Energy Efficiency &
Renewable Energy

Overview of the Advanced Battery Materials Research (BMR) Program and the Battery500 Consortium

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Energy Storage R&D Interactions at DOE

Fundamental Research	Transformational Research	Applied Research
Office of Science	Advanced Research Projects Agency – Energy	U.S. Department of Energy Energy Efficiency and Renewable Energy Fiscal Year 2017: $101M Vehicle Technologies Office
Fundamental research to understand, predict, and control the interactions of matter and energy at the electronic, atomic, and molecular levels ❑ JCESR (energy storage hub) ❑ EFRC ❑ Core scientific research	High-risk transformational research ❑ BEEST (high energy) ❑ AMPED (battery sensors and controls) ❑ RANGE (flow, solid state, multifunctional) ❑ IONICS (solid state)	Advanced Batteries for Automotive applications ❑ Full system development & testing ❑ High-energy density & high-power density cells ❑ Advanced battery materials research (BMR) ❑ Battery500 ❑ Extreme fast-charging

Introduction (2)

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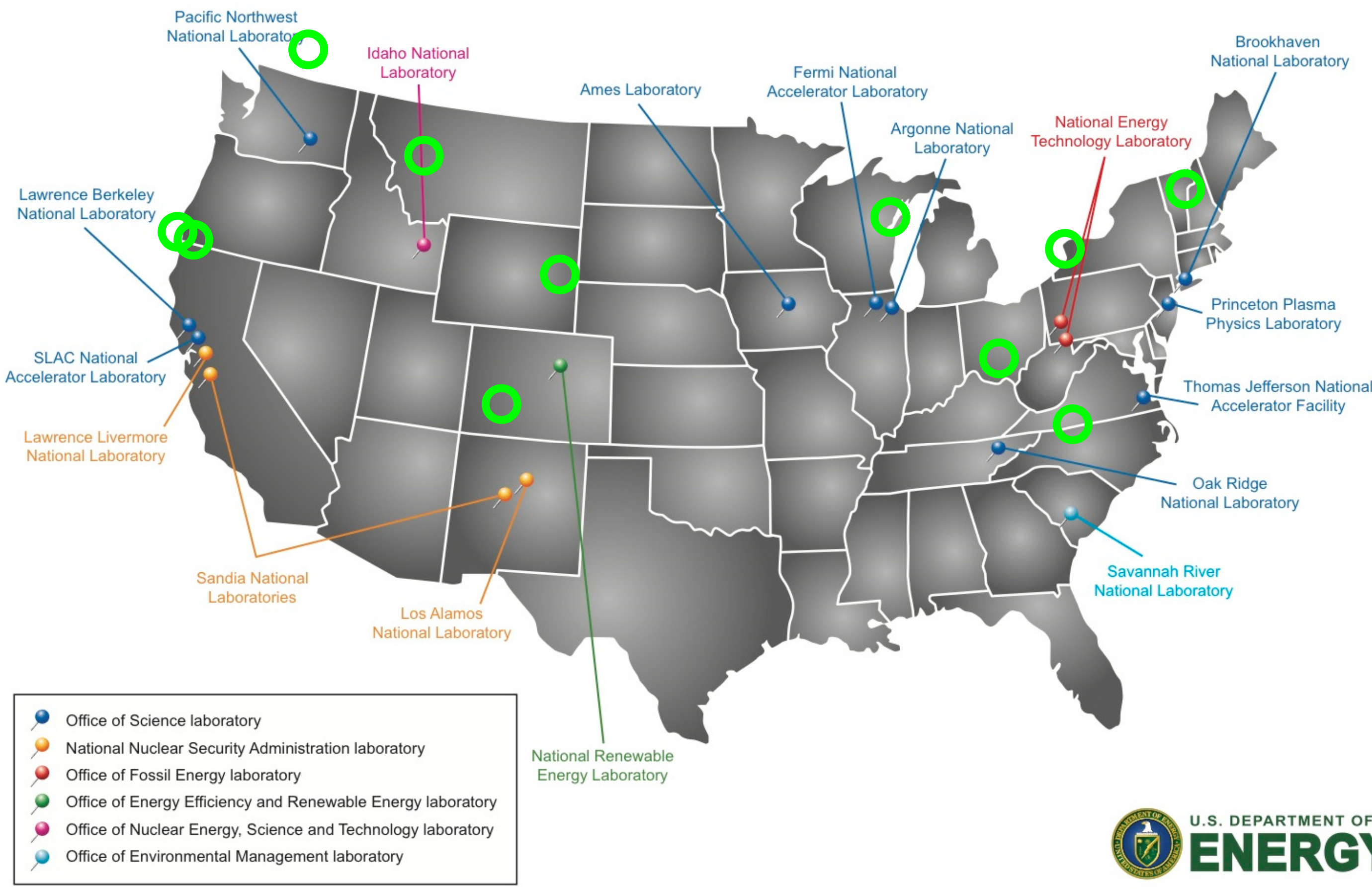
DOE National Laboratory System

- Energy storage R&D currently pursued at 11 of the 17 DOE national laboratories



U.S. DEPARTMENT OF ENERGY

Advanced Battery Materials Research (BMR) Program

- Previously known as:
  - Exploratory Technology Research (ETR) (1980-2001)
    - Exclusively focused on batteries for automobile applications since1992
  - Batteries for Advanced Transportation Technologies (BATT) (2002-2014)
- **Charter:** Perform cutting edge research in new materials and conduct comprehensive modeling and diagnostics analyses of materials and electrochemical cell behavior to address chemical, physical and mechanical instabilities
- 11 Topic areas, 63 research projects
  - Modeling (10), Diagnostics (9), Cell Analysis (4), Silicon Anodes (2), Intercalation Cathodes (8), Polymer/Liquid/Self-Healing Electrolytes (7), Solid State Electrolytes (4), Metallic Lithium (6), Sulfur Electrodes (9), Air Electrode/Electrolyte (3), and Sodium (1)

BMR: Current Participants

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- BMR participants include 7 national labs, 20 universities, and 4 industry partners

National Labs

- Argonne National Laboratory
- Brookhaven National Laboratory
- Berkeley Lab
- Oak Ridge National Laboratory
- NREL National Renewable Energy Laboratory
- Pacific Northwest National Laboratory
- SLAC National Accelerator Laboratory

Academia

- BYU
- Michigan State University (founded 1855)
- Michigan Technological University
- Massachusetts Institute of Technology
- PennState
- Rutgers
- Stanford University
- Stony Brook University
- Binghamton University
- Texas A&M University
- University of Maryland
- Michigan
- University of Pittsburgh
- University of Washington (1861)
- University of Wisconsin UW Milwaukee
- Berkeley University of California
- UC San Diego
- The University of Texas at Austin
- West Virginia University

Industry

- Daikin
- GM
- Hydro Québec
- LIOX

Vehicle Technologies Office
Energy Storage R&D Program Structure

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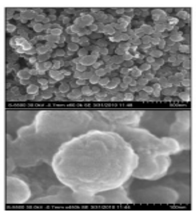
- ❑ The BMR program is one of the three key energy storage R&D programs in VTO

Advanced Battery Materials Research (BMR Program)

SEM of Li_2FeSiO_4/C Nanospheres

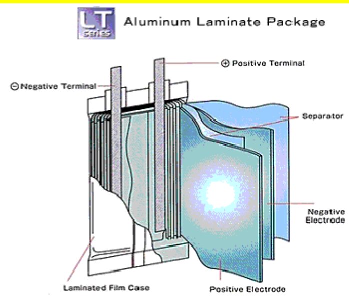


- ❑ High capacity cathodes
- ❑ Alloys, and lithium metal anodes
- ❑ High voltage electrolytes
- ❑ Solid State electrolytes

Cell Materials Targets

- ❑ Anode capacity > 1000mAh/g
- ❑ Cathode capacity > 300mAh/g
- ❑ High-voltage cathodes & 5V stable electrolytes
- ❑ Solid-polymer electrolytes with $>10^{-3}$ S/cm ionic conductivity

High Energy & High Power Cell R&D (ABR Program)



- ❑ Electrodes exhibiting high energy density and high rate capability
- ❑ Fabrication of high energy density cells
- ❑ Cell diagnostics
- ❑ Improved manufacturing processes

Cell Targets

- ❑ 350 Wh/kg
- ❑ 750 Wh/l
- ❑ 1,000 cycles
- ❑ 10+ calendar year life

Full System Development & Testing (Developer Program)

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM LLC

- ❑ Focus on cost reduction, life and performance improvement
- ❑ Robust battery cell and module development
- ❑ Testing and analysis
- ❑ Battery design tools
- ❑ Fast charge

Battery Pack Targets

- ❑ $125/kWh EV pack cost
- ❑ Fast charge (80% SOC in 15 minutes)
- ❑ $180, 12V start/stop pack cost

BMR Program in Context of VTO Battery R&D

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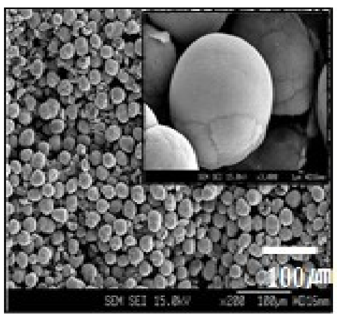
Technology Progression Example: Advanced Cathode Materials

Argonne NATIONAL LABORATORY

Materials R&D
Lithium-rich NMC
1999–2015



BASF
TODA AMERICA
LG Chem
GM
envia SYSTEMS

Materials Scale Up and low Cost Processing
2007–2013

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM

LG Chem

Cells & Electrochemistry Development
Lithium-ion Polymer, Mixed Mn/NMC–Carbon, USABC
2005–2014

Commercialization

Research Emphasis on Li-ion Batteries (1)

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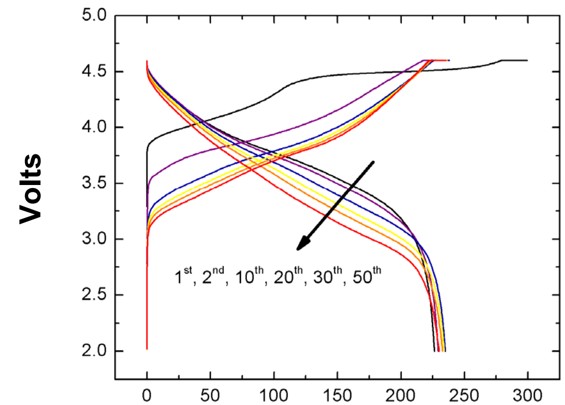
Cathodes

- ❑ **Barrier**: Electrode capacity – still a limiting factor

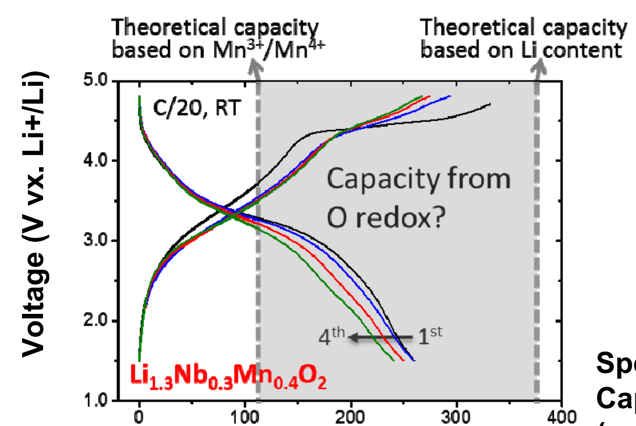
Approaches

- ❑ **Develop Ni-rich cathodes** that exhibit stable operation at high voltage with long cycle life
- ❑ **Optimize the composition** of structurally-integrated Li-rich 'layered-layered' and 'layered-layered-spinel' to mitigate voltage fade during cycling
- ❑ **Discover new materials:** gain fundamental understanding of the role of O_2 in Li-excess cathodes

Voltage Profiles for Li-rich, Layered Cathode



High-Capacity Li-Excess Oxides



Source: BATT projects

Research Emphasis on Li-ion Batteries (2)

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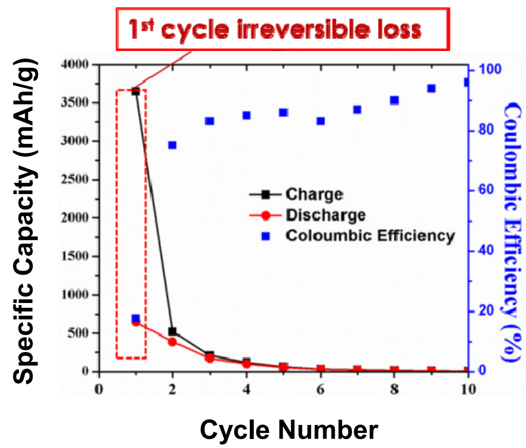
Silicon Anode

- **Barrier:** Continuous formation of the SEI during cycling consumes lithium and solvent

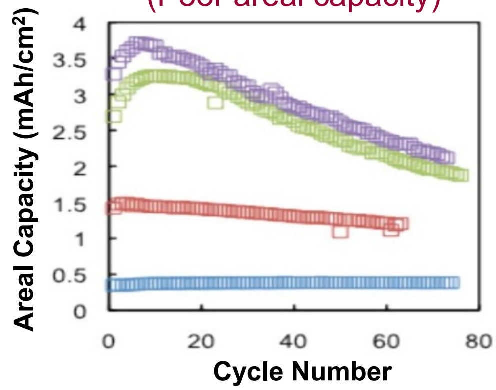
Approaches

- **New architectures:** Design of novel morphologies and configurations; e.g. nanotubes, nanowires, core-shell and nanocomposite structures
- **Development of functional coatings:** metals, Li^+ and e^- conducting ceramics including high strength and elastomeric polymer binders

Bulk Si Anode



Si Nanoparticle Anode
(Poor areal capacity)



(Note: most of the research projects in this area have been transferred to the ABR program.)

Research Emphasis on Li-ion Batteries (3)

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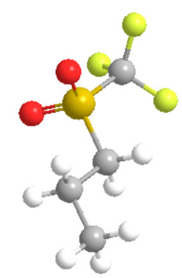
Electrolytes

- **Current focus:** Explore fluorinated carbonate and sulfone solvents

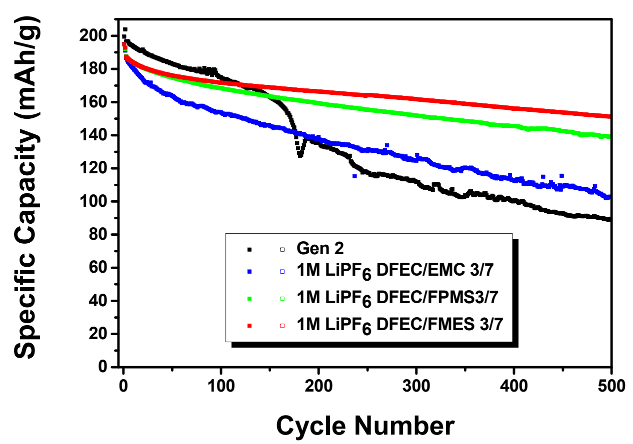
Approaches

- **Understand** reactivity at voltages above 4.3V
- **Design** new electrolytes and additives
- **Maintain current focus** on fluorinated carbonate, and sulfone solvents

Fluorinated Sulfone Molecules
(3D structure)



NMC532/Graphite Cells
(C/3 for 500 cycles, cut-off voltage 3.0-4.6 V)



Li-metal Based Batteries: Enabling A New Class of Electrodes

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Potential Benefits

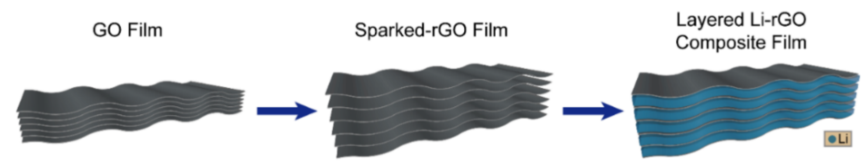
- ❑ Li metal anodes allow doubling of energy density. Enabling new class of high capacity cathodes, such as sulfur and other non-lithiated structures

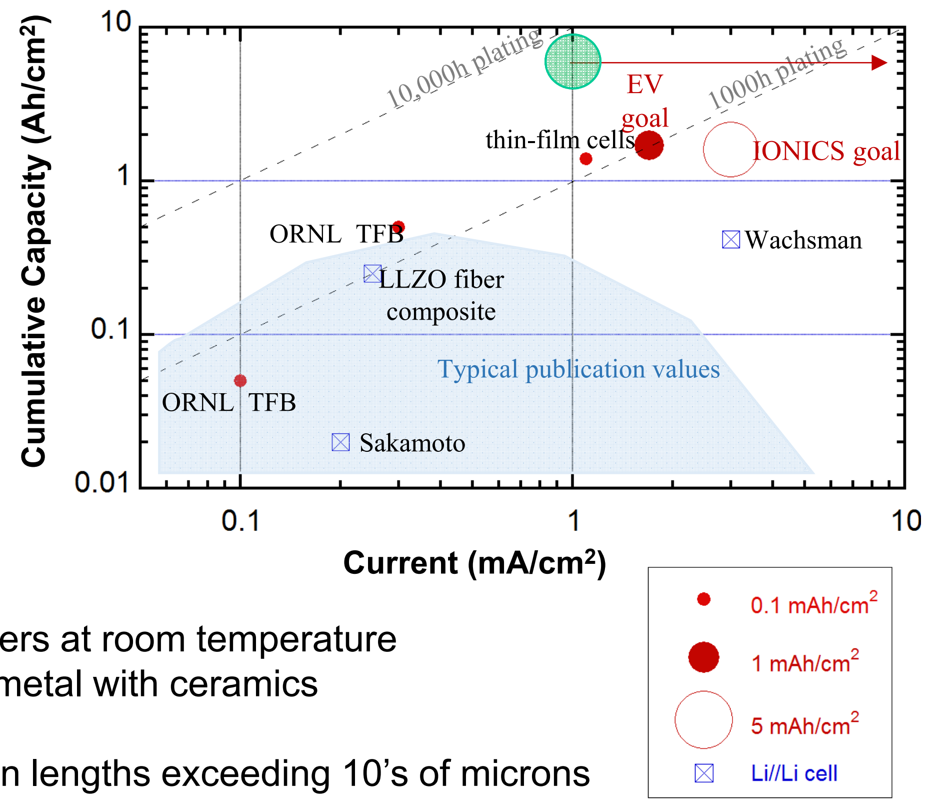
Status

- ❑ Lithium reactivity and dendrite growth remain primary challenges

Approaches

- ❑ Additives/solvents to planarize deposition
- ❑ Polymers to compress protrusions
- ❑ Ceramics with high Li-ion conductivity
- ❑ Novel framework structures for lithium storage and cycling





Future Issues

- ❑ Enable use and operation of functional polymers at room temperature
- ❑ Generate interlayers to protect reaction of Li-metal with ceramics
- ❑ Processing of thin, brittle ceramic layers
- ❑ Maintain compression stability over Li diffusion lengths exceeding 10's of microns
- ❑ Need for consistent testing protocols

Li-Sulfur Batteries: High Specific-Energy System

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Potential Benefits

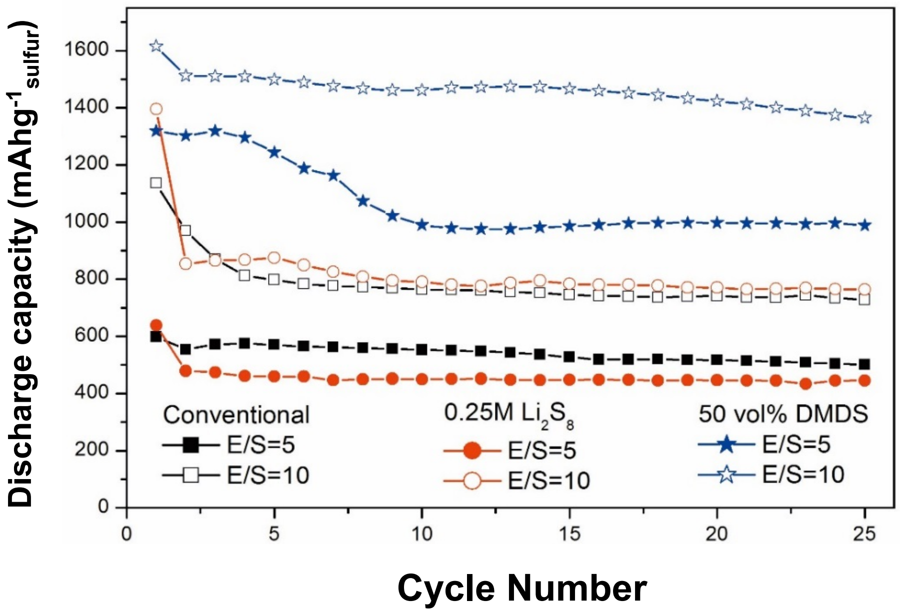
- ❑ Inexpensive, abundant material that promises high specific energy compared to Li-ion

Status

- ❑ Polysulfide "shuttle" and deposition of insoluble polysulfides remain challenges

Approaches

- ❑ Constraining the polysulfide within the cathode
- ❑ Development of separators with blocking ability
- ❑ Mechanistic understanding of speciation



Future Issues

- ❑ Operation of cathodes with high sulfur loading
- ❑ Understanding speciation in different electrolytes
- ❑ Operating under low electrolyte volumes (lean electrolyte)
- ❑ Co-locating the electrochemically oxidized and reduced products to ensure reversibility
- ❑ Ensure isolation of Li metal from the polysulfide species

Solid-State Batteries: A Path to Safer Li Metal-based Batteries

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Potential Benefits

- ❑ Solid electrolytes provide a unique path to lithium metal anodes while enabling safer operation

Status

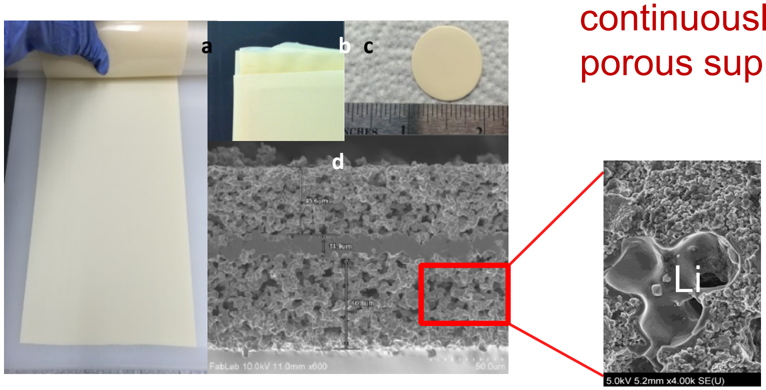
- ❑ Current focus on Li conducting lanthanum zirconate ceramic structures (LLZO) and sulfide based glasses

Approaches

- ❑ All-polymer systems e.g. PEO
- ❑ All inorganic systems with ceramic integrated into porous cathodes

Scalable and reproducible process to fabricate multilayer garnet structures

With surface treatment, Li metal wets garnet surface continuously inside porous support



Future Issues

- ❑ Develop polymers with high room temperature Li-ion conductivity
- ❑ Ceramics with both high- and low-voltage stability
- ❑ Integrate ceramics into porous cathode structures with intimate contact
- ❑ Can we demonstrate an all solid-state Li-ion battery with similar performance to liquid-based systems?
- ❑ Can Li-metal be stabilized to withstand abuse-tolerance?

Battery500 Consortium: Overview

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Timeline

- ❑ Start date: September 2016
- ❑ End date: September 2021
- ❑ Percent complete: 20%

Barriers

- ❑ Barriers to overcome
  - Address the grand scientific and technological challenge:
    - Increase the energy density of advanced lithium (Li) metal batteries beyond the current state of Li-ion batteries

Partners

- ❑ **Project lead:** Pacific Northwest National Laboratory
- ❑ **Partner Institutions:** Binghamton University, Brookhaven National Laboratory, Idaho National Laboratory, SLAC, Stanford University, University of California San Diego, University of Texas at Austin, University of Washington
- ❑ **Other Partners:** Seedling project teams

Battery500 Consortium: Team

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Battery500 Consortium: Relevance/Objectives

- The Battery500 Consortium aims to triple the specific energy density (to 500 Wh/kg) relative to current battery technology with achievement of 1,000 charge/discharge cycles.
- The consortium aims to overcome the existing fundamental scientific barriers and harvest the maximum capacity of electrode materials in two systems: Li metal-high Ni NMC and Li-S.
- The consortium leverages the advances made in the research on electrode materials and battery chemistries supported by DOE.

Advanced Materials to meet Battery500 Goals

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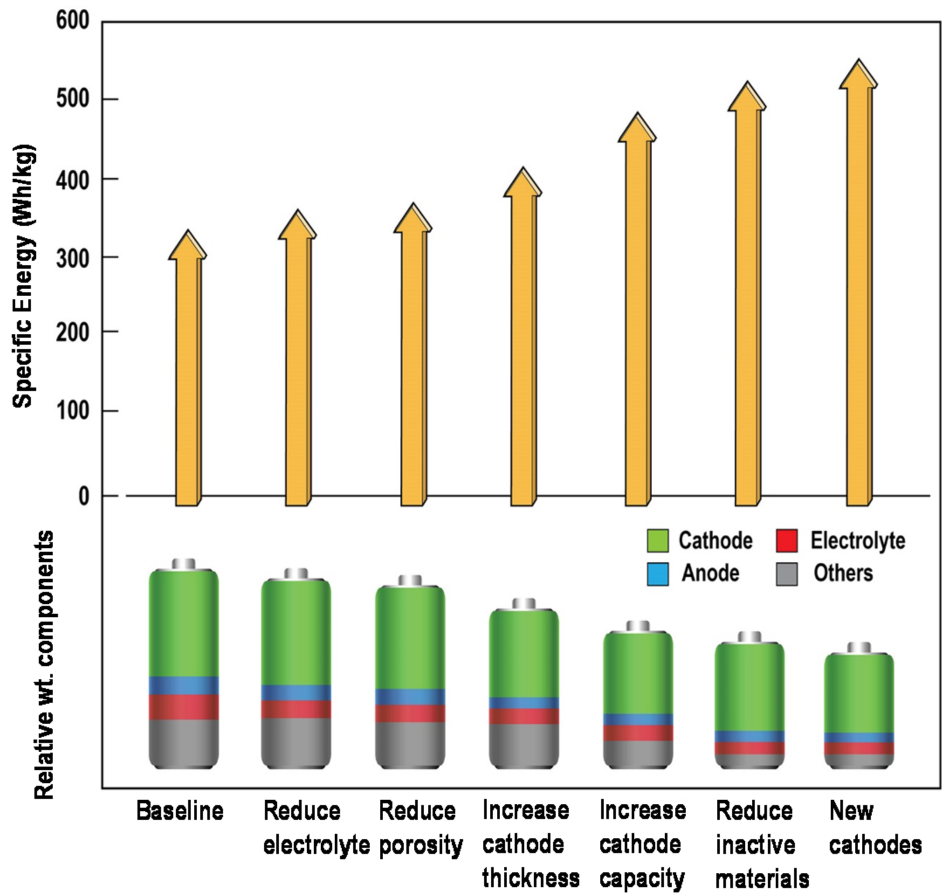

- Achieve dendrite-free Li deposition with more than 99.9% Coulombic efficiency.
- <100% excess Li (compared to cathode).
- Increase cathode capacity to over 220 mAh/g and achieve stability over 4.4 V.
- Increase stability window of electrolytes and achieve interfacial stability at both cathodes and anodes.
- Develop thick (>120 mm) and dense (<23% porosity) electrode architectures.
- Reduce inactive materials (electrolyte, current collectors, separator).
- Optimize materials properties at the cell level.

Battery500 Consortium: Keystone Projects

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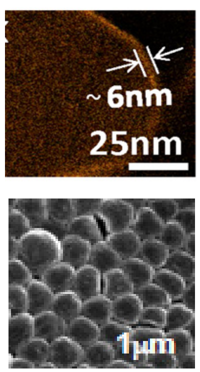
Harvest Maximum Capacity from Promising Battery Chemistries

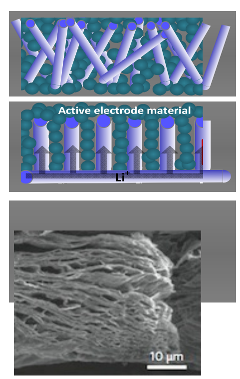
High Ni NMC-Li: achieving >50% of theoretical capacity at cell level
Solid State Li-S: solving polysulfide dissolution and Li degradation problems

Diagnosis & prognosis, assessment and validation

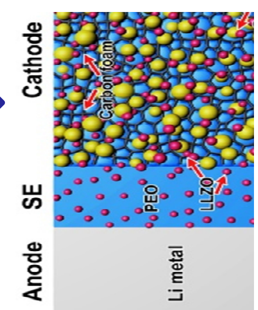
1. Materials/Interfaces:
Mixed conductive coating
Controlled surface reaction



2. Electrode Architecture
Thick, conductive cathode
3D Li composite structure



3. Cell Design/Integration
Cell modeling
1D or 2D Li^+ conductor
De-coupled SEI reactions



Technology exit strategies to improve Li ion batteries

Li batteries
500 Wh/kg
1000 cycles

New test beds or spin-off entities for technology scale-up in the US

Seedling projects: emerging concepts, alternative cathodes, 3D printed architectures, layer-by-layer fabrication of solid electrolytes, etc.

Summary & Conclusions

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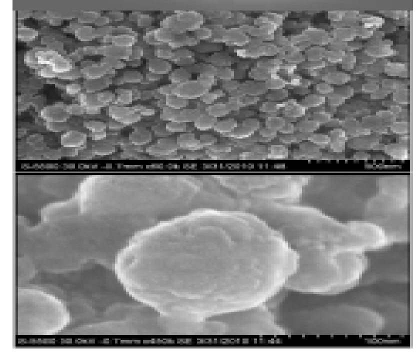
- **VTO's demonstrated track-record of success**
  - NiMH batteries now used in commercial HEVs
  - Li-ion technologies being introduced in commercial PHEVs/EVs
  - American-based battery factories supplying batteries for several car companies
- **Clear pathway to meet 2022 goals**
  - **2022 cost goal:** reduce production cost of an EV battery to **$125/kWh**
  - **Major focus:** Develop advanced Li-ion cells using higher voltage cathodes & intermetallic anodes
  - **Expanded work:** low-cost materials, electrode and cell manufacturing
- **BMR technologies beyond 2022 and Battery500 Consortium**
  - Continued focus on Li metal, sulfur electrodes and solid state electrolytes
  - Closely coordinated with the DOE Office of Basic Energy Sciences and other DOE offices



SEM of Li_2FeSiO_4/C nanospheres

SEM pictures of $LiNi_{0.5}Mn_{1.5}O_4$ made from MnO_2, $MnCO_3$ and hydroxide precursors

THANK YOU!

For more information, contact:

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