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

Acronyms list

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

Overview

Timeline

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

Budget

	FY 14 Funding ($k)	FY 15 Funding ($k)
Life Cycle Analysis	$100	$100
Battery Reuse and Recycling	$125	$125
IEA Task 19	$40	$40
Total	$265	$265

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

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

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

Approach/Strategy: Project flow

Identify Emerging Issues
- Battery chemistries
- Recycling technologies
- Unaddressed issues in battery LCA

Data Collection
- Industry
- Literature

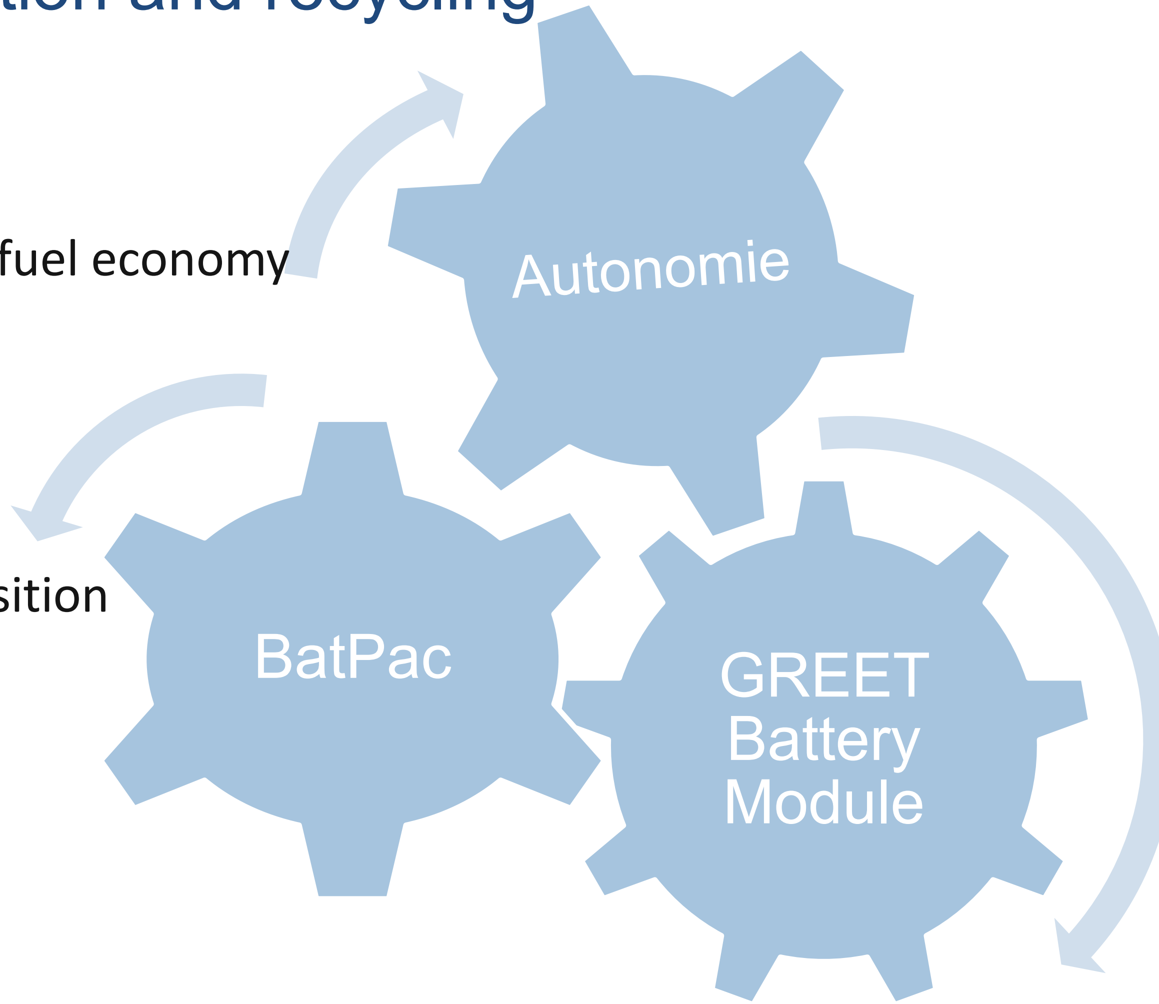
Analysis
- Argonne's BatPaC[1] model
- Argonne's GREET[2] model battery module

Release Results
- Updated GREET model
- Publications and reports

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

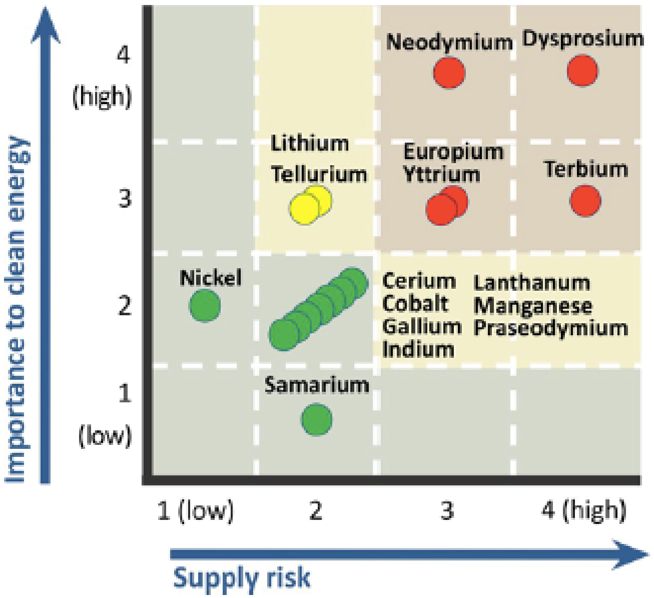
1. Material Scarcity
2. Environmental and Energy Analysis of Lithium-Ion Battery Production from Cradle to Gate
3. Recycling of Automotive Lithium-Ion Batteries
4. International Engagement

Lithium supplies should be adequate but cobalt and nickel supplies could be strained

	Cumulative Li Demand to 2050 (MT)
Large batteries, no recycling	6.5
Smaller batteries, no recycling	2.8
Smaller batteries, recycling	2.0
	Reserve Estimates
USGS Reserves*	13
USGS World Resource*	29
Other Reserve Estimates	30+

*Revised January 2011: http://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2011-lithi.pdf

Material	Availability (MT)	Cumulative Demand	%	Basis
Co	13	1.1	9	World reserve base
Ni	150	6	4	World reserve base
Al	42.7	0.2	0.5	US capacity
Iron/ steel	1320	4	0.3	US production
P	50,000	2.3	~0	US phosphate rock production
Mn	5200	6.1	0.12	World reserve base
Ti	5000	7.4	0.15	World reserve base

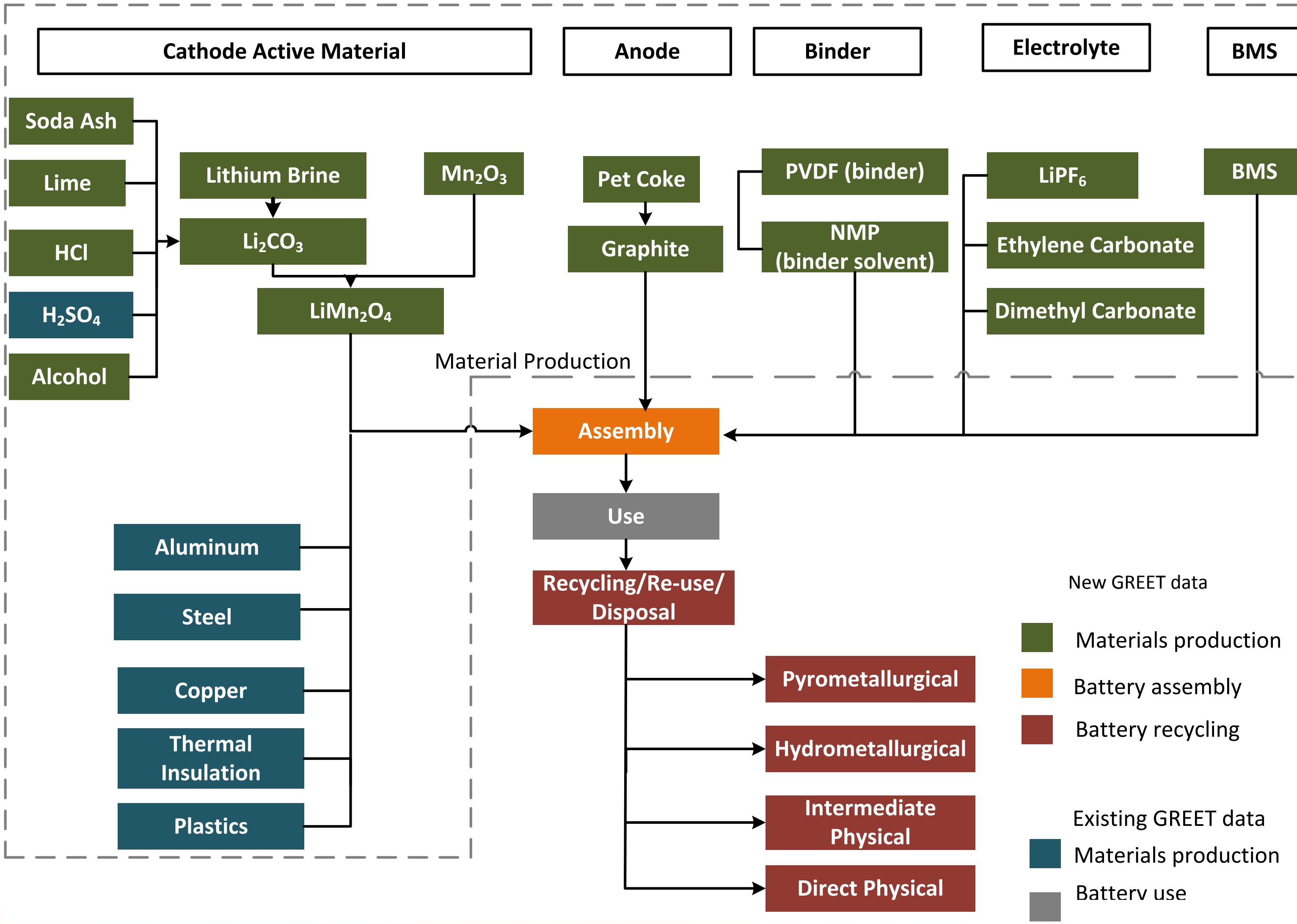


Critical Materials Strategy, USDOE (December 2010)

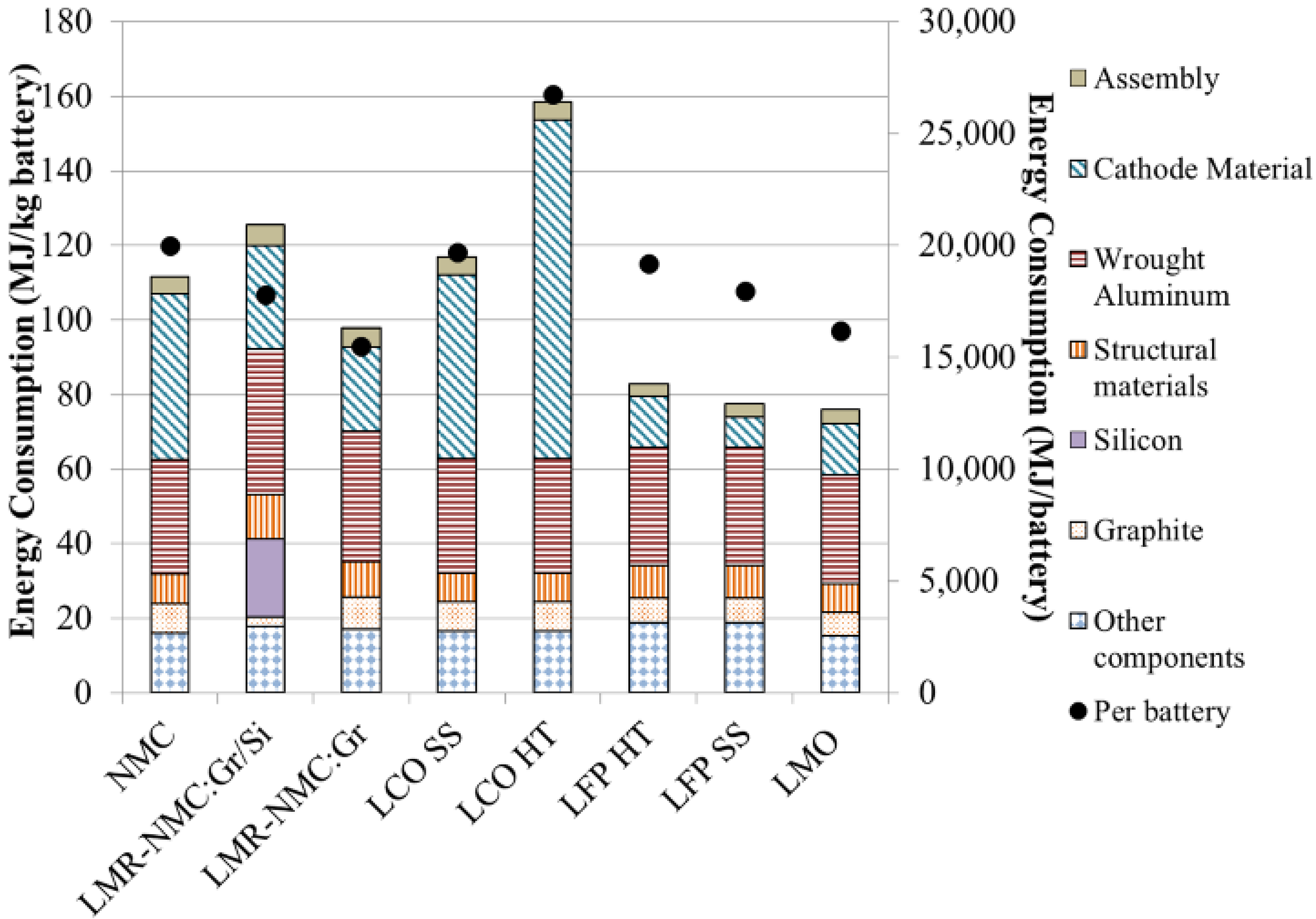
Technical Accomplishments and Progress

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

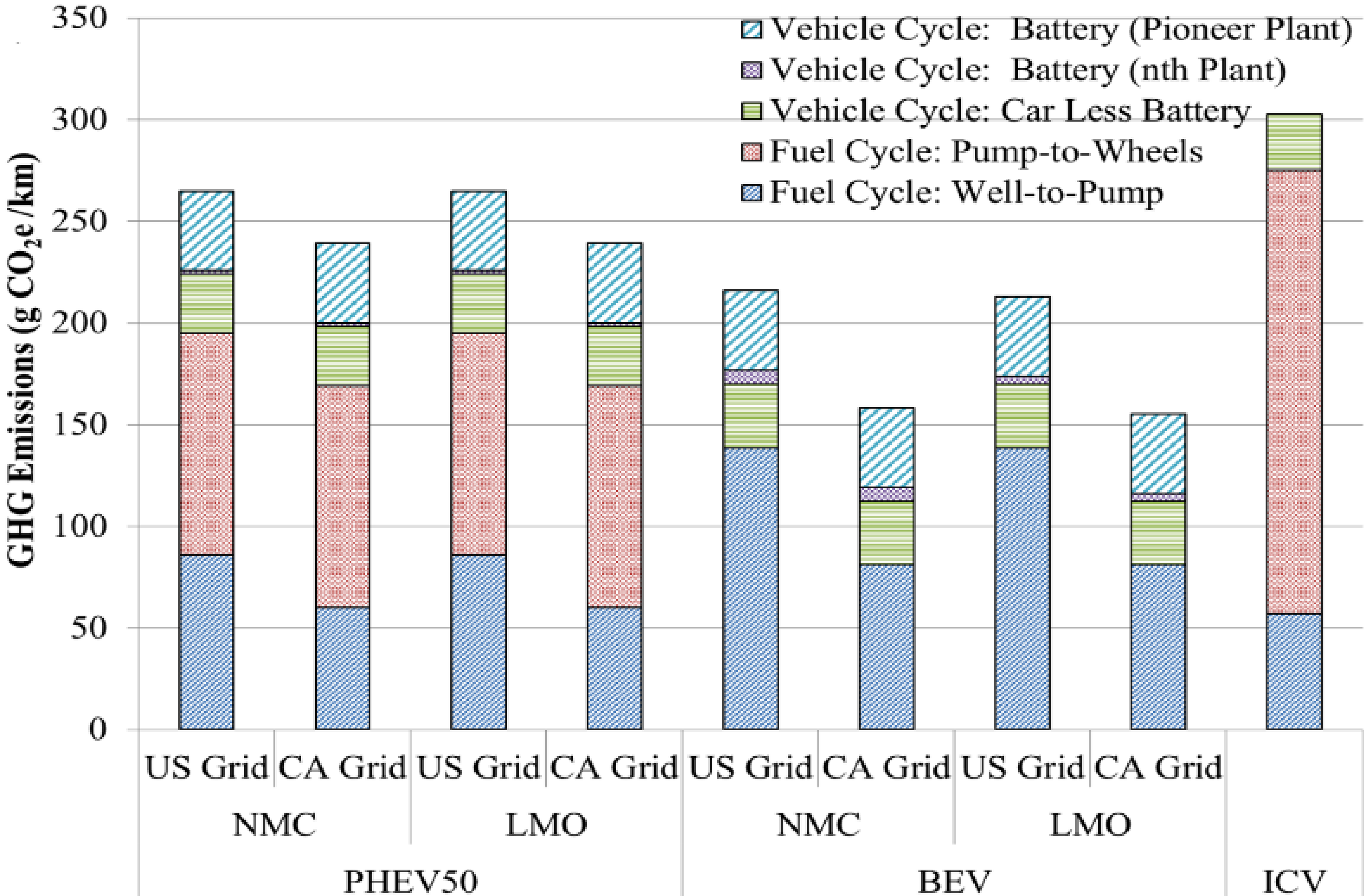


Cobalt and silicon are the most energy-intensive materials to include in supply chain



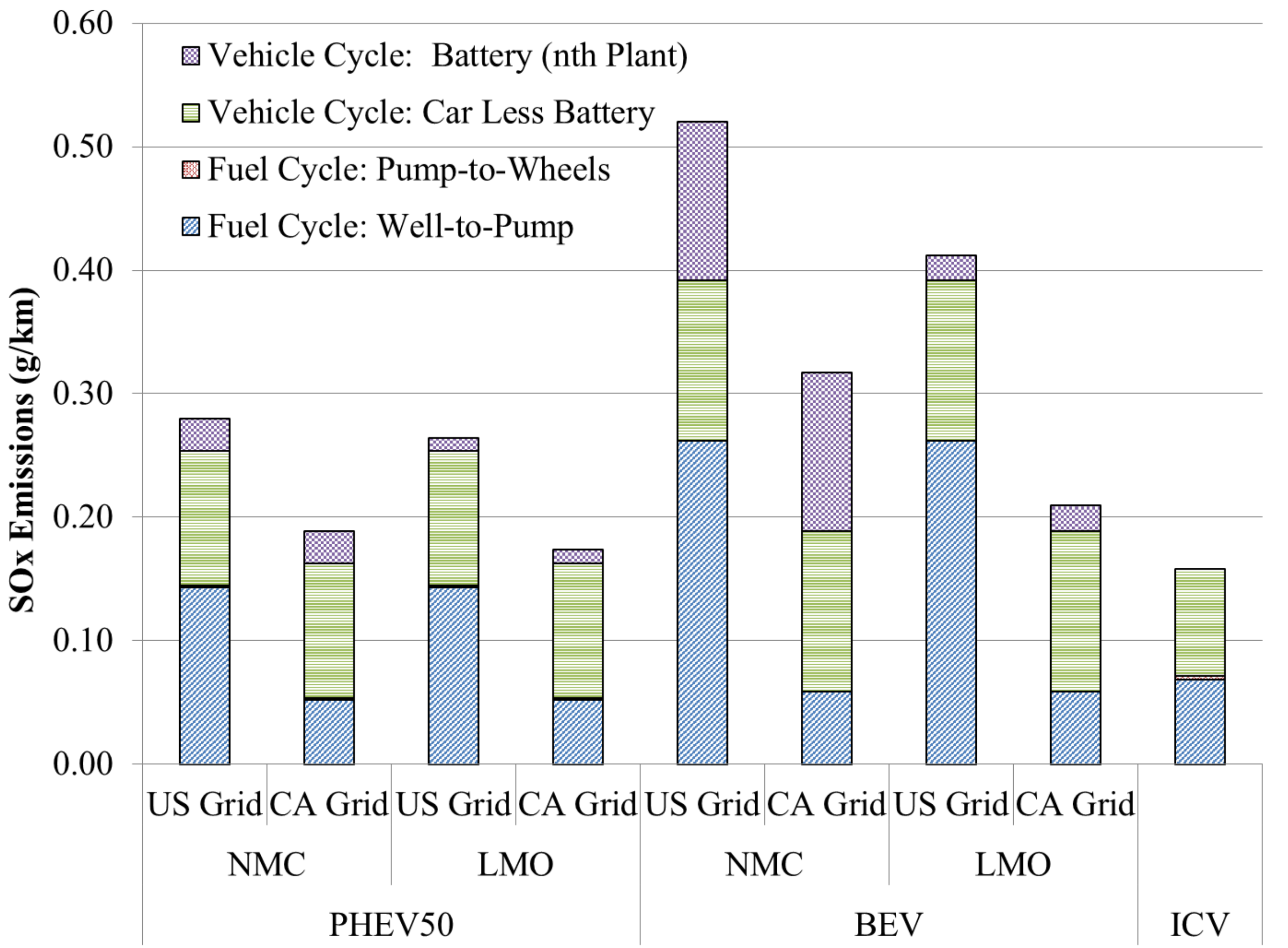
Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G.," The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction.", *Energy and Environmental Science* 8: 158-168 *(2015)*

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

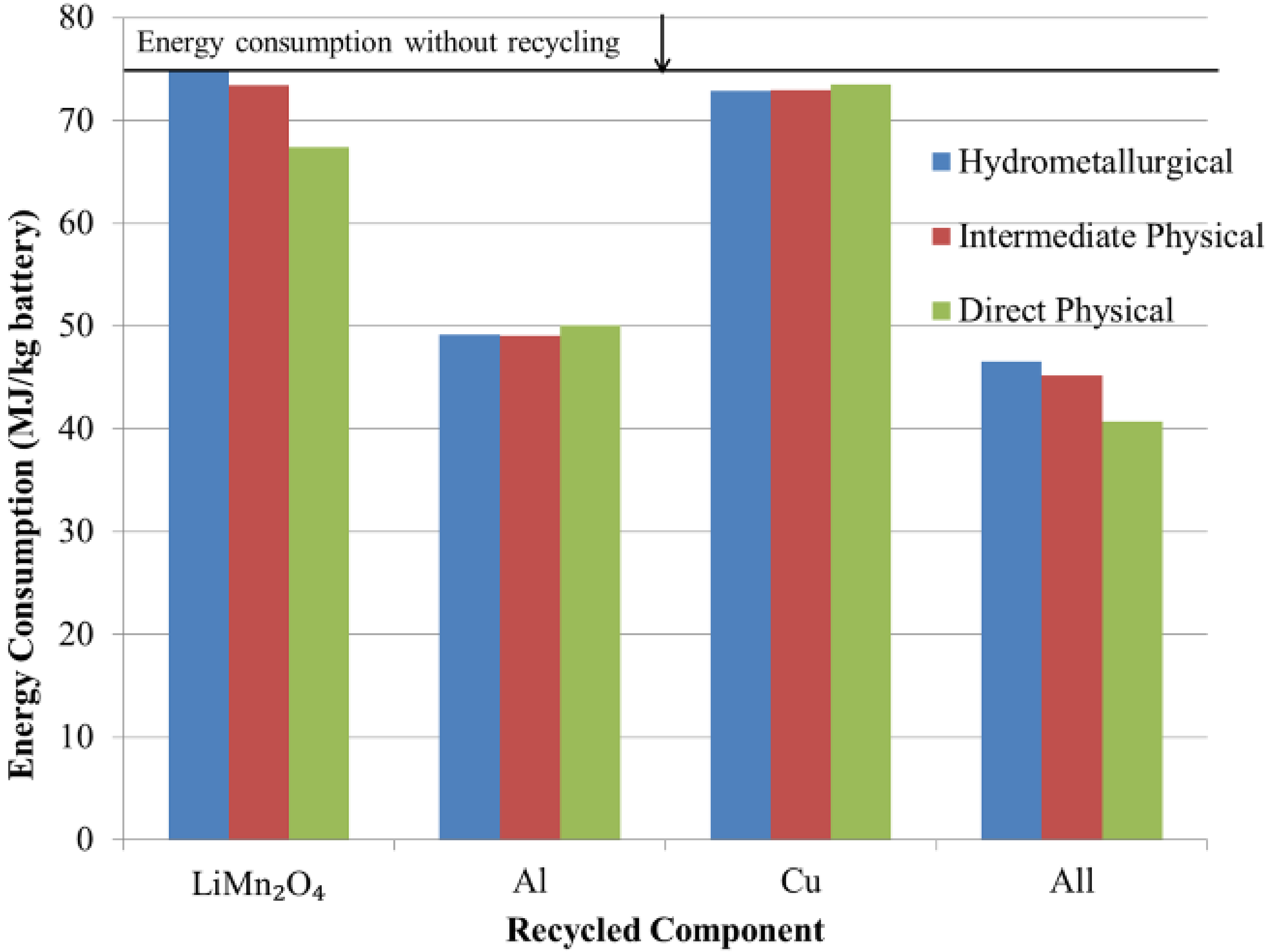


Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G.," The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction.", *Energy and Environmental Science* 8: 158-168 *(2015)*

Technical Accomplishments and Progress

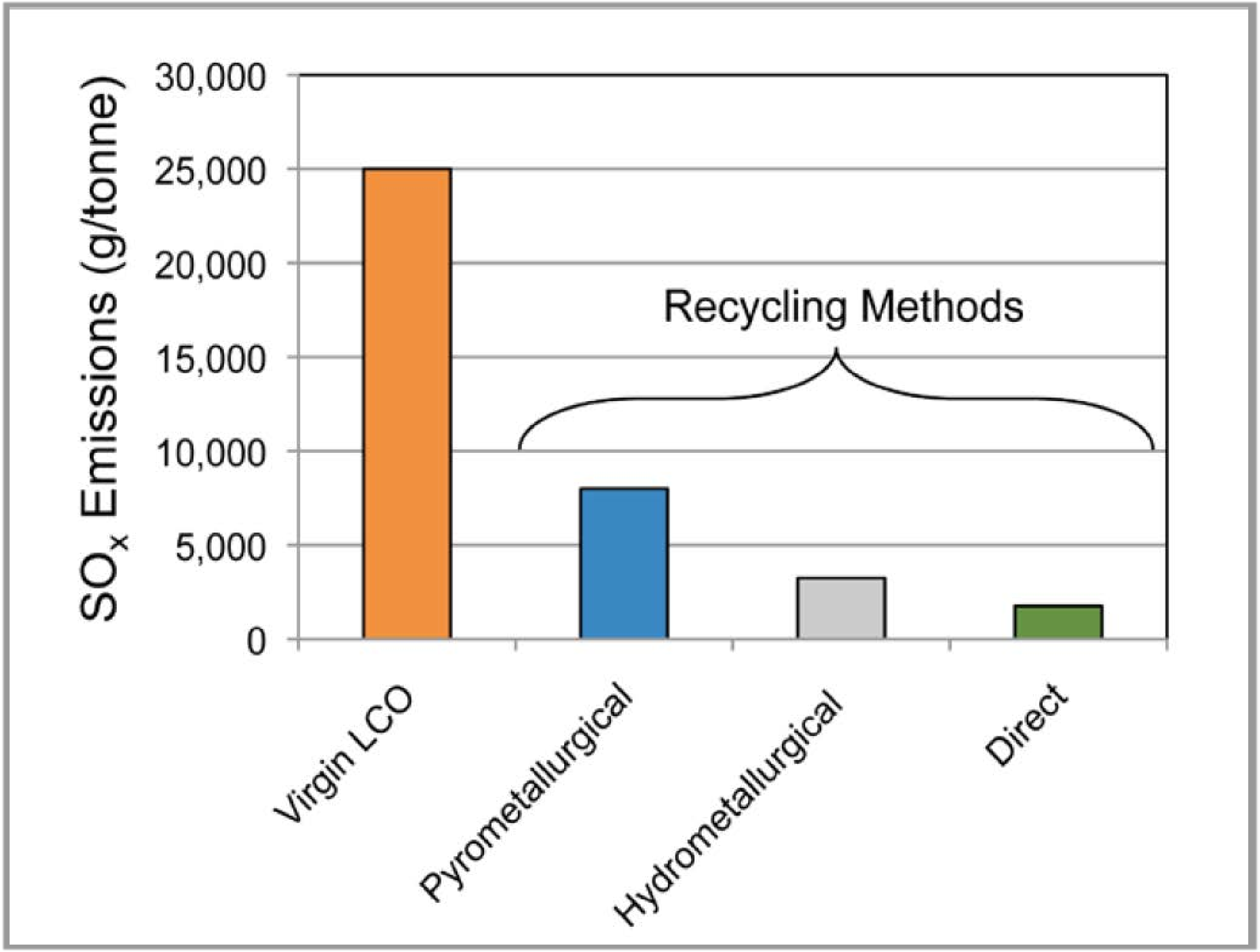
1. Material Scarcity
2. Environmental and Energy Analysis of Lithium-Ion Battery Production from Cradle to Gate
3. Recycling of Automotive Lithium-Ion Batteries
4. International Engagement

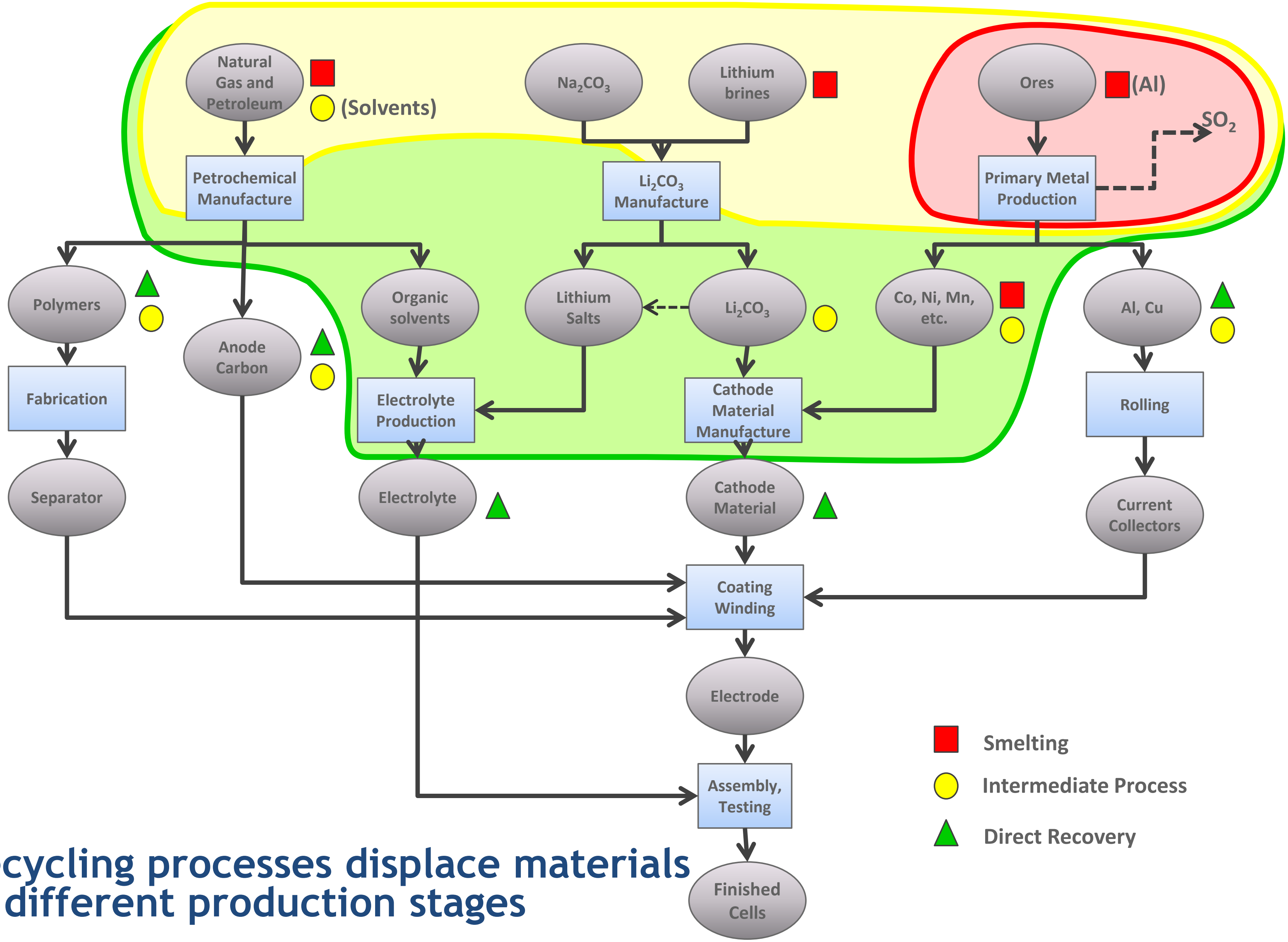
Recycling multiple materials maximizes energy savings and emission reductions



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





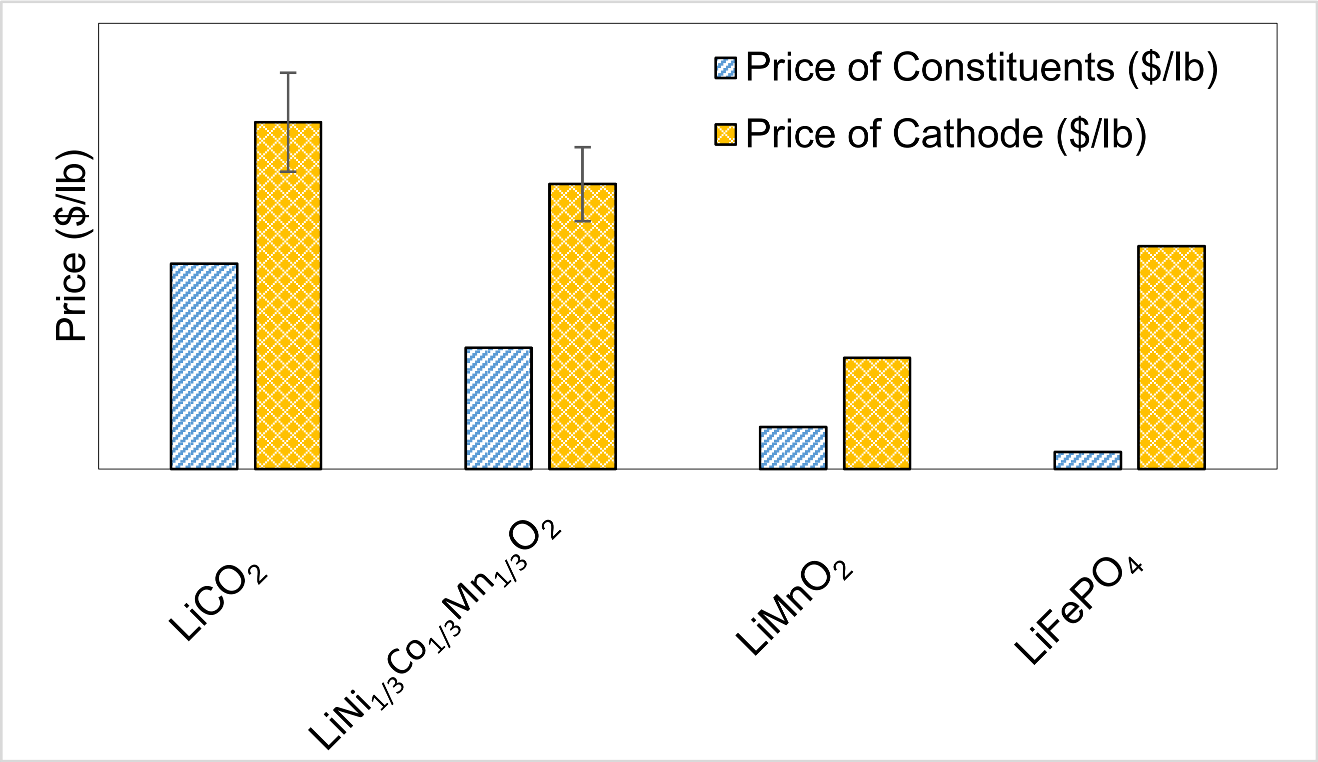
Recycling processes displace materials at different production stages

Available processes recover different products

	Pyrometallurgical	Hydrometallurgical	Physical
Temperature	High	Low	Low
Materials recovered	Co, Ni, Cu (Li and Al to slag)	Metals or 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

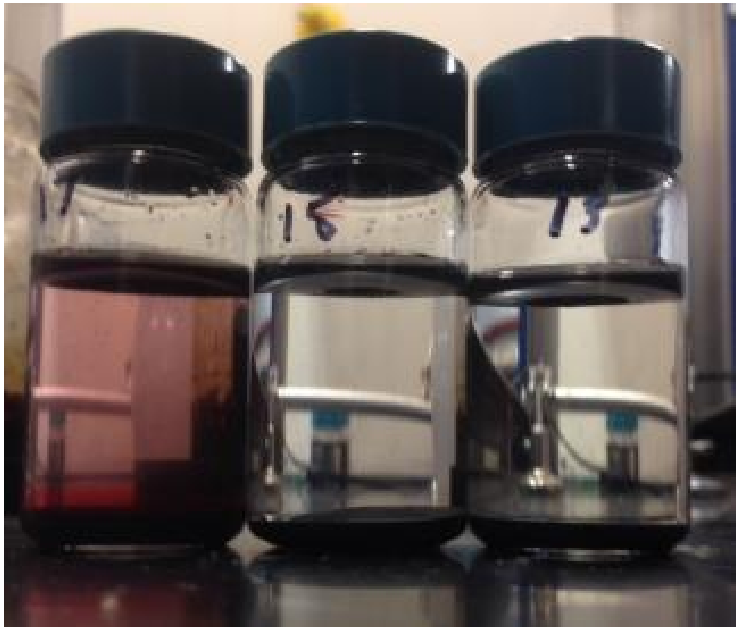
Cathode viability is key to economics
for cathodes with low elemental values

- 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?



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: 30^o, 50^o 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



LCO in acid, water, base

Challenges to recycling can be addressed by R&D

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

Why be Concerned?

Courtesy of Richard Leiby

association of battery recyclers

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

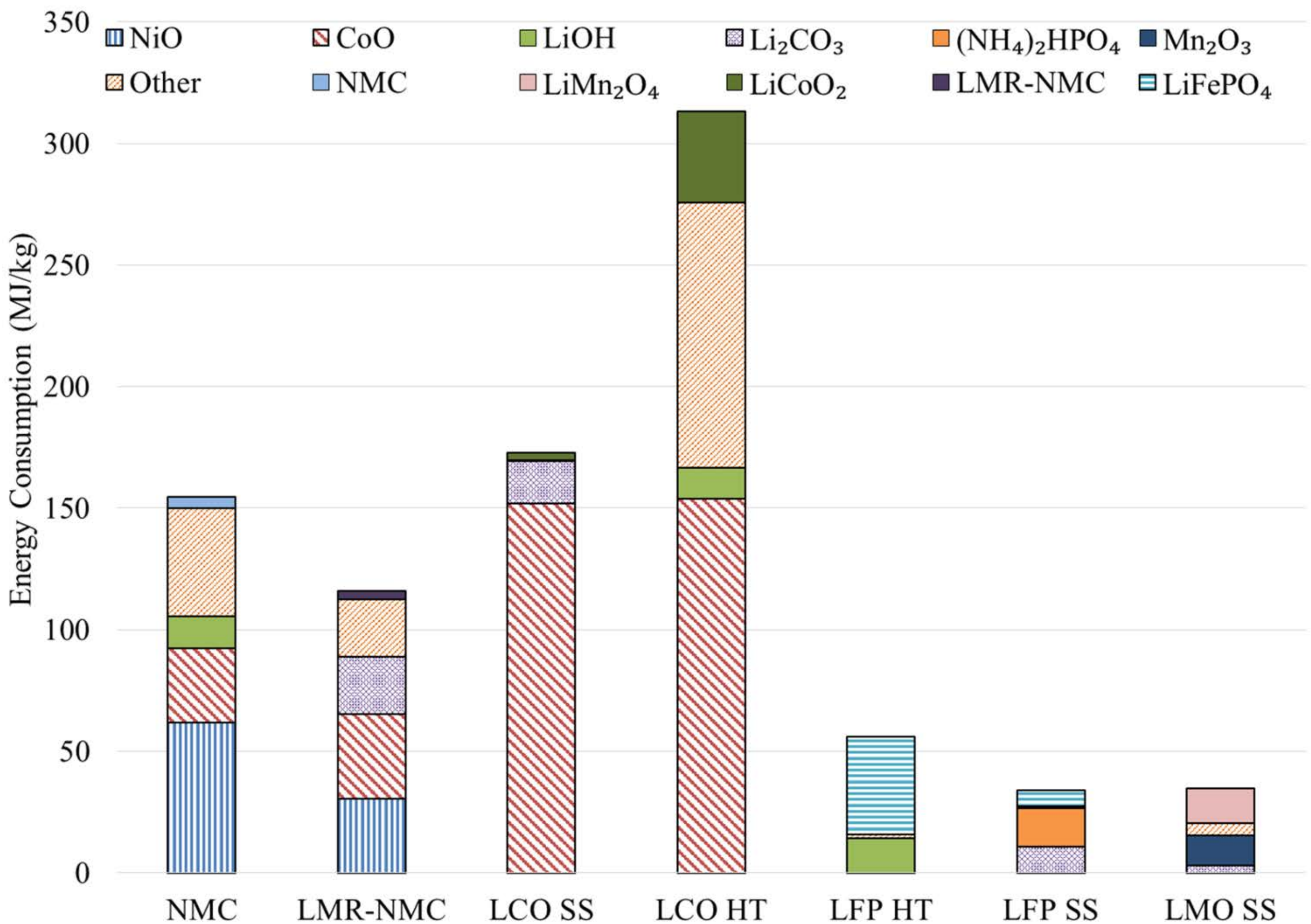
- Argonne's analysis enables VTO to identify the drivers of automotive lithium-ion battery energy and environmental impacts, guide R&D to mitigate them, and address stakeholder concerns regarding these impacts
- Engagement with the international battery analysis community enables information exchange 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: $0.5Li_2MnO_3{\cdot}0.5LiNi_{0.44}Co_{0.25}Mn_{0.31}O_2$
  - 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

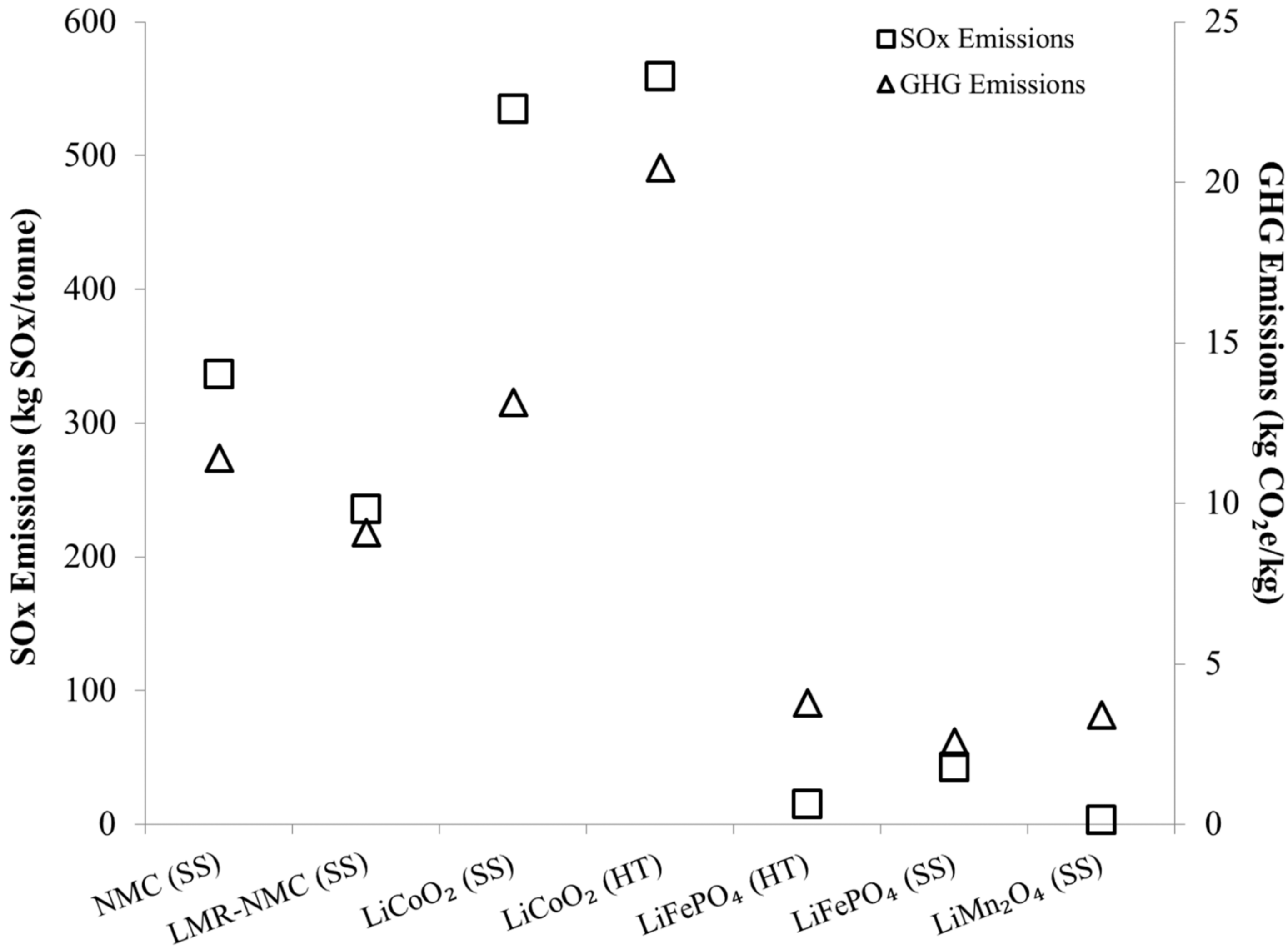
Cobalt- and nickel-containing cathode materials are most energy intensive to produce



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)*

HT: Hydrothermal
SS: Solid State

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)*