Vehicle Technologies Office (VTO)

Electrochemical Energy Storage R&D Overview

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Electric Vehicle Market

Economic Impact: Domestic EV Manufacturing

- **U.S. PEV sales (until April 2017)**
  - Cumulative PEVs: 614,708[1]
  - 2016 Sales: 159,616
  - 2017 Sales: 53,808[1] (projections comparable to 2016)
  - PEV Models available: 33[1]
- **>70% of 2016 U.S.-sold EVs were manufactured in the U.S.**
  - 6 of the 7 top-sellers
- **258,000 U.S. manufacturing jobs were associated with electrification[2]**
  - Job gains forecasted from PEV deployment
    - Current penetration rate[3]: <1%
    - 2030 Projected rates: 6.5%
    - 2030 Projected jobs: >600,000
- **Consumers benefits[4]**
  - The average cost to drive an EV: $0.03/mile (for gasoline, it is $0.11/mile)
- **98% of electricity used in the U.S. is domestically generated**
  - Corresponding figure for gasoline: 61%

2016 EV Sales[5]

1

Tesla Model S
30,200 (19%)

2

Chevrolet Volt
24,739 (15%)

3

Tesla Model X
19,600 (12%)

4

Ford Fusion Energi
15,938 (10%)

5

Nissan Leaf
14,006 (9%)


BMW i3
7,625 (5%)

7

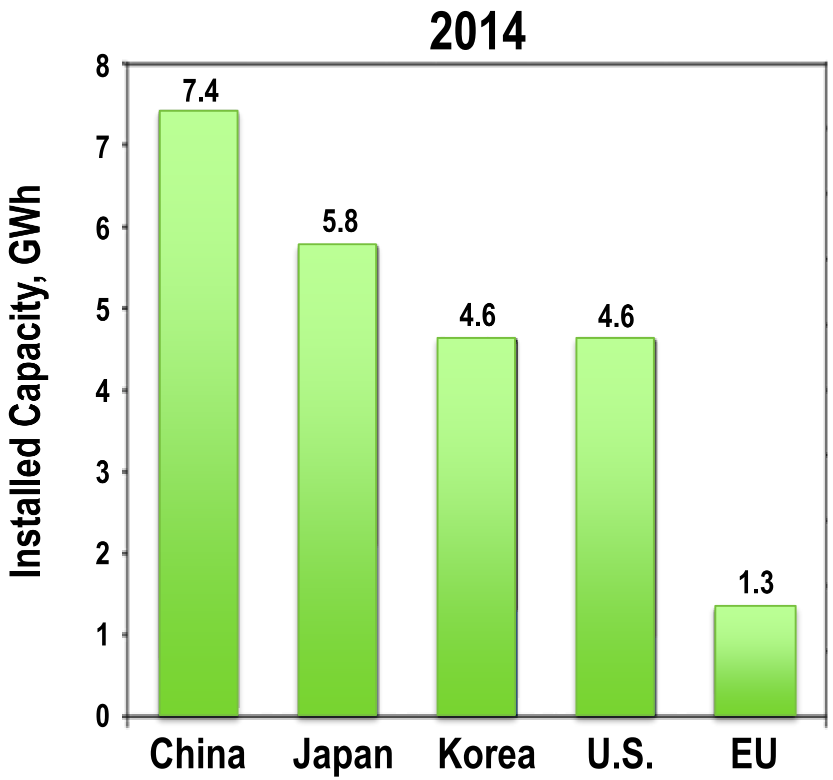
Ford C-Max Energi
7,607 (5%)

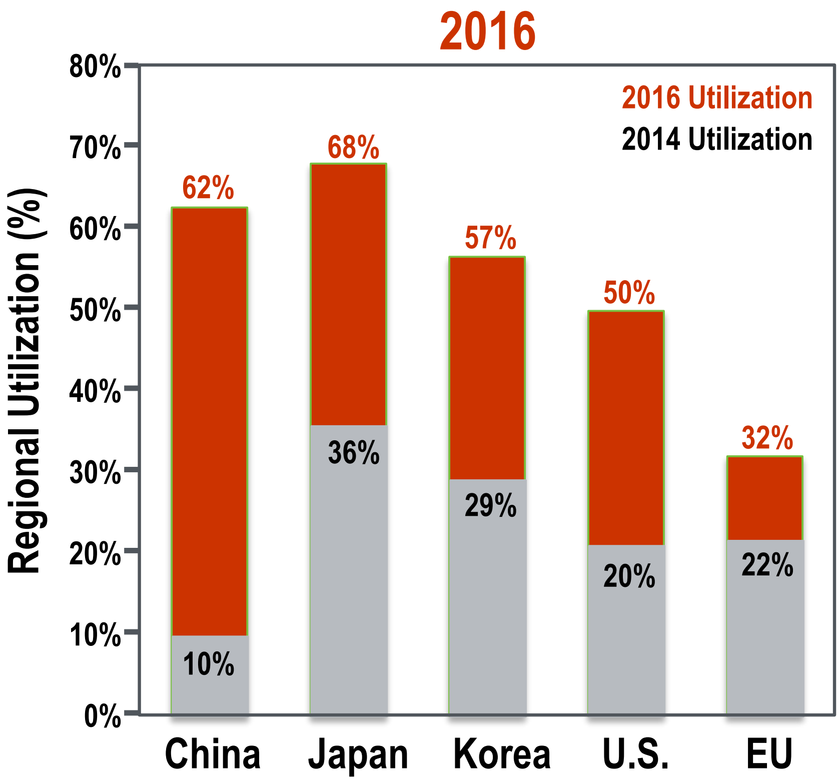
Manufactured in the USA

1 *Until April 2017*
2 *U.S. Department of Energy "2017 U.S. Energy and Employment Report (USEER)," January 2017*
3 *Of new Light-duty Vehicle Sales*
4 *Based on cost/kwh of electric energy: $0.12/KWh for electricity, $2.30/gallon for gasoline, and an average fuel economy of 23.6 mpg*
5 *Source: Wards, 2016; hybridcars.com, 2016*

Electric Vehicle Market

Regional Automotive LIB Cell Capacity and Utilization





- Automotive lithium-ion battery demand growing but short of global manufacturing capacity.
- Utilization of U.S. plants increased from 20% in 2014 to ~50% in 2016.
- Forecasted compound annual growth rates in lithium-ion demand: 22%–41% (through 2020).

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Mission

Enable a large market penetration of electric drive vehicles through innovative battery research and development.

Goal

Research new battery chemistry and cell technologies that can reduce the cost of electric vehicle batteries to less than $100/kWh, increase range to 300 miles and decrease charge time to 15 minutes or less. Ultimate goal is $80/kWh.

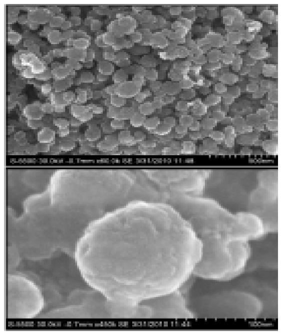
Budget

Funding in millions	**FY 2016** Enacted	**FY 2017** Enacted
Battery Technology R&D	$103.0	$101.2

VTO Battery R&D

Focus Areas

Advanced Battery Materials Research
TRL 2-3



- **Budget: $59.1M**
- National Laboratories
- Universities & Industry
- Battery500 Consortium

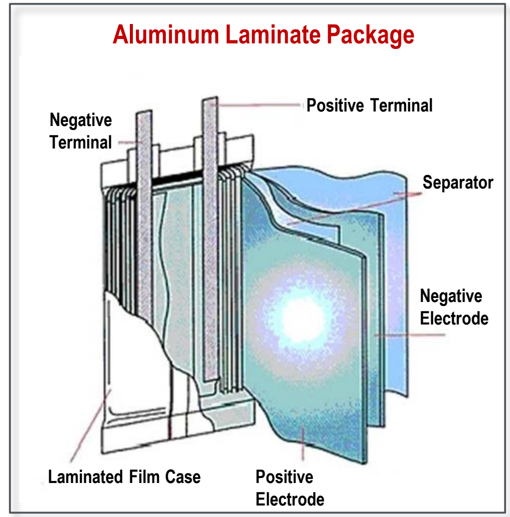
Battery Materials Research

- High capacity/High Voltage cathodes
- High voltage electrolytes and Solid State electrolytes
- Alloy & lithium metal anodes
- Material & Cell diagnostics and modelling

Battery Materials Research

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

Advanced Battery Cell Research
TRL 3-4



- **Budget: $42M**
- USABC
- National Lab Testing
- Industry FOAs
- CAEBAT

Robust EV Battery Cell Development

- Cost reduction
- Power and Capacity Improvement
- Cycle and calendar life
- Fast Charge capability

Battery Pack Targets

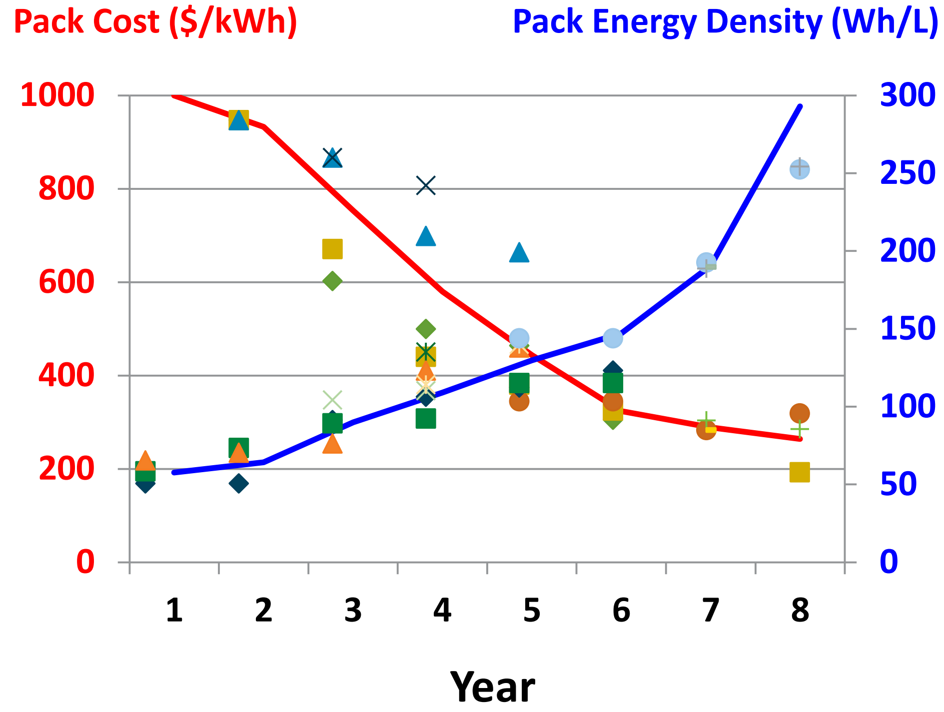
- $100/kWh EV pack cost
- 1,000 cycles and 10+ calendar year life
- Fast charge (20-80% SOC in under 15 min)

Battery Cost

Comparison with Publicly Available Battery Cost Information

- DOE R&D supported significant Battery Cost Reductions (3X) since 2008.
- **GM announcement: LG Chem cells cost $145/kWh (total energy)**
  - ~$170/kWh (useable)
  - Plus ~$50-65/kWh pack component and assembly cost (revised)
  - Total battery cost of ~$220-235/kWh (useable)
- **Tesla estimate: $190/kWh (total energy)**
  - Assuming 85% of the capacity is “useable”, the battery cost is ~$223/kWh (useable)

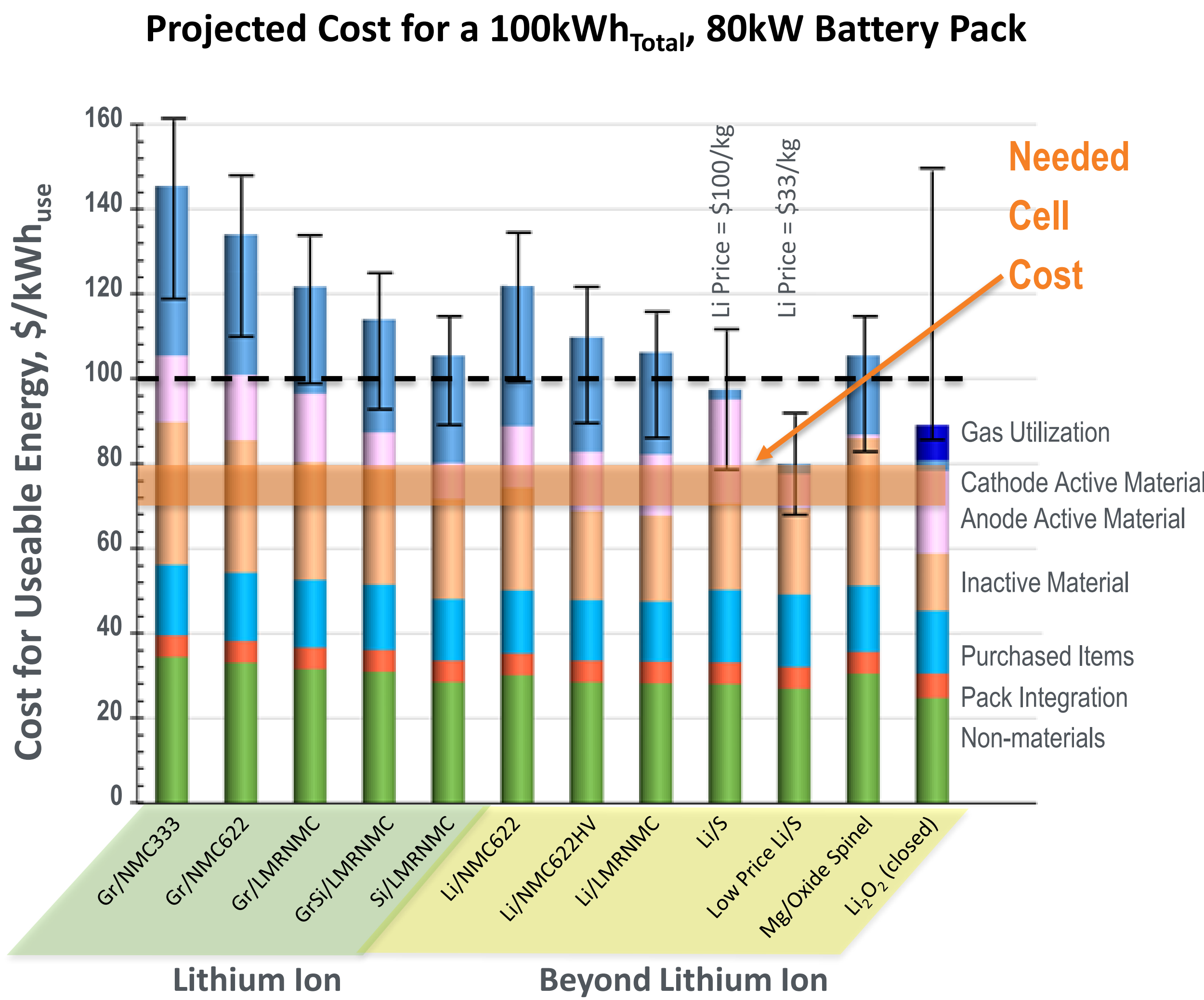
$245 | **Includes pack component and assembly cost of $65-75/kWh**



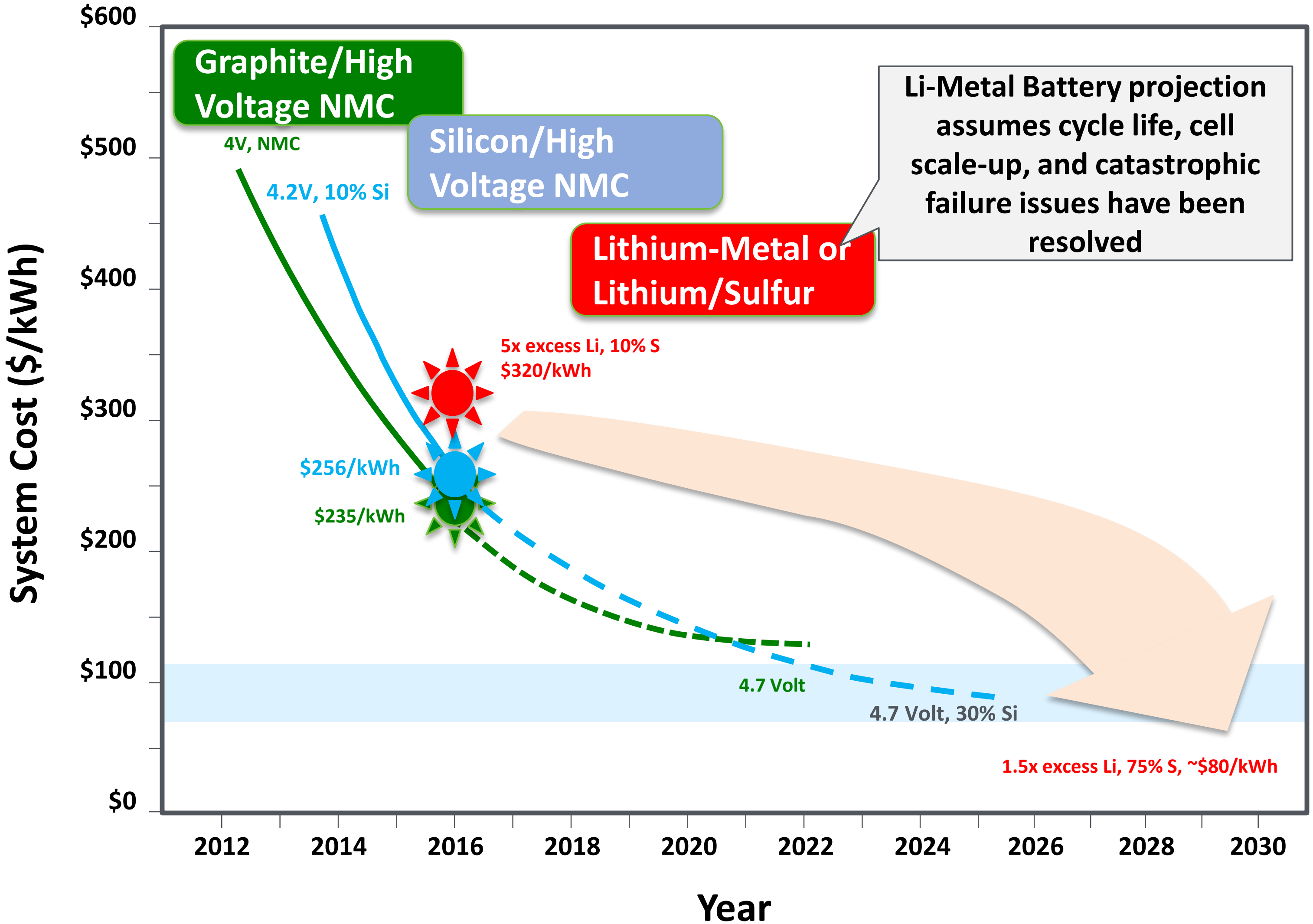
Battery Cost

Potential Cost Reductions for Lithium-ion and Beyond Lithium-ion Technologies

- Cost analysis prepared by U.S. Department of Energy, EERE Vehicle Technologies Office
  - Analysis performed by using the BatPac cost model at Argonne National Lab (March 2017)
- **These are the best case projections:** assuming that all chemistry problems solved, performance is not limiting, favorable system engineering assumptions, and high volume manufacturing.



Cost Trends for Lithium-based EV Batteries



VTO Battery R&D

Future Battery Technology & Science

Current Technology Lithium-ion
Graphite/NMC

Battery Pack Cost

- Current: $235/kWh
- Potential: $100-160/kWh

Large format EV cells	**20-60 Ah**
Current Cycle life	1000-5000
Calendar life	10-15 yrs
Mature manufacturing	
Fast Charge	

R&D Needs

- High Voltage Cathode/Electrolyte
- Lower Cost Electrode Processing Technology
- Extreme Fast Charging

Next Generation Lithium-ion
Silicon Composite/High Voltage NMC

Battery Pack Cost

- Current: $256/kWh
- Potential: $90-125/kWh

Large format EV cells	**20-60 Ah**
Current Cycle life	500-700
Calendar life	Low
Mature manufacturing	
Fast Charge	

R&D Needs

- High Voltage Cathode/Electrolyte
- Lower Cost Electrode Processing
- Durable Silicon Anode with increase silicon content

Longer Term Battery Technology
Lithium Metal

Battery Pack Cost

- Current: ~$320/KWh
- Potential: $70-120/kWh

Large format EV cells	
Current Cycle life	50-100
Calendar life	TBD
Mature manufacturing	
Fast Charge	

R&D Needs

- High Voltage Cathode
- Lithium Protection
- High Conductive Solid Electrolyte

New Focused Research Activity

Silicon Electrolyte Interface Stabilization (SEISta)

Intermetallic Anodes

Target: 1,000+ mAh/g and 1000 cycles

Challenges

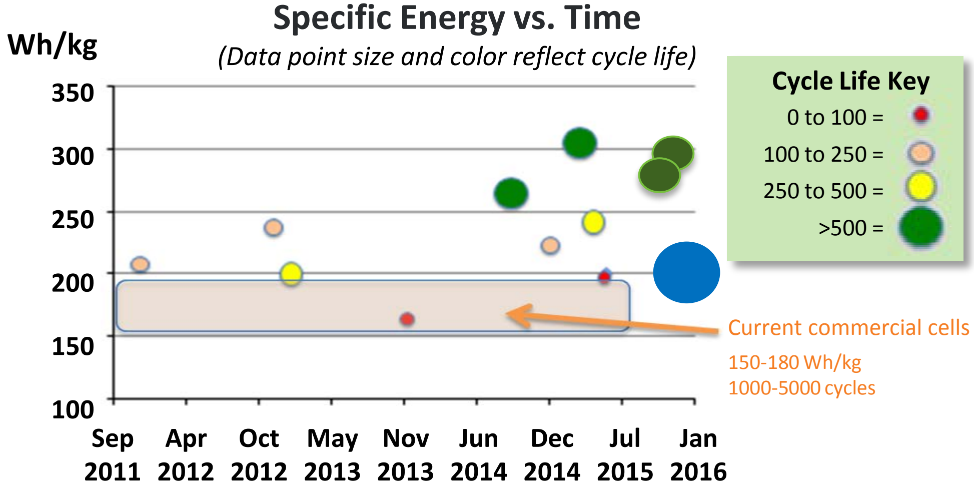
- Large first-cycle irreversible loss
- Low cycle and calendar life/ High capacity fade
- Poor coulombic efficiency
- Inferior power capability

- Develop a stable SEI layer for Silicon Anodes to overcome challenges.
- A more foundational understanding needed of the formation and evolution of the SEI on silicon.

Deliverables from DOE-funded Developers

Specific Energy vs. Time

(Data point size and color reflect cycle life)



New Focused Research Activity

Strategic Goal	Develop and demonstrate cells with a specific energy of 500Wh/kg and achieving 1,000 cycles
Lead	Pacific Northwest National Laboratory

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

Advisors

IBM

Stanford University

Tesla

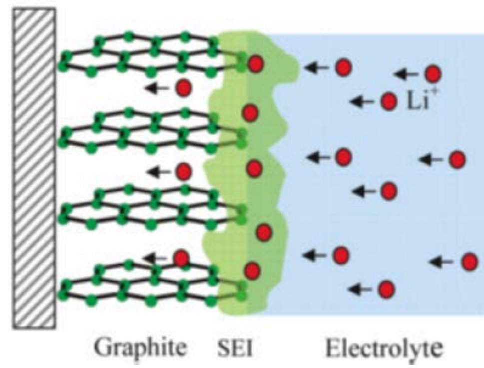
USABC United States Advanced Battery Consortium

Keystone Projects	Lithium metal anode and high nickel NMC cathode	Lithium metal anode and sulfur cathode	Electrode Architecture and Cell Design
Seedlings	New Innovative Research Projects to be added each year		

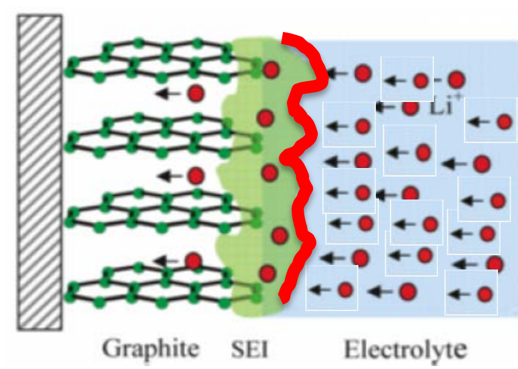
New Focused Research Activity

Extremely Fast Charging (XFC): 350-400 kW

- Combination of fast charge batteries and a network of high capacity chargers can minimize range anxiety and promote the market penetration of BEVs and increase total electric miles driven.
- **FY 2017 Study**
  - Assess the knowledge base of the fast charging capability of automotive batteries
  - Identify technical gaps for fast charging
  - Identify R&D opportunities
- **Issues Identified regarding Fast Charging**
  - Higher cost cells: (2X) compared to today's lithium-ion cells.
  - Cycle Life & Durability of Cells
    - Lithium plating/deposition occurs on the anode above a threshold current density.
    - Cell temperature rise during charge



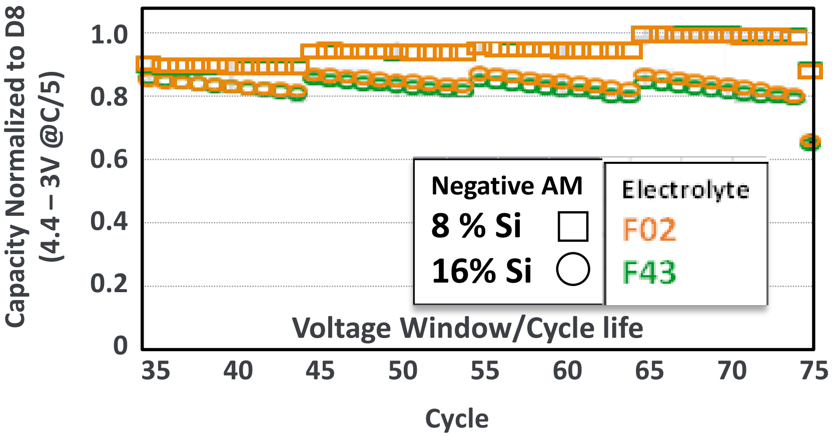
Plated lithium due to fast-charging



Advanced Cell Materials and Designs

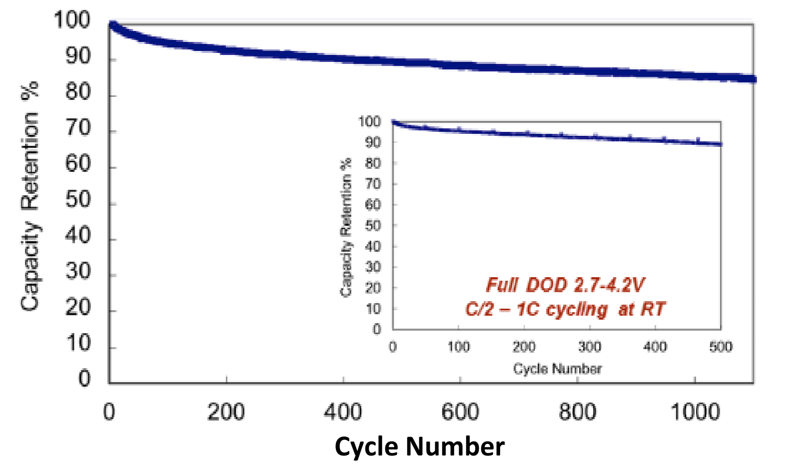
- Improved capacity retention of NCM materials for 4.4+ V operation, through both surface treatment and bulk-doping approaches.
- Improved rate capability.

Farasis Gen2 EV Testing Cell Performance



- CAM-7/Si-Gr PHEV cell achieves 1,000 cycles.
- Delivers >200Wh/kg and >85% capacity retention after 1,000 cycles.
- Models predict chemistry could reach 250Wh/kg in 15Ah pouch cells for PHEV applications.
- Cells capable of >845W/kg down to 10% SOC.

CAM-7/Si-based Anode 18650 Cells – 2.7–4.1V RT Cycling

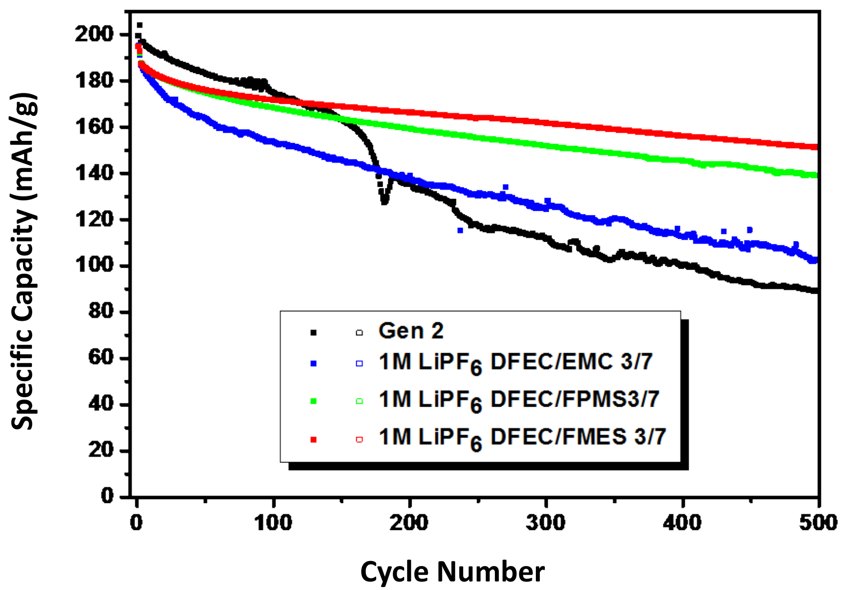


High Voltage Electrolytes

Argonne NATIONAL LABORATORY

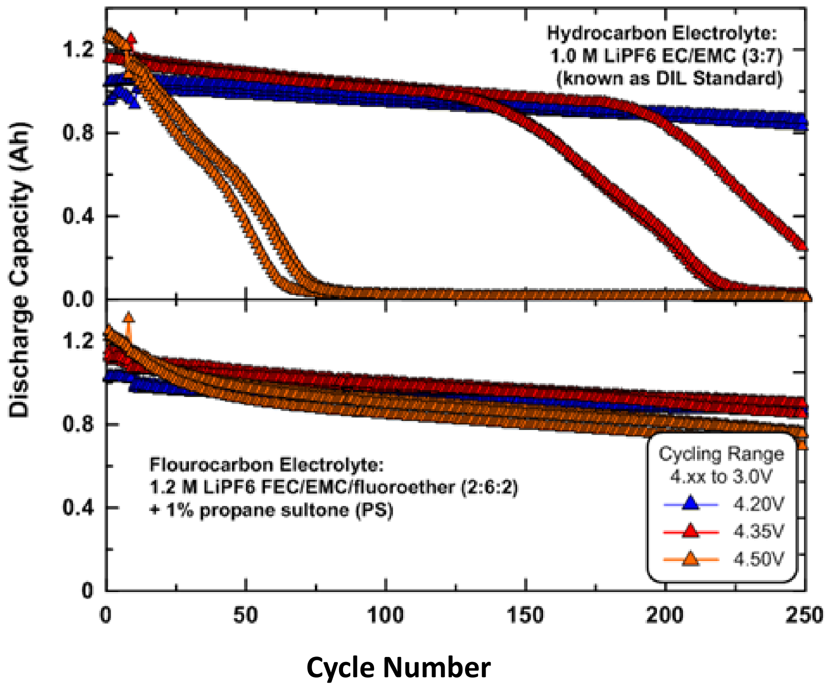
NMC532/Graphite Cells with ANL Fluorinated Sulfones as Additives

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



DAIKIN

Fluoro Carbon Electrolytes for High Voltage Operation

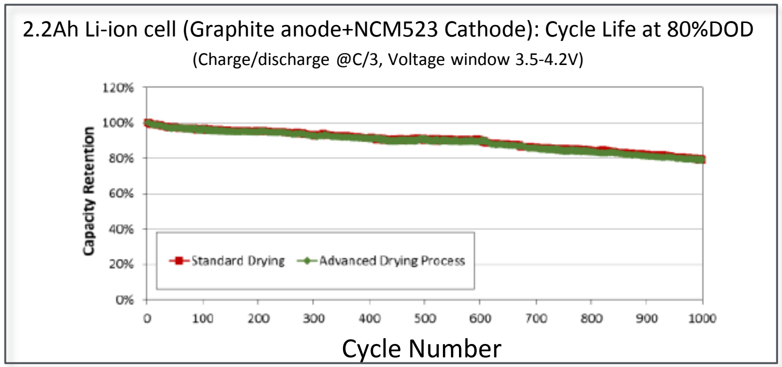


Cycle life showing capacity of 1Ah NMC/graphite cells with both standard carbonate (top) and fluorinated (bottom) electrolytes at cycled at a Vmax of 4.2, 4.35, and 4.45V.

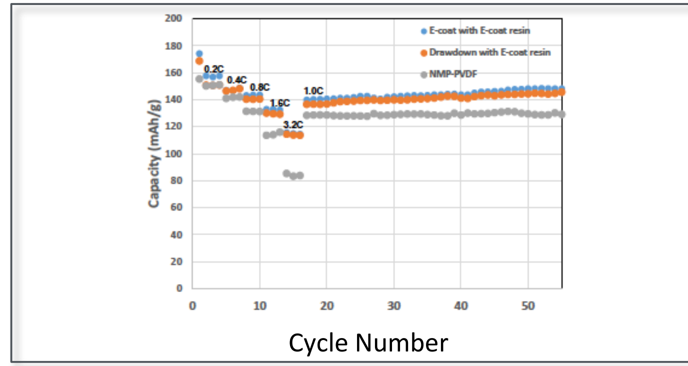
Novel Processing Advances

Potentially 5-10x faster and enabling thicker electrodes (~250 micron, a 3-4x improvement)

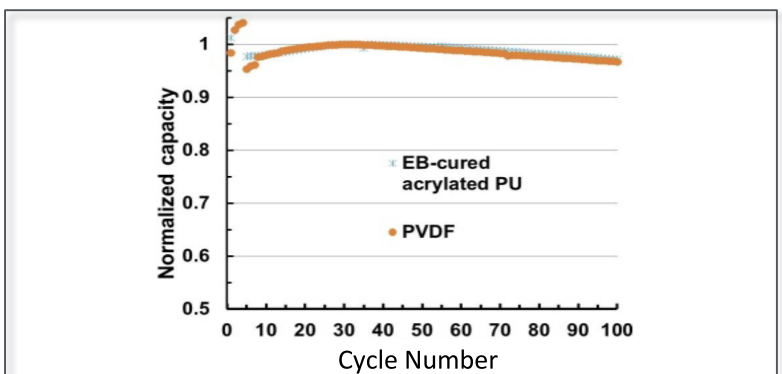
- Variable frequency microwave drying of electrodes



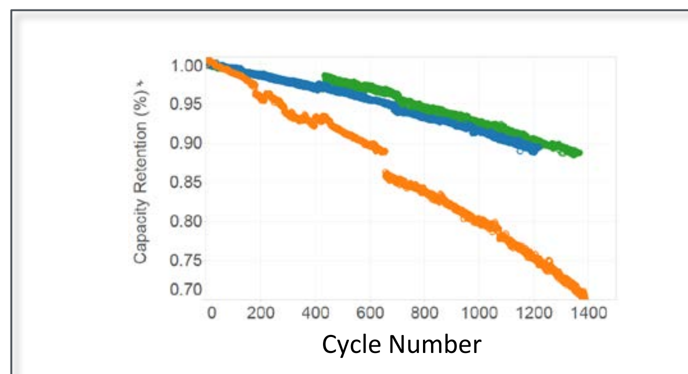
- Electrodeposition of cathode materials



- E-beam curing of cathode materials



- High energy, thick semi-solid electrodes, >1,000 cycles



Novel Structure as Host for Storing Metallic Lithium

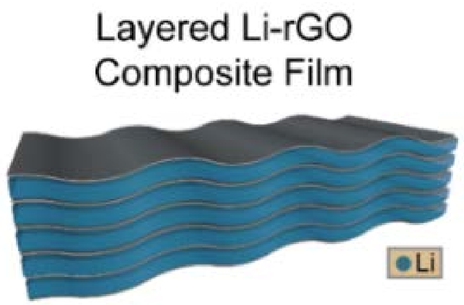
Traditional Li-metal technology

- Uses lithium foil as an anode
- Major hurdles:
  - Uneven and dendritic lithium deposition
  - Unstable solid electrolyte interphase
  - Excessive dimension change during cycling.

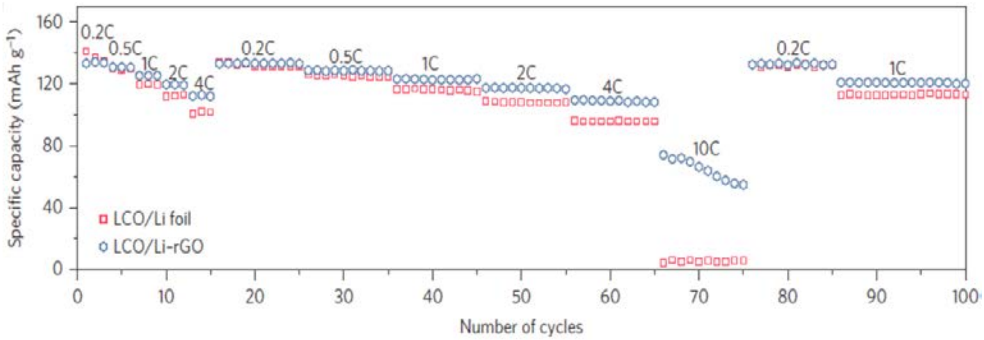
Significant Accomplishment

- In the new approach, reduced graphene oxide (GO) with nanoscale interlayer gaps used as host for lithium metal.
- Almost 93% of lithium weight is able to be loaded into the Graphene Oxide.
- Preliminary data indicates that cycling is very stable.

Reduced Graphene Oxide (GO) with Nanoscale Interlayer Gaps as Stable Host for Li Metal



Cycling of Li–Reduced Graphene Oxide Electrodes



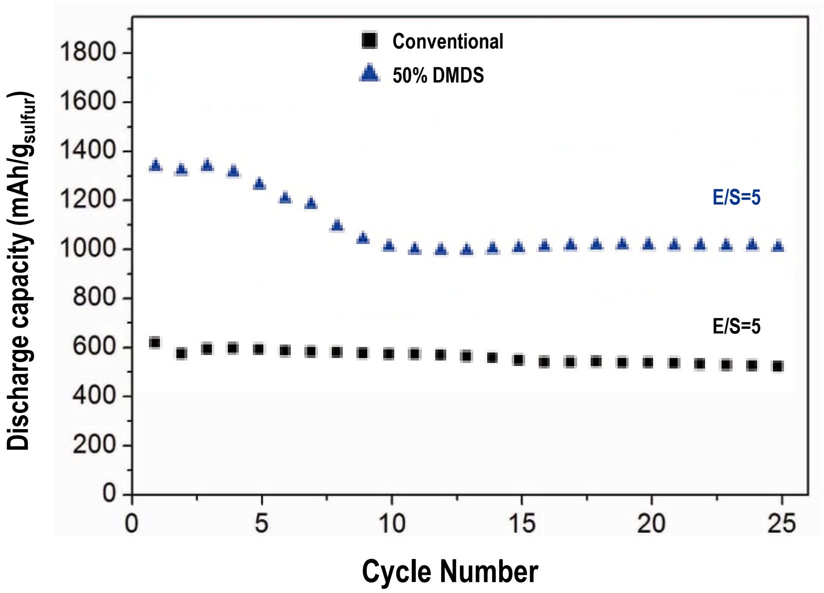
Y. Cui group, *Nature Nanotechnology* (2016)

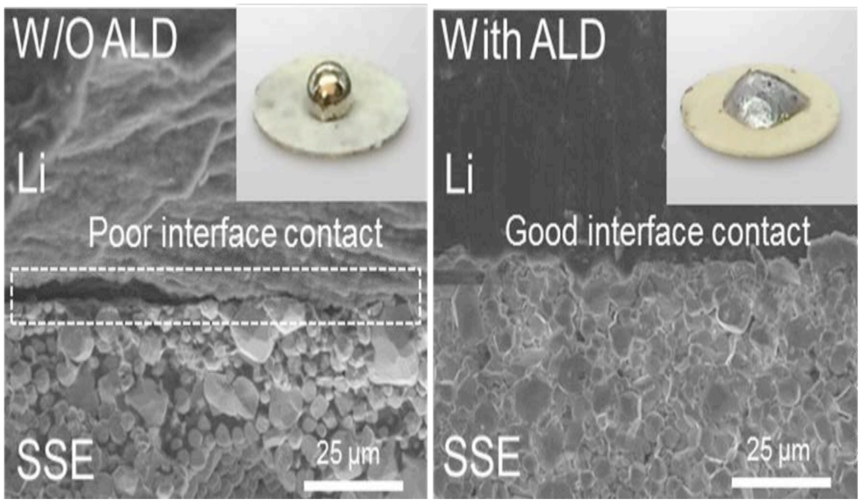
Battery Highlights

Lithium Sulfur and Solid State Electrolytes

- Novel electrolyte mitigates lithium polysulfide (LiPS) shuttle issue

- ALD-coated garnet shows significantly reduced interfacial impedance





VTO Battery R&D

Partners

Industry

USABC (United States Advanced Battery Consortium LLC), GM, Ford, FCA (Fiat Chrysler Automobiles), USCAR, PPG, Navitas Systems, MILTEC, Group14 Technologies, parc (Palo Alto Research Center), LG Chem Power Inc., BASF, 3M, TODA America, 24M, Lambda Technologies, Maxwell Technologies, Hydro Québec, Daikin, Seeo, Soulbrain MI, Farasis, Silatronix, nohms Technologies, Xerion Advanced Battery Corp, TIAX, SiNode Systems, CoorsTek, Forge Nano, Sila, Envia Systems, Wildcat Discovery Technologies, LiOx, XG Sciences (The Material Difference), CD-adapco, EC Power, ANSYS

National Labs/Government

Argonne National Laboratory, Berkeley Lab, NHTSA, TARDEC, Brookhaven National Laboratory, INL (Idaho National Laboratory), ARL, NAVSEA (Naval Sea Systems Command), NREL (National Renewable Energy Laboratory), Oak Ridge National Laboratory, NASA, JPL (Jet Propulsion Laboratory), Pacific Northwest National Laboratory, Sandia National Laboratories, IAPG (Interagency Advanced Power Group), IEA Hybrid & Electric Vehicle Implementing Agreement, SLAC National Accelerator Laboratory

Academia

Stanford University, Stony Brook University, University of Cambridge, University of Maryland, University of Colorado Boulder, Michigan State University, University of Washington, Berkeley University of California, Vanderbilt University, Binghamton University, WPI, BYU, Texas (The University of Texas at Austin), PennState, The University of Rhode Island, Texas A&M University, UC San Diego, Massachusetts Institute of Technology, University of Pittsburgh, Michigan Technological University, University of Missouri

SBIR/SBTT

Axion Power International Inc., Creare, ETP, Hybrid Plastics, OnTo, Giner, TDA Research, Farasis, Excellatron, Motiv, PneumatiCoat Technologies, ADA Technologies, Inc., TIAX, Leyden Energy, Coulometrics, Navitas Systems, SiNode Systems, American Lithium Energy, Ballast Energy, HiCo Tech, Applied Spectra, ASI, Novarials (a nanowire technology builder), Bettergy, XG Sciences (The Material Difference), pH Matter LLC, Sillion, Saratoga Energy, Physical Sciences Inc.

Thank You