US Department of Energy Vehicle Battery R&D:

Current Scope and Future Directions

January 31, 2012

- David Howell (EERE/VTP)
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- Dane Boysen (ARPA-E)
- Dave Danielson (ARPA-E)
- Linda Horton (BES)
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U.S. Oil-dependence is Driven by Transportation

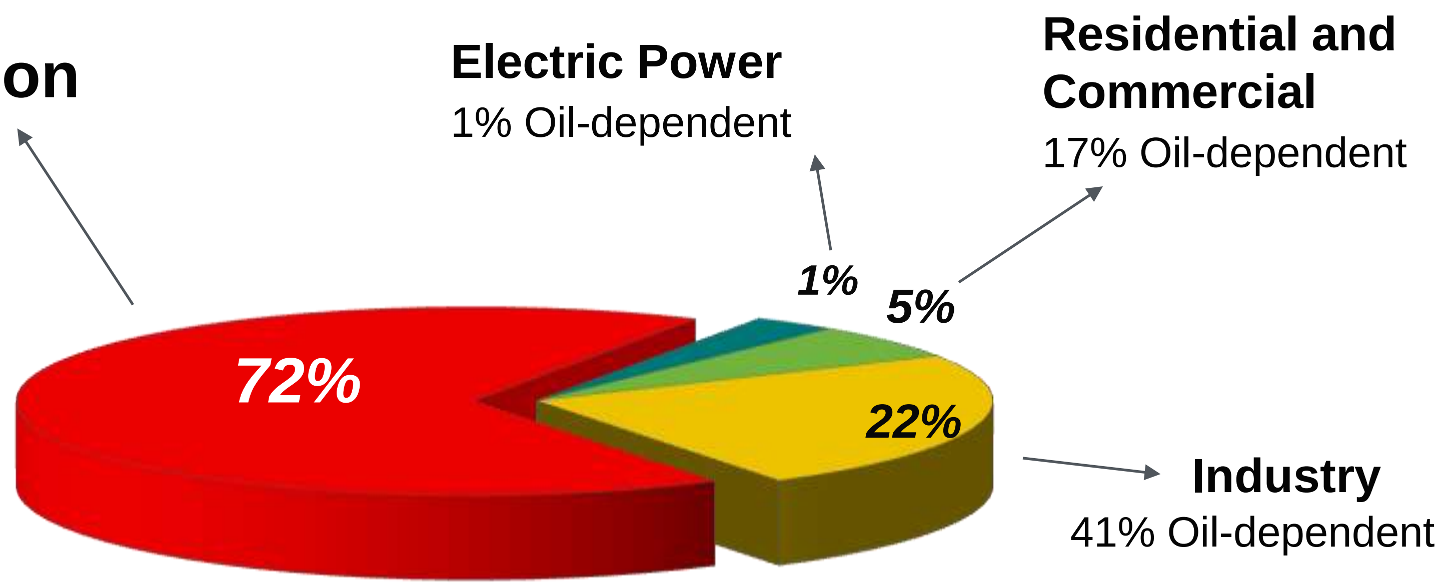
U.S. Oil Consumption by End-use Sector

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

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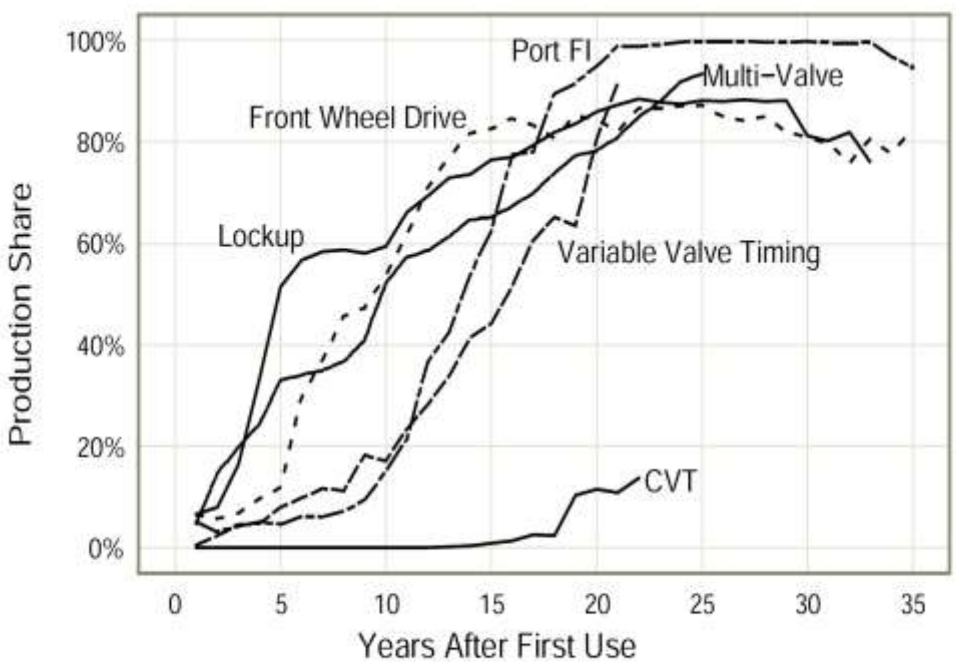
U.S. Vehicle Market

- 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

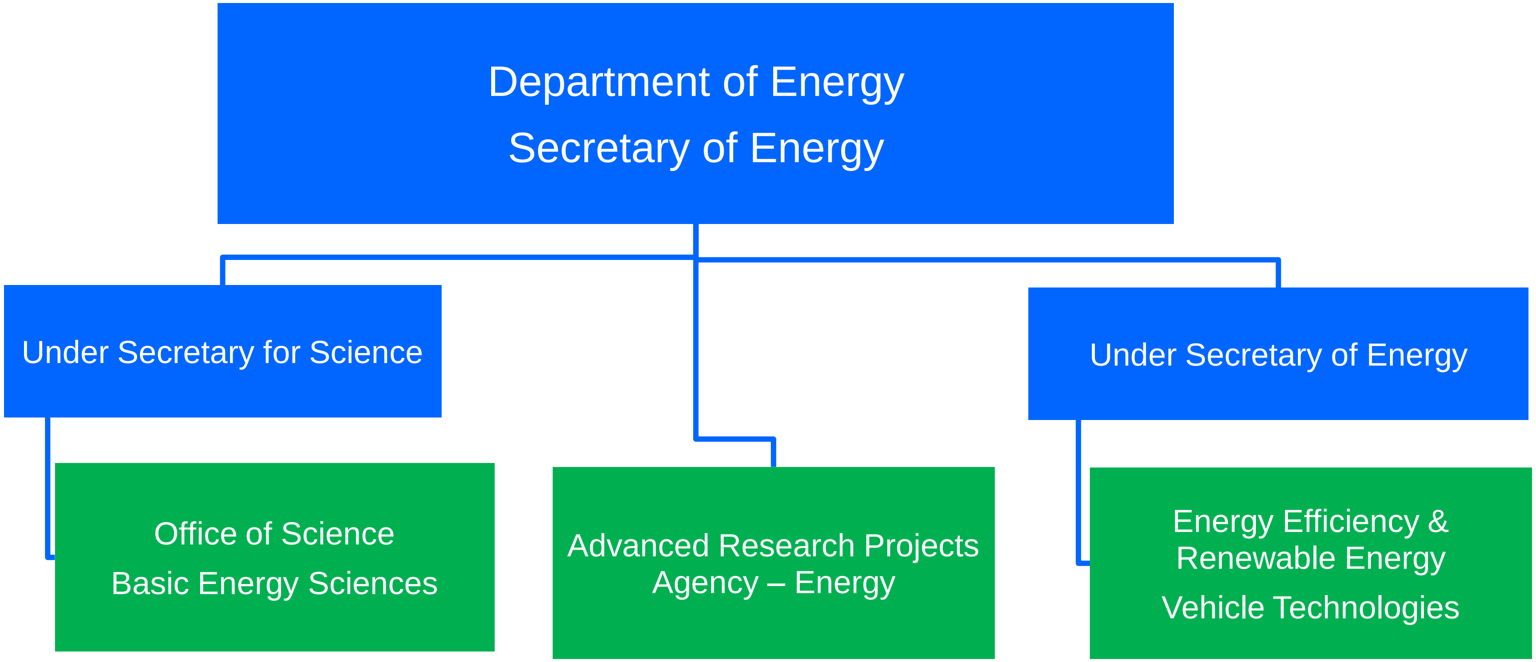
EV

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.

Batteries ITT Management Structure

ITT program management is performed by a Technical Advisory Board

Technical Advisory Board

ARPA-E	EERE/VTP	Science
Dane Boysen	David Howell	John Vetrano
David Danielson	Pat Davis	Linda Horton

Activities

- Develop overarching techno-economic goals and provide advice regarding policy, programmatic direction, program goals and technical targets
- Conduct multi-year program planning and align projects with goals and objectives
- Guide and implement recommended changes through program reviews, R&D assessments, and stakeholder workshops
- Foster interactions among principal investigators across programs

Moving Battery Technology Forward

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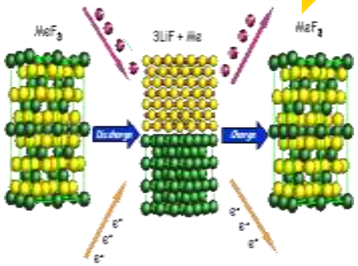
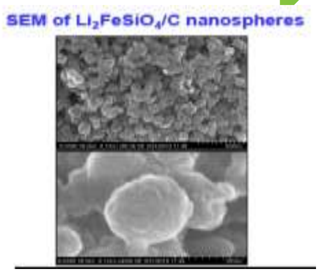
Technology Readiness Level (TRL)

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 and interfaces
- measurement
- mechanisms
- analyses
- user facilities

- cathodes
- anodes
- electrolytes
- modeling
- diagnostics

- electrochemical couples
- electrode design
- testing and diagnostics

- battery design and build
- testing, life prediction
- cost reduction, performance, durability safety

BES

ARPA E

Vehicle Technologies Program

DOE Wide Transportation Battery R&D Funding

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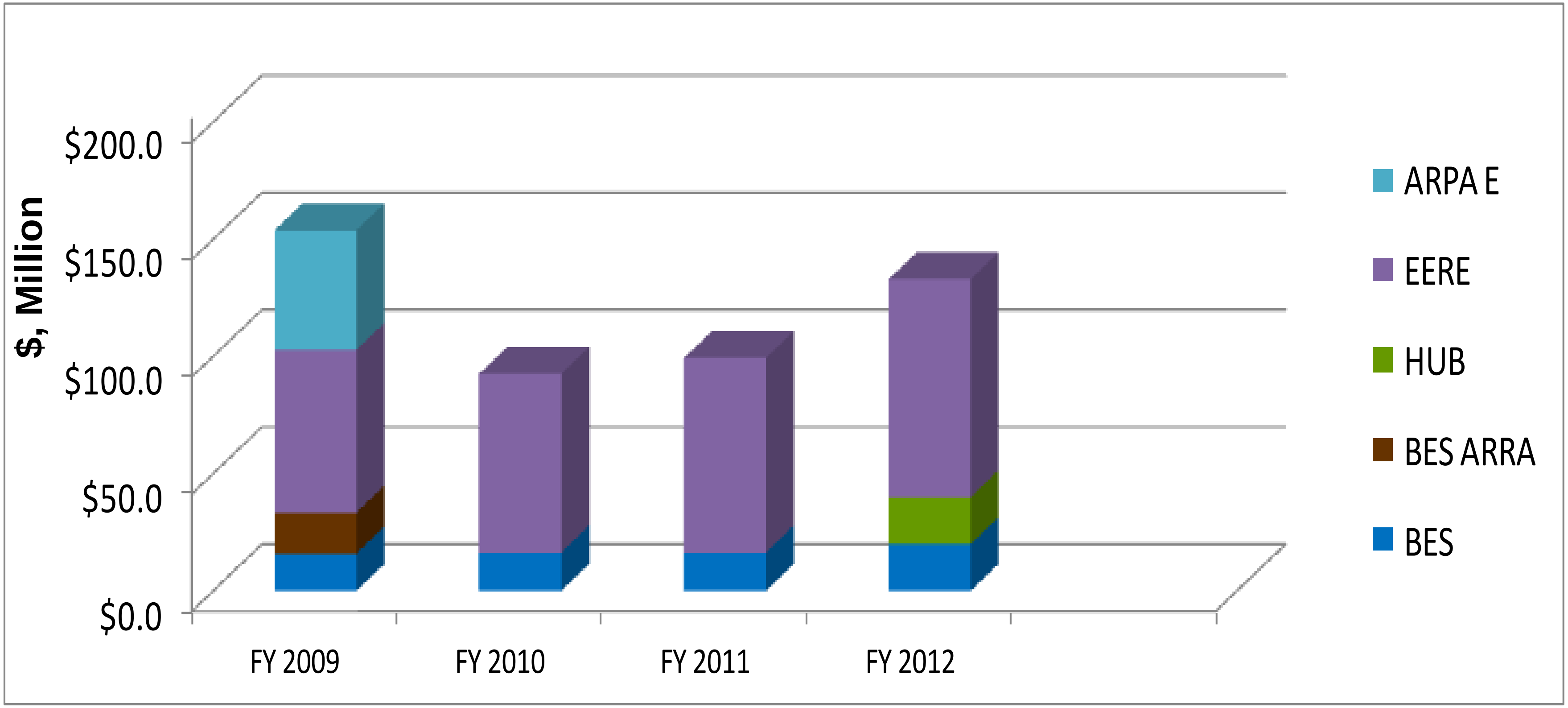

FY2013 budget will be released in February 2012.

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

DOE Integrated Tech Team
Over-Arching Battery Goal #1

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1 penny a mile
Initial cost goal

- 1 penny/mile = battery cost / total electric miles driven
  - *Addresses consumers' concerns about battery life and up-front cost*
- Cost per mile varies based on vehicle architecture/battery size:

Vehicle	Battery	Lifetime range	Cost	Scaled cost
PHEV40	12 kWh	150,000 miles	$1,500	1 cent/mile
EV100	24 kWh	150,000 miles	$3,000	2 cents/mile
EV300	60 kWh	150,000 miles	$7,500	5 cents/mile

Note: The cost for each of these batteries is $125/kWh

This goal is focused on developing affordable, long-lived EV batteries for mass market adoption that alleviate lifetime and first-cost concerns.

DOE Integrated Tech Team
Over-Arching Battery Goal #2

U.S. DEPARTMENT OF ENERGY

10 miles per minute
Fast-charge goal

- 10 miles of range for each minute charging time
  - *Addresses consumers' concerns about vehicle range and charge time*

- Charge time varies based on vehicle architecture/battery size:

Vehicle	Battery	Recharge time	Rate (miles/min)
PHEV40	12 kWh	4 minutes	10
EV100	24 kWh	10 minutes	10
EV300	60 kWh	30 minutes	10

Note: Using a nominal 120-180 kW charger

This goal is focused on alleviating consumer range anxiety and charge-time inconvenience, major barriers to widespread commercial adoption of EVs.

DOE Integrated Tech Team
Over-Arching Battery Goal #3

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Safe, Earth-Abundant, Recyclable

Market-acceptance goals

- Meet/exceed FMVSS and SAE–J2929 Battery Safety Standard
  - *Assure consumer confidence about vehicle safety*
- Constructed of earth-abundant materials
  - *Required for low cost*
  - *Minimize/eliminate foreign material dependencies*
- Recyclable
  - *Environmental stewardship*
  - *Ensure material availability and cost*

This goal is focused on speeding the market acceptance of new battery technologies and avoiding strategic material dependencies.

Current R&D Focus and Associated 2011 Technology Readiness Levels

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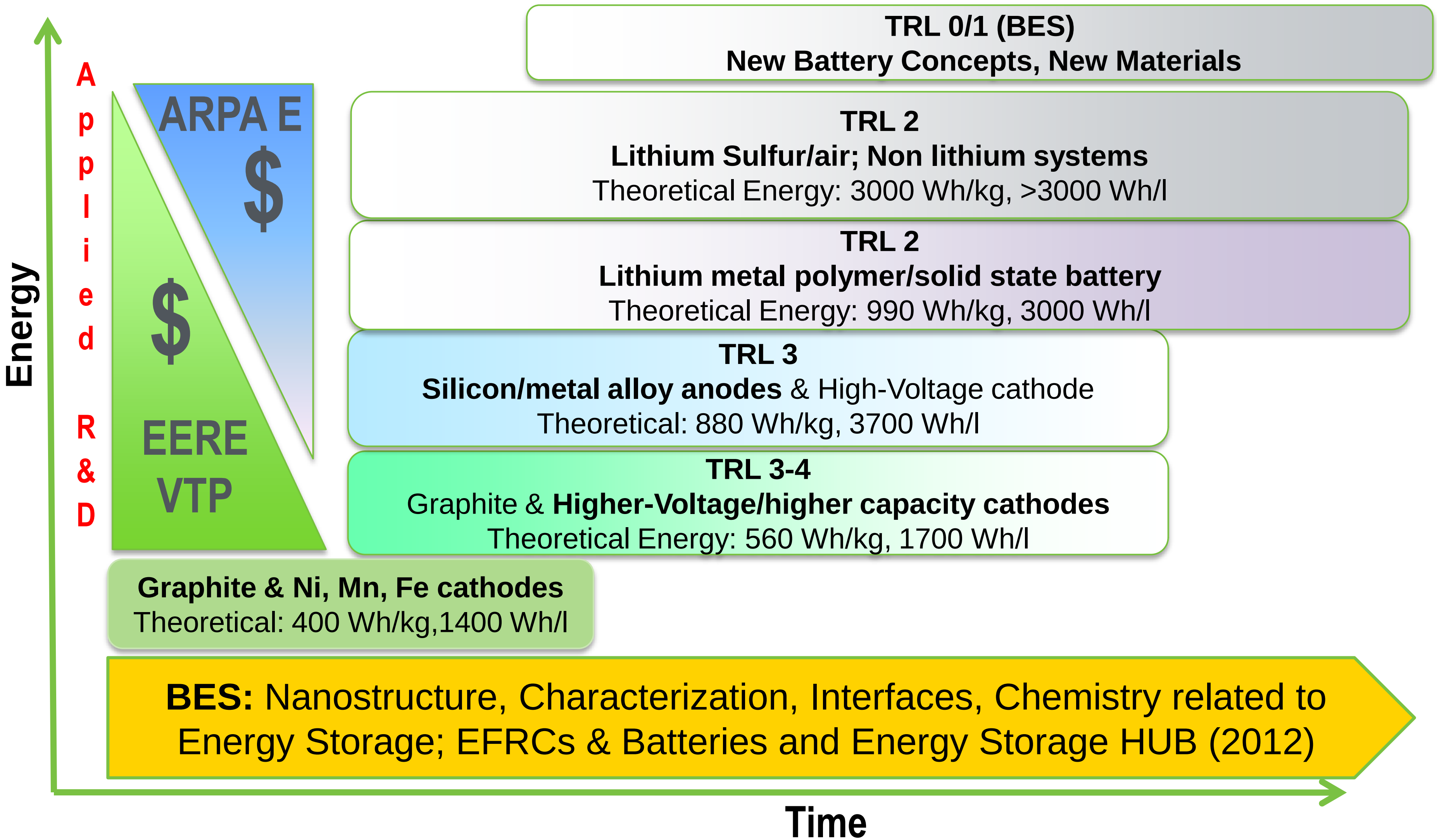

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Attributes of Battery Technologies

	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 Battery Development

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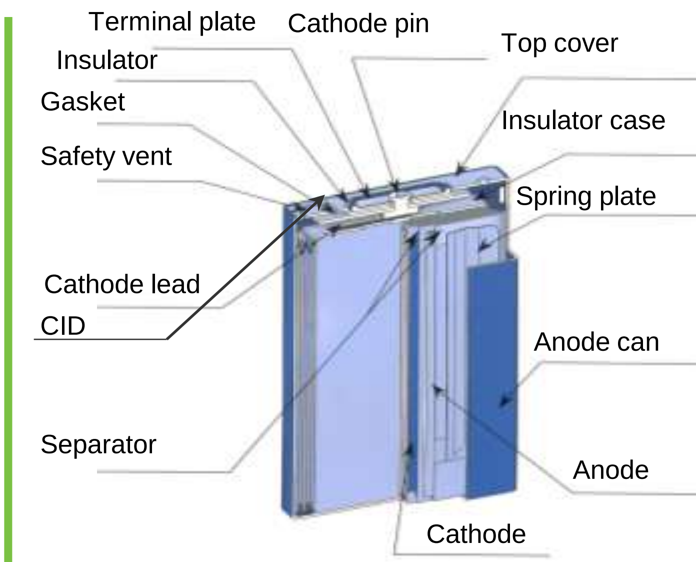
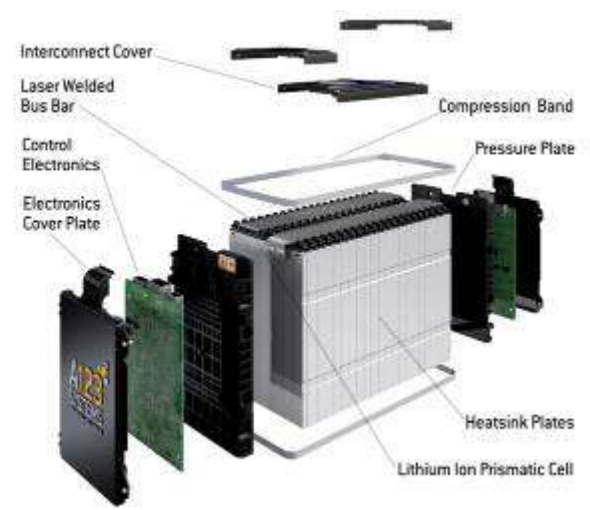
- **Battery Performance Targets**
  - EV $125/kWh (2020)
  - PHEV40 $300/kWh (2015)
  - HEV $20/KW (2010)

- **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

A123 SYSTEMS | ENVIA SYSTEMS | Maxwell TECHNOLOGIES | QUALLION
Johnson Controls | ActaCell | SK energy | CELGARD
COBASYS | K2 Energy | LG Chem | ENTEK





(Used with permission)

VTP Advanced Battery Materials and Cell R&D

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

Battery Materials Research

Advanced Anodes
(600 mAh/g)

Advanced cathodes
(300+ mAh/g)

Next Generation Electrolytes
(5 volt)

2 – Electrode and Cell Fabrication

1 – Advanced Electrochemical Couple Research

3 – Performance & Aging

4 – Scientific Diagnostics and Analysis

Cell Targets
- 300 Wh/kg
- 500 Wh/Liter
- 5,000 cycles

Supports R&D at 19 different Universities and 16 different Industry partners

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 ($57 million total in vehicle-battery R&D).

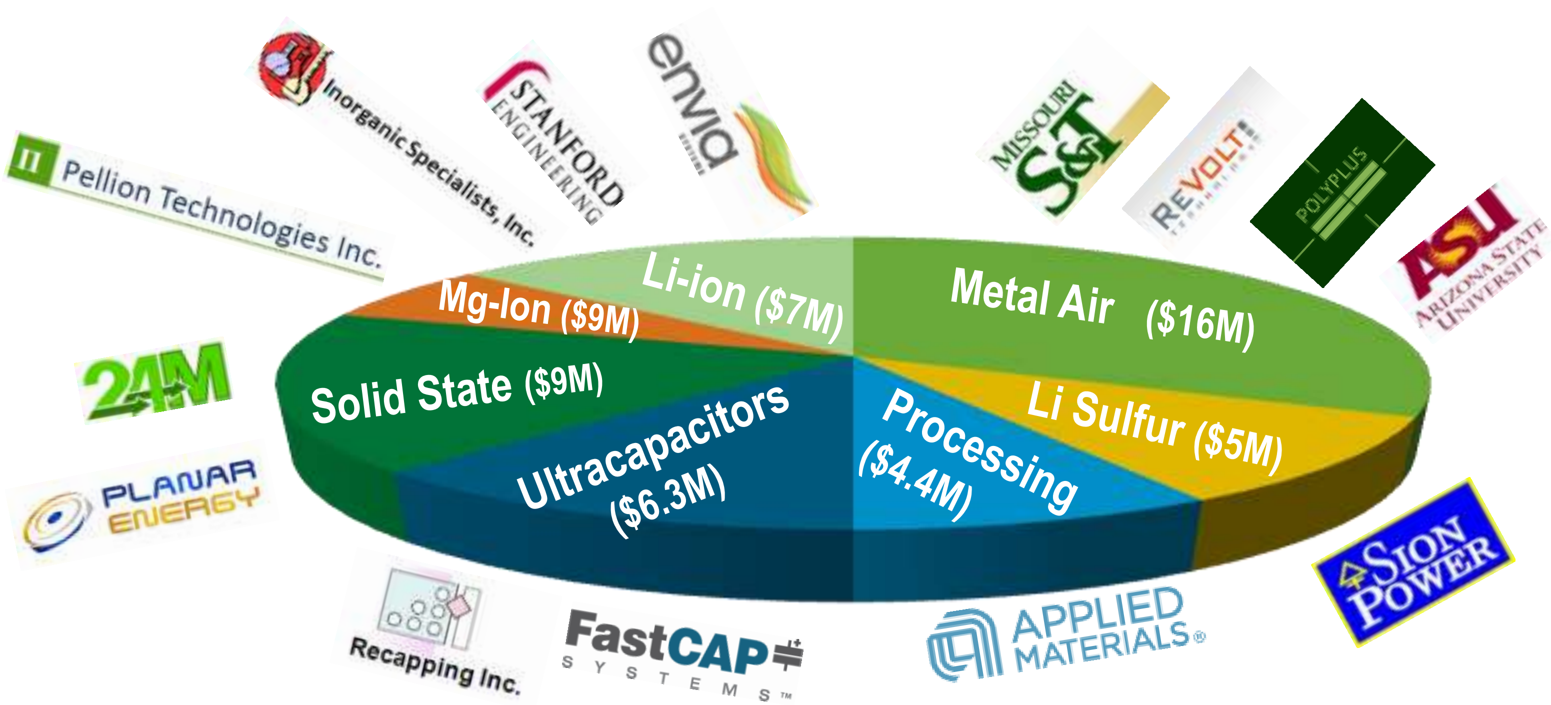
ARPA E Energy Storage Targets for Transportation

Category	Target
Specific Power Density	400 W/kg (system, 80% DOD, 30s)
Volumetric Power Density	600 W/liter (system, 80% DOD, 30s)
Specific Energy Density	200 Wh/kg (system, C/3 discharge)
Volumetric Energy Density	300 Wh/L (system, C/3 discharge)
Cycle Life	1000 cycles (80% DOD)
Calendar Life	10 Years
Round Trip Efficiency	80% (C/3 charge and discharge)

ARPA-E Projects

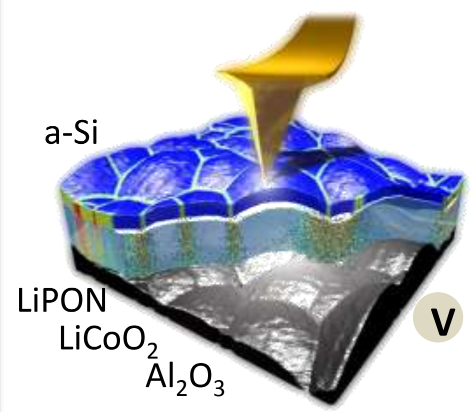
ARPA-E awarded 14 transformational research projects to speed the development of revolutionary, “game-changing” electric drive vehicle energy storage technology.

ARPA E Energy Storage Awards ($57 M)



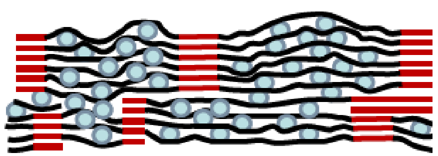
Energy Storage Research in BES:
Core Program and Energy Frontier Research Centers

- **Development of new in-situ measurement techniques**
- **Understanding electrolyte chemistry and behavior**
- **New materials for supercapacitors**
- **Novel materials and structures for electrode materials**
- **Understanding the Solid-Electrolyte Interphase (SEI) layer**
- **Influence of nanostructuring on behavior**
- **Synthesis and processing techniques including bio-inspired approaches**
- **Structural evolution and degradation during cycling**



Atomic Force Microscopy characterizes the local lithium-ion transport in a thin-film battery

Holey graphenic anode supports Si particles and allows fast Li^+ transport



○ = Si nanoparticles (provide high charge capacity)

Batteries and Energy Storage Energy Innovation Hub

Electrify Transportation and Transform the Grid

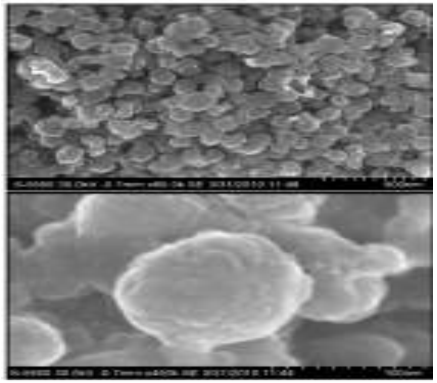
- $20M in FY 2012 funding was appropriated for the Batteries and Energy Storage Hub
- A 5-year award is anticipated later in FY2012
- The Hub will develop electrochemical energy storage systems that safely approach theoretical energy and power densities with very high cycle life – and have the potential for economic and fundamentally new manufacturing
- These are systemic challenges requiring new materials, systems, innovative engineering, and enhanced scientific knowledge
- The Hub will link fundamental science, technology, and end-users, and it will collaborate with relevant BES, Energy Frontier Research Centers, ARPA-E EERE, and OE activities

Summary

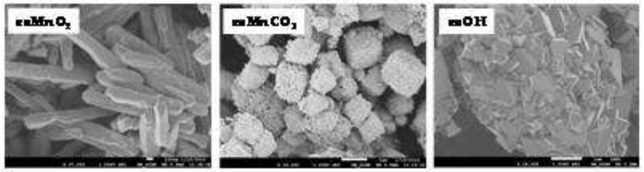
- The Battery Integrated Tech Team (ITT) combines the technical leadership of the BES, EERE, and ARPA-E to guide DOE-wide RD&D on battery technology for transportation applications.

- Techno-economic targets assure that battery R&D activities are focused on developing EV batteries that are;
  - affordable,
  - long-lived ,
  - fast-chargeable, safe, and sustainable

- Action Plan
  - Conduct multi-year program planning and align projects with goals and objectives
  - Guide and implement recommended changes through program reviews, R&D assessments, and stakeholder workshops
  - Foster interactions among principal investigators across programs



SEM of Li_2FeSiO_4/C nanospheres

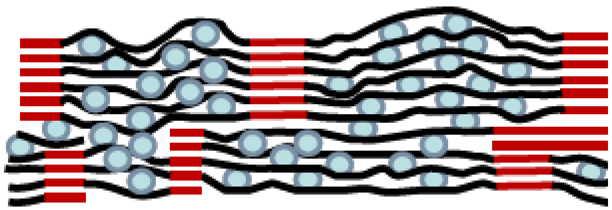


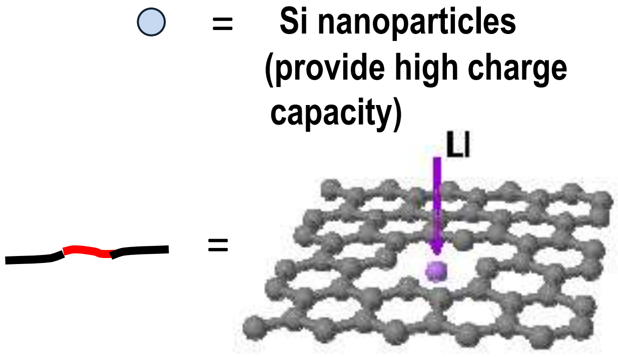
SEM pictures of $LiNi_{0.5}Mn_{1.5}O_4$ made from MnO_2, $MnCO_3$ and hydroxide precursors

- Back-up slides

High–Power Electrodes for Lithium-Ion Batteries

Electrode composite:





graphene sheet of C with in-plane defects (provide high power)

3-D graphenic scaffold with in-plane defects and Si nanoparticles between sheets: A novel method of synthesis creates an anode with a stable structure of holey graphene layers propped up by intermixed Si nanoparticles

Work was performed at Northwestern University and supported by the Center for Electrical Energy Storage EFRC.

Scientific Achievement

For novel 3-D anodes made of sheets of carbon (graphene) and silicon nanoparticles, transport studies found much shorter lithium diffusion paths throughout the electrode and fast lithiation/delithiation of the nanoparticles.

Significance and Impact

This anode design hold a greater charge than conventional lithium-ion anodes and charge/discharge more rapidly while maintaining mechanical stability.

Research Details

– Electrochemical studies: 83% of theoretical capacity (3200 mAh g^{-1}) retained after 150 charge/discharge cycles at high power (1 A g^{-1}).

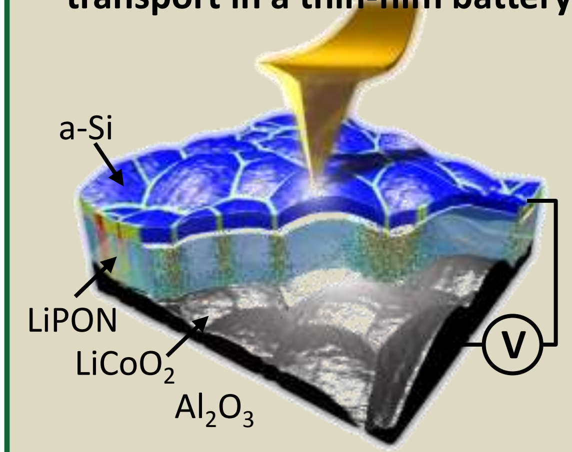
– Anode material is prepared by a process expected to be scalable to commercial quantities.

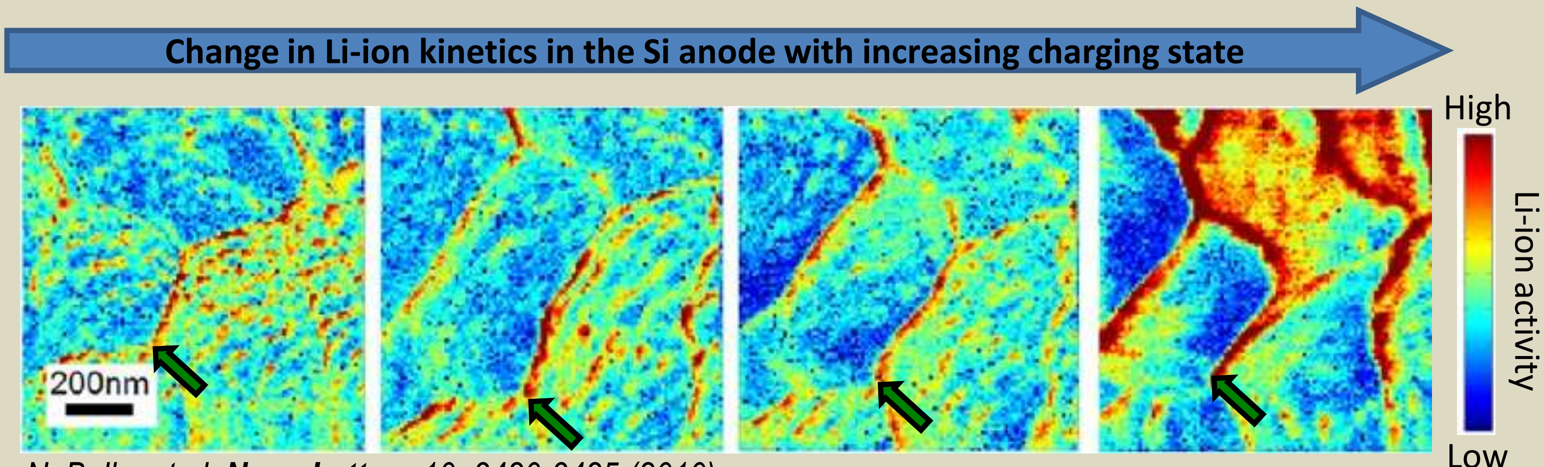
Xin Zhao, Cary M. Hayner, Mayfair C. Kung, and Harold Kung., *Adv. Energy Mater.*, **2011**, 1, 1079-1084

EFRC Research Demonstrates Real Space Mapping of Lithium-Ion Transport in Anodes with Nanometer Resolution

- Understanding ionic flow on a local scale is key to improving battery technologies
- Atomic force microscopy detects local volume changes in heterostructures due to ionic flow induced by tip biasing
  – Probes lithium-ion transport by high frequency biasing
- Lithium-ion flow is correlated with the structure of electrodes and interfaces
- Performed by Fluid Interface Reactions, Structures and Transport (FIRST) EFRC led by Oak Ridge National Laboratory

Atomic Force Microscopy characterizes the local lithium-ion transport in a thin-film battery



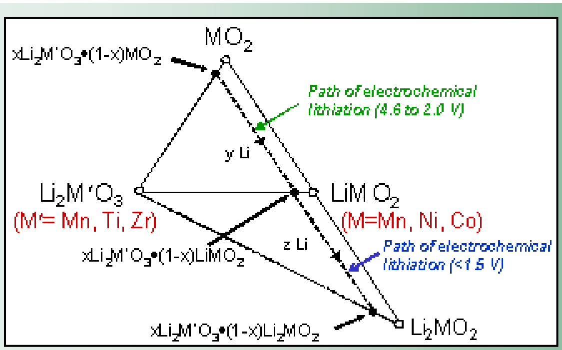


*N. Balke et al, **Nano Letters** 10, 3420-3425 (2010).*

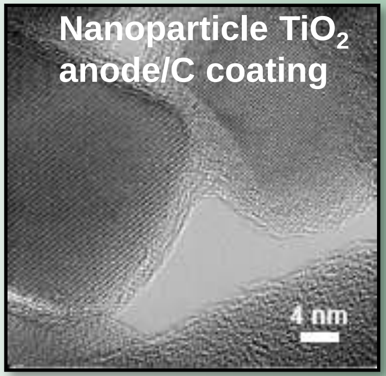
The a-Si anode surface roughness induces localized Li-ion transport which is enhanced with increasing battery charging.

High-Energy Lithium Batteries: From Fundamental Research to Cars on the Road

Basic Science



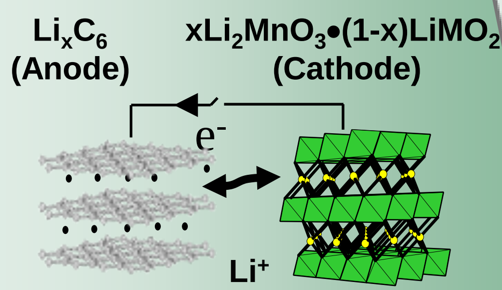
Discovered new composite structures for stable, high-capacity cathodes



EFRC research

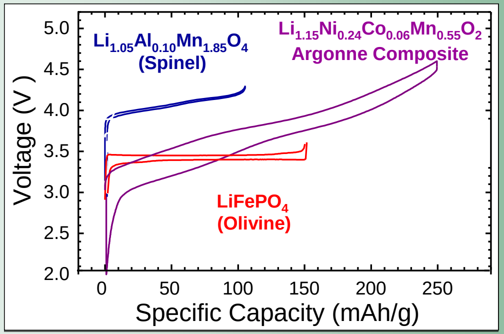
Tailored electrode-electrolyte interface using nanotechnology

Applied R&D



Created high energy Li-ion cells…

…with double cathode capacity, enhanced stability



Manufacturing/ Commercialization

ENVIA SYSTEMS

BASF The Chemical Company

TODA KOGYO CORP.

LG Chem

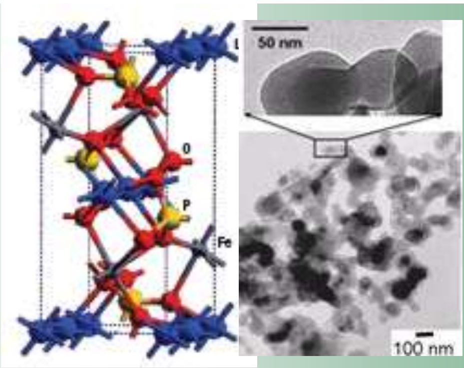
GM

VOLT

Licenses to materials and cell manufacturers and automobile companies

High Impact Basic Research: Nanotechnology Approach Leads to Commercial Batteries

Basic Science



$LiFePO_4$ structural model and nanostructure

- Research at MIT over a decade ago led to the discovery that drastically refining the structure of ceramics enhanced their conductivity (DOE Office of Science)
- Minor chemical additions to the fine-grained $LiFePO_4$ further increased the conductivity by eight orders of magnitude

Applied R&D

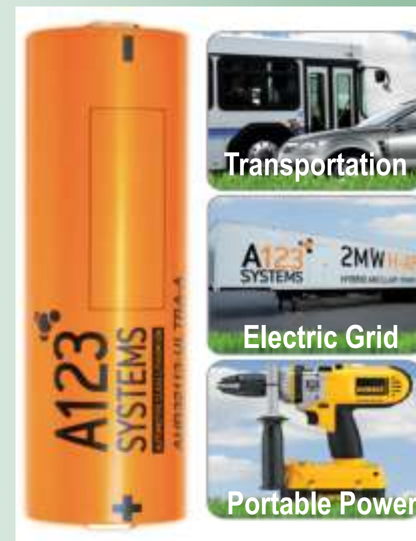
Formation of A123 Start-up

DOE Small Business Innovation Research (SBIR)

Enabled development of an A123 lithium-ion battery that

- Improved battery life by up to 10 times compared to other Li batteries
- Has more than twice the power density of high power NiCd and NiMH batteries
- Operates over a wide temperature range, from -30 to >60°C
- Charges to more than 90% capacity within 5 minutes

Manufacturing/ Commercialization



Today - A123Systems' batteries have reached the commercial marketplace in power tools, hybrid and plug-in hybrid electric vehicles, and grid applications. A recent DOE-Vehicle Technologies grant paved the way for what is now the largest lithium ion automotive battery plant in North America.