US Department of Energy Vehicle Battery R&D:

Current Scope and Future Directions

October 21, 2011

- David Howell (EERE/VTP)
- Pat Davis (EERE/VTP)
- David Danielson (ARPA E)
- Linda Horton (BES)
- John Vetrano (BES)

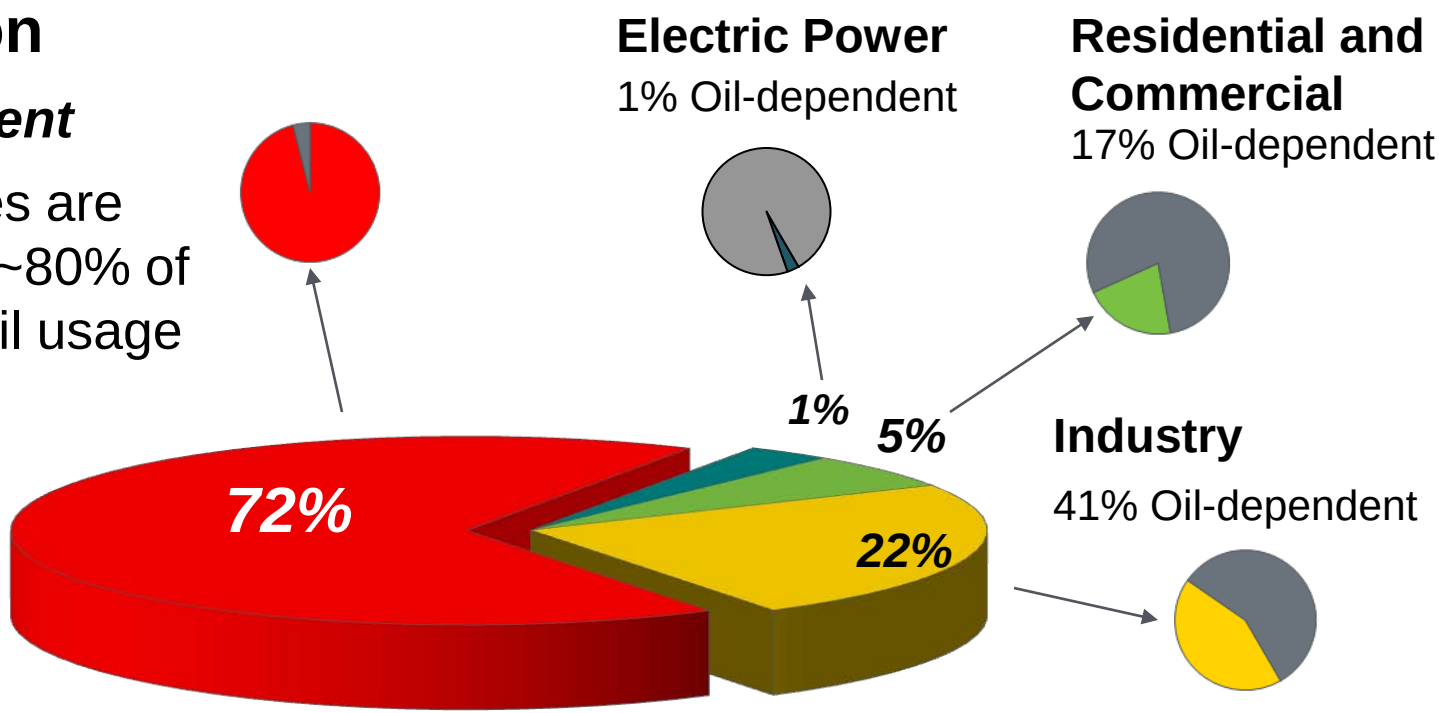
U.S. Oil-dependence is Driven by Transportation

U.S. Oil Consumption by End-use Sector
19.1 Million Barrels per Day (2010)

Transportation

94% Oil-dependent

- On-road vehicles are responsible for ~80% of transportation oil usage



Source: *DOE/EIA Annual Energy Review*, April 2010

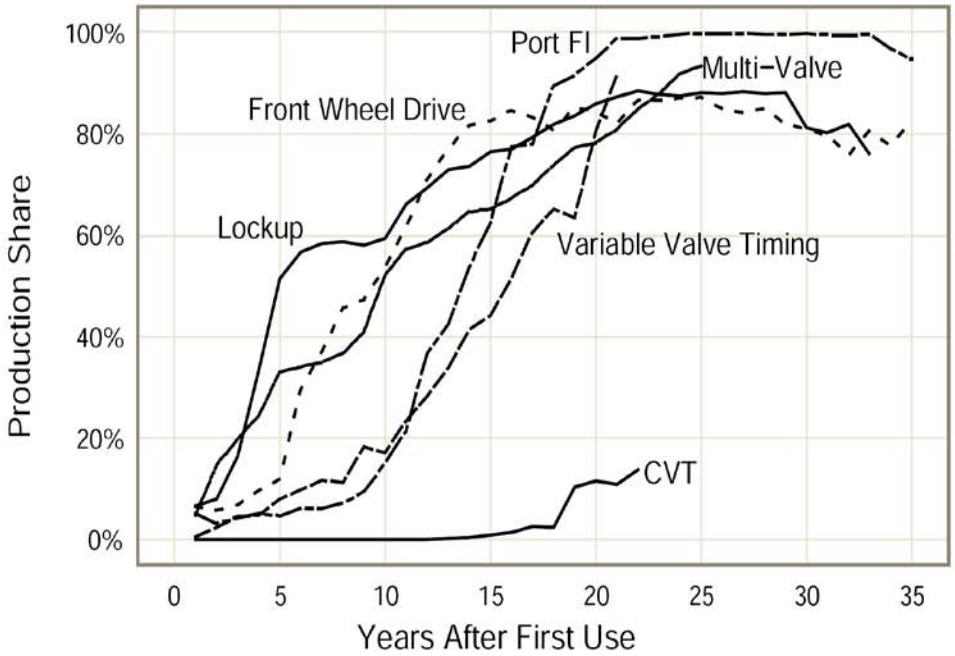
Realizing Benefits of a Vehicle Technology Takes Time

U.S. Vehicle Market

- About 240 million light-duty vehicles on the road
- Approximately 12 million new cars and light trucks sold in 2010
- *It has often taken about 15 – 20 years for a technology to reach maximum market penetration.*

Vehicle Technology Penetration

Years After Initial Significant Use



Light-Duty Automotive Technology and Fuel Economy Trends: 1975 Through 2010, EPA420-R-10-023, November 2010, p. 69

Vehicle Electrification and Benefits

Vehicle Types and Benefits

HEV

Toyota Prius → ~50 MPG

- 1 kWh battery
- Battery Power Rating: 25kW
- Battery Cost: about $1,200

PHEV

Chevy Volt → ~100 MPGe

- 16 kWh battery
- Battery Power Rating: 120kW
- Battery Cost: about $10,000

EV

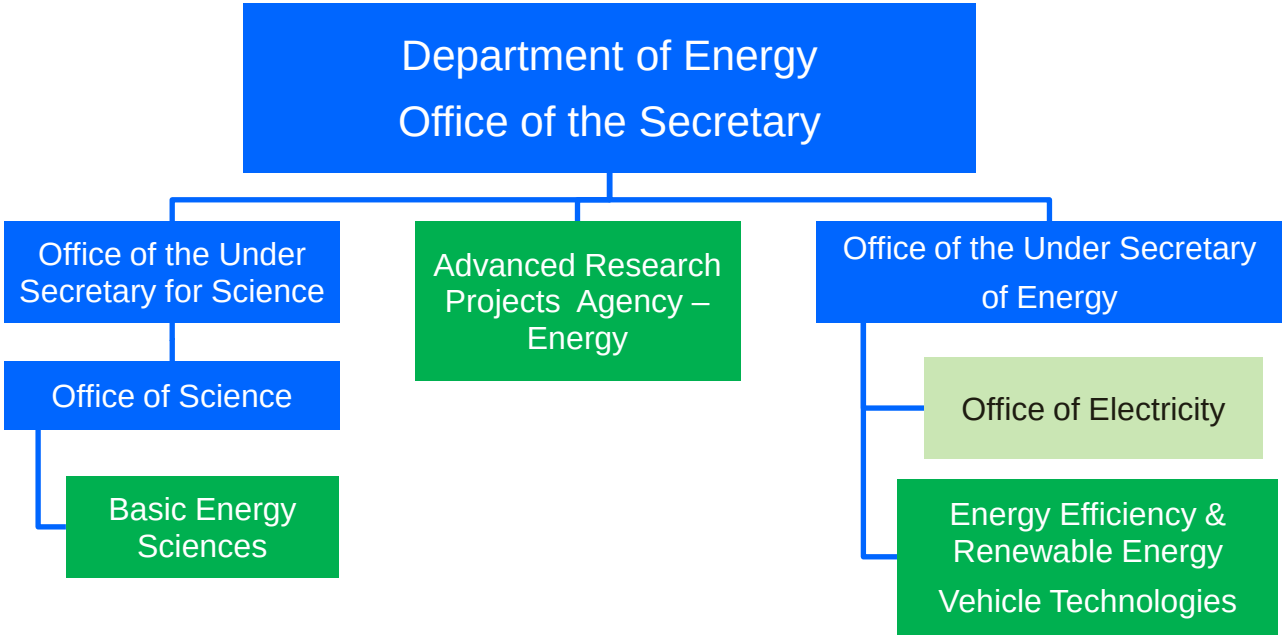
Nissan Leaf → All Electric

- ≥ 24 kWh battery
- Battery Power Rating: ≥ 110kW
- Battery Cost: about $15,000

Achieving large national benefits depends on significant market penetration.

Battery affordability and performance are the keys.

Energy Storage R&D at DOE

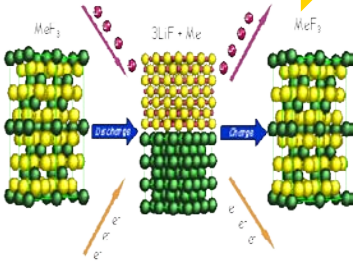


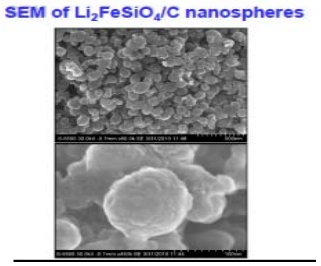
- **Office of Science/Basic Energy Sciences (BES):** Fundamental research to understand, predict, and control matter and energy at electronic, atomic, and molecular levels.
- **Advanced Research Projects Agency – Energy (ARPA–E):** High-risk transformational research with potential for significant commercial impact.
- **EERE Vehicle Technologies (VTP):** Applied battery R&D to enable a large market penetration of electric vehicles.

Moving Battery Technology Forward

Technology Readiness Level (TRL)

0/1	2, 3, 4		5/6
Basic Materials Science	*Advanced Materials* Research	High Energy & High Power Cell R&D	Full System Development &Testing





- structure
- interfaces
- phenomenon

- cathodes
- anodes
- electrolytes

- Electrochemical couples
- Electrodes
- Battery cells

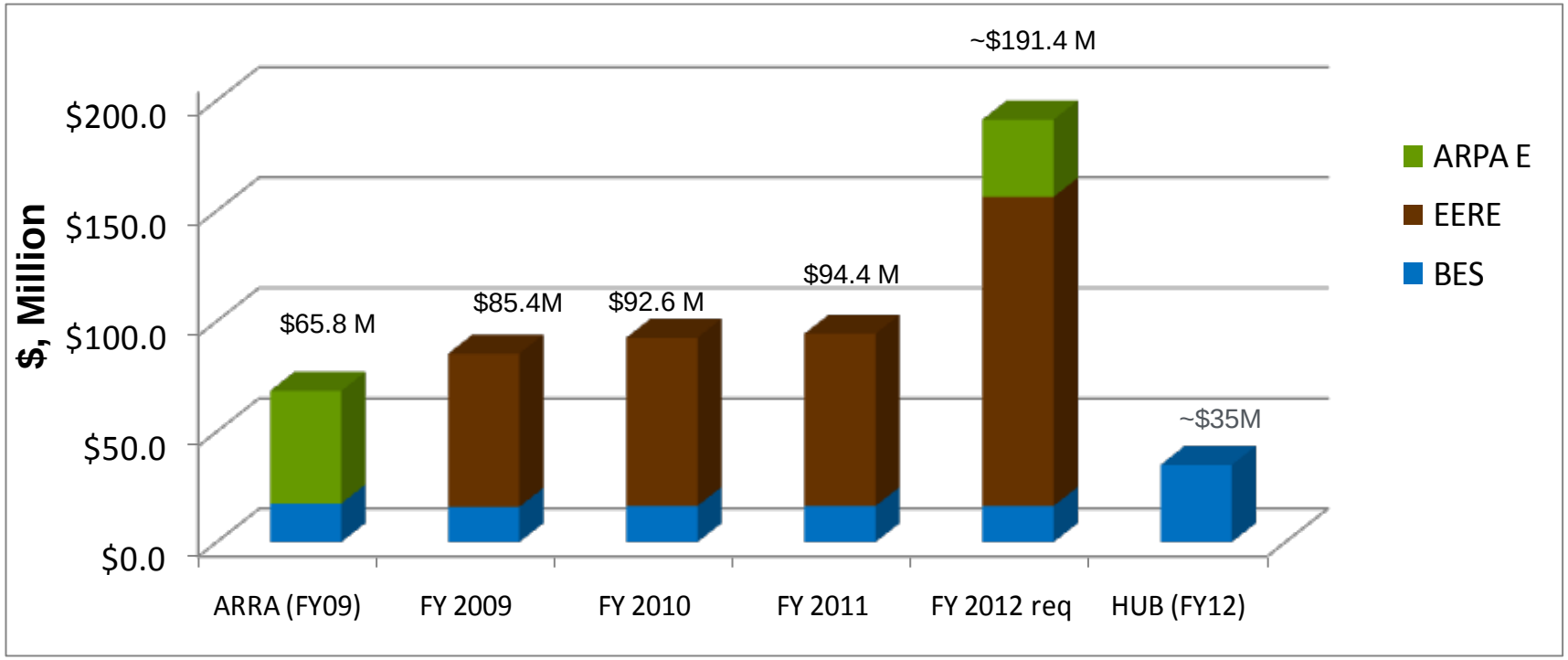
- Electric Drive Vehicle batteries
- Testing, analysis, and design
- Cost reduction

BES

ARPA E

Vehicle Technologies Program

Energy Storage R&D: Transportation Battery Funding



This chart does not include ARRA funding for advanced battery manufacturing ($1.5 B) or demonstrations ($400 M for transportation and $185 M for grid-scale).

DOE Integrated Tech Team
Over-Arching Battery Goal

U.S. DEPARTMENT OF ENERGY

1 penny a mile

"Winning the Race for a Better Battery"

- 1 penny/mile = battery cost / total electric miles driven
  - Addresses consumers' concerns about battery life and cost

- Cost per mile varies based on vehicle architecture/battery size
  - A 150,000 mile PHEV40 battery (~12kWh) will cost 1 penny/mile or $1,500
  - A 150,000 mile EV100 battery (~24kWh) will cost 2 pennies/mile or $3,000
  - A 150,000 mile EV300 battery (~60kWh) will cost 5 pennies/mile or $7,500
    - Note: The cost for each of these batteries is $125/kWh

This goal assures consumers and the auto industry that DOE is driving research to develop **affordable**, long lived EV batteries for mass market adoption.

Fast Charge Goal

- 10 miles per minute fast charge
  - Addresses consumers' concerns about vehicle range and charge time

- Total charge time* varies based on vehicle architecture/battery size
  - A PHEV40 battery (~12kWh) completely recharged in 4 minutes
  - A EV100 battery (~24kWh) completely recharged in 10 minutes
  - A EV300 battery (~60kWh) completely recharged in 30 minutes

*Note: Using a nominal 120-180 kW charger

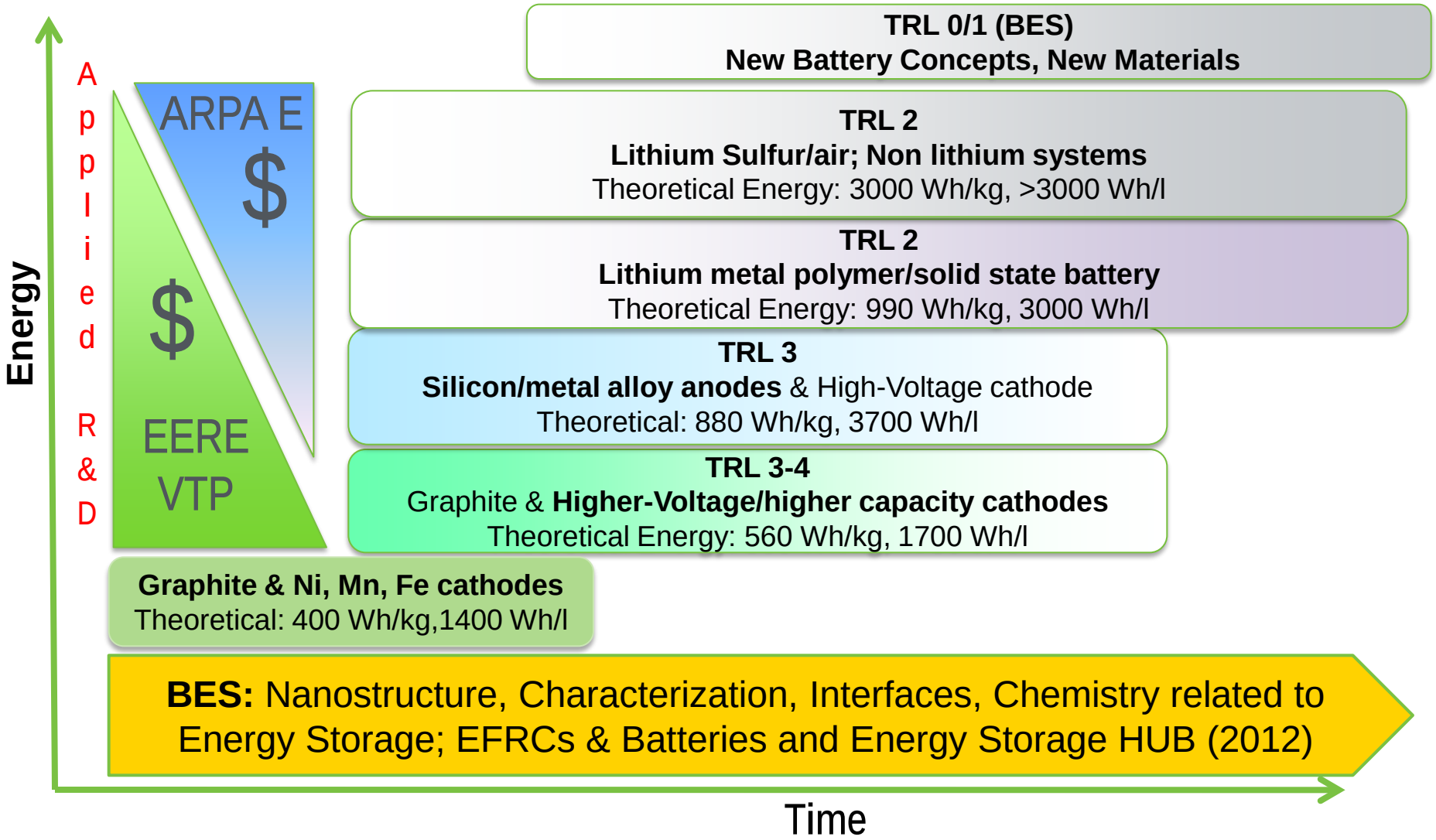
This goal assures that DOE is driving EV battery research which would alleviate consumers' range anxiety, a major barrier to widespread commercial adoption of electric vehicles.

DOE Integrated Tech Team
Over-Arching Battery Goal

- Safe
  - Meet/exceed FMVSS and SAE–J2929 Battery Safety Standard
  - Assure consumer confidence
- Constructed of earth abundant materials
  - Required for low cost
  - Eliminate foreign material resource dependence
- Recyclable
  - Environmental stewardship
  - Assure critical material availability and cost

This goal assures that DOE is driving EV battery research for batteries that are safe, eliminate foreign material resource dependence, and are environmentally sustainable.

Current R&D Focus and Associated 2011 Technology Readiness Levels



Current & Future Technologies

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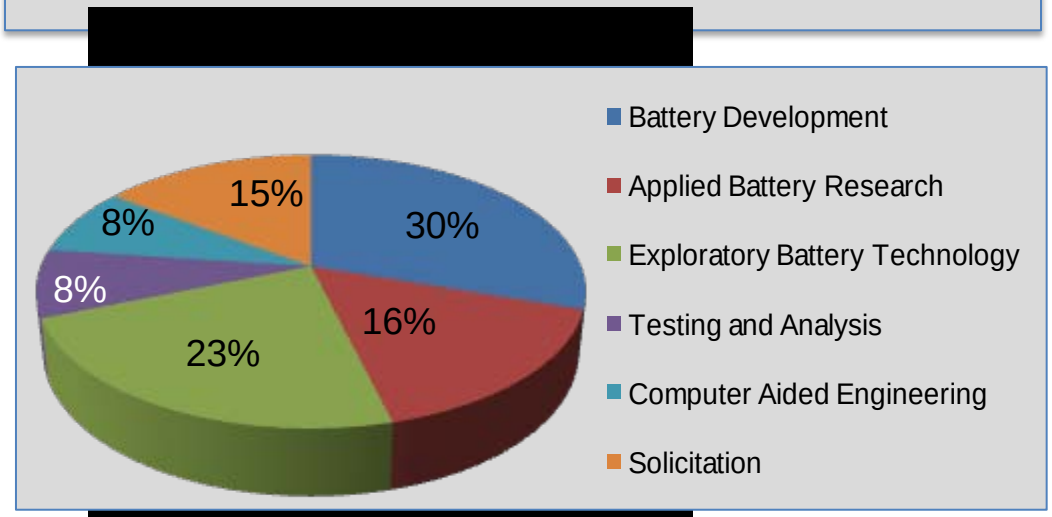
Attributes of Battery Technologies

	Energy (Wh/kg)	Power (W/kg)	Life (cycles)	Energy Efficiency	Safety
Lithium-ion (current status)	80	500-1000	>3,000	> 90%	Meets SAE J2929
Lithium-ion (future generations)	200+	2,000	>3,000	> 90%	Meet SAE J2929
Lithium metal polymer	150-200	500	~1000	85%	Concern
Lithium metal / Sulfur	250-400	750	~100	85%	Concern
Lithium metal / Air	400-800	Poor	~10	<70%	Concern
DOE 2020 Goals	250	2,000	500-3,750	>90%	Meet SAE J2929

VTP-funded Battery R&D

Program targets focus on enabling market success (increase performance at lower cost while meeting weight, volume, and safety targets.)

FY2011 Budget: $83M



2014 GOAL: Reduce the production cost of a PHEV battery to $300/kWh (70% below 2008 value)

2020 GOAL: Reduce the production cost of a PHEV battery to $125/kWh

VTP Battery R&D Targets

Full System Development &Testing

Battery Pack Targets

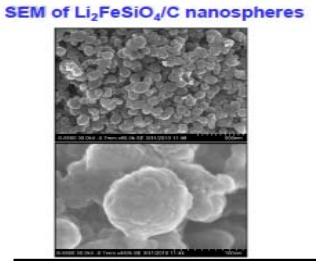
- ❑ EV $125/kWh
- ❑ PHEV40 $300/kWh
- ❑ PHEV10 $300/kWh
- ❑ HEV $20-25/KW

High Energy & High Power Cell R&D

Cell Targets

- ❑ 250-300 Wh/kg
- ❑ 400-500 Wh/Liter
- ❑ 5,000 cycles
- ❑ 10+ calendar year life
- ❑ $300/kWh pack cost by 2014

Advanced Materials Research

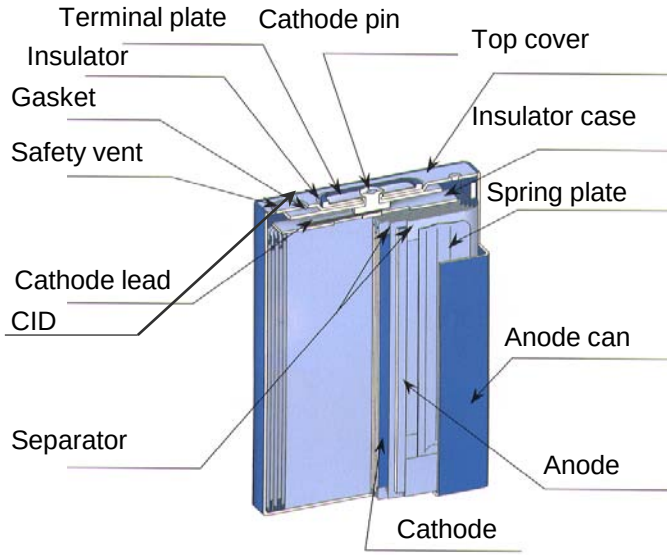


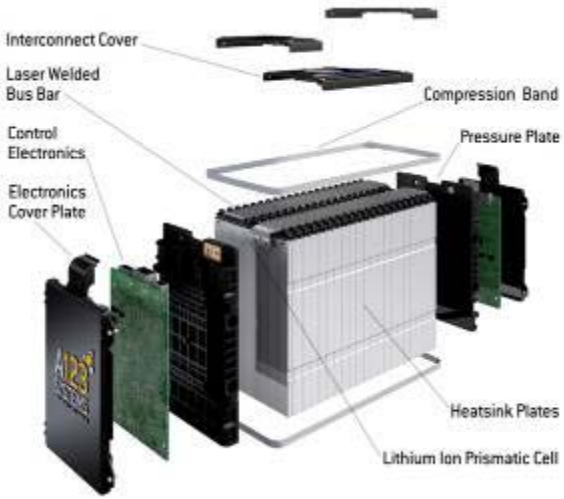
Cell Materials Targets

- ❑ Anode > 500 mAh/g
- ❑ Cathode > 300 mAh/g
- ❑ High-voltage cathodes & electrolytes
- ❑ Solid-polymer electrolytes with > 10^{-3} S/cm ionic conductivity

Full Systems Development

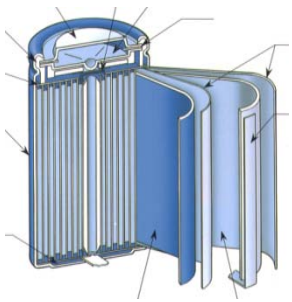
- **Battery Performance Targets**
  - Vehicle/Battery Performance Modeling and Simulation
  - Hardware-In-the-Loop Testing
- **Battery Testing Protocols based on different EDV architectures**
- **Battery Cell /Pack Development**
  - Material Specifications and Synthesis
  - Electrode Design, Formulation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





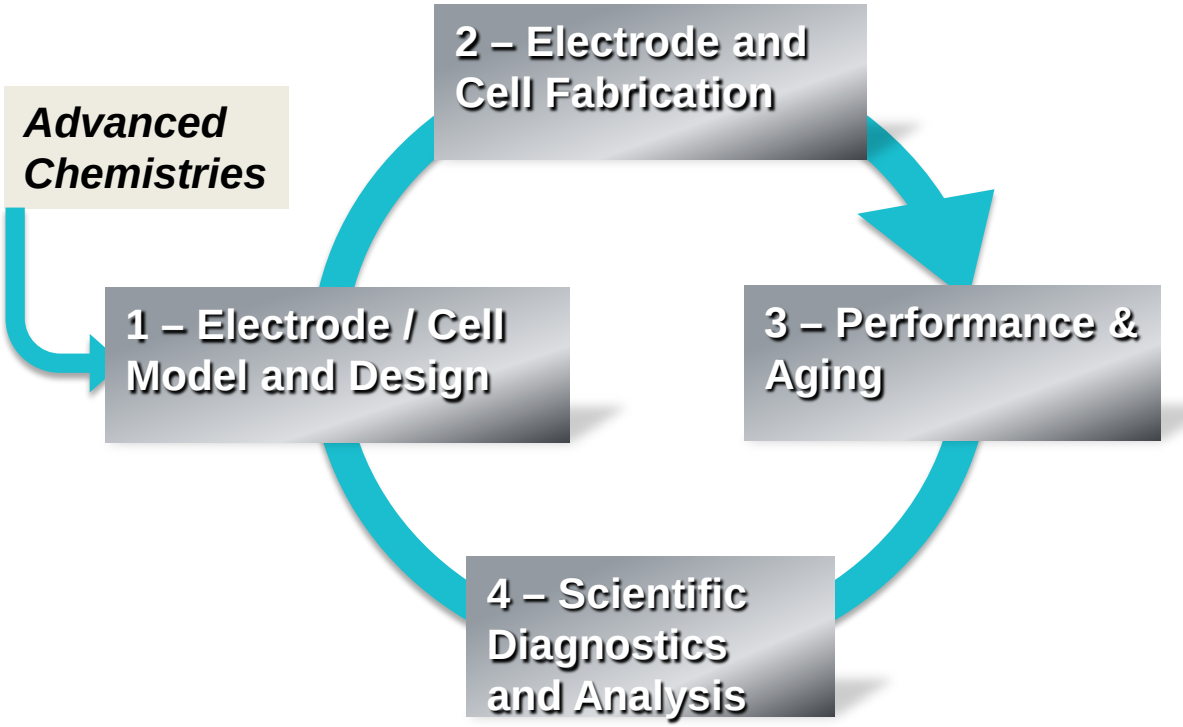
(Used with permission)

High Energy & High Power Cell R&D



Goal: expedite commercialization of advanced materials and electrochemical couples for transportation based lithium-ion batteries

- **Cathode (with graphite anode)**
  - **Layered-Layered**
  - **Lithium rich NMC**
  - **Manganese rich NMC**
- **Advanced Electrolytes and Additives**
  - **High voltage stability**
  - **Safety (overcharge, flammability, thermal stability)**



High Energy & High Power Cell R&D

Various companies were recently awarded ($2-5 M each) to develop advanced Lithium-ion cells and manufacturing processes which would reduce cost

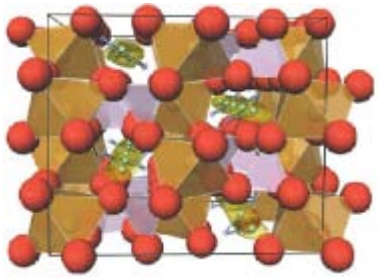
Battery Cells: >300 Wh/kg and >500 Wh/l

Awardee (Location)	Partner	Technology Development
Amprius, Inc.	-	Silicon nanowire anodes / High capacity cathodes
Dow Kokam	Dow Chemical/ORNL	Silicon carbon anode, high-voltage layered-layered cathode
Nanosys, Inc.	LG Chem	Silicon/carbon anodes, high-voltage composite cathode
3M Company	-	Silicon tin anode/high-capacity layered cathode
Applied Materials	LBNL/ORNL	Manufacturing module for metal alloy anodes, high capacity cathodes
Seeo, Inc.	-	Lithium metal anode and a solid polymer electrolyte
Penn. State University	ANL/JCI	Lithium sulfur cells

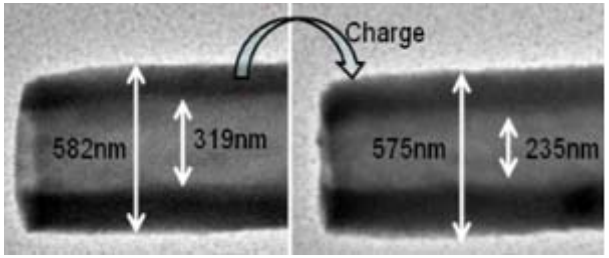
Advanced Materials Research

Perform cutting-edge research on new materials, and address fundamental chemical and mechanical instabilities.

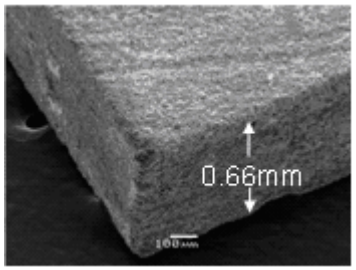
First Principles Material Discovery (Ceder) – Rational design of materials using computational tools



Size & Morphology Control Improves Performance (Cui) – Hollow Si nanotubes show greatly enhanced cycling



Enhanced Processing (Chiang) – 10x thicker electrodes can increase cell energy density by 20%



Advanced Materials Research

U.S. DEPARTMENT OF ENERGY

Next generation lithium-ion can increase the power and energy by 2X while decreasing cost by 70%

Advanced Anodes (600 mAh/g)
- Intermetallics and new binders
- Nanophase metal oxides
- Conductive additives
- Tailored SEI

Advanced cathodes (300+ mAh/g)
- Layered-layered oxides
- High voltage Spinel
- Metal phosphates
- Metal Silicate
- Tailored Surfaces

Next Generation Electrolytes(5 volt)
- High voltage electrolytes
- Solid Polymer
- Electrolytes for Li metal
- Non-flammable electrolytes

Participants

- ❑ National Labs: LBNL, ANL, BNL, NREL, ORNL, PNNL
- ❑ Universities/Industry
  - University of Pittsburgh
  - State University of New York–Binghamton
  - UMASS Boston
  - University of Texas, Austin
  - Arizona State University
  - University of California
  - North Carolina State University
  - University of Rhode Island
  - Case Western Reserve University
  - University of Utah
  - Stanford University
  - Drexel University
  - Massachusetts of Technology
  - University of Michigan
  - Hydro Quebec
  - SWRI

All Projects are Competitively Selected

- Request for Proposals Schedule:
  - Nov. 2008 – New electrolytes
  - Nov. 2009 – New anodes
  - Nov. 2010 – New cathodes

  - Nov. 2011 – Advanced Diagnostics, Modeling and Assembly of Battery Materials and Electrodes
  - Nov. 2012 – Novel Electrolytes and Additives
  - Nov. 2013 – Novel Anode Materials and Structures
  - Nov. 2014 – Novel Cathode Materials and Structures

http://batt.lbl.gov/

Technologies Beyond Lithium-Ion

Li Metal Polymer & Li Sulfur & Li Air – Revolutionary Wh/kg and major cost reductions

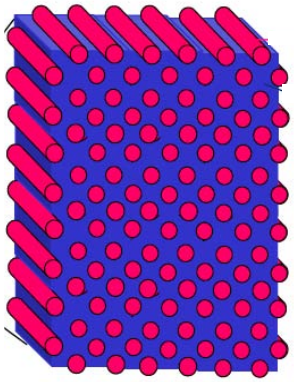
Issues

- Li metal dendrites lead to cell shorting
- Soluble polysulfides leads to self-discharge and poor cycling
- Low efficiency (<70%), need bifunctional catalysts
- Poor power

Projects focused on inhibiting dendrite growth

- *SEEO, LBNL* – Block copolymer electrolyte
- *Planar Technologies* – Glassy electrolytes
- *Sion Power* – Coatings
- LBNL & ANL: collaborative effort to develop new ceramic, polymer, and hybrid structures with high conductivity, low impedance, and structural stability

EERE supports over 11 projects with over $7.5M in funding.



SEEO

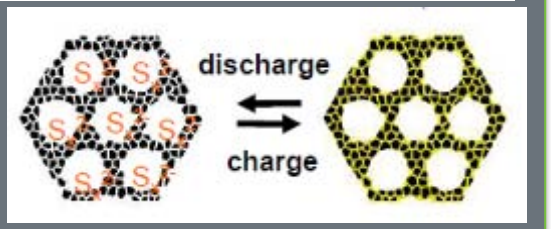
2008 R&D 100

Technologies Beyond Lithium-Ion

Research Projects focused on efficient utilization of sulfur

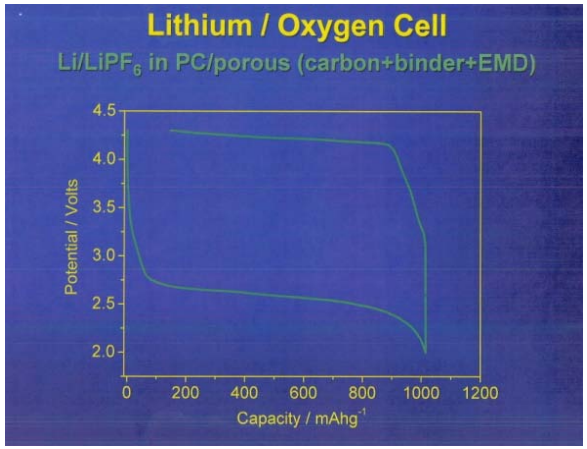
- Sion Power – Dual phase electrolyte to dissolve polysulfides and stabilize Lithium metal.
- ORNL – Mesoporous carbons to confine the polysulfides

ORNL Mesoporous Carbon



Research Projects focused on bifunctional catalyst for oxygen electrode

- BNL, LBNL - New electrolytes for enhanced O_2 solubility, additives to enhance Li-oxide solubility



Source:
Peter G. Bruce, University of St. Andrews, Scotland

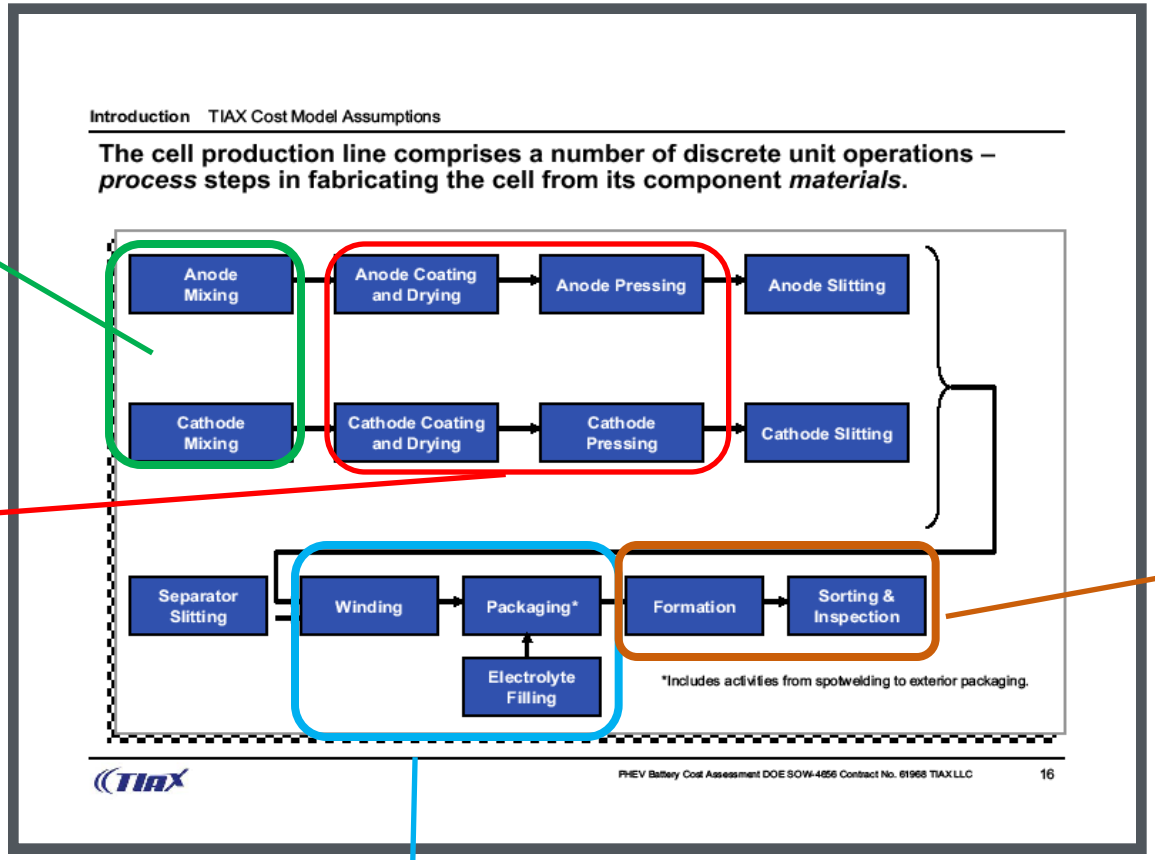
New R&D Thrust: Manufacturing Technology

Electrode manufacturing, cell & pack assembly & hardware are 60-70% of battery cost. Transformational manufacturing technologies are needed.

Breakthrough Needed?
- Low cost material processing/production
- NMP solvent substitute
- Dry processing
- Fast curing binders

Current Process
- Slurry coating, thermal drying, electrode pressing

Breakthrough Needed?
- High-speed deposition
- UV, Microwave, or IR flash lamp drying & curing
- Ultrahigh packing density
- *In situ* separator coatings



Breakthrough Needed?
- Very high speed, high precision winding/stacking equipment
- Electrolyte: high throughput fill, low outgassing, low cost material production
- Innovative module/pack designs

Current Process
- Formation step assures performance, life, & safety of cell
- 2-3 week process
- Requires major capital expenditure

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

High Energy & High Power Cell R&D

Various companies were recently awarded ($2-5 M each) to develop advanced Lithium-ion cells and manufacturing processes which would reduce cost

Low-cost Processing and Design: 2x cost reduction (<$400/kWh)

Johnson Controls	**Maxwell/Entek**	**Dry processing, *in situ* separator coating, reduced formation time**
Miltec UV International	**ANL/ORNL**	**Ultraviolet and Electron Beam processing technology**
A123 Systems	**Maxwell**	**Dry-process electrode fabrication to reduce cost**
Optodot Corp.	**Dow Kokam, URI, Madico, ISP**	**New coating process for inactive components & faster electrode assembly process**
DENSO Intnl. America	**NREL**	**Battery thermal management system to reduce pack size & cost**

Current R&D Focus: ARPA-E BEEST Program Secondary Goals

- Funding Opportunity Announcements (FOAs) through ARPA-E have included energy storage for both transportation and grid-scale applications.
- Projects are 1-3 years in duration and are currently being funded through the American Recovery and Reinvestment Act (ARRA) of 2009 ($400M).

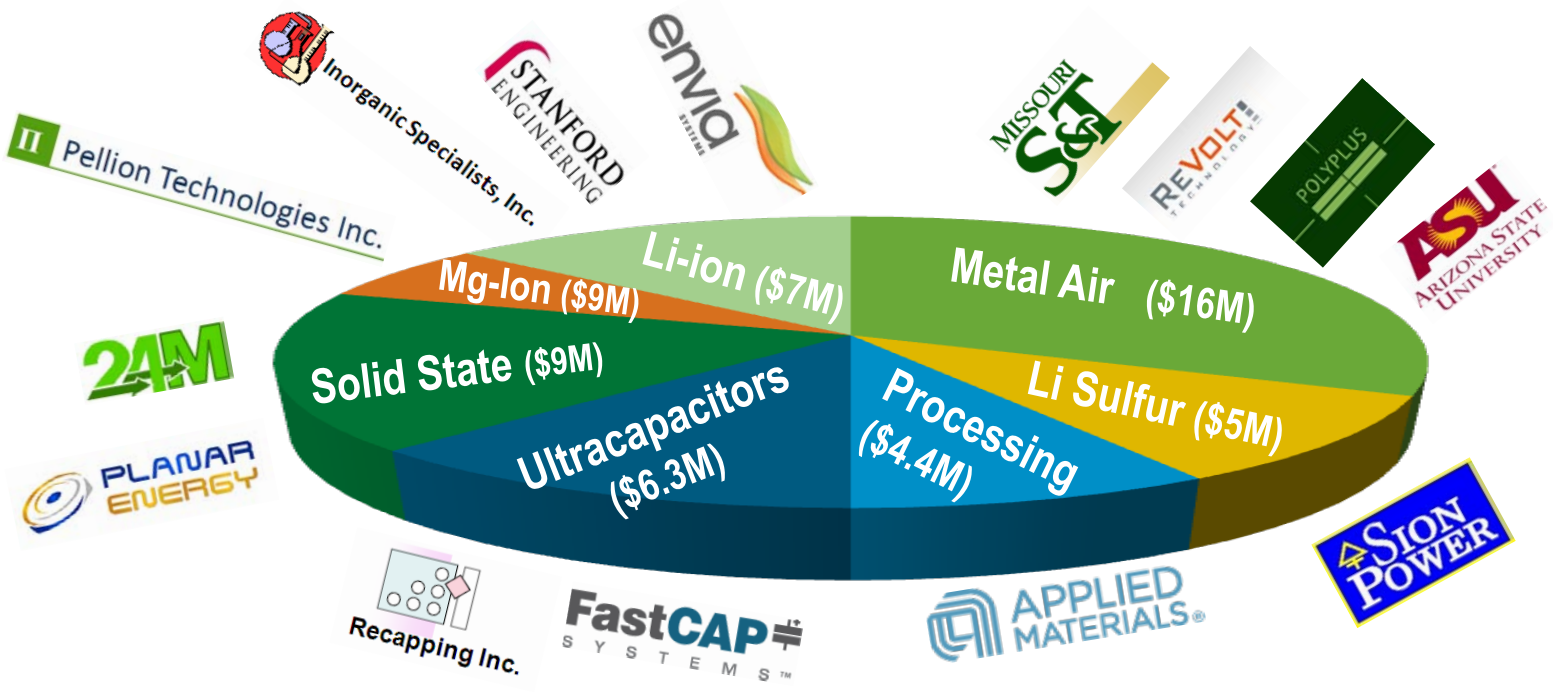
ARPA E Energy Storage Targets for Transportation

Category	Target
Specific Power Density	400 W/kg (system)
Volumetric Power Density	600 W/liter (system)
Specific Energy Density	200-400 Wh/kg (system)
Volumetric Energy Density	300-800 Wh/L (system)
Cycle Life	1000 cycles at 80% Depth of Discharge
Calendar Life	10 Years
Round Trip Efficiency	80% at C/3 charge and discharge

ARPA-E Projects

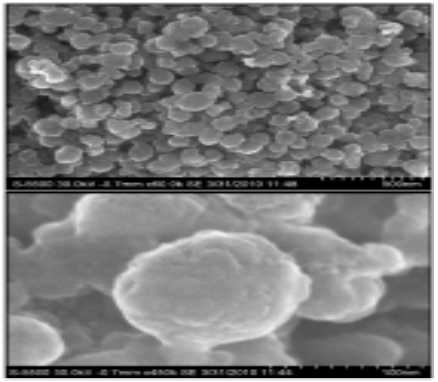
ARPA-E awarded 14 transformational research projects to speed the development of revolutionary, “game-changing” electric drive vehicle energy storage technology.

ARPA E Energy Storage Awards ($57 M)

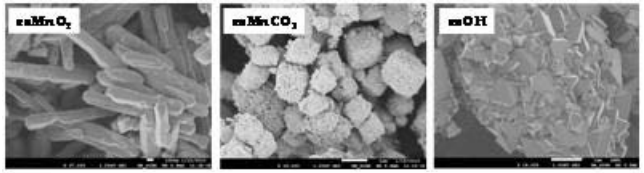


Summary

- Track record of success
  - DOE R&D has brought NiMH and Li-ion batteries into the automotive market
- Clear pathway to meet 2015 goals
  - On track to meet cost and performance targets
- Technologies in the pipeline to go beyond 2015
  - Research program focused on Li metal systems
  - 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