESIGN FOR RECYCLING

MODELING AND ANALYSIS

ReCell does not include battery dismantling, transportation, or 2nd use

PROGRAM MILESTONES

FY19 Q1 Complete Establish the battery recycling center’s mission and include its targets and goals

FY19 Q2 Complete Provide an initial progress report on roll-to-roll relithiation

FY19 Q3 Complete Provide an initial progress report on design for recycle initiative

FY19 Q4 Complete Establish the ReCell Center’s Battery Recycling Laboratory and Scale-up Facility

FY20 Q1 Complete Electron Backscatter Diffraction data comparison of various chemically delithiated NMC-111 versus pristine NMC-111

FY20 Q2 Complete All five relithiation processes added to EverBatt at lab scale and production scale

FY20 Q3 Ongoing Down-select solvent(s) to separate black mass from current collector and optimize the process conditions to achieve >90% recovery of black mass

FY20 Q4 Ongoing Demonstrate recovery of anode and cathode powders using the new pilot scale froth column

Each Individual project has its own milestones that are not listed here.

COVID-19 has reduced lab time and may cause delays in completing FY20 milestones

MODELING AND ANALYSIS OF BATTERY RECYCLING

MODELING AND ANALYSIS INSURES NEW PROCESSES MEET OUR OBJECTIVE

To decrease Li-ion batteries recycling costs to ensure future supply of critical materials and decrease energy use compared to raw material production

Project Title	Laboratory	PI	Status
EverBatt: Cost and Environmental Impact Modeling	Argonne	Qiang Dai	Ongoing
LIBRA: Supply Chain Analysis for Battery Recycling	NREL	Margaret Mann	Ongoing
Battery Recycling Prize Quantification Methodology	Argonne	Jarod Kelly	Completed

A WORKING PROCESS DOESN’T INSURE SUCCESS

Analysis screens for other hurdles for R&D to overcome

- Are there any environmental roadblocks?
- Can the process be economically viable?
- Where do the required materials come from? Is there enough?
- Can DOE R&D alleviate potential material supply constraints? Can recycling?
- How many batteries will be going out of service? How can we get them back?
- How will recycling impact prices and availability?

Courtesy of:
https://www.garbageday.com/gd/everything-you-need-to-know-about-battery-recycling/

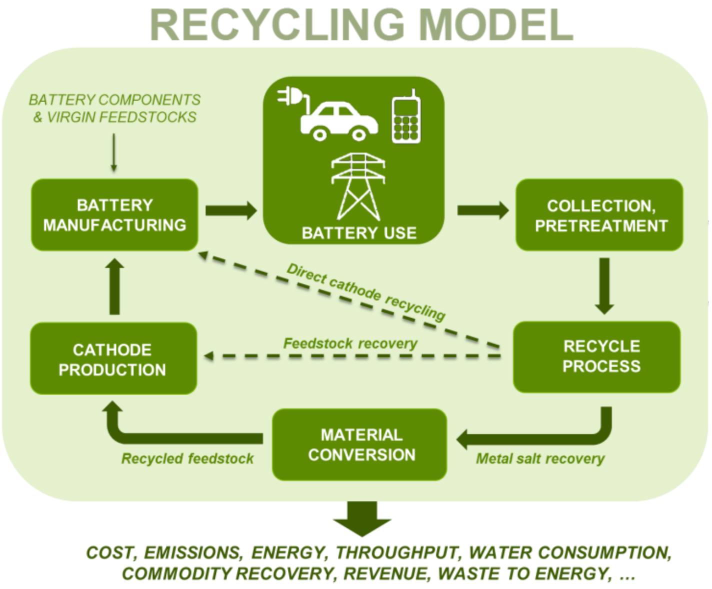
EVERBATT MODEL EVALUATES LIFE CYCLE COSTS AND IMPACTS

Enables process evaluation and comparison

The project's goal is to evaluate the cost and environmental impacts of different battery recycling technologies to inform recycling R&D.

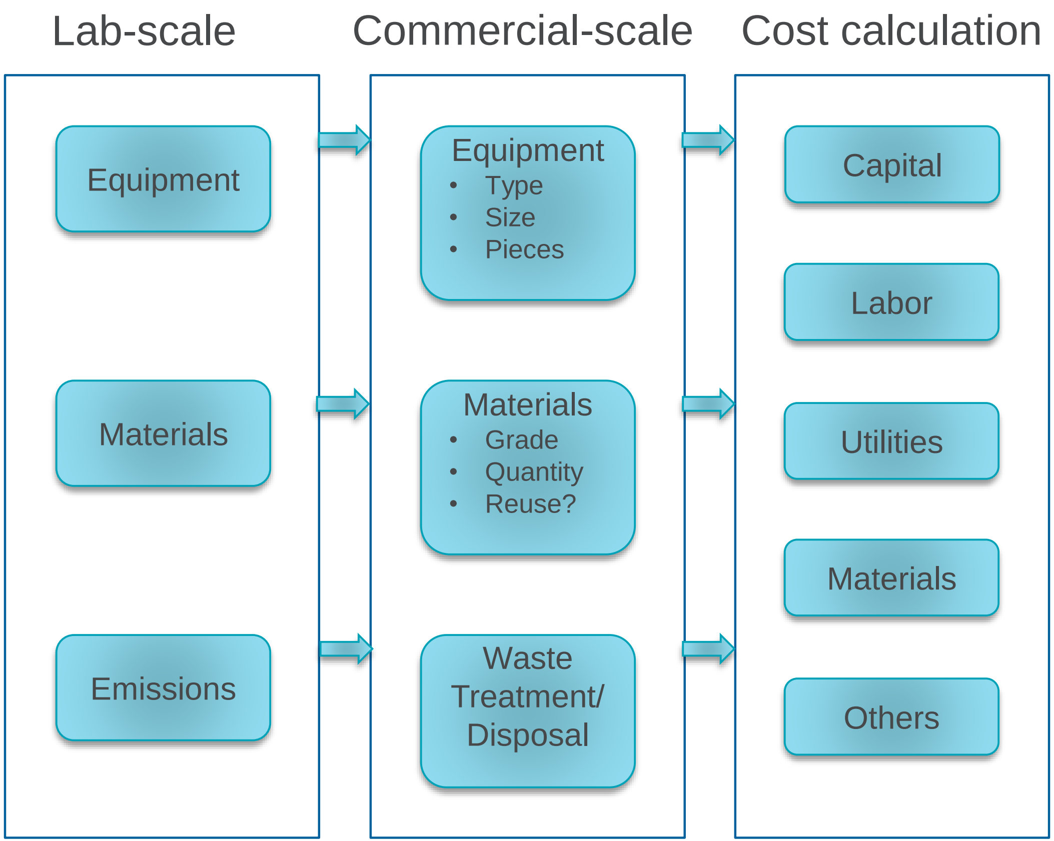
Key functions:

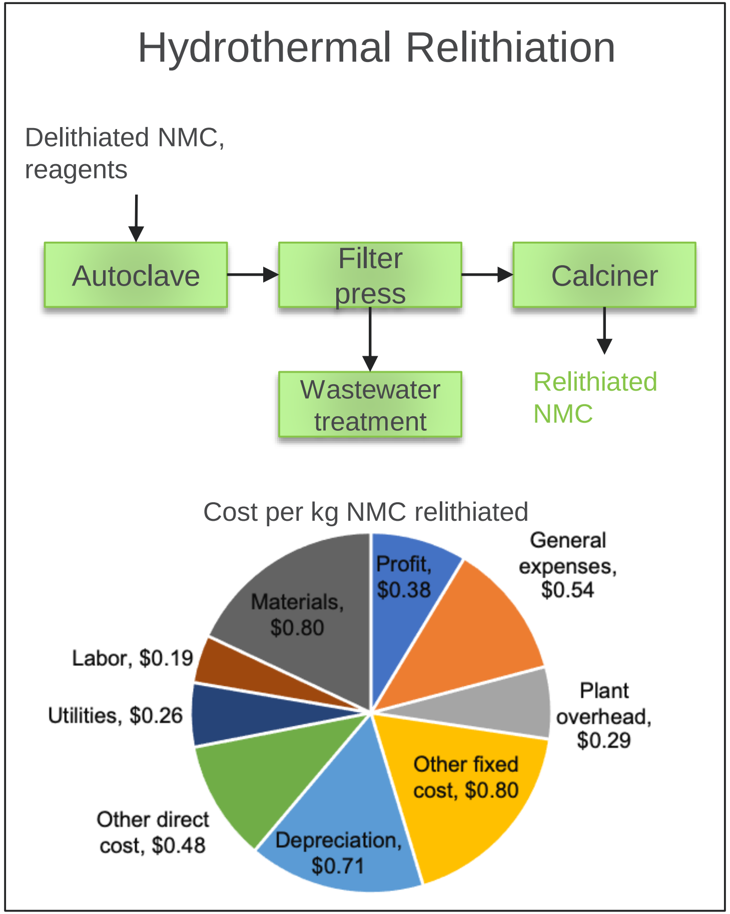
- Pinpoint process and supply chain hotspots, and identify opportunities for improvement.
- Identify barriers to commercialization.
- Provide a holistic picture of battery sustainability over the life cycle.



EverBatt is available for download at:
https://www.anl.gov/egs/everbatt

EXAMPLE: EVALUATING RELITHIATION COST



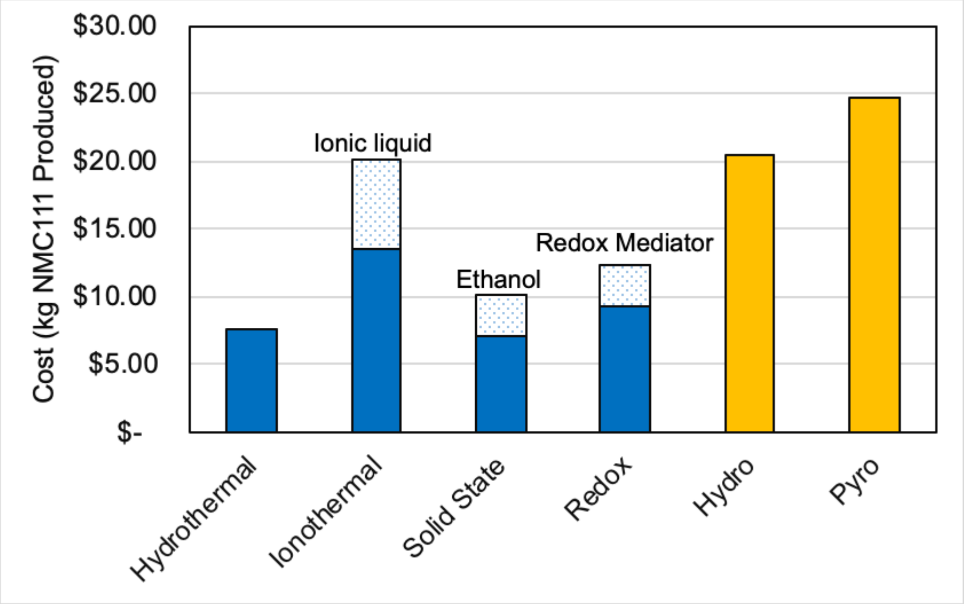


ReCell ADVANCED BATTERY RECYCLING
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
VEHICLE TECHNOLOGIES OFFICE

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.

"HUB AND SPOKE PROCESSING" COULD REDUCE TOTAL RECYCLING COST

Transportation of hazardous material is very costly

- Collected batteries are sent to distributed pretreatment facilities to be neutralized.
- Black mass from pretreatment is transported to one or a few recycling facilities to recover valuable materials.
- Pretreatment plants need to be spread to reduce transport cost but large enough to enjoy economies of scale

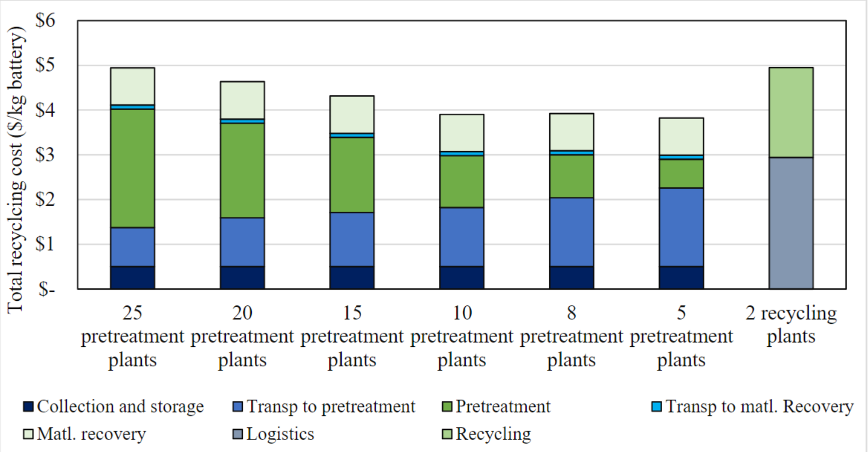


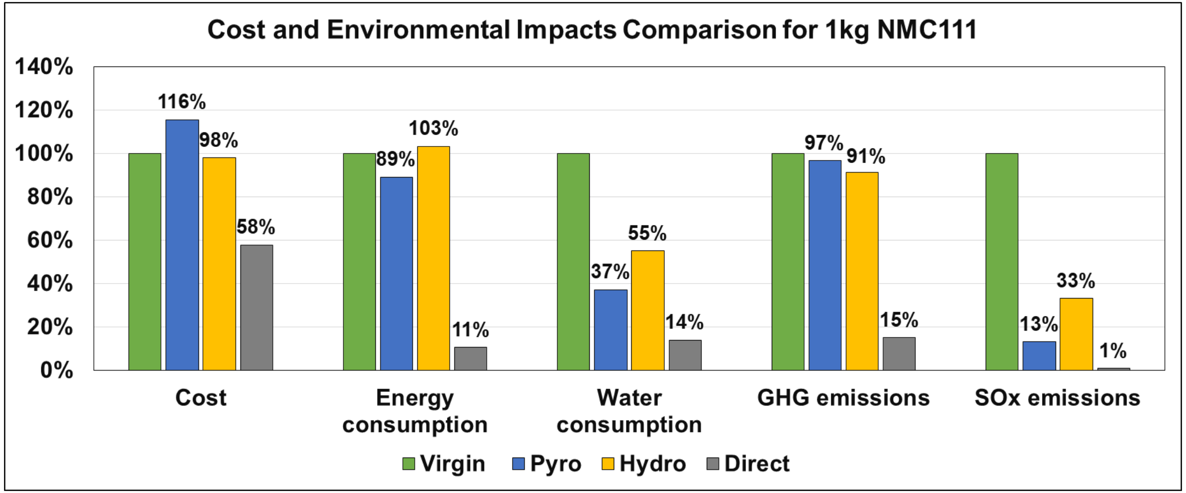
Figure 1 shows the total costs of deploying multiple distributed pretreatment facilities with a combined capacity of 50,000 T/y, plus 2 hydrometallurgical facilities with a combined capacity of 30,000T/y, compared to that for 2 hydrometallurgical facilities with a combined capacity of 50,000 T/y without pretreatment.

TEA SHOWS ADVANTAGES OF DIRECT RECYCLING

Impacts are lower in all categories examined

Accomplishments:

- Released EverBatt2019 in June 2019.
- Identified transport and storage as a significant contributor to battery recycling cost.
- Showed that direct recycling offers significant impact reduction compared to conventional routes.
- Evaluated the cost of all relithiation processes.



Future Work:

- Continue to evaluate ReCell processes and designs.
- Continue communications with industry/ academia/government to improve and validate EverBatt.

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

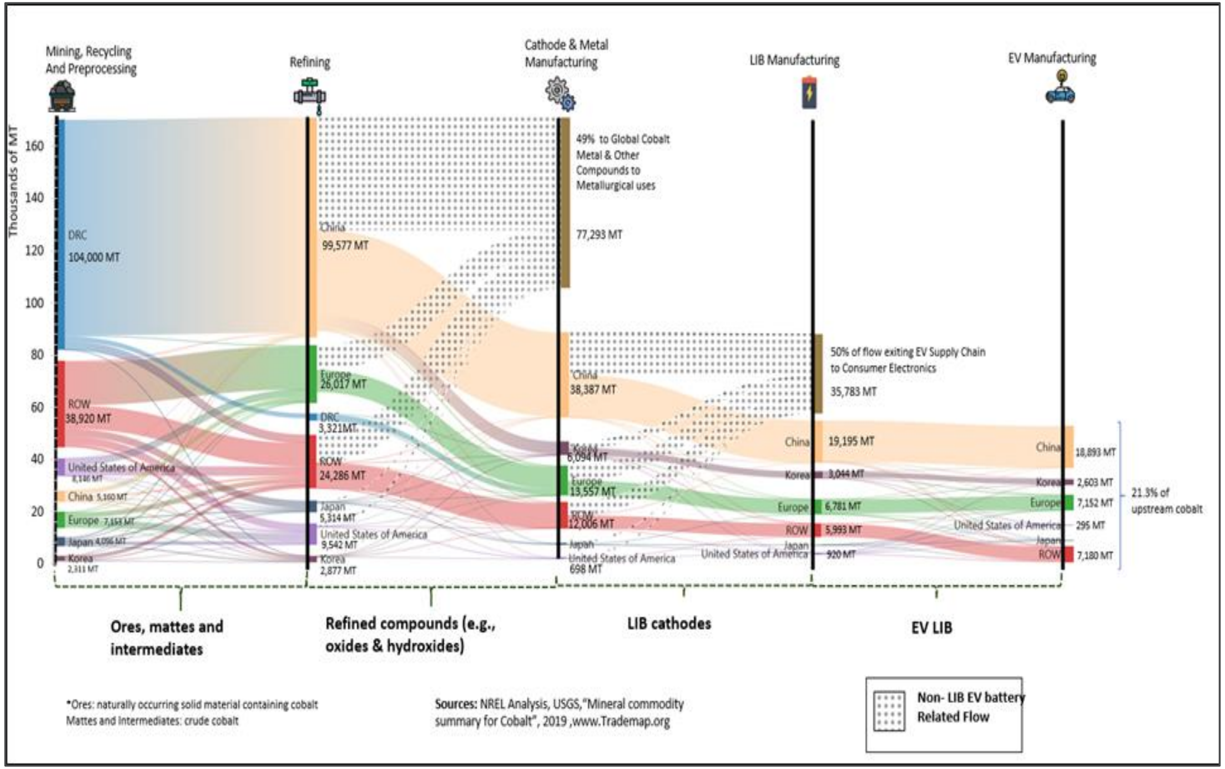
SUPPLY CHAIN ANALYSIS TRACKS FLOWS OF KEY MATERIALS

The majority of battery materials are refined in China

NREL is analyzing the material and component supply chain for Li-ion manufacturing and recycling to determine the dynamic factors driving the economic viability of this nascent industry.

Material availability, supply shocks, and technology adoption all impact the success of battery recycling and the electrification of the transportation sector.

Global Flow of Cobalt



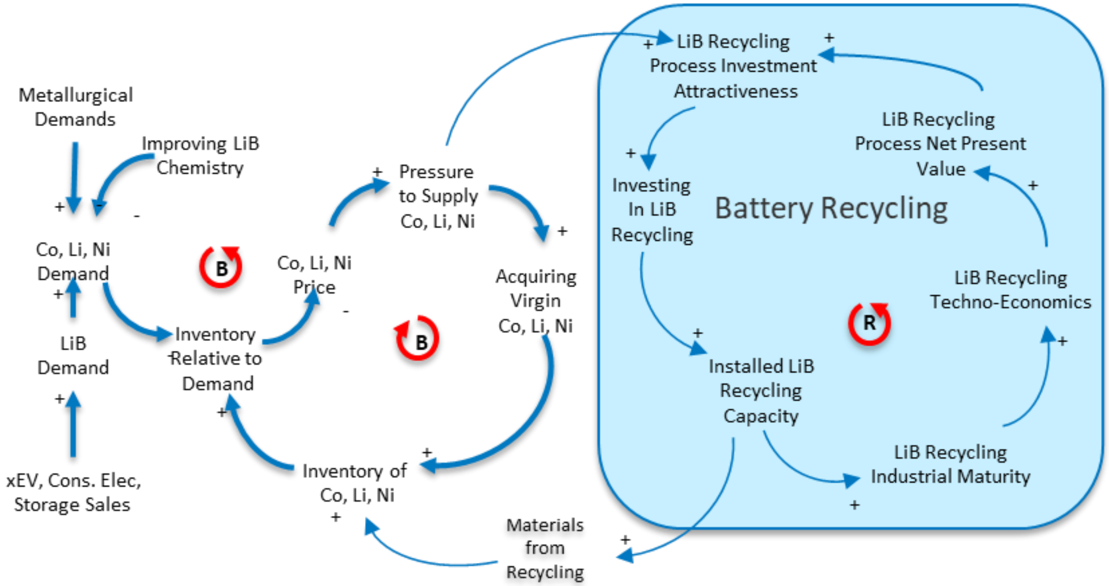
ReCell ADVANCED BATTERY RECYCLING

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

THE LIBRA MODEL PLACES BATTERY MATERIAL SUPPLY AND DEMAND IN A GLOBAL CONTEXT

In an effort to evaluate the macro-economic viability of the battery recycling industry and global supply chain under differing dynamic conditions, NREL is developing a systems dynamics model to clarify the factors affecting financial viability.

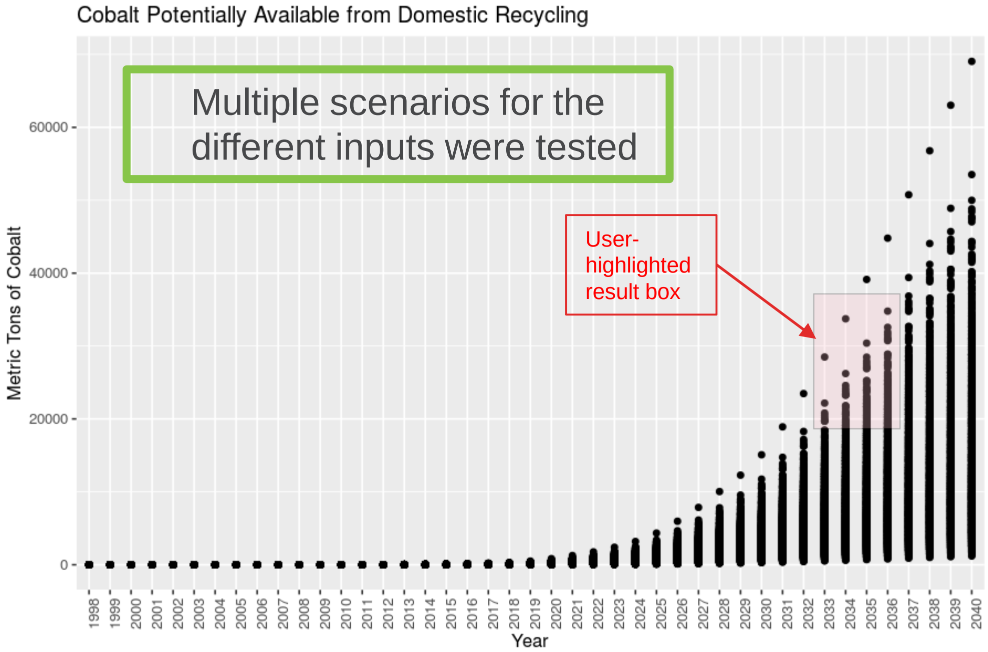
The LIBRA model includes required investments, industry build-out, and the impact of achieving research and programmatic goals.



The success of battery recycling depends on the rest of the supply chain, including battery production, use, and materials acquisition.

ReCell ADVANCED BATTERY RECYCLING
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy VEHICLE TECHNOLOGIES OFFICE

LIBRA MODEL IDENTIFIES CRITICAL SUPPLY CHAIN VARIABLES FOR BATTERY RECYCLING



As the scenario inputs change over time, number of possible results increases

INPUT VARIABLES	Mean Within Highlighted Box	Mean Across All Results
Recovery of EV Batteries *	0.57	0.45
EV Sales *	1.51	1.05
Battery Share NCA *	0.47	0.52
Battery Share NMC622 *	0.48	0.2
Battery Share NMC811 *	0.47	0.53
Recycling Time (months)	0.74	0.54
EV Battery Size (kWh/EV)	75.3	74.7

* Fraction of Baseline Scenario

The LIBRA model's user interface allows for real-time evaluation of the sensitivity of model results. The most significant factors that affect availability of cobalt available from recycling are:

- Recovery of EV Batteries
- EV Sales
- Battery Chemistry

LIBRA LOOKS TOWARDS THE FUTURE

Accomplishments:

- Developed a user interface that allows real-time evaluation of:
  - sensitivity of model factors
  - model runs
- Identified the most significant factors affecting the availability of cobalt from recycling:
  - EV Battery Recovery
  - xEV Sales
  - Battery Chemistry

Future Work:

- Complete LIBRA 1.0 with 3 LIB metals (Co, Li, Ni)
- Add investment and policy modules
- Enhance interface for ease of use, and presentation capabilities

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

IT IS DIFFICULT TO COUNT BATTERIES

Battery Recycling Prize goal is collecting 90% by number

- Prize goal is 9 out of 10 batteries produced delivered to a recycler
  - But battery size varies widely
- Could measure
  - **Number of batteries**
  - **Number of cells**
  - Mass
  - Mass of critical material
  - Battery cost
  - **Energy storage capacity**

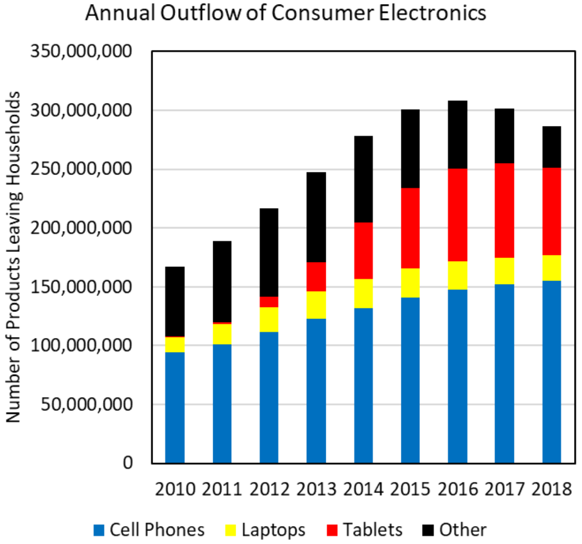
This is one battery.

So is this.

Contact: Jarod Kelly, jckelly@anl.gov

ARGONNE DEVELOPED AN ACCOUNTING METHODOLOGY

- Calculate retirements of product in each year from sales in previous years and product lifetime profiles
- Augment data to consider chemistry type
- Limitations include:
  - Need for sales data
  - Understanding of device/battery retirement rates
- Consumer electronics dominate numbers
- **Argonne submitted final report December 2019***
- Next steps would be to detail outflows, on count, capacity, and chemistry bases, using more granular data sets



* "Proposed Methodology for Assessing the Quantity of Available Lithium-ion Batteries for Recycling in the United States". (2019) Jarod C. Kelly, David Gohlke, Linda Gaines, Michael Wang.

MODELING AND ANALYSIS – ACCOMPLISHMENTS AND RESULTS

Research is steered in most promising directions

- EverBatt performs technical and economic analysis for projects that work
  - Ensures environmentally-sound, economic processes are developed
  - Enables down-select to minimize scale-up costs Completed preliminary analysis of relithiation processes
- Supply chain analysis and LIBRA model tracks material flows and prices
  - Identifies potential material supply constraints
  - Identifies important parameters to lever material prices
- Battery quantification methodology will enable Recycling Prize administrators to estimated percent recoveries potentially achieved by awardees

For more information please see www.recellcenter.org, where our Quarterly Reports are posted.

COLLABORATION AND ACKNOWLEDGEMENTS

Support for this work from the Office of Vehicle Technologies, DOE-EERE, is gratefully acknowledged –

Samm Gillard, Steven Boyd, and David Howell

Shabbir Ahmed (Argonne)
Yaocai Bai (ORNL)
Ilias Belharouak (ORNL)
Ira Bloom (Argonne)
Anthony Burrell (NREL)
Zheng Chen (UCSD)
Jaclyn Coyle (NREL)
Qiang Dai (Argonne)
Sheng Dai (ORNL)
Erik Dahl (Argonne)
Zhijia Du (ORNL)
Alison Dunlop (Argonne)
Jessica Durham (Argonne)
Kae Fink (NREL)
Tinu Folayan (MTU)
Linda Gaines (Argonne)
Daniel Inman (NREL)
Andy Jansen (Argonne)

Sergiy Kalnaus (ORNL)
Jarod Kelly (Argonne)
Matt Keyser (NREL)
Greg Krumdick (Argonne)
Jianlin Li (ORNL)
Albert Lipson (Argonne)
Huimin Luo (ORNL)
Josh Major (NREL)
Margaret Mann (NREL)
Tony Montoya (Argonne)
Helio Moutinho (NREL)
Nitin Muralidharan (ORNL)
Andrew Norman (NREL)
Lei Pan (MTU)
Anand Parejiya (ORNL)
Kyusung Park (NREL)
Bryant Polzin (Argonne)
Kris Pupek (Argonne)

Vicky Putsche (NREL)
Seth Reed (Argonne)
Bradley Ross (Argonne)
Shriram Santhanagopalan (NREL)
Jeff Spangenberger (Argonne)
Venkat Srinivasan (Argonne)
Darlene Steward (NREL)
Nathaniel Sunderlin (NREL)
Jeff Tomerlin (NREL)
Steve Trask (Argonne)
Jack Vaughey (Argonne)
Yan Wang (WPI)
Dustin Weigl (NREL)
Olumide Winjobi (Argonne)
Panpan Xu (UCSD)
Zhenzhen Yang (Argonne)
Jiuling Yu (NREL)
Ruiting Zhan (MTU)

RECELL RECYCLING TOWN HALL

FRIDAY, JUNE 5, 2020 FROM 1:00 TO 3:00 (CENTRAL)

To continue the discussion the ReCell team will hold an interactive town hall meeting.

Please join us at the BlueJeans session shown below and ask questions through Slido

Take a picture of this slide

For Information about ReCell

BlueJeans Meeting Access information

Computer
https://bluejeans.com/749203749/9534?src=htmlEmail

Phone
(866) 226-4650
Meeting ID: 749 203 749

Slido Q/A website

Computer or Smart Phone
www.Slido.com

Event Code
"recell"

ReCell ADVANCED BATTERY RECYCLING

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