Lithium-Ion Battery Production and Recycling Materials Issues

Project ID: ES229

VTO Annual Merit Review
June 9, 2015

Linda Gaines and Jennifer Dunn
Argonne National Laboratory

This presentation does not contain any proprietary, confidential, or otherwise restricted information
# Acronyms list

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BatPaC</td>
<td>Battery Performance and Cost (model)</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery electric vehicle</td>
</tr>
<tr>
<td>BMS</td>
<td>Battery management system</td>
</tr>
<tr>
<td>EV</td>
<td>Electric vehicle</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GREET</td>
<td>Greenhouse gases, Regulated Emissions, and Energy use in Transportation</td>
</tr>
<tr>
<td>HT</td>
<td>Hydrothermal</td>
</tr>
<tr>
<td>ICP-MS</td>
<td>Inductively coupled plasma mass spectroscopy</td>
</tr>
<tr>
<td>ICV</td>
<td>Internal combustion engine vehicle</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle analysis</td>
</tr>
<tr>
<td>LCO</td>
<td>Lithium cobalt oxide</td>
</tr>
<tr>
<td>LFP</td>
<td>Lithium iron phosphate</td>
</tr>
<tr>
<td>LMO</td>
<td>Lithium manganese oxide</td>
</tr>
<tr>
<td>LMR-NMC</td>
<td>Lithium manganese-rich nickel manganese cobalt</td>
</tr>
<tr>
<td>NCA</td>
<td>Nickel cobalt aluminum</td>
</tr>
<tr>
<td>NMC</td>
<td>Nickel Manganese Cobalt</td>
</tr>
<tr>
<td>NMP</td>
<td>n-Methylpyrrolidone</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene fluoride</td>
</tr>
<tr>
<td>SS</td>
<td>Solid state</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
</tbody>
</table>
Overview

Timeline

- Project start date: FY2008
- Project end date: Ongoing
- On schedule

Barriers

- Automotive lithium-ion battery performance, safety, and environmental metrics must be co-optimized
- Battery recycling technology must handle uncertainty in battery chemistry developments
- Computational models, design, and simulation methodologies must be developed
- Constant advances in technology require model updating

Budget

<table>
<thead>
<tr>
<th></th>
<th>FY 14 Funding ($k)</th>
<th>FY 15 Funding ($k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life Cycle Analysis</td>
<td>$100</td>
<td>$100</td>
</tr>
<tr>
<td>Battery Reuse and Recycling</td>
<td>$125</td>
<td>$125</td>
</tr>
<tr>
<td>IEA Task 19</td>
<td>$40</td>
<td>$40</td>
</tr>
<tr>
<td>Total</td>
<td>$265</td>
<td>$265</td>
</tr>
</tbody>
</table>

Partners

- In-kind
  - JOANNEUM Research
  - German Aerospace Center (DLR)
  - EMPA

- Supported
  - OnTo Technology
  - University of Wisconsin at Milwaukee
Relevance and Project Objectives

- **Project Objectives:**
  - Examine material scarcity issues that may influence viability of automotive lithium-ion batteries
  - Characterize drivers of cradle-to-gate energy and GHG emissions intensity of lithium-ion batteries and identify means for their reduction
  - Characterize lithium-ion battery recycling in the United States and abroad to identify the most promising recycling technologies as they evolve, barriers to recycling, and influence of recycling on material scarcity
  - Engage with the international battery analysis community to exchange information, improve analysis, and formulate electric vehicle life cycle analysis results communication

- **Relevance:**
  - Examining cradle-to-gate lithium ion battery production and battery recycling can identify unforeseen barriers and significant environmental impacts in the battery supply chain
## Key Milestones

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/14</td>
<td>Present electrolyte and cobalt/nickel production influence on recycling benefits at international conference</td>
<td>Complete</td>
</tr>
<tr>
<td>9/14</td>
<td>Journal article submitted analyzing FY14 lithium-ion recycling research</td>
<td>Complete</td>
</tr>
<tr>
<td>3/15</td>
<td>Present battery recycling barrier analysis at International Battery Seminar</td>
<td>Complete</td>
</tr>
<tr>
<td>6/15</td>
<td>Preliminary data in hand for revised and expanded anode choices in GREET and available in draft GREET version</td>
<td>On track</td>
</tr>
<tr>
<td>9/15</td>
<td>Cradle-to-gate life cycle results for lithium-ion batteries with graphite, silicon, and lithium anodes provided in memo to VTO</td>
<td>On track</td>
</tr>
<tr>
<td>9/15</td>
<td>Provide a report on the progress and status of IEA Task 19</td>
<td>On track</td>
</tr>
</tbody>
</table>
Approach/Strategy: Project flow

1. Battery Performance and Cost
2. Greenhouse gases, Regulated Emissions, and Energy use in Transportation
**Approach/Strategy:** GREET battery module estimates material and energy consumption, air emissions associated with battery production and recycling.

Vehicle characteristics and fuel economy

Battery cost and composition to achieve a given performance

Energy, GHG, and air emissions intensity of battery cradle-to-gate production and recycling
Technical Accomplishments and Progress

1. Material Scarcity
2. Environmental and Energy Analysis of Lithium-Ion Battery Production from Cradle to Gate
3. Recycling of Automotive Lithium-Ion Batteries
4. International Engagement
Technical Accomplishments and Progress

1. Material Scarcity
2. Environmental and Energy Analysis of Lithium-Ion Battery Production from Cradle to Gate
3. Recycling of Automotive Lithium-Ion Batteries
4. International Engagement
Lithium supplies should be adequate but cobalt and nickel supplies could be strained

<table>
<thead>
<tr>
<th>Material</th>
<th>Availability (MT)</th>
<th>Cumulative Demand</th>
<th>%</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>

Reserve Estimates

USGS Reserves* 13
USGS World Resource* 29
Other Reserve Estimates 30+


Critical Materials Strategy, USDOE (December 2010)
Technical Accomplishments and Progress

1. Material Scarcity
2. Environmental and Energy Analysis of Lithium-Ion Battery Production from Cradle to Gate
3. Recycling of Automotive Lithium-Ion Batteries
4. International Engagement
GREET battery module contains life-cycle inventory of lithium-ion battery production and recycling.
Cobalt and silicon are the most energy-intensive materials to include in supply chain

Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G., “The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling’s role in its reduction.”, *Energy and Environmental Science* 8: 158-168 (2015)
Batteries are small contributors to life-cycle energy use and CO$_2$ emissions.

Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G.," The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction."; *Energy and Environmental Science* 8: 158-168 (2015)
But they make significant contributions to life-cycle SOx emissions, especially if the cathode contains Co or Ni.

Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G., “The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling’s role in its reduction.”, *Energy and Environmental Science* 8: 158-168 (2015)
Technical Accomplishments and Progress

1. Material Scarcity
2. Environmental and Energy Analysis of Lithium-Ion Battery Production from Cradle to Gate
3. Recycling of Automotive Lithium-Ion Batteries
4. International Engagement
Recycling multiple materials maximizes energy savings and emission reductions

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.”, *Environmental Science and Technology*, 46: 12704-12710 (2012)
Recycling metals made from sulfide ores reduces cathode environmental burden
Recycling processes displace materials at different production stages.
### Available processes recover different products

<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, Li$_2$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>
<td>New chemistries yield reduced product value</td>
<td>Recovers potentially high-value materials; Could implement on home scrap</td>
</tr>
</tbody>
</table>
Cathode viability is key to economics for cathodes with low elemental values

- Cathode materials are valuable, even if elements aren’t.
- What processes enable retaining cathode properties?
- Acid/base could separate active materials from substrates
  - Would that damage cathode morphology?
  - How does the answer depend on pH, temperature, and time?

![Bar chart showing the price of constituents and cathode for different materials](chart.png)

- Price of Constituents ($/lb)
- Price of Cathode ($/lb)
Cathode materials’ performance will be tested after treatment with acid or base

- The plan:
  - Characterize the materials after treatment in aqueous solutions

- Details:
  - Cathodes: LCO, NMC, NCA, LMO and LFP
  - Solutions: hydrochloric acid, water, ammonium hydroxide
  - pH: 2, 7, 12 (0.25 molar)
  - Temperatures: 30⁰, 50⁰ C

- Before and after measurements:
  - Analysis by ICP-MS
  - Electrochemical testing in half cells

- Preliminary results show loss of Li in acid
  - Final results will be available by July
Challenges to recycling can be addressed by R&D

<table>
<thead>
<tr>
<th>Challenge</th>
<th>R&amp;D needed to address</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term performance of some recycled materials is not proven</td>
<td>Long-term testing</td>
</tr>
<tr>
<td>There is no standard chemistry or design</td>
<td>Convergence of chemistries and designs</td>
</tr>
<tr>
<td></td>
<td>Flexible processes</td>
</tr>
<tr>
<td></td>
<td>Design for recycling</td>
</tr>
<tr>
<td></td>
<td>Automation</td>
</tr>
<tr>
<td>There are no regulations, so restrictive ones could be imposed</td>
<td>Fashioning regulations that will protect health and safety without hindering recycling</td>
</tr>
<tr>
<td>Many of the constituents have low market value</td>
<td>Process development to recover multiple high-value materials</td>
</tr>
<tr>
<td>Low value of mixed streams, prevention of fires and explosions</td>
<td>Effective labeling and sorting</td>
</tr>
</tbody>
</table>
Why be Concerned?

Courtesy of Richard Leilby
Technical Accomplishments and Progress

1. Material Scarcity
2. Environmental and Energy Analysis of Lithium-Ion Battery Production from Cradle to Gate
3. Recycling of Automotive Lithium-Ion Batteries
4. International Engagement
IEA Hybrid and Electric Vehicle Implementing Agreement Task 19: Electric Vehicle Life Cycle Analysis

- Engaged in task planning and now serve as Vice Operating Agent
- Objectives include facilitating information exchange among international experts, identifying outstanding issues in EV LCA, and communicating results and information to a broader audience.
- Argonne presented at all workshops
  - LCA Methodology and Case Studies (December 2012, Braunschweig)
  - LCA Aspects of Battery and Vehicle Production (April 2013, Argonne)
  - End of Life Management (October 2013, Davos)
  - LCA of Electricity Production and Infrastructure (October 2014, Barcelona)
- Conference papers and presentations produced
- Workshop planned to cap off project in Vienna, fall 2015
- Task extension to address air, water, land (use, waste, and resource use) impacts of EVs in depth
Response to Previous Year Reviewers’ Comments

This project has not been previously reviewed.
Collaboration and Coordination with Other Institutions

- Collaboration with entities involved in IEA Task 19
  - JOANNEUM Research (Austria)
  - German Aerospace Agency (DLR)
  - EMPA (Switzerland)

- Interactions with battery industry (e.g., SAFT, Johnson Controls, East Penn)

- Interactions with recycling companies (e.g. Entek, JCI, BCI, ALABC, Umicore, Onto)

- Collaboration with Beijing Institute of Technology led to energy and environmental assessment of hydrometallurgical recycling process and paper
Remaining Barriers and Challenges

- New cathode materials and battery compositions require expansion of GREET battery module to address evolving technology
- Data access can be limited given emerging and evolving technology status, proprietary data concerns
- Analysis has focused on GHG and energy impacts; other media (e.g., water) should be examined for show-stoppers
- Characterizing material and energy flow data for anode materials (ongoing)
- Demonstration and analysis of viable recycling processes for promising chemistries
Proposed Future Work

- Collaboration with Joint Center for Energy Storage Research and BatPaC model developers at Argonne to identify emerging chemistries that merit analysis
- Refine GREET module as new data become available
- Examine local impacts of battery material production (e.g., emissions to air and water)
- Refine analysis of recycling processes to better estimate benefits and enable optimum process development
- Examine alternative sources of cathode metals, such as recycled batteries from electronic devices
Summary

- Argonne’s analysis enables VTO to identify the drivers of automotive lithium-ion battery energy and environmental impacts, guide R&D to mitigate them, and address stakeholder concerns regarding these impacts.
- Engagement with the international battery analysis community enables information exchange and results dissemination.
- The cradle-to-gate energy consumption and GHG emissions associated with battery production and recycling vary with battery chemistry.
- Material production, especially that of Co- and Ni-containing cathode materials, drives cradle-to-gate lithium-ion battery production impacts.
- Recycling reduces concerns about material supply, production impacts, and waste disposal.
Backup Slides
Battery module constructed to evaluate different chemistries

- Selected chemistries based on BatPaC and Argonne Research and Development
  - NCM: LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2
  - LMR-NMC: 0.5Li_2MnO_3·0.5LiNi_{0.44}Co_{0.25}Mn_{0.31}O_2
  - LCO: LiCoO_2
  - LFP: LiFePO_4
  - LMO: LiMn_2O_4

- Graphite-Silica anodes for LMR-NMC; other chemistries are paired with graphite anodes

- For some cathode materials investigated two preparation techniques:
  - HT: Hydrothermal
  - SS: Solid State

- Material and energy flows developed based on literature data, engineering calculations
Cobalt- and nickel-containing cathode materials are most energy intensive to produce

Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G.,“The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling’s role in its reduction.”, Energy and Environmental Science 8: 158-168 (2015)
Cobalt and nickel production is SOx intensive

Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G.," The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling’s role in its reduction." , *Energy and Environmental Science* 8: 158-168 (2015)