DOE Battery Efforts and VTO Energy Storage Portfolio

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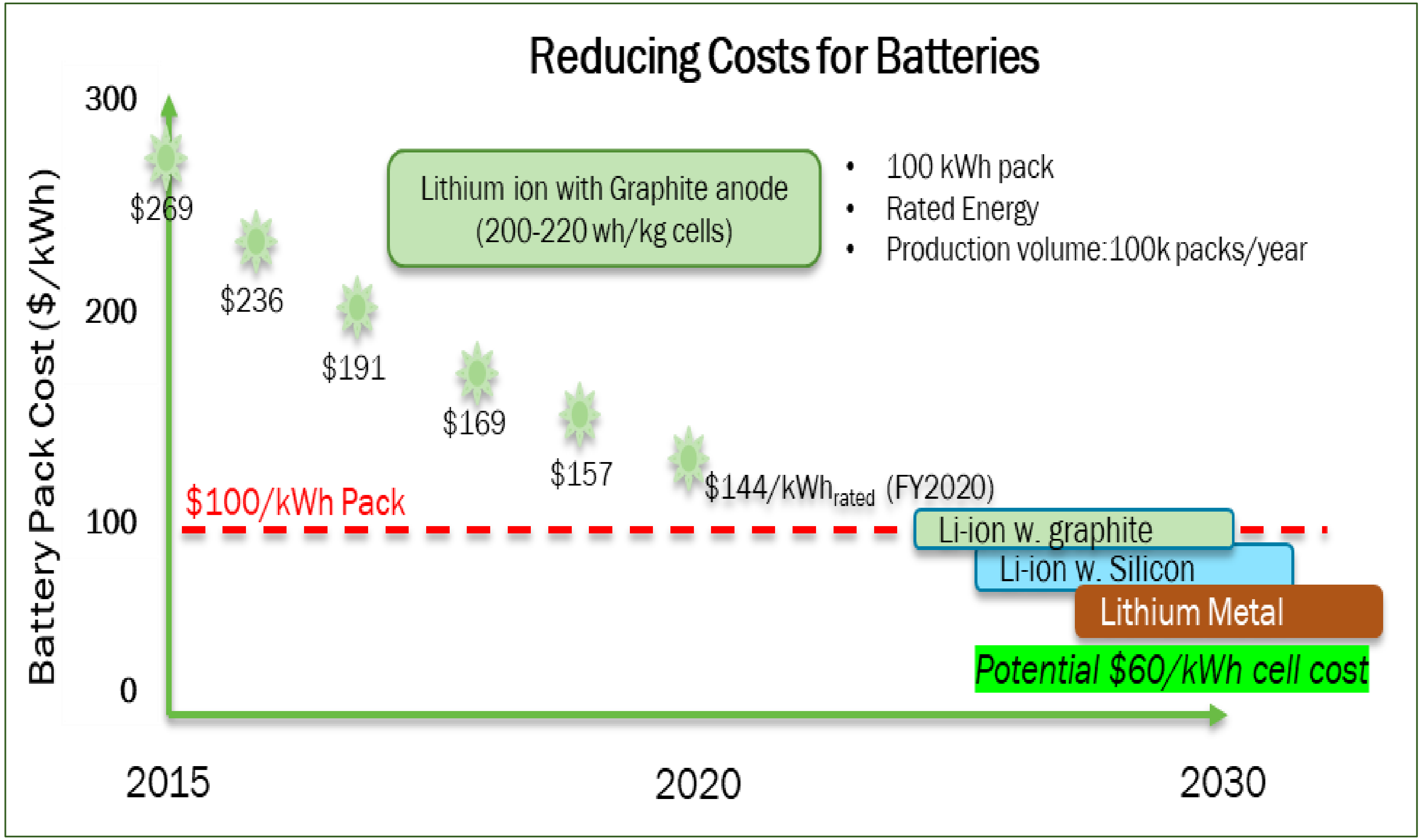
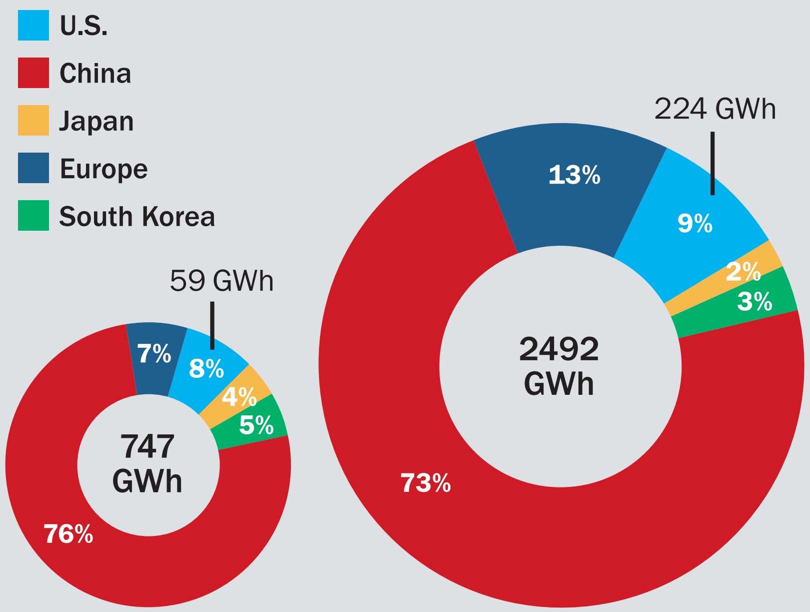
Electric Vehicle Battery R&D (EERE/VTO)

FY2021 Battery R&D Budget -$115M

BY 2025, reduce the cost of EV battery packs to less than $100/kWh, and increase range to 300 miles, and decrease charge time to 15 minutes or less.

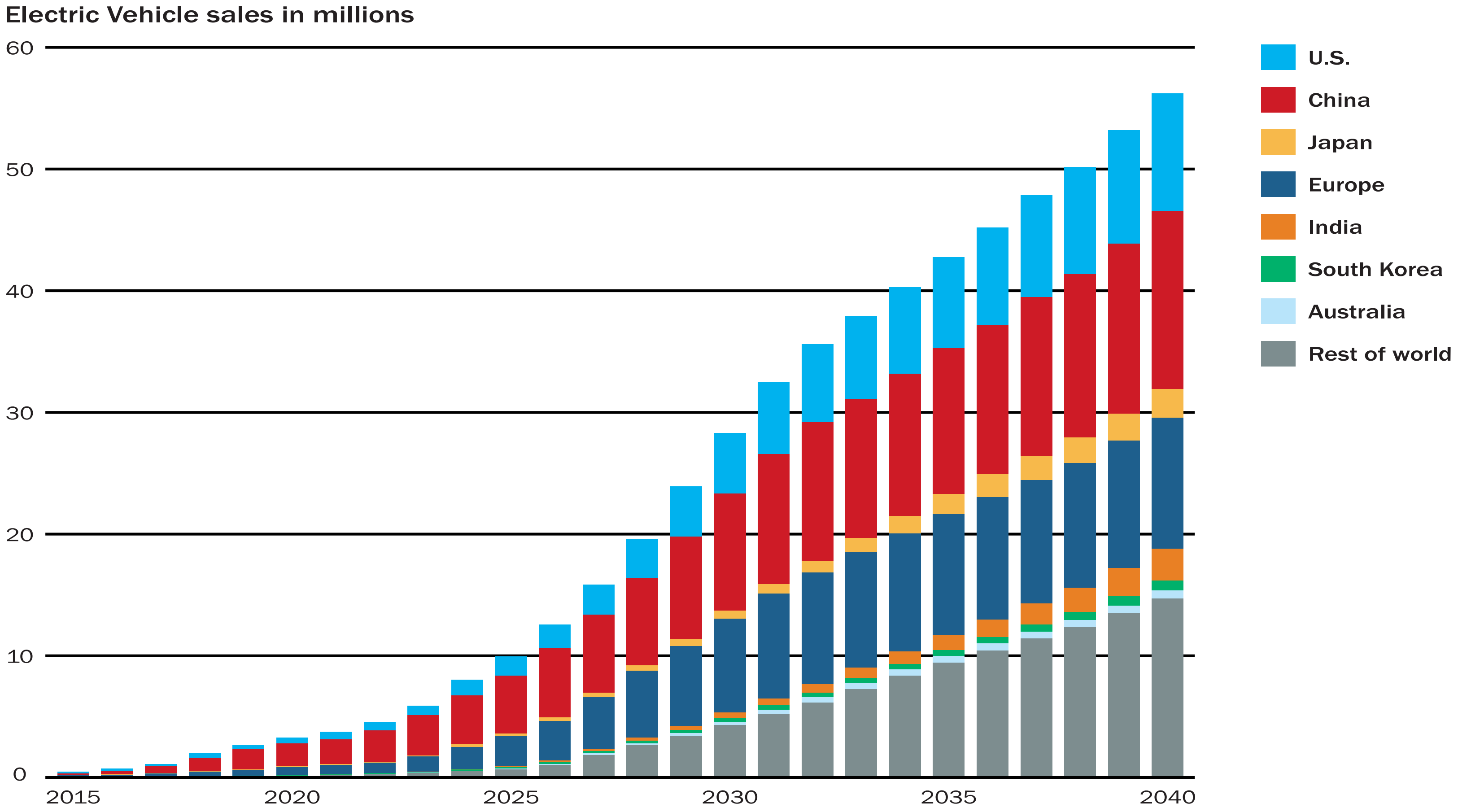


Anticipated Rise in Electric Vehicle Purchases

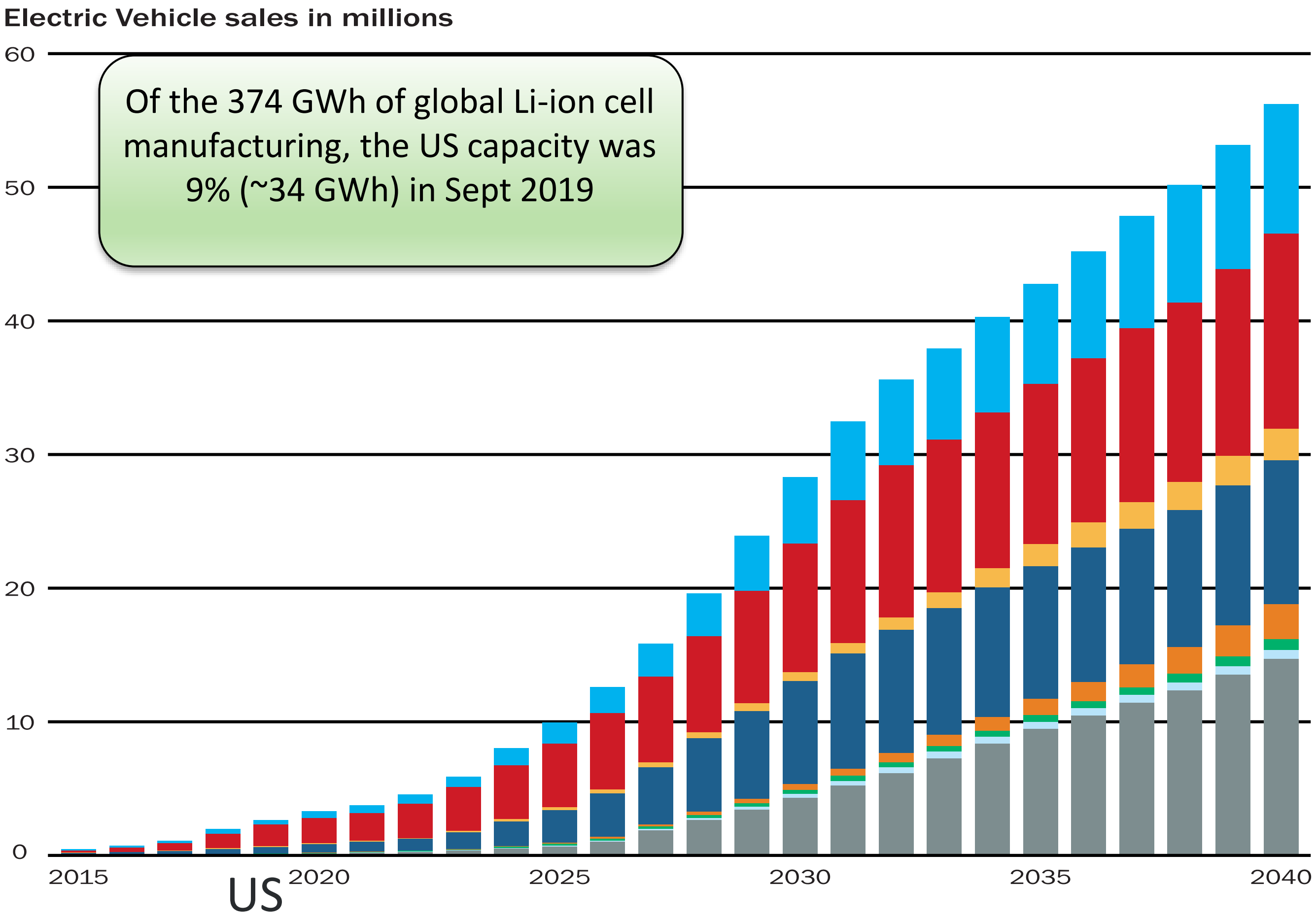


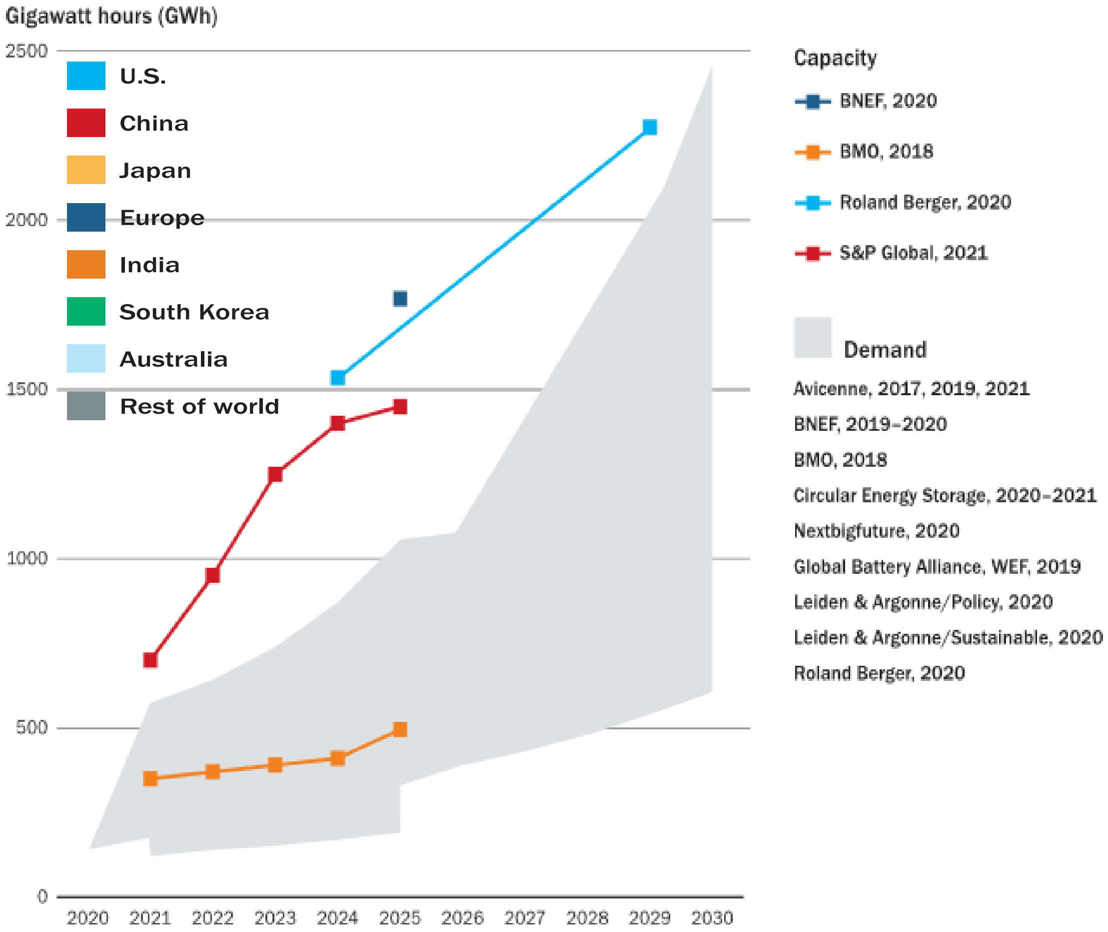
2020
Commissioned manufacturing capacity by plant location

2025
Pipeline and commissioned manufacturing capacity to be online, by plant location



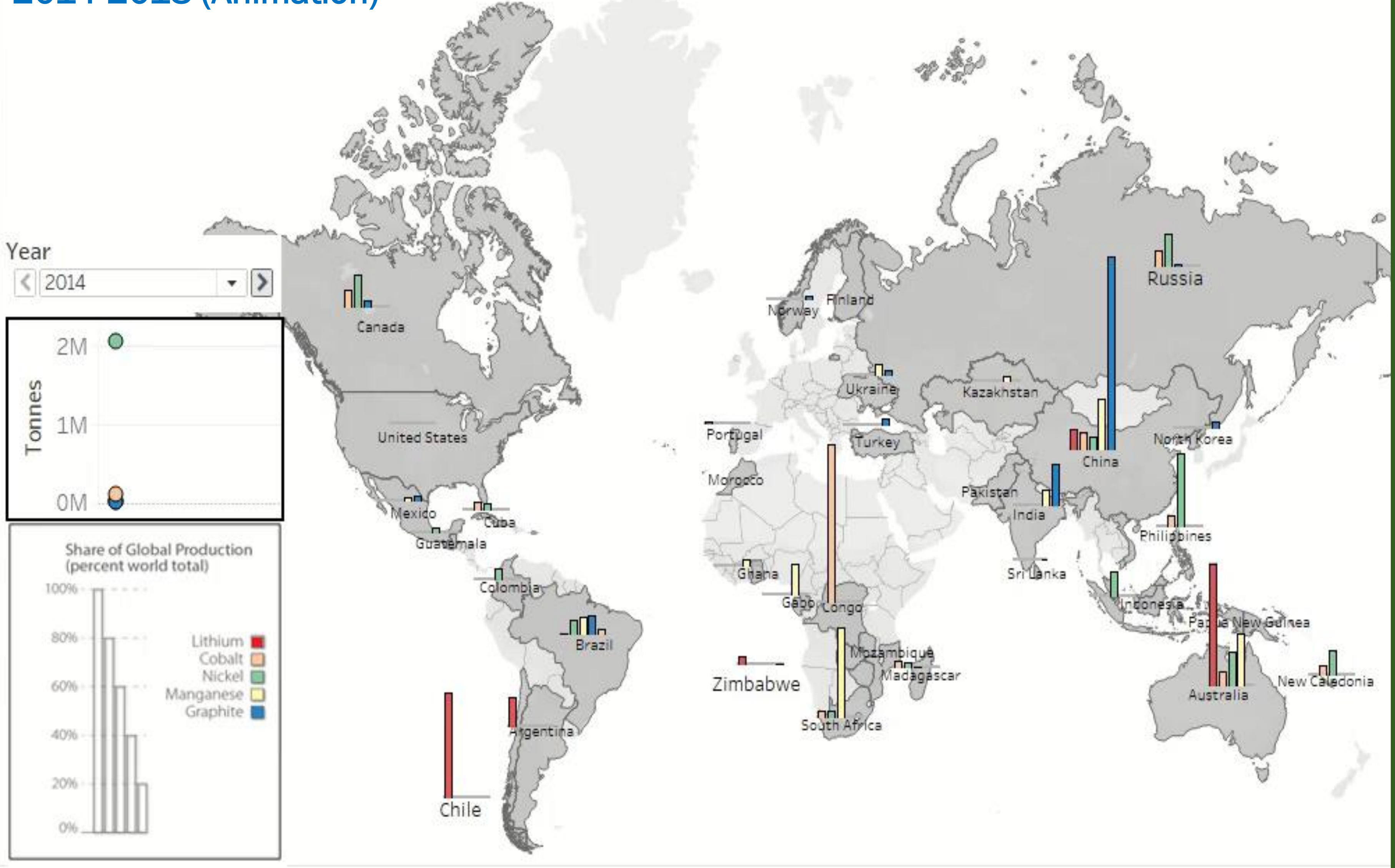
EVs will dominate the demand for Li-ion batteries





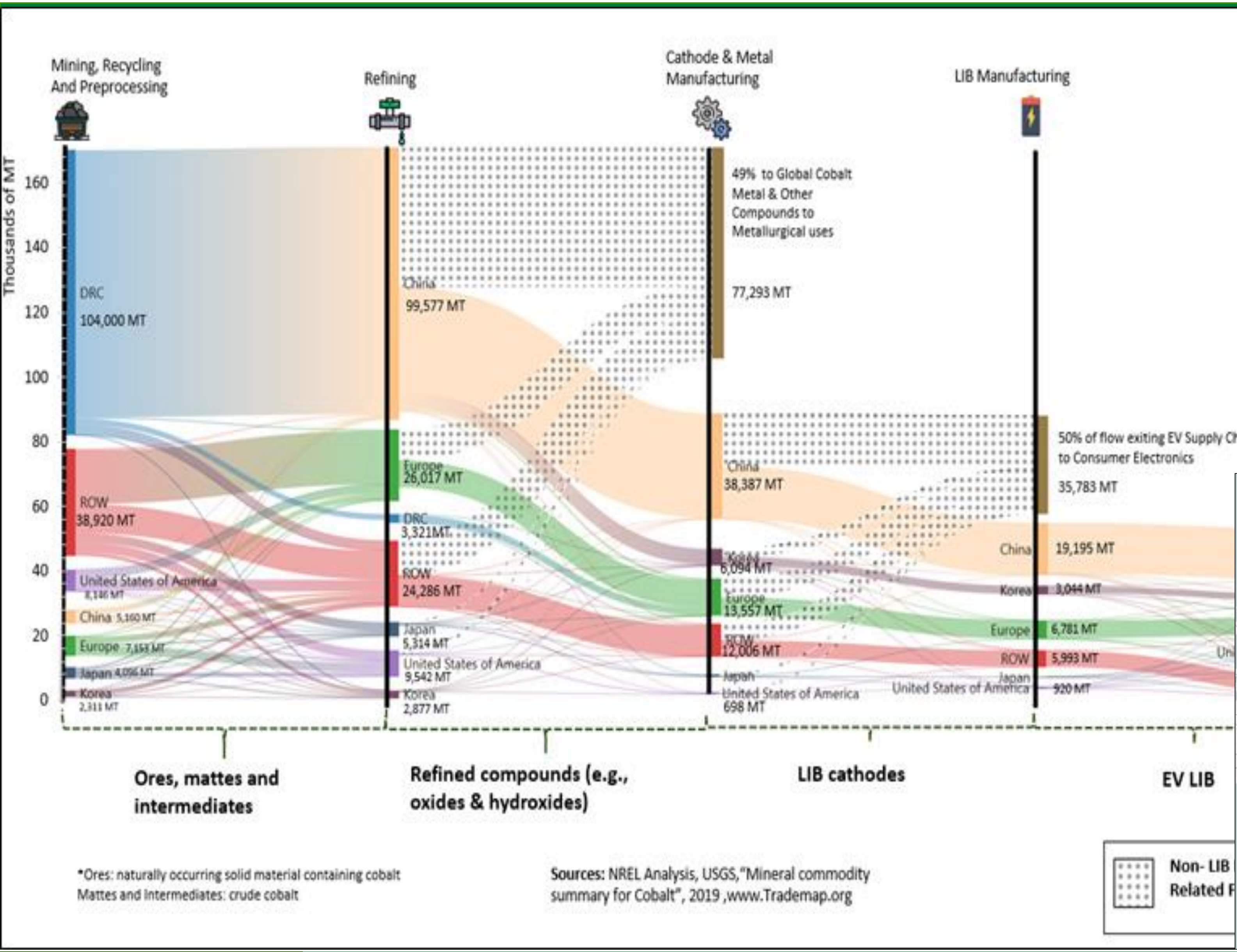
Global Mining of Materials for Lithium-Ion Batteries (animated)

2014-2018 (Animation)

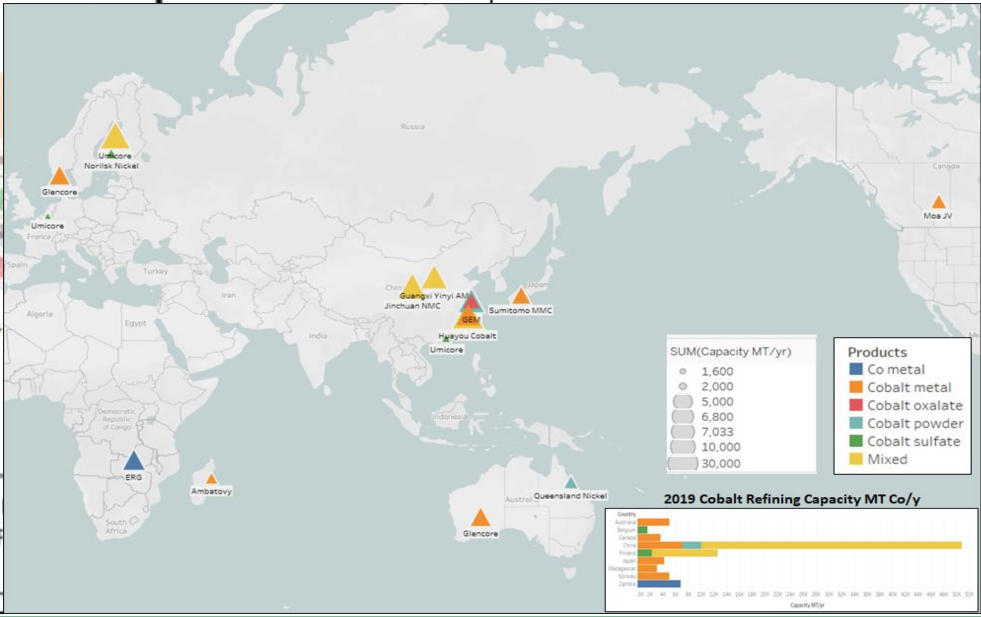


- **In 2019, 41 countries accounted for all global production of Li, Co, Ni, Mn and Graphite, with > 50% of production of three elements (Co, Graphite, Li) originating in one country.**
  - Congo continued to be the world's leading source of mined cobalt, supplying more than 60% of world cobalt mine production
  - Since 2017, U.S. consumption of natural graphite has increased, after dropping by 39% in 2015.
  - Beginning in 2017, worldwide output of lithium grew substantially in response to projected increases in battery manufacturing. as a result of growing demand for lithium for battery applications. The majority of this growth occurred in Australia as a result of Chinese investment in spodumene operations.

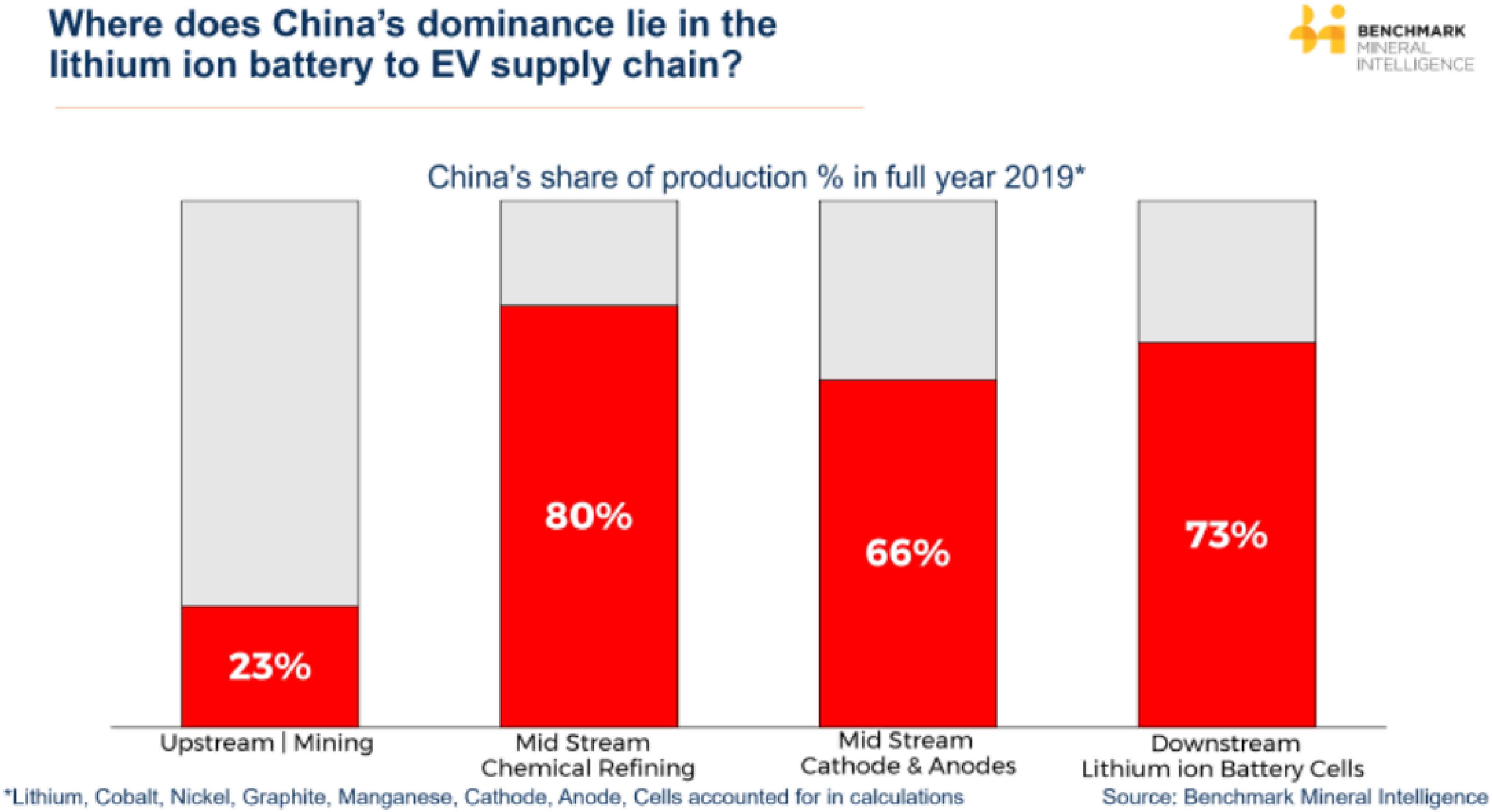
Cobalt Supply Chain



The majority of cobalt is produced in the DRC and is processed in China, for both battery and steel manufacturing. Once cobalt goes to China, very little of it is made available for battery manufacturing elsewhere. Cobalt flowing through the U.S. supply chain primarily comes from steel recycling operations, with a small amount of domestic mining in Michigan and from mine tailings in Missouri.

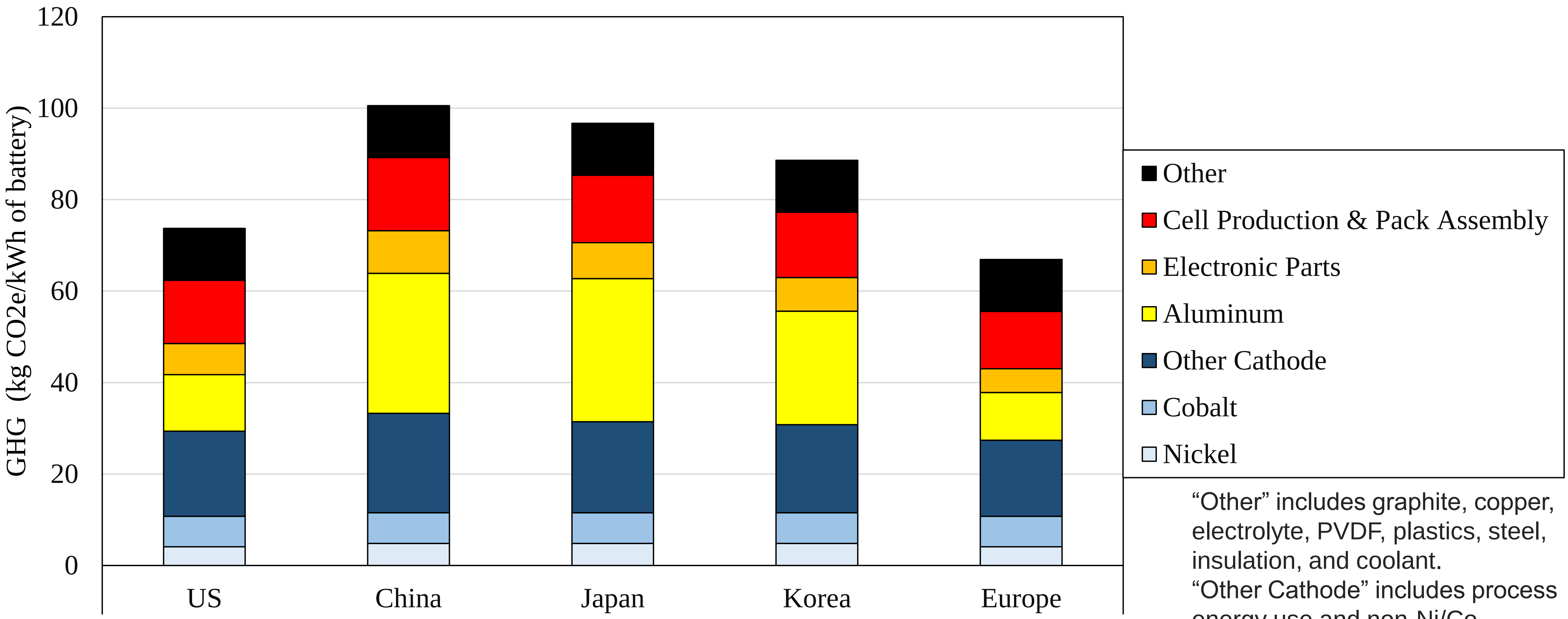


China’s Outsized Impact on the Supply Chain



Manufacturing Emissions by Country

Li-Ion battery LCA result regional variation: country specific GHG emissions



"Other" includes graphite, copper, electrolyte, PVDF, plastics, steel, insulation, and coolant.
"Other Cathode" includes process energy use and non-Ni/Co reagents.

Source: Kelly *et al.*, Mitigation and Adaptation Strategies for Global Change, 2019.

US Competitive Position in Lithium Batteries

SWOT ANALYSIS

STRENGTHS

- Market-leading vehicle manufacturers and battery companies
- Skilled labor
- R&D and manufacturing innovation
- Natural resources
- Strong trade partners
- Access to capital

WEAKNESSES

- Lack of industrial policy and national strategy
- Easy access of competing nations to U.S. market
- Lack of integrated national/regional supply chain
- Labor costs and environmental policy

OPPORTUNITIES

- Expected rapid growth of the battery market
- Job creation
- Economic growth
- Global boost to U.S. auto industry
- U.S. manufacturers capable of responding to federal support

THREATS

- Predatory pricing from foreign competition destroys domestic manufacturing
- Vulnerability to supply disruptions
- Vulnerability to price hikes
- Limited number of domestic cell manufacturers

Federal Consortium for Advanced Batteries (FCAB)

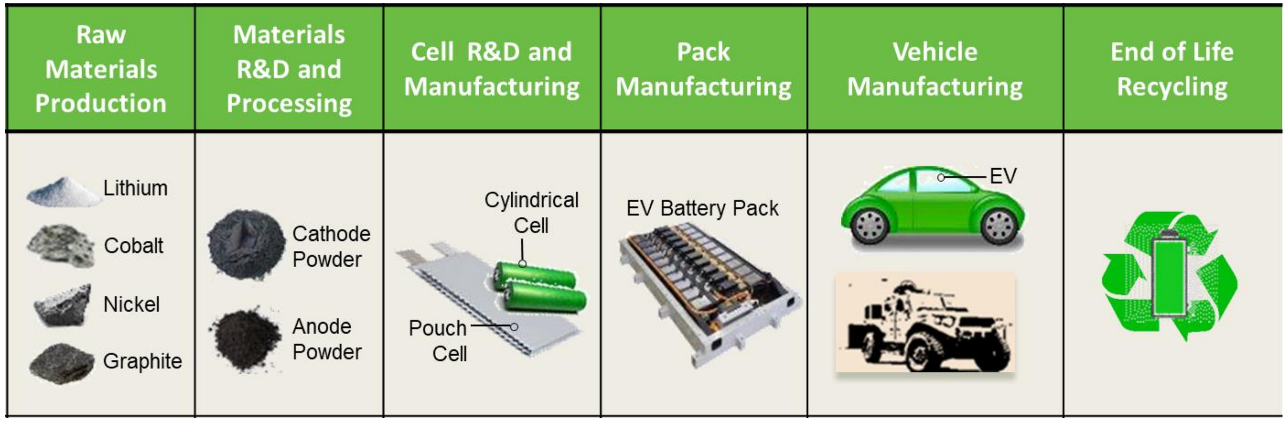
New *Federal Consortium on Advance Batteries* (FCAB) established in 2020

- Purpose: Establish a domestic lithium battery materials and technology supply chain
- 17 Federal Agencies: DOE (EERE Chair), DOC, DOD, DOS, and CIA are leads
- Drafting a National Battery Strategy
  - Identify key actions that the Federal Agencies will take to accomplish vision
  - Technology, Market, and Policy Focus
  - Ready March/April

Raw Material Focus: Cobalt, Lithium and Nickel

- Reduce/Eliminate Cobalt needed for EV batteries
- Establish domestic supplies (Li, Co, Ni) and refining/processing capacity
- Establish a sustainable lithium battery recycling and material recovery system

Lithium Battery Supply Chain



Additional FCAB Focus Areas

- Domestic, Global, and Defense Markets
- Technology Advancement
- Technology Transition across End-Use Applications
- Intellectual Property and Knowledge Protection
- Federal Policies and Authorities

FCAB's Lithium Battery Blueprint (2021-2030)

Release Date – 06/08/2021

Establishes the collaboration framework for Lithium batteries across the Federal government.

Vision for the Lithium-Battery Supply Chain

By 2030, the United States and its partners will establish a secure battery materials and technology supply chain that supports long-term U.S. economic competitiveness and equitable job creation, enables decarbonization, advances social justice, and meets national security requirements.

GOALS TO ACHIEVE OUR VISION

1. Secure access to raw and refined materials and discover alternates for critical materials for commercial and defense applications
2. Support the growth of a U.S. materials-processing base able to meet domestic battery manufacturing demand
3. Stimulate the U.S. electrode, cell, and pack manufacturing sectors
4. Enable U.S. end-of-life reuse and critical-materials recycling at scale and a full competitive value chain in the U.S.
5. Maintain and advance U.S. battery technology leadership by strongly supporting scientific R&D, STEM education, and workforce development

Executive Order 14017: America's Supply Chains – High Capacity Batteries

Release Date – 06/08/2021

Stimulate demand for end products using domestically manufactured high-capacity batteries

- *Create an estimated 450GWh battery demand by electrifying federal, state and local purchases of vehicles and busses*
- *"**Point of Sale**" rebates for consumers and other tax incentives for MDHD vehicles and utilities sector*

Strengthen responsibly-sourced supplies for key advanced battery minerals

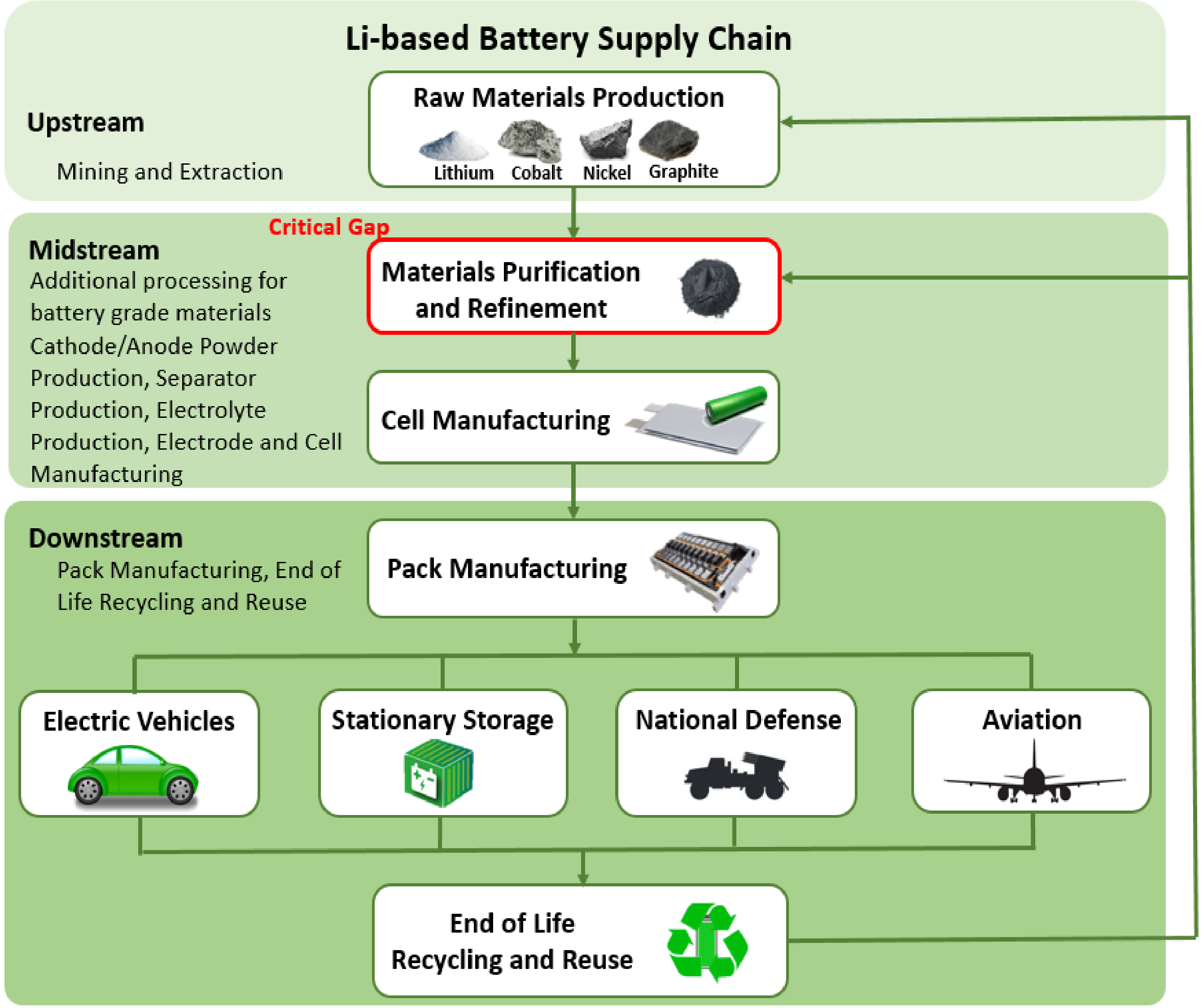
- *Invest in targeted **mineral specific strategies** with better environmental and labor standards*
- *Establish a comprehensive recycling policy recommendation to drastically increase battery capture*

Promote sustainable domestic battery materials, cell, and pack production

- *Incentivize private investment through new federal grant processes, tax credits, and leverage existing programs*

Invest in the people and innovations that are central to maintain a competitive edge

- *Increase R&D to meet cost goals and decrease critical material dependence*
- *Develop workforce and labor standards consistent with US values*



DOE VTO Battery R&D: Near, Next, and Long Term

Enhanced Li-ion (**2020-2025**)
Graphite/NMC

Projected Cell Specific Energy, Cost
300Wh/kg, $100/kWh

Current cycle life	> 1000
Calendar life	> 10 years
Mature Manufacturing	Yes
Fast charge	No
Cost positive recycling	No

R&D Needs

- Fast charge
- Low temperature performance
- Low/no cobalt cathodes
- Cost positive recycling

Next Gen Li-ion (**2025-2030**)
Silicon/NMC (below 5wt%)

Projected Cell Specific Energy, Cost
400Wh/kg, ~$75/kWh

Current cycle life	> 1000
Calendar life	~3 years
Mature Manufacturing	No
Fast charge	Yes, at BOL
Cost positive recycling	No

R&D Needs

- Enhanced calendar life
- Abuse tolerance improvement
- Low/no cobalt cathodes
- Cost effective and scalable pre-lithiation

Lithium Metal (**2025-2030**)
Li metal/DRX, Sulfur, other

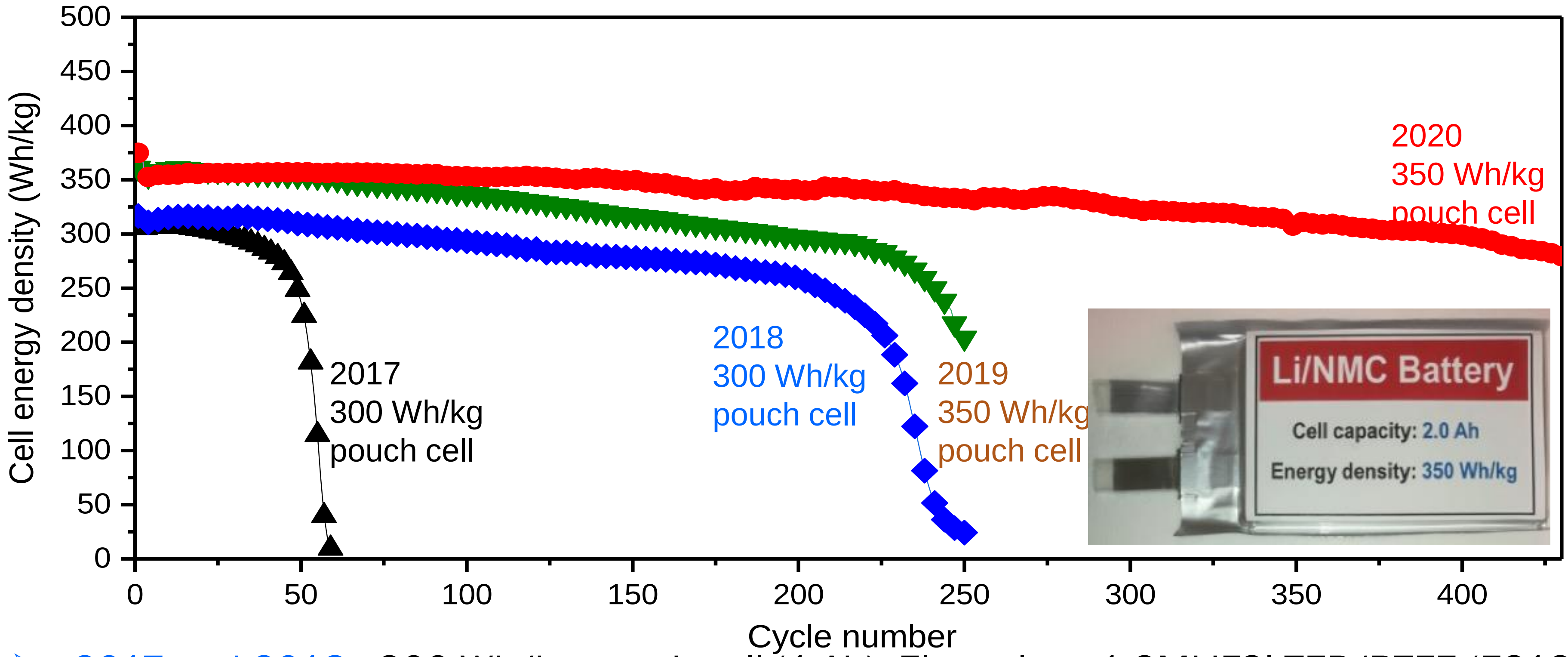
Projected Cell Specific Energy, Cost
500Wh/kg, ~$50-60/kWh

Current cycle life	> 500
Calendar life	???
Mature Manufacturing	No
Fast charge	No
Cost positive recycling	No

R&D Needs

- Enhanced cycle and calendar life
- Protected lithium
- Dendrite detection and mitigation
- Cost effective manufacturing
- High conductivity solid electrolyte

Lithium Metal Progress – Battery500



National Labs

Pacific Northwest National Laboratory
Brookhaven National Laboratory
INL Idaho National Laboratory
SLAC National Accelerator Laboratory

Universities

Binghamton University
The University of Texas at Austin
Stanford University
University of Washington
UC San Diego

All pouch cells:
- NMC622
- 50 um Li
- C/10 charge
- C/3 discharge

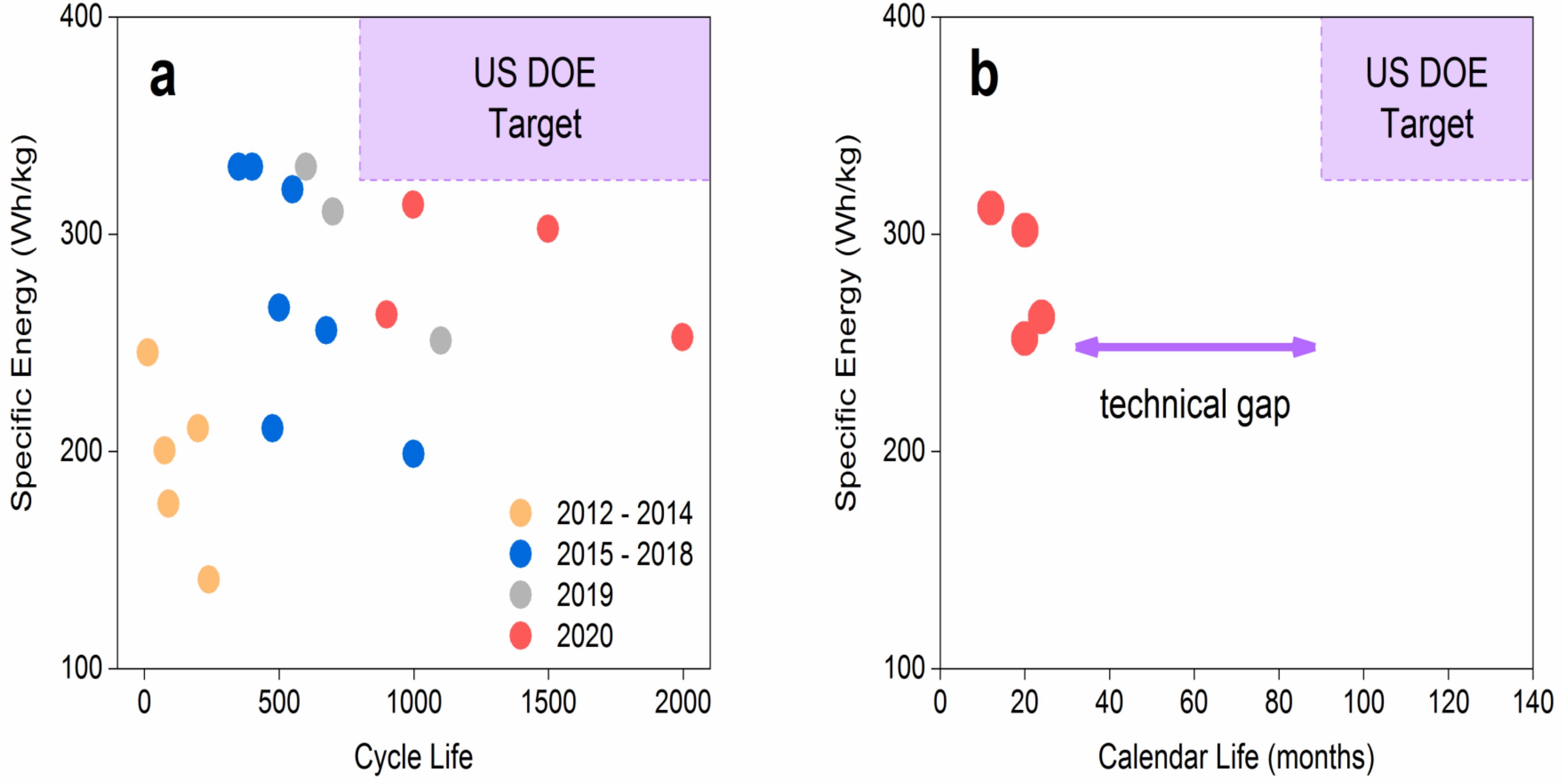
- 2017 and 2018: 300 Wh/kg pouch cell (1 Ah); Electrolyte: 1.2MLiFSI-TEP/BTFE (E313);
- 2019 and 2020: 350 Wh/kg pouch cell (2 Ah level); Electrolyte: 1.5 M LiFSI-DME-TTE (M47);
  - An integration of innovations developed by the consortium
    - Localized concentrated electrolyte: better SEI, decelerated side reactions
    - Electrode architecture: accelerate mass transport, fast ion diffusion
    - Cell design and balance: identify the rate-limiting step and improve

BATTERY 500 CONSORTIUM

Silicon Anodes

Advantages
- 10X capacity of graphite,
- Abundant, (hopefully) inexpensive,
- Enables fast charge.

But….
- Poor calendar life (goal is 10-15 years)
- Very high temperature thermal runaway

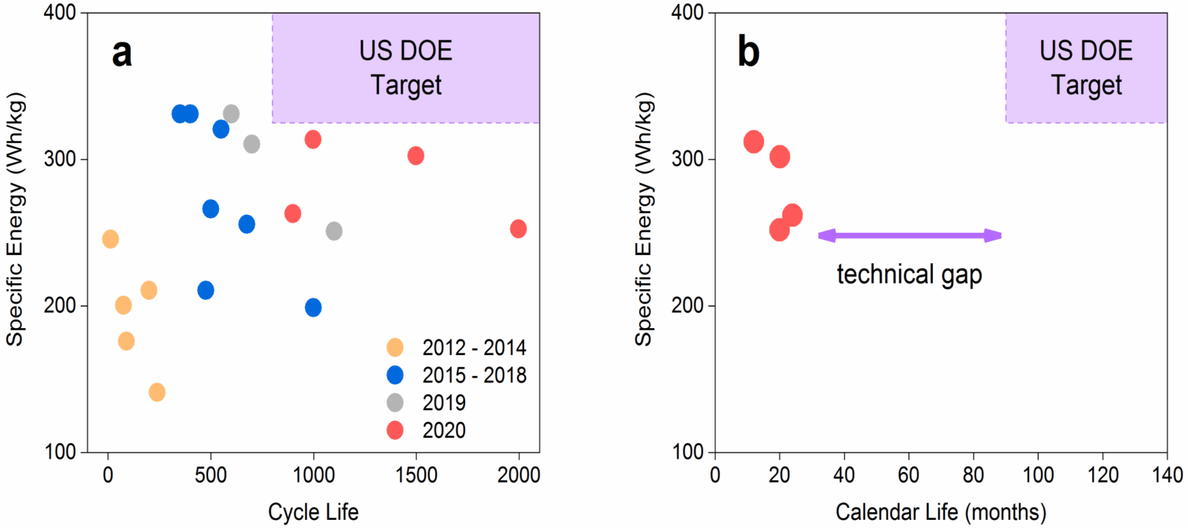


Silicon Consortium Project (SCP)

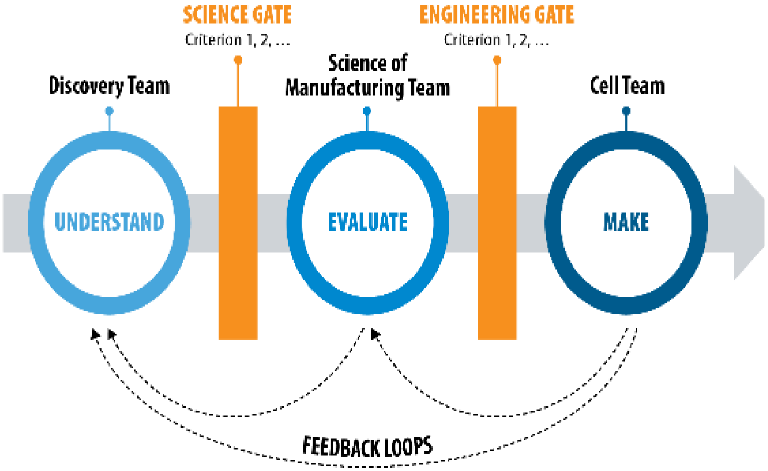
Goal: To understand the issues limiting calendar life in energy storage using silicon anodes and develop mitigation methods to enable automotive applications.

Silicon cell limitations: While the cycle life of silicon-based cells and the overall capacity have improved significantly, calendar life achieves only ~10% of the target.

Understanding the issues: Historically, Si anode research has focused on the large crystallographic expansion (~320%) that Si experiences upon lithiation to form LixSi. However, it has become clear that other failure mechanisms are also present. Specifically, the limited calendar life of Si cells demonstrates that a passivating solid electrolyte interphase does not form on the Si anode. This project uses a knowledge-based approach to the development of scalable solutions to the calendar life in silicon cells, using defined stage gate feedback loops in an integrated team that is focused on the full cell solutions.



Performance gap in the calendar life of silicon cells.



>2-Ah full cells, with Si-based anodes, that deliver 1,000 cycles at C/3, have useable energy of >375 Wh/kg, energy density of >750 Wh/L, and a calendar life >10 years.

2020 Silicon FOA

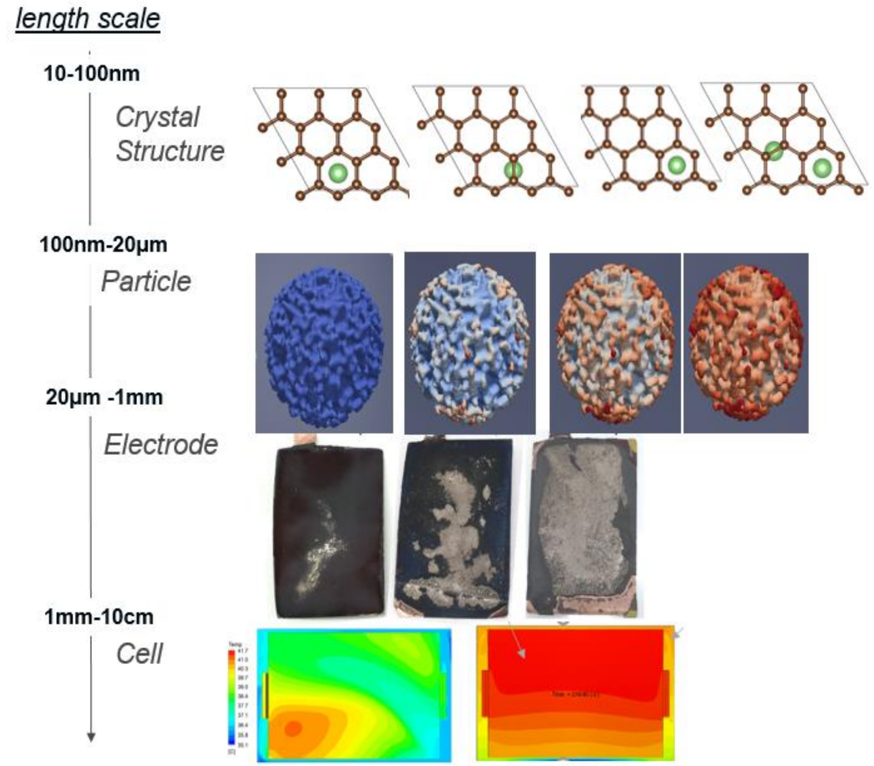
Performance Targets

Beginning of Life Characteristics at 30°C	Cell Level	
Useable Specific Energy @ C/3	>350 Wh/kg	
Useable Energy Density @ C/3	>750 Wh/L	
Calendar Life (<20% energy fade) (1)	>5 Years	>10 Years
Cycle Life (C/3 deep discharge to 350Wh/kg, <20% energy fade) (1)	>3,000	>1,000

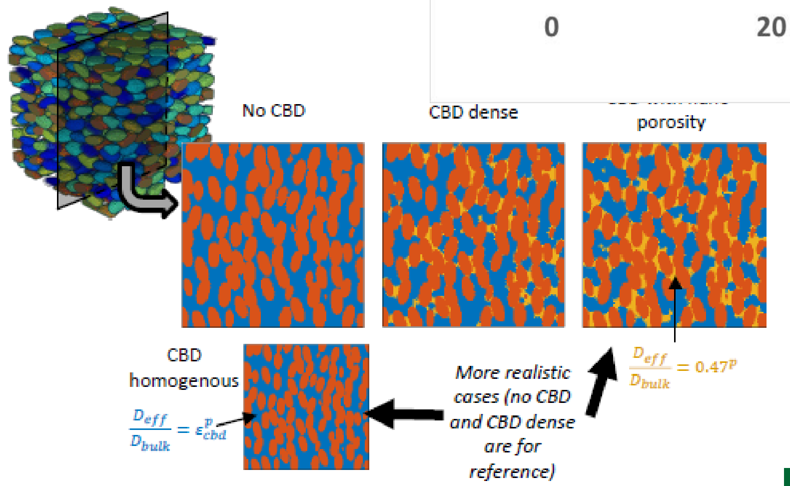
Lead Organization	Project Title
University of Maryland: College Park	Rational Electrolyte Design for Li-ion Batteries with Micro-Sized Si Anodes
University of Delaware	Devising mechanically compliant and chemically stable synthetic solid-electrolyte interphases on silicon using ex situ electropolymerization for long cycling Si anodes
SUNY University at Stony Brook	Fully Fluorinated Local High Concentration Electrolytes Enabling High Energy Density Si Anodes
Solid Power Inc	Solid State Li Ion Batteries using Si Composite Anodes
Sila Nanotechnologies	Ultra-Low Volume Changing Silicon-Dominant Nanocomposite Anodes
Group14 Technologies Inc.	Rationally Designed Lithium Ion Batteries Towards Displacing Internal Combustion Engines
Enovix Corporation	Structurally and Electrochemically Stabilized Si-rich Anodes for EV Applications

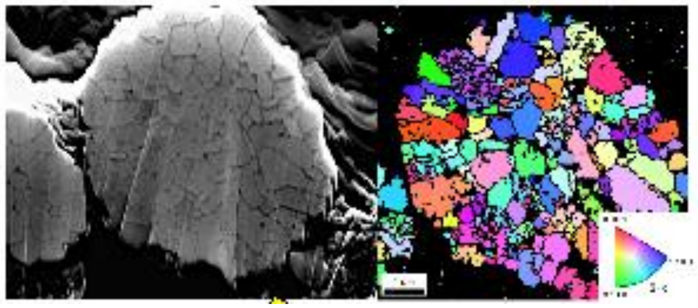
Extreme Fast Charging (XFC)

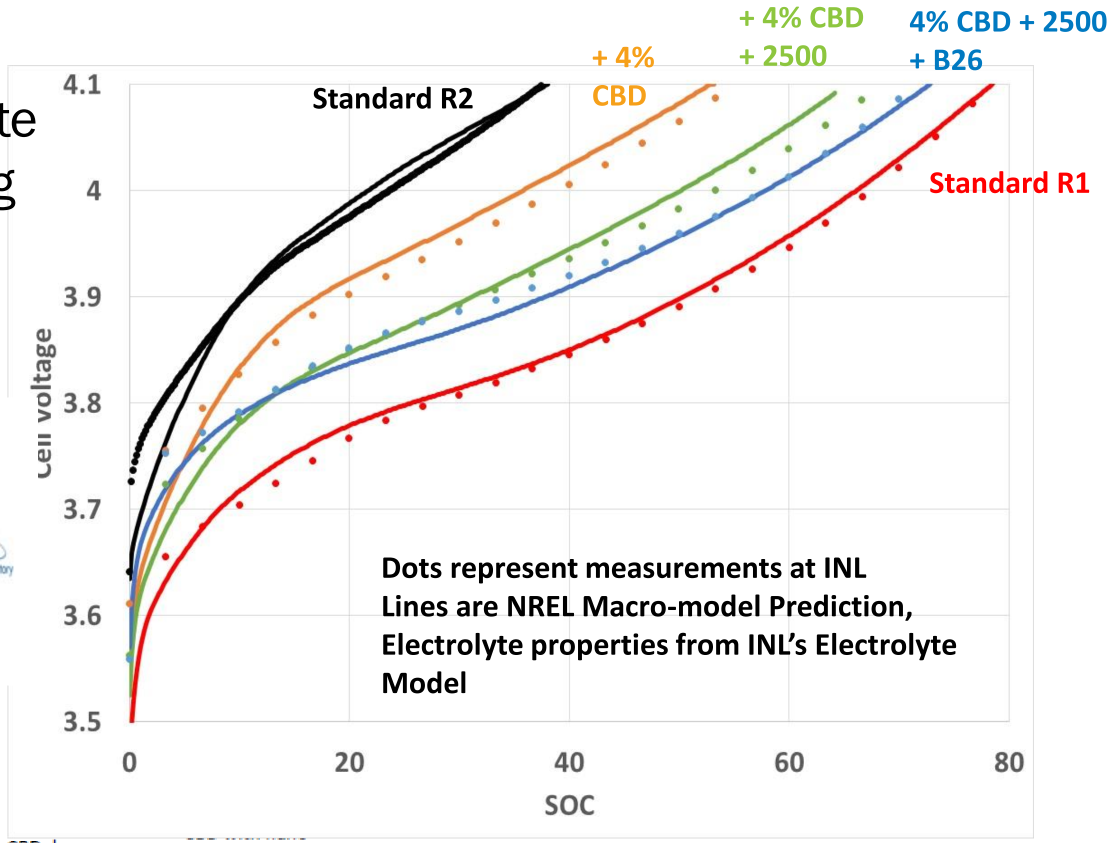
Enable fast charging (10 minutes or less) of high-capacity batteries (above 200Wh/kg) using novel cell designs with state of the art materials. Developing a fundamental understanding of the complex multivariable interactions for fast charging helps us identify solutions for rate optimization while minimizing life and energy density impacts.



Argonne NATIONAL LABORATORY
NREL
BERKELEY LAB
XCEL
eXtreme Fast Charge Cell Evaluation of Lithium-ion Batteries
INL Idaho National Laboratory
SLAC NATIONAL ACCELERATOR LABORATORY





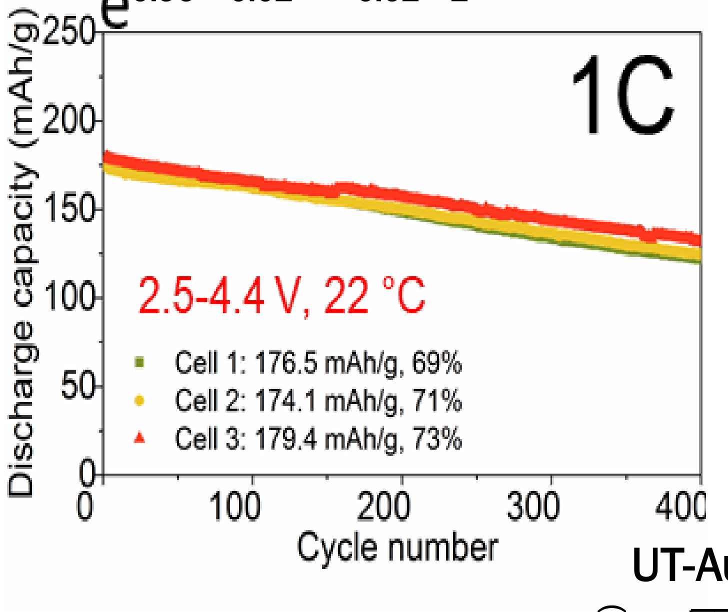


Low/No Cobalt R&D

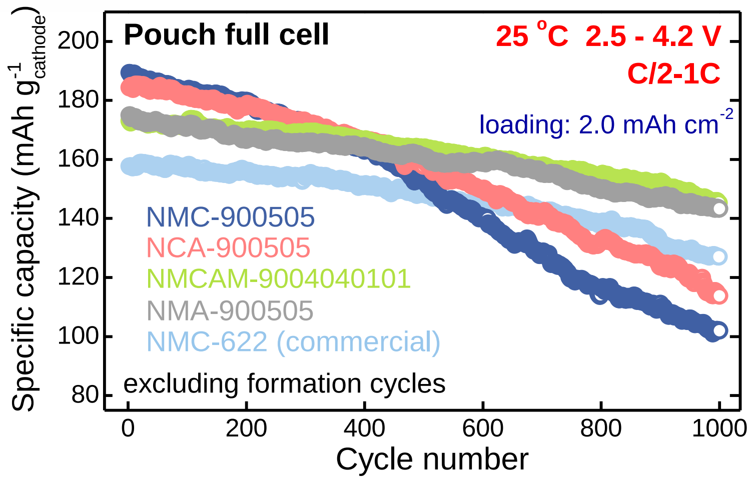
Cobalt (and increasingly nickel) are considered to be critical materials and are essential to today's Li ion batteries.

- In 2019, DOE awarded six contracts to develop and improve cathodes with low or no Cobalt.
- The main chemistries under research high nickel NMC cathodes (Ni > 80%) and Cobalt free materials like the 5 Volt spinel, $LiMn_{1.5}Ni_{0.5}O_4$

UC-Irvine/VA-Tech high-Ni ($LiNi_{0.96}Ti_{0.02}Mg_{0.02}O_2$).



UT-Austin/NREL/Tesla



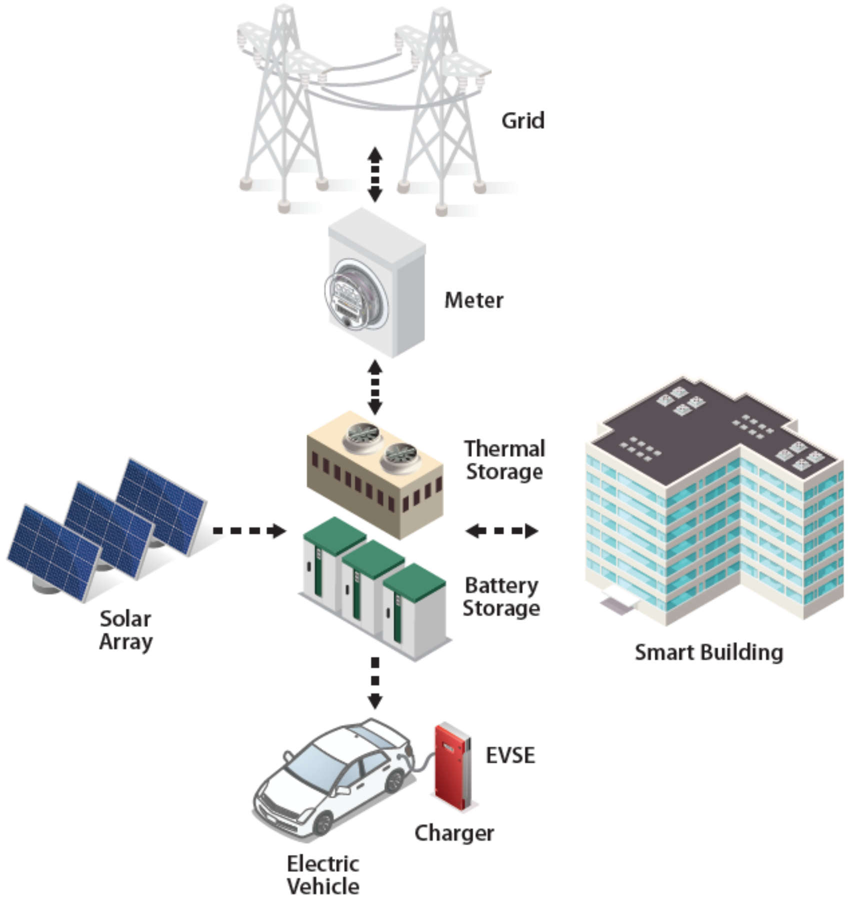
Behind-the-Meter Storage

Goal: To produce behind-the-meter batteries deployed at scale for high-power electric-vehicle charging.

Extreme Fast-Charging: Is an initiative in U. S. Department of Energy Vehicle Technologies Office. As EV deployment increases, individual access to charging may limit uptake. To allow equitable access to EVs commercial charging stations like today's gas stations will be required.

Substantial Power Levels: For the extreme fast-charging (10 minutes) of light duty vehicles peak power levels of >800 kW per vehicle maybe required. For medium and heavy-duty transportation charging power levels of multiple MW will be needed. Novel solutions are needed to avoid negative grid impacts and VTO is enabling BTMS battery solutions that are cost effective safe, last 20 years and 8000 cycles from earth abundant elements.

Partnership with the U. S. Department of Energy Buildings Technology Office and Solar Energy Technology Office



NREL Transforming ENERGY | Idaho National Laboratory | Sandia National Laboratories | Argonne NATIONAL LABORATORY

The ReCell Center

Mission -Decrease the cost of recycling lithium-ion batteries to ensure future supply of critical materials and decrease energy usage compared to raw material production

DIRECT CATHODE RECYCLING

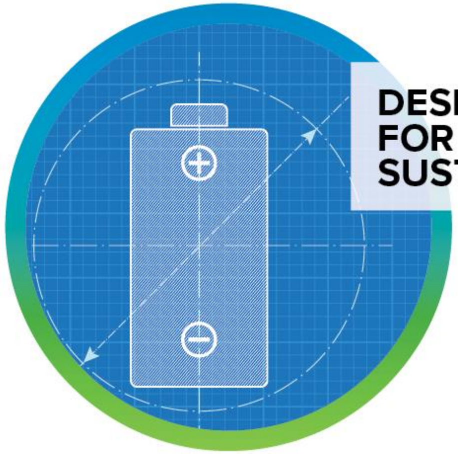
- Binder Removal
- Cathode/ Cathode Separation
- Relithiation
- Cathode Upcycling
- Impurity Impact

OTHER MATERIAL RECOVERY

- Cell Shredding
- Electrode Delamination
- Anode/ Cathode Separation
- Electrolyte Component Recovery

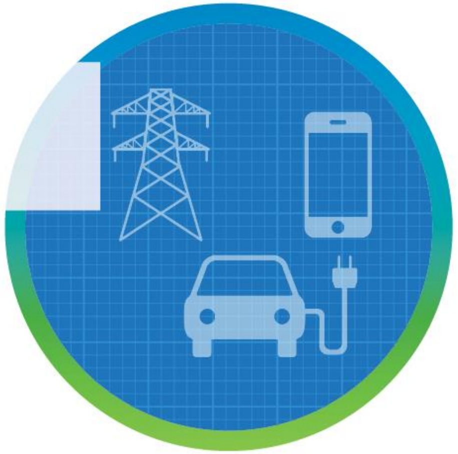
Cross Cutting Projects

DESIGN FOR SUSTAINABILITY



- Cell Design for Rejuvenation
- Standards setting for disassembly

MODELING AND ANALYSIS



- EverBatt (TEA/LCA)
- LIBRA (Supply Chain Modeling)

16 inventions and 23 publications in ~2.5 years

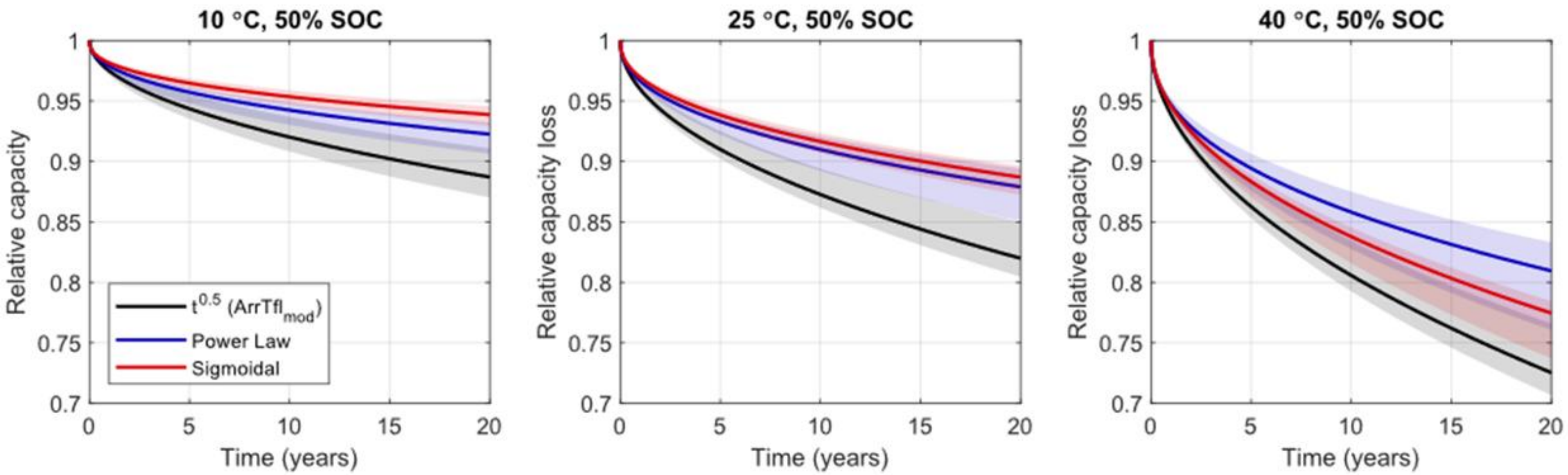
Argonne NATIONAL LABORATORY | NREL NATIONAL RENEWABLE ENERGY LABORATORY | OAK RIDGE National Laboratory | Michigan Technological University 1885 | WPI | UC San Diego

Machine Learning for Accelerated Life Prediction and Cell Design

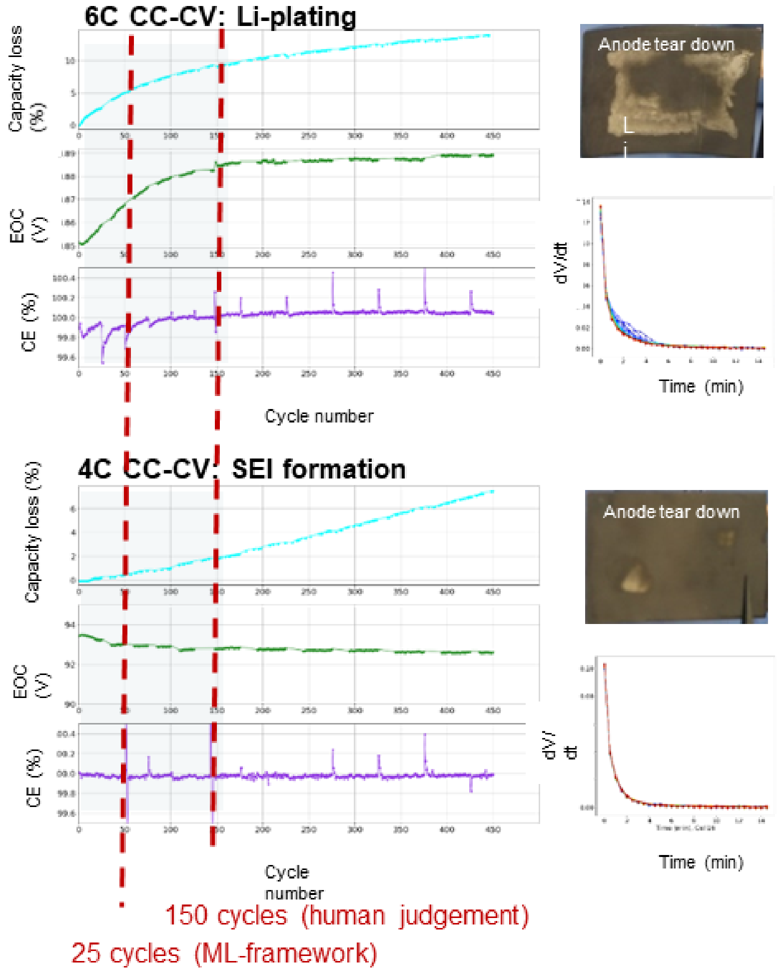
Reducing the time needed to diagnose failure modes and make life predictions is vital to the implementation of rapid validation. VTO has started activities using machine learning to predict both life and failure mode to decrease the time needed between technology innovation and deployment

Major focus areas are:

- **Early classification and prediction of failure mode**
- **Auto-generation of algebraic models**
- **Life prediction**
- ***a priori* prediction of life and failure mode based on chemistry, design and use profile**



Decreased uncertainty using autogenerated models when compared to human model development



Considering multiple signatures leads to a 4x reduction in time needed to classify degradation mode

Gasper, P., Gering, K., Dufek, E., Smith, K. *J. Electrochem. Soc.* **2021,** 168(2), 020502
Chen, B.R., Kunz, M.R., Tanim, T.R., Dufek, E.J. *Cell Reports Physical Science* **2021**, 2, 100352

Battery Recycling Prize - Congratulations Phase II Winners

- Seven Phase II Winning Teams:
  – Li Industries
  – OnTo Technology
  – Powering the Future
  – Renewance
  – Smartville
  – Team Portables
  – Titan Advanced Energy Solutions