A Comparison of Li-Ion Battery Recycling Options

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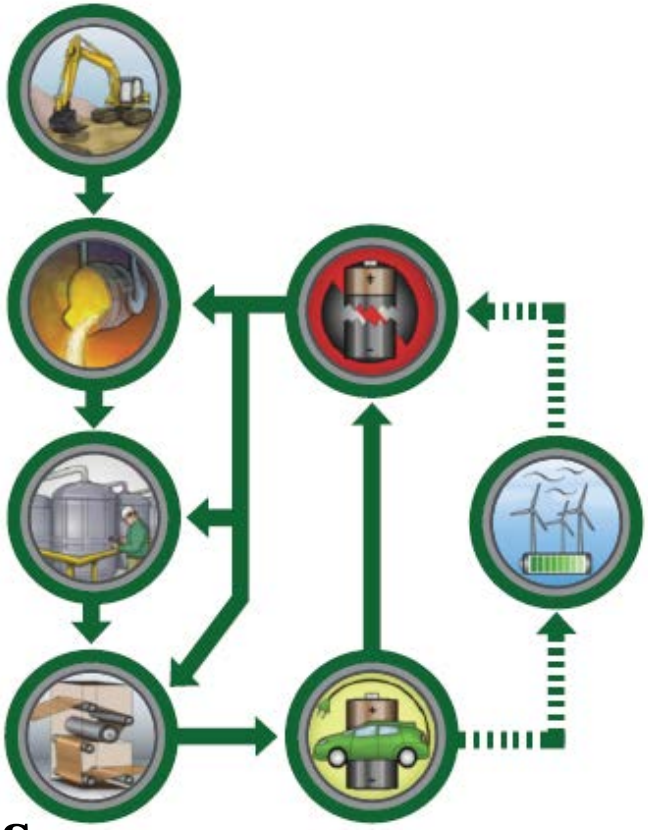
Why think about recycling?

- Material scarcity alleviated
- Recycled materials cheaper
- Production impacts avoided
  - Energy use
  - Emissions
  - Mining impacts
- Legally required



- But not all recycling processes are created equal
- Which is best?
  - LCA identifies "greenest" processes
  - May not be most economical
    - *Economics depends on what is recovered*
  - There may be other issues as well

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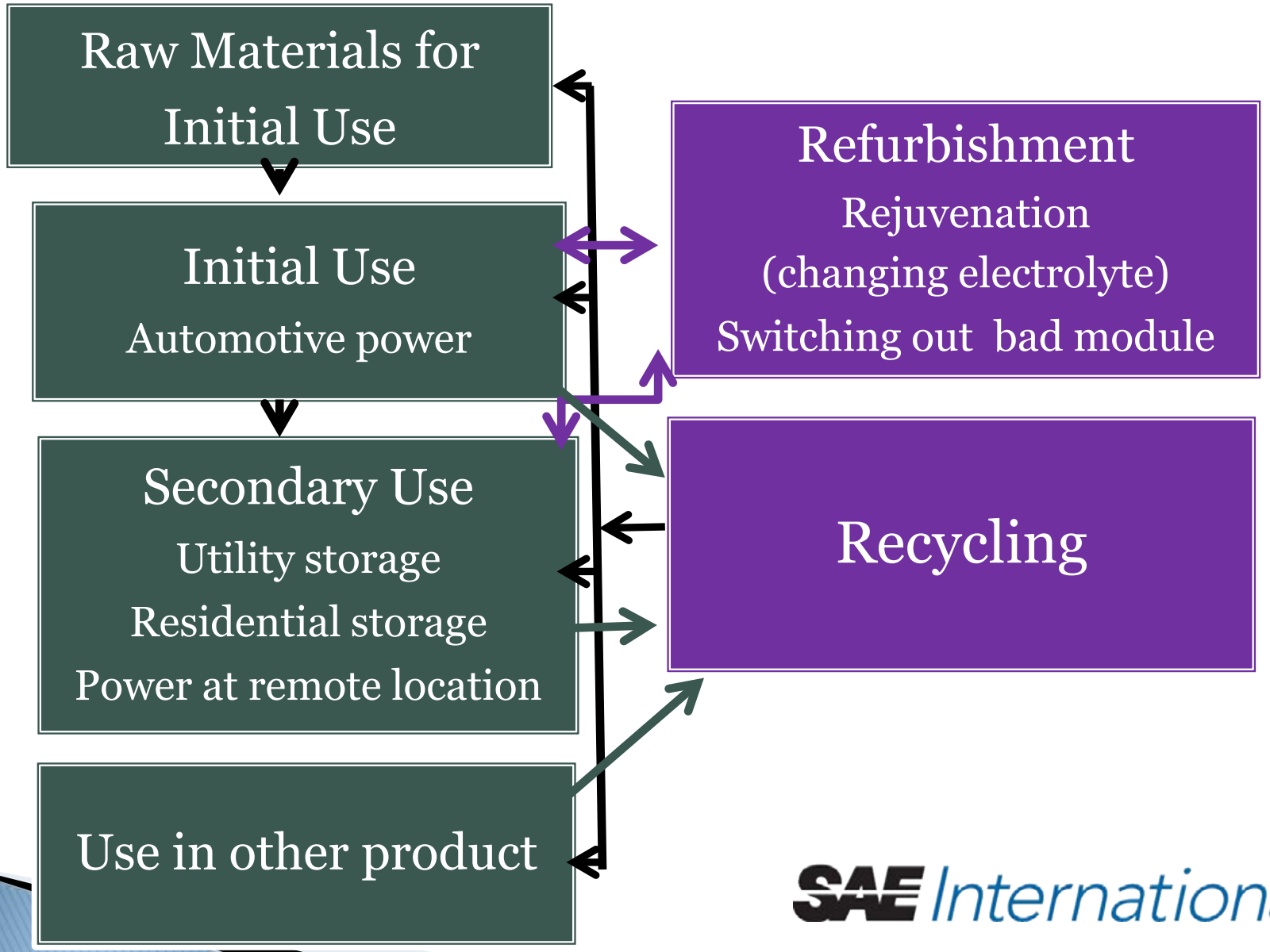
Battery materials could get used multiple times



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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)

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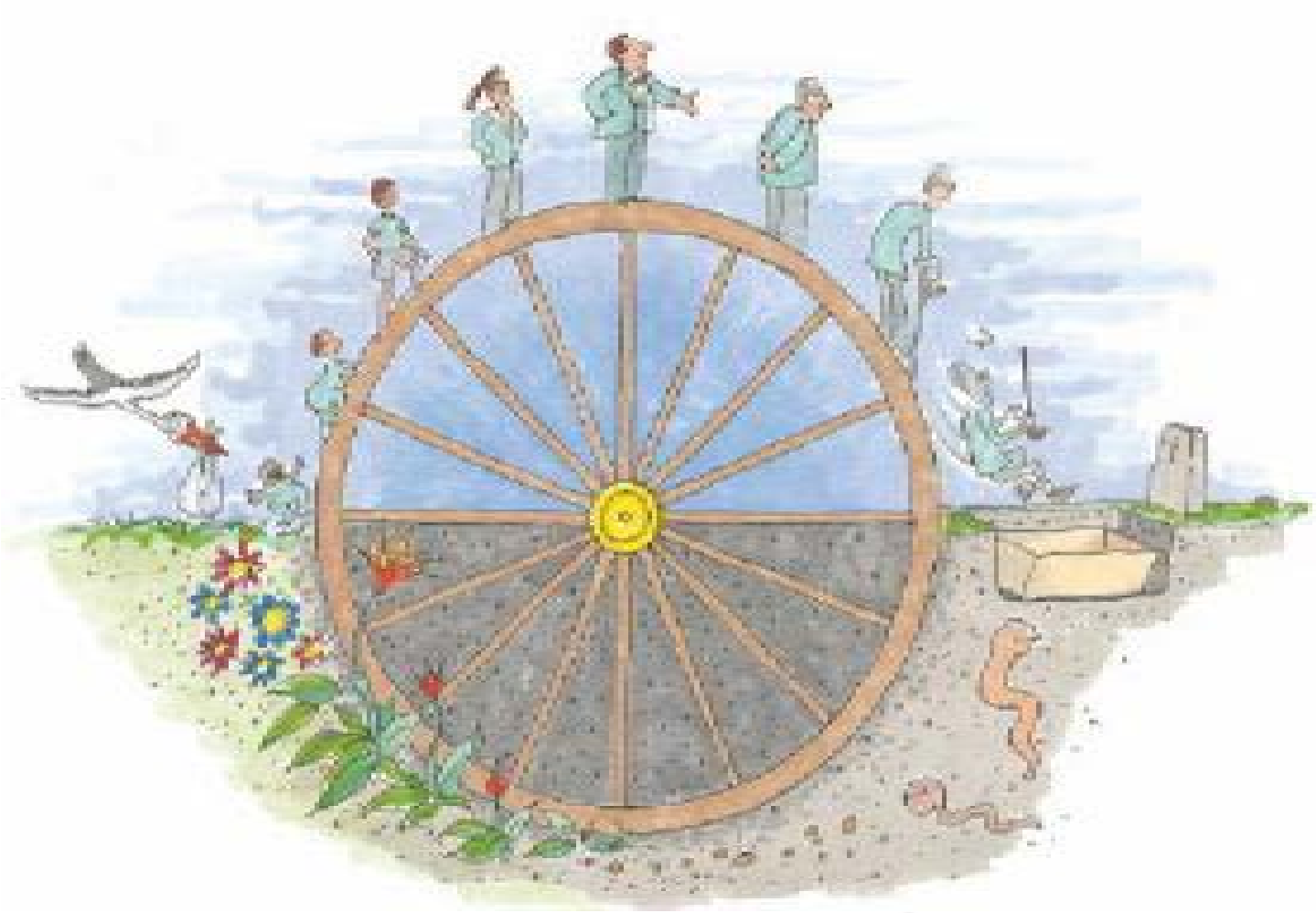
Lifecycle analysis compares all process impacts

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



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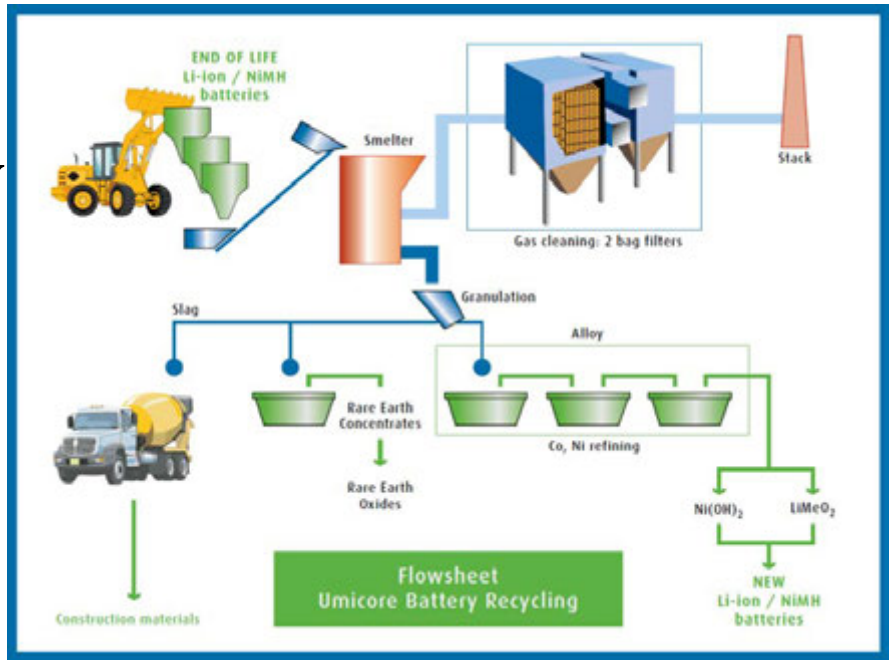
Smelting processes avoid some metal ore processing

- **These can take just about any input, high volume**
- **High-temperature required**
  - Organics are burned for process energy
- **Valuable metals (Co, Ni, Cu) are recovered and sent to refining**
  - Suitable for any use
  - 70% of cobalt production energy
  - Fabrication still needed
  - Less Co → less value
- **Volatiles burned at high-T**
- **Li, Al go to slag**
  - Could be recovered



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

- **Value of product stream is reduced**
  - Cu is still recovered in smelter
  - Co plant probably won't want the shredded batteries
- **Ni is recovered in the product stream**
- **Fe from the $LiFePO_4$ will be partially in the metal fraction and partially in the slag with the phosphate**
- **Heat available for smelter is reduced if titanate replaces carbon**
- **Li, Al, Mn, and Ti from titanate anodes all go to slag**
- **Material recovery from slag may have greater impacts than primary production**
- **Smelter chemistry could be altered to recover Li**

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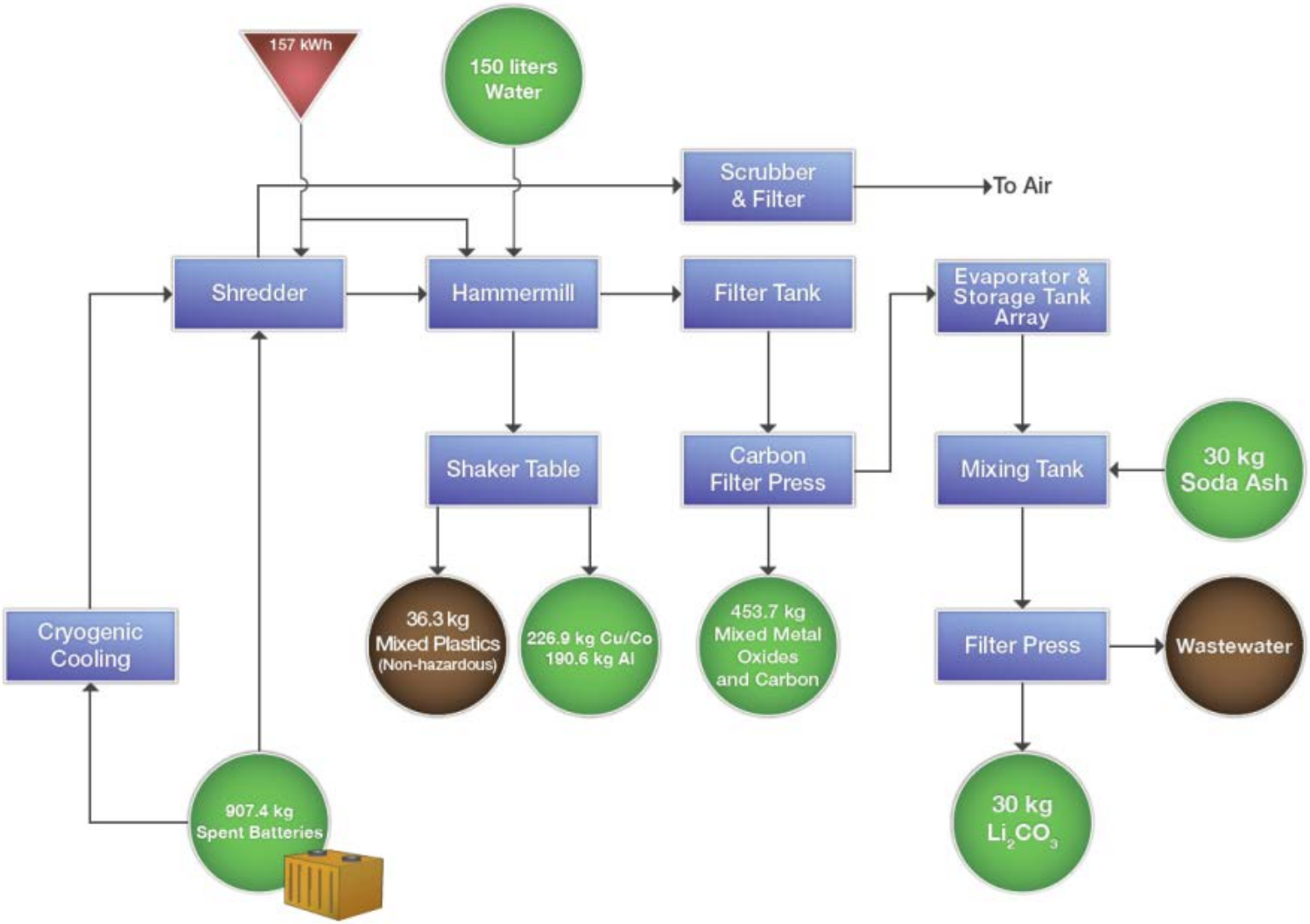
Lithium carbonate and cobalt can be recovered in current Toxco process



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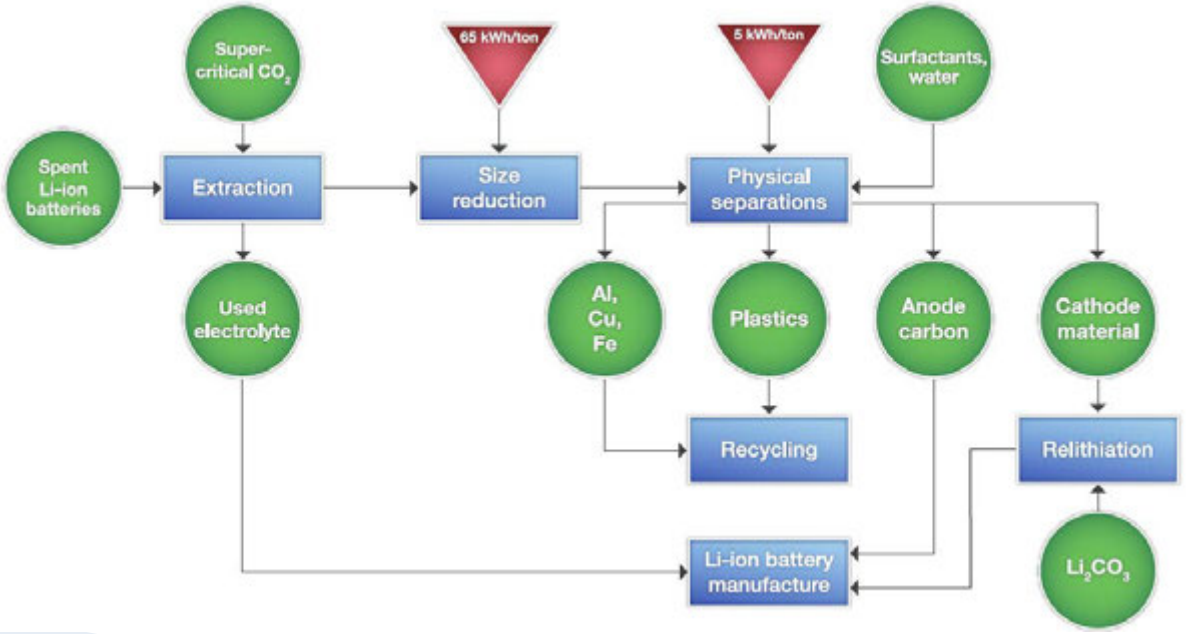
Recovery of battery-grade materials avoids impacts of virgin material production

- **Requires as uniform feed as possible**
- **Components are separated to retain valuable material structure**
  - **Costs lower than virgin materials**
  - **Purify/reactivate components if necessary for new batteries**
  - **Separator unlikely to be usable, as form cannot be retained**
- **Low-temperature process, low energy requirement**
- **Does not require large volume; could process prompt scrap**



DOE is funding a large-format battery recycling facility

- **New plant will recycle Ni-MH and Li-ion batteries**
- **Undisclosed process will separate/isolate constituents to produce battery-ready materials**
  - **From Ni-MH batteries**
    - *Rare earths*
    - *Nickel*
  - **From Li-ion batteries (possible)**
    - Anode materials
    - *$LiCoO_2$*
    - *$LiFePO_4$*
    - *Electrolyte (EC, EMC, DC)*

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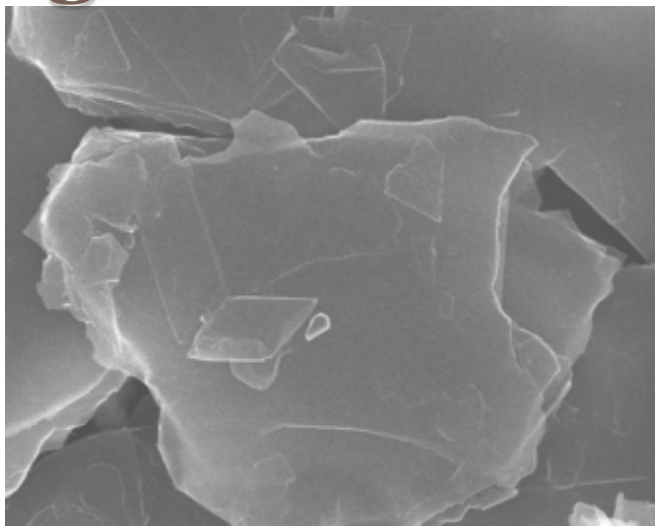
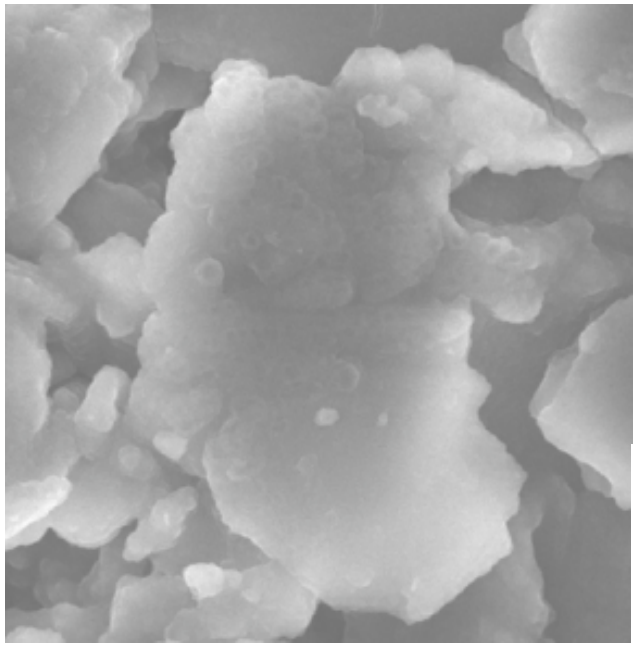
Active materials may be degraded after use

- Quality and performance must be verified
- Treatment to upgrade could be developed
- Material may be suited for lower-performance uses
- Number of re-uses might be limited for some materials
- Material may be obsolete when recovered

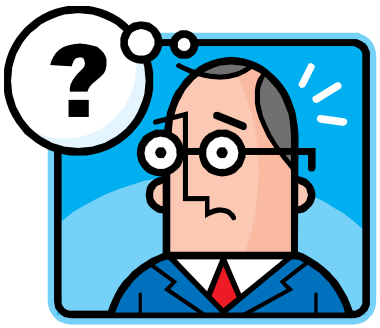


Graphite:
New and after 50% power fade



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

- **Process should work, with minor modifications**
  - **Demonstration has been funded**
  - **Also demonstrated with Ni-MH**
- **Work in progress to separate mixed cathode streams**
- **High-value cathode material could still be recovered for possible reuse in new batteries**
  - **Even if cathode made from low-cost raw materials**
  - **But will the material be obsolete when it is recovered?**
  - **Could other high-value products be produced?**



- **We haven't even begun to think about Li-S or other developmental chemistries yet.**

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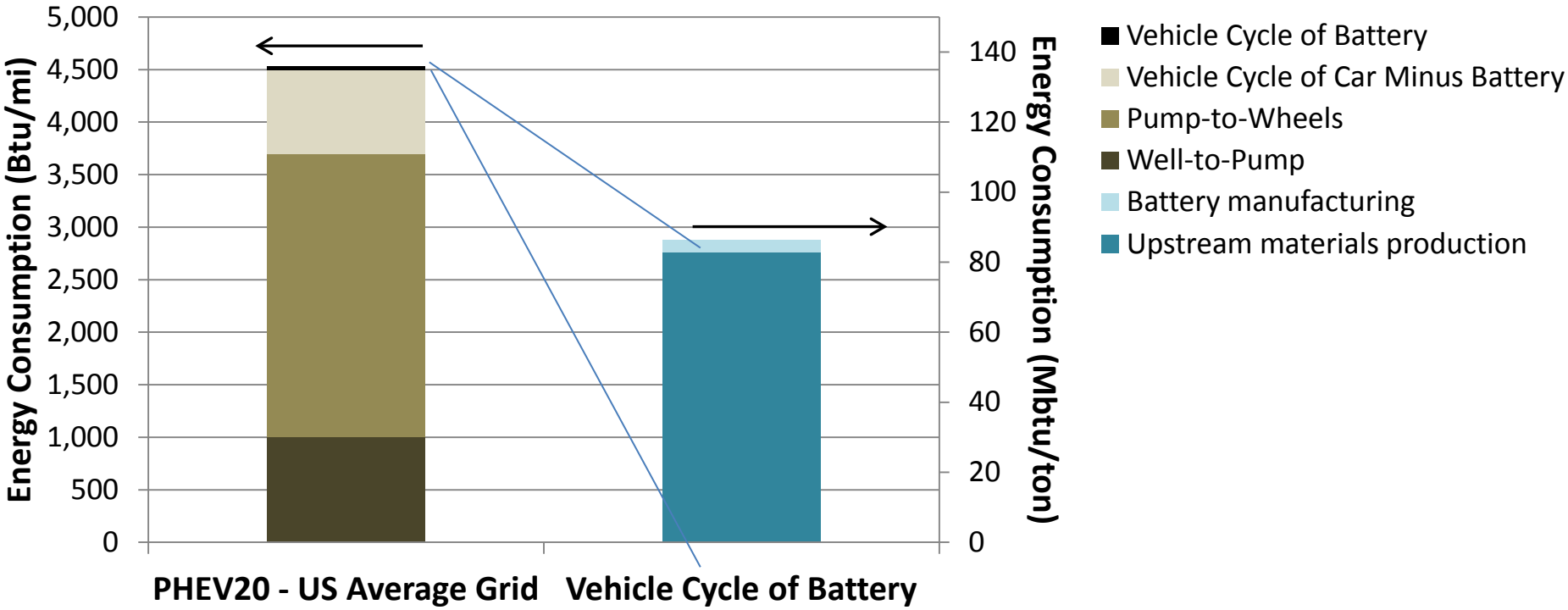
Battery materials are responsible for only 2% of energy but as much as 20% of life-cycle SOx!



This is for a PHEV-20.
Battery impacts rise with all-electric range.
SOx result is for Co- or Ni-based cathode.

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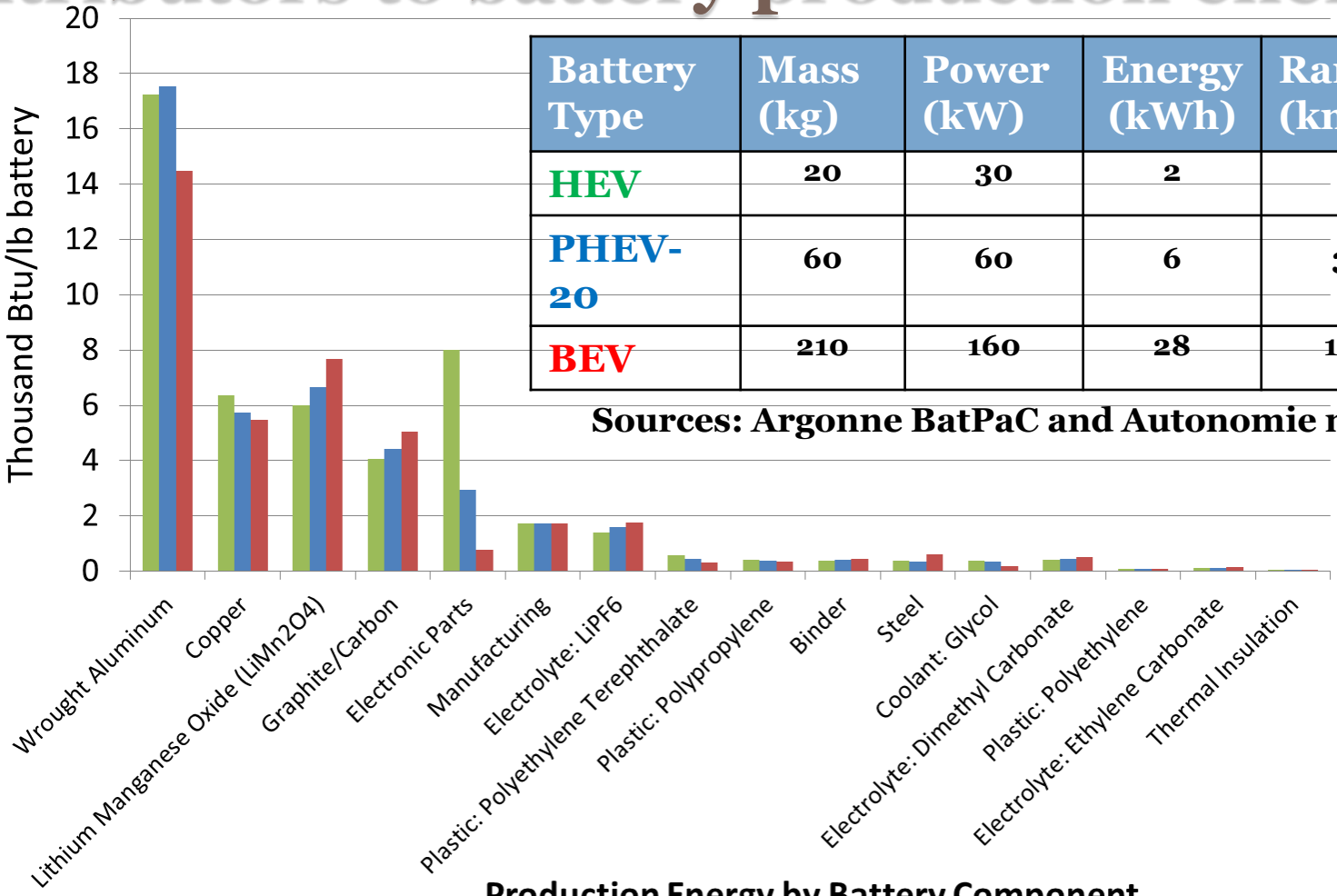
Recyclable structural metals are key contributors to battery production energy



Battery Type	Mass (kg)	Power (kW)	Energy (kWh)	Range (km)
HEV	20	30	2	
PHEV-20	60	60	6	32
BEV	210	160	28	160

Sources: Argonne BatPaC and Autonomie models

Production Energy by Battery Component

(Preliminary Results)

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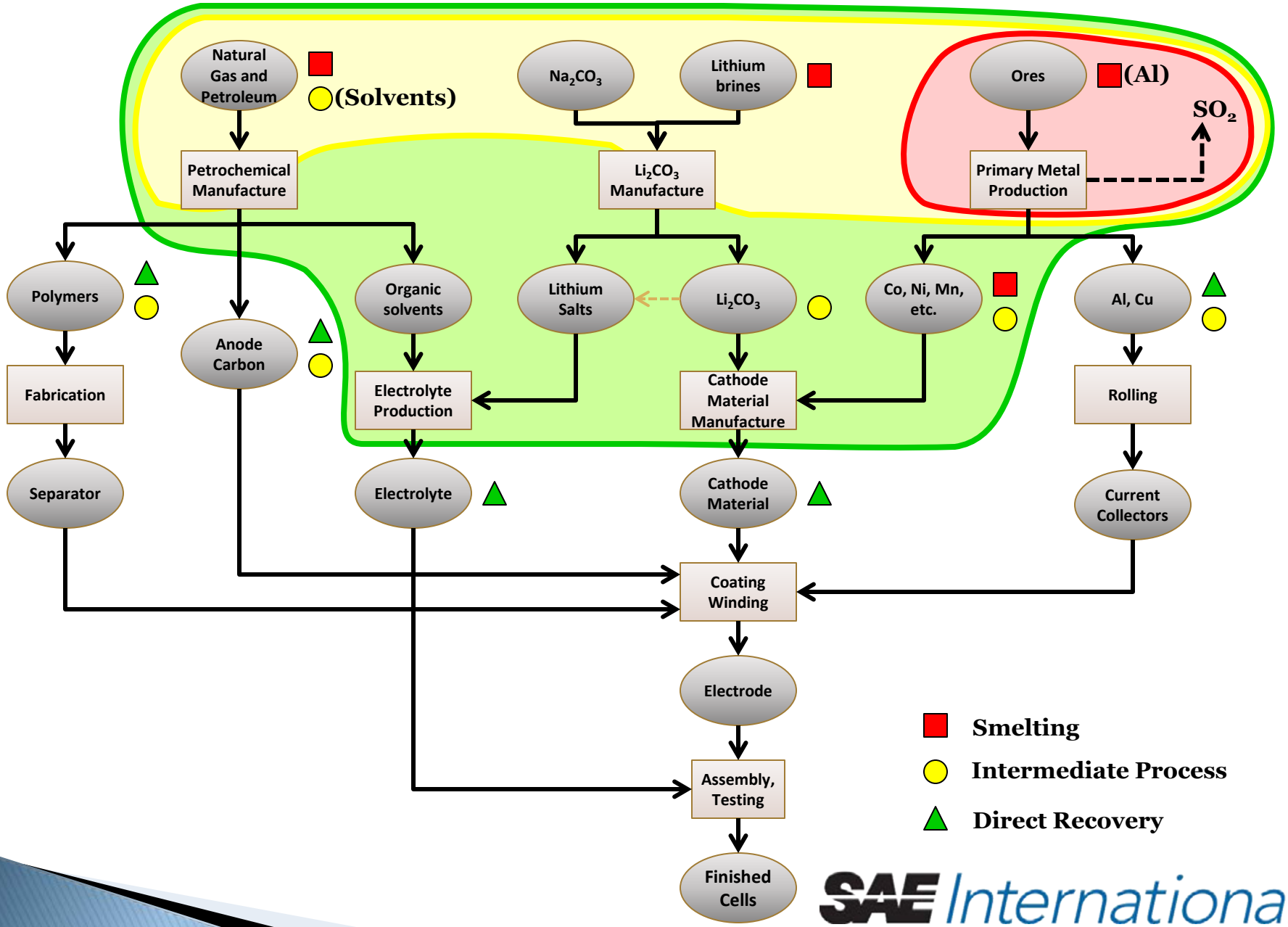
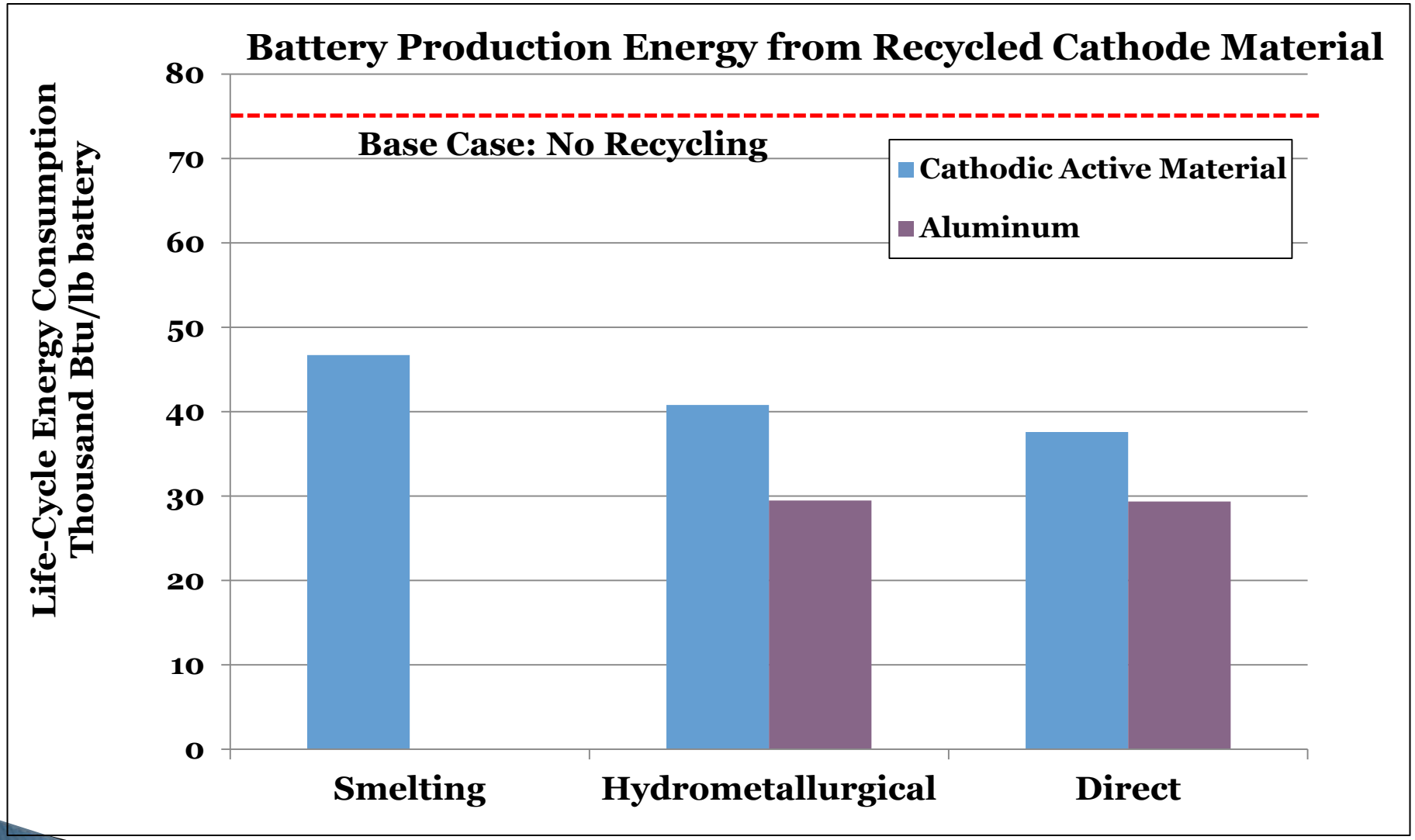
Source: J. B. Dunn, M. Barnes, L. Gaines, J. Sullivan. Material and Energy Flows in the Life Cycle of Lithium-Ion Batteries. Argonne Technical Report. http://greet.es.anl.gov/publications (2012)


Natural Gas and Petroleum
(Solvents)
Na_2CO_3
Lithium brines
Ores
(Al)
SO_2
Petrochemical Manufacture
Li_2CO_3 Manufacture
Primary Metal Production
Polymers
Organic solvents
Lithium Salts
Li_2CO_3
Co, Ni, Mn, etc.
Al, Cu
Anode Carbon
Fabrication
Electrolyte Production
Cathode Material Manufacture
Rolling
Separator
Electrolyte
Cathode Material
Current Collectors
Coating Winding
Electrode
Assembly, Testing
Finished Cells
Smelting
Intermediate Process
Direct Recovery

Aluminum recovery increases energy savings



(Preliminary results)

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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

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Several strategies could facilitate recycling

- **Standard configuration enables design of recycling equipment**
- **Chemistry standardization reduces need for sorting**
- **Cell labeling enables sorting**
- **Design for disassembly enables material separation**
- **SAE working group is discussing recycling issues**

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Thank you!

- **USDOE Office of Vehicle Technologies sponsors**
- **Contact me: lgaines@anl.gov**

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