Overview of the DOE Advanced Battery R&D Program

June 8, 2015

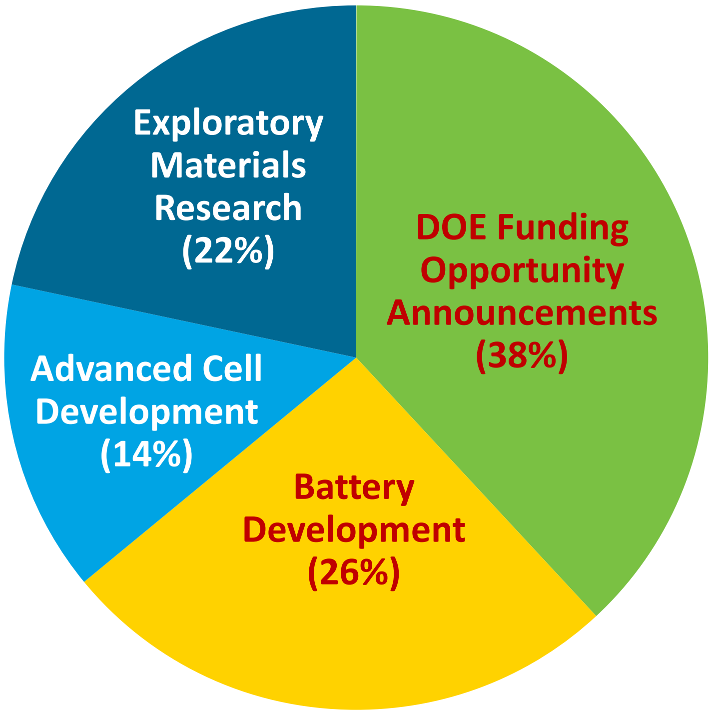
Peter Faguy
Energy Storage
Hybrid Electric Systems

Battery R&D Budget

Advance the development of batteries and other electrochemical energy storage devices to enable a large market penetration of electric drive vehicles.

Battery/Energy Storage R&D Funding ($M)	
FY 2013	$88
FY 2014	$85
FY 2015	$82.7
FY 2016 (request)	TBD
inclusive of SBIR/STTR	

FY 2015 Budget: $83M



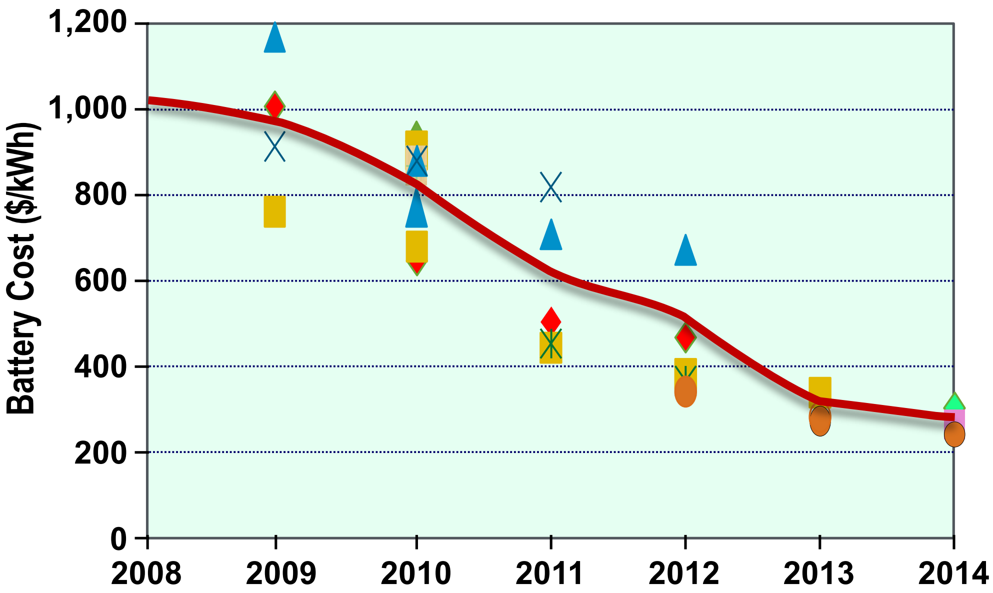
Reduce the cost of a PEV battery to $125/kWh by 2022

Progress and Results

Cost Reduction & Energy Density

DOE/USABC reduced the cost of PEV batteries by 70% and doubled their energy density during the past 5 years

- Projected cost of advanced PHEV battery technology of $289/kWh of useable energy, on average.
- Batteries were sized to PHEV 40 packs (~14 kWh).
  - These battery development projects focus on advance cathodes, processing improvements, cell design and pack optimization.
  - Most batteries use advanced but already commercialized chemistries.
- Results based on prototype cells & modules meeting DOE/USABC performance targets.

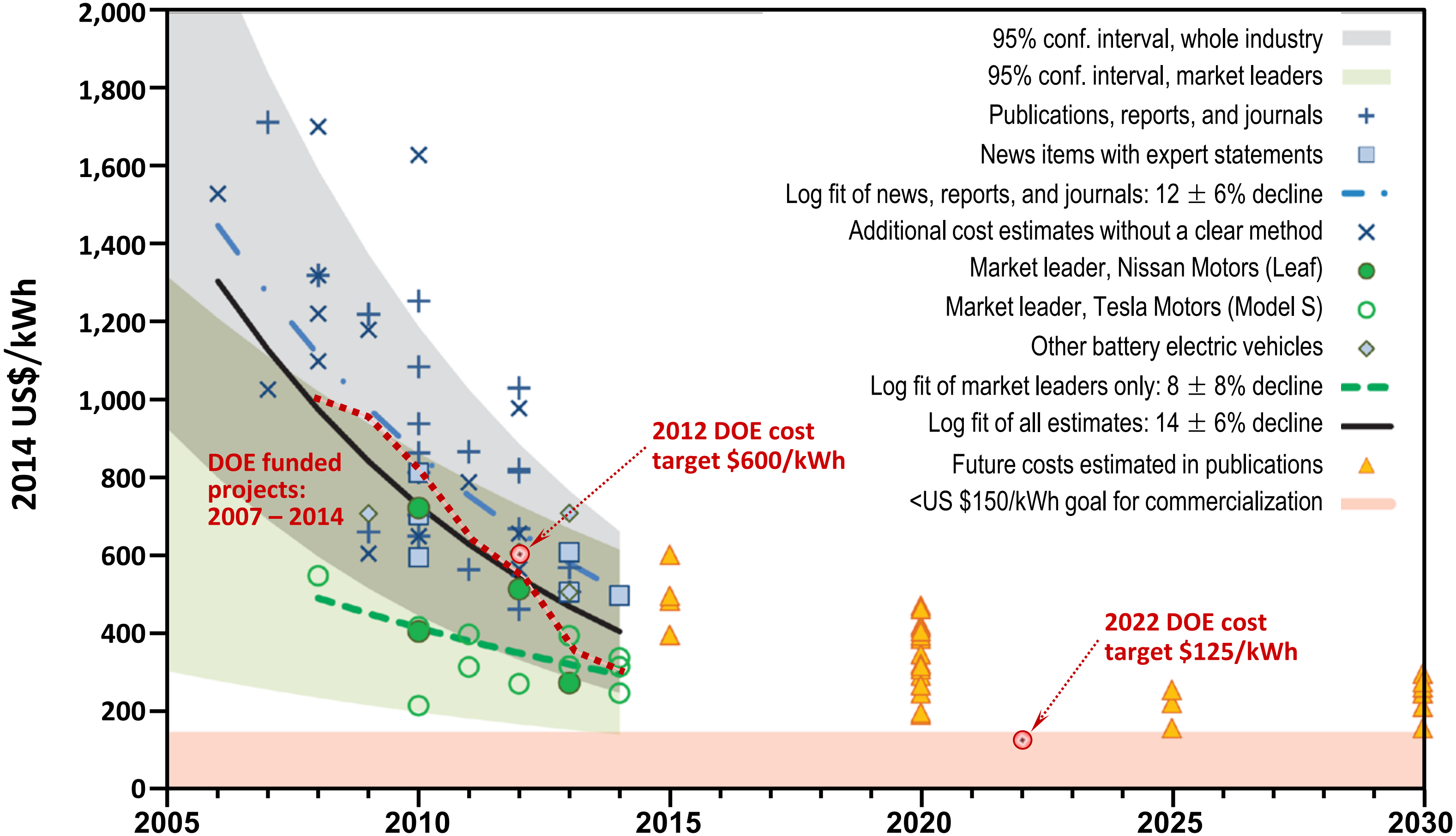


- Detailed USABC battery cost model used to estimate the cost of PEV battery packs assuming that 100,000 batteries are manufactured annually.

Cost Parity with ICEs is reachable

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

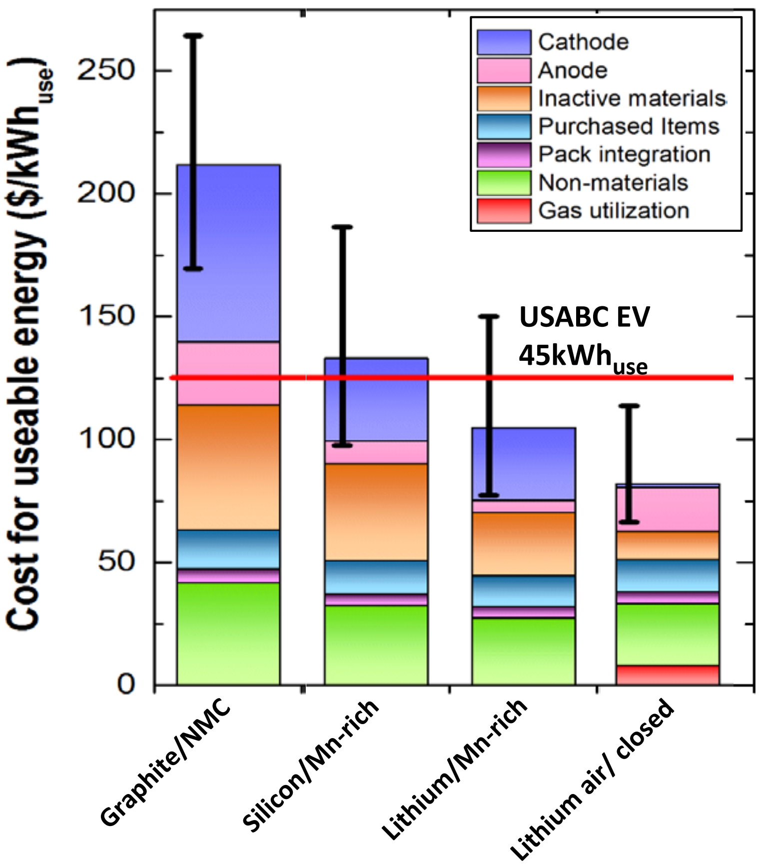
Production of EDV batteries has been ~ doubling globally every year since 2010 with ~ 8% annual cost reductions for major manufacturers. Economies of scale continue to push costs towards $200/kWh. With new material chemistries and lower-cost manufacturing, cost parity with ICEs should be reached in the next ten years.



"**Rapidly falling costs of battery packs for electric vehicles**", B. Nykvist and M. Nilsson; *Nature, Climate Change*; March 2015, DOI: 10.1038/NCLIMATE2564

Projected Cost for a 100kWh Battery Pack

- Extensive cost modeling has been conducted on advanced battery chemistries using the ANL BatPaC model.
  - **Lithium-ion:** silicon anode coupled with a high capacity cathode presents moderate risk pathway to less than 125/kWh$_{use}$
  - **Lithium metal:** a higher risk pathway to below \$100/kWh$_{use}$
- **These are the best case projections:** all chemistry problems solved, performance is not limiting, favorable system engineering assumptions, high volume manufacturing



EDV Energy Storage R&D at DOE

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

Under Secretary for Science and Energy

Office of Science Basic Energy Sciences	Advanced Research Projects Agency – Energy	EERE Vehicle Technologies Office Energy Storage
Fundamental research to understand, predict, and control matter and energy at electronic, atomic, and molecular levels.	**High-risk transformational research with potential for significant commercial impact.**	**Applied battery materials, cell, and pack R&D to enable a large market penetration of EDVs.**
• JCESR (Hub) • EFRCs • Core Scientific Research	• AMPED (Battery Controls) • RANGE (Flow, Solid State, Multifunctional)	• BMR • ABR • USABC • CAEBAT

VTO Battery R&D Activities and Target Metrics

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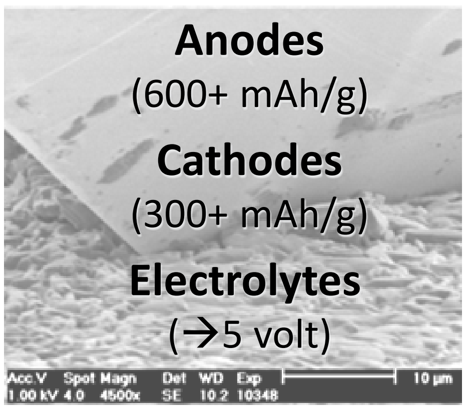
Advanced Battery Materials Research

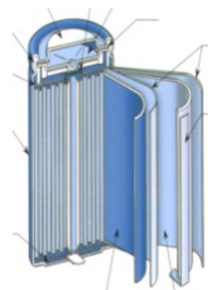
- ✓ New materials discovery
- ✓ Structure –activity exploration at materials level



materials characterization
in operando spectrocopy
½ cell data
10 - 100 mAh full cells

Applied Battery Research

- ✓ Cell chemistry optimization
- ✓ Advanced processing technologies
- ✓ Life Improvement



Cell Targets
350 Wh/kg
750 Wh/l
1,000 C/3 cycles

component characterization
processing R&D
½ cell data
0.5 - 1.0 Ah full cells

Advanced Battery Development

- ✓ Performance Optimization
- ✓ Cost Reduction

Pack Targets
$125/kWh
250 Wh/kg ; 400 Wh/l
2,000 W/kg

5 - 40+ Ah full cells
performance testing
modules
packs

39 ORAL & 57 POSTER PRESENTATIONS Tues – Thur. JUNE 9 – 11 Crystal Gateway Marriott

VTO Awards 2014

Area of Interest 3: Beyond Li-ion Technologies

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

FY 2014 Vehicle Technologies Program Wide FOA (DE-FOA-0000991)

Awardee	Technology	Funding
Michigan State University	***Polycrystalline membranes in Li-metal and Li-sulfur batteries***	$1.23M
Stanford University	***Nanomaterials to improve interface between lithium metal anodes and electrolytes to improve cycle life***	$1.35M
University of Pittsburgh	***High-throughput cost-effective approaches to scale-up synthesis of high-capacity cathodes***	$1.25M (with TARDEC)
Binghamton University	***Sn-Fe-C composite anodes***	$1.22M
Liox Power	***High energy, high power, highly reversible Li-air batteries***	$1.5M
University of Maryland	***Interfacial impedance issues in solid state Li-ion batteries***	$1.21M (with TARDEC)
Oak Ridge National Laboratory	***Nanoindentation to determine mechanical properties and identify causes of premature failure at protected lithium interface***	$1M (with TARDEC)
Texas A&M University	***Improved electrolyte chemistry and cathode architecture for Li-sulfur batteries***	$0.99M
Brookhaven National Laboratory	***Low-cost anodeless Li-sulfur battery utilizing dual-functional cathode additives***	$1.5M (with TARDEC)

Solid-state electrolytes

Li-air systems

Li-sulfur systems

Protected Li metal

ORAL SESSIONS Tues. – Thur. JUNE 9 - 11 (Tien Duong)

VTO Awards 2014

VTO Incubator

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

FY2014 Vehicles Technologies Incubator FOA (DE-FOA-0000988)

Awardee	Technology	Funding
Miltec UV International, LLC	***High speed precision printing and UV curing for ceramic separators for LiBs***	$1.56M
Sila Nanotechnologies	***Core shell non-intercalation cathodes and anodes***	$1.00M
24M Technologies, Inc.	***High active loading cathodes by new manufacturing approach***	$1.95M
Amprius	***A commercially scalable process for silicon anode prelithiation***	$1.26M
Lambda Technologies, Inc	***Variable frequency microwave drying of electrodes***	$1.01M
Parthian Energy LLC	***Unique S-cell design for reduction of inactive materials***	$0.59M

Processing R&D

New active materials

New cell designs

POSTER SESSION Wed. JUNE 10 (Brian Cunningham, Tien Duong, Peter Faguy)

USABC Cooperative Agreement

Support battery manufacturers to develop batteries that meet EDV performance, safety, and cost requirements.

- **Focus**
  - Cell design/fabrication
  - Module/pack design & fabrication
  - Cell component enhancement (electrolyte, separator)
  - Detailed cost modeling
  - Application specify battery requirements and associated test procedures.

Recent USABC Awards
EV Battery Development: Amprius, Envia Systems, LG Chem Power, SEEO
PHEV Battery Development: Xerion
12V Start/Stop Battery Development: Saft, Maxwell Technologies, LG Chem Power

Open USABC Solicitations
EV, PHEV, 12V start/stop, and 48V HEV battery development
Novel electrolytes, novel separators, recycling

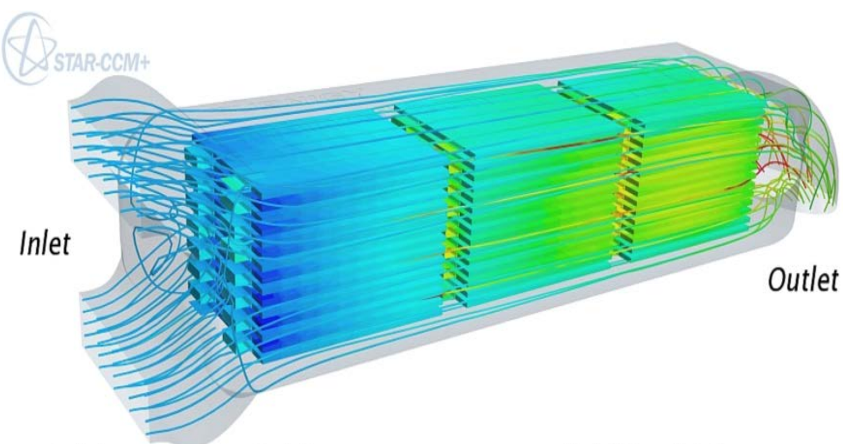
POSTER SESSION – Tues/Wed JUNE 9,10 (David Howell, Brian Cunningham)

Computer-aided Battery Energy Tools (CAEBAT)

NREL NATIONAL RENEWABLE ENERGY LABORATORY · GM · ANSYS · ESIM

Support battery manufacturers to develop batteries that meet EDV performance, safety, and cost requirements.

- **Focus**
  - Computer Aided Engineering tools for EDV Batteries accelerate design of high-performance lithium-ion batteries through development and validation of multi-scale, multi-physics modeling tools.



Commercialization: The three contractor teams of the CAEBAT project have released three competitive electrochemical-thermal software suites for battery simulation and design.

- GM and partners have developed a flexible and efficient 3-D battery modeling tool based on the Fluent multi-physics simulation platform.
- CD-adapco and partners have developed electrochemical-thermal module for the Star-CCM+ multi-physics simulation platform.
- EC Power and partners developed thermal electrochemical design tools in AutoLion™.

These software tools were validated with comprehensive battery test data. More than 50 end-users (material and cell developers, pack integrators, vehicle manufacturers, and others) have used these tools to consider battery design for better performance, life, and thermal response characteristics.

POSTER SESSION Tues. JUNE 9 (Brian Cunningham)

Advanced Battery Development
Testing

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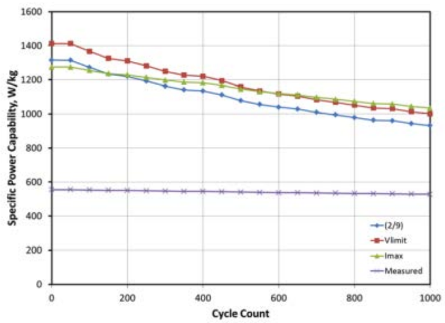
DOE national labs provide independent testing support to USABC, IC^{3}P, incubator, and other contracts to confirm battery performance, life, thermal performance, and abuse characteristics.

They also lead test methods development, test manual writing, and requirements analysis efforts.

Performance

Argonne NATIONAL LABORATORY

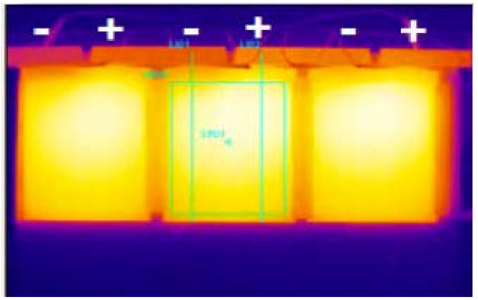
INL Idaho National Laboratory



Sample of cells tested in 2014:
3M, Actacell, Amprius, Cobasys, Dow Kokam, Envia, Farasis, Hydro Quebec, JCI, LG Chem, Miltec, Navitas, Penn State, SKI, Optodot, Sakti3, SEEO, Tiax

Thermal

NREL National Renewable Energy Laboratory



Sample of cells tested in 2014:
Farasis, JCI, Leyden Energy, LG Chem, SK Innovation

Abuse

Sandia National Laboratories

Sample of cells tested in 2014:
Entek, Farasis, JCI, LG Chem, Leyden Energy, Maxwell, Saft

POSTER SESSION Tues. JUNE 9 (Brian Cunningham)

FY2013 FOA Awards *Improvements in Cell Composition, Chemistry, and Processing*

IC^{3}P Projects:

- Cell chemistry focus
- Full cell deliverables: baseline and advanced (1 - 3 Ahr pouch & 18650)
- Team-based expertise / workload
- 24 month duration
- $2M - $4M funding

POSTER SESSION Tues. JUNE 09 (Peter Faguy)

Cell Design/Electrochemistry Optimization

Power & Capacity Increase and Life Improvement

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

Applied Battery Research Efforts at National Laboratories

Thrusts

Focused Research Project ("Deep-Dive") **– a multi-laboratory consortium**

Enabling High-Energy/Voltage Lithium-Ion Cells for Transportation Applications

Oak Ridge National Laboratory | Argonne National Laboratory | NREL

Processing R&D

- Battery Manufacturing R&D Facility (BMF) — Oak Ridge National Laboratory
- Materials Engineering Research Facility (MERF) — Argonne National Laboratory

R&D Support Facilities

- Abuse Tolerance for ABR projects — Sandia National Laboratories
- Cell Analysis, Modeling, and Prototyping (CAMP) Facility
- Post-test Diagnostic Facility
- Materials Engineering Research Facility (MERF)

Argonne National Laboratory

POSTER SESSION Tues. JUNE 09 (Peter Faguy)

Advanced Battery Materials Research (BMR)

Anodes
- ❑ Intermetallics/alloys
- ❑ Nanophase metal oxides
- ❑ Tailored SEI and new binders

Cathodes
- ❑ Layered-layered oxides
- ❑ High voltage spinels and oxides
- ❑ Metal phosphates
- ❑ Modified surfaces

Electrolytes
- ❑ High voltage electrolytes
- ❑ Solid polymer
- ❑ Electrolytes for Li metal

Beyond Lithium-Ion
- ❑ Inhibit dendrite growth
- ❑ Efficient utilization of sulfur
- ❑ Bifunctional catalyst for $Li-O_2$

Participants

Universities:
- Brigham Young University
- Drexel University
- Michigan State University
- Massachusetts Institute of Technology
- Pennsylvania State University
- Stanford University
- Binghamton University (SUNY)
- Texas A&M University
- University of California, Berkeley
- University of California, San Diego
- University of Cambridge
- University of Colorado, Boulder
- University of Maryland
- University of Massachusetts, Boston
- University of Pittsburgh
- University of Texas, Austin

National Labs:
- ANL
- BNL
- LBNL
- NREL
- ORNL
- PNNL

Industry:
- Daikin
- GM
- Hydro Quebec/ IREQ
- WildCat Discoveries/3M

ORAL PRESENTATIONS Tue–Thurs, JUNE 9,10,11 (Tien Duong)

Battery R&D Highlights

FeF_2 Conversion Cathode Material

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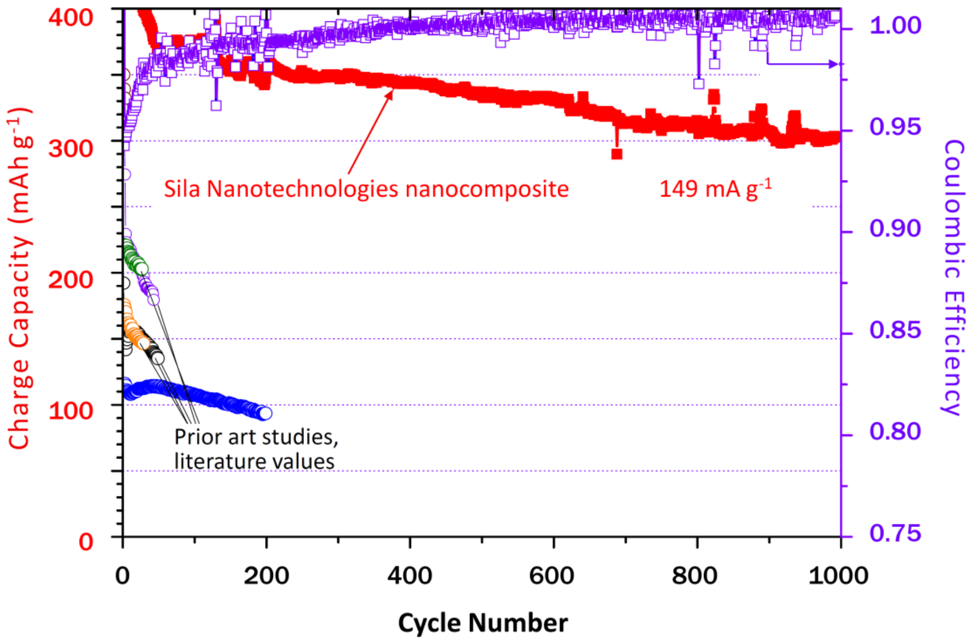
SILA NANOTECHNOLOGIES

Low Cost, High Capacity Non-Intercalation Chemistry Automotive Cells

- Lithium – metal fluoride (MFx) containing cathodes high theoretical energy density, but are highly unstable and suffer from low capacity utilization and very low power
- Sila's results on FeF_2 / carbon nanocomposite cathodes show potential: excellent stability, rate performance, and coulombic efficiency at the material level
- Sila materials show significantly higher capacity and cycle stability demonstrated vs. state of the art FeF_2 cathodes reported in literature



Charge capacities and coulombic efficiencies of nanocomposite FeF_2/ C – Li cells compared to previously reported literature values. (Source: Sila Nanotechnologies.)

Battery R&D Highlights

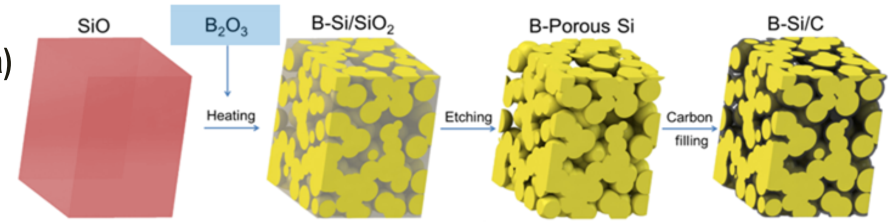
Nanoporous Si-C Anode and Binders

Cross-linkable binders

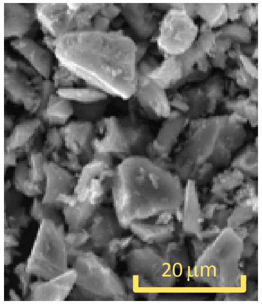
High Energy, Long Cycle Life Lithium-ion Batteries for EV Applications

- Scaled-up developed micron-sized Si-C and B-doped $Si/SiO_2/C$ composite anode
- Novel cross-linked binders enable to fabricate high mass loading electrodes with good flexibility and cycling stability
- Achieved high efficiency of 99.7%, and low capacity fading due to volume change and particle fracture

a)



b)



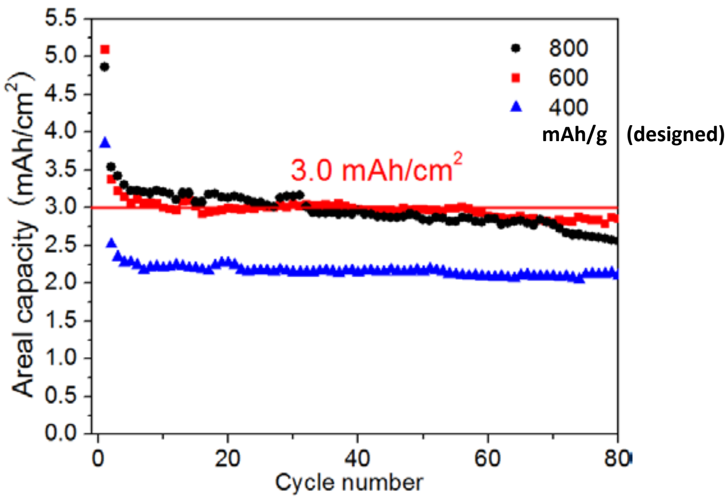
a) *Schematic representation of nanocomposite synthesis;*

b) *SEM image of the boron doped micron-sized nanoporous Si-C composite;*

c) *Representative cycling performance for blended anodes (B-Si/C : graphite) with different specific capacities and using a novel cross-linked binder*

(Source: Pennsylvania State University)

c)

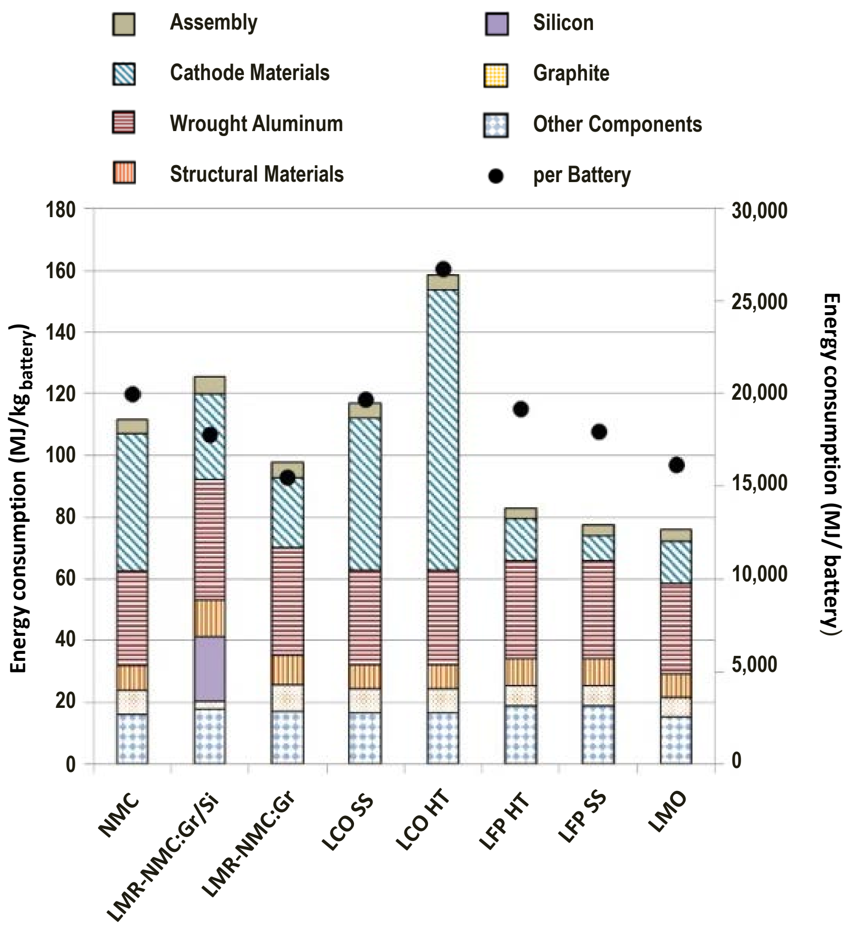


Battery R&D Highlights

Energy Intensity of EV Battery Production

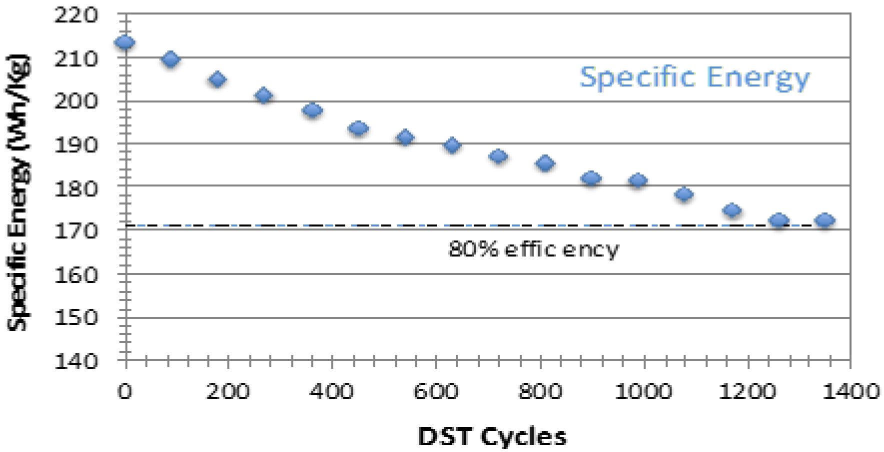
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- The energy intensity of EV battery production from cradle-to-gate varies greatly based on the cathode material used.
- Materials processing represents the majority of the energy required to manufacture EV batteries.
- Recycled material demonstrate energy efficiencies, and potential cost reduction opportunity.



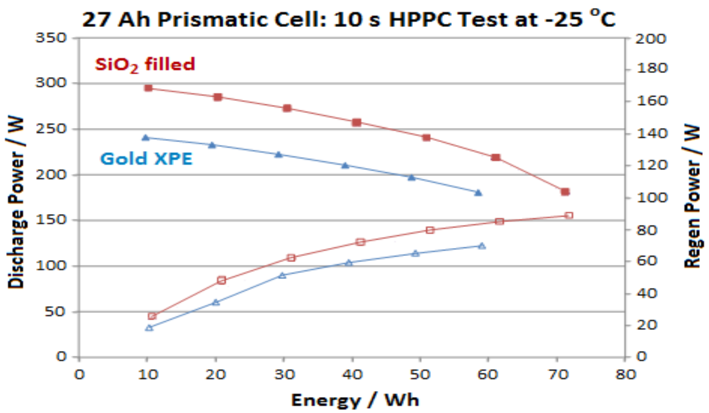
Energy intensity of battery EV production with 28 kWh batteries from cradle-to-gate with different cathode materials (Source: ANL)

Envia Systems worked to develop and integrate their high capacity cathode with commercial graphitic anodes and high voltage electrolytes into high capacity pouch cells to meet the long-term USABC goals for electric vehicles.



Cycle Life versus Specific Energy for 20 Ah Pouch Cells

Entek has addressed high temperature separator integrity by producing silica-filled membranes with ultra-high molecular weight polyethylene. The separators have <5% shrinkage at 200°C. In addition, the silica filler provides other benefits (higher porosity, faster wetting), which lead to unanticipated improvements in battery performance.



HEV cells with a silica-filled separator show improved low-T power over cells with an UHMWPE separator.

VTO Energy Storage FY2015 FOAs

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

Solicitations are currently in the selection process

FY 2015 Vehicle Technologies Program Incubator FOA (DE-FOA-0001213)	
… to support innovative technologies and solutions not represented in a significant way in VTO's' existing Multi-Year Program Plans (MYPPs) or current portfolios.	• $14M total (Energy Storage, ~~50%) • $0.5M - $3M, 1 – 3 year projects

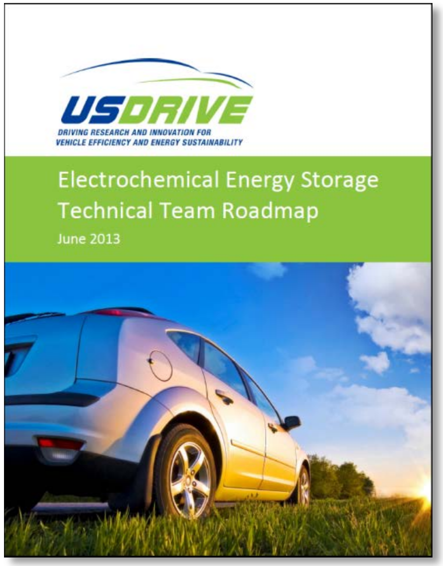
FY 2015 Vehicle Technologies Program Wide FOA (DE-FOA-0001201)	
AOI-4: Advances in Existing and Next-Generation Battery Material Manufacturing Processes	• Processing R&D projects • ~3 to be funded in each category • $1.5M - $3M, 2 – 3 year projects
AOI-5: Advances in Electrode and Cell Fabrication Manufacturing	
AOI-6: Electric Drive Vehicular Battery Modeling for Commercially Available Software	• CAEBAT • $1M - $2M, 3 – 4 projects

For More Information…

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

USDRIVE Energy Storage R&D Roadmap

- Tabulates performance and cost targets for HEV batteries and EV batteries.
- Describes ongoing /planned R&D efforts on EDV battery technologies.
- For a copy of the roadmap, visit:
  http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eestt_roadmap_june 2013.pdf



Energy Storage R&D Annual Progress Report for FY 2014

- Describes all energy storage R&D projects funded by DOE Vehicle Technologies Office (VTO) at a national laboratory or in partnership with industry.
- For obtaining a copy of the Annual Progress Report, visit:
  http://energy.gov/eere/vehicles/downloads/vehicle-technologies-office-2014-energy-storage-rd-annual-report

Contacts

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