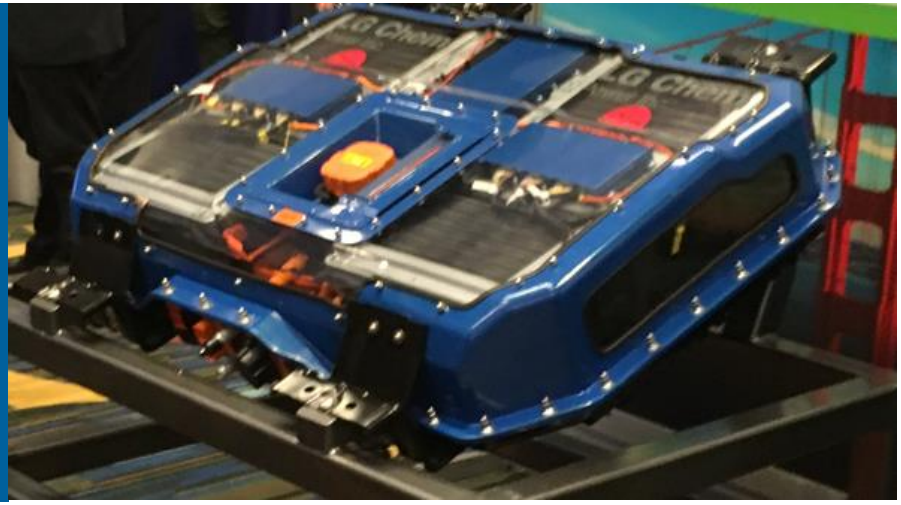
LITHIUM ION BATTERY MATERIAL SUPPLY AND RECYCLING ISSUES



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IEA/HEV Task 40

CRM4EV

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MATERIALS CAUSE A SIGNIFICANT FRACTION OF EV IMPACTS

The battery represents the biggest bump over ICEs

- LCA and related studies characterize the current situation
  - Impacts per unit from production, transport, use, and final disposition of materials and products
  - Competition with other material uses for limited supply
  - Origin in politically sensitive areas
  - Policies affecting material supply
- Analysis also examines longer-term material supply issues
  - Opportunities to improve processes and reduce impacts and material demand
  - Demand projections vs. limited reserves
  - Alternative designs, substitute materials to mitigate shortages
- Proactive thinking can enable leapfrog
  - China planned ahead for EV material dominance
  - US still has significant opportunities (example: lithium metal)

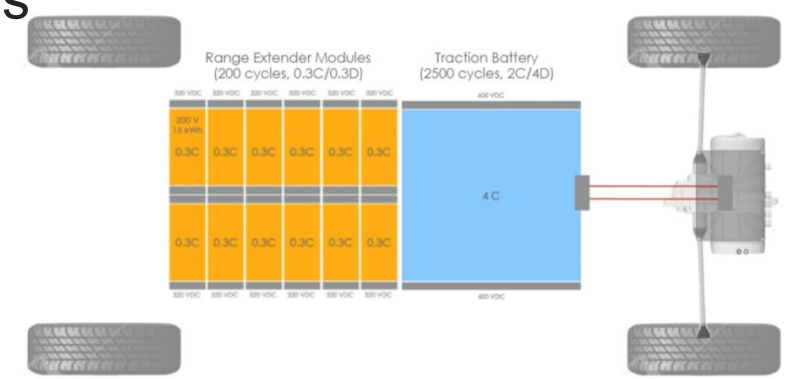
IT PAYS TO LOOK AT WHAT'S AROUND THE BEND

- US and EU did not invest in EV supply chain until China was well ahead
- Perhaps we can learn to think farther ahead
- High risk, high reward may apply here

ELECTRIFICATION WILL REQUIRE HUGE QUANTITIES OF MATERIAL

Demand derives from powertrain shift, population growth, and rising living standard

- Existing supply chains are inadequate and unstable
  - On a finite planet, there is no such thing as sustainable growth
  - Disruptions happen from pandemics and war
  - New sources of materials are being explored
- Recycling can make a major contribution after demand growth slows
- Shorter vehicle range would help alleviate shortages
  - Smaller batteries use less material and energy
  - Cost less
  - Can be charged quickly to 80%
  - Can accommodate most trips
    - For occasional long trips, rent a vehicle or auxiliary battery
  - Can we overcome the idea that bigger is better?



- Use of domestic materials could reduce conflict from competition for materials
- Alternative materials, technologies, and lifestyles should be explored

ALTERNATIVE ANODES: LI METAL

Rapid expansion could enable US to be a long-term leader as market grows

- Additional Li metal capacity will be needed
- US is a player in this arena
- US does have Li reserves
  - Can supply our own needs, but cost uncertain
  - Geothermal brine coproduction lab call issued
- 100's of 1000's of tons may be needed, vs. current 5000 T (Li^0) market*
  - Larger demand if solid state batteries succeed
- Need better technology, on large scale
- **US has potential to get ahead of the curve on Li metal**
  - Can control our entire Li metal supply chain

	2020 BG Li Metal Capacity	2050 BG Li Metal Demand
US	0.55	--
World	2.5	1,000

Units: 1000 metric tons

* Half of Li metal is battery grade

GEOTHERMAL LITHIUM PRODUCTION REQUIRES TITANIUM

Li-containing brines are extremely corrosive

- Ti metal has superior strength-to-weight ratio and corrosion resistance
- US has minimal reserves of titanium minerals
- In 2020, 2 US companies extracted titanium from minerals or tailings
  - Others were idled
- About 90% goes to TiO_2 pigment
  - Coatings and aircraft bodies use much of the rest
- US production in 2020 was 100,000 T, imports 780,000 T
  - Sources: South Africa, 39%; Australia, 20%; Madagascar, 10%; Mozambique, 9%; other, 22%
- China dominates production and reserves
  - Australia and Canada also have large reserves
- Argonne will further investigate the titanium supply chain

WHY LFP IS INTERESTING

- It could be made with all domestic materials
  - No need to worry about sourcing Co and Ni
- It is cheaper and safer than NMC
- New designs like BYD Blade compensate for lower energy density
  - And I don't think you need a 400 mile range
- It can be directly recycled at low cost and with low impacts

PHOSPHOROUS COULD BE IMPORTANT

US does have domestic phosphate rock

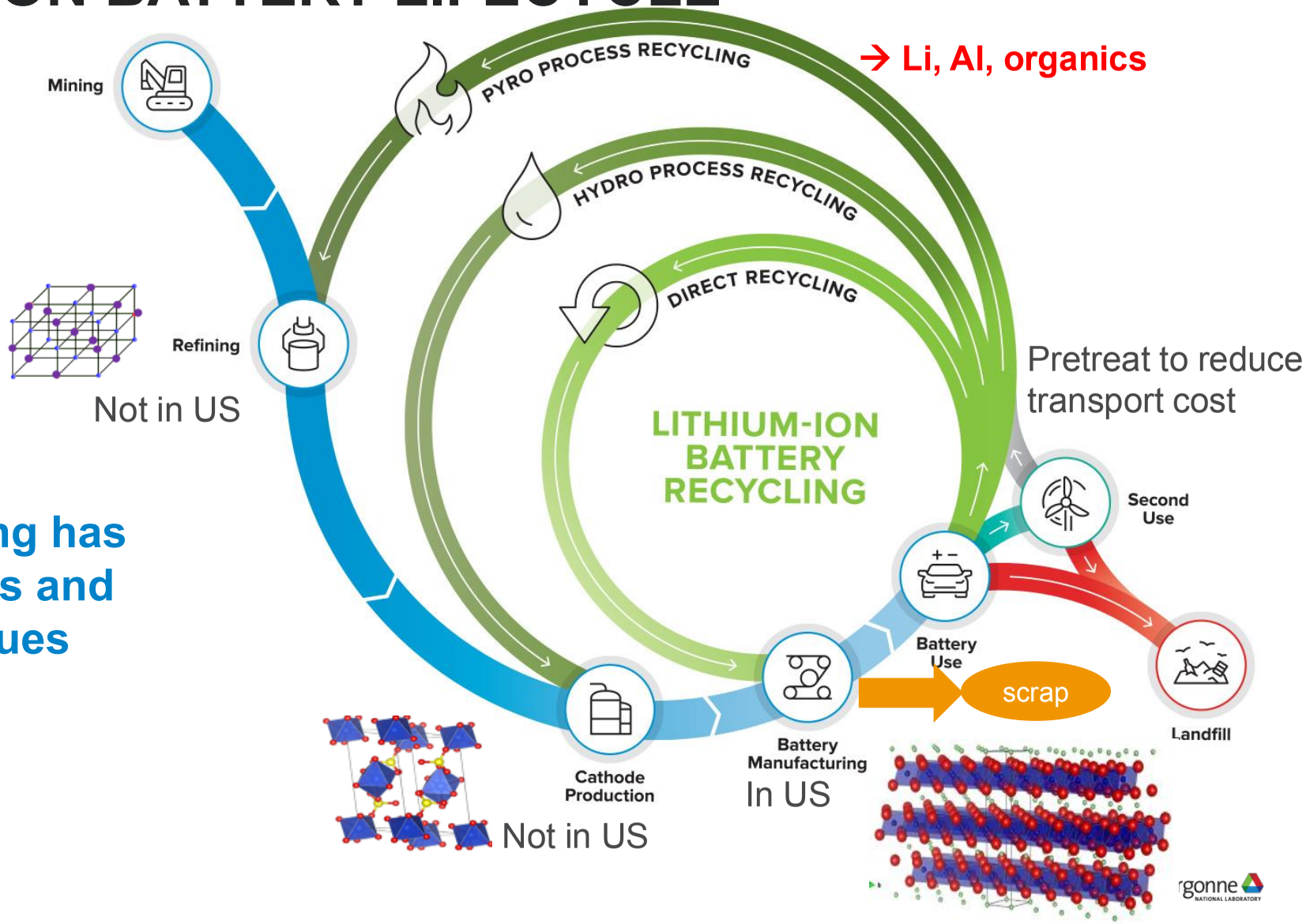
- EU classifies P as critical, with reserves but minimal production in Finland
- Major use is agricultural
- US also produces pure phosphoric acid
  - Precursor for LFP
  - Could develop complete domestic supply chain
- Major use for batteries could eventually impact fertilizer market
- There is potential to recover phosphorus lost in agricultural use
  - There would be ecological benefits
  - Research would be needed on methods

Major Phosphate Rock Producers and Reserves (USGS 2022)

Country	Mine Production 2021	Reserves
United States	22,000	1,000,000
China	85,000	3,200,000
Morocco	38,000	50,000,000
Russia	14,000	600,000
World Total	**220,000**	**71,000,000**

Units: 1000 metric tons

LITHIUM-ION BATTERY LIFECYCLE



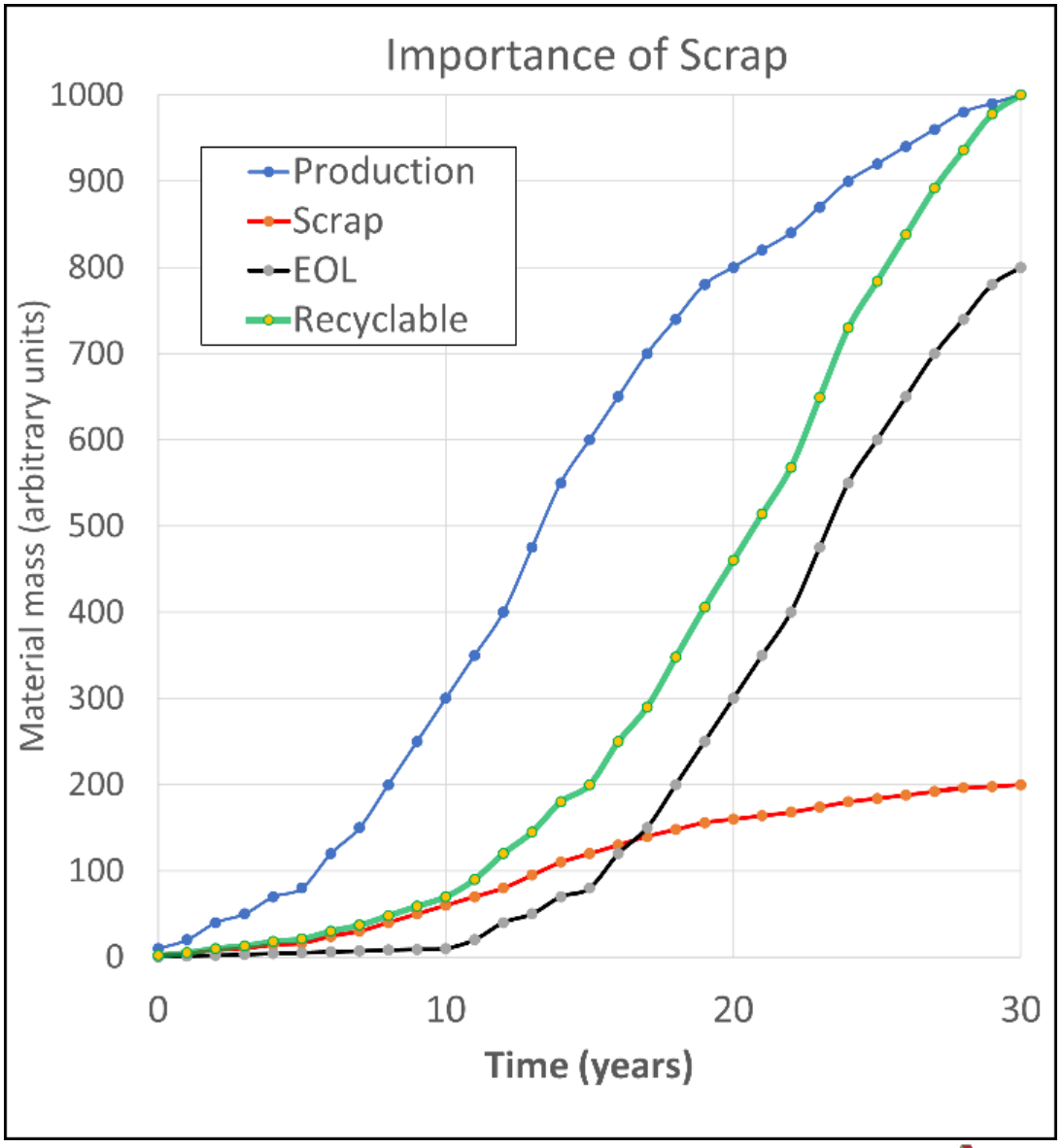
Direct recycling has lowest impacts and highest revenues

WHAT IS RECOVERED DURING LIB RECYCLING?

Process	Mechanism(s)	Recovered	Lost
Pyrometallurgy	High-T heat	Mixed alloy of cobalt, nickel, and copper	Lithium, aluminum, crystal structure, organics
Hydrometallurgy	Acid	Cathode precursors, copper, aluminum, some lithium	Crystal structure, some lithium, organics
Direct Recycling	Mechanical, solvents, mild heat	Cathode, anode, electrolyte, copper, aluminum	separator

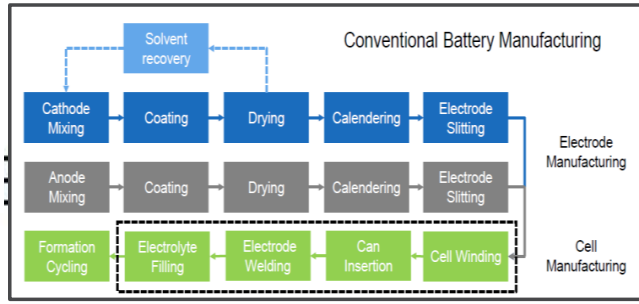
NEW RECYCLING PLANTS' MAIN FEED IS PRODUCTION SCRAP

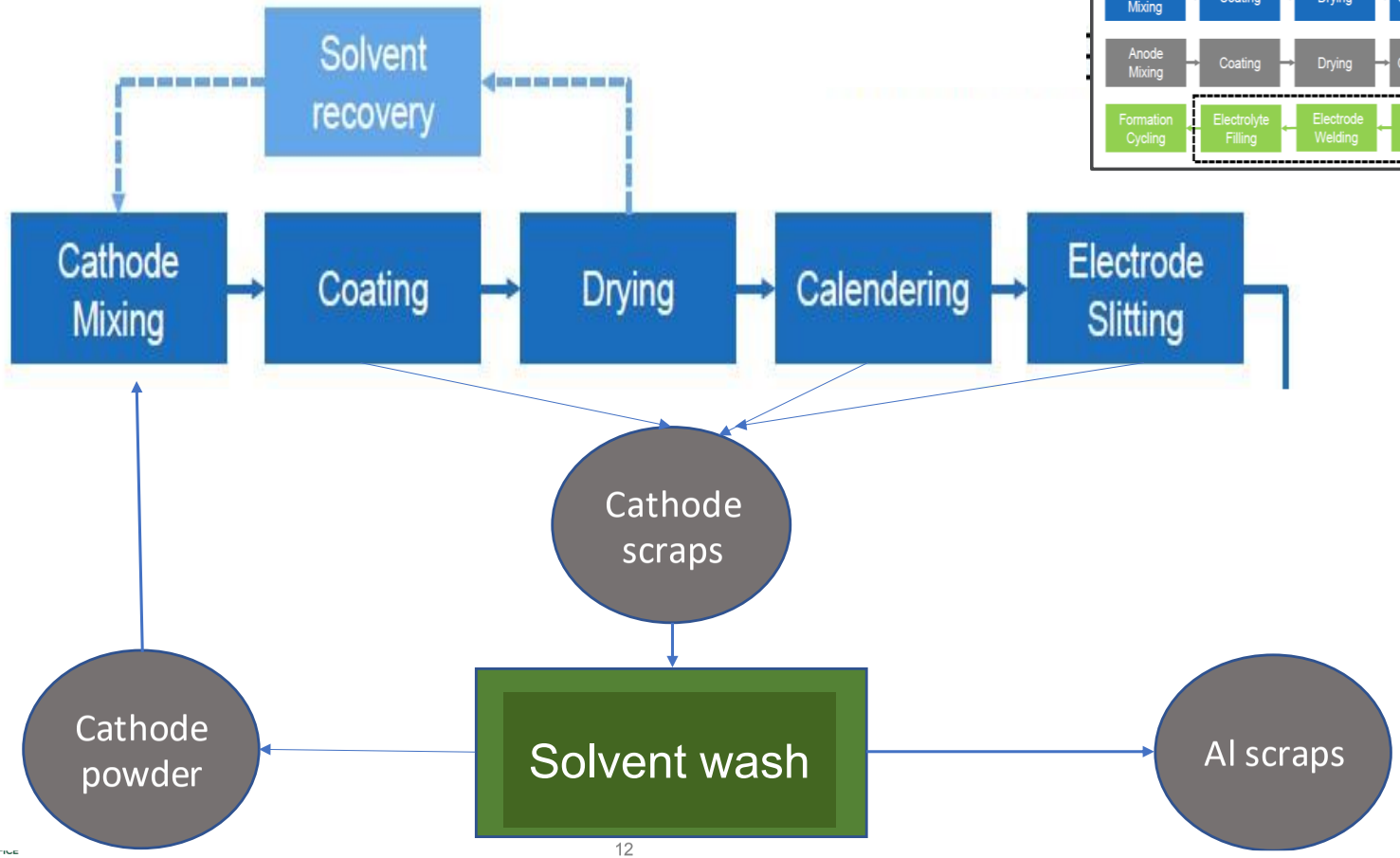
Artifact of rapid growth



AFTER SIMPLE PROCESSING, SCRAP CAN RETURN TO MANUFACTURING

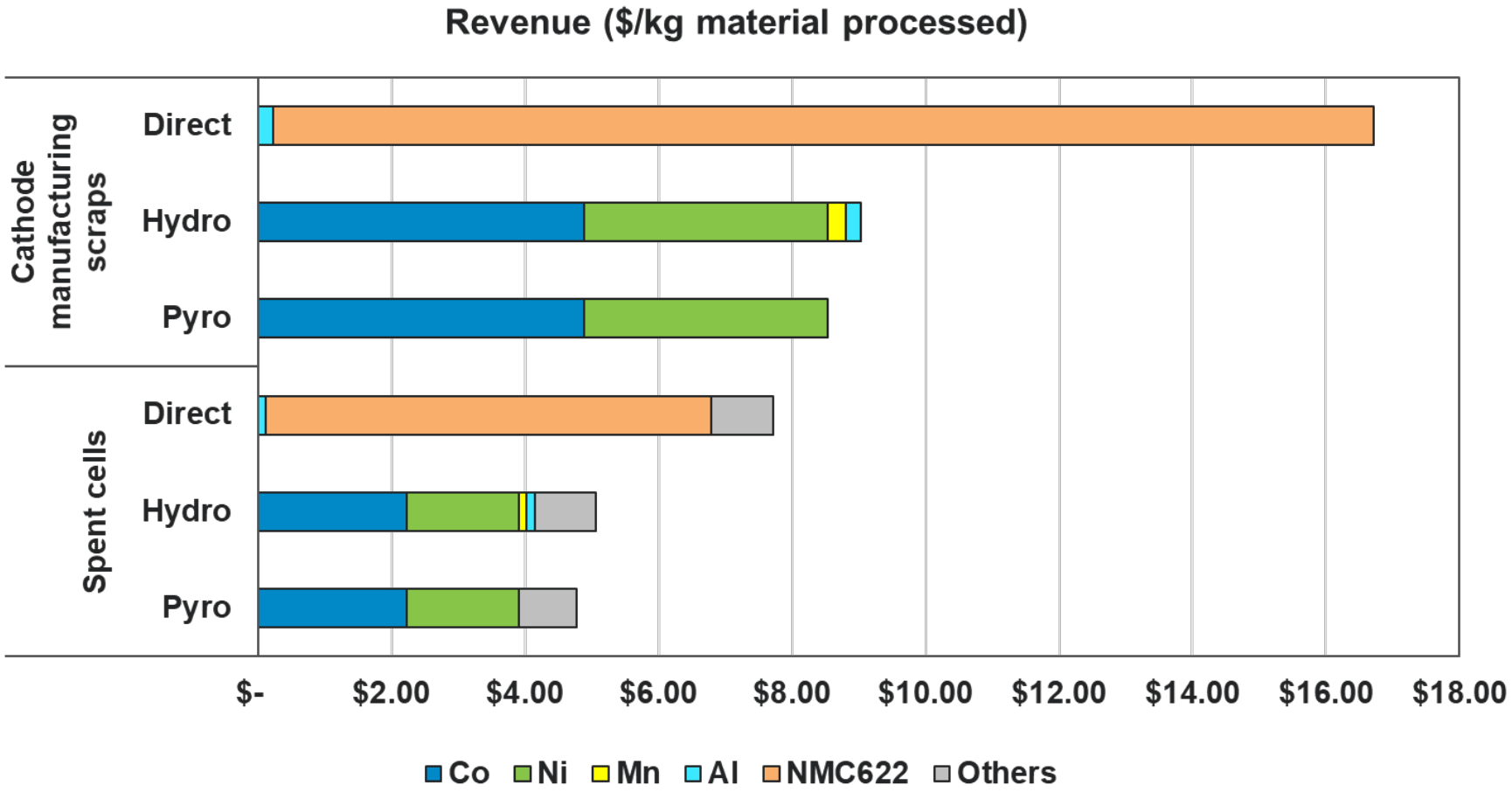
Need to compare to full recycle loop





EVERBATT SHOWS DIRECT RECYCLING IS PROMISING

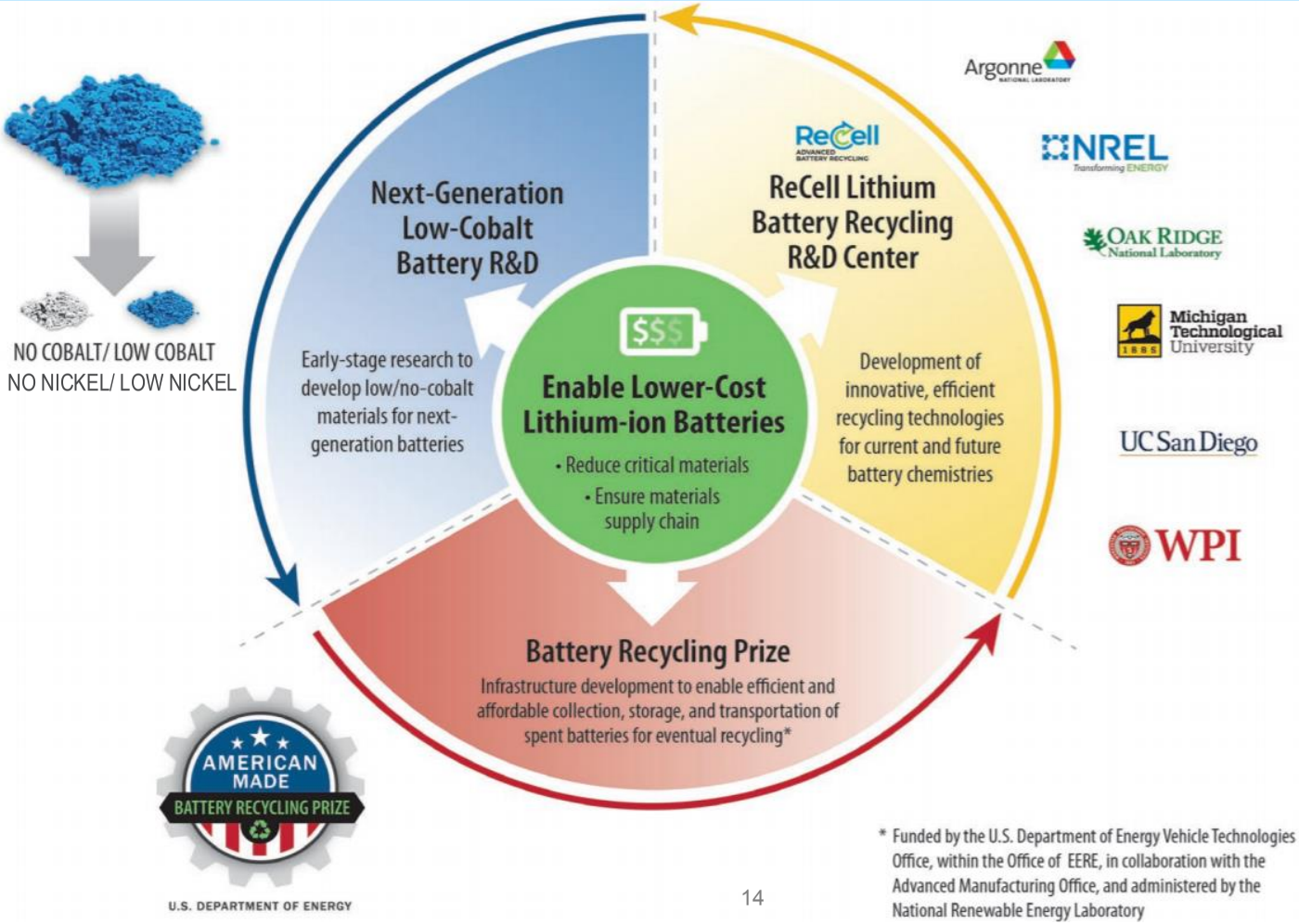
Direct recycling maximizes revenues and also minimizes impacts



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

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.

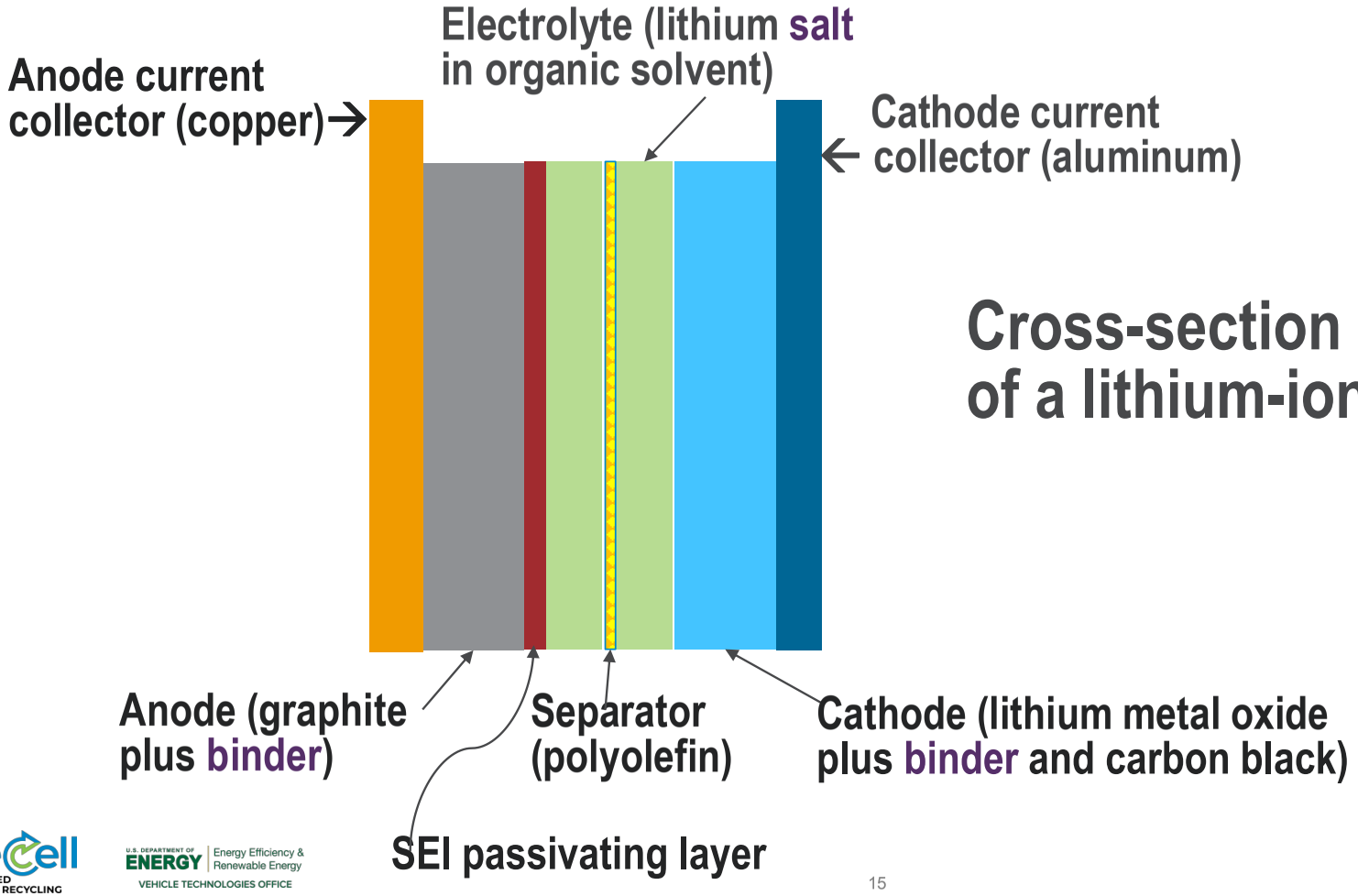


Argonne leads ReCell's $5+ million/y collaboration of 3 national labs and 3 universities, funded in 2019 by Vehicle Technology Office to develop a viable recycling process.

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

PROCESSING REQUIRES MANY SEPARATIONS

Commercial technologies lose some of the materials



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

ELECTROLYTE RECOVERY FAVORED OVER DISPOSAL

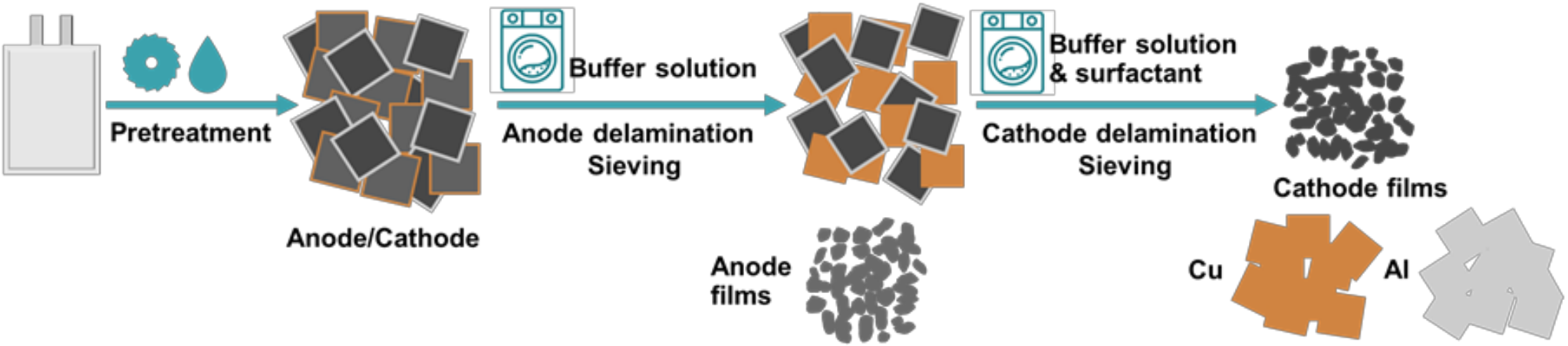
	Electrolyte Recovered	Dispose of Rinse Solvent
DEC consumed	0.1 kg/kg	1 kg/kg
Cost of disposal ($0.50/kg)	$0.05/kg	$0.50/kg
Cost to recycle 1 kg of cells	$4.05/kg	$5.42/kg
Estimated Revenue	$10.60/kg	$10.20/kg
Estimated Profit	$6.55/kg	$4.78/kg

- The cost to concentrate the output electrolyte is small ($0.13/kg)
- Significant savings can be had by reusing the DEC ($0.90/kg)
- Recovery of electrolyte increases profit by $1.77/kg
- Disposal costs could be a major factor

AQUEOUS SEQUENTIAL SEPARATION AVOIDS MIXING ELECTRODE POWDERS

Most recycling processes produce black mass as intermediate

- Buffer solution first separates anode films from the mixed shreds
- Surfactants added to delaminate cathode film from aluminum foil
- Process reclaims high-purity active materials
- One-pot system has high separation efficiency and low cost.



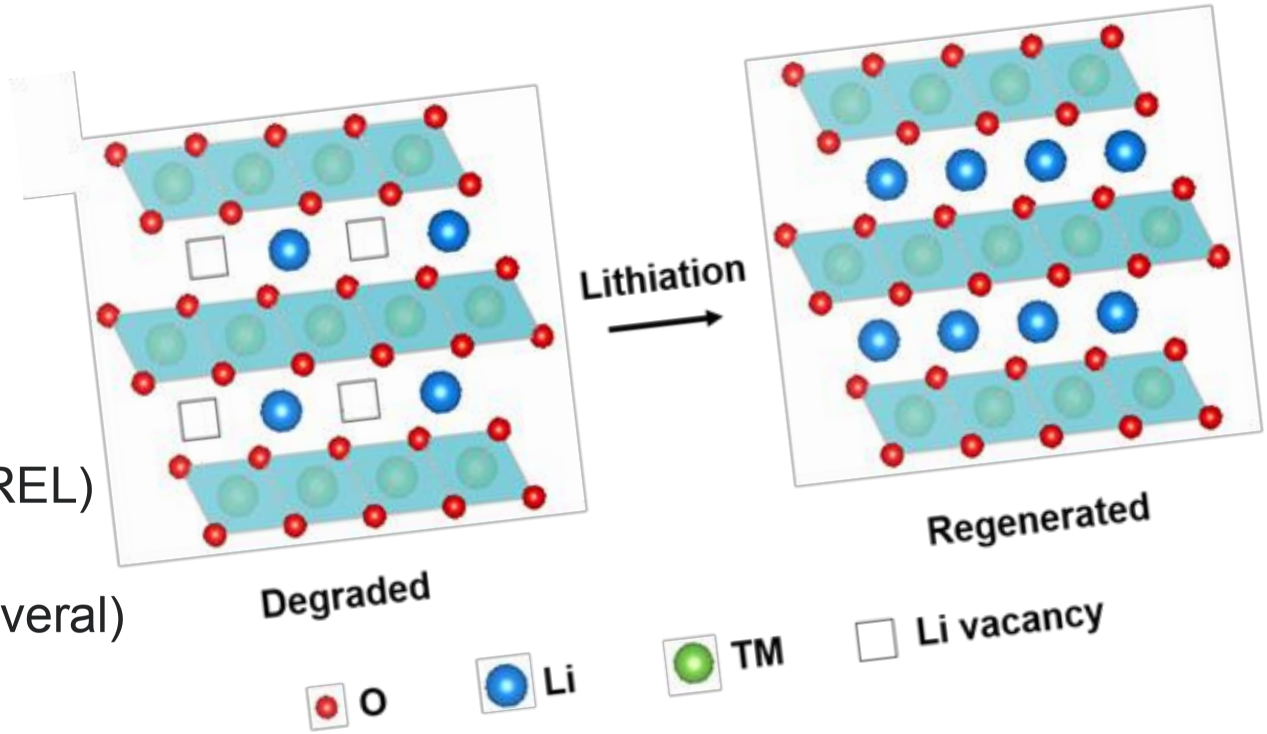
Courtesy Oak Ridge National Laboratory

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.

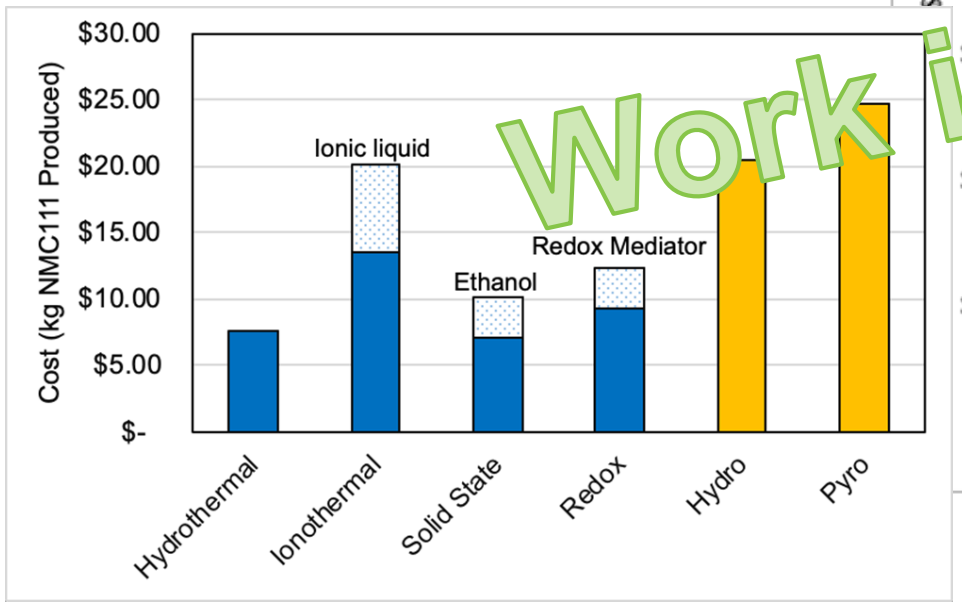
- **Relithiation**
  - Electrochemical (NREL)
  - Solid State (Argonne)
  - Hydrothermal (UCSD)
  - Ionothermal (ORNL)
  - Redox Mediated NREL)
  - Roll to Roll Processing (NREL)
- **Upcycling**
  - Compositional Change (several)

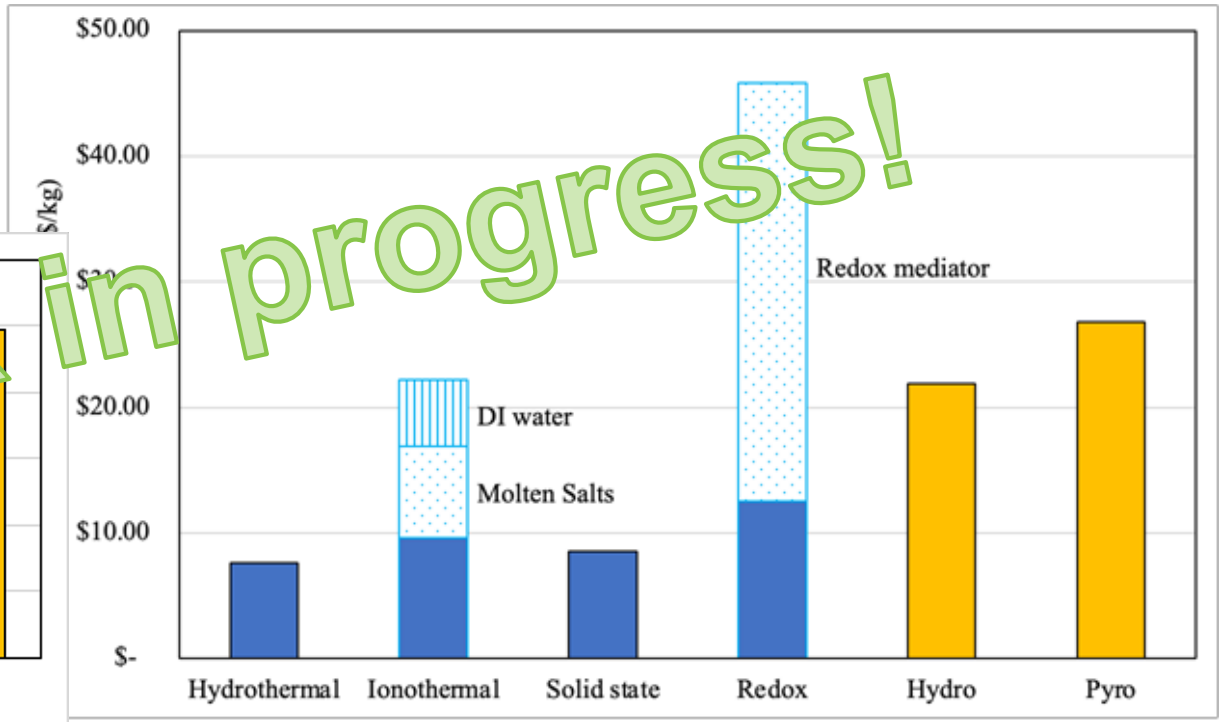


EVERBATT MAPS PROCESS EVOLUTION

Identifies pressure points to improve processes under development

Earlier results





Work in progress!

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.

ReCell ADVANCED BATTERY RECYCLING

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

TECHNICAL ACCOMPLISHMENTS

- Recovered usable cathode from spent cells and scrap
  - Made working cells
- ~40 papers, ~20 patents in process
- Dedicated ReCell laboratory space ready for collaboration
- Industry meeting in 2019 provided an opportunity for ReCell and industry stakeholders to exchange challenges and ideas. We will have another!


Thank you!
US Department of Energy, Vehicle Technologies Office
Staff of the ReCell Center