Enabling Future Li-Ion Battery Recycling

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An automotive battery pack is a complex system.
Lithium-ion cells use many materials, and cathodes vary

<table>
<thead>
<tr>
<th>Cell component/battery type</th>
<th>Pb-acid</th>
<th>Ni-MH</th>
<th>Li-ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode</td>
<td>PbO₂</td>
<td>Ni(OH)₂</td>
<td>LCO, NCO, LFP, or LMO</td>
</tr>
<tr>
<td>Cathode plate/foil</td>
<td>Pb</td>
<td>Ni foam</td>
<td>Al</td>
</tr>
<tr>
<td>Anode</td>
<td>Pb</td>
<td>MH (AB₅)</td>
<td>graphite</td>
</tr>
<tr>
<td>Anode plate/foil</td>
<td>Pb</td>
<td>Ni-plated steel</td>
<td>Cu</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>H₂SO₄</td>
<td>KOH</td>
<td>Organic solvent + LiPF₆</td>
</tr>
<tr>
<td>Separator</td>
<td>PE or PVC + silica</td>
<td>polyolefin</td>
<td>PE/PP</td>
</tr>
<tr>
<td>Cell case</td>
<td>PP</td>
<td>Stainless steel</td>
<td>Metal or laminate</td>
</tr>
</tbody>
</table>

LCO = lithium cobalt oxide; NCM = nickel, cobalt, manganese; LFP = lithium iron phosphate; LMO = lithium manganese oxide
PE = polyethylene; PVC = polyvinyl chloride; PP = polypropylene
Life-cycle 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.
Most lithium comes from salars in the Andes and is concentrated in a series of ponds

- Impacts from this production are minimal
- Extraction from brine is slow, not energy-intensive
- The process energy comes primarily from sunlight
- Other salts are co-produced
Some assembly steps are performed in energy-intensive dry room

The areas in this diagram for each processing step are approximately proportional to the estimated plant areas in the baseline plant.
Aluminum and cathode materials dominate lithium-ion battery production energy

Batteries are small contributors to life-cycle energy use and CO$_2$ emissions
But make significant contributions to SO$_x$ emissions, especially if cathode contains cobalt or nickel.
Sulfur emissions cause environmental damage

Source: NASA poster NW 2011-10-093-GSFC
Why recycle?

- Recycling is a means, not an objective
- Objective is to provide some function with minimum impacts
  - Emissions reduction
  - Energy savings
  - Waste management
  - Cost reduction
  - Resource conservation
- Trade-offs among impacts may lead to different paths

`Would you tell me, please, which way I ought to go from here?'

`That depends a good deal on where you want to get to,' said the Cat.

`I don't much care where--' said Alice.

`Then it doesn't matter which way you go,' said the Cat.

`--so long as I get somewhere,' Alice added as an explanation.

`Oh, you're sure to do that,' said the Cat, `if you only walk long enough.'
Materials could get used multiple times before recycling

- **Raw Materials for Initial Use**
  - Initial Use
    - Automotive power
  - Secondary Use
    - Utility storage
    - Residential storage
    - Power at remote location
  - Use in other product

- **Refurbishment**
  - Rejuvenation (changing electrolyte)
  - Switching out bad module

- **Recycling**
Recycling multiple materials maximizes energy savings and emission reductions.
Recycling metals made from sulfide ores reduces cathode environmental burden
Recycling enables Li reserves to meet world demand to 2050, even if demand is high

<table>
<thead>
<tr>
<th>Cumulative Demand to 2050 (Contained Li, 1000 Metric Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large batteries, no recycling</td>
</tr>
<tr>
<td>Smaller batteries, no recycling</td>
</tr>
<tr>
<td>Smaller batteries, recycling</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Reserve Estimates</th>
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</thead>
<tbody>
<tr>
<td>USGS Reserves*</td>
</tr>
<tr>
<td>USGS World Resource*</td>
</tr>
<tr>
<td>Other Reserve Estimates</td>
</tr>
</tbody>
</table>

Without recycling, Co use in U.S. alone could impact reserves

<table>
<thead>
<tr>
<th>Material</th>
<th>Availability (Million Tons)</th>
<th>Cumulative Demand</th>
<th>Percent Demanded</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>13</td>
<td>1.1</td>
<td>9</td>
<td>World reserve base</td>
</tr>
<tr>
<td>Ni</td>
<td>150</td>
<td>6</td>
<td>4</td>
<td>World reserve base</td>
</tr>
<tr>
<td>Al</td>
<td>42.7</td>
<td>0.2</td>
<td>0.5</td>
<td>US capacity</td>
</tr>
<tr>
<td>Iron/steel</td>
<td>1320</td>
<td>4</td>
<td>0.3</td>
<td>US production</td>
</tr>
<tr>
<td>P</td>
<td>50,000</td>
<td>2.3</td>
<td>~0</td>
<td>US phosphate rock production</td>
</tr>
<tr>
<td>Mn</td>
<td>5200</td>
<td>6.1</td>
<td>0.12</td>
<td>World reserve base</td>
</tr>
<tr>
<td>Ti</td>
<td>5000</td>
<td>7.4</td>
<td>0.15</td>
<td>World reserve base</td>
</tr>
</tbody>
</table>
Lead-acid battery recycling can serve as a model

- ~98% of U.S. Pb-acid batteries are collected and recycled
- Returned to producer by back-haul
- Transport and processing are regulated to protect people and the environment
- The product is standardized and accepted in the marketplace
Why does the Pb-acid system WORK so well?

- It’s profitable
- It’s illegal to discard them
- There’s a standard format
- The design is simple
- There’s a single chemistry
- The process is simple
What about nickel-metal hydride?

- Cell chemistry very similar across manufacturers
- Established recycling recovers ferronickel for use in stainless steel
- Chinese export restrictions are incentive to recover RE
- Several projects underway to recycle Ni-MH
- So they’re pretty much on track for successful recycling
All Li-ion recycling processes are NOT created equal!

- Different feedstock requirements
- Different products
- Different economics
- Different impacts
Recycling processes displace materials at different production stages.
Smelting avoids some metal ore processing

- High-temperature required; organics are burned
- Valuable metals (Co, Ni, Cu) are recovered
- Volatiles burned at high-T
- Li, Al go to slag
- Flexible process input
- Requires high volume
Lithium carbonate and metals are recovered in Trail, BC.
Recovery of battery-grade materials avoids impacts of virgin material production

- Components are separated to retain valuable material structure
- Requires uniform feed
- Low-temperature process
- Does not require large volume
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
# Recycling processes differ in important ways

<table>
<thead>
<tr>
<th></th>
<th>Pyrometallurgical</th>
<th>Hydrometallurgical</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Materials recovered</strong></td>
<td>Co, Ni, Cu (Li and Al to slag)</td>
<td>Metals or salts, (\text{Li}_2\text{CO}_3) or LiOH</td>
<td>Cathode, anode, electrolyte, metals</td>
</tr>
<tr>
<td><strong>Feed requirements</strong></td>
<td>None</td>
<td>Separation desirable</td>
<td>Single chemistry required</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>New chemistries yield reduced product value</td>
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<td>Recovers potentially high-value materials; Could implement on home scrap</td>
</tr>
</tbody>
</table>
Constituent elements may not be worth recovering, but cathode materials are
Making lithium-ion recycling work involves challenges

- There are many cell/pack sizes and shapes
- Complex packs include electronics and thermal control systems
- There are no regulations, so restrictive a threat
- The technology is still changing
- There is no standard chemistry
- Many materials have low market value
- Long-term performance of recycled materials is not proven
However, there are many positive factors

- Packs are large and recognizable
- If they last entire vehicle life, they will go to scrapyard
- Housing, circuitry may actually add to value
- Recovery of component materials intact could add value
- We’ve got 10 years to work it out!
What is needed to make Li-ion recycling viable?

- Separation technology to provide uniform streams
- Viable recycling processes for each chemistry, or
- Technology for processing mixed stream
- Process flexibility, or
- Convergence of materials and designs
- No regulations that impede recycling
Design for recycling can reduce recycling costs

- Include labels or other distinguishing features
- Use a minimum number of different materials
- Standardize formats and materials
- Avoid bad-actor materials (Cd, Ar, Hg, halogens)
- Enable easy separation of parts
  - Reversible joining (nuts and bolts, not welds)
  - No potting compounds
Segregation methods for large batteries will help

• Optimum separation point in recycling process chain is unclear
  – But rescreening might still be necessary

• Labeling technologies could help… eventually
  – Bar code
  – RFID chips
  – Paint color or type (e.g., visible under black light)

• Incentives and penalties might enhance compliance

• Careful separation is likely to increase recycling costs
The model system has encountered a problem

- There have been explosions at secondary lead smelters
- The cause is look-alike Li-ion batteries in feed
- Mixed in delivered pallets by accident or on purpose
  - Suppliers paid for Pb-acid, must pay to leave Li-ion
- Large volumes of material on rapidly-moving conveyors
- Lead batteries in Li-ion stream could also be problematic
Identification and sorting will is necessary

• Correct routing retains product value
• Where in the return flow is sorting done?
• Many possible methods
  • Visual: Training, labels, color coding
  • Density: Sink/Float separation before breaking
  • X-ray: Scanning plus gray scale analysis
  • RFID: Label manufactured in or added
• Misrouting can lead to explosions
Why be Concerned?

Courtesy of Richard Leiby
SAE Battery Recycling Committee is addressing this issue

• Mission: To coordinate and integrate battery recycling issues into the overall strategy of electrification and hybridization of transportation

• Diverse group has members from auto companies, battery makers, material suppliers, and recyclers
  – Coordinates with many other groups
  – Contacts are Patricia Ebejer [pebejer@sae.org] or Tim Ellis [Tellis@RSRCorp.com]
Drafted RP on preventing cross-contamination

- Already addressed labeling in Document J2984
  - Identification of Transportation Battery Systems for Recycling RP
- Preparing Document J3071
  - Automotive Battery Recycling Identification and Cross-Contamination Prevention

Input welcomed!
Thank you!

- Battery Council International
- USDOE Office of Vehicle Technologies
- Contact me: lgaines@anl.gov

- http://www.anl.gov/energy-systems/project/lithium-ion-battery-recycling-and-life-cycle-analysis