Life-cycles of lithium ion batteries: Understanding impacts from extraction to end-of-life

Extraction → Deployment → End of Life

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Hi! I'm….
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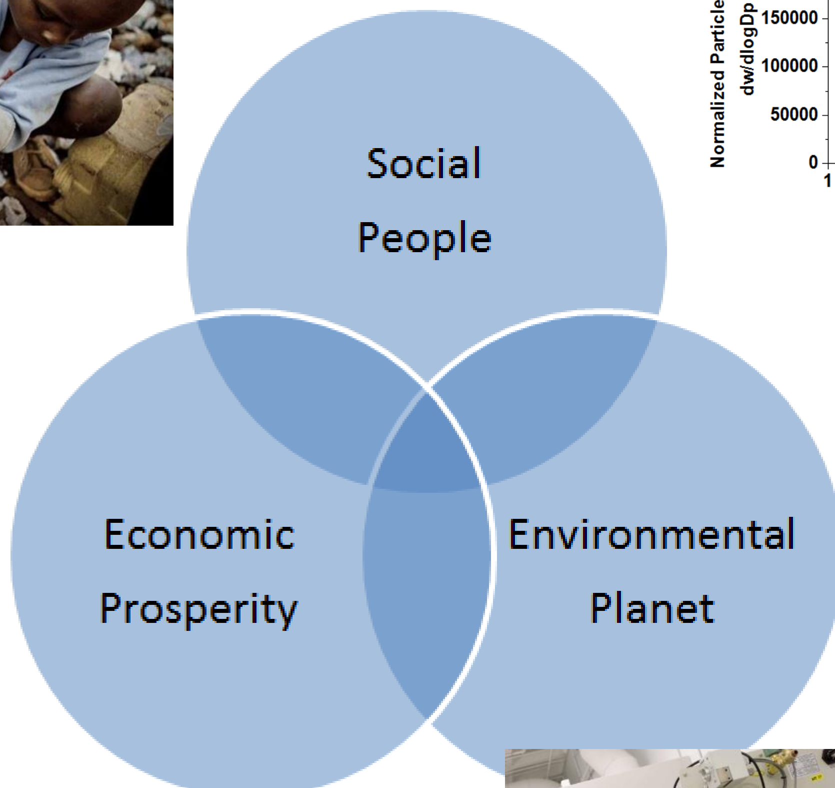
Summary of my research:

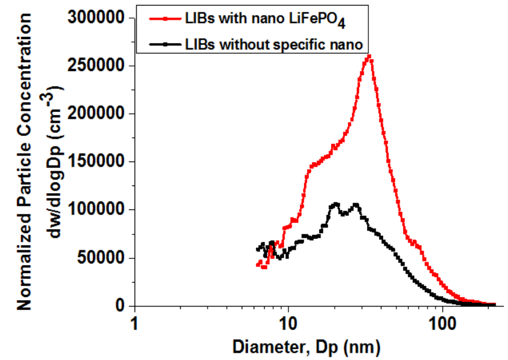
- Quantifying the economic and environmental trade-offs for materials at their end-of-life with a focus on recycling and resource recovery. Recent work emphasizing implications of material scarcity and criticality for clean energy technologies

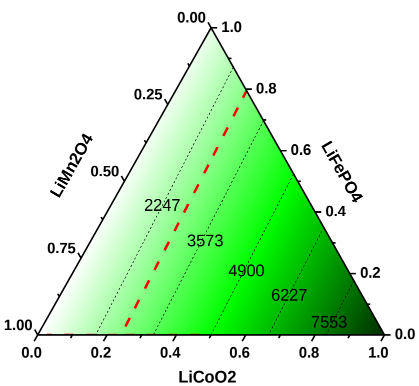
Resources/Skills I can offer	Resources/Skills I could use:
• Material compositional characterization (XRF, ICP-OES) • Environmental impact assessment and material flow analysis (MFA, LCA) • Modelling/Programming (Decision Analysis, Optimization, Simulation)	• Survey design • Mathematical epidemiology • Resource conflict • Commodity trading • Students interested in cross-disciplinary graduate research

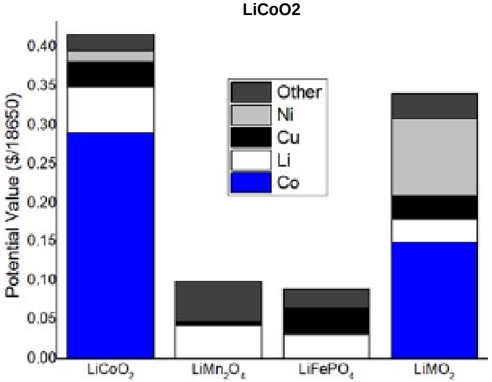
Quantifying sustainability impacts

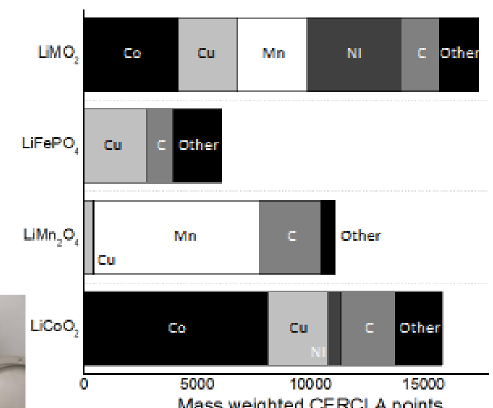
Lithium Ion Batteries (LIBs)



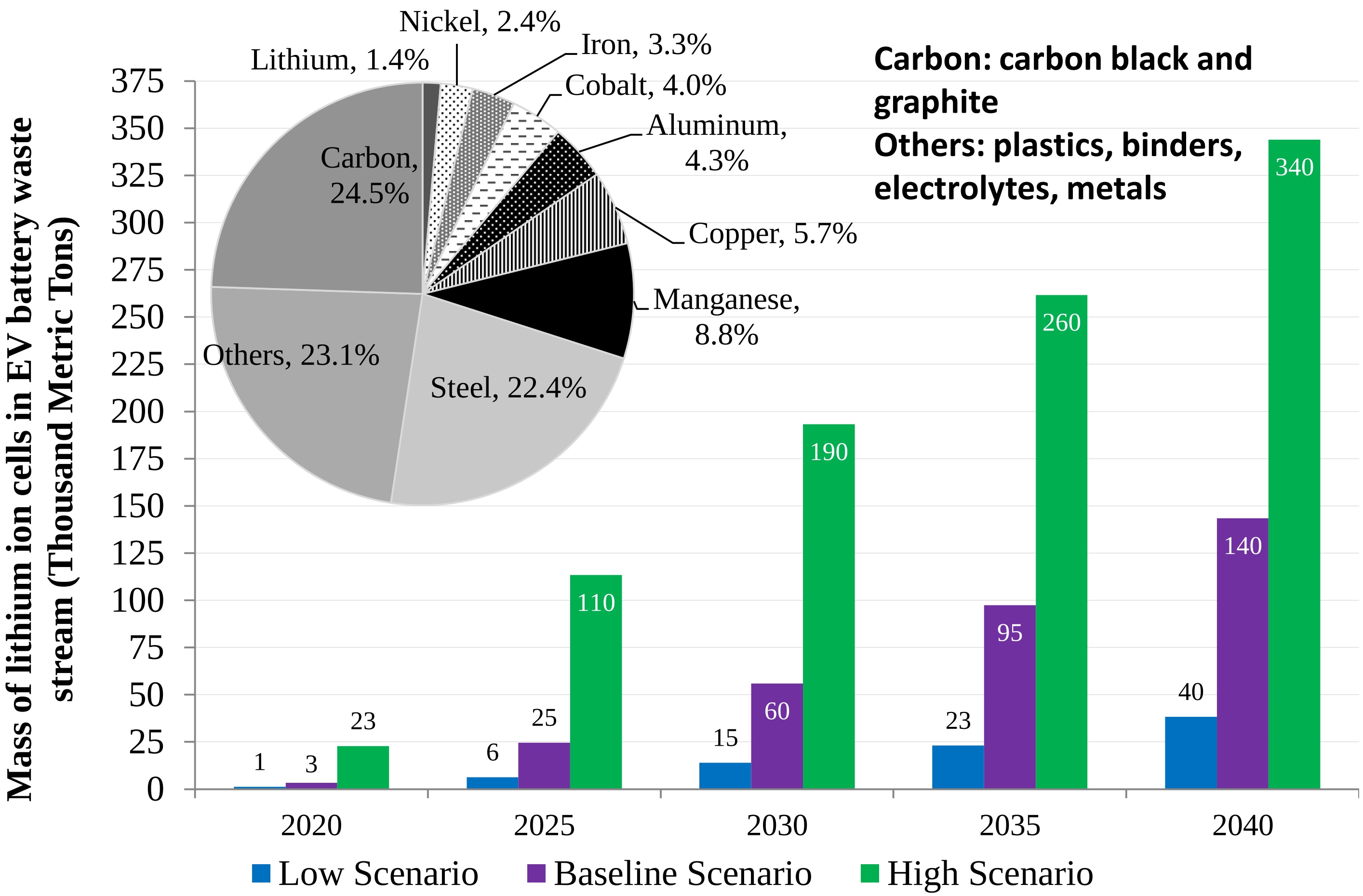








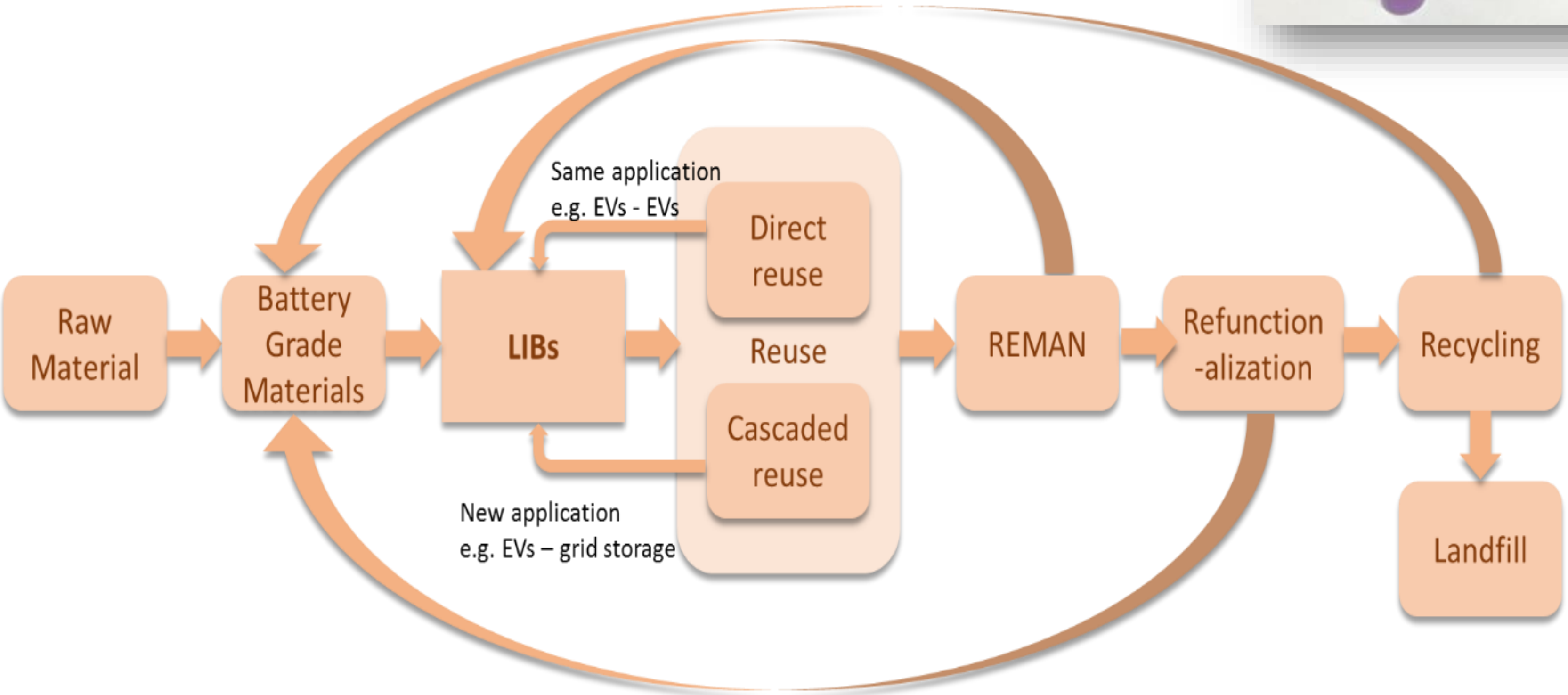
EV LIBs reaching end of life – how much??



A cumulative outflow between 0.30 million metric tons to 4 million metric tons of lithium-ion cells could be generated between 2015 to 2040.

Richa, Babbitt, Gaustad, Wang (2014), A future perspective on lithium-ion battery waste flows from electric vehicles, Resources, Conservation, and Recycling. v 83, 63-76

Options at End of Life



Richa, Babbitt, Gaustad, (2017), Eco-efficiency analysis of LIB waste hierarchy inspired by the circular economy, Journal of Industrial Ecology, forthcoming.

Extraction → Deployment → **End of Life**

REUSE

- Key barriers
  - Liability/Negative PR
  - Proprietary BMS
    - + cooling, CAN bus
  - Supply/Demand Mismatch

Direct Reuse

Peak Shaving

Demand Response

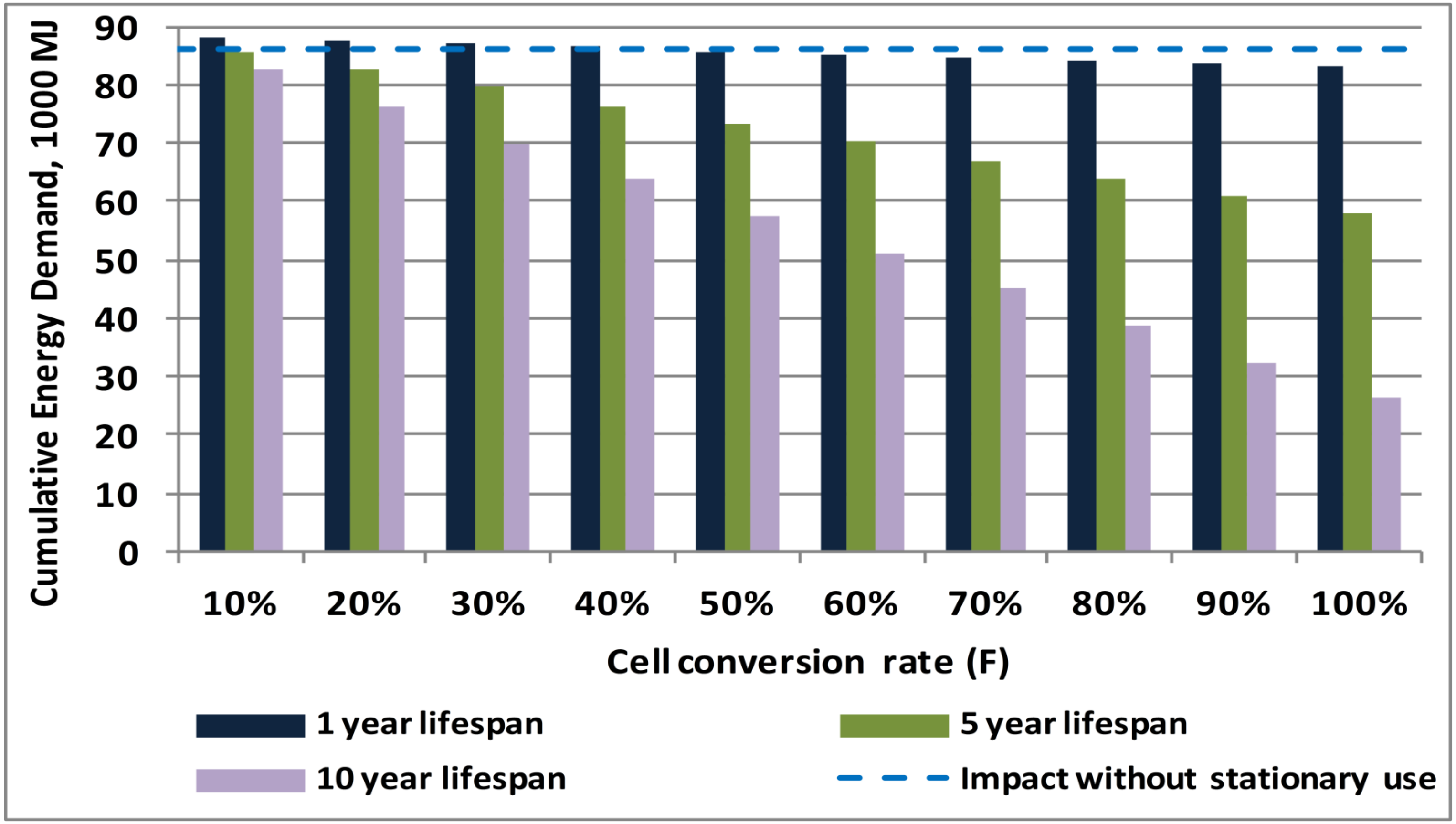
Reserve

Firming

Renewables

MicroGrids

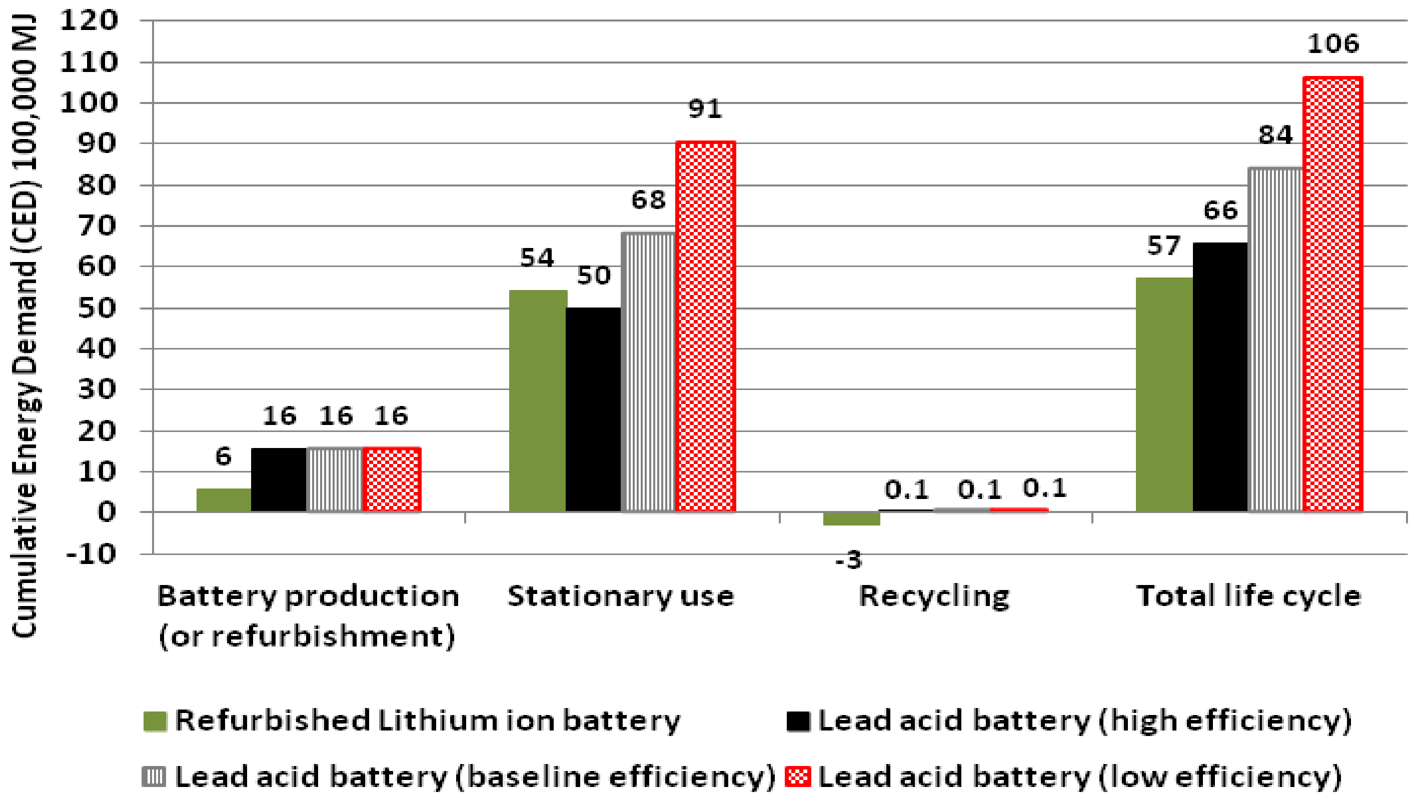
Secondary usage of electric vehicle (EV) batteries



- Reduction in EV Li-ion battery environmental impact in most cases, except in scenarios of extremely low refurbished battery lifespan or cell conversion rate
- Reduction in 0.3 to 69% of impact due to stationary application
- Only < 3% increase in CED in unfavorable cases

Richa, Babbitt, Nenadic, Gaustad (2015), "Environmental trade-offs across cascading lithium-ion battery life cycles", International Journal of Life-cycle Assessment

Secondary usage of electric vehicle (EV) batteries

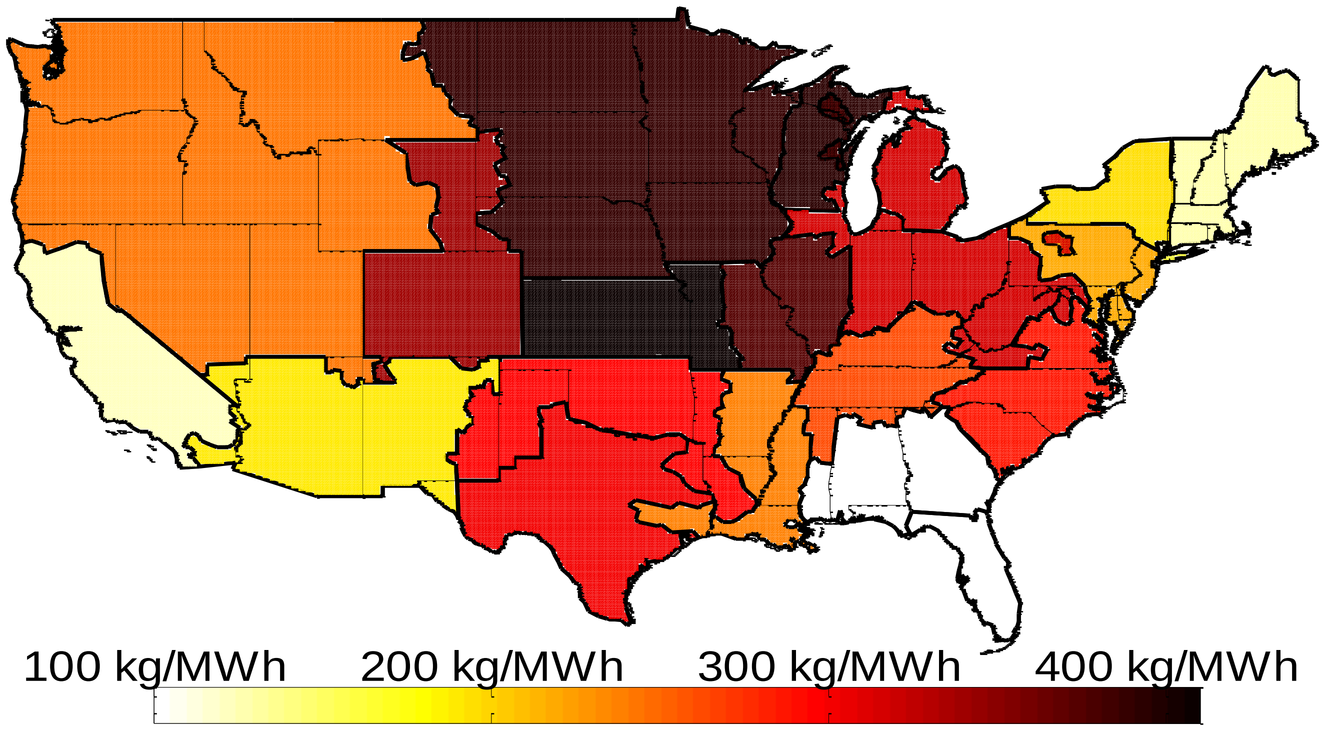


- PbA battery manufacturing impact >double of refurbishing a LIB pack.
- Due to lower efficiency of lead acid battery, use phase impacts can be higher in lead acid battery
- 12% to 46% reduction in CED and GWP impacts

Richa, Babbitt, Nenadic, Gaustad (2015), "Environmental trade-offs across cascading lithium-ion battery life cycles", <u>International Journal of Life-cycle Assessment</u>

Energy storage is…
"green technology" "holy grail for PV & wind"
"renewable energy enabler" "clean tech" …..

- But actually CO_2 emissions from bulk energy storage are significant



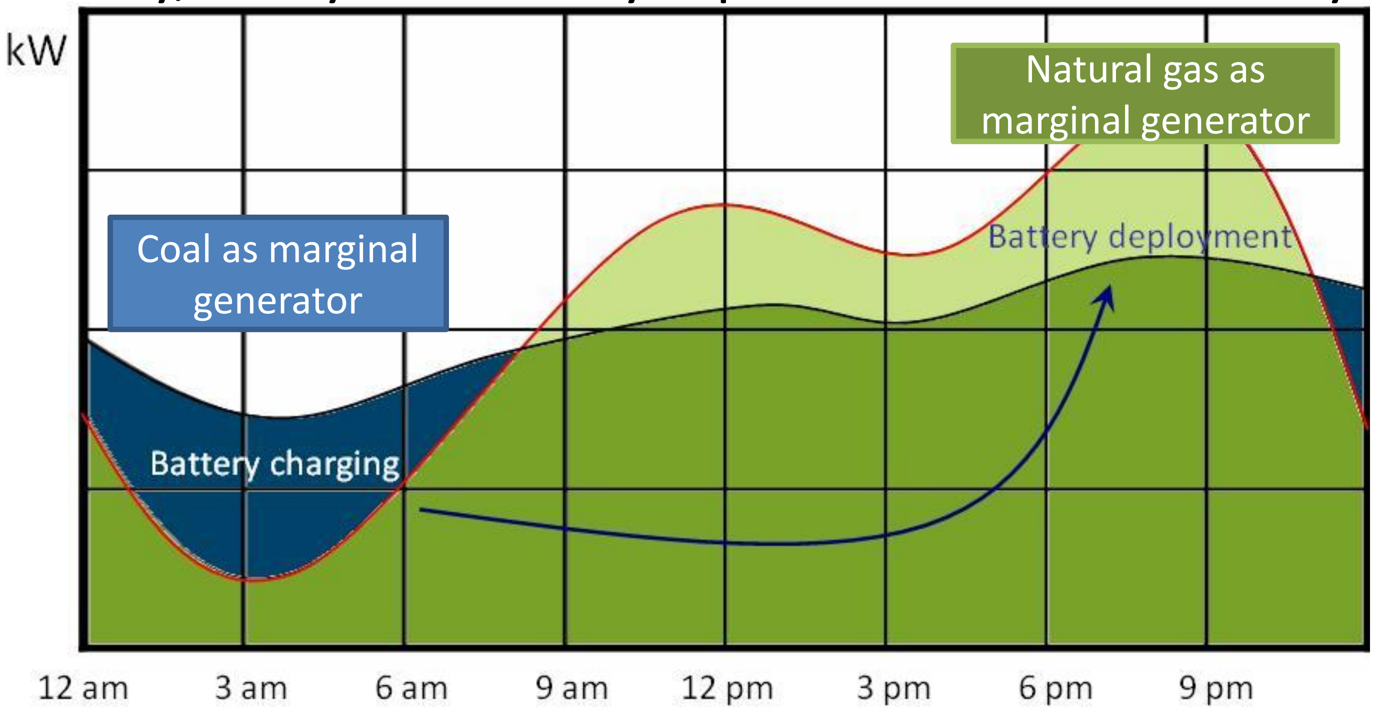
Hittinger and Azevedo, Bulk Energy Storage Increases US Grid Emissions, ES&T 2018

Why?!

Energy arbitrage

– bc $ varies f(time) – buy at night, sell at day

Generally, "dirty" electricity replaces "clean" electricity.



Effect holds for charging from renewables as well!

Grid Integration Key Area

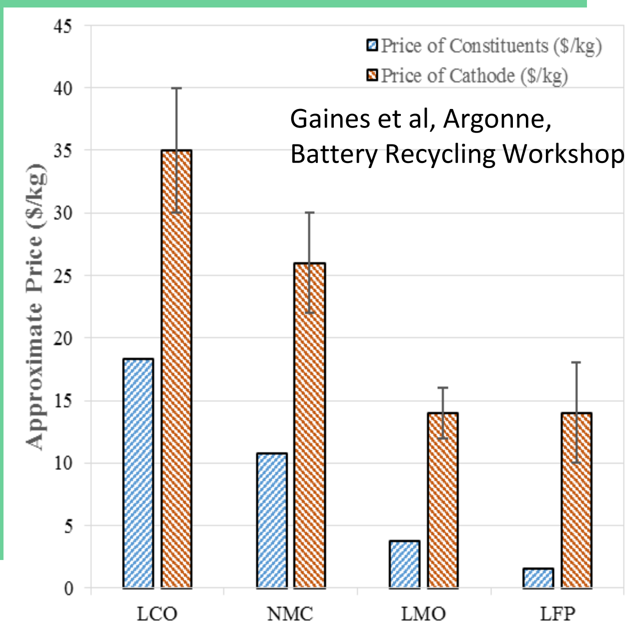
Image: http://greensmith.us.com/applications/peak-shifting

Storage is not 100% efficient – an energy-consuming device

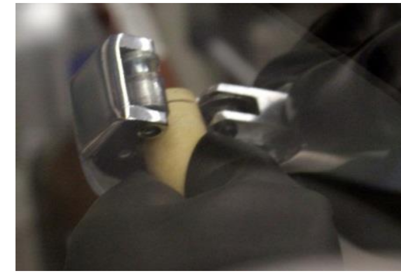
Refunctionalization

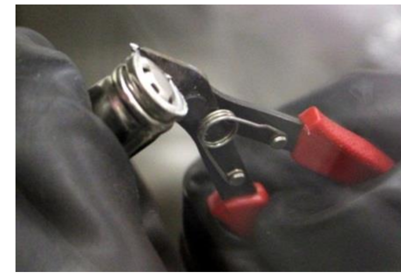
Cathode

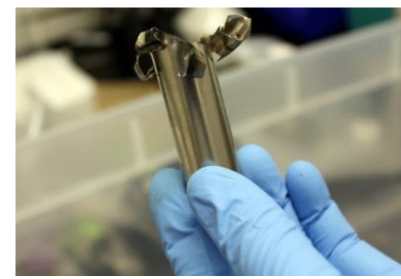
Anode

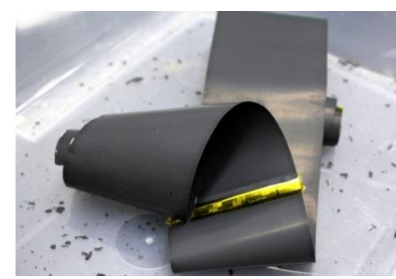


- Key barriers
  - Scale-Up
  - Economics
  - Quality

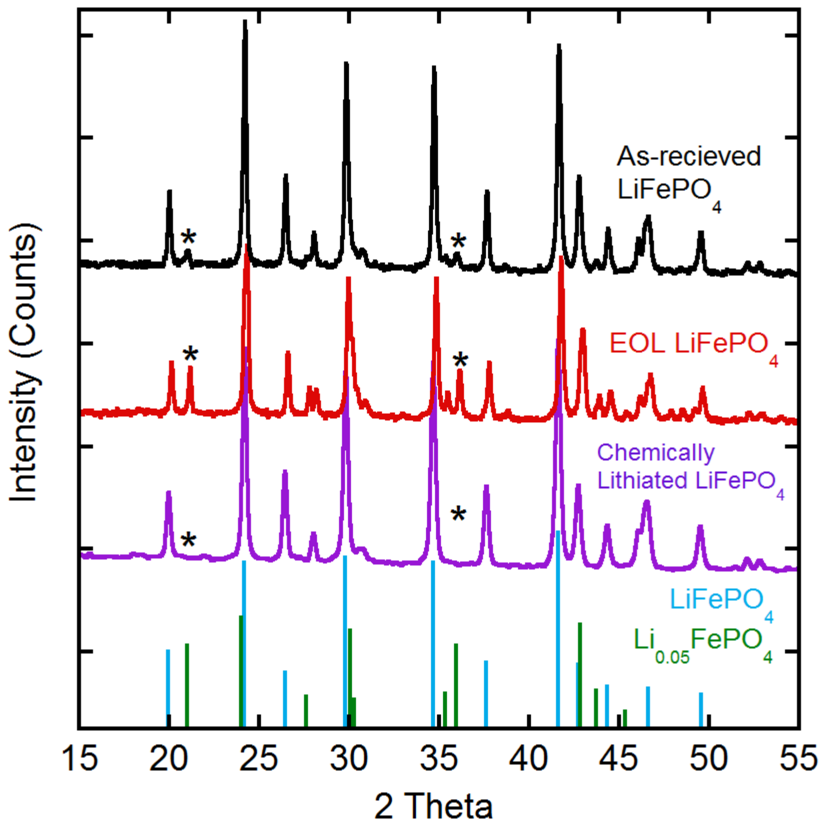


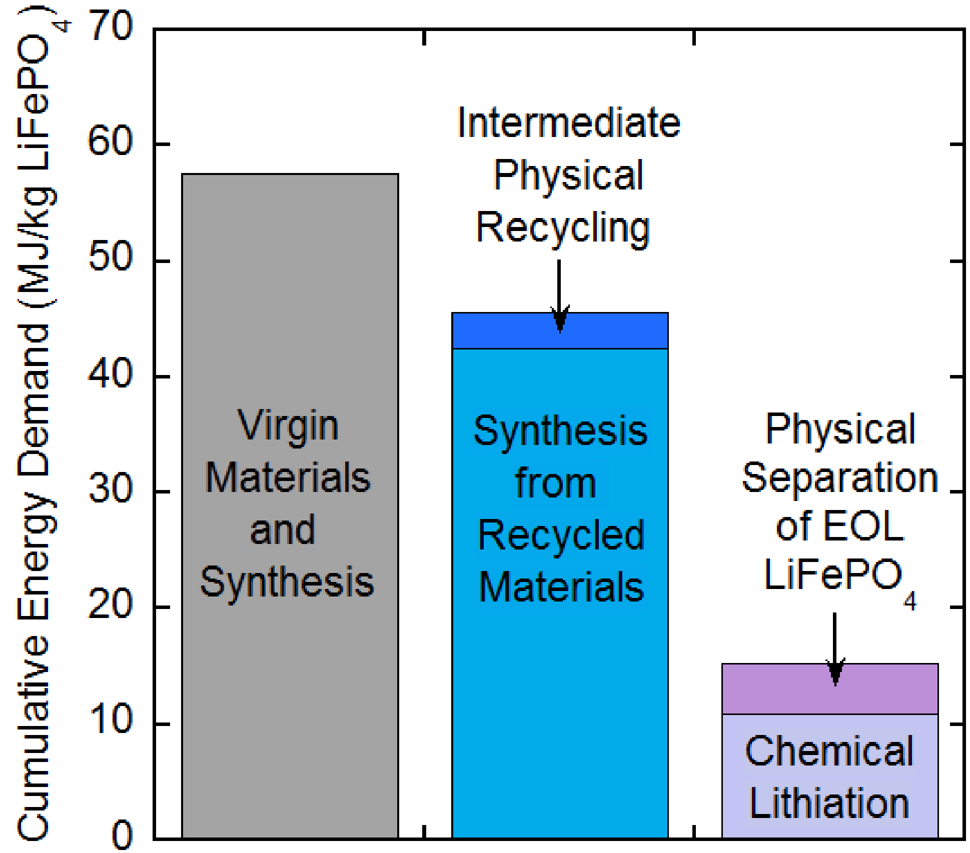






Refunctionalization





<u>Chemical Lithiation of EOL Cathode</u>

A solution based, **more scalable,** chemical lithiation technique was investigated. XRD shows the reduction of peaks associated with delithiated $LiFePO_4$.

$$FePO_4 + LiI \rightarrow LiFePO_4 + 0.5I_2$$

Ganter, M. J., Landi, B. J., Babbitt, C. W., Anctil, A., & Gaustad, G. (2014). Cathode refunctionalization as a lithium ion battery recycling alternative. *Journal of Power Sources*, *256*, 274-280.

RECYCLING

Cobalt

Nickel

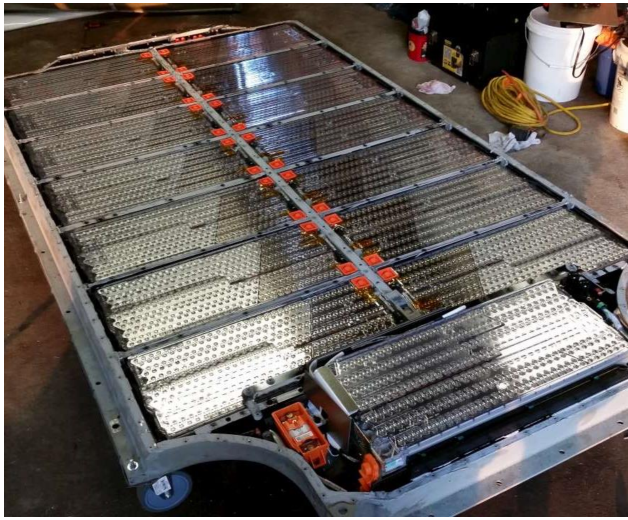
Copper

Lithium

Manganese

Aluminum

- Key barriers
  - Safety
    - transportation regulation
  - Economics
  - Uncertainties
    - Compositional
    - Outflows
  - Collection
  - Infrastructure



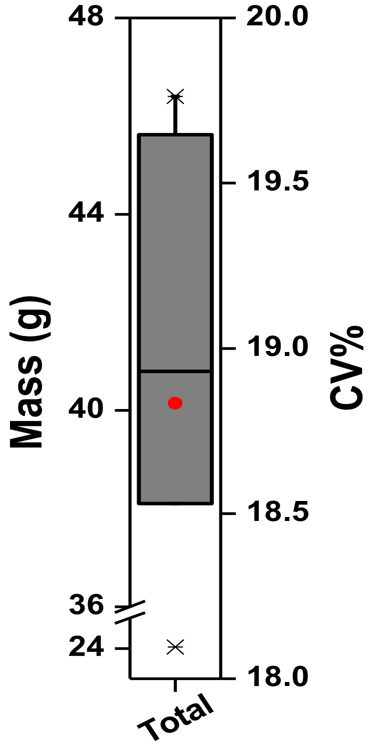
Recycling- multiple approaches

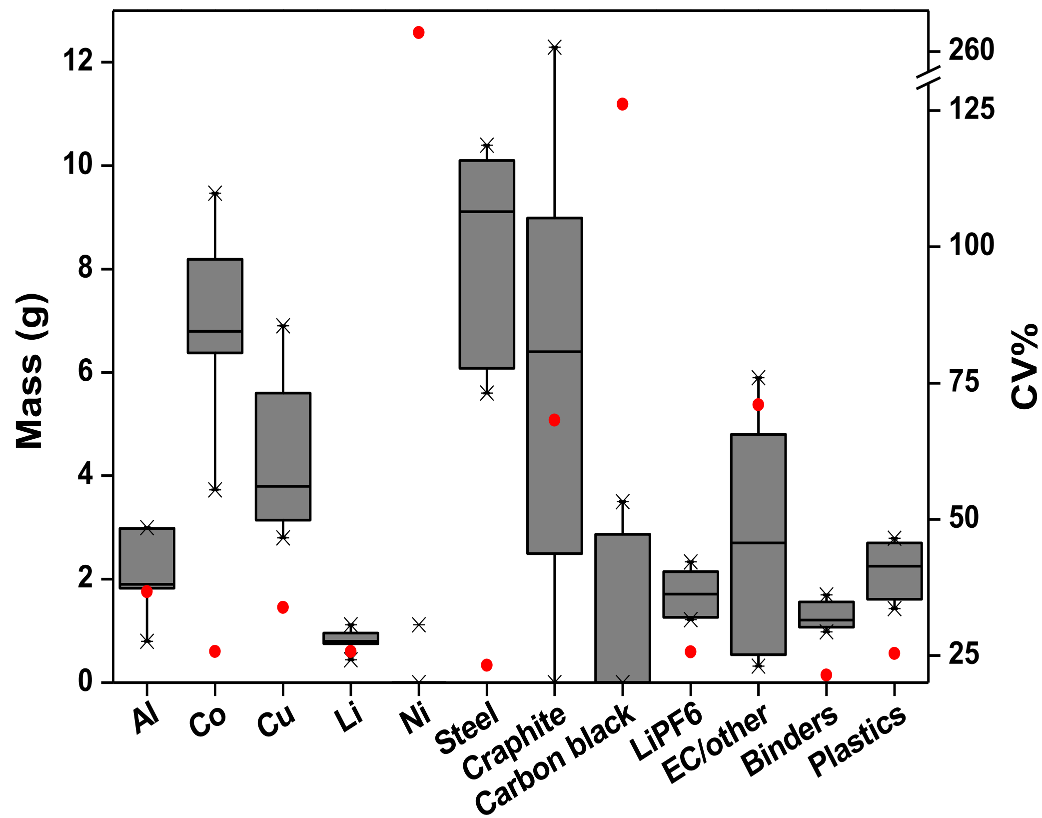
	Pyrometallurgical	Hydrometallurgical	Physical
Temperature	High	Low	Low
Materials recovered	Co, Ni, Cu (**Li and Al to slag**)	Metals or salts, Li_2CO_3 or LiOH	**Cathode**, anode, electrolyte, metals
Feed requirements	None	Separation desirable	Single chemistry required
Comments	New chemistries yield reduced product value	New chemistries yield reduced product value	Recovers potentially high-value materials; Could implement on home scrap

- Table above from Gaines et al, Argonne Battery Recycling Workshop Presentation

Recycling	Energy Consumption	GHG Emission	Hazardous Wastes	Safety
Pre-recycling				
Pyrometallurgical				
Hydrometallurgical				

Compositional variability is high

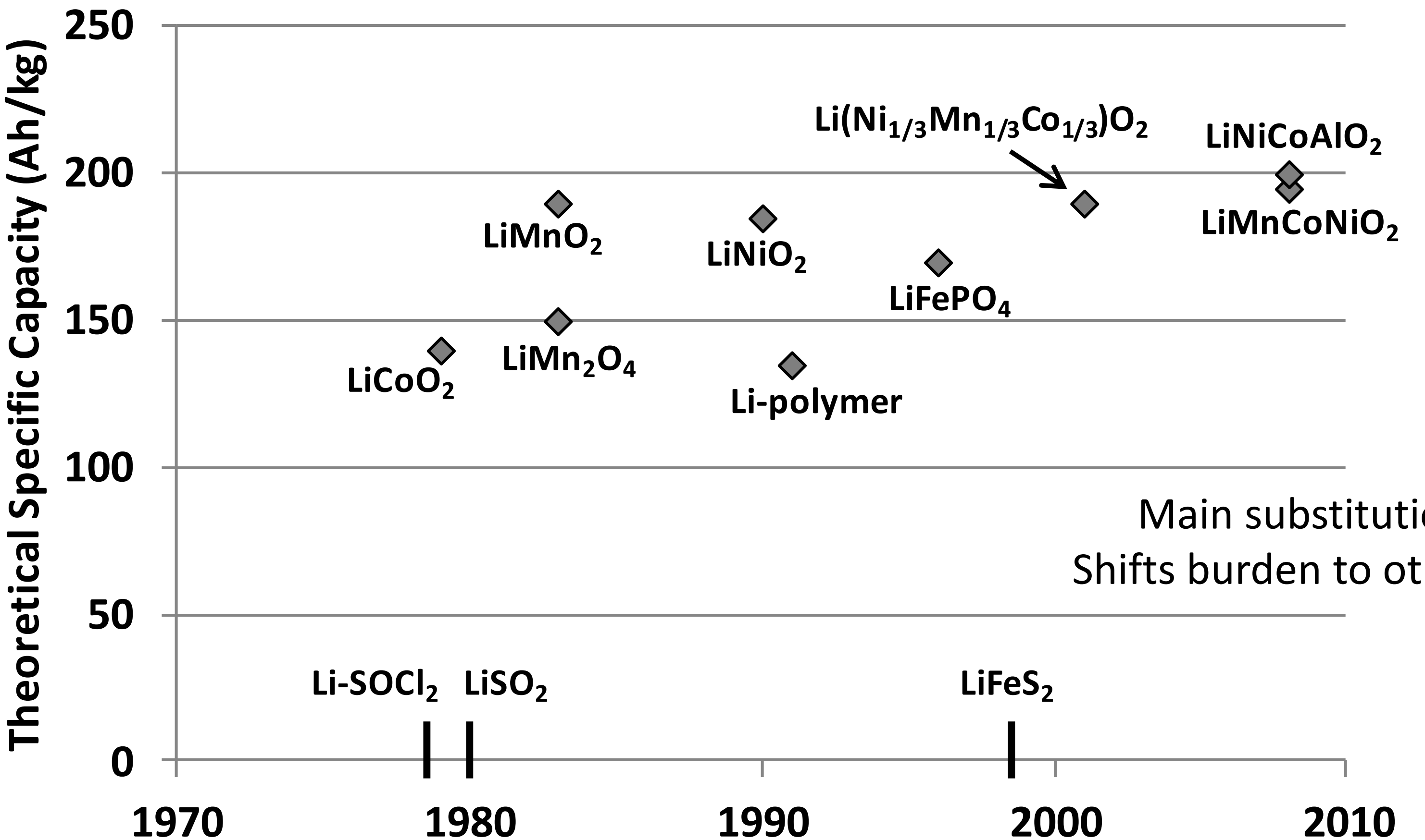




- 24 $LiCoO_2$ 18650 cells
  - 10 bill of materials, MSDS, lit review
    - Sanyo, Panasonic, Lishen, Sony, Moli, AT&T, Matsushita
  - EV LIBs have even more diversity of form factor and content

Wang, Gaustad, Babbitt, Bailey, Ganter, Landi (2014), "Economic and environmental characterization of an evolving Li-ion battery waste stream," Journal of Environmental Management, v 135, 126-134

Cathode chemistries evolving



Main substitution challenge:
Shifts burden to other materials

For other energy storage: Pb-acid, flywheel, flow, etc

For mobility: lithium based for a while but cathodes can shift burden

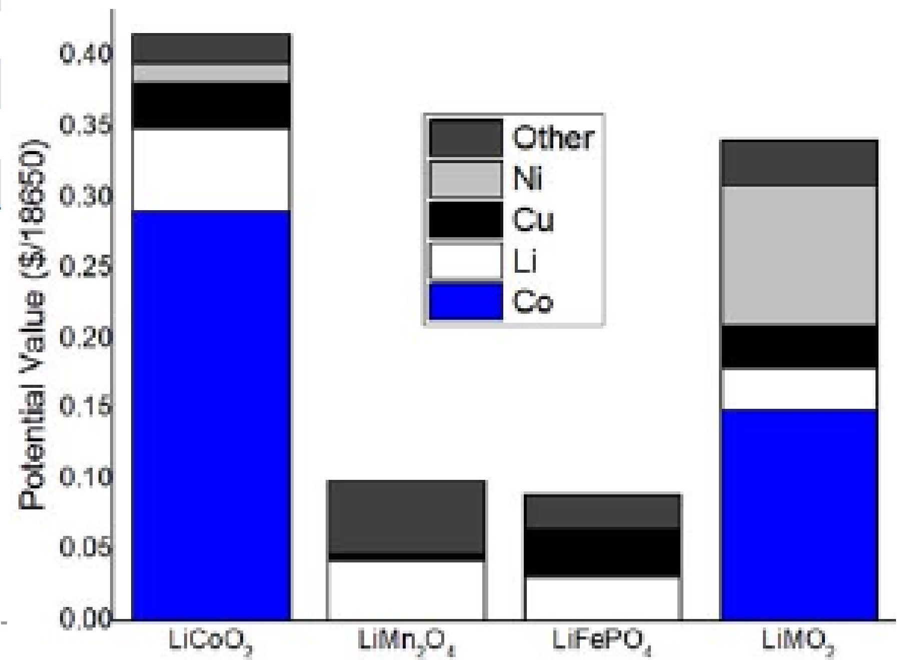
- LiFePO4 – still Li and P an issue
- 523, 622, 811 potential – shift burden to nickel

Economics

	$LiCoO_2$	$LiMn_2O_4$	$LiFePO_4$	$LiMnCoNiO_2$
Aluminum	5.2%	1.1%	6.5%	5.3%
Cobalt	17.3%	0.0%	0.0%	9.7%
Copper	7.3%	1.1%	8.2%	7.8%
Lithium	2.0%	1.5%	1.2%	1.1%
Manganese	0.0%	20.4%	0.0%	9.0%
Nickel	1.2%	0.0%	0.0%	9.6%
Steel	16.5%	16.5%	33.5%	17.3%
Iron	0.0%	0.0%	9.7%	0.0%
Graphite	23.1%	33.6%	13.0%	17.2%
Carbon Black	6.0%	0.0%	2.3%	6.0%
Plastics	4.8%	20.1%	4.4%	3.2%

Table Representative composition for four selected case study cathode chemistries (by wt.%)

- Contained materials vary by cathode chemistry, form factor, and size
- Compositional variability indicates uncertainties in their potential recoverable value

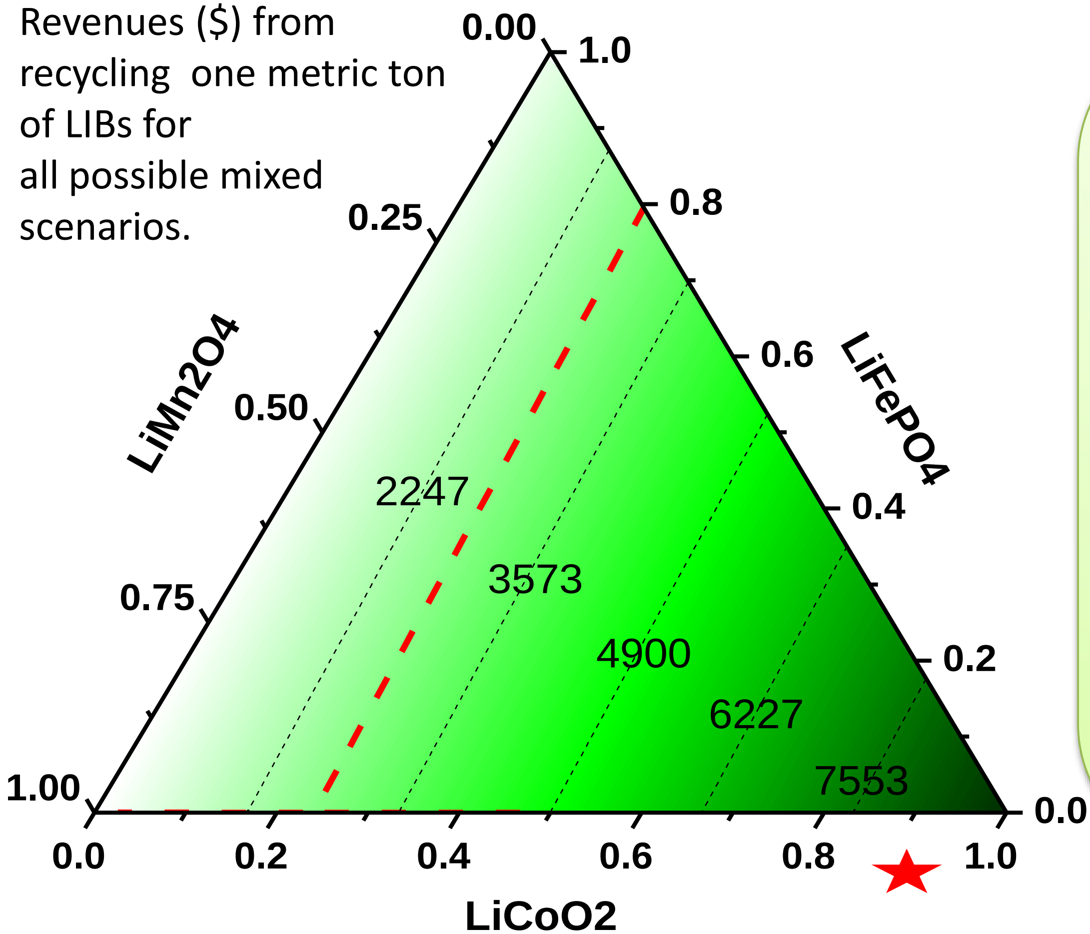


- Cobalt content varies a lot among different cathode types
- Low potential recoverable values for Mn-spinel and iron phosphate batteries

Wang, Gaustad, Babbitt, Bailey, Ganter, Landi (2014), "Economic and environmental characterization of an evolving Li-ion battery waste stream," Journal of Environmental Management, v 135, 126-134

Economies of Scale

Revenues ($) from recycling one metric ton of LIBs for all possible mixed scenarios.



- Darker green means higher economic values; vice versa
- Larger proportion $LiCoO_2$ cathode LIBs means higher profitability
- Theoretical threshold **21%**
- Collection key
  - Export complicates
- “Cottage industry”

Wang, Gaustad, Babbitt, Richa (2014), “Economies of scale for recycling Li-ion batteries”, Resources, Conservation, and Recycling. v 83, 53-62

Environmental impacts

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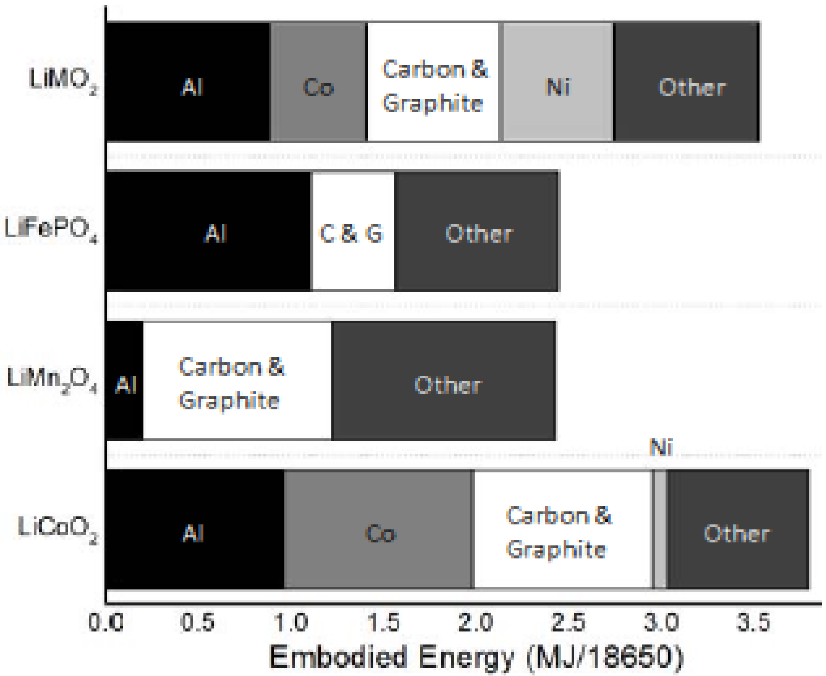
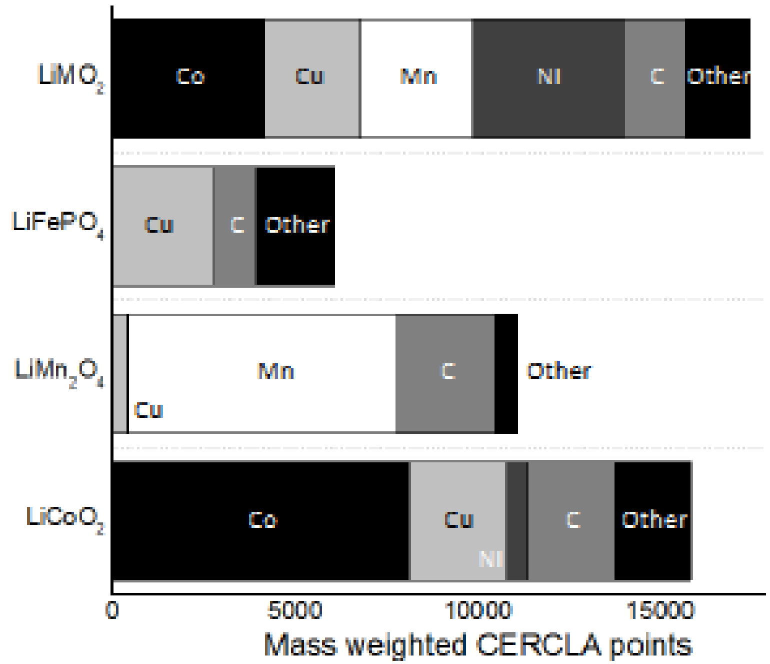
Estimated embodied energy



EPA CERCLA points weighted by mass



Besides Co, some other types of materials show recycling incentives:

- Li needs to be targeted from an economic perspective
- Al recovery needs to be improved from the energy savings perspective
- Cu and Mn need to be properly recycled from the eco-toxicity perspective

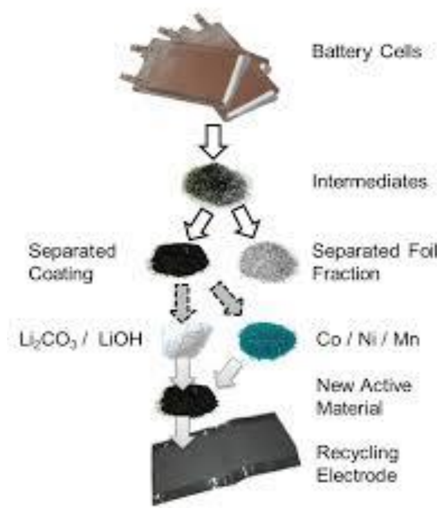
Major Policy Gaps……the US perspective

- Regulations and voluntary programs in U.S. do not include collection of large size EV LIBs
- Reuse or cascaded use not defined in battery waste laws
- No recycling rate or process efficiency targets in U.S.
- Landfill ban with ineffective or no penalty for non-compliance in U.S.
- Landfill bans in U.S. for LIBs limited to only 3 states

Richa, Babbitt, Gaustad, (2017), Eco-efficiency analysis of LIB waste hierarchy inspired by the circular economy, Journal of Industrial Ecology, forthcoming.

Looking forward

- Policy intervention likely needed for both reuse and recycling routes
  - economics alone won't drive especially as Co decreases
  - Need standardization of form and cathode, labelling
  - Transportation rules and guidelines to aid collection
- Lots of fundamental R&D still needed to keep up with battery development
    - BMS and CANbus across reuse platforms
    - Scale-up of refunctionalization
    - High yield, low impact recycling processes
    - Safety in processing and transport



Collaborators and Funding

- Dr. Callie Babbitt, Dr. Brian Landi, RIT
- Dr. Nenad Nenadic, Dr. Eric Hittinger, RIT
- RIT PhD Students: Xue Wang, Kirti Richa, Michele Bustamante, Matt Ganter, Chris Schauerman
- Dr. Elsa Olivetti, MIT

Thank you!