Impact of the Manufacturing and Recycling Stages on Battery Life Cycles

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Battery Benefits

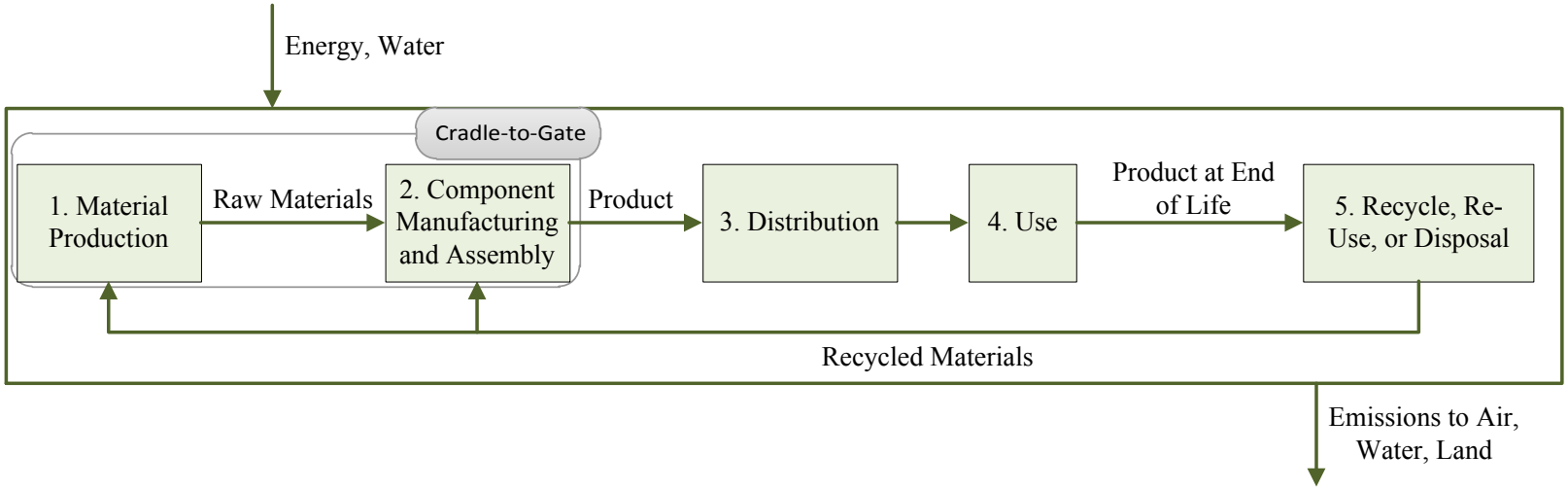
- Through their widespread application, batteries provide performance benefits to numerous products.
  - Use in electronic equipment, tools, energy storage, and vehicles.

- However, batteries have an environmental footprint (more than just energy).
  - How much so?
  - What are their life cycle performances?
  - What is the impact of recycling on the battery life cycle?

- Our focus here is primarily on the lithium manganese oxide battery

Is Battery Assembly a Key Contributor to Battery Life-Cycle Energy Consumption?

It might depend where you draw the boundary



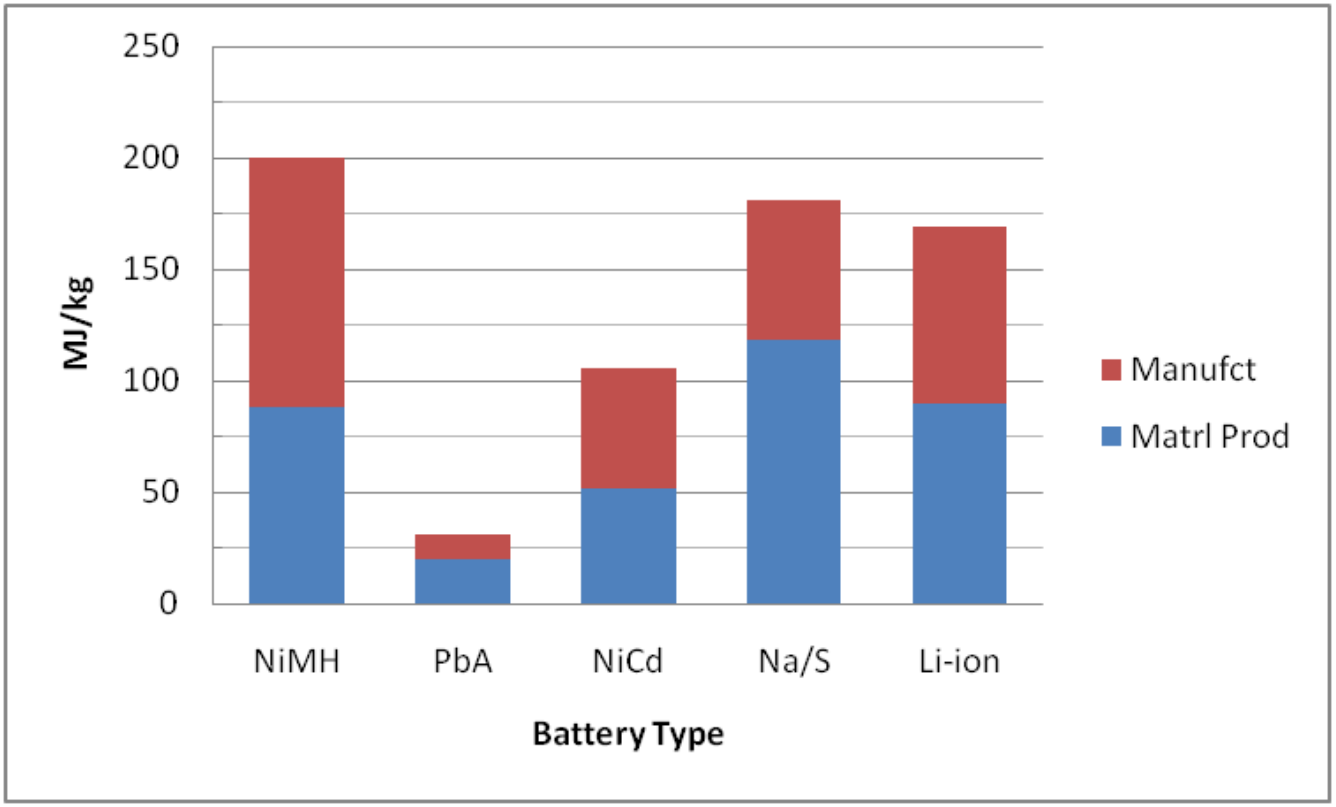
Boundary

- How do we define “materials production” versus “manufacturing”?
  - Material production provides commodity materials such as:
    - Sheet aluminum, steel, copper; silicon, polymers, other
    - Lithium carbonate, manganese dioxide, graphite. Lithium hexafluorophosphate
    - Electrolytes
    - Etc.
  - Manufacturing forms commodity materials into shapes and structures for design purposes
    - For batteries this includes
      - Forming anodes and cathodes,
      - cycling and manufacturing control circuitry, if any,
      - other

- If boundary variation occurs between studies, boundary blur results

Cradle to Gate Production Energy

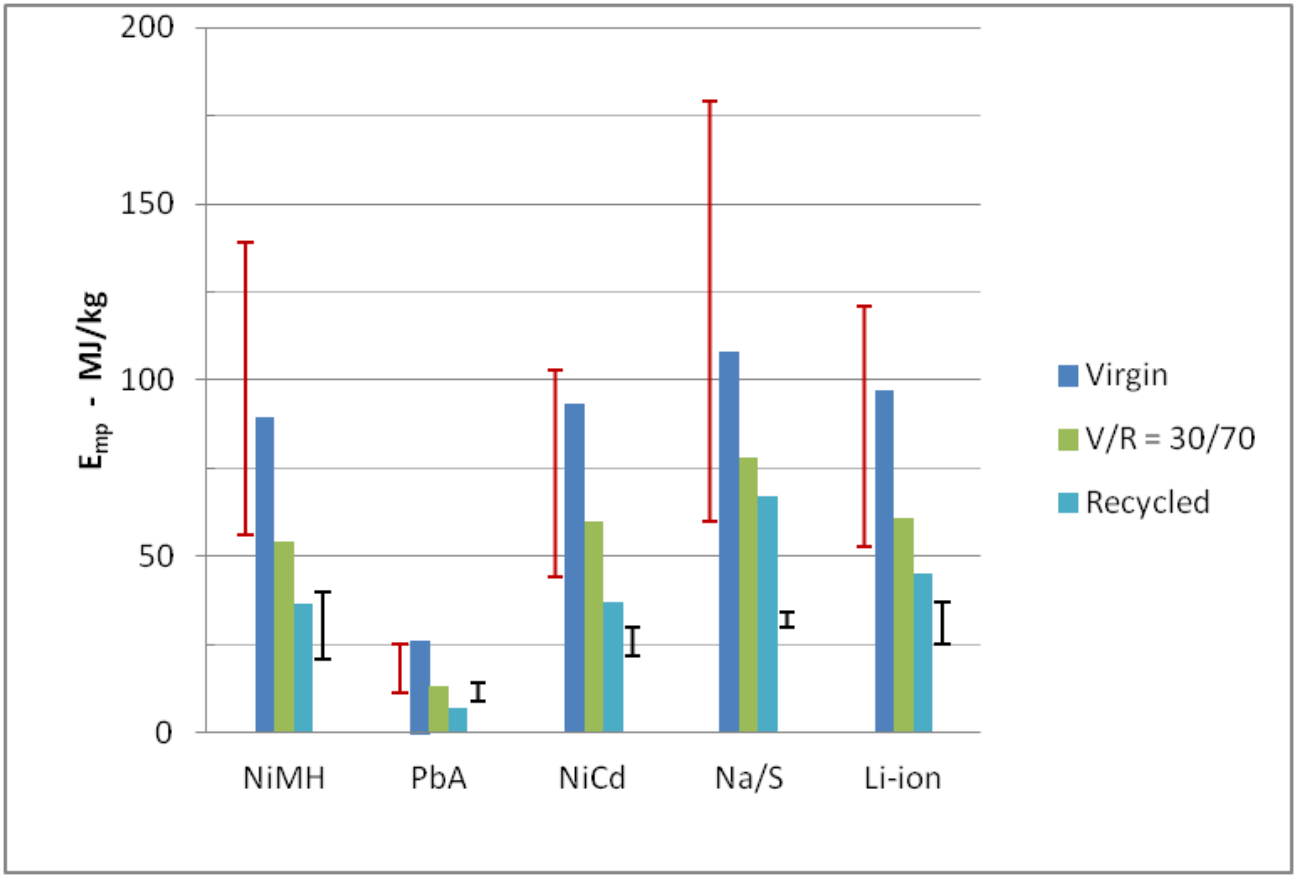
$$E_{ctg} = E_{mp} + E_{mnf}$$



- These results are from a literature review and indicate that battery manufacturing is a significant component of ctg

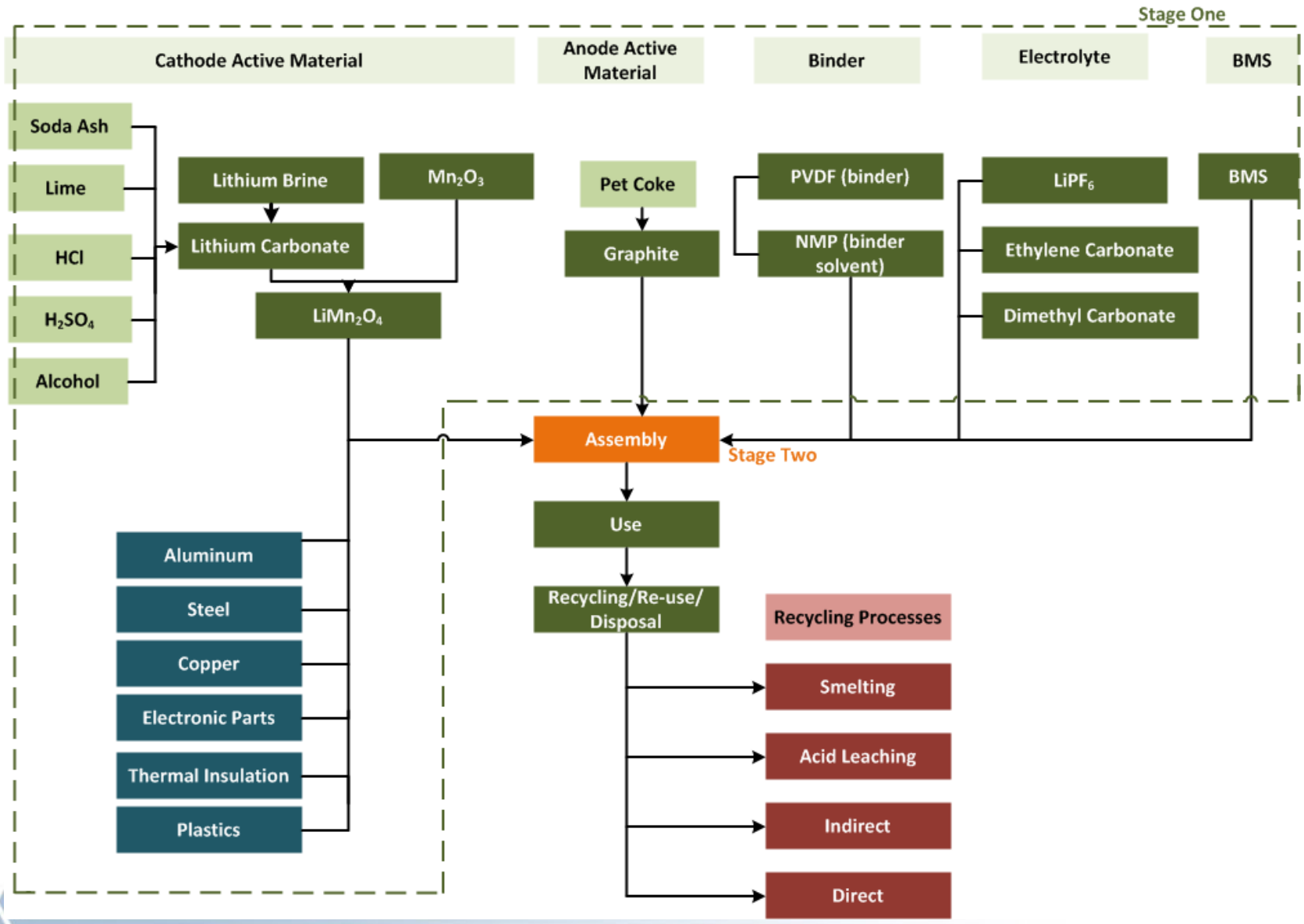
Calculated E_{mp} Values for Five Batteries

Bars denote existing range data from the literature

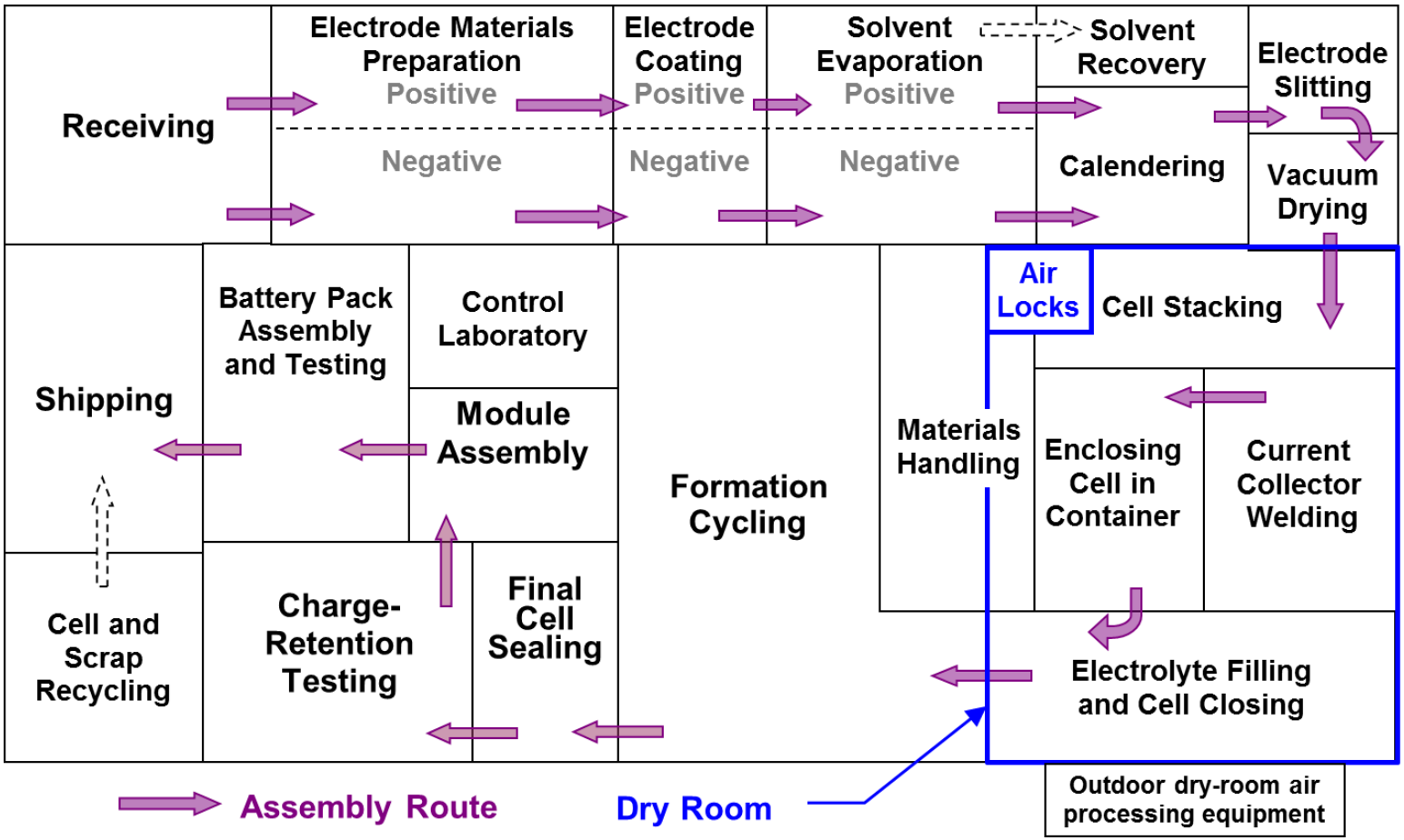


- Our calculations based on available constituent material production energy (PE_j) data
- Some of the data sources provide insufficient detail; sometimes there are omissions; and other times surrogates are employed
- Nonetheless, our estimates show the impact of recycling on battery material production

Argonne life-cycle inventory covers battery production and recycling – a lithium-ion battery is shown



BatPaC model estimates battery production material flows and costs



The areas in this diagram for each processing step are approximately proportional to the estimated plant areas in the baseline plant.

Nelson et al. (2011) Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles. ANL/11-32

Key features of battery manufacturing process

- Low-temperature
- Electricity-driven equipment
- Formation cycling could be large energy consumer
- Dry room for cell assembly limits air moisture content

Deserves a closer look….

Are there any phase transitions?

Conceptual dry room design

- Specifications
  - Relative humidity: 0.5%
  - Temperature: 21°C
  - Area: 1,860 m^2
- Components
  - Two dehumidification systems with:
  - Desiccant wheel with indirect-fired natural gas reactivation
  - Electric heating of air
  - Electric motors for fans
- Total dry room energy consumption is 1.7 MJ/kg

Dry room specification provided by SCS Systems.

Formation Cycling

Two charge cycles and one discharge cycle

$$E_{C1} = \frac{C \times OCV_{avg}}{\eta_{C1} \times \eta_{Cell}}$$

C = Cell capacity (Ah)
OCV_{avg} = Average open circuit voltage (V)
η_{Cell} = Cell efficiency (0.98)
η_{C1} = First cycle Coulombic efficiency (0.87)

$$E_{C2} = C \times OCV_{avg} / \eta_{Cell}$$

$$E_D = C \times OCV_{avg} \times \eta_{Cell}$$

Result: 0.034 MJ/kg for a battery to power a PHEV

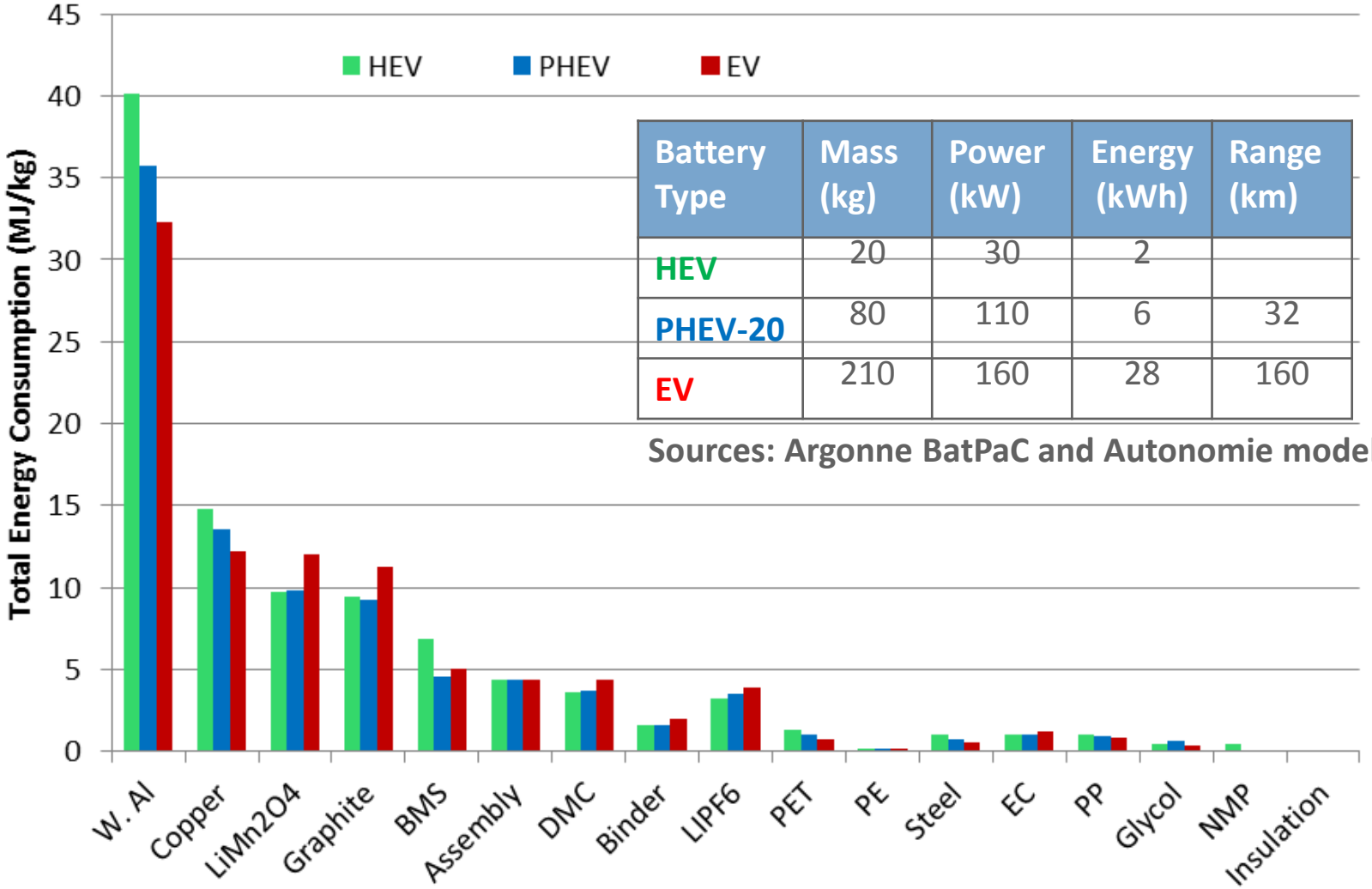
Process level approach results in lower energy consumption

- If dry room and cycling are 60% of facility energy consumption, total life-cycle energy consumption for Stage 2 would be 2.7 MJ/kg.
- Process level analysis results in lower energy estimate than shown in previous figure.
- Two recent life cycle assessments of lithium-ion batteries report strikingly different energies for battery "manufacturing" or stage 2
  - Majeau-Bettez et al. (2011): 84 MJ/kg --- top down
  - Notter et al. (2010): 1.3 MJ/kg --- process level

Next question: How important is battery assembly in the overall life-cycle energy consumption of a battery

- If Stage 2 >> Stage 1, recycling will not reduce the life cycle energy much
- If Stage 1 >> Stage 2, recycling would be much more attractive

Recyclable structural metals are key contributors to battery production energy



Battery Type	Mass (kg)	Power (kW)	Energy (kWh)	Range (km)
HEV	20	30	2	
PHEV-20	80	110	6	32
EV	210	160	28	160

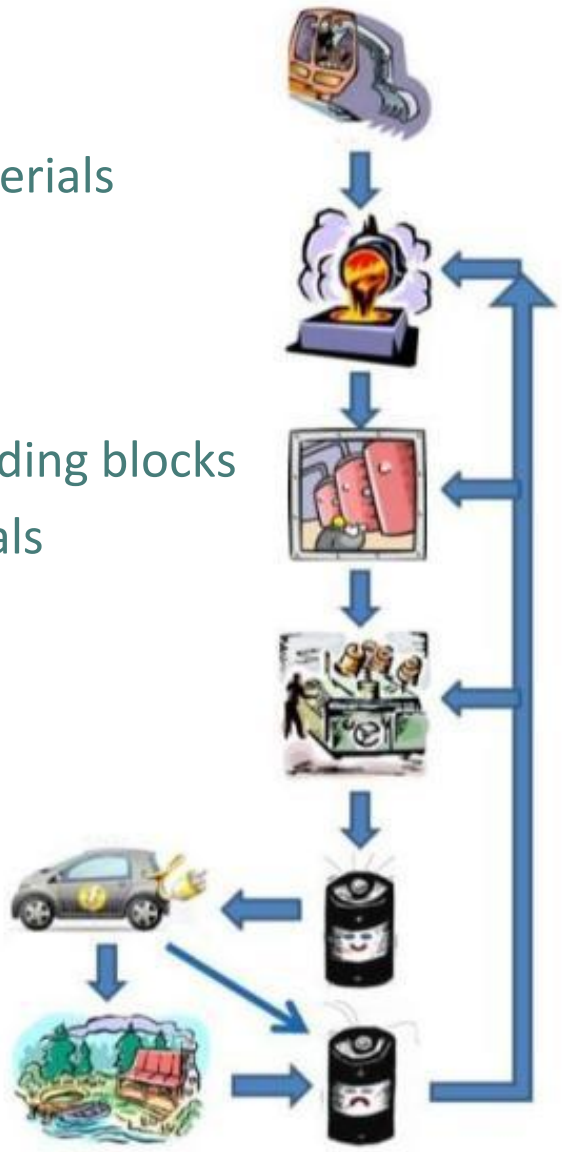
Sources: Argonne BatPaC and Autonomie models

(Preliminary Results)

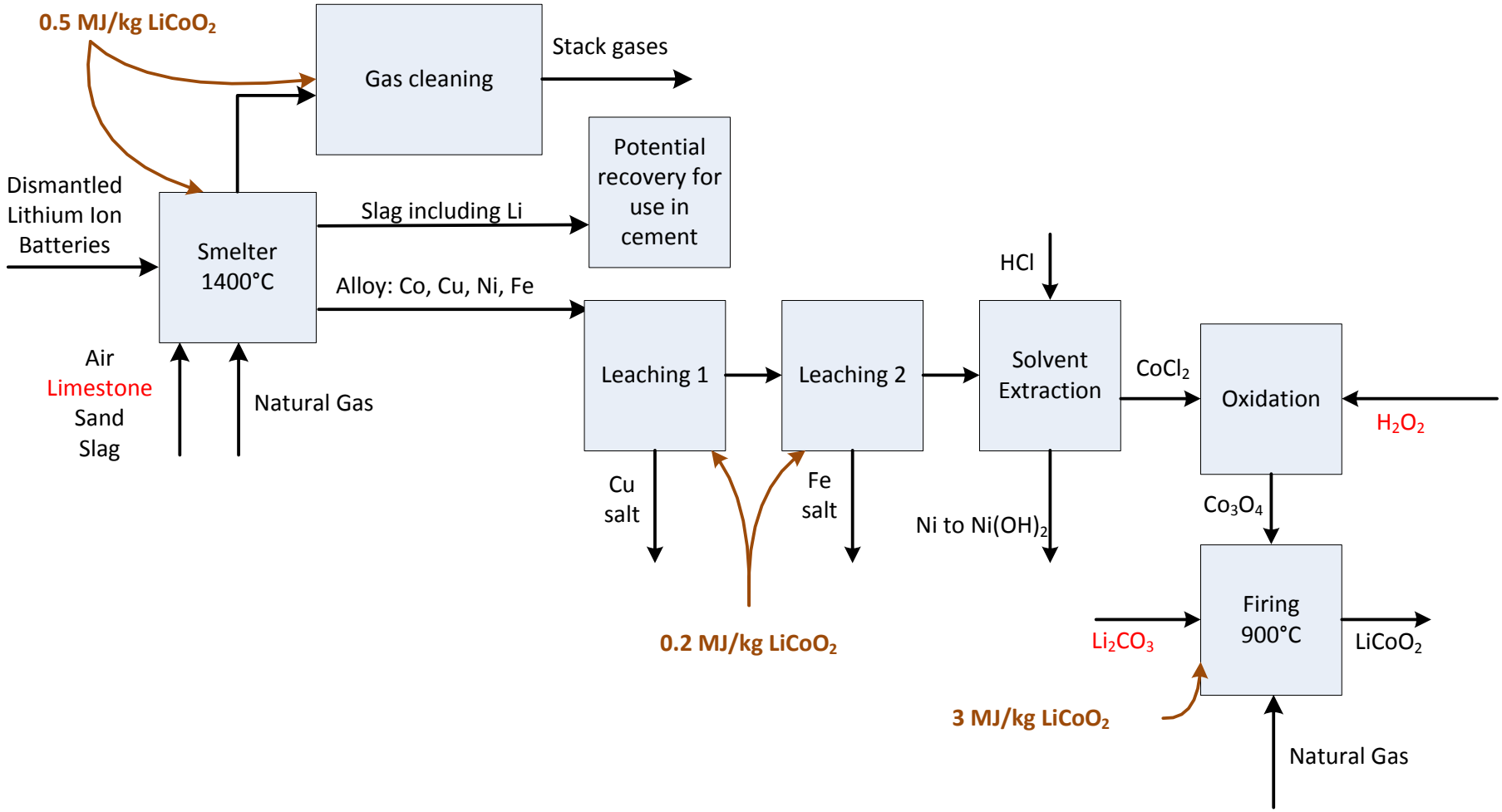
Source: J. B. Dunn, M. Barnes, L. Gaines, J. Sullivan. Material and Energy Flows in the Life Cycle of Lithium-Ion Batteries. Argonne Technical Report. http://greet.es.anl.gov/publications (2012)

Recycling can recover materials at different production stages

- It is difficult to recover all materials
- One possible goal is to recover battery-grade materials
  - More energy saved if more steps avoided
  - More emissions (to air and water) avoided
  - Must account for battery recycling burdens
- The other extreme would be to recover basic building blocks
- Business drives recovery of most valuable materials
- There are pros and cons of different approaches
- LCA identifies “greenest” processes



Commercial smelting process recovers metals



(Preliminary Results)

Rare earths can be recovered from Ni-MH batteries

NiMH battery slag

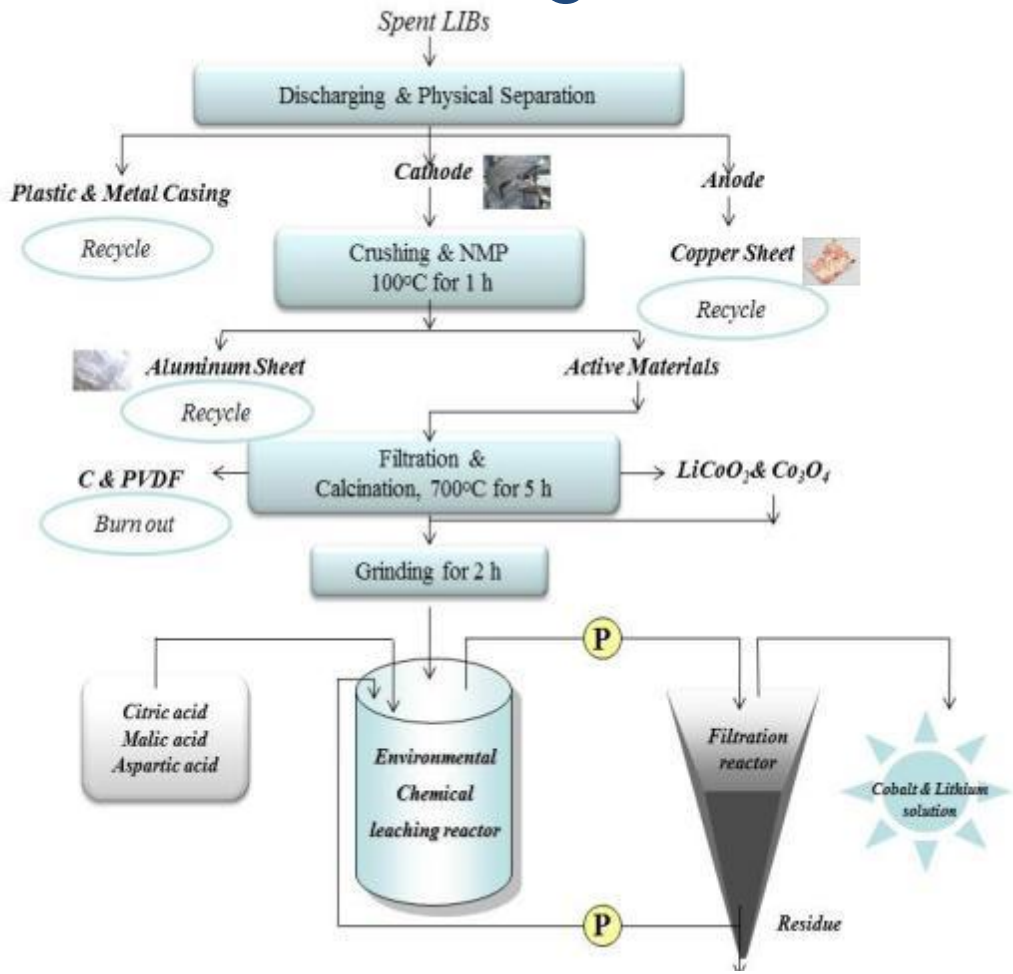
- Dedicated process for NiMH batteries; not for other REE's waste
  - Mixing REE's from different applications ➔ much more refining efforts
- Joint project with Rhodia:
  - Umicore makes a REO-concentrate
  - Rhodia refines the concentrate into pure REO's

REE = Rare Earth Element
REO = Rare Earth Oxide

umicore Battery Recycling

Hydrometallurgial process leaches with organic acids

- No toxic gases (e.g. HCl) released
- Carbon burned off in calcination
- Lithium and metal salts recovered
- Lab work complete for Co cathodes



Recovery of metals from spent lithium-ion batteries with organic acids as leaching reagents and Life Cycle Environmental Assessment

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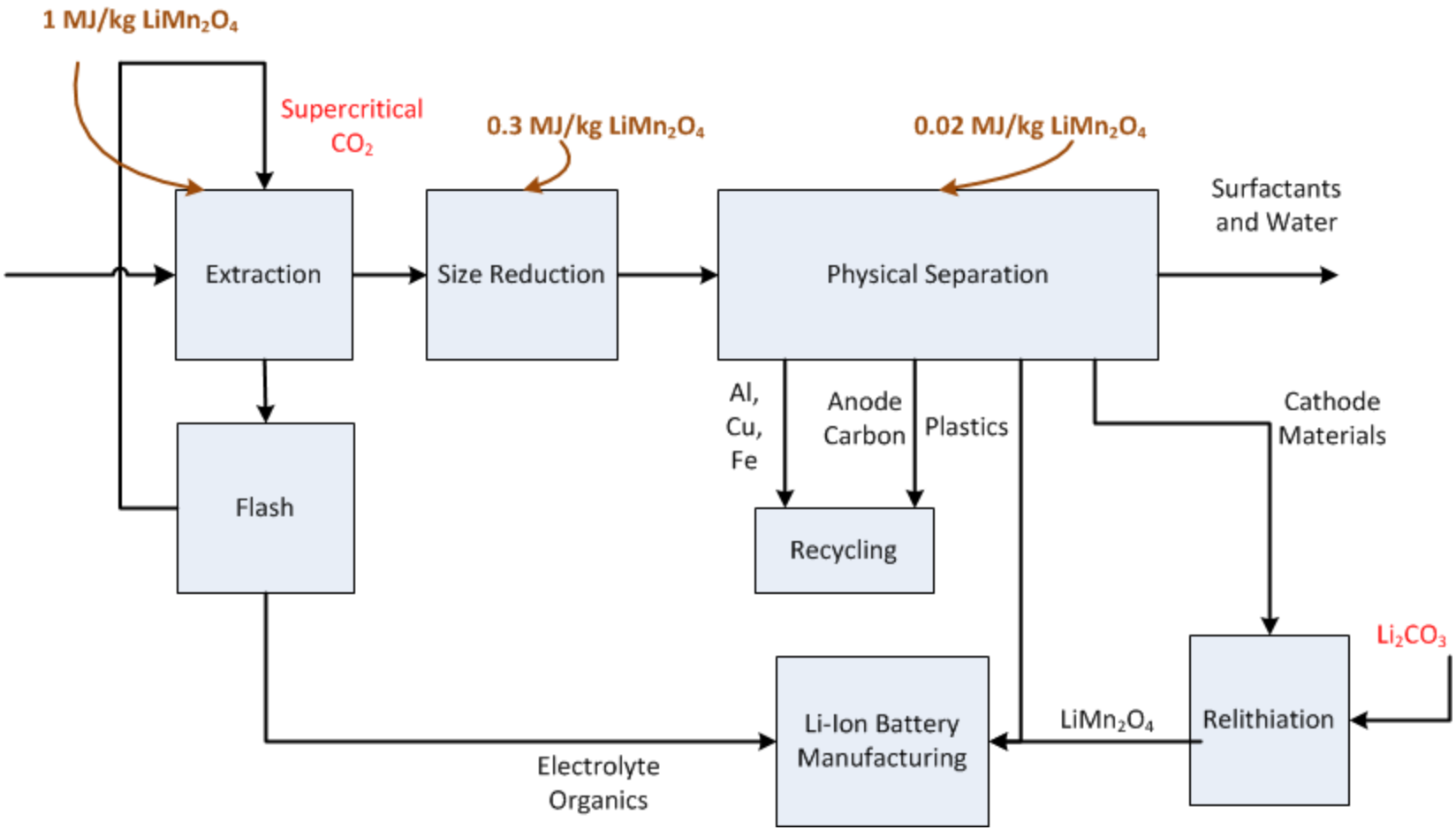
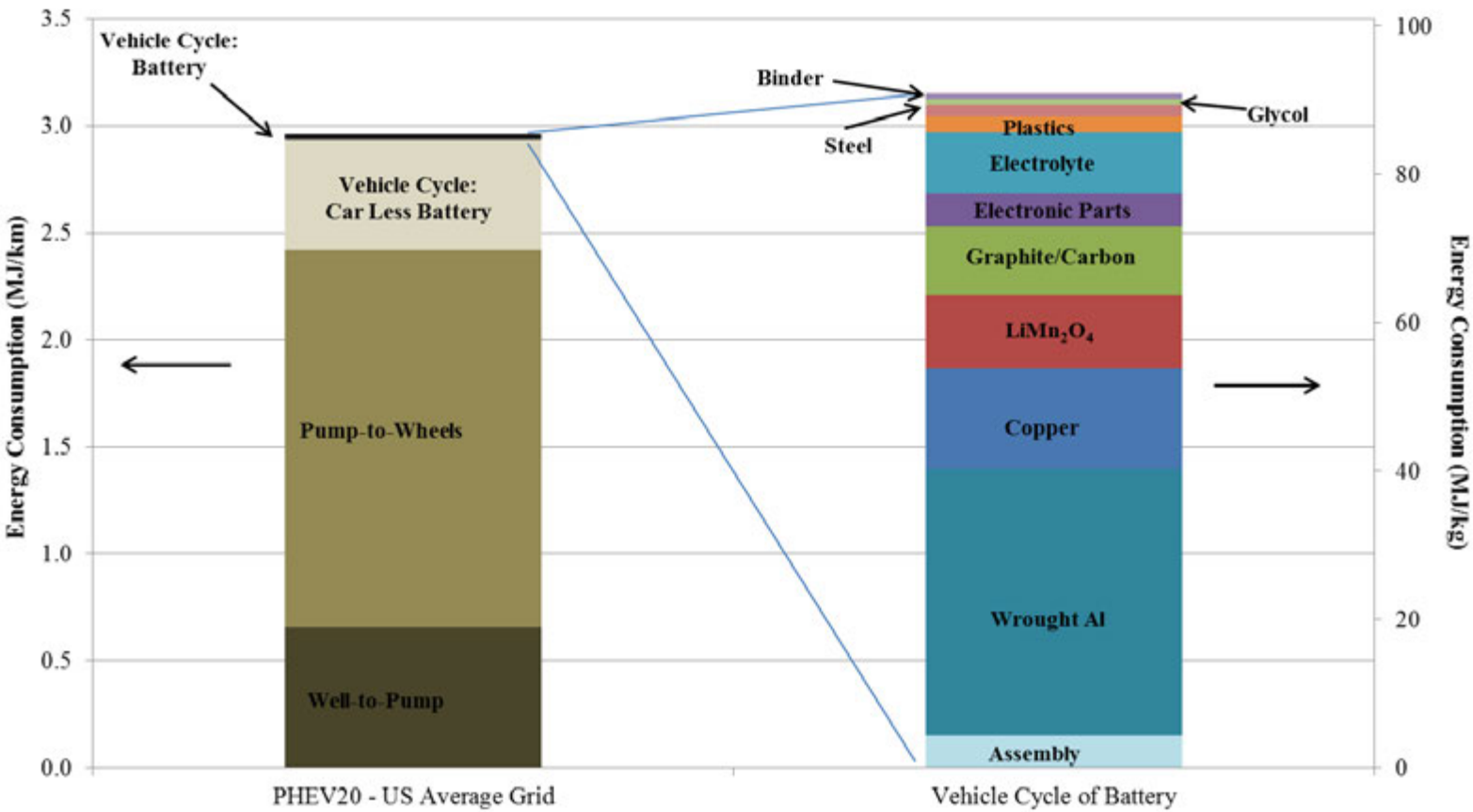
Direct recycling has promise to recover and re-use all battery components



(Preliminary Results)

Although the vehicle cycle is a fraction of total energy impact, and the battery is a fraction of that, other impacts are important to consider



Battery impacts rise with all-electric range.

(Preliminary Results)

Batteries can reduce vehicle operational energy up to 25%

Conclusions

- The use of batteries is expanding, an increase which could be quite dramatic when routinely used for vehicle traction.

- Despite their own energy and carbon burdens, batteries impart significant savings in LCE and LC-CO_2 for vehicles when compared to their SI counterparts.

- Our process level analysis suggests that battery manufacturing energy consumption is considerably smaller than previously reported.

- The benefits of battery recycling are:
  - ✓conservation of rare materials, elements
  - ✓ reduced upstream air and water emissions
  - ✓Significant reductions in battery production energy when manufacturing energy is small.

What are the data needs for battery life cycle analyses

- For some batteries, we estimated critical material production energies PE_j.
- More LCI PE_j data is needed for virgin materials, including Co, $LiCoO_2$, rare earth metal hydrides, Mn, graphite, $LiFePO_4$, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, β-alumina, Co_3O_4.
    - Data for Ni, Al, Pb, plastics, steel are quite satisfactory
- There is a critical need for LCI data for recycled Ni, Co, Mn, Na, and S.
- Data are needed for the manufacturing of cathodes, anodes, and electrolytes are needed.

References:

J.L. Sullivan and L. Gaines., Status of Life Cycle Inventories for Batteries, in press, Energy Convers Manage (2012), http://dx.doi.org/10.1016/j.enconman.2012.01.001

L. Gaines, J. L. Sullivan, A. Burnham, and I. Belharouak, *Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling*, 90th Annual Meeting of the Transportation Research Board, Washington, D.C. (January 2011)

L. Gaines and P. Nelson, *Lithium-Ion Batteries: Examining Material Demand and Recycling Issues*, TMS Annual Meeting, Seattle, WA (February 2010)