Comparison of Li-Ion Battery Recycling Processes by Life-Cycle Analysis

Electric Vehicles and the Environment Informal Working Group

Baltimore, MD
September 13-14, 2012

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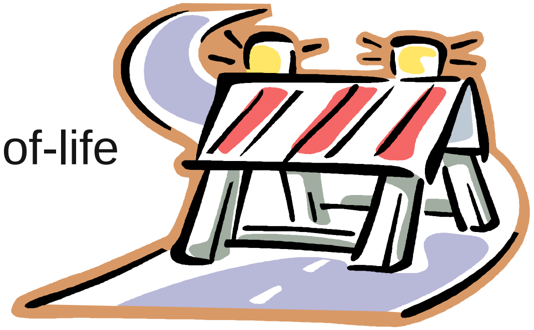
Analysis can help identify a clear path for battery production and recycling

- ☐ Purpose is to clear the road for mass-market introduction of battery-powered vehicles by identifying any roadblocks on the way

- ☐ Life cycle analysis (LCA) is used to identify significant environmental issues

- ☐ Availability of recycling processes can:
  - ➢ Assure against major waste problems at end-of-life
  - ➢ Reduce environmental impacts
  - ➢ Reduce raw material supply issues
  - ➢ Reduce net material costs
  - ➢ Create viable business opportunities

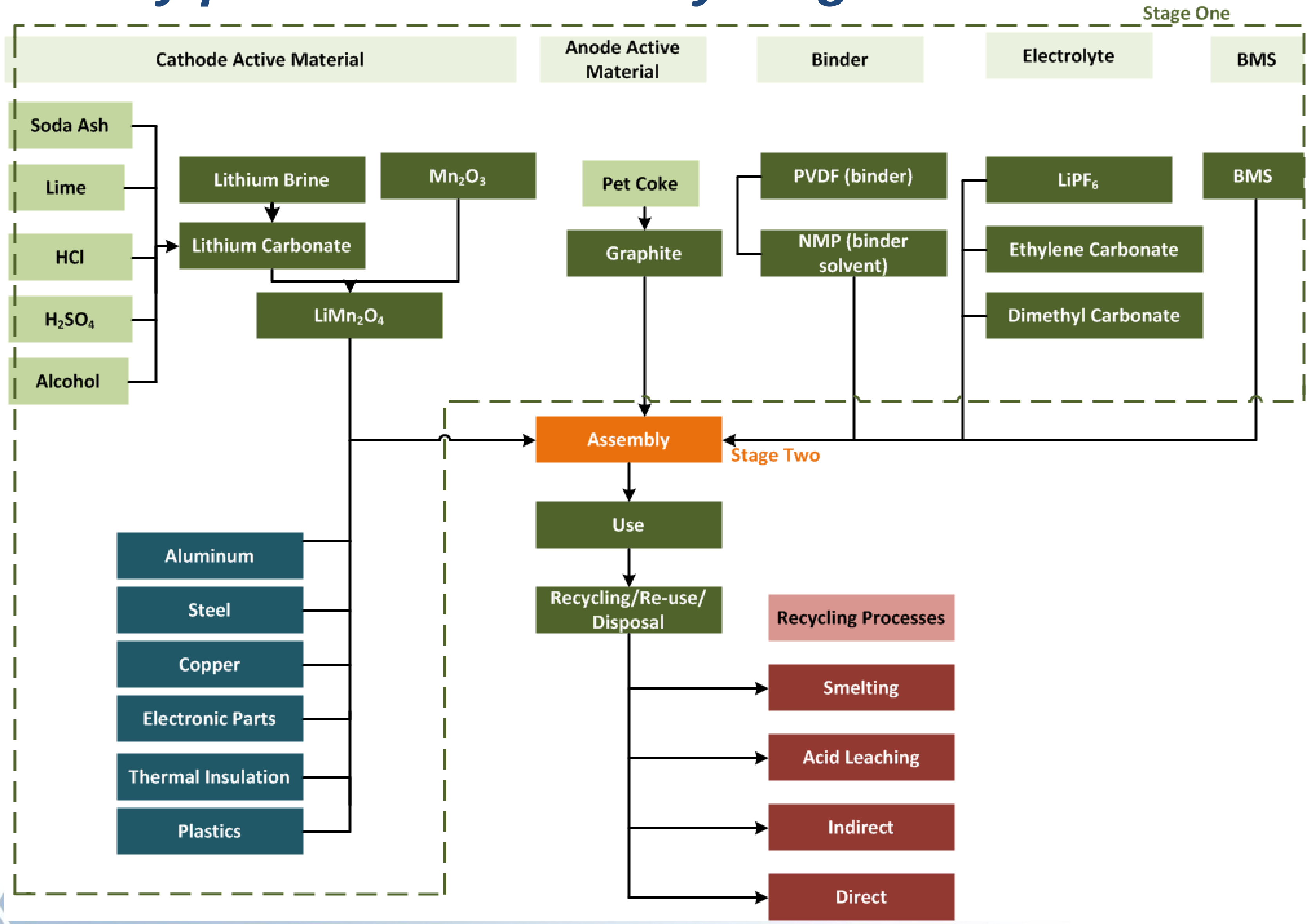


- ☐ Economic and institutional constraints must also be accounted for

Lifecycle analysis compares all process impacts

of a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal if any.

Argonne life-cycle inventory covers battery production and recycling



Approach

- ☐ With output from the **Autonomie** model, identify power and energy specifications for batteries for use in hybrid electric vehicles, plug-in hybrid electric vehicles, and battery electric vehicles
- ☐ Develop material inventories for these three battery types with the **BatPaC** model
- ☐ Establish material and energy flows for each battery component
- ☐ Estimate the energy consumed during battery assembly and recycling
- ☐ Assemble all data in **GREET**
- ☐ Analyze data to address key questions

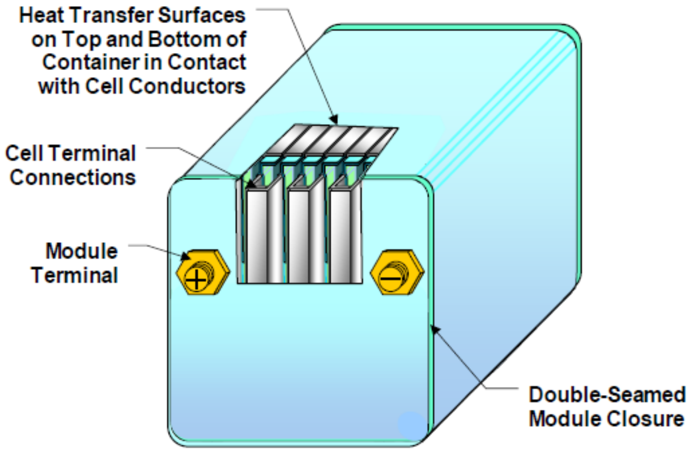


Figure 2.4 Hermetically-sealed module

Analysis Approach: Top-Down versus Process-Level

Study	Approach	Cathode	Material Production Energy (MJ/kg battery)	Assembly Energy (MJ/kg battery)	Assembly as % of Total
Notter *et al.* 2010	Process-level	$LiMn_2O_4$	103	1.3	1.2%
Majeau-Bettez *et al.* 2011	Top-down	NCM and $LiFePO_4$	125-129	80	39%
Zackrisson *et al*. 2010	Top-down	$LiFePO_4$	Not given	74	-
Dunn *et al.* 2012	Process-level	$LiMn_2O_4$	75-79	4.3	5%

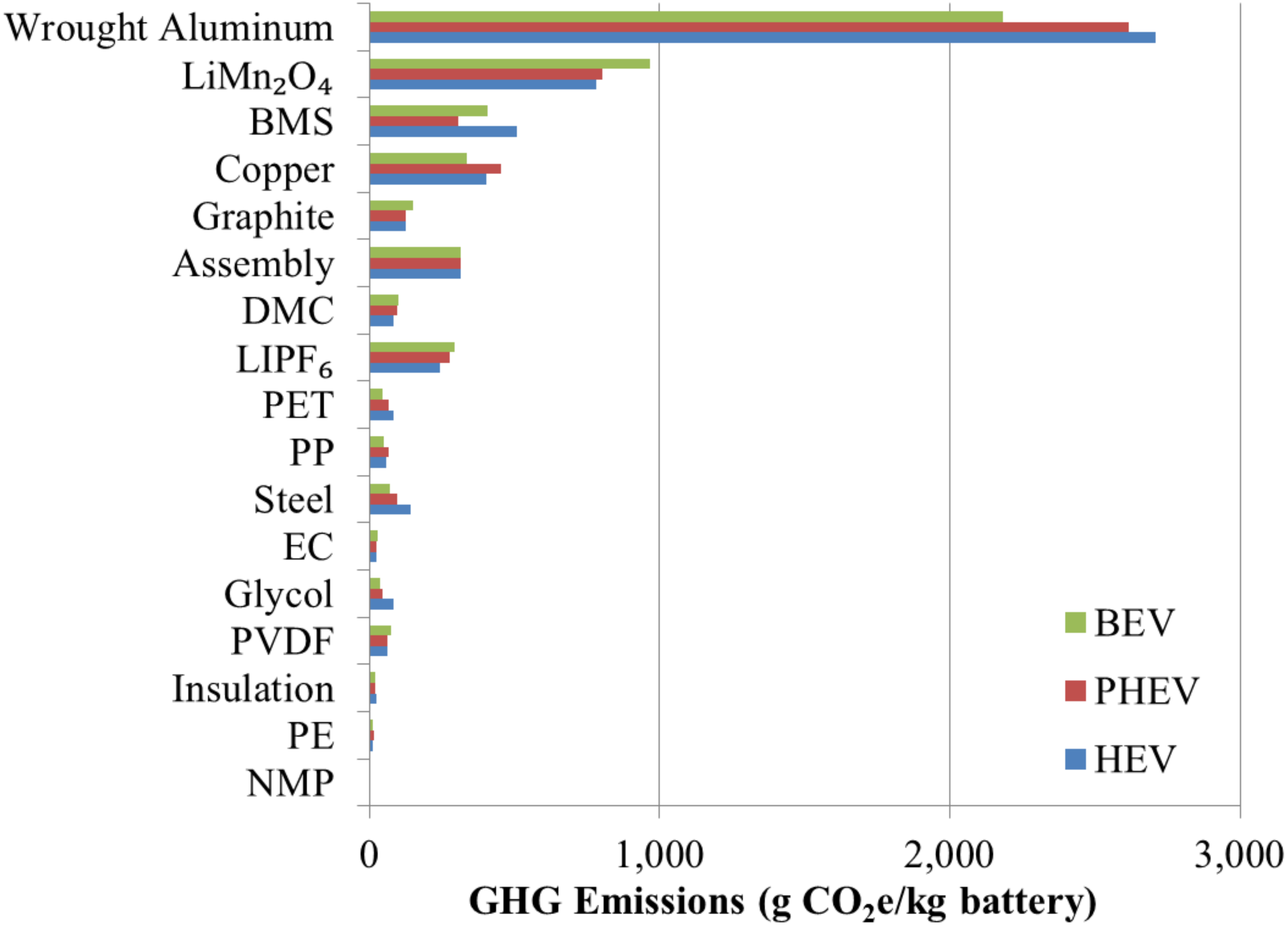
If assembly is a large fraction of the cradle-to-gate impacts, recycling may be of minimal benefit.

Challenges in Top-Down Analyses

- Can be unclear where materials production ends and manufacturing begins… ***boundary blur***
- Energy use is allocated based upon economic value
  - Energy use and economic value may not be well correlated
  - Uses high-level corporate data
  - May obscure differences in production of dissimilar products (*e.g.*, automotive batteries versus space or medical equipment).

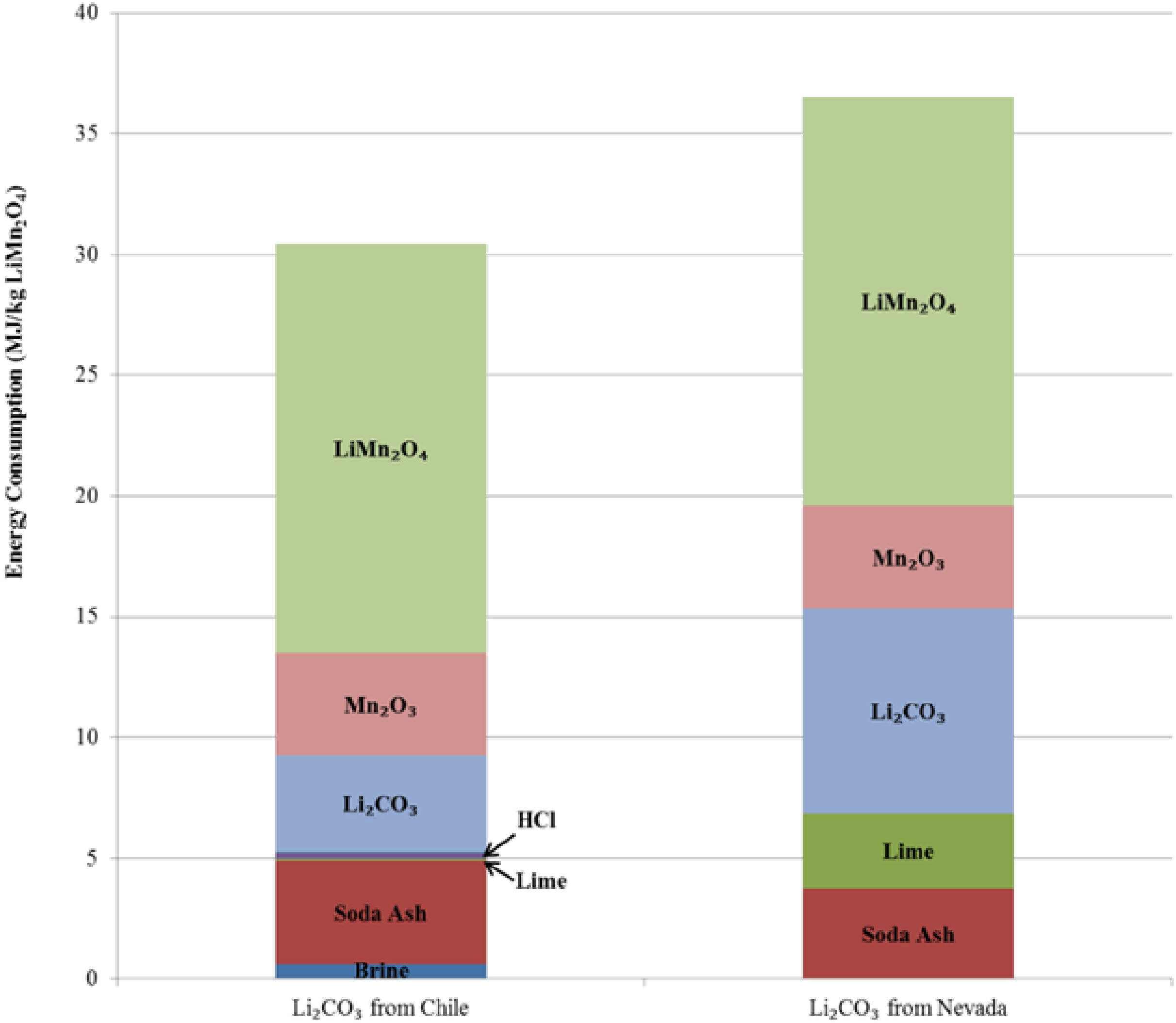
- Process-level analyses require more detailed data, and provides a clearer picture.

Structural and cathode materials dominate lithium-ion battery production GHG Emissions



Dunn, JB; Gaines, L; Sullivan, J; Wang, MQ,” The Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries, Accepted to *Env Sci Tech*

Obtaining Li_2CO_3 from Chile is less energy intensive than obtaining it in the U.S.

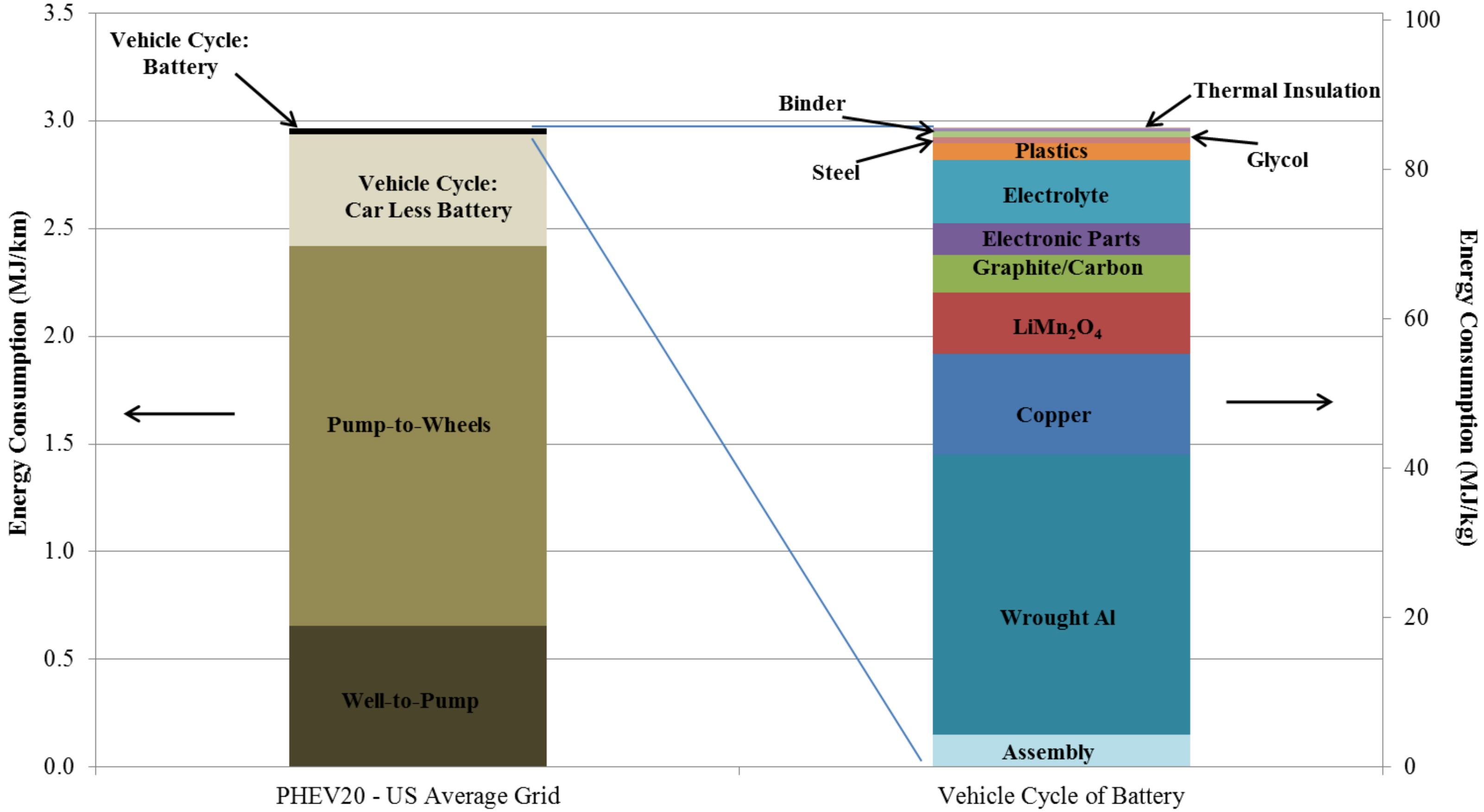


Preliminary results indicate that none of candidate cathode materials is energy intensive

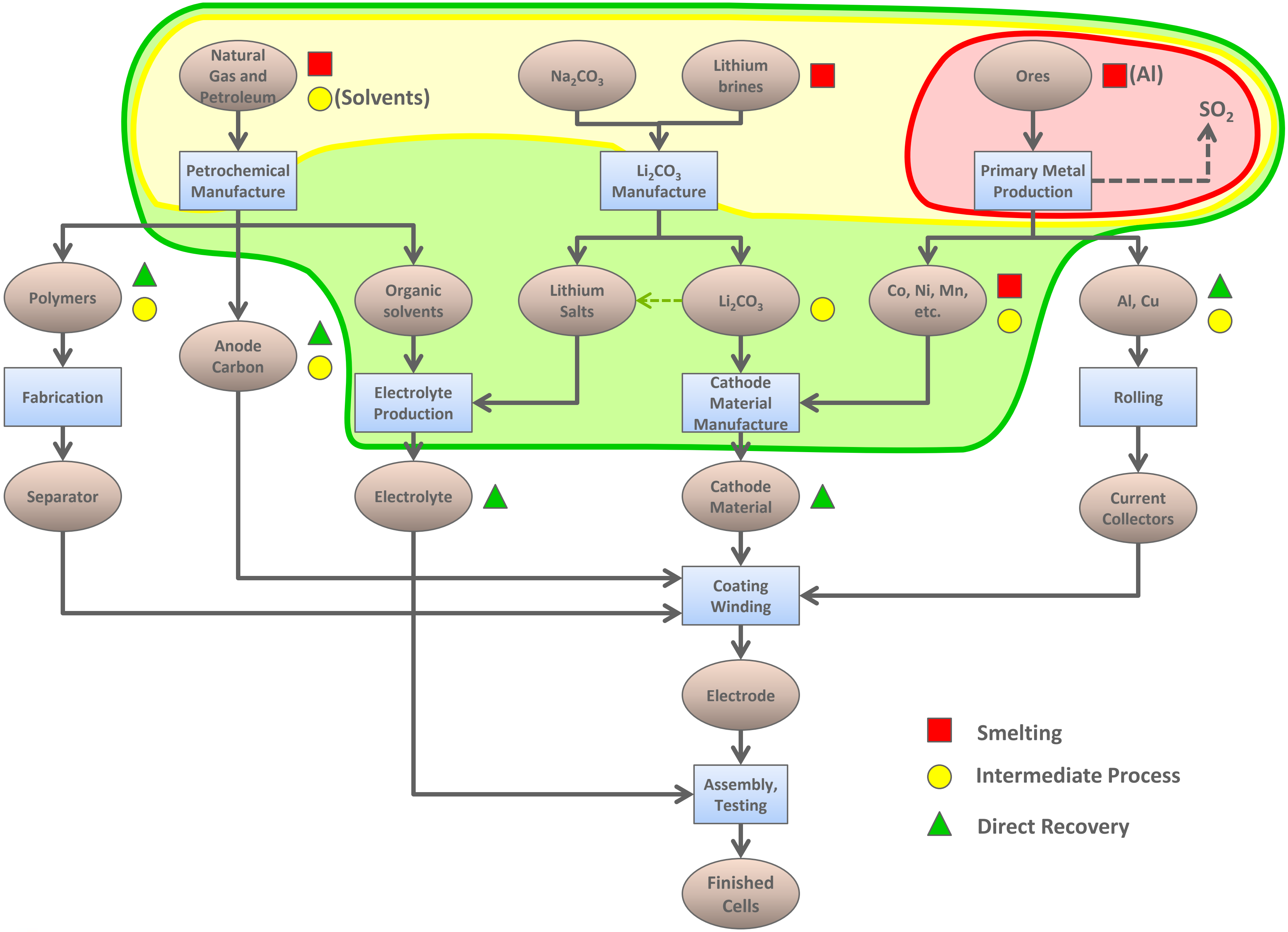
Cathode Material	Energy Consumed During Production from Raw Materials (MJ/kg)
Lithium Iron Phosphate	Solid-state method: 2.9 Hydrothermal method: 17
Lithium Nickel Cobalt Manganese Oxide	Solid-state method: 2.2
Lithium Cobalt Oxide	Solid-state method: 1.3 Hydrothermal method: 15
Advanced Lithium Nickel Cobalt Manganese Oxide	Solid-state method: 2.1-4.1

We are also analyzing impacts of different anode materials: lithium metal, graphite-silicon, graphite

Although the battery represents a small fraction of the total energy input, other impacts are important



- ❑ **Battery impacts rise with all-electric range**
- ❑ **Battery materials are responsible for only 2% of energy but as much as 20% of life-cycle SOx (Co- or Ni-based PHEV20)!**



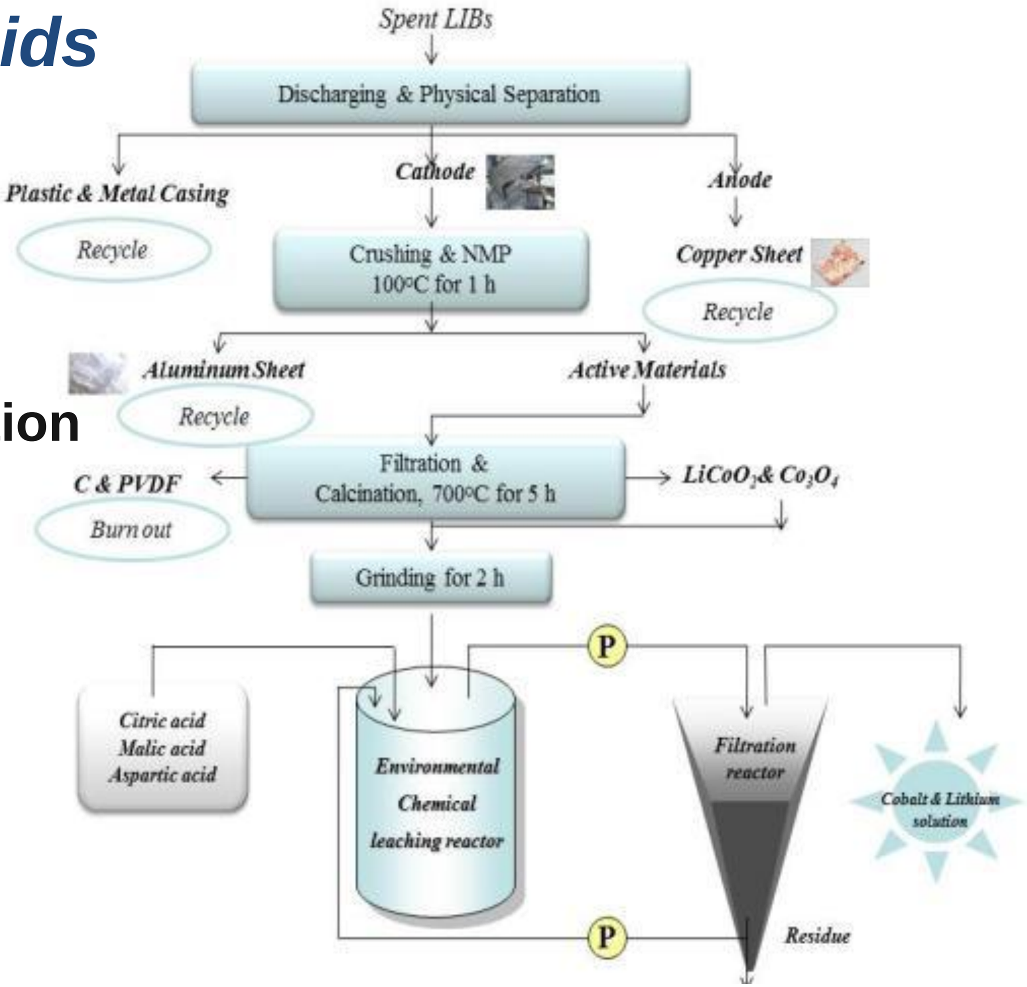
🟥 Smelting

🟡 Intermediate Process

▲ Direct Recovery

Chinese hydrometallurgical process leaches with organic acids

- Bench-scale process
- No toxic gases (e.g. HCl) released
- Carbon burned off in calcination
- Lithium and metal salts recovered
- Lab work complete for Co cathodes
- Joint China-US LCI paper



Recovery of metals from spent lithium-ion batteries with organic acids as leaching reagents and Life Cycle Environmental Assessment, L. Li[a, b], J.B.Dunn[b], X.X Zhang[a], L.Gaines[b], F. Wu[a], R.J Chen[a] *

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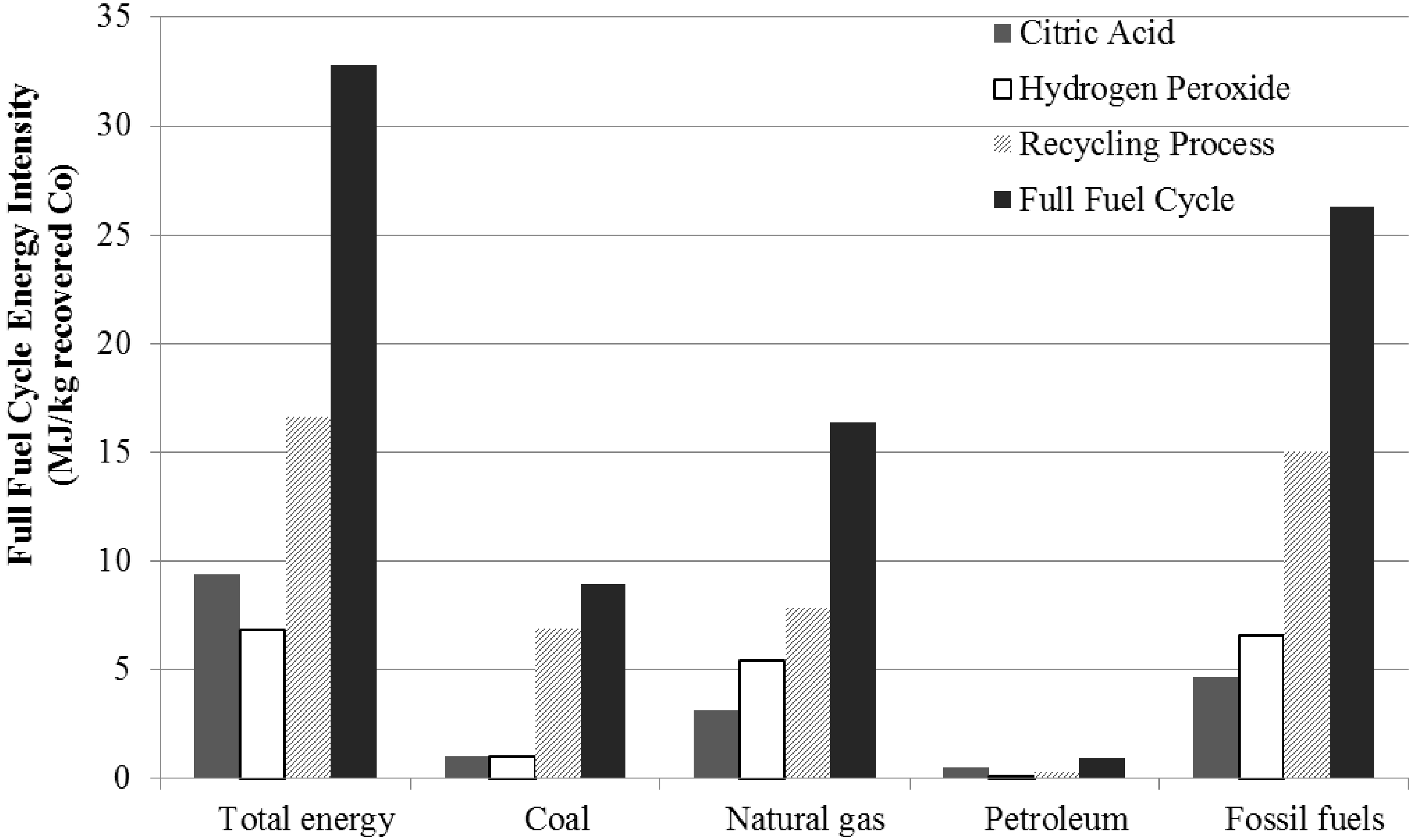
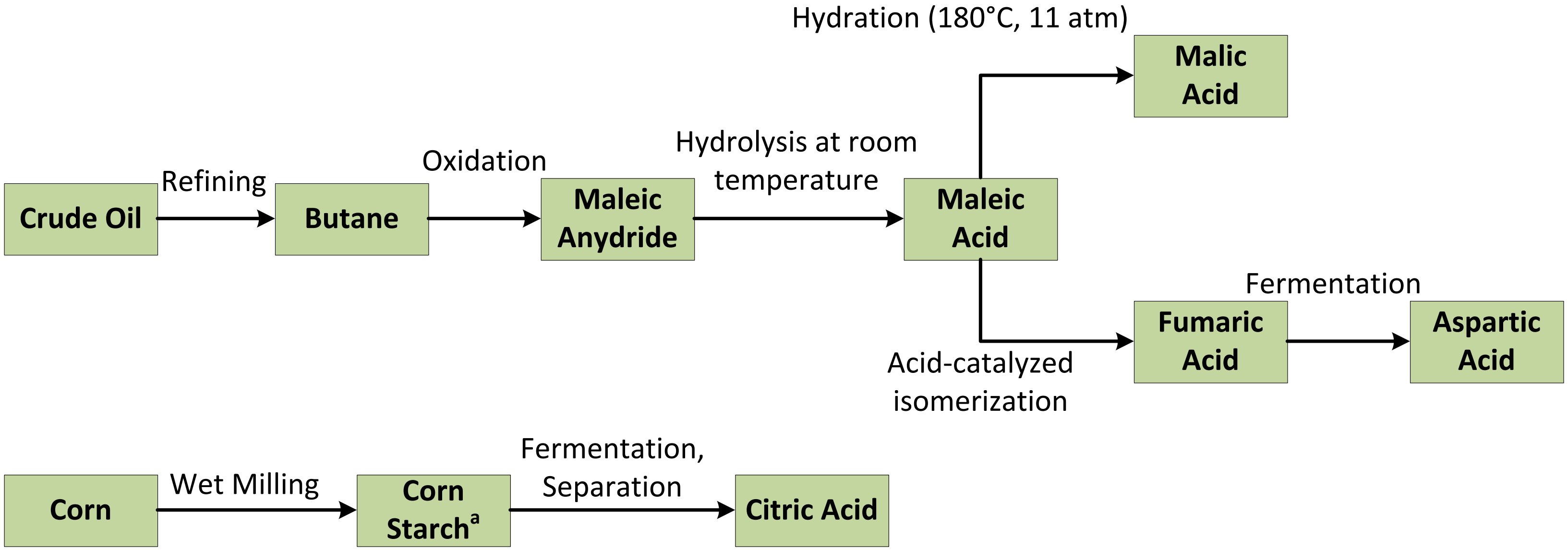
Energy to recover Co comes from upstream materials and calcination step, and is about half of that from ore

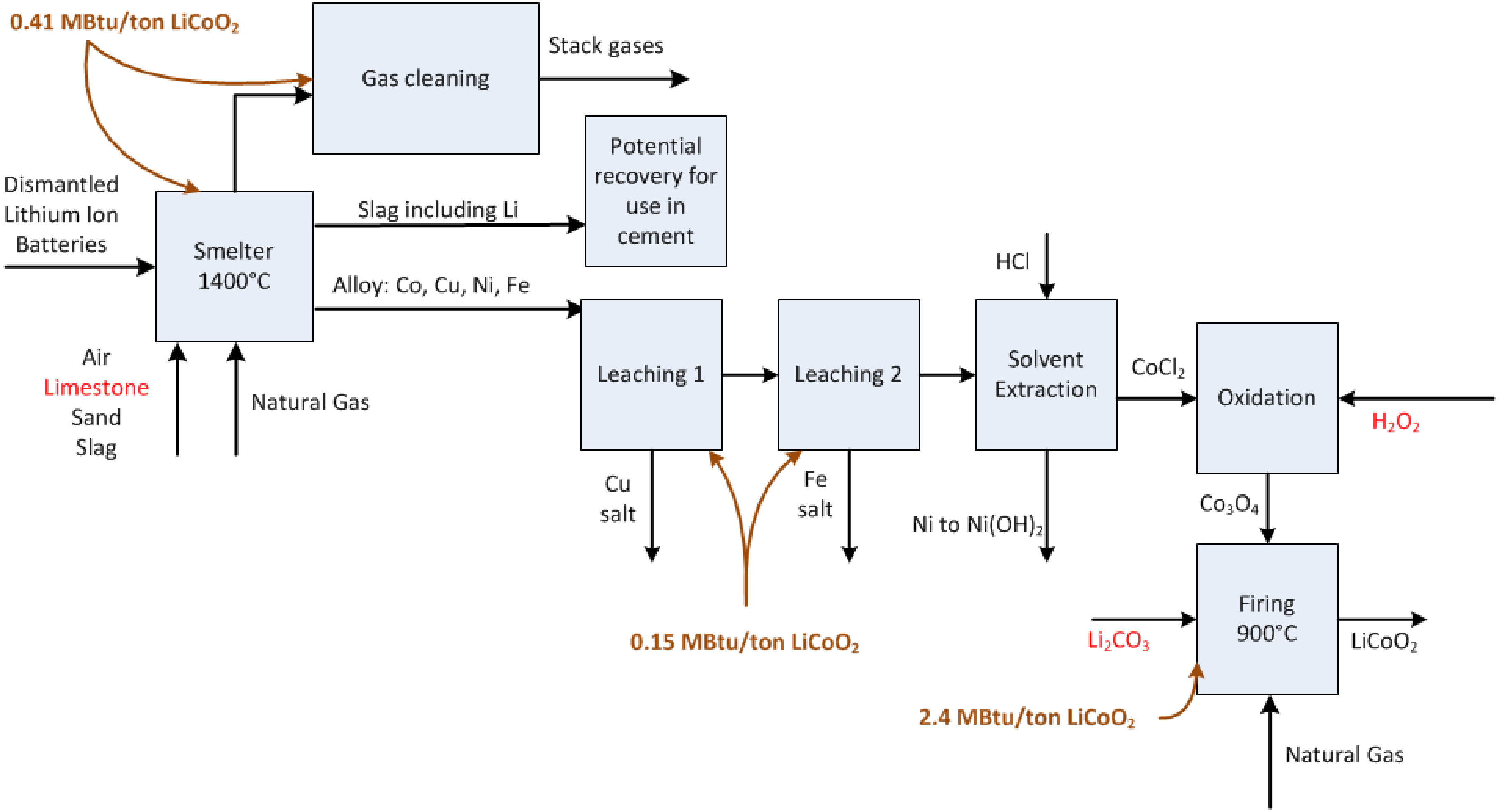


Raw material for organic acids is key factor

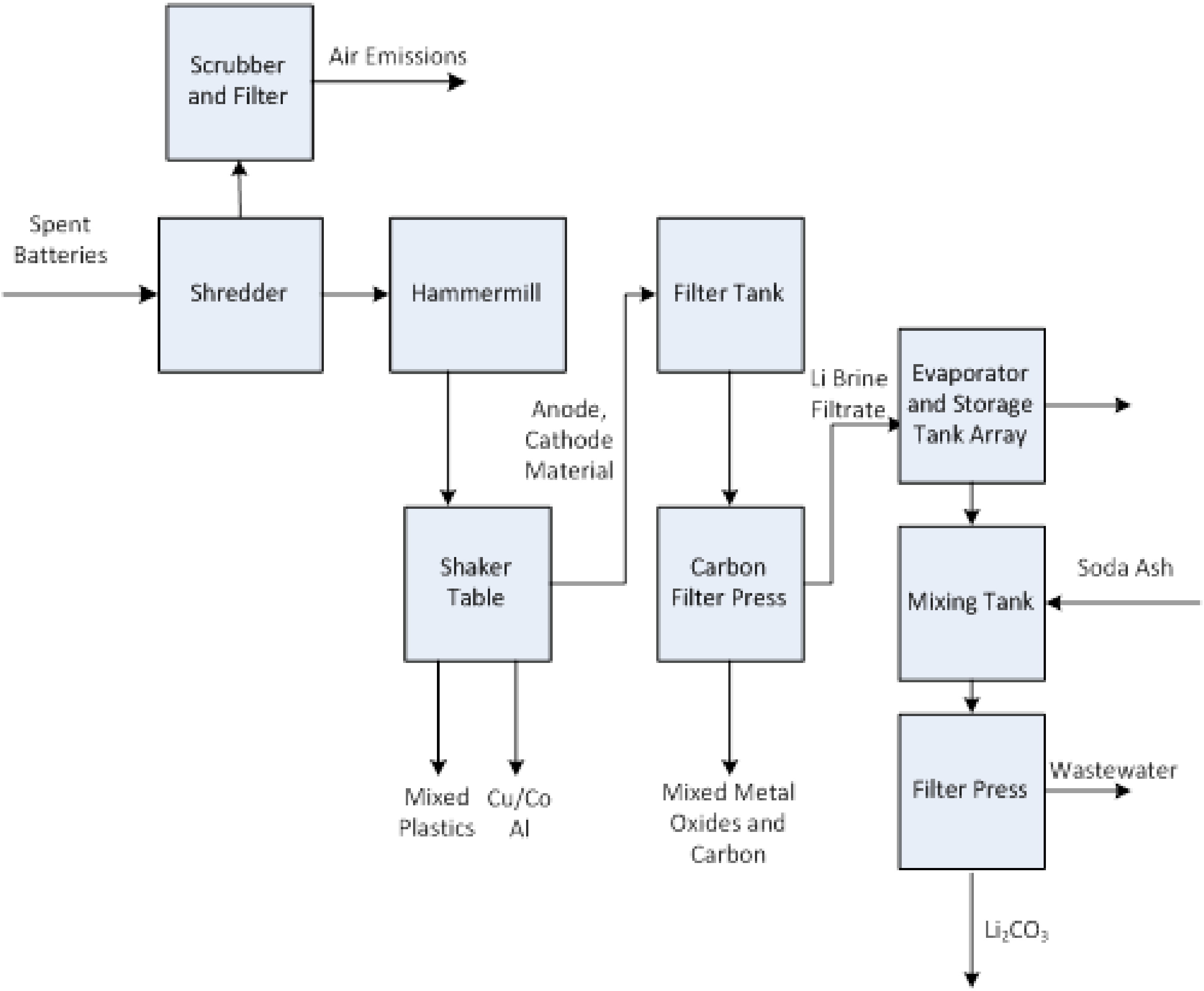


- ❑ **Benefits of using an organic acid motivated development**
  - **No toxic gases released**
  - **Waste solution is low-impact**
- ❑ **Citric acid is the least energy-intensive of the organic acids**
  - **Corn production uses 1/10th as much fossil fuel as butane production**

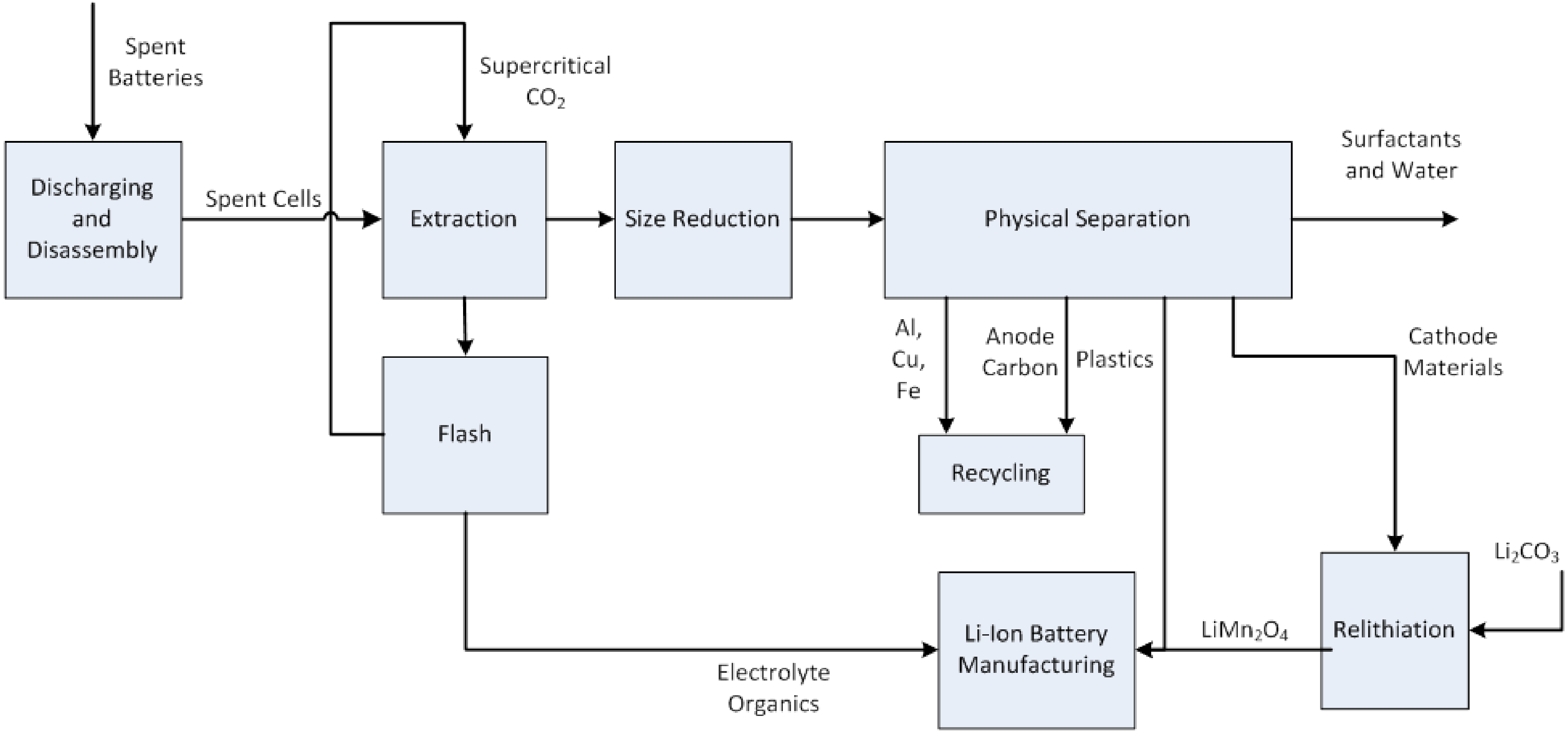
Pyrometallurgical Process: Commercial smelting process recovers some metals



Intermediate physical recycling process recovers lithium carbonate and all metals



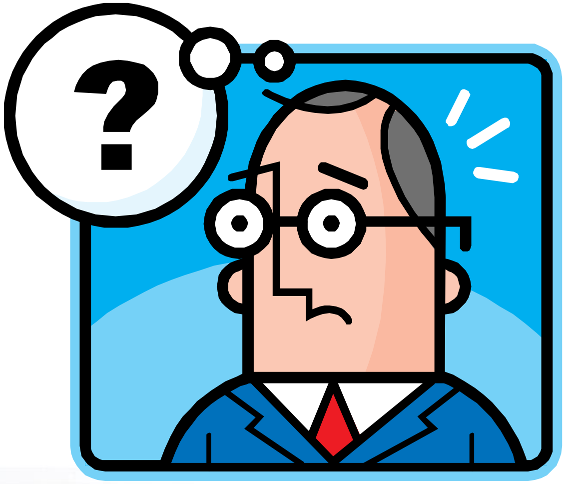
Bench-scale direct physical recycling process recovers battery-grade materials



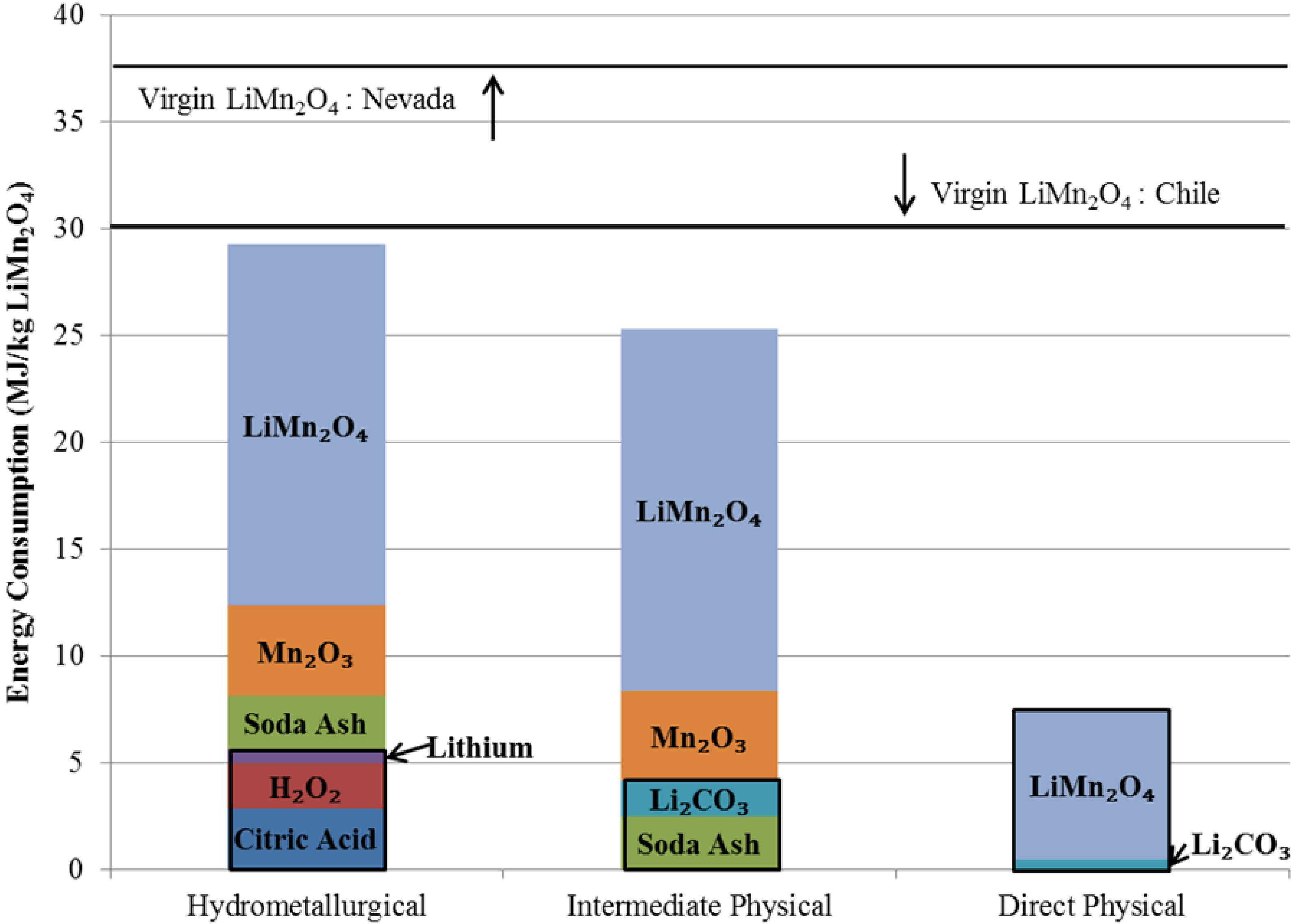
What if another cathode is used instead of $LiCoO_2$?

- ☐ **Value of product streams relying on Co is reduced**
- ☐ **Direct process could still be recover high-value cathode material**
- ☐ **Work is in progress to separate mixed cathode streams**

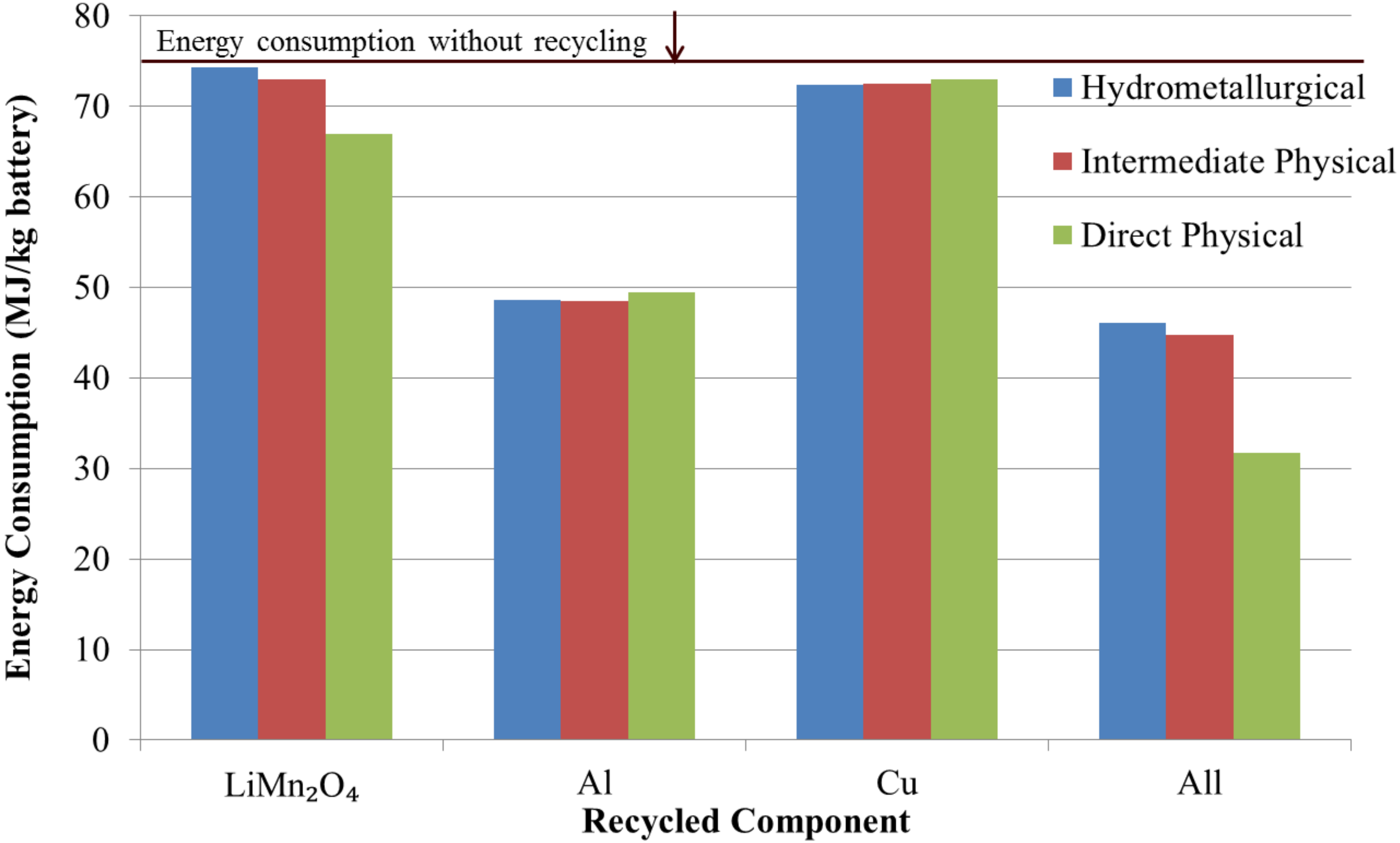
- ☐ **We haven’t even begun to think about Li-S, Li-air or other developing chemistries yet.**



Recycling the cathode material offers energy savings



Recycling structural materials increases the savings



The key factor in Li-ion battery recycling is economics

- ☐ **Value of elements contained may be low**
- ☐ **Value of active materials is high**
- ☐ **Objective is to recover highest value product**

Cathode	Price of Constituents ($/lb)	Price of Cathode ($/lb)
$LiCoO_2$	$9.90	12.00[3,4]
$LiNi_{.3}Co_{.3}Mn_{.3}O_2$	$6.10	$8.80[4]
$LiMnO_2$	$1.35	$4.50[2]
$LiFePO_4$	$0.75[1]	$9.10[2]

Sources:
1 Battery Recycling Technology, T. Ellis and J. Hohn, RSR Technologies (adjusted)
2 Modeling of Manufacturing Costs of Lithium-Ion Batteries for HEVs, PHEVs, and EVs, D. Santini, K. Gallagher, and P. Nelson
3 http://www.asianmetal.com/news/viewNews.am?newsId=782720
4 Chinese prices of cathode material for lithium-ion batteries rise, Metal-Pages (8/17/11)

Rest-of-battery recycling will help economics

- **In Europe, 50% of cell materials must be recycled as of 9/26/11**
  - **Collection is assumed**
  - **Goals have not yet been achieved**
- **The rest of the battery is included in the EU 95% auto recycling requirement**
  - **This may include enough valuable materials to make recycling the battery pay, even if $LiFePO_4$ cathodes are used**
- **The responsibility for EU recycling belongs to the company that makes the consumer product**

Recycling processes differ in important ways

	Pyrometallurgical	Hydrometallurgical	Physical
Temperature	High	Low	Low
Materials recovered	Co, Ni	Metal 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

How can we make it happen?

Several strategies could facilitate recycling

Ideal world:

- Standard configurations of packs and cells
  enable design of recycling equipment
- Standardization of chemistry
  reduces need for sorting and multiple processes

Real world:

- Cell labeling will enable sorting
  - SAE working groups are developing chemistry identification and labeling
- Design for disassembly would enable material separation
- Favorable economics and regulations both needed
  - US and China rely on development of economically-viable processes
    - *Must also be environmentally sound*
  - Europeans mandate recycling because it’s the right thing to do
  - A combination of the two might work better

Thank you!

- ❑ US work sponsored by USDOE Office of Vehicle Technologies
- ❑ Contact me: lgaines@anl.gov