Vehicle Technologies Program

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

Energy Storage R&D and ARRA Activities at the US DOE
July 26-27, 2010

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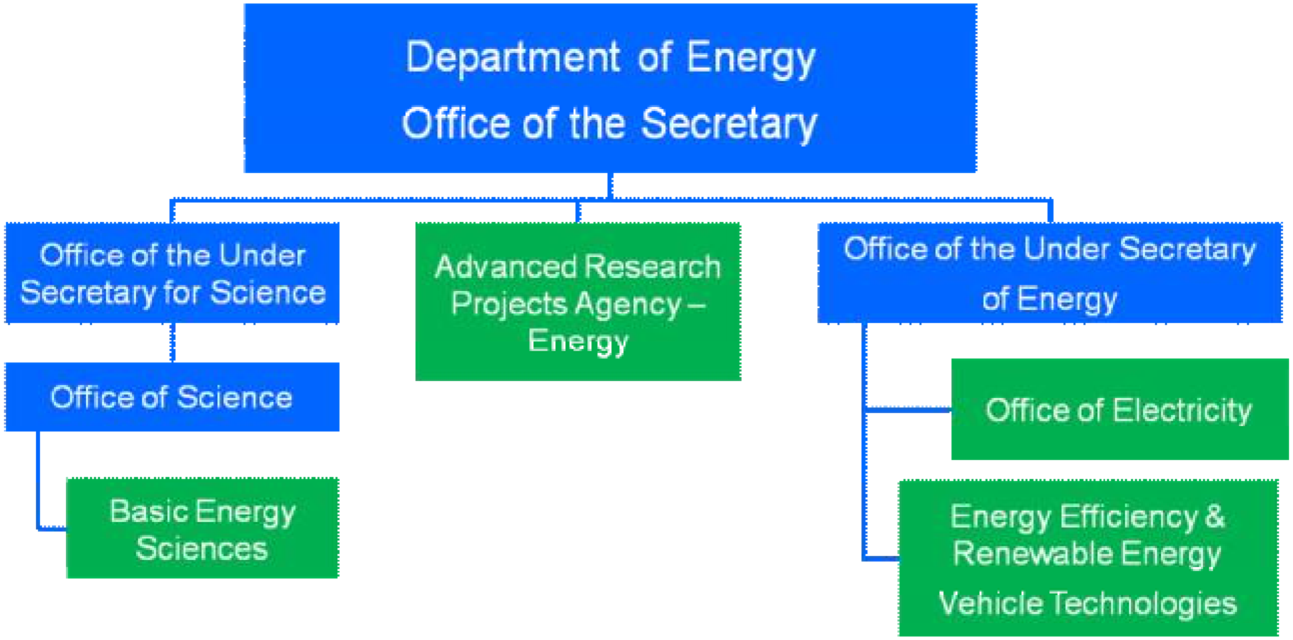
Overview

- Energy Storage R&D at the U.S. Department of Energy
- EERE Vehicle Technologies Program
  - Battery Development
  - Battery Cost Modeling
  - Material and Processing Improvement
  - Laboratory and University Research
- Advanced Research Projects Agency - Energy
- Office of Science Basic Energy Sciences
- Office of Electricity Delivery and Energy Reliability

Introduction



- **Office of Energy Efficiency and Renewable Energy (EERE) Vehicle Technologies** Advance the development of batteries and other energy storage devices to enable a large market penetration of hybrid and electric vehicles.
- **Advanced Research Projects Agency-Energy (ARPA-E)** funds high-risk, translational research with potential for significant commercial impact
- **Basic Energy Sciences (BES)** supports fundamental research to understand, predict, and control matter and energy at electronic, atomic, and molecular levels
- **Office of Electricity Delivery and Energy Reliability (OE)** leads efforts to modernize the electric grid; enhance security and reliability of the energy infrastructure

Energy Storage R&D Funding from DOE and Recovery Act

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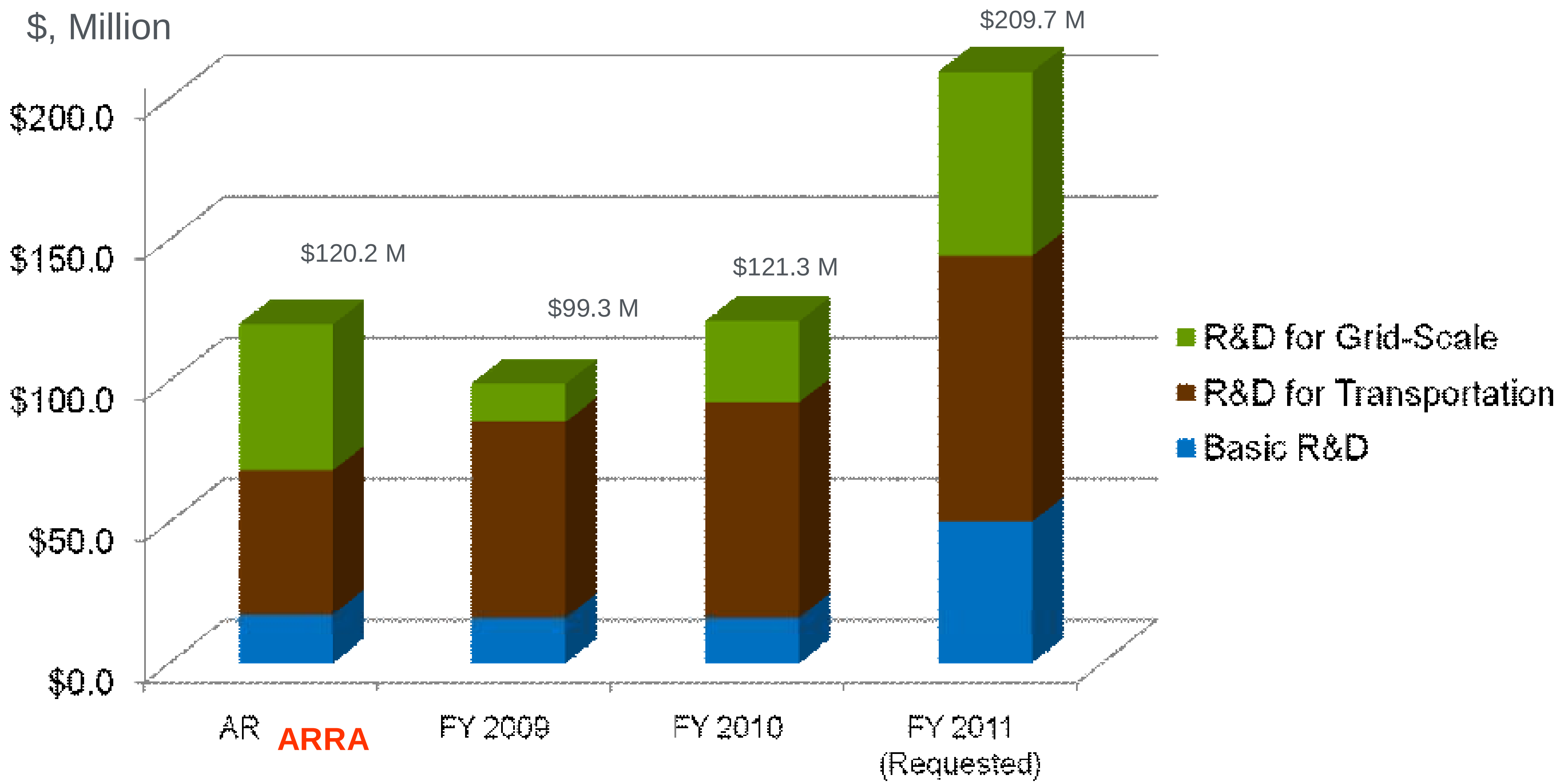

This chart does not include ARRA funding for advanced battery manufacturing ($1.5 B) or demonstrations ($400 M for transportation and $185 M for grid-scale)

Vehicle Technology Battery R&D Activities

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The energy storage effort is engaged in a wide range of topics, from fundamental materials work through battery development and testing

Advanced Materials Research → **High Energy & High Power Cell R&D** → **Full System Development And Testing** → **Commercialization**

- High energy cathodes
- Alloy, Lithium anodes
- High voltage electrolytes
- Lithium air couples

- High rate electrodes
- High energy couples
- Fabrication of high E cells
- Ultracapacitor carbons

- Hybrid Electric Vehicle (HEV) systems
- 10 and 40 mile Plug-in HEV systems
- Advanced lead acid
- Ultracapacitors

Lab and University Focus

Industry Focus

FY 2010 R&D Budget

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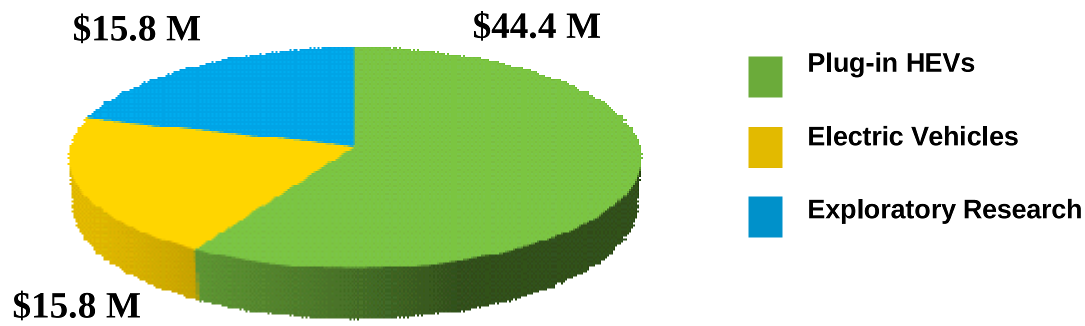
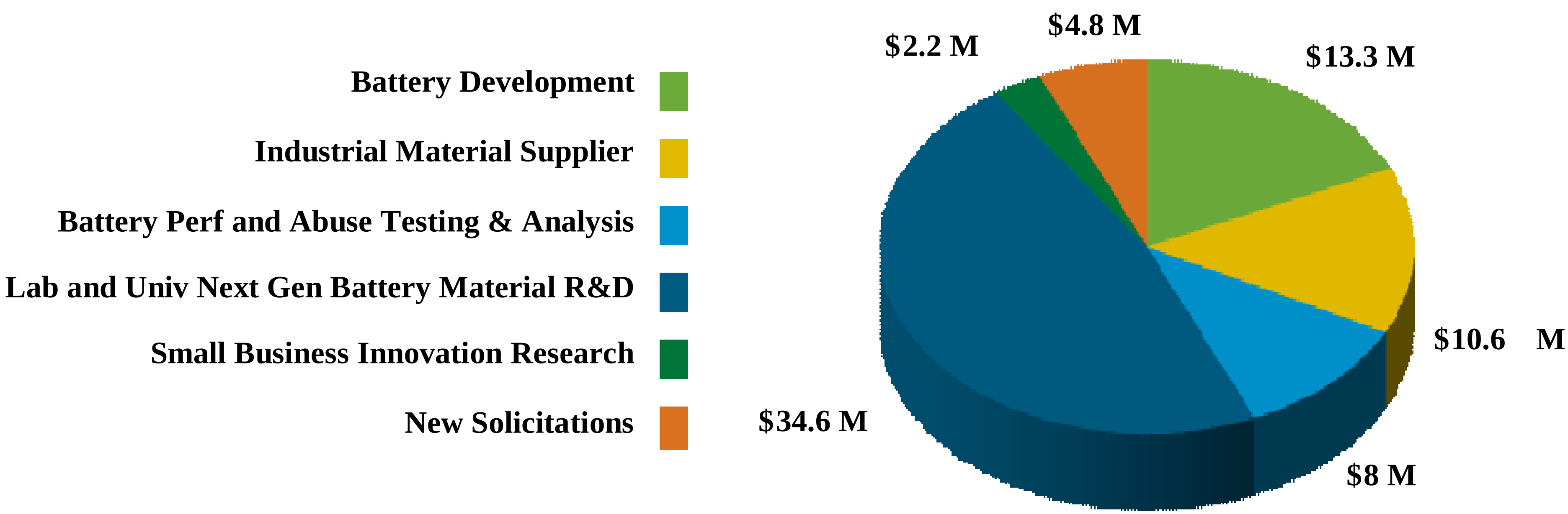
FY2010: $76 M
FY2011 Request: $96M





Accomplishments of USABC/Battery Development Partners

This activity has a documented track record of success

Johnson Controls-Saft (JCS)

- Supplying lithium-ion batteries to BMW and to Mercedes for their Hybrids.

A123Systems

- Selling a 5kWh battery for Hymotion's Prius conversion.
- Partnering with Chrysler on EV battery development.

Compact Power/LG Chem

- Will supply GM Volt PHEV battery.

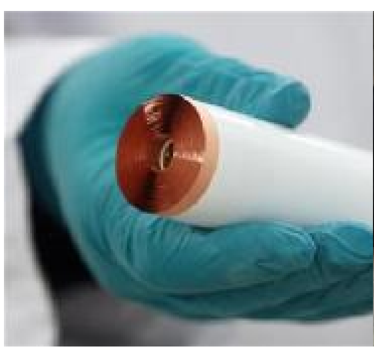
JCS high-power lithium-ion battery pack

A123 Systems high-power lithium-ion cell

CPI/LG lithium-ion battery pack for GM Volt

DOE and USABC Battery Performance Targets

DOE Energy Storage Goals	HEV (2010)	PHEV (2015)	EV (2020)
Equivalent Electric Range (miles)	**N/A**	**10-40**	**300**
Discharge Pulse Power (kW)	**25**	**38-50**	**80**
Regen Pulse Power (10 seconds) (kW)	**20**	**25-30**	**40**
Recharge Rate (kW)	**N/A**	**1.4-2.8**	**5-10**
Cold Cranking Power @ -30 ºC (2 seconds) (kW)	**5**	**7**	**N/A**
Available Energy (kWh)	**0.3**	**3.5-11.6**	**30-40**
Calendar Life (year)	**15**	**10+**	**10**
Cycle Life (cycles)	**3000**	**3,000-5,000, deep discharge**	**1500 deep discharge**
Maximum System Weight (kg)	**40**	**60-120**	**300**
Maximum System Volume (l)	**32**	**40-80**	**133**
Operating Temperature Range (ºC)	**-30 to +52**	**-30 to 52**	**-40 to 85**



Status of Conventional HEV Battery Development

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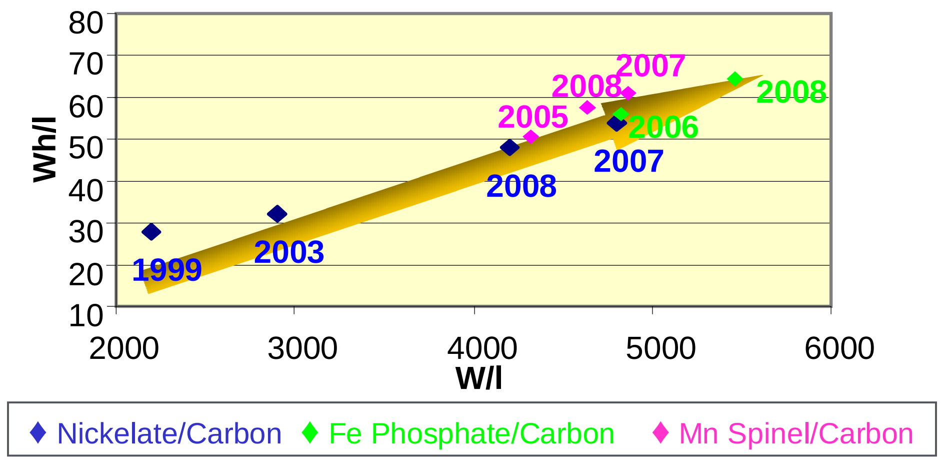
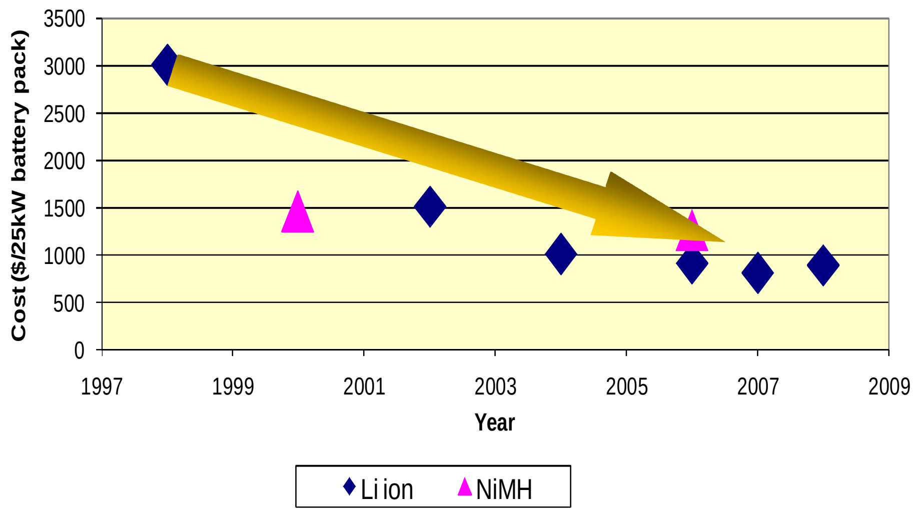
Most HEV performance targets met by Li-ion batteries.

- Mature Li-ion chemistries have demonstrated more than 300,000 cycles and 10-year life (through accelerated aging)
- R&D focus remains on cost reduction, improved abuse tolerance and the development of alternative technologies such as ultracapacitors.

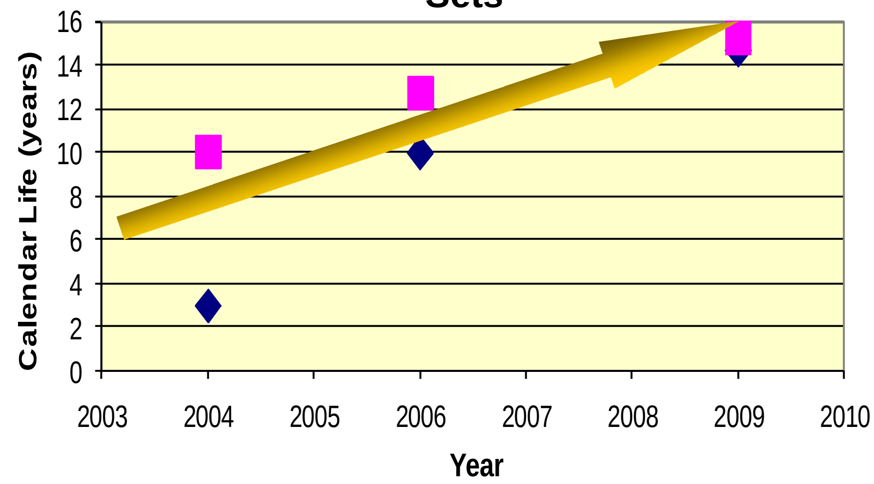
Energy and Power Density of USABC HEV Technologies - 3 Sample Data Sets



25kW HEV Battery Pack Cost



Calendar Life -- Two Sample Data Sets



DOE/USABC PHEV Battery Development Contracts

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A123 SYSTEMS	Develop batteries using nanophase iron-phosphate
Johnson Controls / SAFT	Develop batteries using a nickelate/ layered chemistry
cpi compact power inc / LG Chem	Develop batteries using manganese spinel chemistry
EnerDel Lithium Power Systems	Develop cells using nanophase lithium titanate and a high voltage spinel cathode material
3M	Develop and screen Nickel-Manganese -Cobalt cathode materials
CELGARD	Develop low-cost separators with high temperature melt integrity
ENTEK INTERNATIONAL	Develop low-cost separators with high temperature melt integrity

USABC Request For Proposals Topics

•Advanced High-Performance Batteries for **Electric Vehicles**

•Advanced Energy Storage Systems for high Power, Lower Energy **Power Assist Hybrids**

•Advanced High-Performance Batteries for **Plug-in Hybrid Electric Vehicles**

•Technology Assessment - Electric Vehicle Applications

12 Proposals Selected for negotiation

Performance Status of PHEV Batteries

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(Subset of goals)

Characteristics (End of Life)	STATUS (PHEV-10)	PHEV – 10 2012	PHEV-40 2014
Reference Equivalent Electric Range (miles)	10	10	40
POWER AND ENERGY			
Peak Pulse Discharge Power - 2 Sec / 10 Sec (kW)	50 / 45	50 / 45	46 / 38
Peak Regen Pulse Power (10 sec) (kW)	30	30	25
Available Energy: Charge Depleting @10 kW (kWh)	3.4	3.4	11.6
BATTERY LIFE			
Charge Depleting Life / Discharge Throughput (Cycles/MWh)	$2,500^{+}$	5,000 / 17	5,000 / 58
Charge sustaining (HEV) Cycle Life (cycles)	300,000	300,000	300,000
Calendar Life, 35°C (years)	6-12	15	15
WEIGHT, VOLUME, & COST			
Maximum System Weight (kg)	60-80	60	120
Maximum System Volume (liter)	50+	40	80
Battery Cost ($)	$\$2,500^{+}$	1,700	3,400

Battery Cost Models

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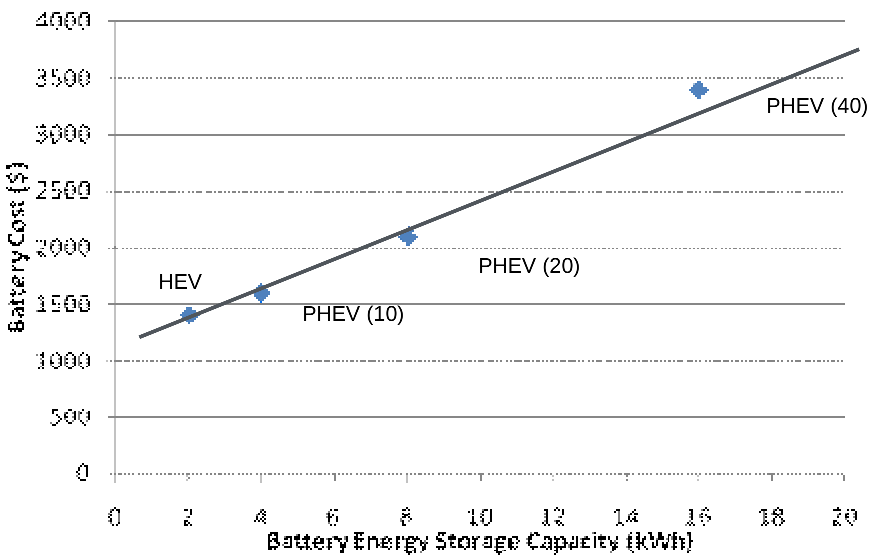
Objectives of Battery Cost Modeling

- Provide a common basis for calculating battery costs
- Provide checks and balances on reported battery costs
- Gain insight into the main cost drivers
- Provide realistic indication of future cost reductions possible



USABC model –

- Detailed hardware-oriented model for use by DOE/USABC battery developers to cost out specific battery designs with validated cell performance

Argonne model –

- Optimized battery design for application
- Small vs. large cell size
- Effect of cell impedance and power on cost
- Effect of cell chemistry
- Effect of manufacturing production scale

TIAX model –

- Assess the cost implications of different battery chemistries for a frozen design
- Identify factors with significant impact on cell pack costs (e.g., cell chemistry, active materials costs, electrode design, labor rates, processing speeds)
- Identify potential cost reduction opportunities related to materials, cell deign and manufacturing

Key Results

- Current high volume PHEV lithium-ion battery cost estimates are \$700 -\$950 /kWh.
  - Cost (\$/kWh) should be determined on "useable" rather than "total" capacity of a battery pack
  - ANL & TIAX models project that lithium-ion battery costs of \$300/kWh of useable energy are plausible.

- Material Technology Impacts Cost
  - Cathode materials cost is important, but not an over-riding factor for shorter range PHEVs Cathode & anode active materials represent less than 15% of total battery pack cost.
  - In contrast, for longer range PHEV's and EVs, materials with higher specific energy and energy density have a direct impact on the battery pack cost, weight, and volume.
  - Useable State-of-Charge Range has direct impact on cost for a given technology
  - Capacity fade can dramatically influence total cost of the battery pack

- Manufacturing scale matters
  - Increasing production rate from 10,000 to 100,000 batteries/year reduces cost by ~30-40% (Gioia 2009, Nelson 2009)
  - For example, consumer cells are estimated to cost about \$250/kWh.

VTP collaborated with the DOE Industrial Technologies Program to fund Advanced Battery Processing Technology Development

A123 SYSTEMS	Domestic supply chain for and processing methods of anodes ($1.5M total effort).
Johnson Controls	Substantial improvement of electrode processing quality control ($762k total effort).
DOW KOKAM	Processing and characterization of novel cathode materials ($870k total effort).
PLANAR Energy Devices	Scalable and cost-effective processing for all solid-state LIBs ($1M total effort).
POROUS POWER TECHNOLOGIES	Improved separator and unique method of production ($1.7M total effort).

Materials & Processing Improvement

DOE/NETL has selected ten companies to focus on advanced materials development, safety, and manufacturing process improvement

3M	Advanced high-energy anode materials
Angstron Materials	Hybrid Nano Carbon Fiber/ Graphene Platelet-Based High-capacity Anodes
NC State & ALE Inc	High-Energy Nanofiber Anode Materials
FMC	Stabilized Lithium metal powder
Sion Power	Develop and improve Lithium sulfur cells for electric vehicle applications

TIAX	Internal short diagnostics & mitigation technologies
EnerDel Lithium Power Systems	Develop technologies to mitigate abuse tolerance
BASF The Chemical Company	High volume, low cost, manufacturing techniques for cathode materials
A123 Systems	Develop advanced, low cost electrode manufacturing technology

DOE cost-share: $17.8 million (cost-shared by industry)

Laboratory and University Applied and Exploratory Research

Cell analysis and Construction
10 Projects

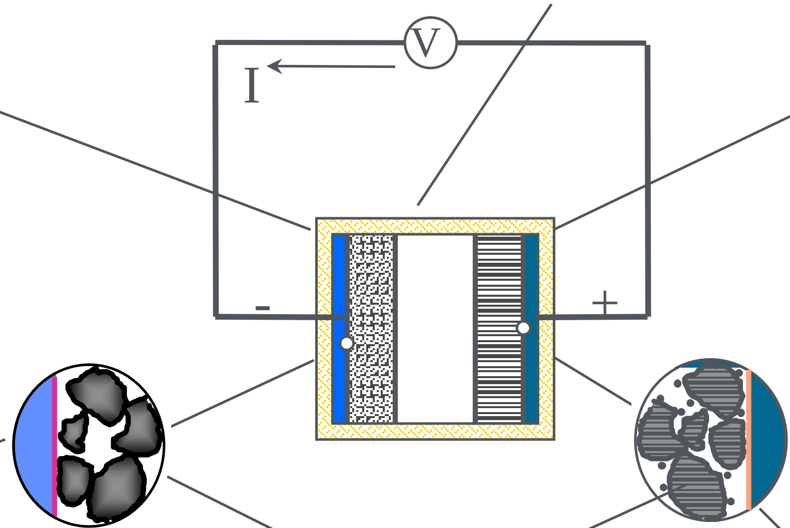
Lawerance Berkley, BNL, ANL, SNL, Hydro-Quebec

Modeling
5 Projects

LBNL, ANL, NREL, INL, U of Michigan

Electrolytes
12 Projects

LBNL, ANL, ARL, JPL,
BYU, CWRU, NCSU,
UC Berkeley, U of Rhode Island, U of Utah



Advanced Anodes
11 Projects

ANL, PNNL, ORNL
SUNY Binghamton
U of Pittsburgh

Diagnostics
6 Projects

LBNL, BNL, ANL
SUNY Stony Brook, MIT

Advanced Cathodes
15 Projects

ANL, PNNL, LBNL
UT Austin, SUNY Binghamton

Commercialization Activities and Notable Accomplishments

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- **Composite high energy cathodes**
  - licensed to Toda and and to BASF
  - developed by Dr. Thackeray of ANL
- **Conductive, electroactive polymers**
  - licensed to Hydro Quebec, world's leading supplier of this material.
  - developed by Prof. Goodenough at Univ Texas
- **Hydrothermal synthesis technique for $LiFePO_4$**
  - licensed to Phostech, for production
  - developed by Dr. Whittingham at SUNY
- **Conductive polymer coatings and a new $LiFePO_4$ fabrication method**
  - used by Actacell Inc fabricate high power Li ion cells
  - developed by Prof. Manthiram at Univ Texas
- **Polymer electrolytes for Li metal rechargeable batteries**
  - Seeo Inc a start-up of Prof. Balsara (LBNL) will commercialize material
  - 2008 R&D100 award
- **Nano-phase Li titanate oxide (LTO)/Manganese spinel chemistry**
  - licensed to EnerDel
  - developed by Dr. Khalil Amine at ANL, 2008 R&D100 award

Research Directions

- Concentrated search for high-capacity cathode materials.
- Develop new solvents and salts that allow for high-voltage electrolytes with stable electrochemical voltage windows up to 5 Volts.
- Develop advanced tin and silicon alloys with low irreversible loss and stable cycle life at capacity under 1,000 mAh/g.
- Initiate a new Integrated Laboratory/Industry Research Program
  - Explore the feasibility of pre-lithiated high capacity anodes.
  - Explore novel ideas to address the dendrite problem in using lithium metal.

Advanced Battery Prototype Fabrication and Testing Facilities

Laboratory	DOE Grant	Facility Description
Argonne National Laboratory	$8.8 M	-Battery Prototype Cell Fabrication Facility -Materials Production Scale-up Facility -Post-test Analysis Facility
INL Idaho National Laboratory	$5.0 M	High-energy Battery Test Facility
Sandia National Laboratories	$4.2 M	Battery Abuse Testing Laboratory
NREL	$2.0 M	Battery Design and Thermal Testing Facility

Advanced Research Projects Agency – Energy (ARPA-E)

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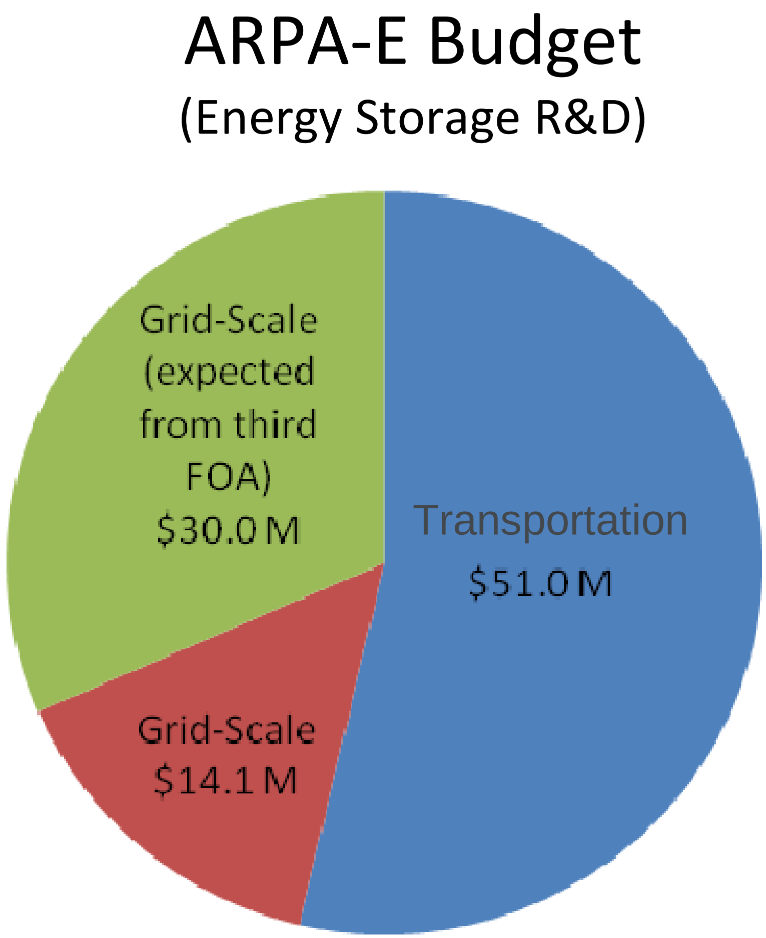
- Funding Opportunity Announcements (FOAs) through ARPA-E have included energy storage for both transportation and grid-scale applications.
- Projects are 1-3 years in duration and are currently being funded through the American Recovery and Reinvestment Act (ARRA) of 2009 ($400M).



ARPA-E: First FOA

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Six (6) energy storage projects awarded under the first open FOA

Awardee	Amount ($ M)	Project Title
First FOA (Energy Storage for Transportation)		
Arizona State University	5.1	Sustainable, High Energy Density, Low Cost Electrochemical Energy Storage Metal Air Ionic Liquid Batteries
Envia Systems	4	High Energy Density Lithium Batteries [over 400 Wh/kg, Li-ion silicon-carbon composite anodes and layered cathodes]
FastCap Systems	5.3	Low Cost, High Energy and Power Density, Nanotube-Enhanced Ultracapacitors
Inorganic Specialists	2	Silicon-Coated Nanofiber Paper as a Lithium-Ion Anode
First FOA (Grid-Scale Energy Storage)		
Eagle Picher Technologies	7.2	Planar sodium-beta Batteries for Renewable Integration and Grid Applications
Massachusetts Institute of Technology	6.9	Electroville: High Amperage Energy Storage Device – Energy for the Neighborhood (liquid-metal battery)

ARPA-E: Second FOA

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Ten (10) awardees under "Batteries for Electrical Energy Storage in Transportation (BEEST)" topic area

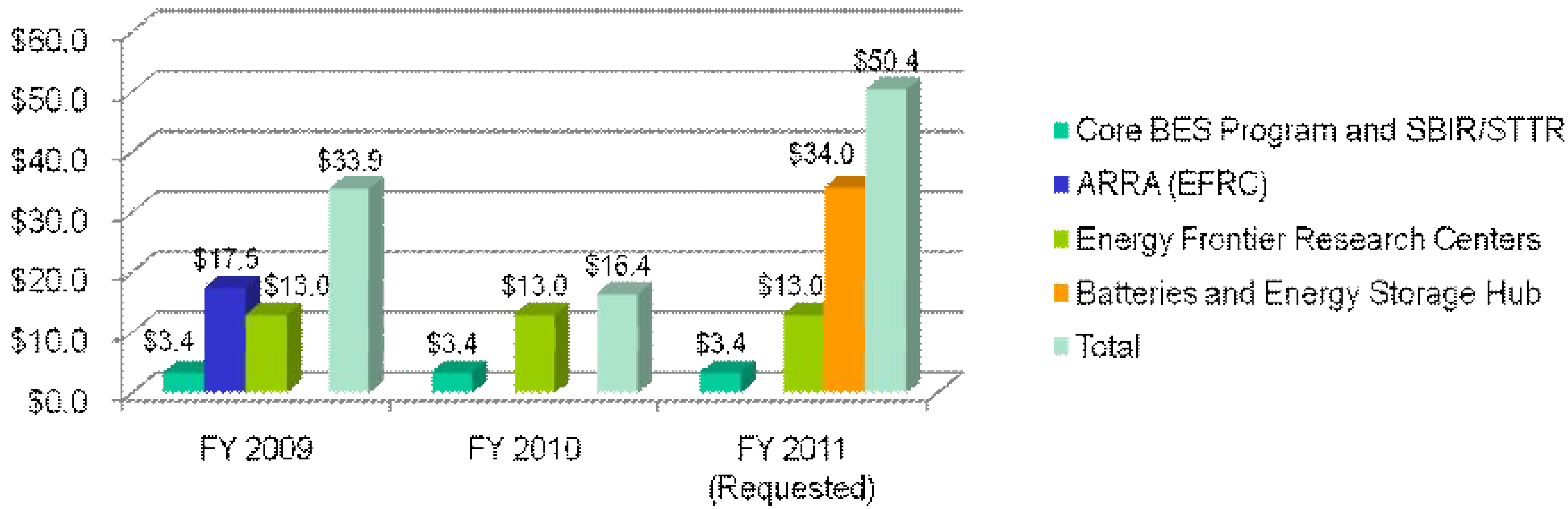
Awardee	Amount ($ M)	Project Title
Second FOA (BEEST)		
Missouri University of Science & Technology	1	High Performance Cathodes for Li-Air Battery
Recapping, Inc.	1	High Energy Density Capacitor
Stanford University	1	The All-Electron Battery: A Quantum Leap Forward in Energy Storage
Applied Materials, Inc.	4.4	Novel High Energy Density Lithium-Ion Cell Designs via Innovative Manufacturing Process Modules for Cathode and Integrated Separator
Massachusetts Institute of Technology	5	Semi-Solid Rechargeable Power Sources: Flexible, High Performance Storage for Vehicles at Ultra-Low Cost
Pellion Technologies, Inc.	3.2	Low-Cost, Rechargeable Magnesium-Ion Batteries with High Energy Density
Planar Energy Devices, Inc.	4	Solid-State, All Inorganic Rechargeable Lithium Batteries
PolyPlus Battery Company	5	Development of Ultra-High Specific Energy Rechargeable Lithium/Air Batteries Based on Protected Lithium-Metal Electrodes
ReVolt Technology LLC	5	Zinc Flow Air Battery, the Next Generation Energy Storage for Transportation
Sion Power Corporation	5	Development of High Energy Li-S Cells for Electric Vehicles

Proposals for "Grid-Scale, Rampable, Intermittent Dispatchable Storage (GRIDS)" under the third FOA are being evaluated

Basic Energy Sciences (BES)

- R&D focuses on fundamental materials research and exploration of electrochemical processes and concepts
- Two major programs:
  - Core BES (single investigator and small group research): each project award is ~$300,000/year and is renewable for a total of 3 years
  - Energy Frontier Research Centers (EFRCs): each project award is ~$3 M/year and is renewable for a total of 5 years

BES Budget for Energy Storage R&D ($, M)



Current projects focus on electrode and electrolyte phenomena

Investigator	Affiliation	Project Title
Wesley Henderson	North Carolina State University	Linking Ion Solvation and Lithium Battery Electrolyte Properties
Chengdu Liang	Oak Ridge National Laboratory	*In-situ* Studies of Solid Electrolyte Interphase on Nanostructured Materials
Shirley Meng	University of California – San Diego	New *in-situ* Analytical Electron Microscopy for Understanding Structure Evolution and Composition Change in High Energy Density Electrode Materials in Lithium-Ion Batteries
Rod Ruoff	University of Texas – Austin	Improved Electrical Energy Storage with Electrochemical Double Layer Capacitance Based on Novel Carbon Electrodes, New Electrolytes, and Thorough Development of a Strong Science Base
Grant Smith	University of Utah	The Influence of Electrolyte Structure and Electrode Morphology on the Performance of Ionic-Liquid Based Supercapacitors: A Combined Experimental and Simulation Study
Esther Takeuchi	University of Buffalo	Bimetallic Electrochemical Displacement Materials Yielding High Energy, High Power, and Improved Reversibility

BES EFRC Projects

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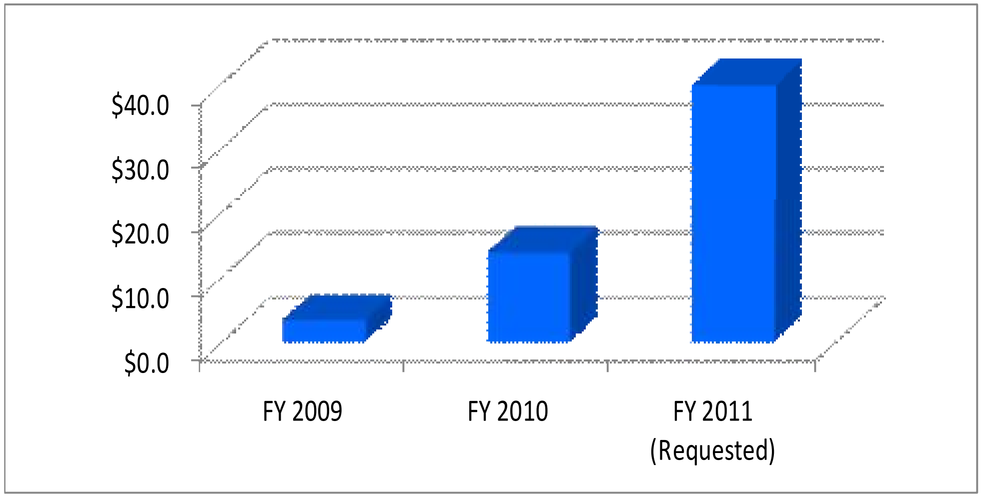
- Five (5) of the 46 EFRCs are energy-storage related
- Current projects focus on tailored interfaces, nanostructures, and fundamentals of chemistry and chemical reactions

Director	EFRC Name	Lead Institution	Objective
Hector Abruna	Nanostructured Interfaces for Energy Generation, Conversion, and Storage	Cornell University	Understand and control the nature, structure, and dynamics of reactions at electrodes in fuel cells, batteries, solar photovoltaics, and catalysts
Clare P. Grey	Northeastern Chemical Energy Storage Center (NOCESC)	Stony Brook University	Understand how fundamental chemical reactions occur at electrodes and use that knowledge to tailor new electrodes to improve the performance of existing batteries or to design entirely new ones
Gary Rubloff	Science of Precision Multifunctional Nanostructures for Electrical Energy Storage	University of Maryland	Understand and build nano-structured electrode components as the foundation for new electrical energy storage technologies
Grigorii Soloveichik	Center for Electrocatalysis, Transport Phenomena and Materials for Innovative Energy Storage	General Electric Global Research	Explore the fundamental chemistry needed for an entirely new approach to energy storage that combines the best properties of a fuel cell and a flow battery
Michael Thackeray	Center for Electrical Energy Storage: Tailored Interfaces	Argonne National Laboratory	Understand complex phenomena in electrochemical reactions critical to advanced electrical energy storage

OE's energy storage R&D activities focus on grid-scale applications

- •FY2009: $3.6M
- •FY2010: $14M
- •FY2011 (request): $40M



OE ARRA-Funded Storage Demonstration Projects ($185 M) to deploy and demonstrate the effectiveness of utility-scale grid storage systems

Primary Awardee	Amount ($ M)	Project Title and Description
Primus Power Corporation	14	**Wind Firming EnergyFarm™ –** Deploy a 25 MW - 75 MWh EnergyFarm for the Modesto Irrigation District in California's Central Valley (flow battery)
Southern California Edison Company	25	**Tehachapi Wind Energy Storage Project –** Deploy and evaluate an 8 MW utility-scale lithium-ion battery from A123 Systems
Duke Energy Business Services, LLC	22	**Notrees Wind Storage –** Deploy a 20 MW hybrid-energy storage system at the Notrees Windpower Project in western Texas (multiple battery systems)

Summary

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- DOE VTP has a successful track record of developing electric drive vehicle batteries
  - More than a decade of R&D efforts have brought lithium-ion batteries into the auto market.
  - Focus is on developing next generation lithium-ion batteries for longer range PHEVs and EVs.
  - The American Reinvestment and Recovery Act provides significant funding to address the lack of domestic battery manufacturing.
- ARPA-E, BES and OE contributing significant funding for novel and transformational battery technologies.

Dave Howell, Team Lead

Hybrid and Electric System

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