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


# Overview of the DOE VTO Advanced Battery R&D Program

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# VTO Battery R&D Funding

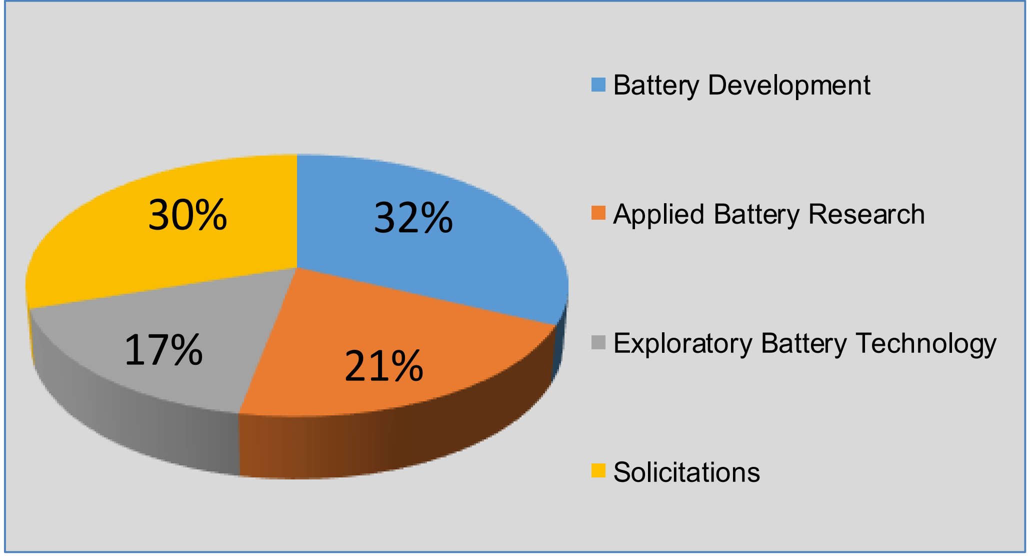
**MISSION: Advance the development of batteries to enable a large market penetration of hybrid and electric vehicles.**

## Program targets focus on enabling market success

- ❑ Increase performance (energy, power, life)
- ❑ Reduce weight & volume
- ❑ Increase abuse tolerance
- ❑ LOW COST!

**FY2016 Budget: $103M**

FY2015: $83M

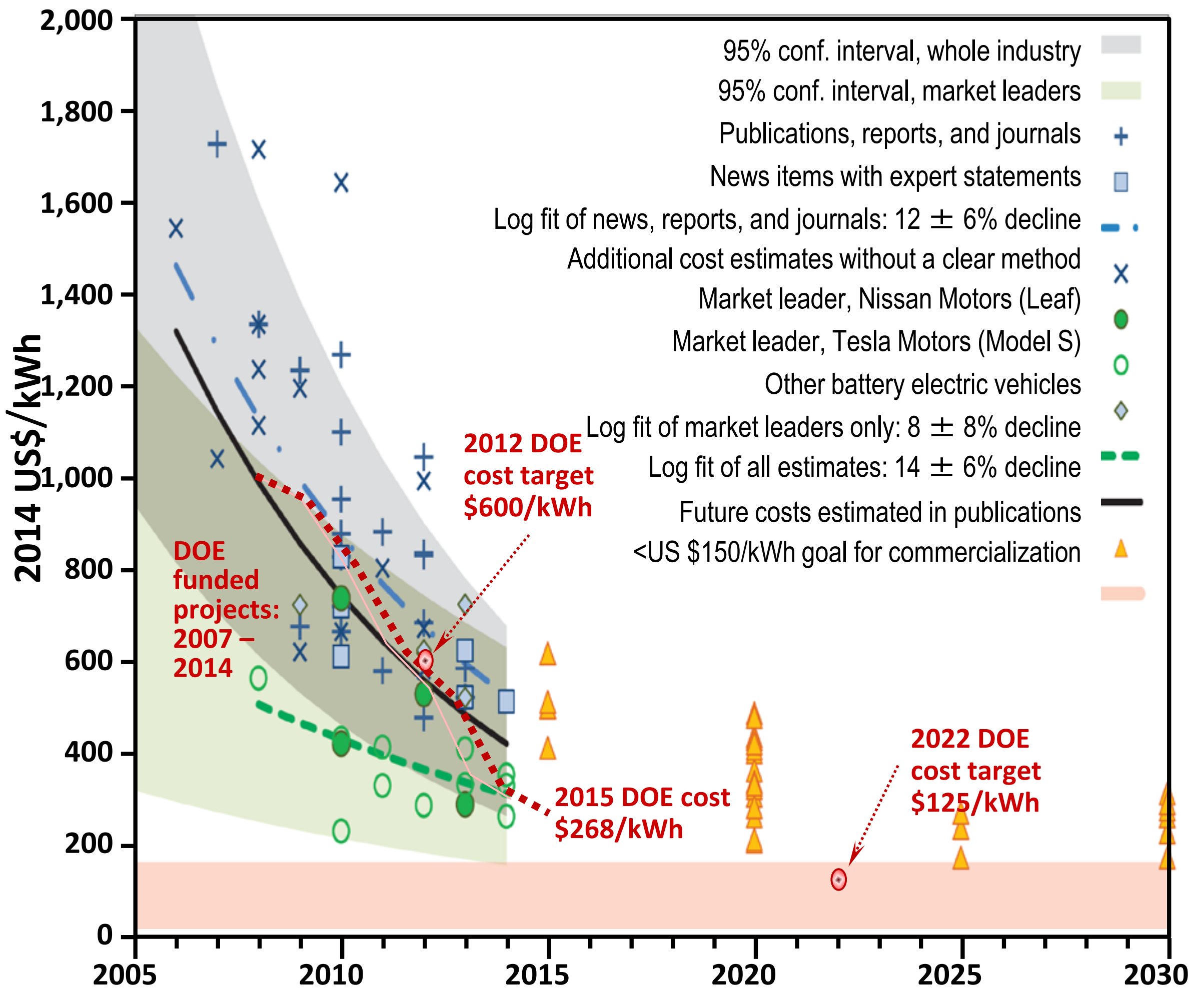



**2020 GOAL: Reduce the production cost of an EV battery to $125/kWh (75% decrease from 2012 baseline)**

# Cost Parity with ICEs is reachable

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

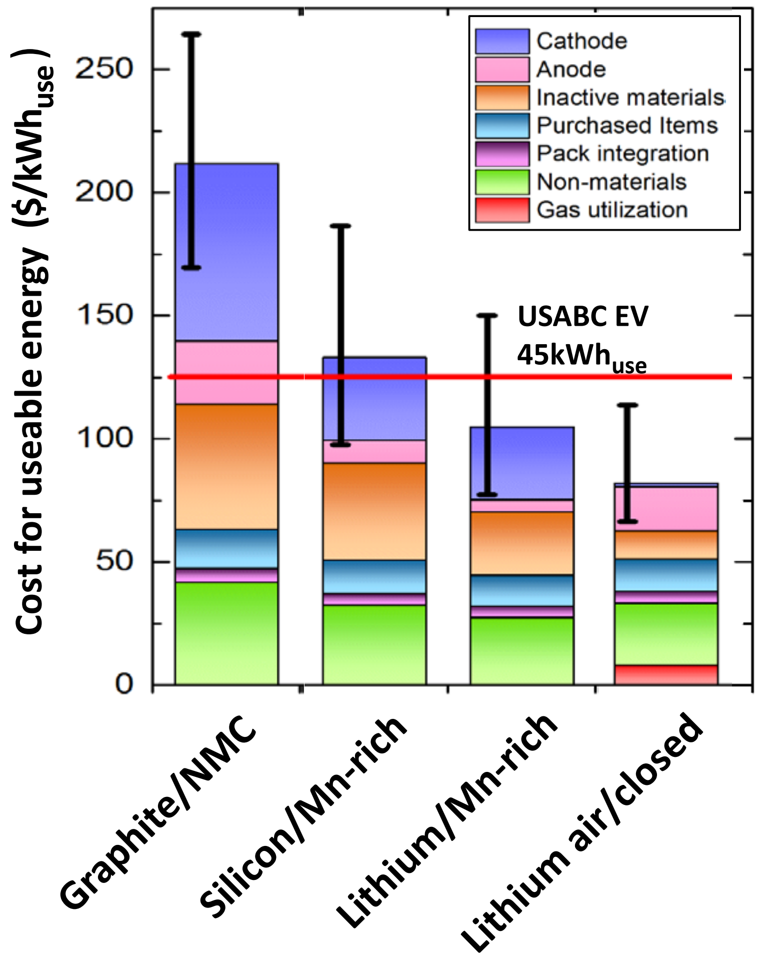
- Production of EDV batteries doubling globally every year since 2010.
- 8% annual cost reductions for major manufacturers.
- Economies of scale continue to push costs towards $200/kWh.
- With new material chemistries and lower-cost manufacturing, cost parity with ICEs could be reached in the ten years.



# Battery R&D

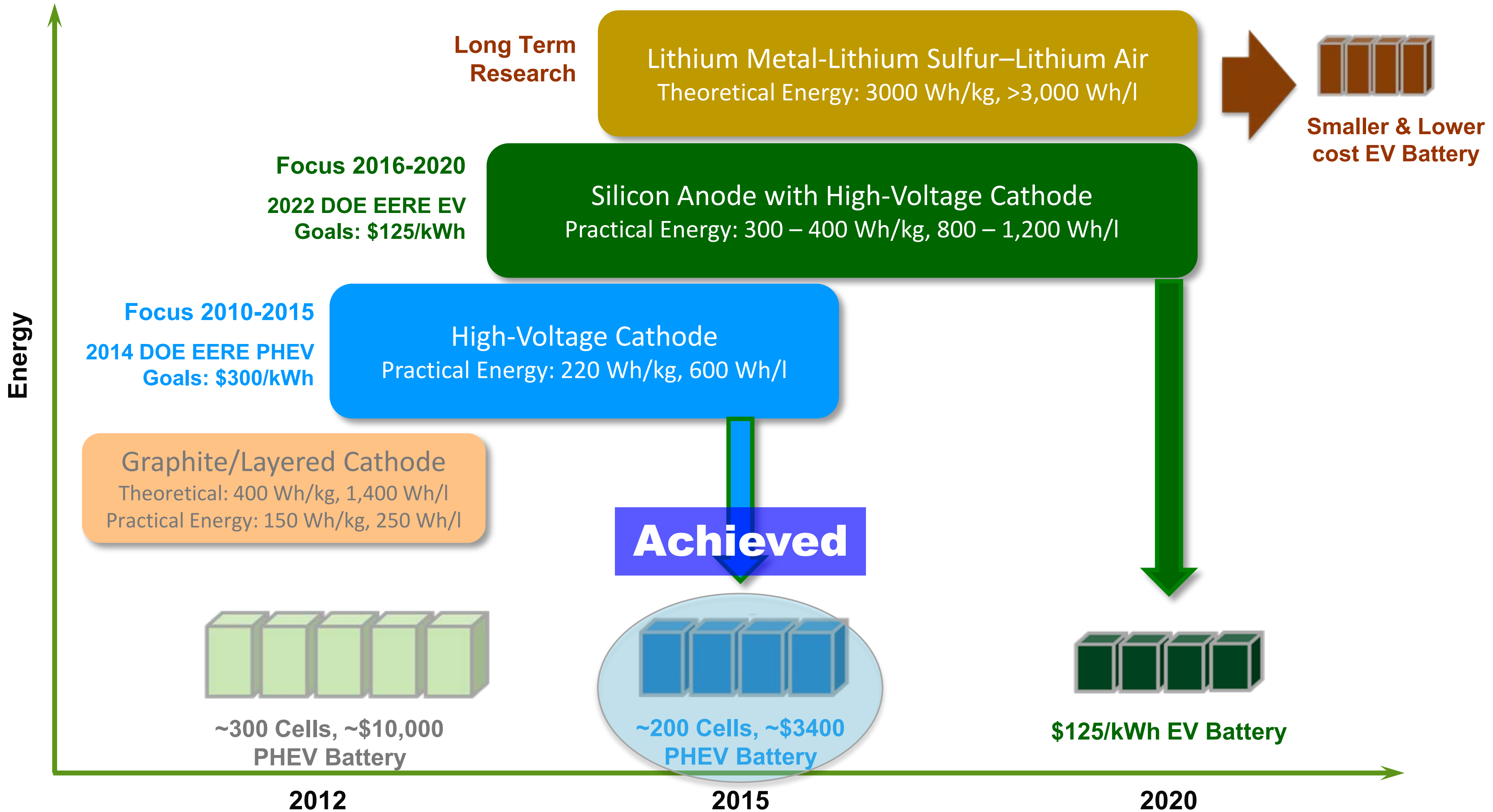
- Extensive cost modeling has been conducted on advanced battery chemistries using the ANL BatPaC model.
  - **Lithium-ion:** silicon anode coupled with a high capacity cathode presents moderate risk pathway to less than $125/kWh_{use}$
  - **Lithium metal:** a higher risk pathway to below $\$100/kWh_{use}$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

## Projected Cost for a $100/kWh Battery Pack



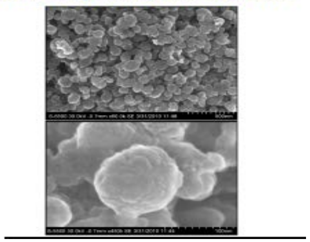
# Research Roadmap for 2015 & Beyond

**Current emphasis:** The development of high voltage cathodes and electrolytes coupled with high capacity metal alloy anodes. Research to enable lithium metal-Li sulfur systems.



# Strategy: Integrated Portfolio

*Advanced Materials Research*

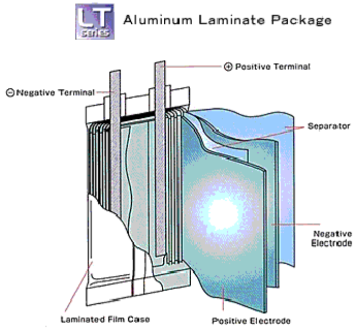



- ❑ High energy cathodes.
- ❑ Alloy, lithium metal anodes.
- ❑ High voltage electrolytes.
- ❑ Solid State.

**Cell Materials Targets**

- ❑ Anode capacity >1,000mAh/g.
- ❑ Cathode capacity >300mAh/g.
- ❑ High-voltage cathodes & electrolytes stable up to 5 V.
- ❑ Solid-polymer electrolytes with $>10^{-3}$ S/cm ionic conductivity.

High Energy & Power Cell R&D




- ❑ High energy couples.
- ❑ High energy and rate electrodes.
- ❑ Fabrication of high E cells.
- ❑ Cell diagnostics.
- ❑ Improved manufacturing processes.

**Cell Targets**

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

Full System Development & Testing

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

**Battery Pack Targets**

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

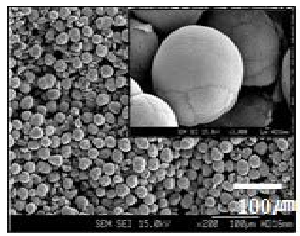
# Advanced Cathode Materials Highlights

**Knowledge Benefit Analysis concluded significant link between DOE-funded R&D and the most prominent EDV battery technology**

- 108 patent families from 1992-2012.
- VTO ranks first among top companies based on average citations by the top companies.
- 2,337 publications and presentations since 2000.

**Materials R&D**
Lithium-rich NMC
1999-2015

Argonne NATIONAL LABORATORY



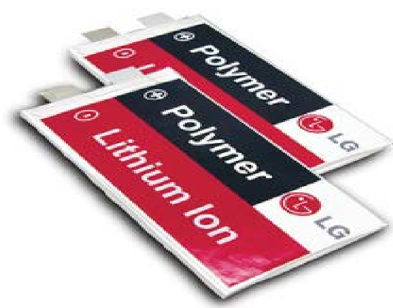
**License of Cathode IP**

BASF
TODA AMERICA
LG Chem
GM
envia

***VTO FOAs***
**Material Scale Up and Lower Cost Processing 2007-2013**

USABC UNITED STATES ADVANCED BATTERY CONSORTIUM
LG Chem

**Electrochemistry Optimization & Cell Development**
Lithium-ion Polymer, Mixed Mn/NMC–Carbon, USABC (2005 -2014)

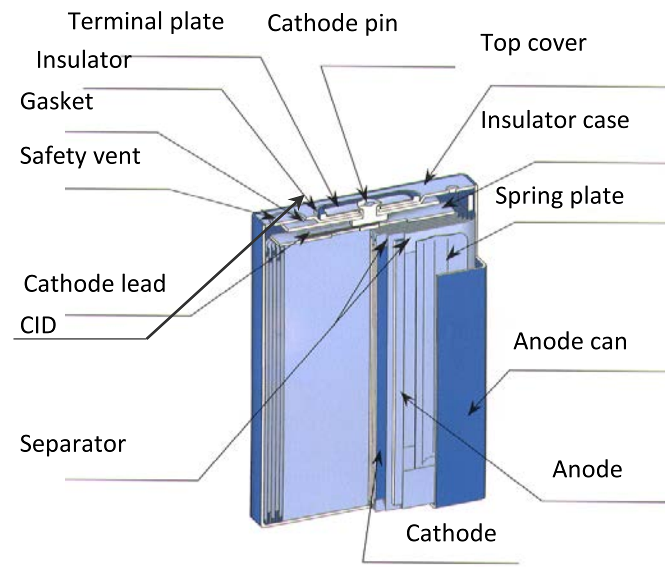


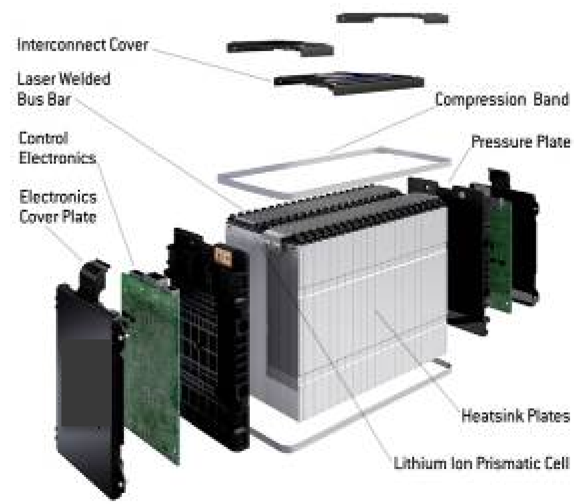

**Commercialization**

# Battery Development Progress and Plans

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM

- **Battery Performance Targets**
  - Vehicle/Battery Performance Modeling and Simulation.
  - Hardware-in-the-Loop Testing.
- **Battery Testing Protocols based on different EDV architectures**
- **Battery Cell/Pack Development**
  - Material Specifications and Synthesis.
  - Electrode Design, Formulation and Coating.
  - Cell Design/Fabrication.
  - Module & Pack Design/Fabrication.
  - Battery Control & Safety Devices.
  - Detailed Cost Modeling.




*(Used with permission)*

# EV Battery Performance Status

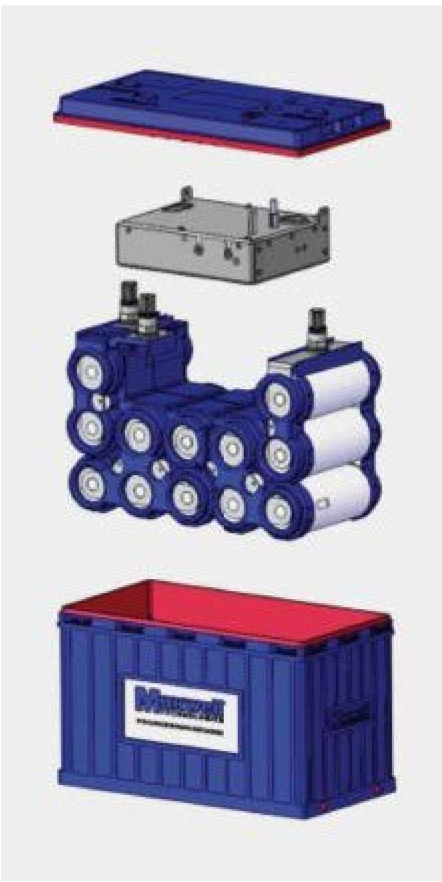
| Energy Storage Goals | AEV (2020) | Current | 2012 EV Battery |
| --- | --- | --- | --- |
| Equivalent Electric Range, miles | 200 (45 kWh) | ✓ | |
| Discharge Pulse Power (10 sec), kW | 120 | ✓ | |
| Regenerative Pulse Power (10 sec), kW | 40 | ✓ | |
| Recharge Rate, kW | 1.20 | ✓ | |
| Calendar Life, years | 15 | tbd | tbd |
| Cycle Life, cycles | 1,000 deep cycles | 500-600 | 200 |
| System Weight, kg | 190 | 200-280 | 500 |
| System Volume, liters | 90 | 90-140 | 200 |
| Production Cost at 100,000 units/year | $125/kWh | < $268 | $600 |

- Focus on high voltage/high capacity cathodes, Si based anodes.
- Data from USABC contracts.
- Cost projection by using the BatPaC model.

# Progress and Results: *Maxwell Ultracapacitors*

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM

## Maxwell Ultracapacitor-based Engine Start Module (ESM)



**Plastic Lid**
Thermal weld (heat plate) to case

**Electronics Assembly**
DC-DC converter and controller electronics

**Laser-welded Cell Pack**
(A dozen Maxwell ultracapacitor cells, 3,000F each) with plastic spacers and terminals

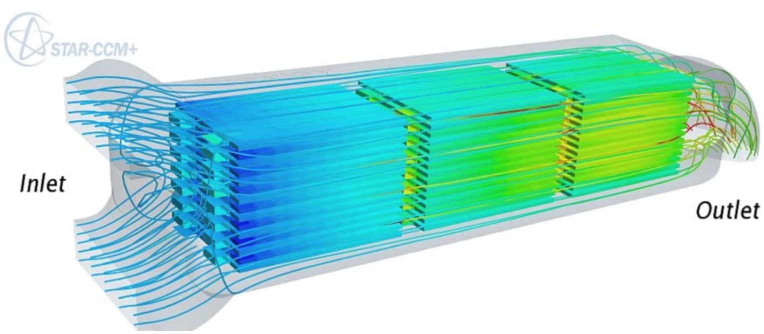
**Polypropylene Plastic Case**

## Maxwell Ultracap-ESM offered as a factory-installed Option

- In 2013, Kenworth was the first OEM to offer the Maxwell ultracapacitor-based engine start module (ESM) as a factory-installed option on new Kenworth T680 and T880 trucks.
- Accessories (e.g., lights, lift-gates) can be used without being concerned about insufficient power.
- ESM can crank truck engines over a temperature range of -40°F to +149°F.
- In September 2015, GM announced that it would use Maxwell Technology's ultracapacitors in its voltage stabilization system.

# Battery R&D Highlights: Computer-Aided Engineering for Batteries

- ❑ Computer-aided Battery Energy Tools (CAEBAT).
- ❑ 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.

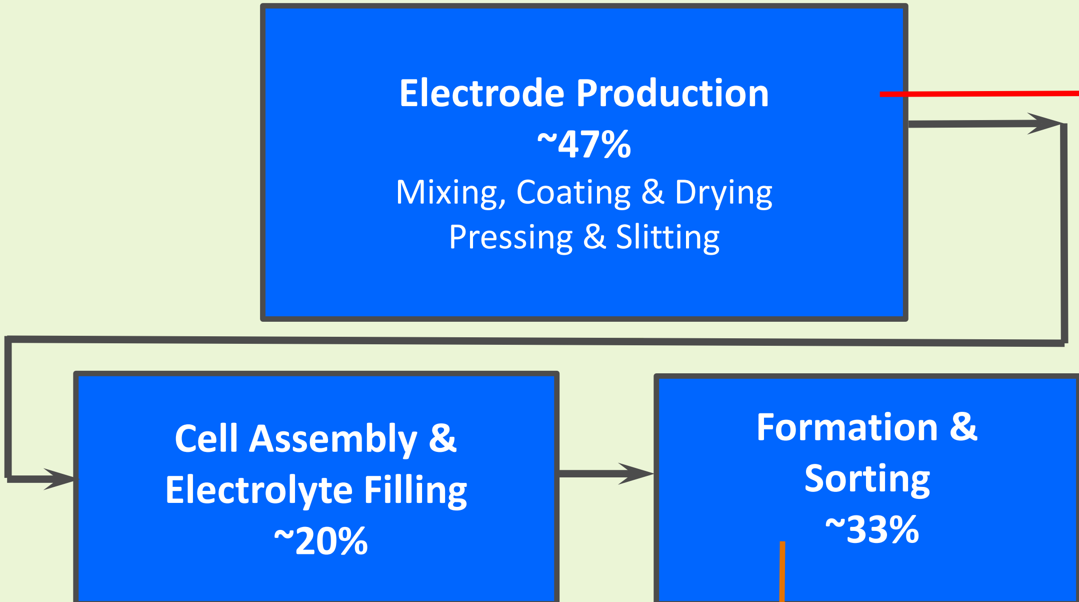
- ❑ GM and partners have developed a flexible and efficient 3-D battery modeling tool based on the Fluent multi-physics simulation platform.
- ❑ CD-adapco and partners have developed electrochemical-thermal module for the Star-CCM+ multi-physics simulation platform.
- ❑ EC Power and partners developed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

The 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 them to consider battery design for better performance, life, and thermal response characteristics.

# Advanced Processing Progress and Plans

## Electrode manufacturing and cell fabrication are 30-45% of battery cost.

**The cell production line comprises a number of discrete unit operations – *process* steps in fabricating the cell from its component *materials*.**




### Breakthroughs Needed

- ❑ NMP solvent substitute;
- ❑ Dry processing;
- ❑ Fast curing binders;
- ❑ High-speed deposition;
- ❑ UV, Microwave, or IR flash lamp drying;
- ❑ Ultrahigh packing density; and
- ❑ *In situ* separator coatings

Currently a 3-6 week process that assures performance, life, & safety of a cell

### Breakthroughs  Needed

- ❑ Form SEI layer during material mixing or electrode processing.
- ❑ High speed In-Situ NDI techniques to detect flaws & internal shorts.

# ANL Advanced Processing and Battery Materials Accomplishments

- Argonne's Materials Engineering Research Facility (MERF) facilities were established to scale up promising exploratory materials and help expedite the transfer of advanced battery materials from the lab bench to industry.
  - In 2015, Strem Chemicals, licensed 23 pieces of intellectual property from Argonne and will distribute nine battery solvents and redox shuttles.
  - In 2016, Aldrich licensed 10 pieces of intellectual property from Argonne and will distribute one redox shuttle and two electrolyte solvents.
- Argonne will be providing Aldrich and Strem technology transfer packages that detail:
  - the exact material specifications; and
  - economical materials synthesis and process validation procedures.


The MERF produces kg level quantities of new battery materials using scalable manufacturing processes to enable testing in industrially relevant sized cells and faster adoption by industry.

# New Advanced Processing Technology Awards

| | |
|---|---|
| 24M | Semi-solid Li ion - simpler cell construction. |
| LAMBDA TECHNOLOGIES | Microwave electrode drying |
| MILTEC | UV electrode drying |
| parc A Xerox Company | Novel electrode structure with both high energy and power regions |
| PPG | Electrolytic electrode deposition process |
| NAVITAS SYSTEMS | Nano composite Si manufacturing process |
| VANDERBILT | Novel Processing of Electrospun Silicon Anodes |

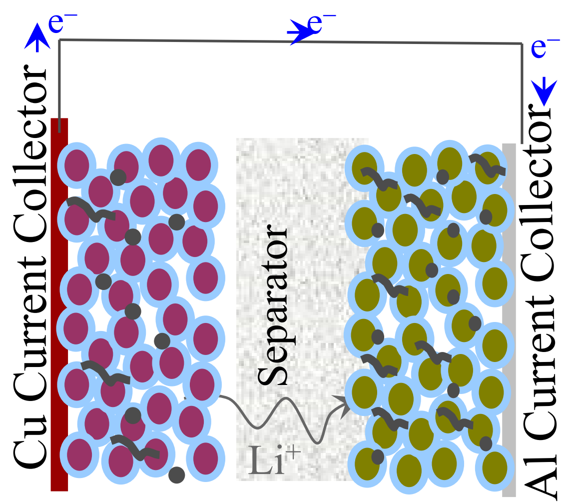
# Advanced Battery Materials Progress and Plans

**Anodes** — 100% Increase

**Today's Technology**
600 mAh/g vs 300 (2012)

**Next Generation**
1,000$^{+}$ mAh/g

*Intermetallic Composites*




**Electrolytes** — 0.3 V Increase

**Today's Tech**
<4.3V vs <4.0V (2012)

**Next Generation**
4.6-5.0 volts

**Cathodes** — 80% Increase

**Today's Technology**
200 mAh/g vs 120 (2012)

**Next Generation**
300 mAh/g

*High Voltage Layered Oxides (Ni & Mn rich)*

# Advanced Cathode Materials Progress

**Layered-Layered Cathode Voltage Fade Project**

2011-2015

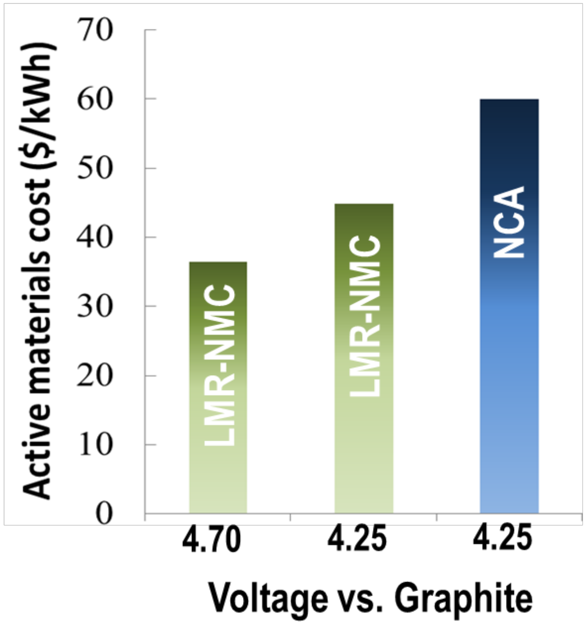
Multi-Lab/Multi-Disciplined Team

6 Labs

~$5M per year

- ❑ Four-year project to understand and mitigate Voltage Fade in lithium rich, manganese rich cathodes.
- ❑ Target: 4.7 V, achieved 4.35 V (200 mAh/g)
- ❑ A “No Go” decision was reached.

**LMR-NMC @ 4.3 volts a good option**




*Source: ANL*

LMR-NMC, with no voltage fade, has the same energy density as NCA but is less expensive.

Argonne National Laboratory | Oak Ridge National Laboratory | Brookhaven National Laboratory | Berkeley Lab | NREL National Renewable Energy Laboratory | JPL Jet Propulsion Laboratory California Institute of Technology

# Advanced Cathode Materials Plans

**High Energy/ High Voltage Cathode Project**

2015-TBD

Multi-Lab/Multi-Disciplined Team

6 Labs

$4M per year

- Enable the use of cathode materials at >4.4 V.
- Target: 4.7-5.0 V (300 mAh/g)
- Focus: Layered Cathodes
- Thrusts include electrolytes and additives; surfaces and interfaces; cell testing and analysis; theory and modeling.
- Key team members include:

Argonne National Laboratory

Oak Ridge National Laboratory

Berkeley Lab

NREL National Renewable Energy Laboratory

- Additional universities and companies working on HV/HE Cathodes

ENVIA Systems

TIAX

LG Chem Power Inc.

Penn State

The University of Texas at Austin

# Advanced Anode Materials Progress

## Anodes

**Today's Technology**

600 mAh/g vs 300

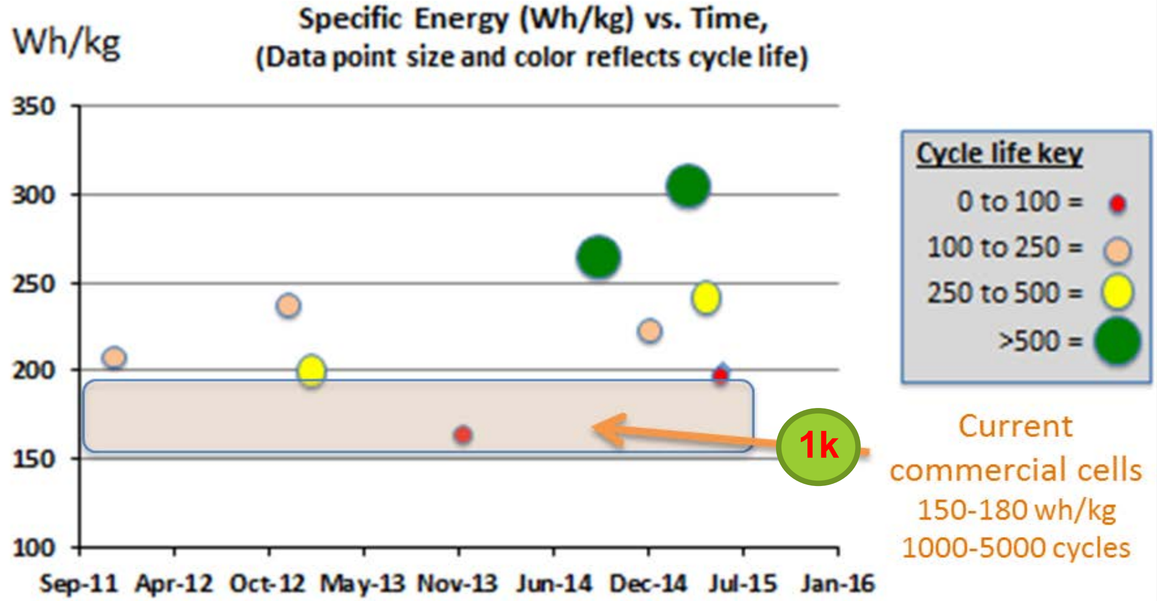
(2012)

**Challenges:**

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

**Wh/kg and Cycle Life of Si-based Cell Deliverables from 7 DOE Funded Developers**

*Improvements in Energy and Cycle Life Continue*




- Additional universities and companies working on advanced anodes

# Advanced Anode Materials Plans

**Silicon Anode Deep Dive Project**

2016-TBD

Multi-Lab/Multi-Disciplined Team

5 Labs

$5M per year

- Enable the use of intermetallic silicon composite anodes
- Target: 1,000$^{+}$ mAh/g and 1,000 EV Cycles
- Focus is on:
  - Improving alloy material characteristics.
  - Development of more durable material binders.
  - Investigation surface modifications and advanced coatings.
- Key team members include:

Argonne NATIONAL LABORATORY | OAK RIDGE National Laboratory | BERKELEY LAB | NREL NATIONAL RENEWABLE ENERGY LABORATORY | Sandia National Laboratories

# Advanced Electrolyte Materials Progress

**Electrolytes**

**Today's Tech**
<4.3 V vs <4.0 V (2012)

**Next Generation**
4.6-5.0 volts

- As part of improving the life and performance of cells containing high energy and high voltage cathodes and intermetallic anodes, DOE is funding a number of projects to develop novel and improved electrolytes.
- National labs, universities and companies working on these include:

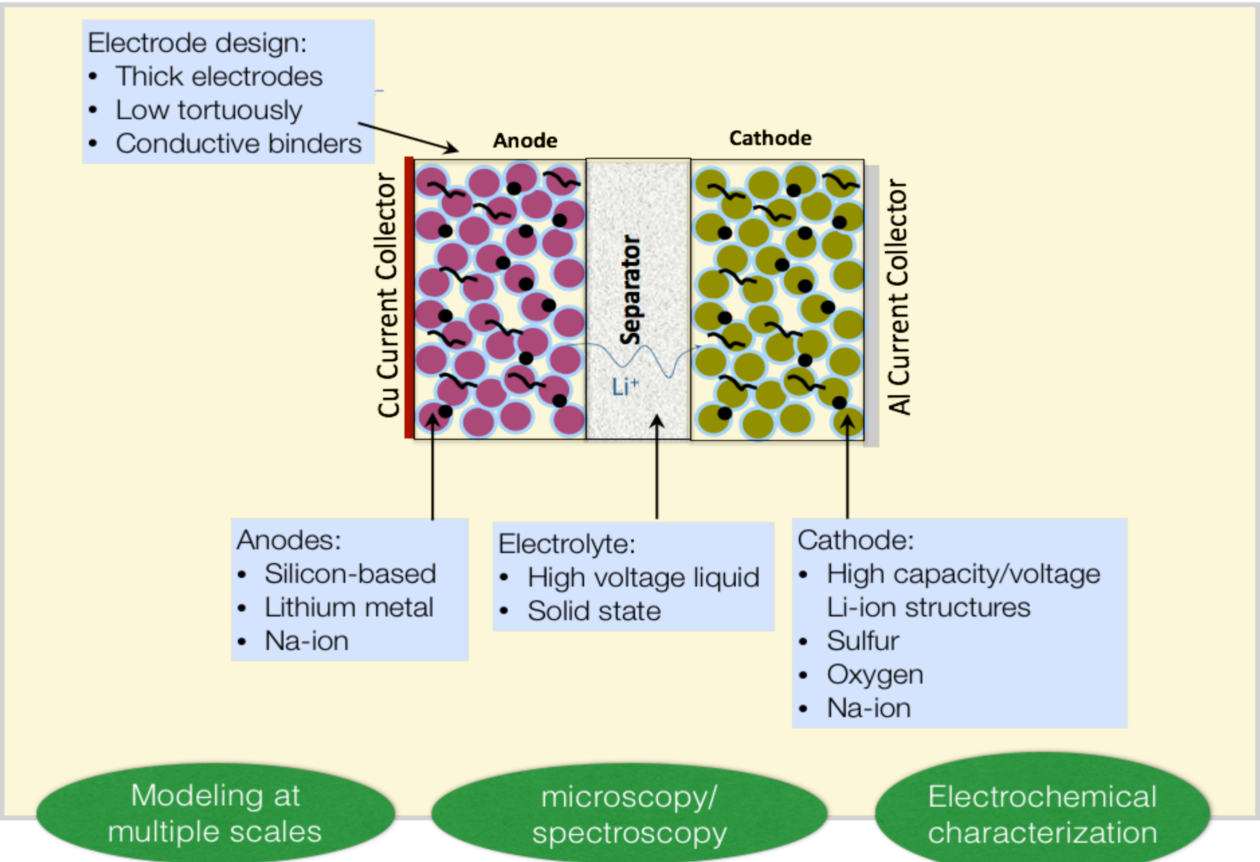
DAIKIN
Silatronix
NOHMs TECHNOLOGIES
soulbrain MI
THE UNIVERSITY OF RHODE ISLAND
Wildcat Discovery Technologies
COORSTEK Amazing Solutions
FARASIS
Argonne NATIONAL LABORATORY
ARL
Sandia National Laboratories

# Advanced Battery Materials Research (BMR)

**BMR Objective:** Address the fundamental problems of electrode chemical and mechanical instabilities that have slowed the development of affordable, high performance automotive batteries.

**Key Activities:**

(1) Understand the limitations in the electrode; and
(2) Modify material/electrode to overcome limitations.




- ❑ 53 projects
- ❑ 14 universities
- ❑ 5 industry members
- ❑ 6 national labs

# Beyond Lithium Ion Research

## Solid State Electrolytes

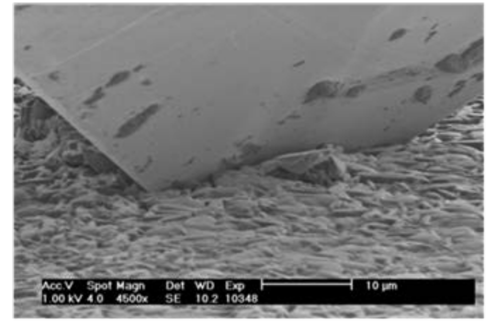
- LLZO garnet solid state electrolyte (U Michigan: Prof. Jeff Sakamoto).
- LLZO garnet interface study (U Maryland: Prof. Eric Wachsman).
- Nanoindentation of LLZO/Li interface (ORNL: Dr. Nancy Dudney).

## Lithium Sulfur

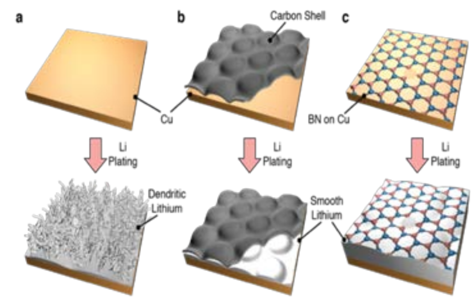
- Li/S laminated and doped cells to improve inherently low S conductivity and minimize S/electrolyte contact (U Pittsburgh: Prof Prashant Kumta).
- Dual Functional Cathode Additives will: (1) improve cathode electronic conductivity; (2) provide Li; and (3) reduce polysulfide dissolution. (BNL: Dr. Hong Gan).
- Modeling and synthesis of Sulfur cathodes (Texas A&M: Prof. Perla Balbuena).

## Lithium metal

- Lithium anode protection through nano-engineering (Stanford U: Prof. Yi Cui).




Polymer electrolyte indented in SEM



# SBIR and STTR Programs: 2012-Present

## Since 2012, VTO has supported 28 SBIR/STTR Advanced Battery Research Projects

Phase I programs ($150,000, 9-month) SBIR projects addressed the following areas:

- Solid State Batteries
- Li-Sulfur
- Supercapacitors
- Lead Acid Batteries
- Novel Thermal Management Systems
- Novel Manufacturing Techniques
- Novel Electrode Structures
- Advanced Battery Management Solutions
- High Temperature Stability Silicon Anodes
- Advanced Cathodes
- Li-ion Battery Recycling

Seven Phase II projects ($1M, 2 year) focused on:

- Improving Li-ion battery recycling processes
- Metrology equipment for Li-ion battery manufacturing
- Silicon anode material and electrode improvements
- Coating materials to improve high voltage stability
- Novel electrode structures to reduce battery cost

### Phase I Recipients

Axion Power International Inc., Creare, Farasis, Hybrid Plastics, TDA Research, ETP, Excellatron, Motiv, TIAX, Leyden energy, ASi, Giner, Ballast energy, American Lithium Energy, Bettergy, Novarials, pH Matter LLC, Sillion, HICO Tech

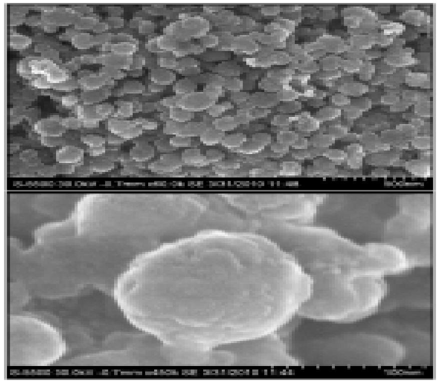
### Phase I & II Recipients

OnTo, Applied Spectra, PneumatiCoat Technologies, XG Sciences, Navitas Systems, SiNode Systems, Physical Sciences Inc.

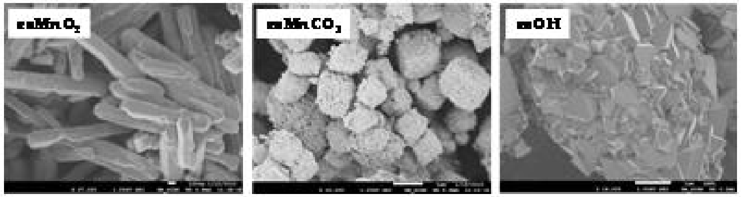
| Year | Company | Funding |
|---|---|---|
| 2012-2015 | OnTo Technologies | $1,000,000 |
| 2012-2015 | Applied Spectra | $1,150,000 |
| 2013-2016 | Sinode | $1,150,000 |
| 2013-2016 | XG Sciences | $1,150,000 |
| 2013-2016 | Navitas | $1,150,000 |
| 2013-2016 | Pneumaticoat | $1,150,000 |
| 2014-2017 | Physical Sciences | $1,150,000 |

# Summary

- ❑ Track record of success.
  - – American based battery factories supplying PEV batteries to multiple PEVs.
  - – Cost goals met or on track to be met.
- ❑ Clear pathway to meet 2022 goals.
  - – Major focus on advanced Lithium ion using higher voltage cathodes & intermetallic anodes.
  - – Expanded work on low cost materials, electrode and cell manufacturing.
- ❑ Technologies to go Beyond 2022
  - – Continued focus on Li-metal and solid state batteries.
  - – Closely coordinated with ARPA-E and the Office of Science.



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