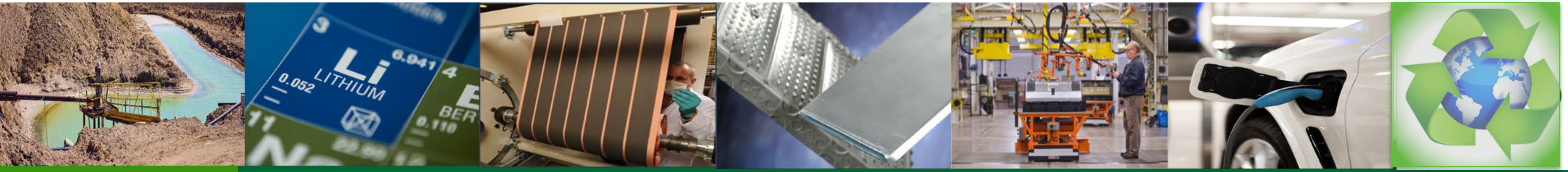
U.S. Federal Efforts to Support the Lithium Battery Supply Chain, Innovation, and Sustainability

Anthony Burrell, NREL
on behalf of the Vehicle Technologies Office, DOE

September 13, 2022



Significant Growth Projection for High-Capacity Batteries

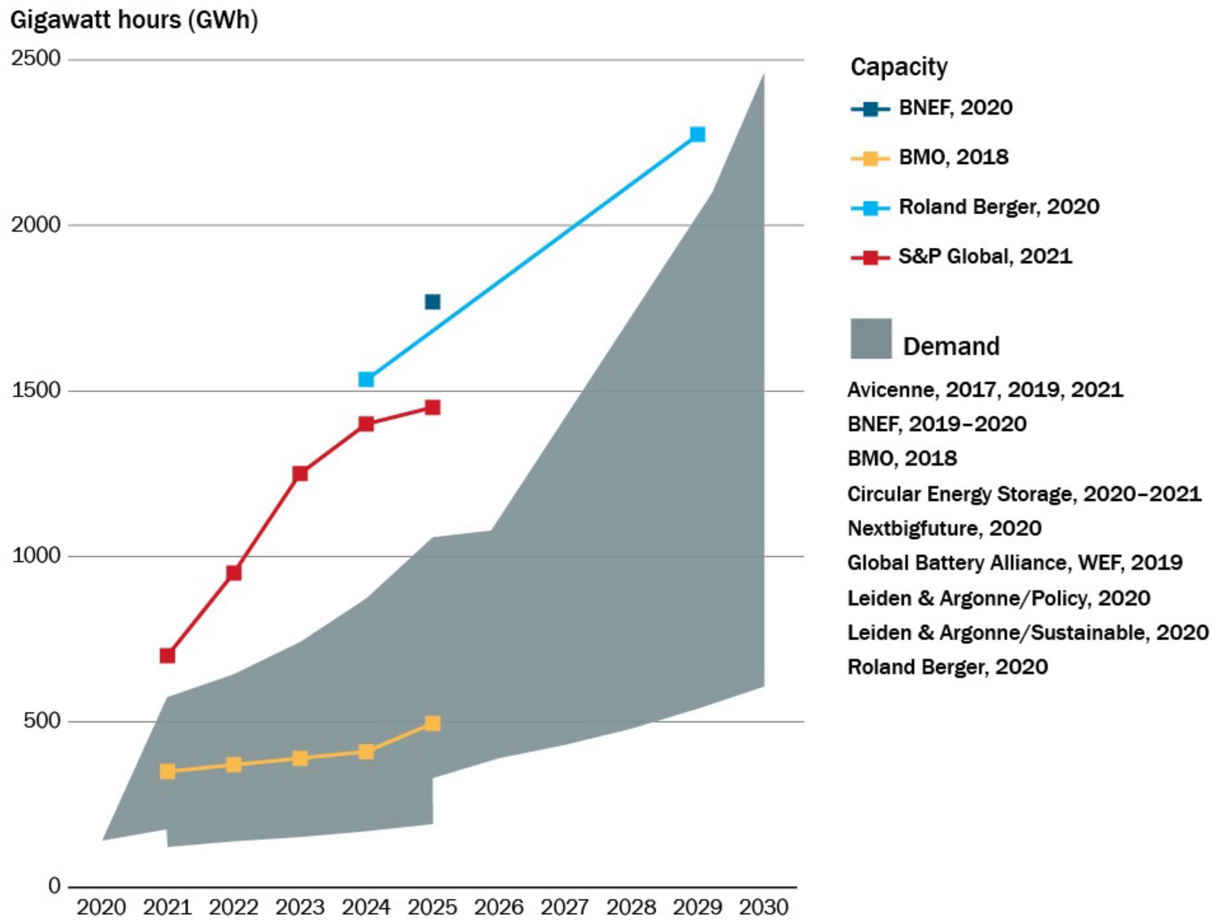
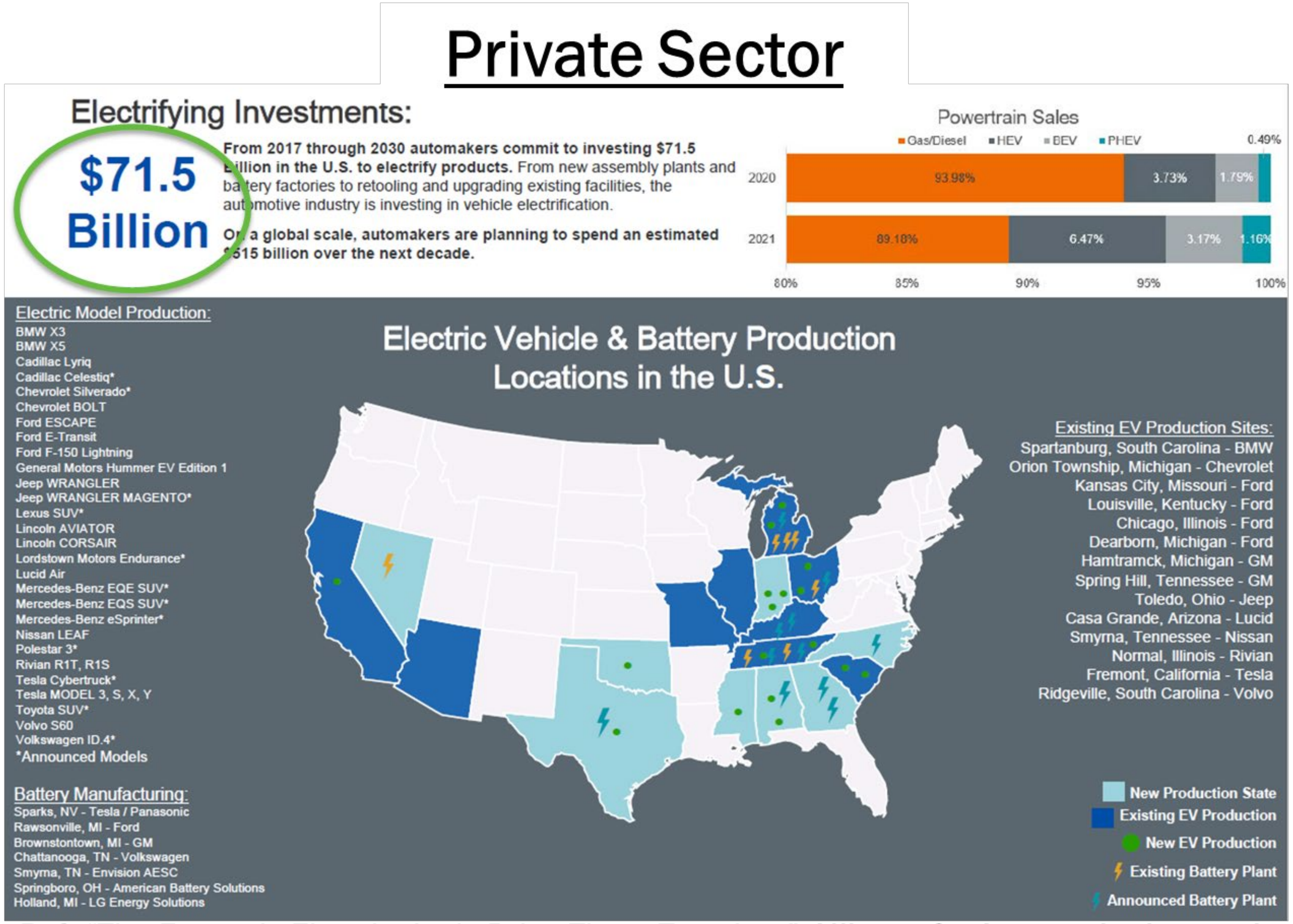


Figure 2. Global Li-ion EV Battery Demand Projections. Yan Zhou, David Gohlke, Luke Rush, Jarod Kelly, and Qiang Dai (2021) Lithium-Ion Battery Supply Chain for E-Drive Vehicles in the United States: 2010–2020.
Source: Argonne National Laboratory ANL/ESD-21/3.

Expansion of Lithium Battery Demand and Manufacturing Capacity is Occurring in the U.S.



Ref: "The Future is Electric: Let's Drive There Together," Alliance for Automotive Innovation

U.S. Lithium-ion battery cell production capacity poised to expand from 59 GWh in 2020 to almost 350 GWh by 2026 (~6X increase)

Government

Bipartisan Infrastructure Law Provides:

nearly **$7B**

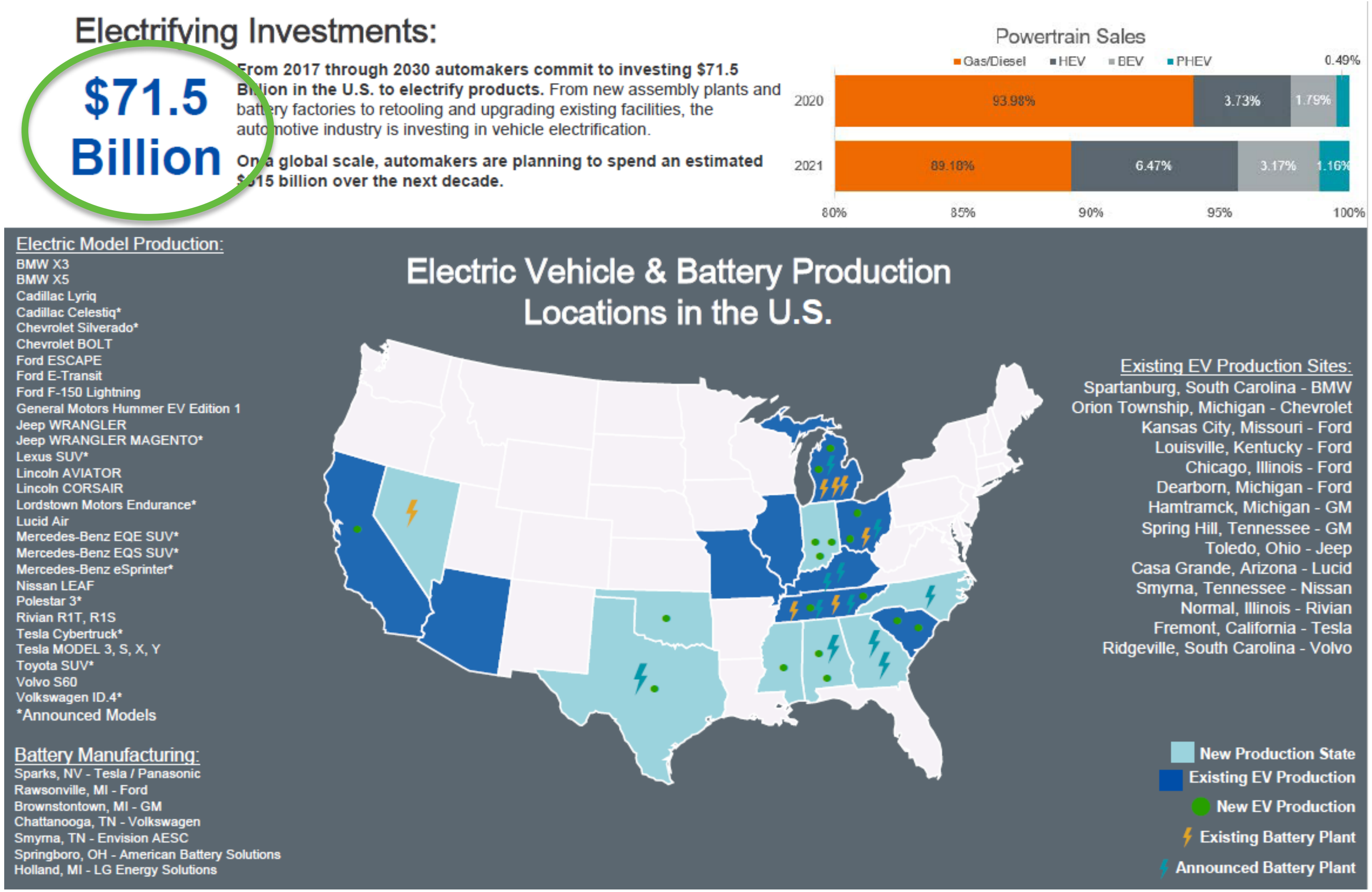
For battery material processing, component/cell manufacturing, and recycling

+

$7.5B

To build out EV charging infrastructure

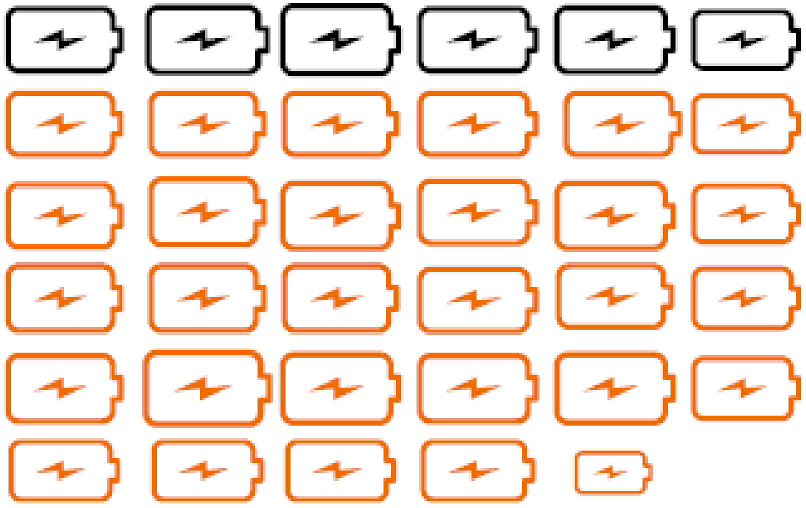
Private Sector



Ref: “The Future is Electric: Let's Drive There Together,” **Alliance for Automotive Innovation**

Battery Cell and Component Manufacturing Plans

Battery Plant Manufacturing Capacity in the U.S. Increasing 428% By 2026



59 GWh
(as of 2021)
+
284.5 GWh
(by 2026)
=
343.5 GWh

In 2020, there was about 630 GWh of global battery production capacity, which is expected to grow to about 2,300 GWh by 2025.

U.S. and China Global Subcomponent Capacity Share

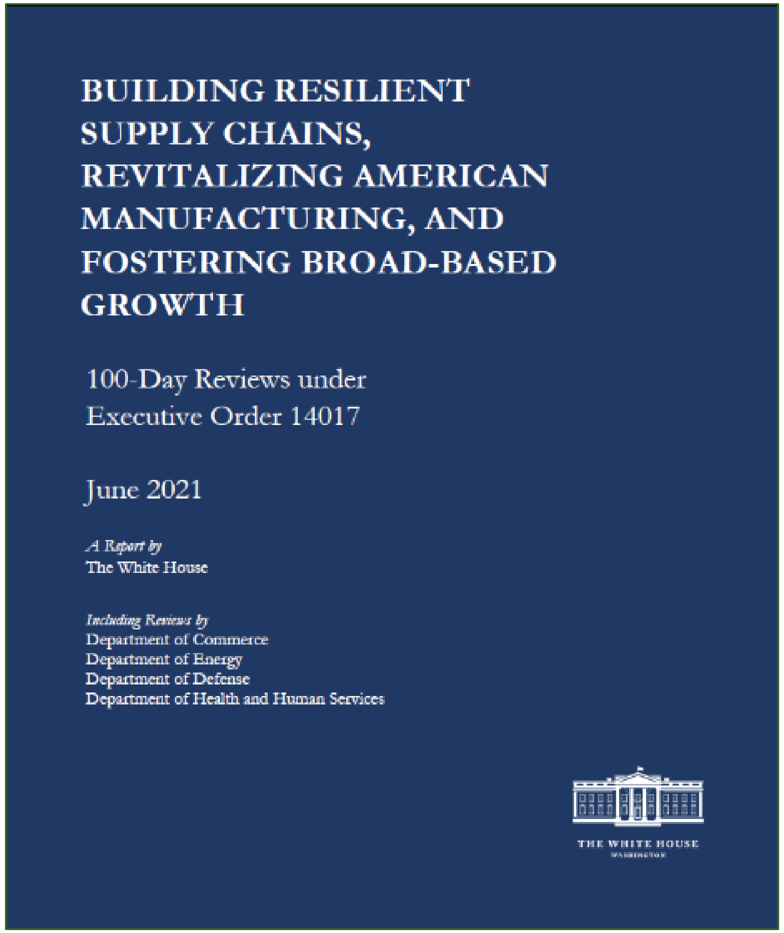
	Current		Under Development	
	U.S.	China	U.S.	China
Cathode Share	0.7%	63.0%	0.0%	84.0%
Anode Share	0.6%	84.0%	0.0%	91.0%
Separator	3.0%	66.0%	0.0%	76.0%
Electrolyte	7.0%	69.0%	2.0%	75.0%

Ref: "The Future is Electric: Let's Drive There Together", Alliance for Automotive Innovation

Guiding Documents

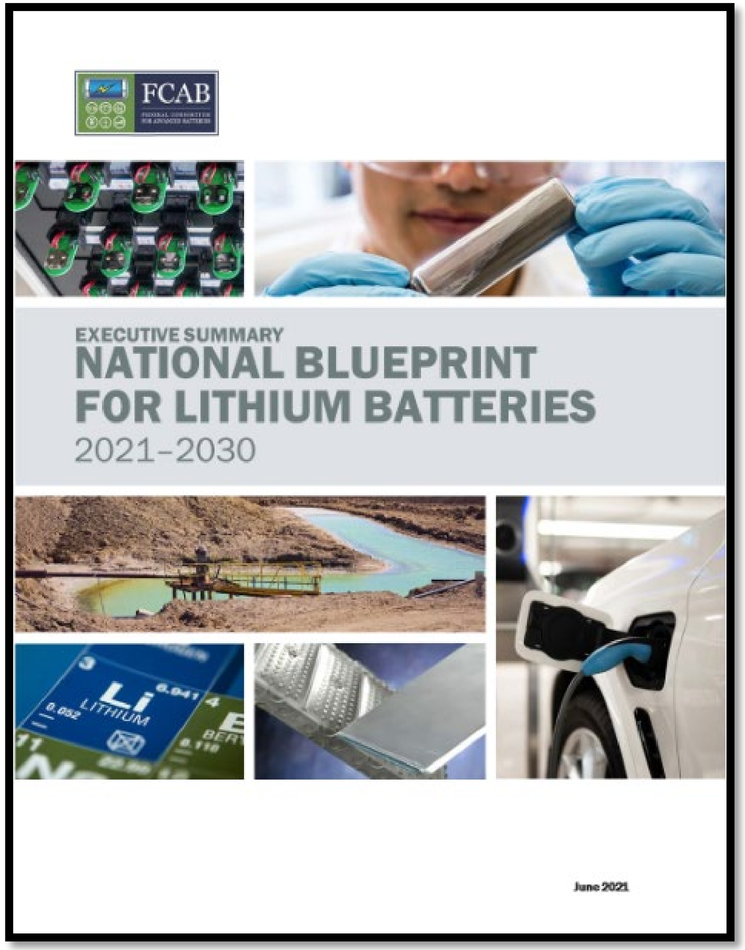
President's Executive Order 14017: America's Supply Chains

100 Day Report on Supply Chain for High-Capacity Batteries



Federal Consortium for Advanced Batteries

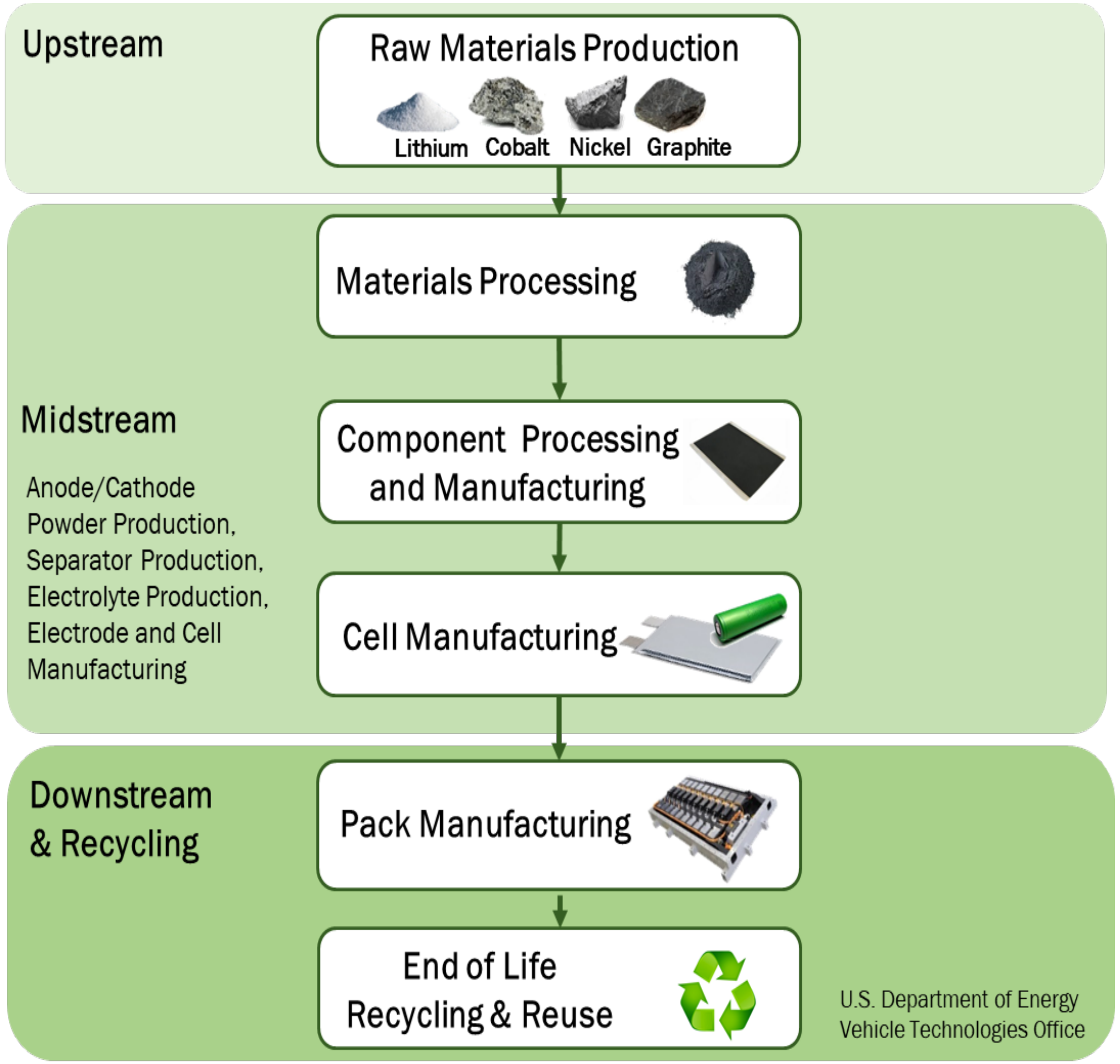
National Blueprint for Lithium Batteries(2021-2030)



Executive Order 14017: America's Supply Chains

Release Date – 06/08/2021

100 Day Report on the High-Capacity Battery Supply Chain



Up Stream

- **Vulnerability:** Class I nickel, lithium, and cobalt are the primary supply chain vulnerabilities.

Mid Stream

- **Vulnerability:** U.S. has a <u>significant deficit</u> in mineral refining and processing.
- **Vulnerability:** Domestic battery materials production capacity sorely lacking.
- **Vulnerability:** The U.S. has less than 10 percent of global market share for cell fabrication.

Down Stream

- **Vulnerability:** U.S. lags other markets in <u>lithium battery recycling</u>, with less than 5% of lithium-ion batteries estimated are recycled each year.
- **Vulnerability:** U.S. lacks policy incentives needed to accelerate domestic demand and production of lithium batteries

The Big Challenges

Cost

Manufacturing

Supply Chain

Infrastructure

Inclusion

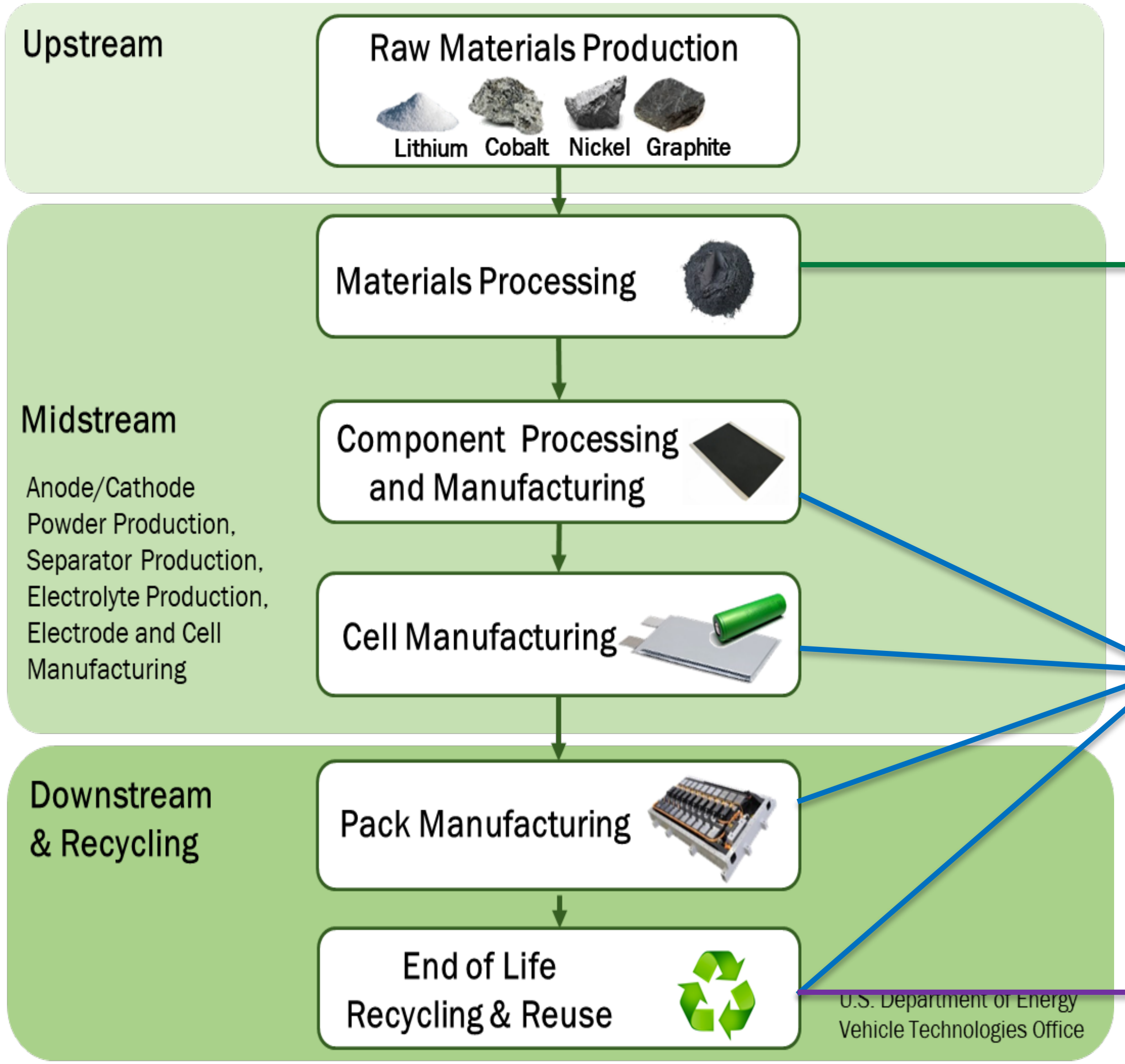
Relevant Bipartisan Infrastructure Law (BIL) Investments

Biden Administration Announces $3.16 Billion from Bipartisan Infrastructure Law to Boost Domestic Battery Manufacturing and Supply Chains

May 2, 2022
Secretary Granholm at Focus Hope in Detroit, Michigan

Supports new, retrofitted, and expanded domestic facilities for battery recycling and the production of battery materials, cell components, and battery manufacturing and large-scale demonstrations.

President's Executive Order 14017: America's Supply Chains: Supply Chain for High-Capacity Batteries



Sec. 40207(b) Battery Material Processing Grants ($3 billion total over 5 years)

Note: Includes separation of materials from extracted feedstocks and materials processing or refining

Sec. 40207(c) Battery Manufacturing and Recycling Grants
($3 billion total over 5 years)

Research, Development, and Demonstration

Sec. 40208 Electric Drive Vehicle Battery Recycling and Second-Life Applications Program ($200 Million Total over 5 years)

FOAs released 5/2/2022

BIL Battery Materials Processing and Battery Manufacturing FOA - $3.1 billion - support the creation of new, retrofitted, and expanded commercial facilities as well as manufacturing demonstrations and battery recycling.

BIL Electric Drive Vehicle Battery Recycling and Second Life Applications FOA - $60 million - support research, develop, and demonstrate, electric drive vehicle battery recycling and second use applications.

Visit https://eere-exchange.energy.gov/

Lithium Battery Supply Chain Sustainability

Reverse Logistics

40207
($135 Million Total)

Design for 2nd Use and Recycling

Consumer adoption of recycling

Spent Battery Disposal and Collection Sites

Qualification/Diagnostics of spent batteries

Component and Material Recovery

Intermediate processing

Environmental and safety protocols and processes

Safe storage and transport

2nd Use and Material Recovery

40208
($200 Million Total over 5 years)

Improvements to EV battery Chemistries to decrease processing costs for battery recycling

Expanded uses for critical materials

Innovative recycling processing to achieve scale-up and profitability

Second Use Demonstrations

Innovation Provides Pathways Toward a Sustainable Battery Ecosystem

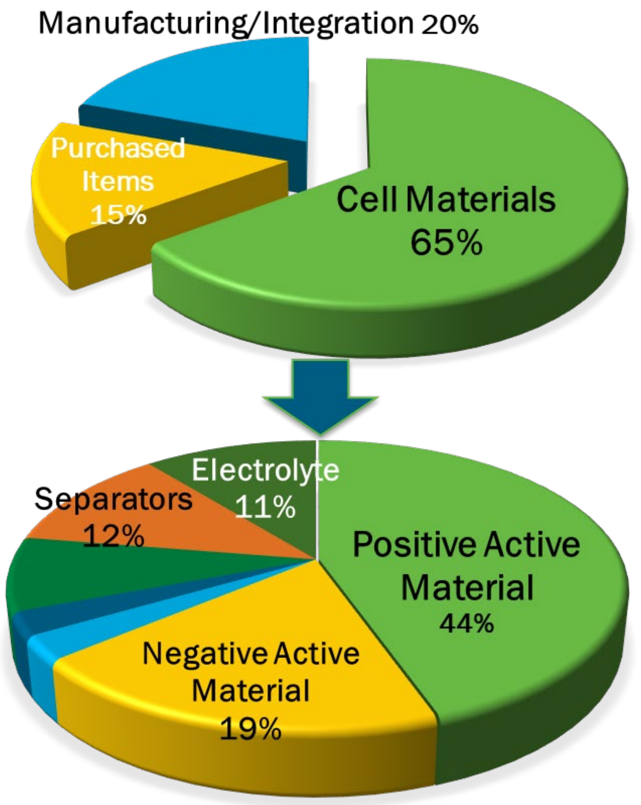
Significantly reduce battery cost, and enhance performance and safety

Reduce or eliminate dependence on critical minerals and support domestic supply chain

Reduce EV battery cell cost by 50% to $60/kWh by 2030 to achieve EV cost parity with ICE vehicles

Enable a safe, 15 minute or less, fast charge capability

Battery Pack Cost Components



R&D Budget of $120 million annually

1. **Accelerate and Scale-Up Lithium Metal Battery**
   - Battery500 Consortium
   - Solid State Materials and Cell Technology
2. **Accelerate Next Generation Lithium-Ion**
   - Low or No Cobalt and Nickel Cathodes
   - Silicon-based anodes
3. **Expand Lithium Battery Recycling R&D**
   - Recover 90% of spent lithium batteries
   - Reclaim 90% of key materials

Battery Recycling

Recycling has the potential to supply significant quantities of key materials for the domestic lithium battery supply chain and reduce cost, energy and water needs, and emissions.

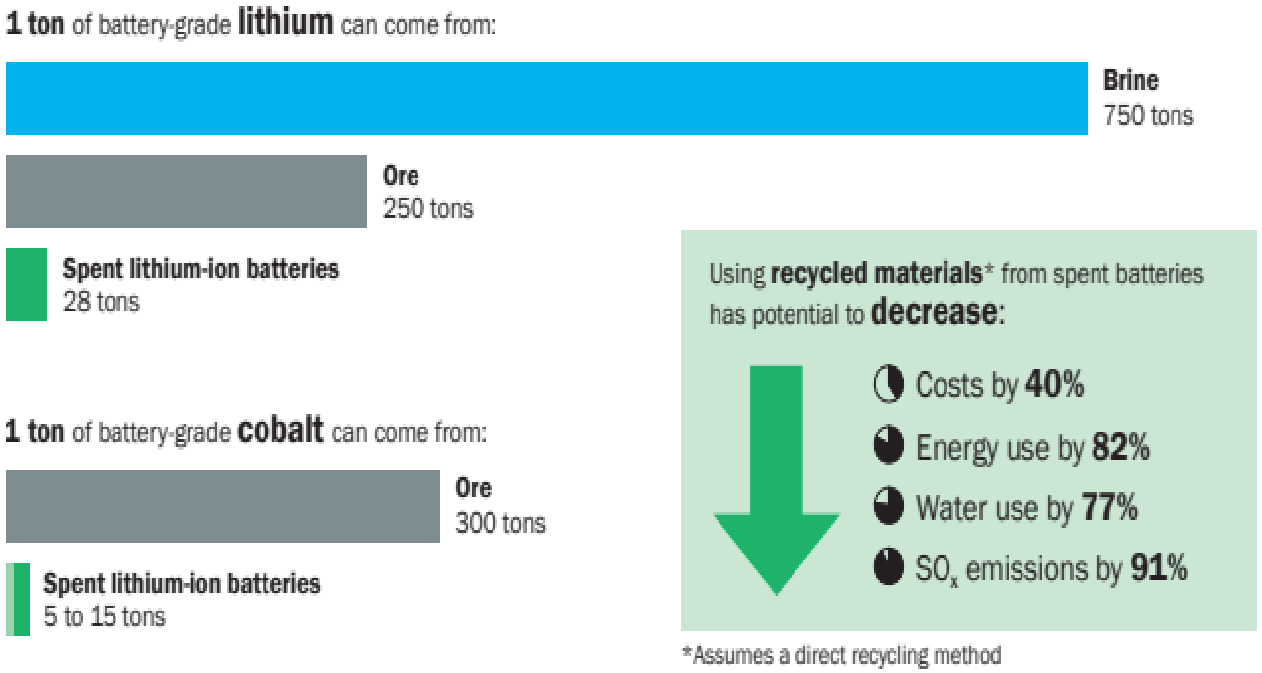
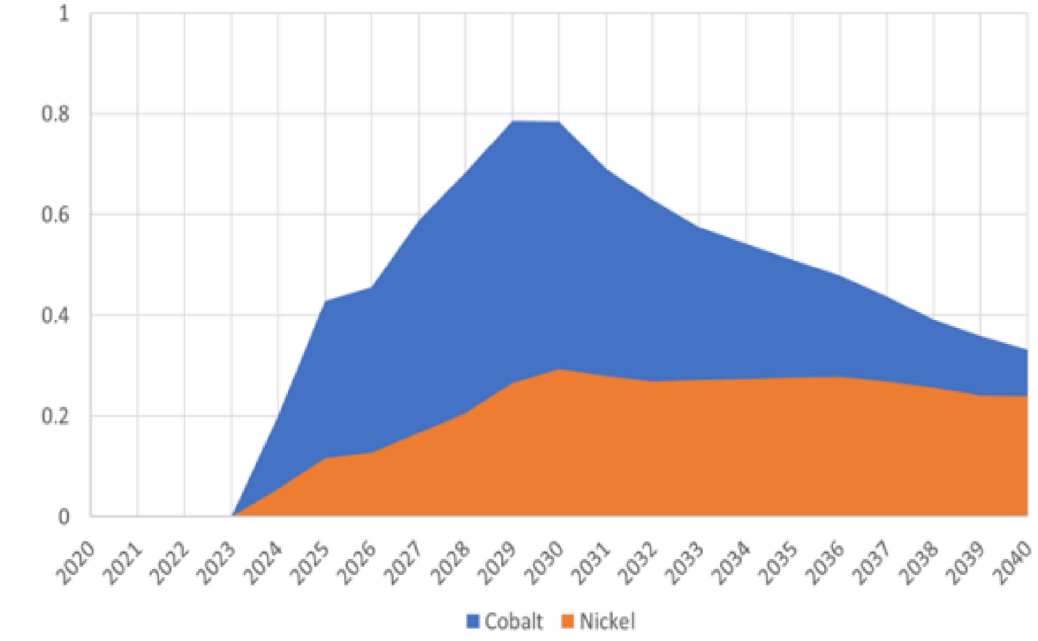


Figure 8. Proportion of nickel and cobalt required for new batteries that could be met with metals recovered from recycled batteries.[72]

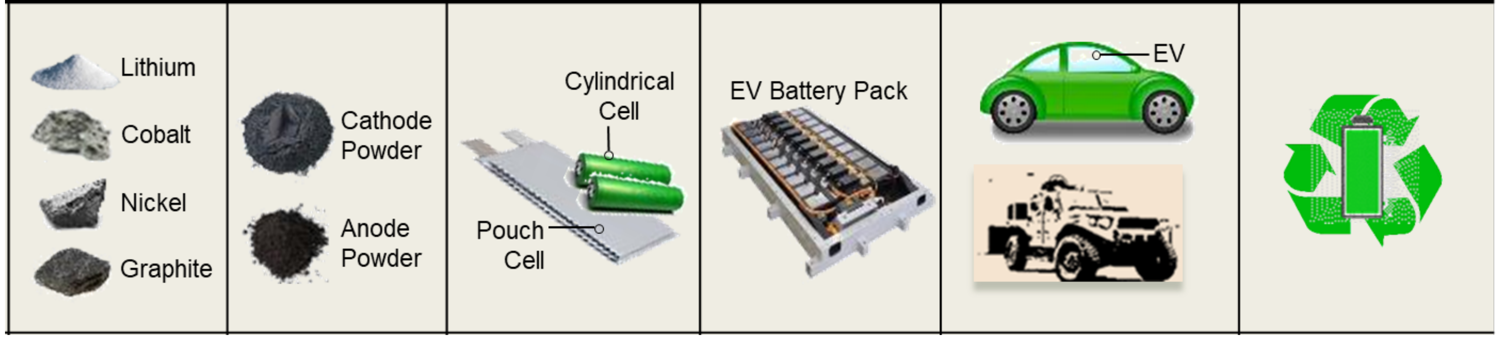


Federal Consortium for Advanced Batteries (FCAB)

Establishes the framework for collaboration on lithium battery interests across the Federal Government

FCAB includes 17 Federal Agencies lead by DOE (EERE Chair), Dept of Commerce, Dept. of Defense, and Dept. of State

Raw Materials Production	Materials R&D and Processing	Cell R&D and Manufacturing	Pack Manufacturing	Vehicle Manufacturing	End of Life Recycling



Lithium Battery Supply Chain

+

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

the Li-Bridge Alliance

Building Bridges Across the Battery Ecosystem

Facilitating Industry-Government interaction to support a resilient high-capacity battery supply chain for the U.S

FEDERAL SECTOR WILL BE ENGAGED THROUGH THE FEDERAL CONSORTIUM FOR ADVANCED BATTERIES

> 14 Federal Agencies

PRIVATE SECTOR WILL BE ENGAGED THROUGH US-BASED TRADE ASSOCIATIONS

> 600 Industrial partners

US-Germany collaboration on Solid State Batteries

BERKELEY LAB
ATM
UNIVERSITY OF MICHIGAN
Pacific Northwest NATIONAL LABORATORY
PennState
Stanford University
Massachusetts Institute of Technology
Argonne NATIONAL LABORATORY
UNIVERSITY OF MARYLAND
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory

Joint publication

Student exchange

HIU Helmholtz Institute Ulm Electrochemical Energy Storage
ZSW
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
JÜLICH Forschungszentrum | HELMHOLTZ-INSTITUT MÜNSTER
meet
JÜLICH Forschungszentrum
KIT Karlsruher Institut für Technologie
TUM TECHNISCHE UNIVERSITÄT MÜNCHEN

Fundamental R&D to understand challenges in solid state batteries, leveraging expertise from the two countries

US - UK Energy Storage Research Collaboration

Joint publication

Student exchange

Initial participants with others to join

Fundamental R&D Related to the development of high energy batteries, materials supply chain and recycling

DOE Updates

- New DOE Office of the Under Secretary for Infrastructure established
  - Establishes the *Office of Manufacturing and Energy Supply Chains (MESC)*
    - Manages programs that develop clean domestic manufacturing and workforce capabilities in support of the Energy Sector Industrial Base
    - Includes a *Battery and Critical Materials Office*
- MESC/EERE Funding Opportunity Announcement (FOA) worth $3.1 billion from President Biden's Bipartisan Infrastructure Law to support a domestic Battery Materials Processing and Battery Manufacturing capability
- Loan Program Office (LPO) announced a conditional commitment to lend up to $107 million to Syrah Technologies, LLC expand capacity to produce natural graphite-based active anode material (AAM) for lithium-ion batteries at the Syrah Vidalia Facility in Vidalia, Louisiana.
- Vehicle Technologies and the Advanced Manufacturing Offices launched a Lithium-Battery Workforce Initiative, providing $5 million to establish five Pilot Programs to Train Battery Manufacturing Workers

DOE Updates

- Vehicle Technologies Office (VTO) launched Phase 2 of the Battery500 Research Consortium, up to $75 million over the next five years. Specific Phase II goals are to demonstrate 5-10 Ah Li-NMC and Li-S cells meeting the program goal of 500 Wh/kg and 1000 EV cycles.
- VTO awarded over $60 million supporting solid state battery materials R&D and over $60 million supporting next generation silicon materials and cells, liquid electrolyte, lithium-sulfur, and lithium-metal battery technology innovations with industry, National Laboratories, and Universities
- SuperTruck 3 Initiative: VTO and the Hydrogen Fuel Cell Office awarded $128 million (matched by recipients) to support innovative RD&D to enable medium- and heavy-duty trucks and freight system efficiency, focused on battery electric and fuel cell technology.
- Advanced Manufacturing and Processing: The Advanced Manufacturing Office and VTO awarded over $60 million to support lower cost battery manufacturing process innovations, including scale-up and device development.
- Advanced Research Projects Agency-Energy (ARPA-E) launched $45M in funding to develop extreme fast charging, low/no nickel and low/no cobalt, batteries.
- Office of Basic Energy Sciences released Funding Opportunities to support fundamental research that could underpin component of energy storage, including Up to $100M/year for new and renewals of Energy Frontier Research Centers, and up to $50M/year to Advance Clean Energy Technologies and Low-Carbon Manufacturing.

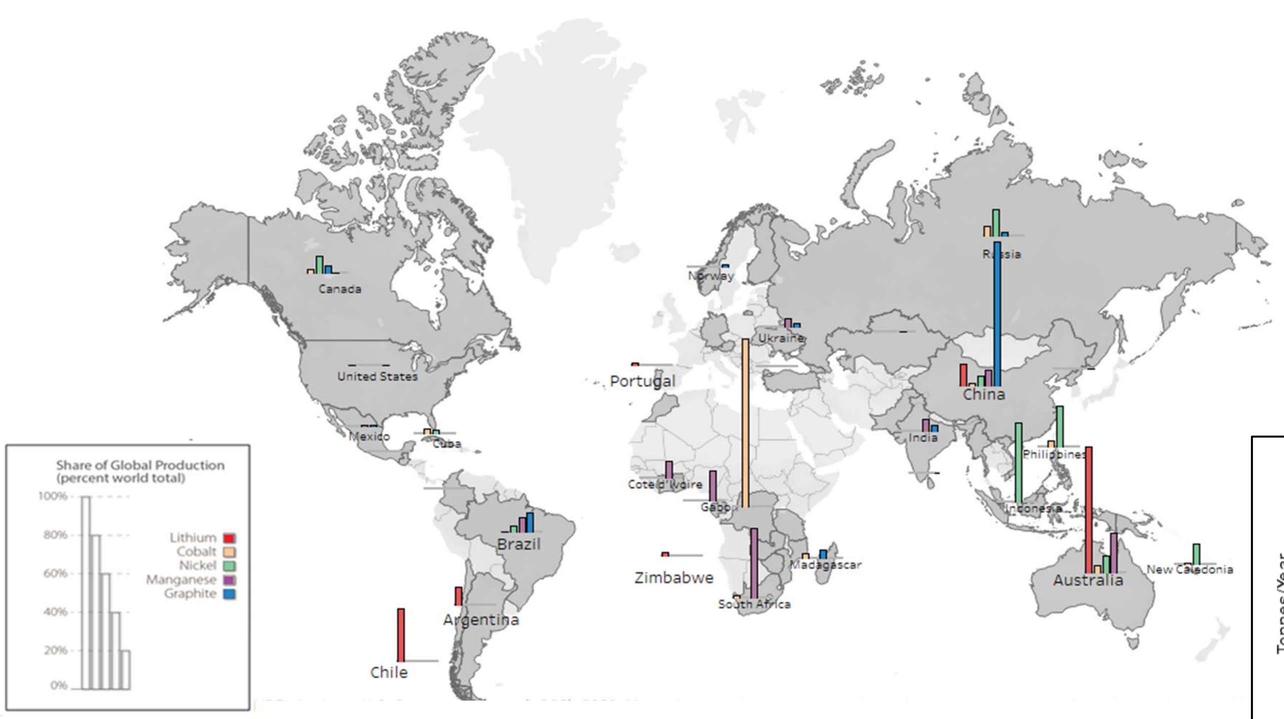
NREL
Transforming ENERGY

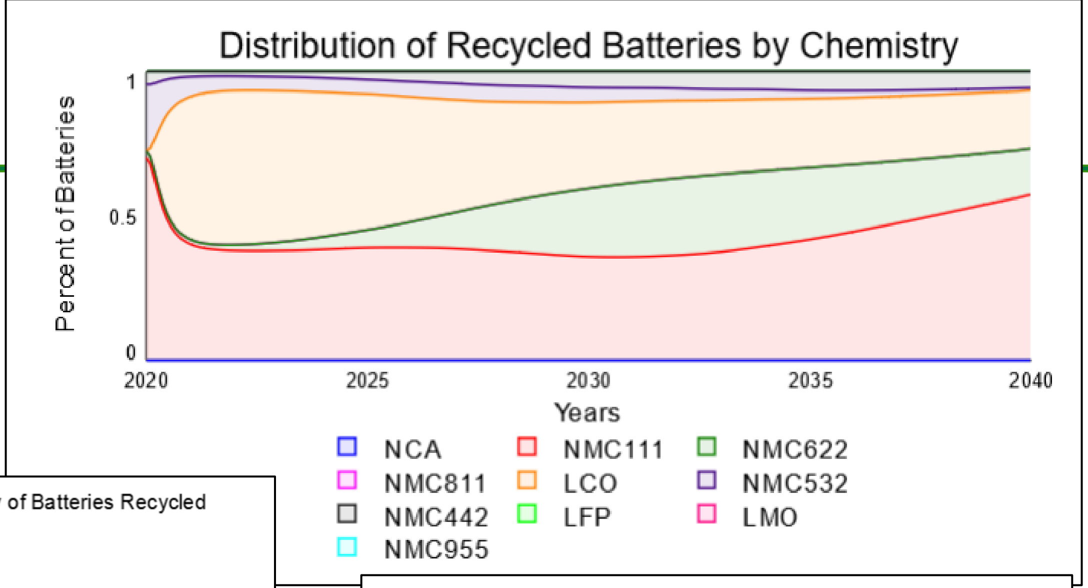
Systematic Evaluation of Supply Chain Dynamics for Lithium-ion Battery Manufacturing & Recycling – The LIBRA Model

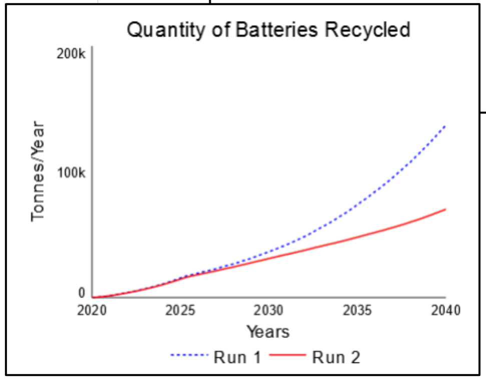
Margaret K Mann, Vicky Putsche, Danny Inman, Dustin Weigl
National Renewable Energy Laboratory

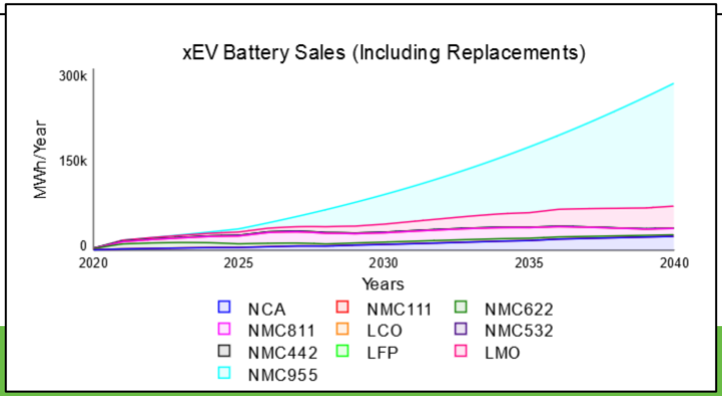
July 2022

Contact: margaret.mann@nrel.gov









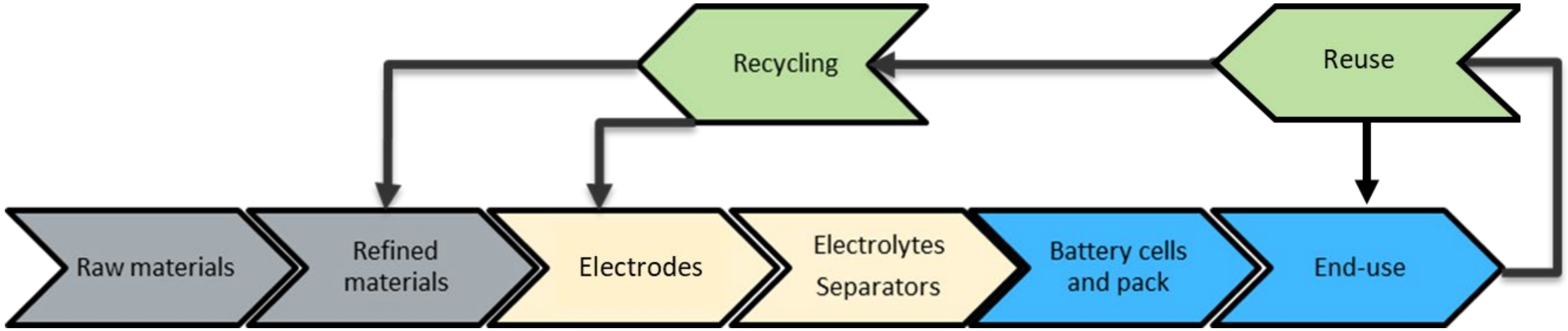
LIBRA – Lithium-Ion Battery Resource Assessment Model

LIBRA is a system-dynamics model that evaluates the economic viability of the battery manufacturing, reuse, and recycling industries across the global supply chain under differing ***dynamic*** conditions

https://www.nrel.gov/transportation/libra.html

Supply Chains are Interconnected and Dynamic

Investments along the entire supply chain are needed to ensure a reliable and resilient supply chain



Nothing in life (or markets) is ever static. Changes in one part of the system can affect everything across the supply chain. *Some examples:*

- Prices of raw materials, components, shipping
- Policies on emissions, competitiveness, government investments
- Demand from other sectors
- Public sentiment, NIMBY

The position of the jack (viability of industry) depends on how the other portions of the cord (the supply chain) are pushed and pulled.

LIBRA Dimensionality

- **Multiple battery demand streams**
  - EV market
    - Light duty vehicles
    - Light duty, medium duty, heavy duty (commercial) vehicles
    - E-bus
    - Two and three wheeled vehicles
  - Consumer electronics
  - Battery Energy Storage (BES)
- **Three Minerals:**
  - Cobalt, Nickel, Lithium
- **Ten Chemistries (LFP, LMO, LCO, NCA, NMC111,NMC442,NMC532,NMC622,NMC811,NMC955)**
- **Two "destructive" recycling pathways with reclaimed minerals as output (Hydro, Pyro)**
- **One "non-destructive" recycling pathway with refurbished cathode as output (Direct)**
- **Cathode manufacturing in US, ROW**
- **Battery Manufacturing in US, ROW**

DOE Battery Research

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

Improved Li-ion
Graphite/NMC

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

Current cycle life	> 1,000
Calendar life	> 10 years
Mature Manufacturing	Yes
Fast charge	Reduced cycle life
Cost positive recycling	No

R&D Needs

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

Next-Gen Li-ion
Silicon (-composite)/NMC

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

Current cycle life	> 1,000, for ~320 Wh/kg
Calendar life	~3 years
Mature Manufacturing	No
Fast charge	Yes, at BOL
Cost positive recycling	No

R&D Needs

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

Lithium Metal
Li metal/NMC or Sulfur

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

Current cycle life	> 400
Calendar life	TBD
Mature Manufacturing	No
Fast charge	Maybe
Cost positive recycling	No

R&D Needs

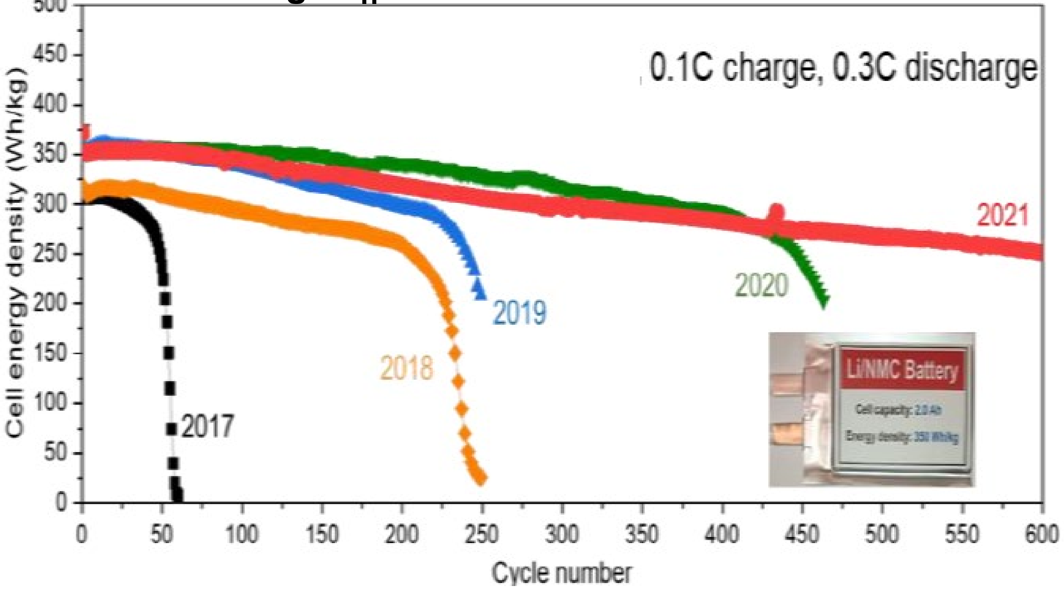
- Improved cycle and calendar life
- Protected lithium
- Dendrite detection and mitigation
- Cost effective manufacturing

Battery500 Consortium Phase II

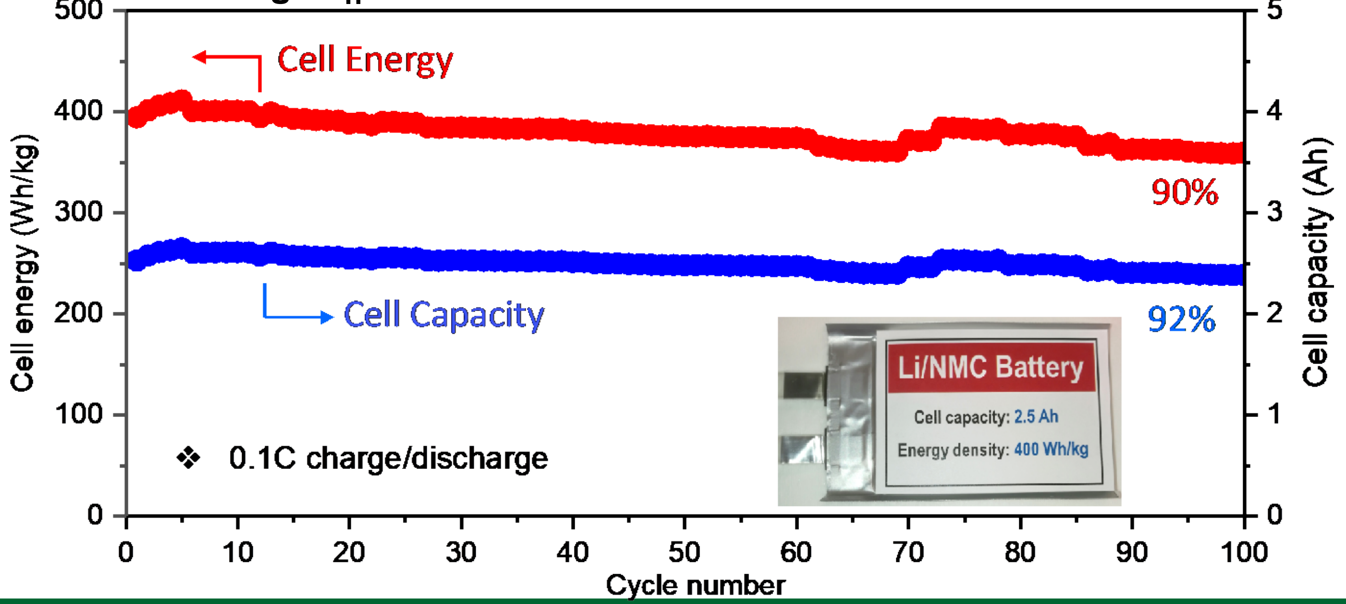
- Develop, integrate materials and technologies and enable robust, scalable and commercially viable high-energy batteries
- Initiated October 2021 (5 years, $75M)
- Multi-Disciplinary Team
- Goals:
  - Near Term: Li//S (300 Wh/kg, SPAN)
  - Long Term: Li//High-Ni NMC (500 Wh/kg); Li//(S) 500 Wh/kg (sulfur)

Pacific Northwest National Laboratory
Brookhaven National Laboratory
INL Idaho National Laboratory
SLAC National Accelerator Laboratory
The University of Texas at Austin
UC San Diego
gm
Stanford University
University of Washington
Binghamton University
A&M
University of Maryland
University of Pittsburgh
PennState

350 Wh/kg Li || NMC Pouch Cell



400 Wh/kg Li || NMC Pouch Cell

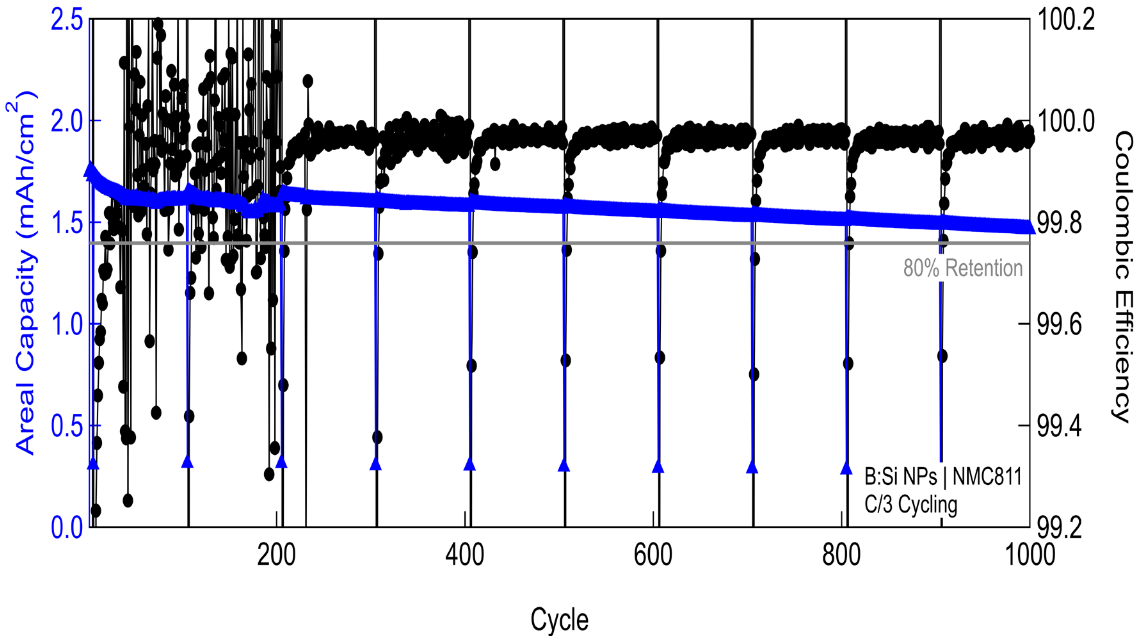


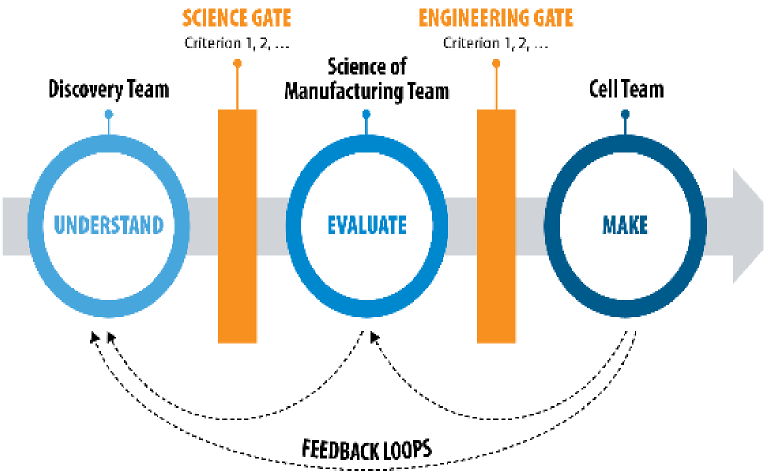
Silicon Consortium Project

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.





>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.

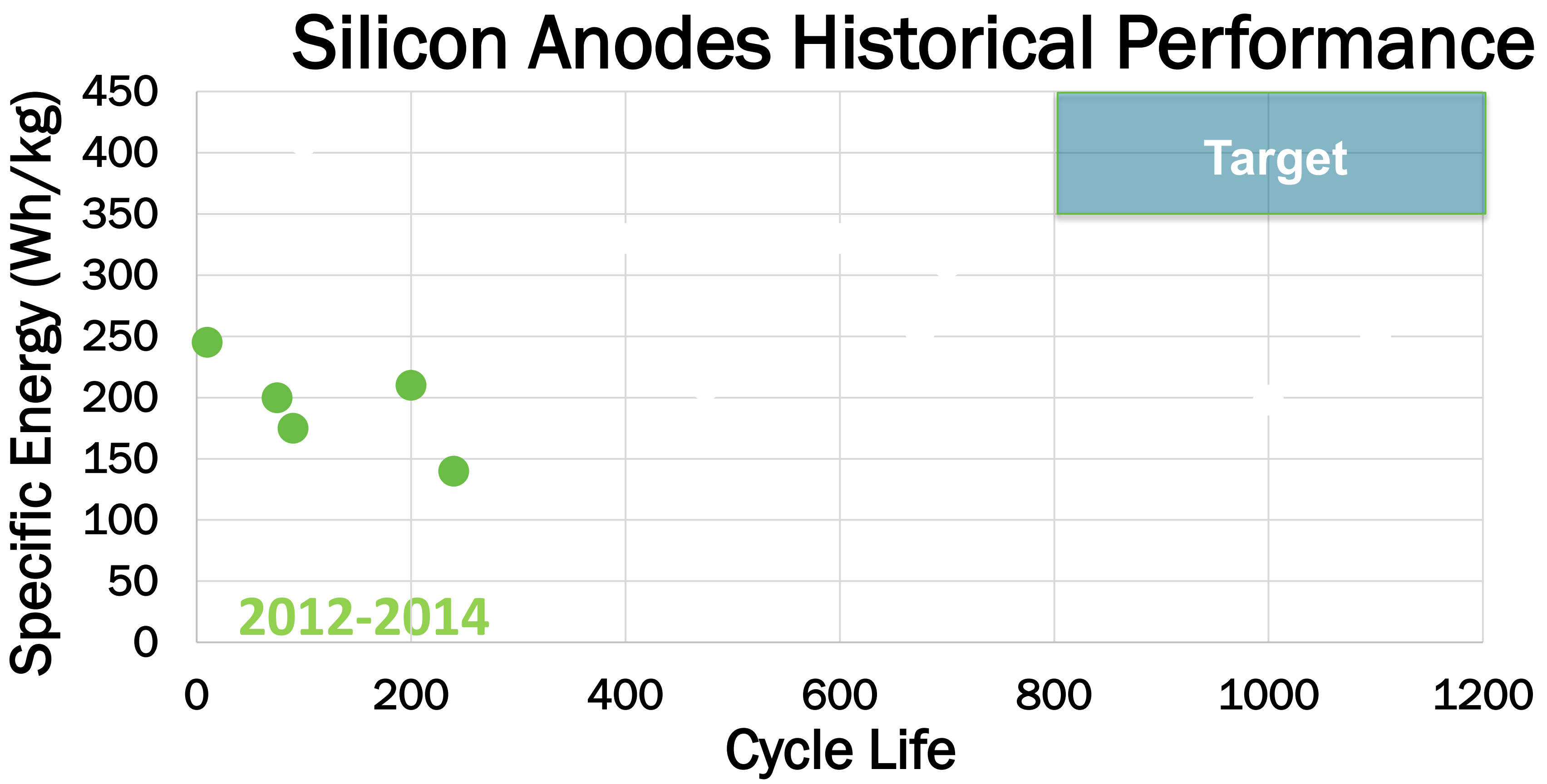
Silicon Anodes: Key Technical Results

Targets

- 1,000+ mAh/g
- 10 years & 1000 cycles

Challenges

- Large first-cycle irreversible loss
- Low cycle and calendar life / High capacity fade



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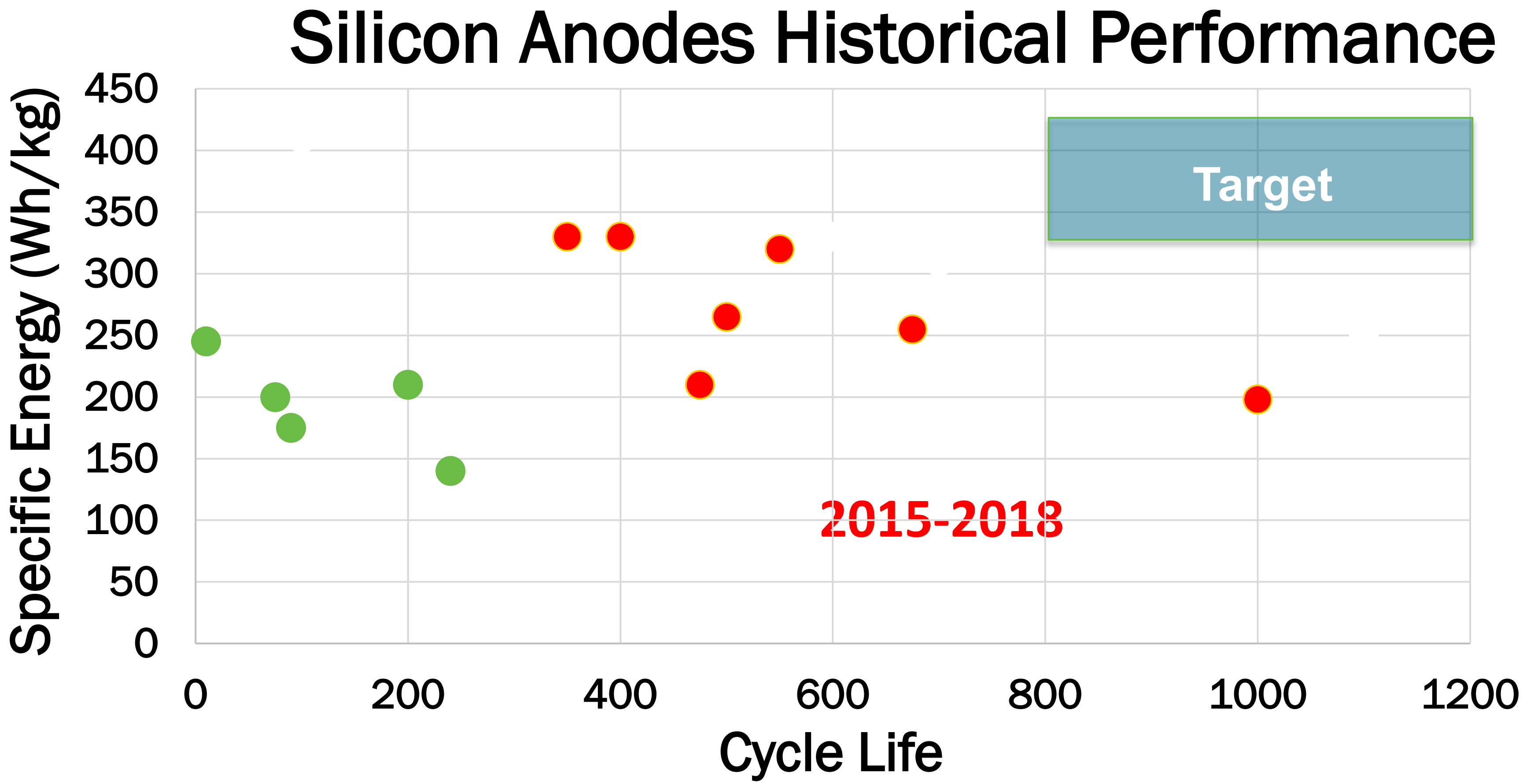

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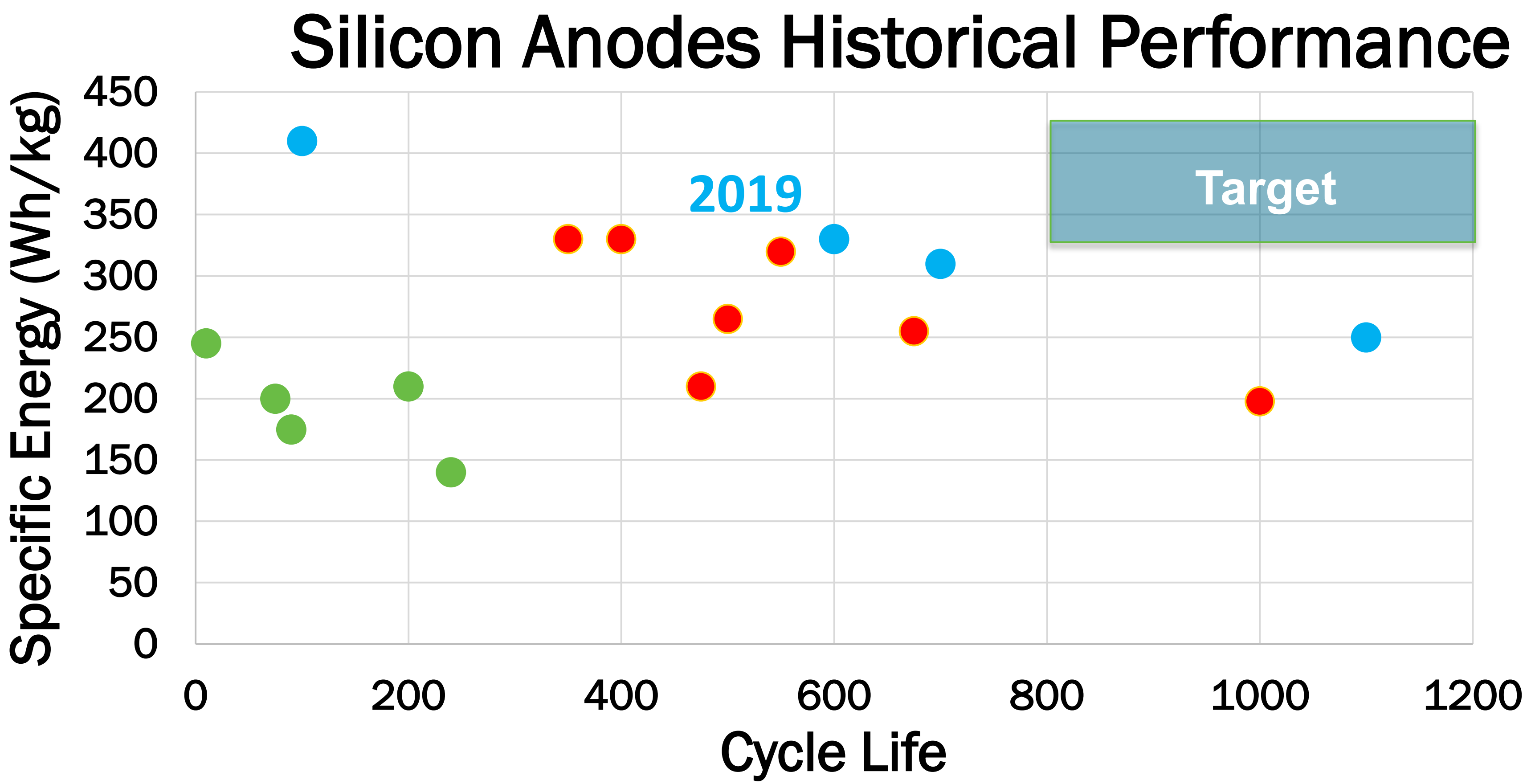

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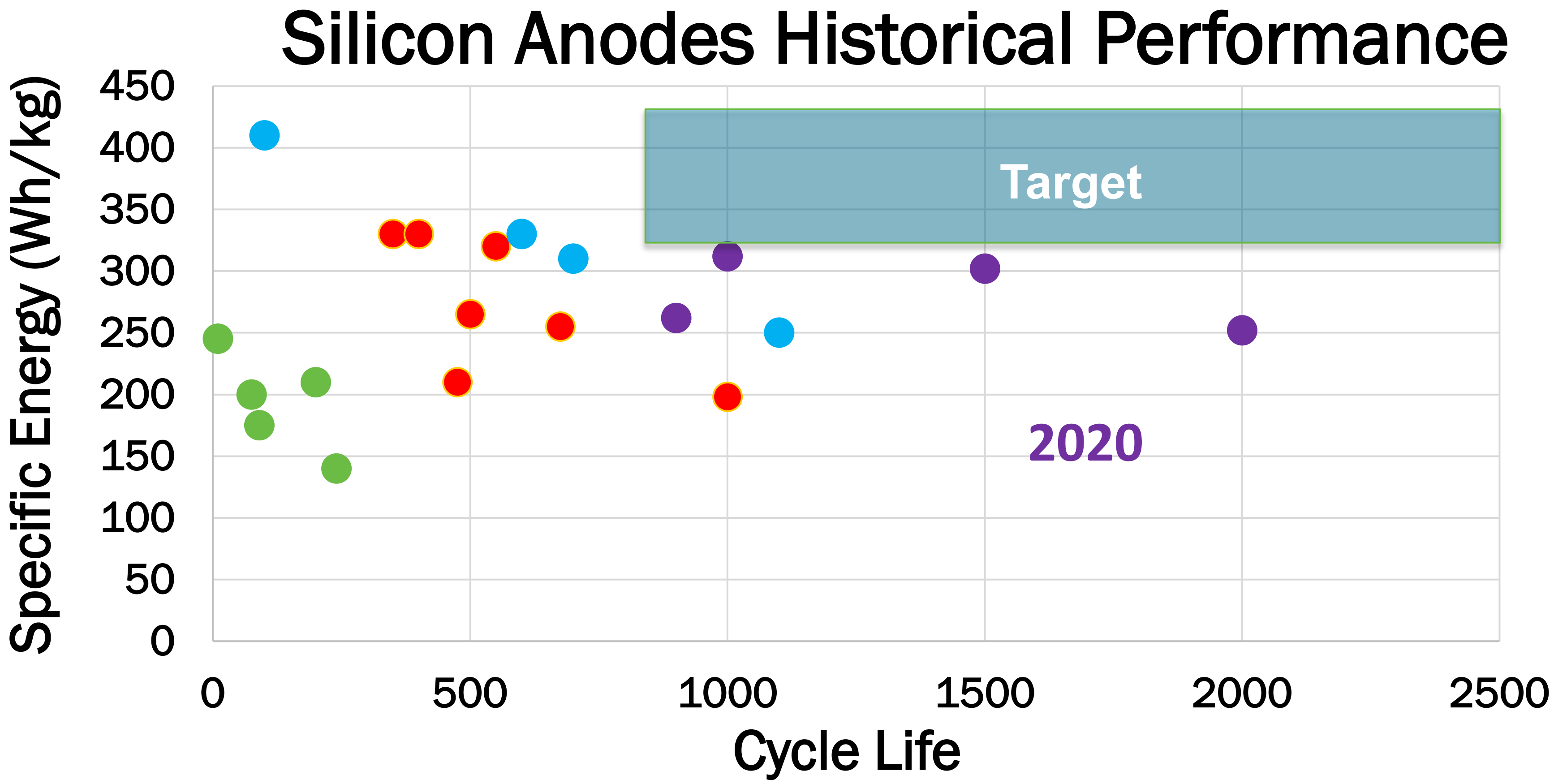

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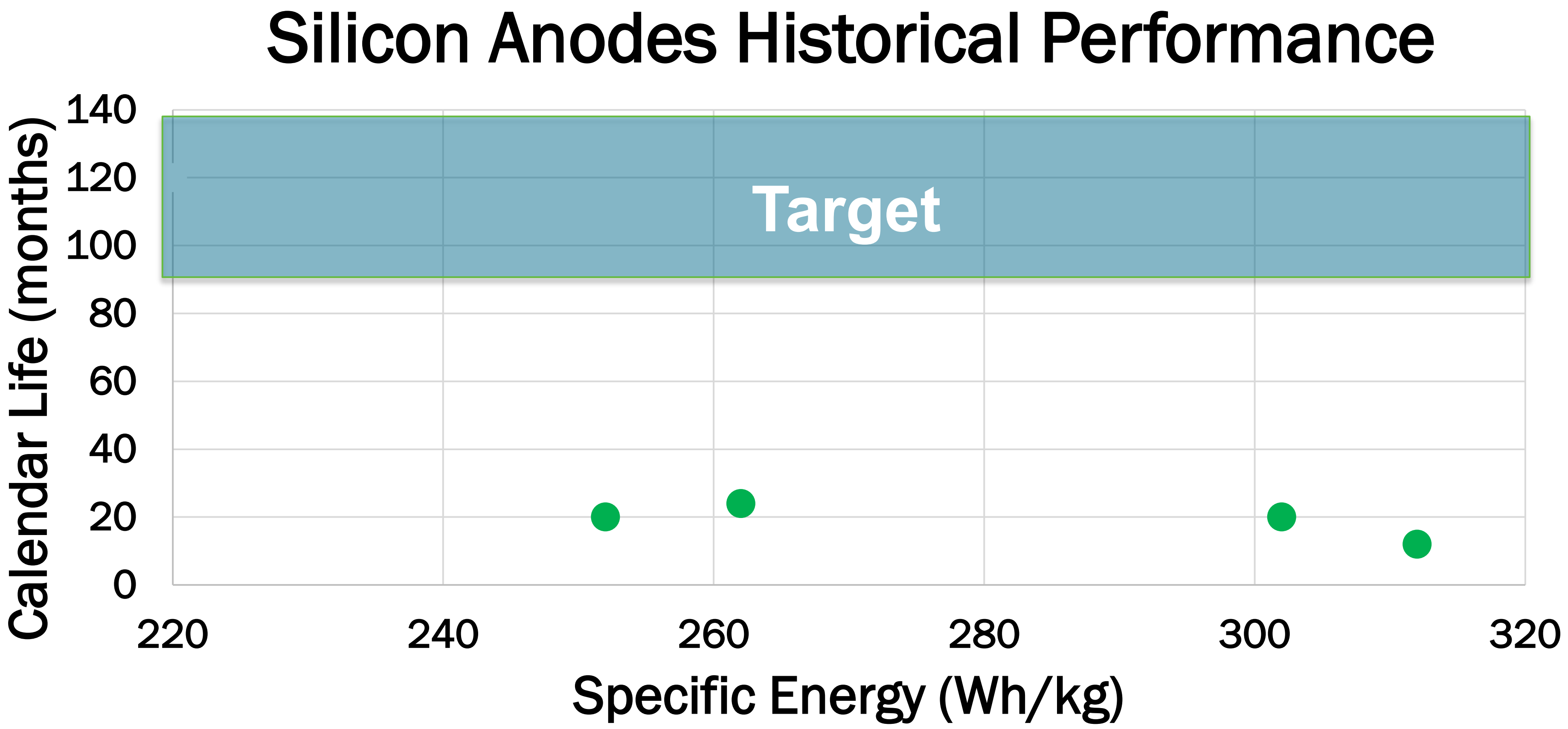
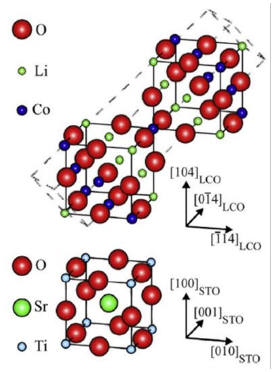


Realizing Next-Generation Cathodes for Li-Ion Batteries: Low-Cobalt Cathodes

- The objective of this ANL-led project is to realize high-capacity, high-energy cathodes with stabilized long-term performance.
- The project is developing lithiated transition-metal (TM) oxides, in concert with strategies to minimize/ eliminate cobalt as well as particle surface-engineering efforts to mitigate the effects of surface reactivity.
- NREL is exploring Co-free cathode materials and advanced electrolytes to stabilize nickel-rich surfaces.

Developed Epitaxial High Nickel Cathodes Model Electrodes

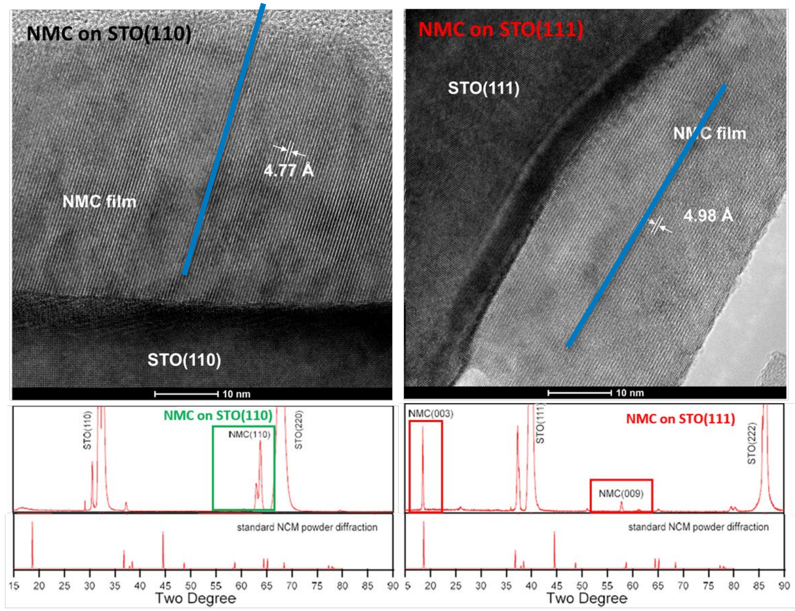


Cubic on Cubic Structural Relationship

Cubic (100) → NMC {104}

Cubic (110) → NMC {110}
NMC {108}

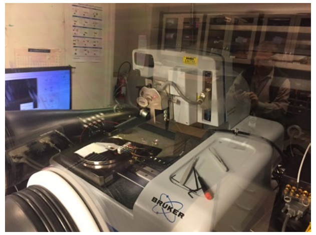
Cubic (111) → NMC {003}

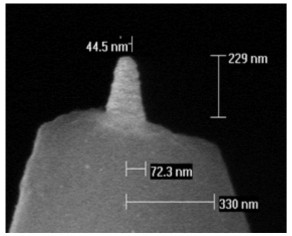


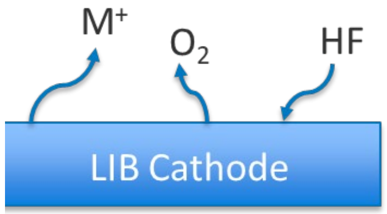
Oriented model NMC thin films can be prepared by using substrate ($SrTiO_3$) with various orientation through PAD (polymer-assisted deposition) method.

In collaboration with Di Huang

Understand how surface chemistry affects electrochemical reactivity at NMC surfaces using AFM/SECM







- Metal Dissolution
- Oxygen Evolution
- HF attack

Argonne NATIONAL LABORATORY · NREL NATIONAL RENEWABLE ENERGY LABORATORY · Pacific Northwest NATIONAL LABORATORY · BERKELEY LAB · OAK RIDGE National Laboratory

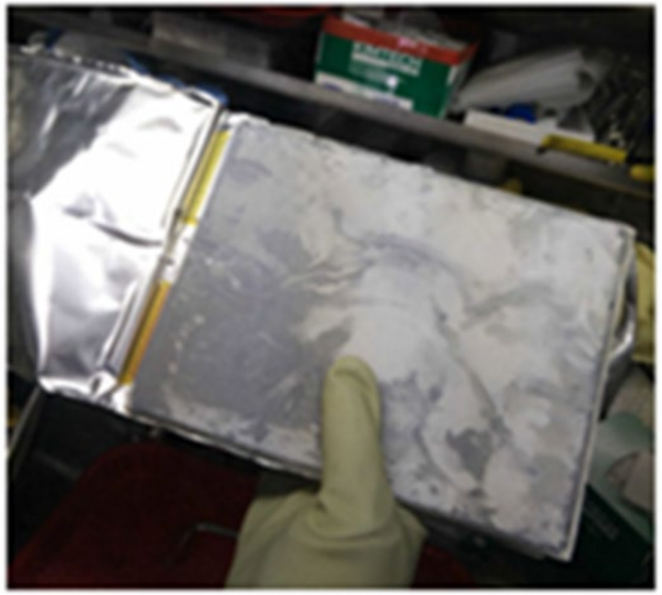
Extreme Fast-Charging (XCEL): Enabling the EV Market

Aim is to develop onboard batteries able to achieve at 15 minutes per complete charge, with < 20% fade in specific energy.

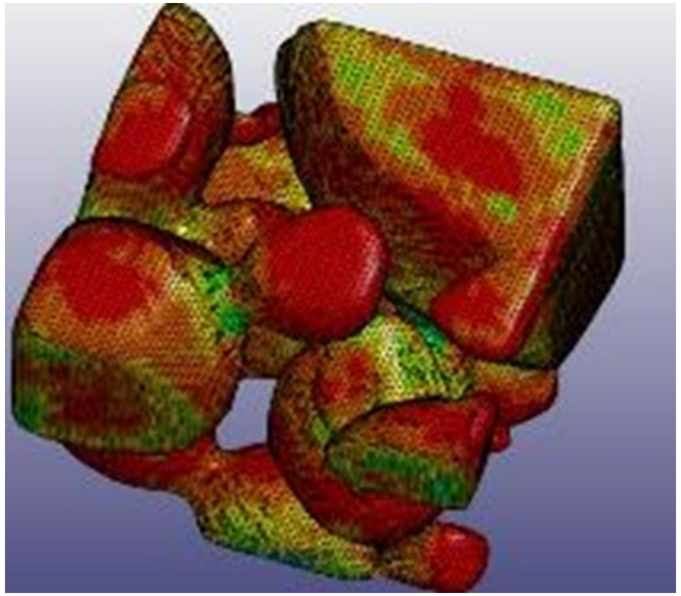
However, serious lifetime issues result from fast charging that will need new understanding and new approaches to meet lifetimes.

So, the XFC project is developing a foundational understanding of the negative impacts of fast charging.

15 Minute EV charging



Lithium plating at the anode reduces cell lifetime at fast charging rates



Modeling intercalation stresses due to fast charging will help us understand limitations in lifetime

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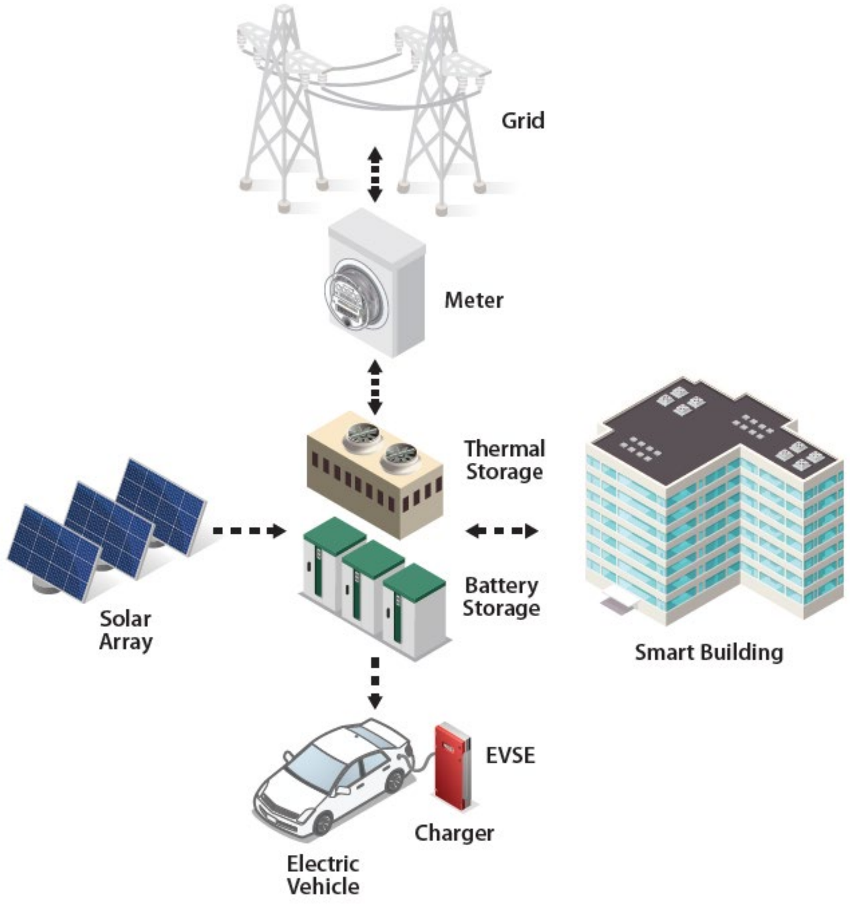
Behind-the-Meter Storage

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



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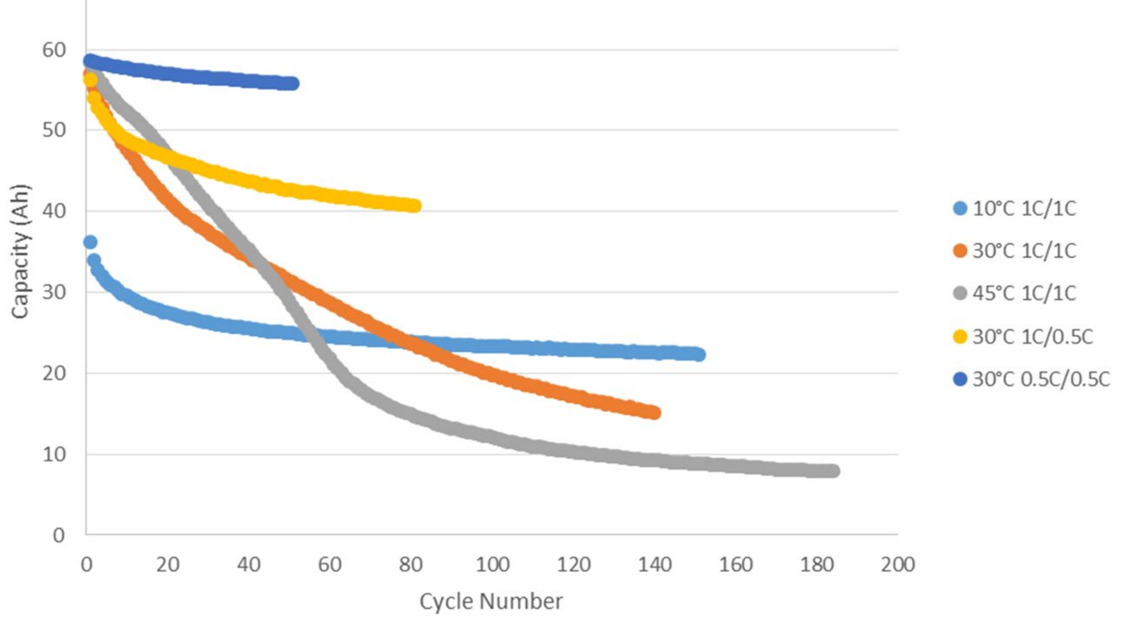
AI – Machine Learning approach to battery lifetime prediction

Goal: Advance storage applications will use batteries new ways (fast charging, grid storage and behind the meter storage) and accelerated life predictions will be critical to accelerated deployment.

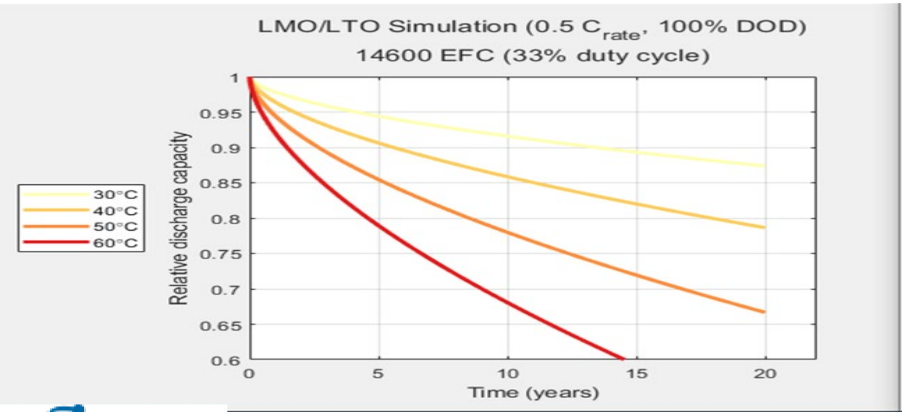
Validation whether for stationary or transportation challenges is tedious and long process. Standard methods can get reasonable understanding in 2-5 years to project life, but new uses cases seldom can gain traction from prior work.
Machine learning and other AI approaches are by default rooted in the need for both high volumes of data as well as high quality data.

Large amounts of high-quality data are required.

The application matters: The dark blue line is normal battery use and all other have minor application changes from the standard.



Preliminary work on the BTMS cells indicate 20 year lifetimes are possible.



NREL's Range of Energy Storage R&D