Battery Recycling Supply Chain Analysis

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Project ID #VAN029

Overview

Timeline

- Project start date: 10/1/2015
- Project end date: Ongoing
- Percent complete: Ongoing

Budget

- Total project funding: $1.2M
  - DOE share: 100%
- Funding for FY 2017 - $250k
- Funding for FY 2018 – $300k

Barriers

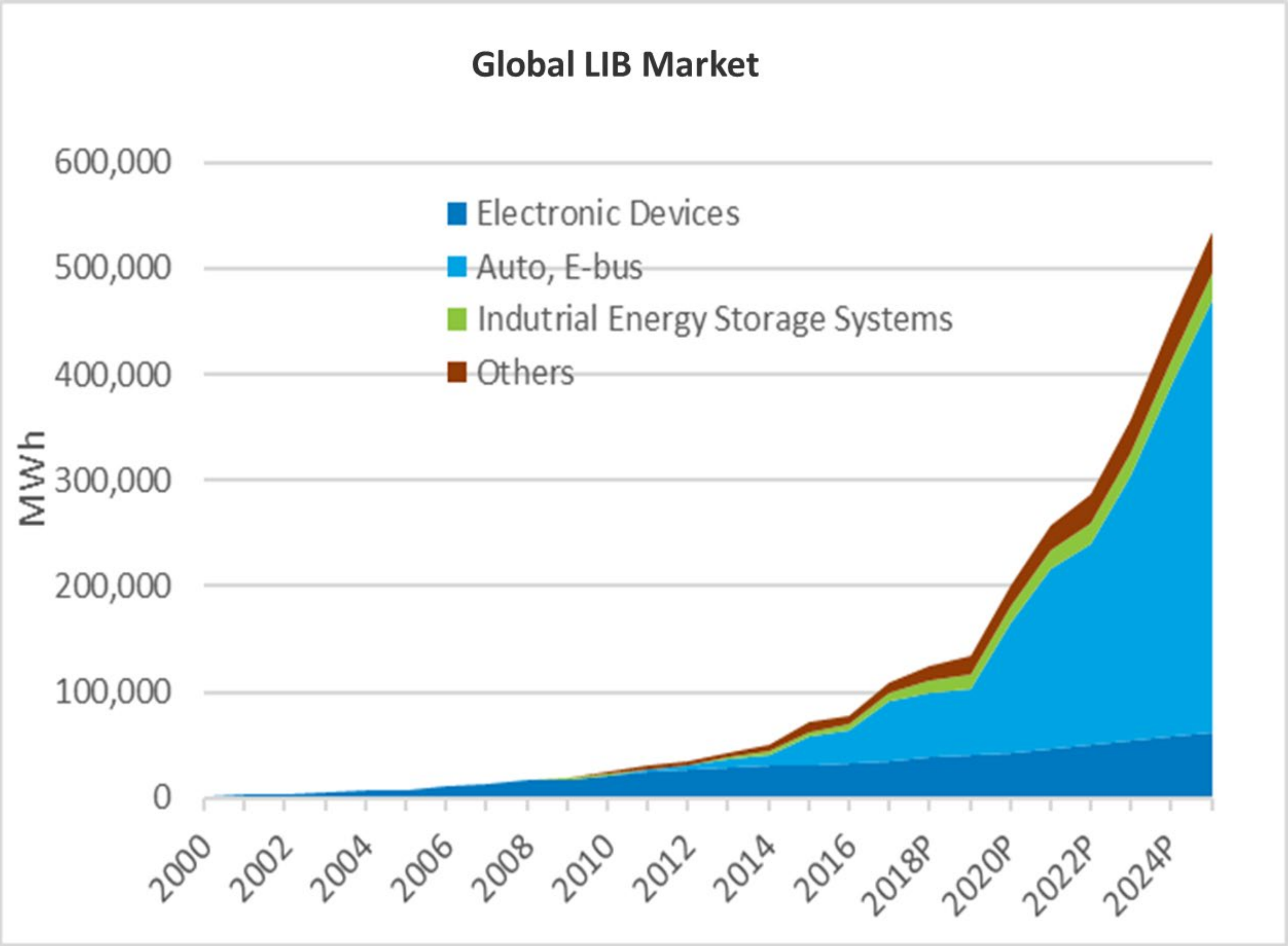
- Barriers addressed
  Electrochemical energy storage:
  - Recycling and Sustainability
  - Cost
  - Secure supply of materials and components

Partners

- Interactions/collaborations
  - Argonne National Laboratory
  - USGS
  - USITC
  - EU and IEA

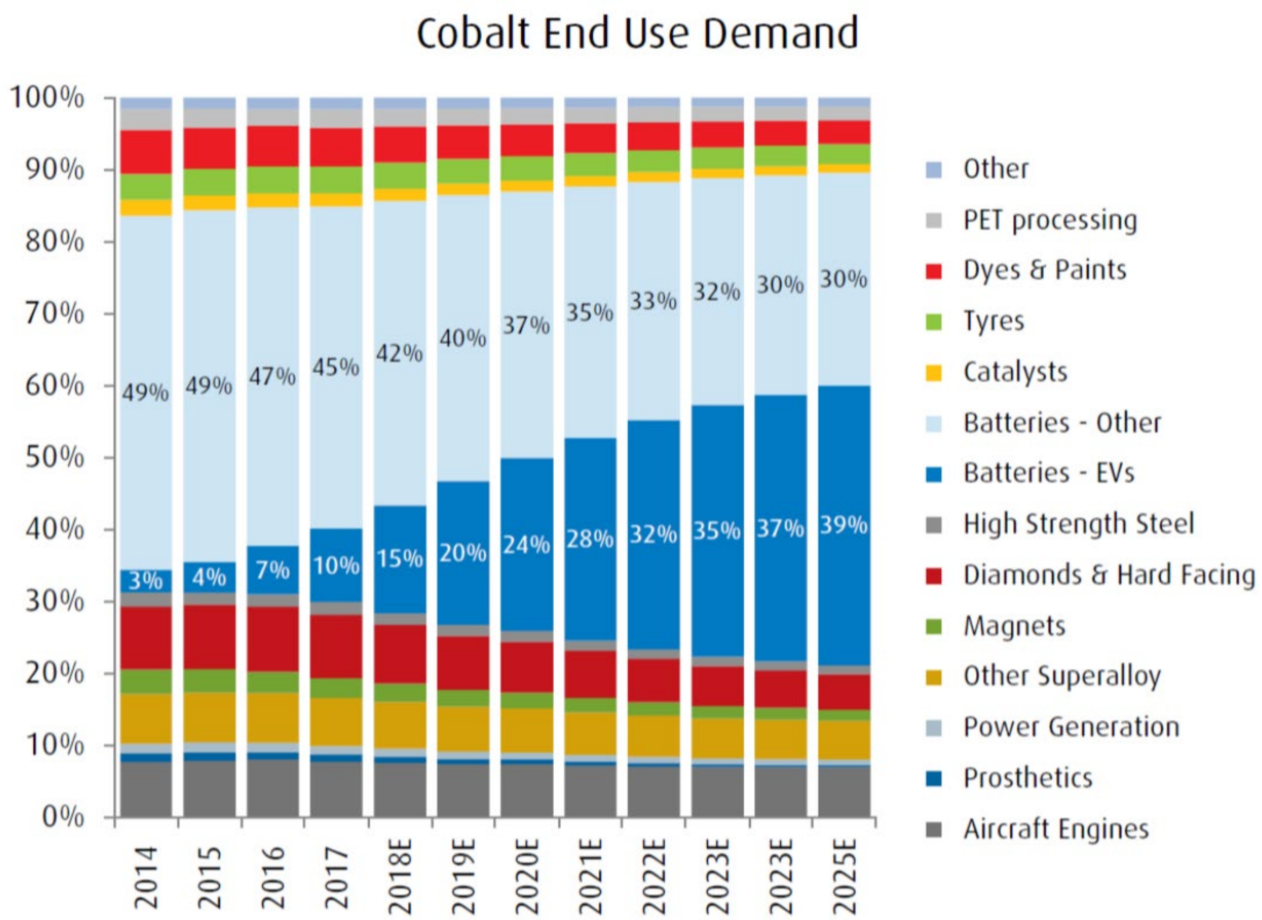
Relevance – The Situation

- Increasing electrification of the U.S. transportation sector will create a strong demand for vehicle batteries.
- The U.S. is currently competitive in the global battery manufacturing market.
- However, the U.S. does not have secure long-term access to the raw materials needed for battery manufacturing.
- Battery recycling can supply the U.S. a significant quantity of raw materials for domestic manufacturing.



Source of data: BNEF 2017, Avicenne 2017, Navigant 2016, NREL analysis 2018

Relevance – Study of Global Supply Chains Supports VTO Goals for Battery Recycling and EV Deployment



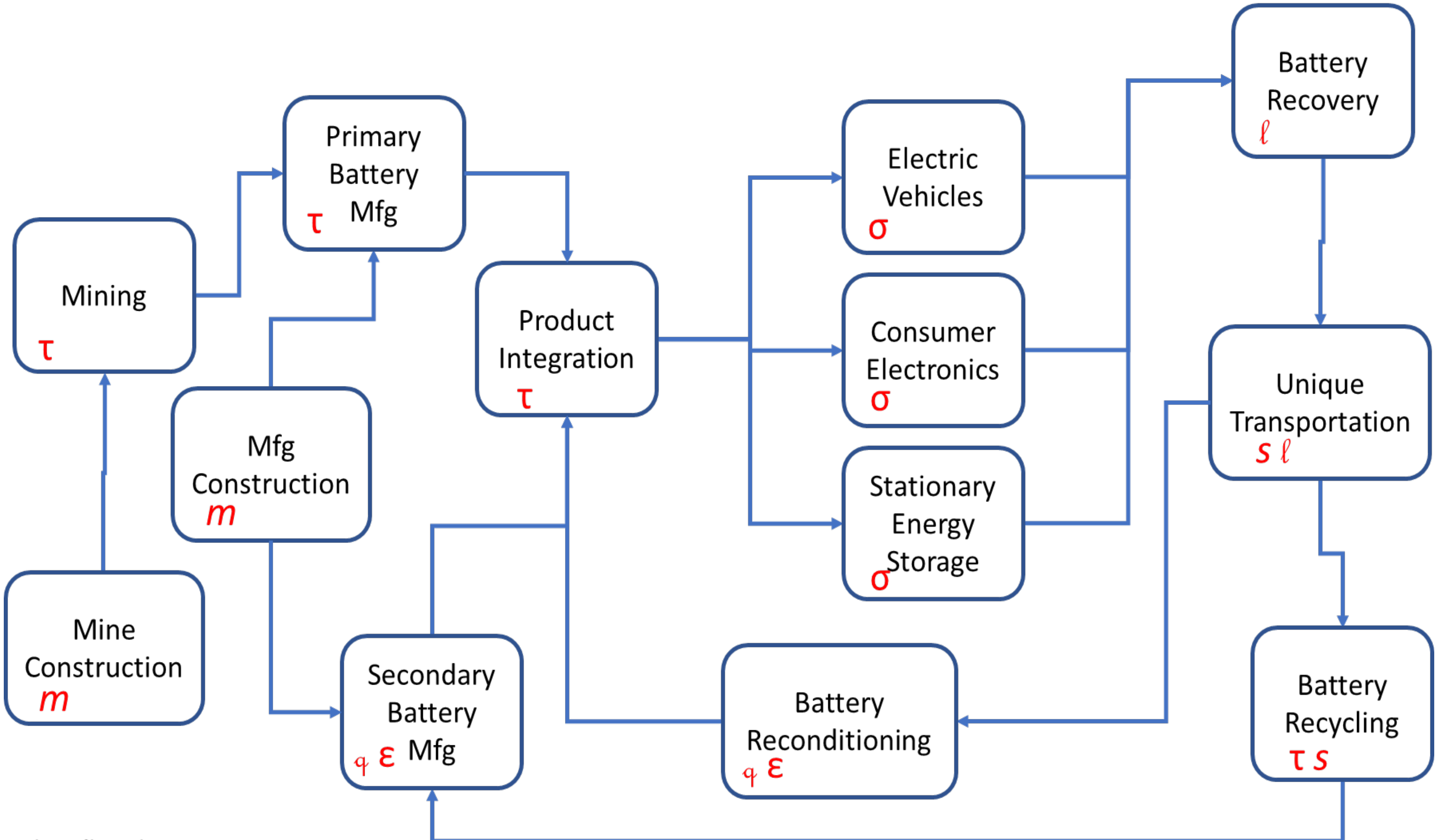
We anticipate EV demand surpassing portable electronics by 2023…even assuming less cobalt in cathodes

Source: CBO Capital Markets, Dec 2017

This study evaluates and quantifies global trends in supply and demand for materials critical for Li-ion batteries, battery design, and battery manufacturing technologies

Materials of Interest:
Co, Li, Ni, Mn, and graphite

Relevance: Battery Recycling is a Complex System



σ = stock & flow lag

τ = timing determined by downstream requirements and economic projections

m = scale determined by downstream requirements and economic projections

s = unique safety conditions

ε = evolving technology and economics

ℓ = evolving logistics

ɋ = evolving and unique quality considerations

Relevance – Key Questions

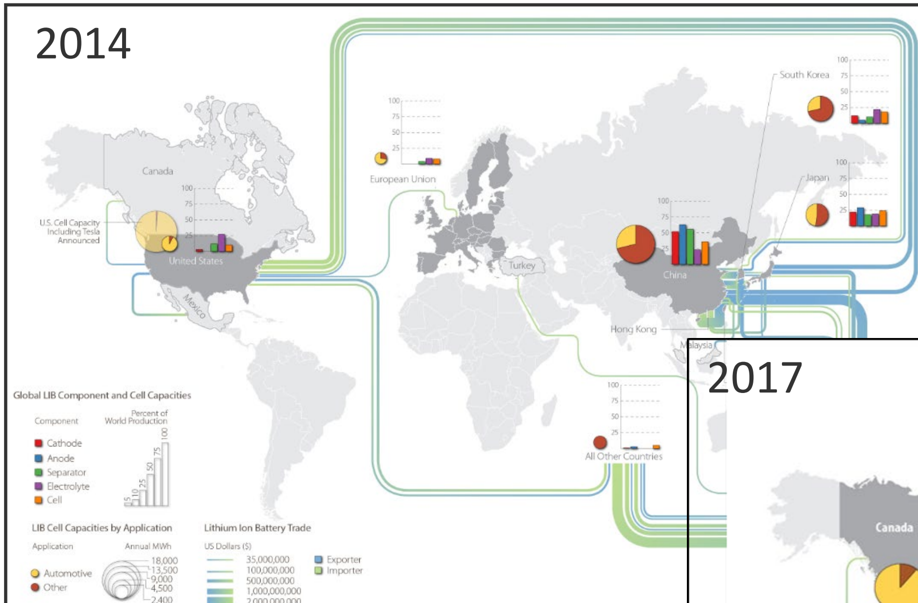
- How could battery recycling affect the material supply availability and price risk?
  - Globally?
  - In the U.S.?
- How does battery chemistry affect the economics of battery recycling over time?
- How much battery recycling is needed to enable X% EV deployment?
- How will R&D success in battery recycling affect material supply vulnerabilities?
- How will regional policies battery availability and clean energy manufacturing?
- How could the different energy storage markets affect EV deployment goals?

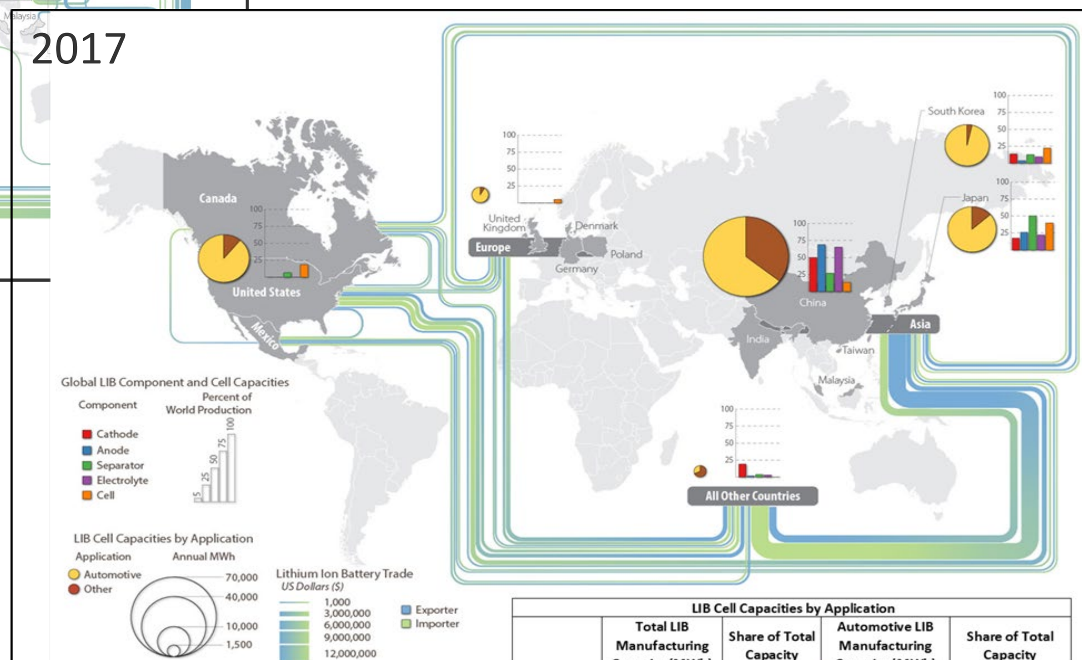
ReCell ADVANCED BATTERY RECYCLING

This project supports the U.S. DOE ReCell Center

Resources

VTO has provided sufficient resources to create the foundations for significant results from this effort





LIB Cell Capacities by Application

	Total LIB Manufacturing Capacity (MWh)	Share of Total Capacity	Automotive LIB Manufacturing Capacity (MWh)	Share of Total Capacity
China	118,234	62.3%	50,670	44.3%
Japan	22,479	11.8%	19,414	17.0%
S. Korea	18,547	9.8%	17,874	15.6%
U.S.	24,766	13.1%	22,016	19.2%
E.U.	2,626	1.4%	2,400	2.1%
Rest of World	3,110	1.6%	2,110	1.8%
Total	**189,762**	**100%**	**114,484**	**100%**

Note: Automotive manufacturing capacities were calculated based on the total production capacity of the studied facilities that make batteries for autos. Some of these facilities make batteries for autos and other applications.

Global manufacturing and trade flows for LIBs have seen dramatic changes over the last few years.
How do these changes affect U.S. manufacturing competitiveness?

Approach - Milestones

- Provide insights into critical supply chain questions regarding the opportunities and challenges of lithium ion battery recycling, including insights into the impact that R&D achievements can have on the successful development of recycling capabilities.
- In FY19, NREL is building a system dynamics model for battery recycling to evaluate the critical feedbacks and limitations within the system.
- Lithium-ion Battery Recycling Analysis - LIBRA

LIBRA

FY19 Tasks/Milestones:

1. Model Supply/Demand Relationship (Q1)
2. Create user interface (Q2)
3. Evaluate investment decisions for recycling = f(price of Co, policies, cost of recycling technology, purity requirements.....) (Q3)
4. Evaluate material supply risk (Q4)

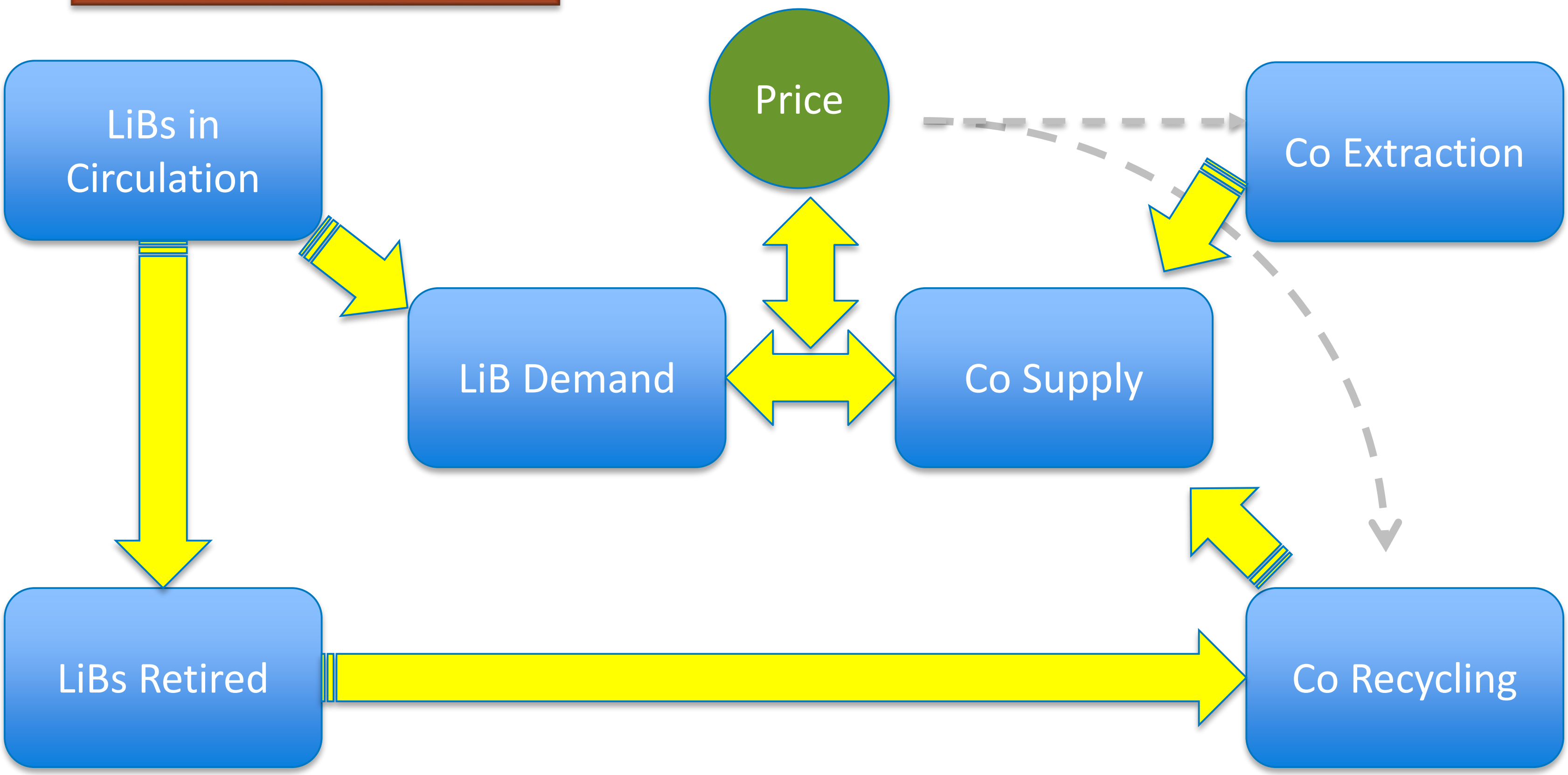
Approach – Current Status

- Continuing to monitor and analyze global supply chains
  - Battery manufacturing
  - Materials flows
  - Demands for LIBs and materials by other sectors
  - Evolution of battery recycling
- Incorporate previous years' data and analysis into a system dynamics framework – LIBRA model
- Continue collaboration with ReCell Center Partners, including with ANL, to utilize BatPaC and EverBatt models as inputs
- Continue to summarize current situations through graphics, presentations, and papers

Approach – FY19 LIBRA Model Development

LIBRA

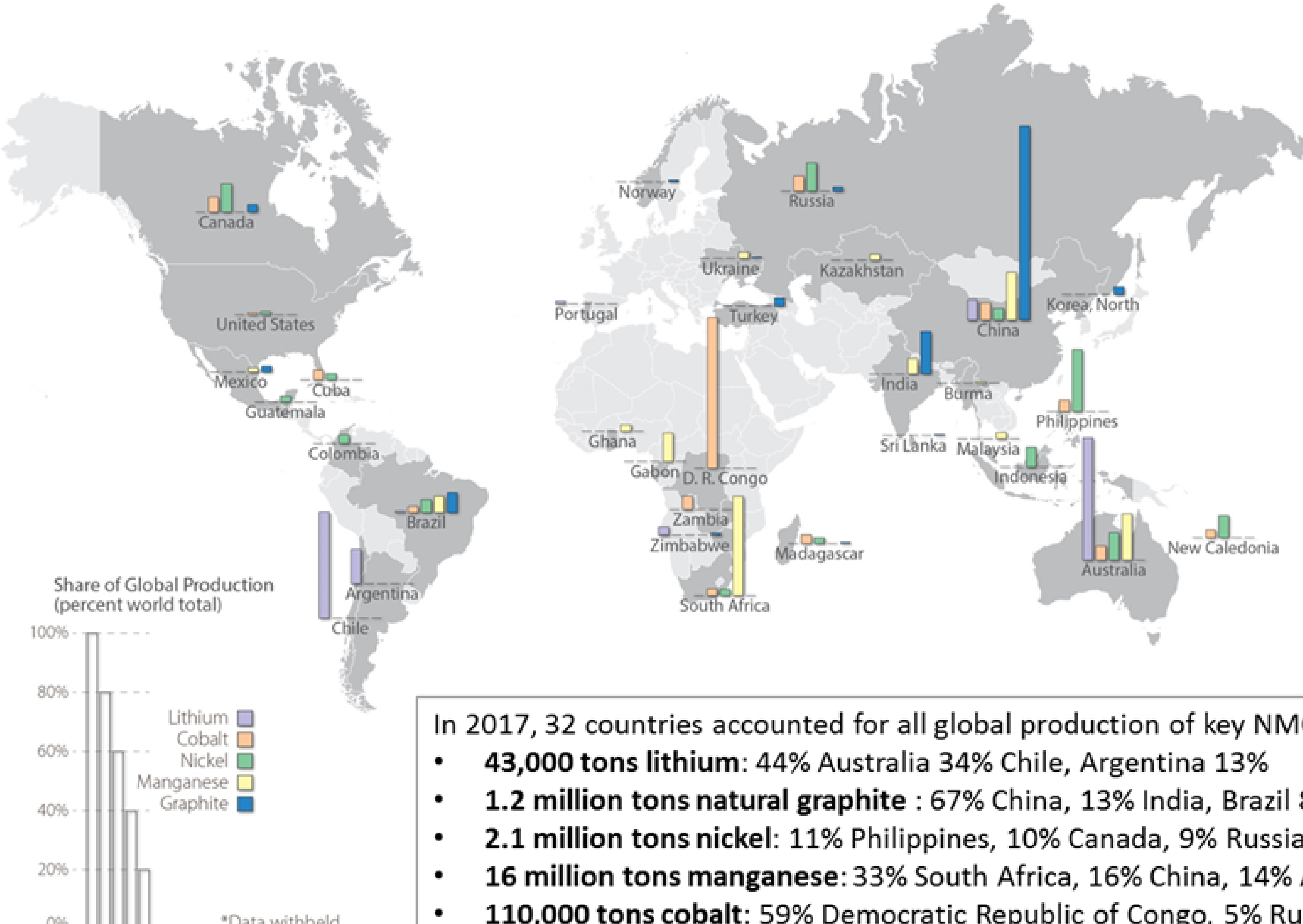
LIBRA Schematic



The above schematic represents the high-level mass balance and supply/demand relationships currently modeled in the LIBRA model. Note that this is a high-level Illustrative example.

Technical Accomplishments and Progress

In 2017, 32 countries accounted for all global production of Li, Co, Ni, Mn and Graphite, with 50% of production of each element originating in one or two countries.



In 2017, 32 countries accounted for all global production of key NMC materials

- **43,000 tons lithium**: 44% Australia 34% Chile, Argentina 13%
- **1.2 million tons natural graphite** : 67% China, 13% India, Brazil 8%
- **2.1 million tons nickel**: 11% Philippines, 10% Canada, 9% Russia, 9% Australia
- **16 million tons manganese**: 33% South Africa, 16% China, 14% Australia
- **110,000 tons cobalt**: 59% Democratic Republic of Congo, 5% Russia, 5% Australia

Technical Accomplishments and Progress

LIB Battery Manufacturing Costs/Value
Areas of potential competitiveness: Innovation, Process Know-how, and Proximity to Markets

Value share

Raw materials	Processed materials	Electrodes ✦	Cells ✦	Battery pack ✦
12%	28%	7%	35%	18%
Indigenous resources, export restrictions, or limitations	**Demand assurance** Cost of capital **Production cost inputs** (regulatory, energy, etc.) Corporate income taxes	***Processing know-how***: e.g. coating thickness uniformity, solvent & moisture content, etc. **Supplier-leverage**	***Proximity to customers:*** shipping costs, materials transport restrictions **Processing know-how:** e.g. coating, drying, formation, electrolyte additives	***Proximity to customers***: shipping costs, exchange of technical specifications

✦ Regional Mfg

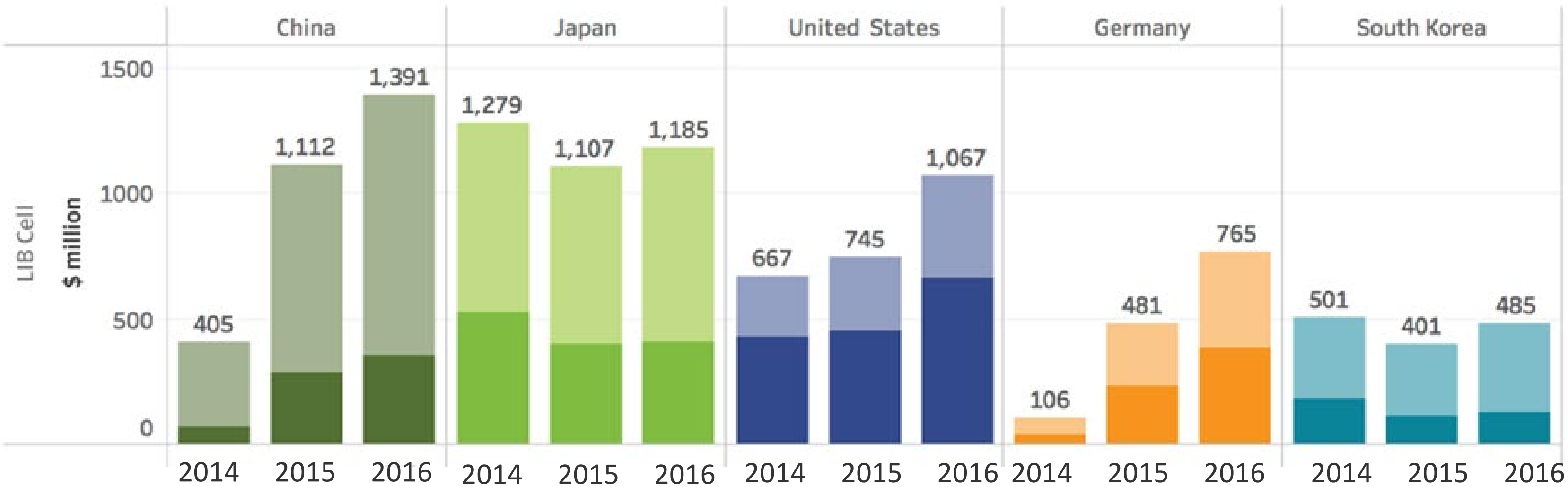
As U.S. demand grows and stabilizes, packs will likely be assembled domestically. Electrode production, cell manufacture, and pack assembly may occur regionally.

62% of the Value Chain

Sources: NREL estimates 2018; Aviceene, 2017; BNEF 2017

Technical Accomplishments and Progress

Impact of Battery Manufacturing on the Economy



Economic Value Add (Solid colors are direct VA, shaded colors are indirect VA)

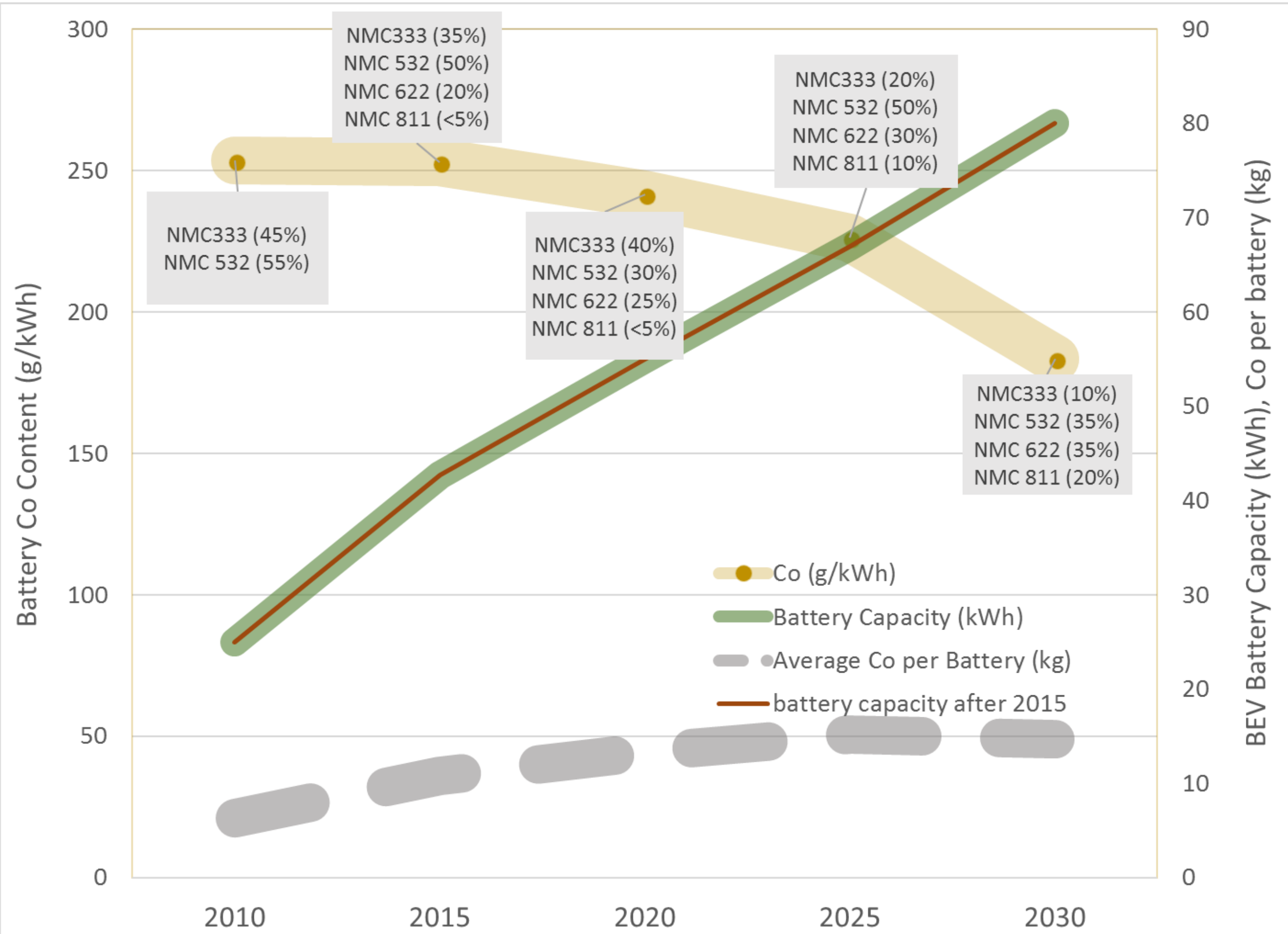
While the total number of batteries manufactured in the U.S. is less than in China, the economic impact is comparable and growing.

CEMAC Clean Energy Manufacturing Analysis Center
Operated by the Joint Institute for Strategic Energy Analysis

Source: Benchmarks of Global Clean Energy Manufacturing, 2014–2016. Clean Energy Manufacturing Analysis Center, NREL, *In-press*.

Technical Accomplishments and Progress

The Amount of Co in Batteries is a Combination of Changes in Cathode Chemistry and Battery Size (kWh)



New cathode chemistries are being developed to reduce Co content, but vehicle batteries are also getting bigger so the amount of Co per battery will continue to increase for some time

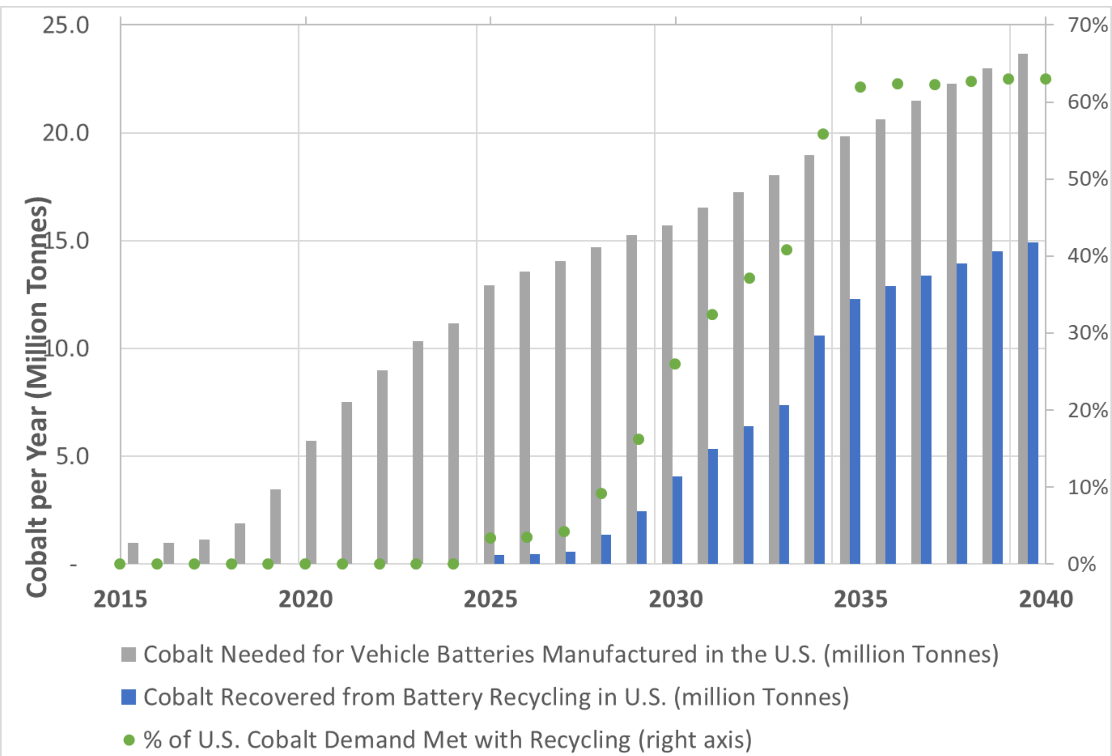
Sources: Projections of cathode chemistries; Pillot, Christopher. 2017. “The rechargeable battery market and main trends 2016-2025.” International battery seminar and exhibit. Fort Lauderdale, FL., BEV battery capacity (kWh); Bloomberg New Energy Finance to 2015, NREL estimate 2020 – 2030, NREL Analysis

Technical Accomplishments and Progress

What fraction of the cobalt needed for vehicle demand in the U.S. can be met with Li-ion battery recycling?

Answer: Approximately 65% by 2040

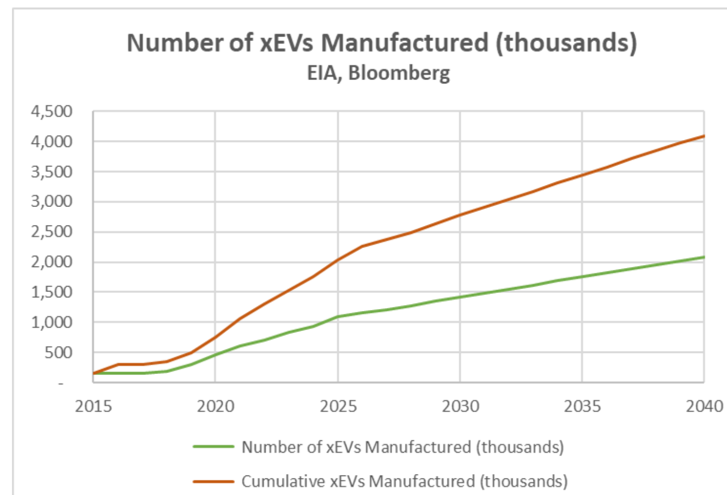
Cobalt Available from Recycling of Spent LIB from U.S. Vehicles



Spent batteries from vehicles sold in the U.S. could supply a significant amount of U.S.-based manufacturing operations.

The amount of material recovered depends on:

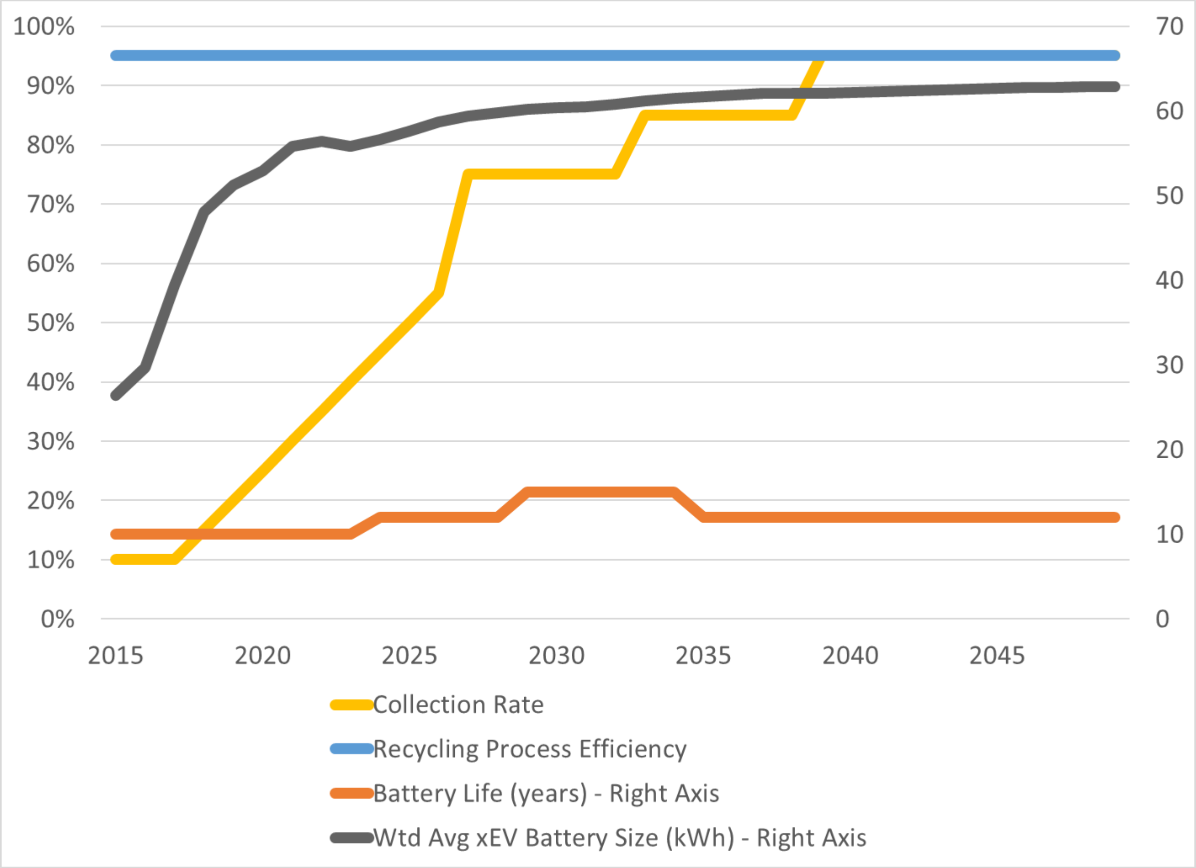
- *Battery chemistry at the time the batteries were manufactured*
- *The number of batteries manufactured*
- *Battery collection efficiency*
- *Recovery of material from recycling processes*



Technical Accomplishments and Progress

Data inputs have considerable variability and uncertainty.
Sensitivity analysis is critical for providing insights and direction.

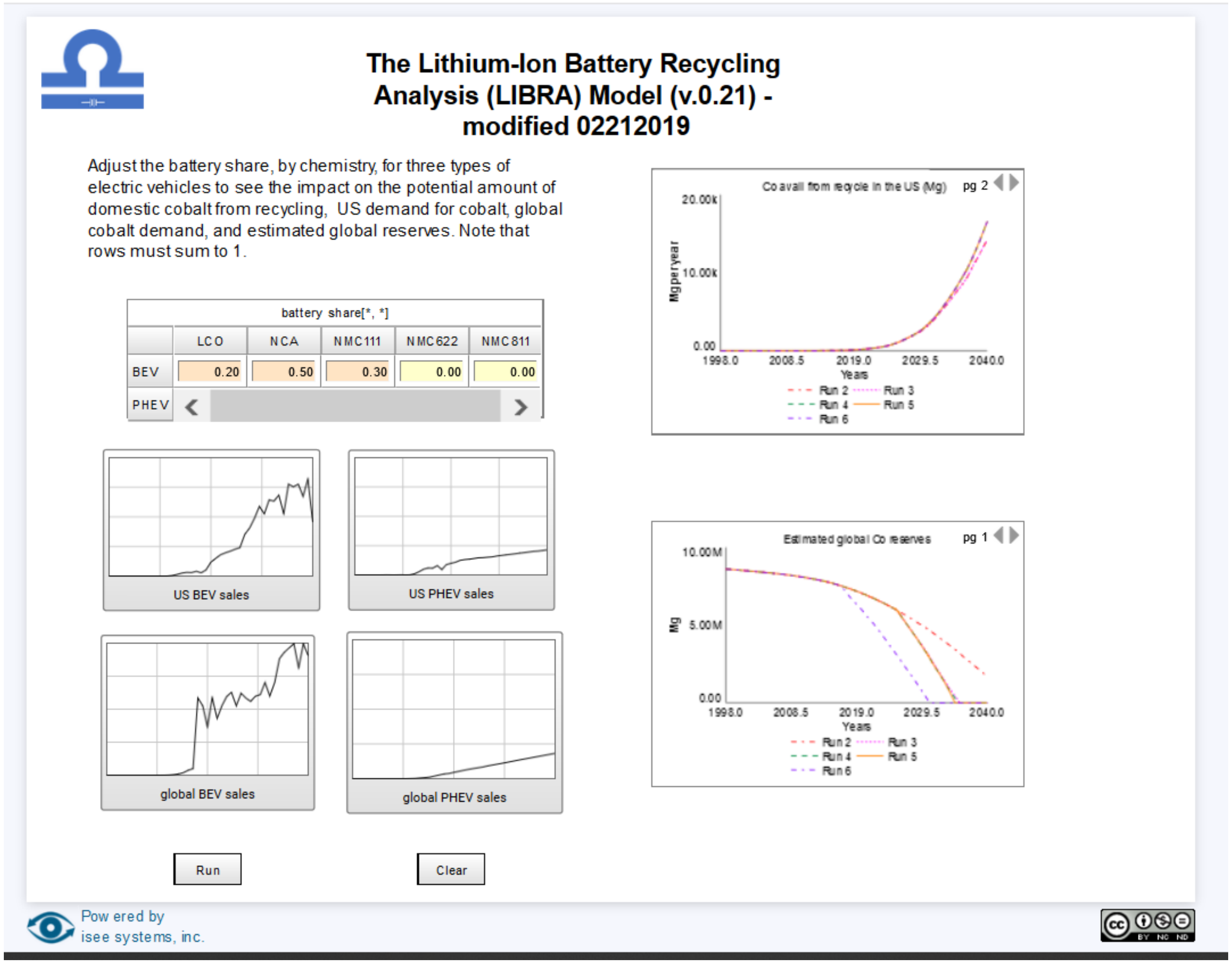
Assumptions for Previous Figure



The LIBRA model varies these (and other) assumptions to understand the factors driving material price, availability, and global flow

Technical Accomplishments and Progress

An early web-based interface for the LIBRA model is available at https://exchange.iseesystems.com/public/danielinman/libra-01-demo/index.html#page1



Current public interface provides early ability to test scenarios

Current Functionality of interface:

- How does battery chemistry affect Co supply?
- How does demand for batteries affect recycling stream?

Future interface will allow for slider and more sensitivity analyses for more scenarios

Responses to Previous Year Reviewers' Comments

- While this project was not reviewed last year, we have presented and published several findings over the last three years.
- We look forward to the recommendations from this audience.

Collaboration and Coordination

- As part of the U.S. DOE's ReCell Center (http://recellcenter.org/), this project closely collaborates with ANL, ORNL, and industry leaders
- This project benefits from discussions and data exchange with USGS and USITC, as well as IEA Task on Critical Materials for Batteries

ReCell
ADVANCED BATTERY RECYCLING

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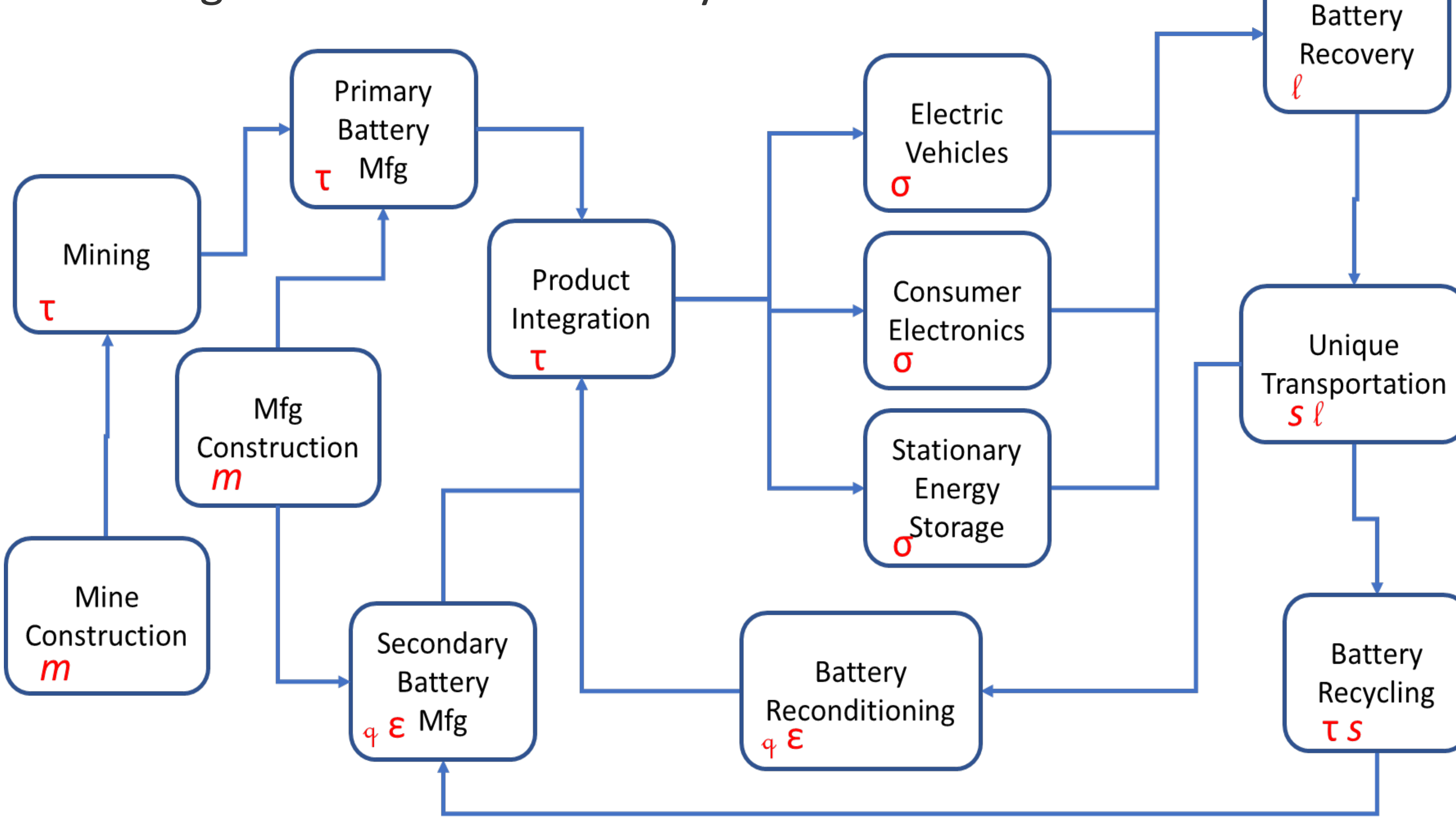
Remaining Challenges and Barriers

- Increased demand for very large LIBs in the stationary energy storage market (e.g., utilities, data centers, financial markets) will have a significant effect on the supply chains for EV batteries.
- Greater electrification of medium- and heavy-duty vehicles will influence supply availability for light-duty vehicles.
- Multiple uses of LIBs, including second-life, will complicate the projected quantities of used batteries entering waste and recycling streams.

Proposed Future Research

- Continue to gather and analyze relevant data – global markets, material and component flows, company announcements
- Expand the LIBRA model with new modules and data
- Improve the user interface
- Generate insights based on data analysis and LIBRA results



Summary

- Electrification of transportation and stationary energy storage markets are growing extremely fast
- A systems-approach to understanding the demands, flows of materials, and costs is required to evaluate the impacts of R&D in battery chemistry, recycling, and EV deployment
- Supply chain analysis can provide systems-level insights
  - Data and trends gathering
  - Collaboration with ReCell partners, USGS, USITC, and international (through IEA)
  - *Dynamic* modeling can capture the feedback loops and evolution of trends: LIBRA model
  - Project provides key updates and insights throughout the year – to researchers, DOE, industry

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www.nrel.gov

Thank You

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