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

US Department of Energy Vehicle Battery R&D: *Progress Update*

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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

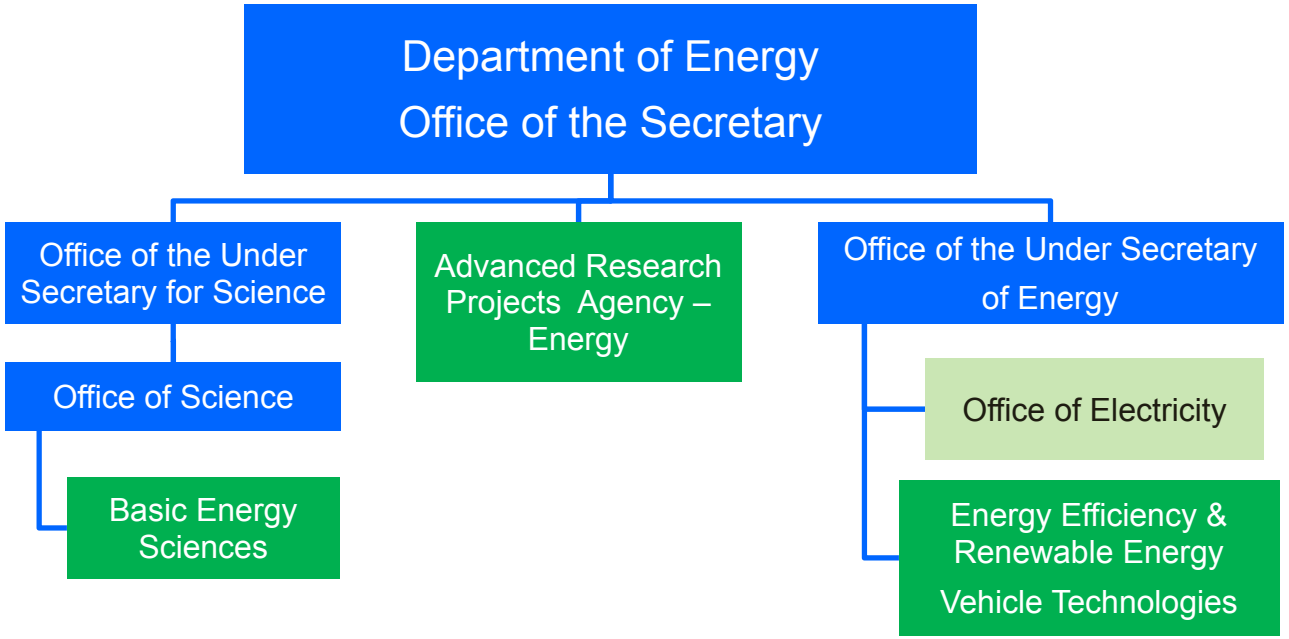
Nissan Leaf → All Electric
- ≥ 24 kWh battery
- Battery Power Rating: ≥ 110kW
- Battery Cost: about $15,000

Achieving large national benefits depends on significant market penetration.

- Potential oil savings in 2030: ~1.25 Mbpd with 10% market penetration
- Corresponding GHG emissions reduction : ~170 million metric tons of CO_2 equivalent per year

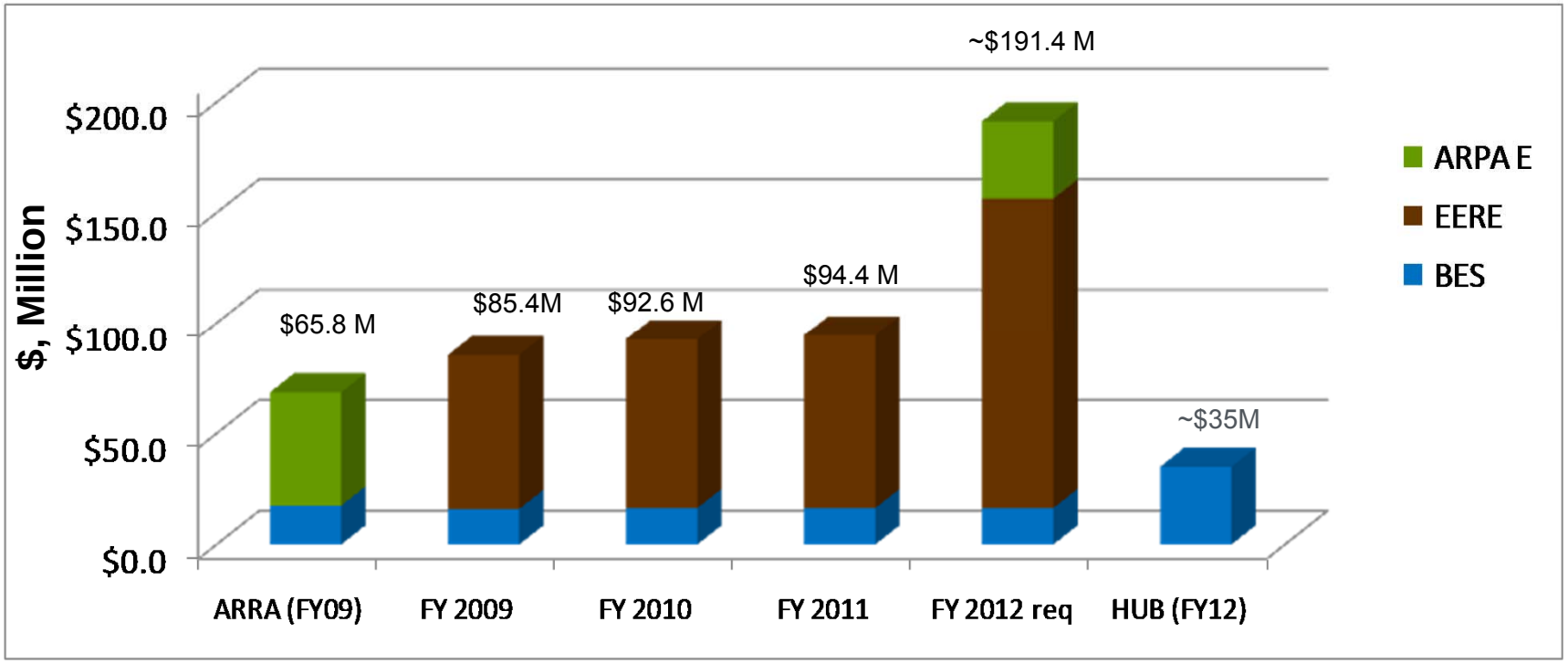
Battery affordability and performance are the keys.

Energy Storage R&D: Involved DOE Offices



- **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.

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

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.

Commercial Applications

DOE-funded Technologies Move to Commercial Applications

Several technologies supported by VTP have moved into commercial applications.

- 1990s Nickel Metal Hydride
  - **Cobasys** NiMH technology: Every HEV sold uses intellectual property developed in the DOE battery program. The US Treasury received royalty fees.
- 1998 High-Power Lithium-ion (HEVs)
  - **Johnson Controls Saft (JCS)** nickelate technology: BMW, Mercedes and Azure Dynamics/Ford Transit Connect
- 2004 High-Energy Lithium-ion (EVs)
  - **A123Systems** nano iron phosphate technology: Fisker, BAE, Hymotion, Prius, Navistar
  - **CPI/LG Chem** manganese technology: GM Volt extended range PHEV, Ford Focus EV

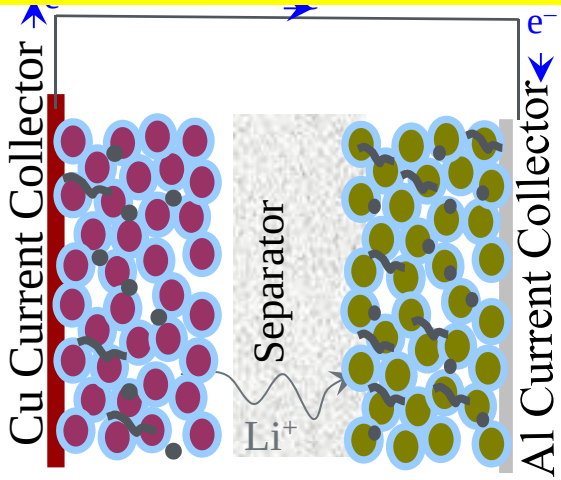
Next Generation Lithium-Ion

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

Anode

Today's Technology
(300 mAh/g)
-Graphite
-Hard carbon

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



Electrolyte

Today's Tech (4 volt)
Liquid organic solvents & gels

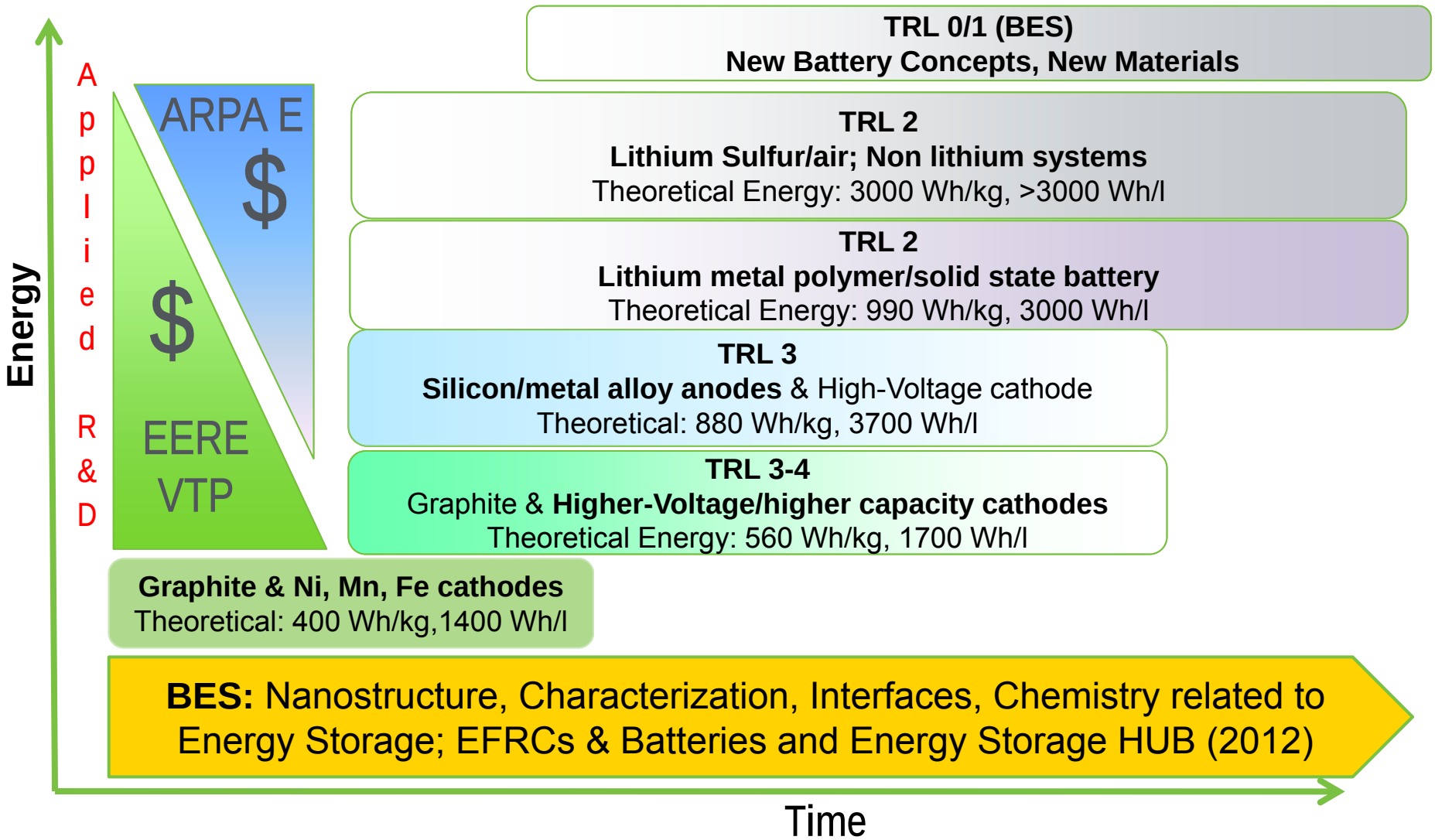
Next Generation (5 volt)
-High voltagelectrolytes
-Electrolytes for Li metal
-Non-flammable electrolytes

Cathode

Today's Technology
(120-160 mAh/g)
-Layered oxides
-Spinels
-Olivines

Next Generation
(300 mAh/g)
-Layered-layered oxides
-Metal phosphates
-Tailored Surfaces

Current R&D Focus and Associated 2011 Technology Readiness Levels



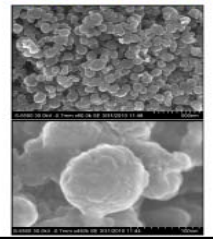
Current & Future Technologies

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	<100	~1000	85%	Concern
Lithium metal / Sulfur	250-400	<300	~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 R&D Activities and Targets

Advanced Materials Research

SEM of Li_2FeSiO_4/C nanospheres



- High energy cathodes
- Alloy, lithium anodes
- High voltage electrolytes
- Lithium metal/ Li-air

Cell Materials Targets

- Anode > 500 mAh/g
- Cathode>300 mAh/g
- High-voltage cathodes & electrolytes (5Volts)
- Solid-polymer electrolytes with > 10^{-3} S/cm ionic conductivity

High Energy & High Power Cell R&D

- High energy couples
- High rate electrodes
- Fabrication of high E cells
- Cell diagnostics

Cell Targets

- 200-300 Wh/kg
- 400-500 Wh/Liter
- 5,000 cycles
- 10+ calendar year life
- $300/kWh pack cost

Cell & Pack Development &Testing

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

Battery Pack Targets

- USABC Electric Vehicle ($100-150/kWh)
- USABC PHEV40 ($300/kWh)
- USABC PHEV10 ($300/kWh)
- USABC HEV ($20-25/KW)

Key Battery Performance Targets

Targets established through:

- **Electric drive vehicle modeling, simulation, and testing**
- **Battery Performance Modeling and Simulation**
- **Battery Hardware-In-the-Loop Testing**

Battery PerformanceTargets

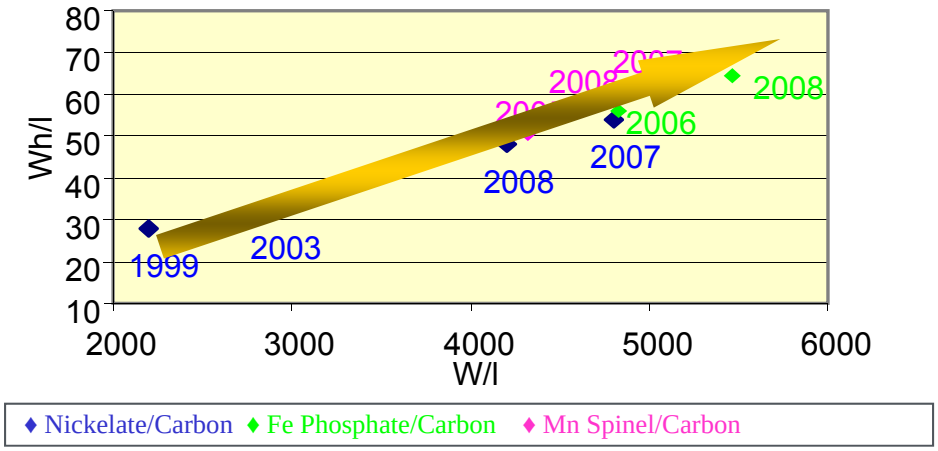
USDRIVE Energy Storage Targets	HEV	PHEV (2015)		EV (2020)
		PHEV-10	PHEV-40	
Equivalent Electric Range (miles)	N/A	10	40	200-300
Discharge Pulse Power: 10 sec (kW)	25	45	38	80
Regen Pulse Power: 10 sec (kW)	20	30	25	40
Recharge Rate (kW)	N/A	1.4	2.8	5-10
Cold Crank Power:-30 ºC/2sec (kW)	5	7		N/A
Available Energy (kWh)	0.3	3.4	11.6	40
Calendar Life (year)	15	10+		10
Cycle Life (cycles)	300,000 (shallow)	3,000-5,000 (deep)		1,000 (deep)
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

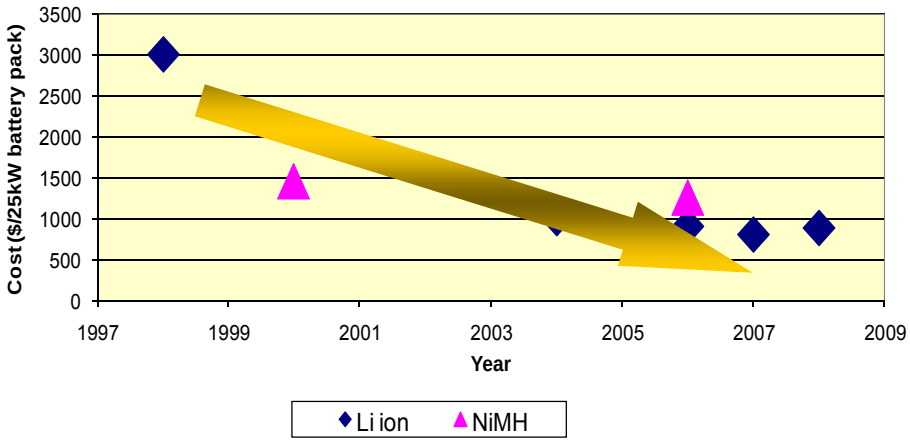
Most HEV performance targets met by Lithium-ion batteries.

- Mature Li-ion chemistries have demonstrated more than 300,000 cycles and 10-year life (through accelerated aging)
- Reduced R&D focus
  - cost reduction
  - improved abuse tolerance
  - Ultracapacitor development

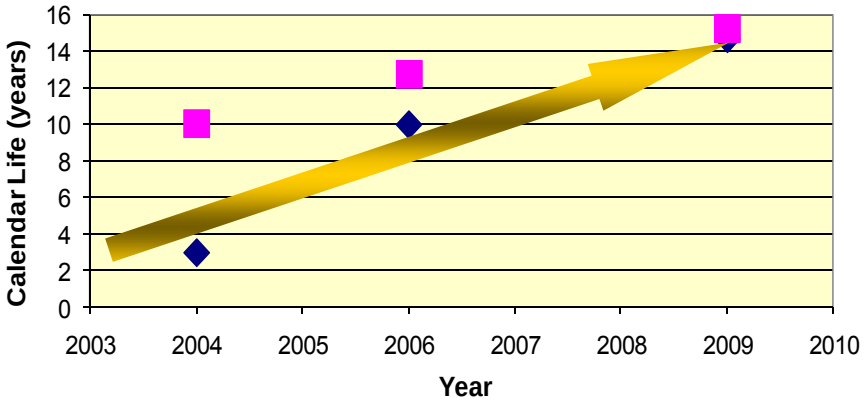
Energy and Power Density of USABC HEV Technologies - 3 Sample Data Sets



25kW HEV Battery Pack Cost



Calendar Life -- Two Sample Data Sets



Status of Conventional PHEV Battery Development

- Initial PHEV battery development contracts were completed in FY2011
  - Focus was to optimize mature HEV technologies for PHEV application
  - Significant gains in cost reduction (25-40%), cycle and calendar life
- New contracts to focus on high voltage/high capacity cathodes

DOE Energy Storage Targets	PHEV (10 mile AER)		PHEV(40 mile AER)	
	Target	Status (2011)	Target	Status (2011)
Discharge Pulse Power: 10 sec (kW)	45	~70	38	~95
Regen Pulse Power: 10 sec (kW)	30	~40	25	~70
Available Energy (kWh)	3.4	3.4	11.6	11.6
Calendar Life (year)	10+	8-10	10+	8-10
Cycle Life (deep cycles)	5000	3000-5000	5,000	3000-5000
Maximum System Weight (kg)	60	~57	120	~175
Maximum System Volume (l)	40	~45	80	~100
System Production Price @ 100k units/yr	$1,700	~2600	$3400	~6850

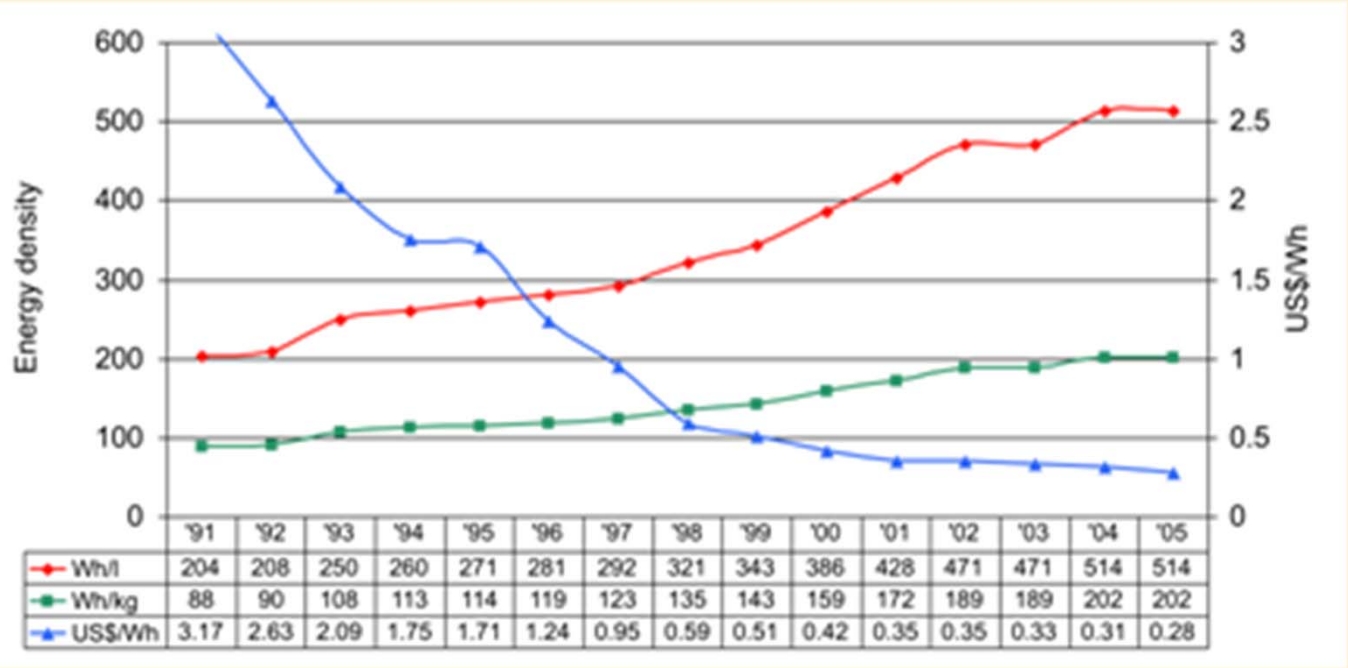
Status of Conventional EV Battery Development

- Initial EV battery development contracts were started in FY2011
- Contracts focus on high voltage/high capacity cathodes & EV cell design optimization
- Initial EV cell deliverables expected this quarter—information in table is based mostly on PHEV cell performance

Energy Storage Goals	**AEV (2020)**	Current
Equivalent Electric Range, miles	200-300	✓
Discharge Pulse Power (10 sec), kW	80-120	✓
Regenerative Pulse Power (10 sec), kW	40	✓
Available Energy, kWh	40-60	✓
Recharge Rate, kW	120	50
Calendar Life, years	10+	tbd
Cycle Life, cycles	1000 deep cycles	tbd
Operating Temperature Range, C	-40 to 60	0 to 40
System Weight, kg	160-240	500-750
System Volume, liters	80-120	200-400
Production Cost at 100,000 units/year	$125/kWh	< $600

Historic Trends of Commercial Lithium Ion Batteries

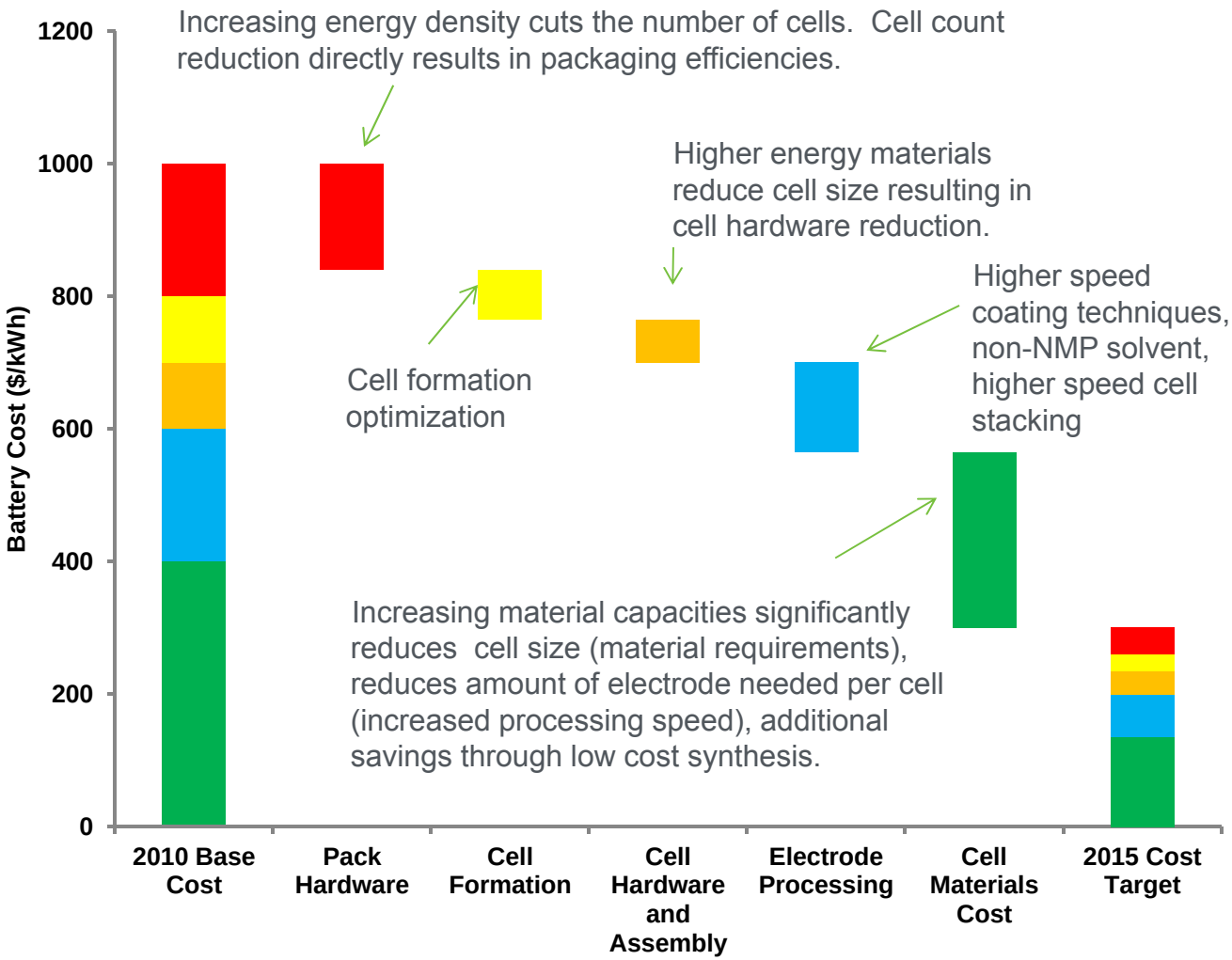
TRENDS FOR 18650 LI-ION CELLS

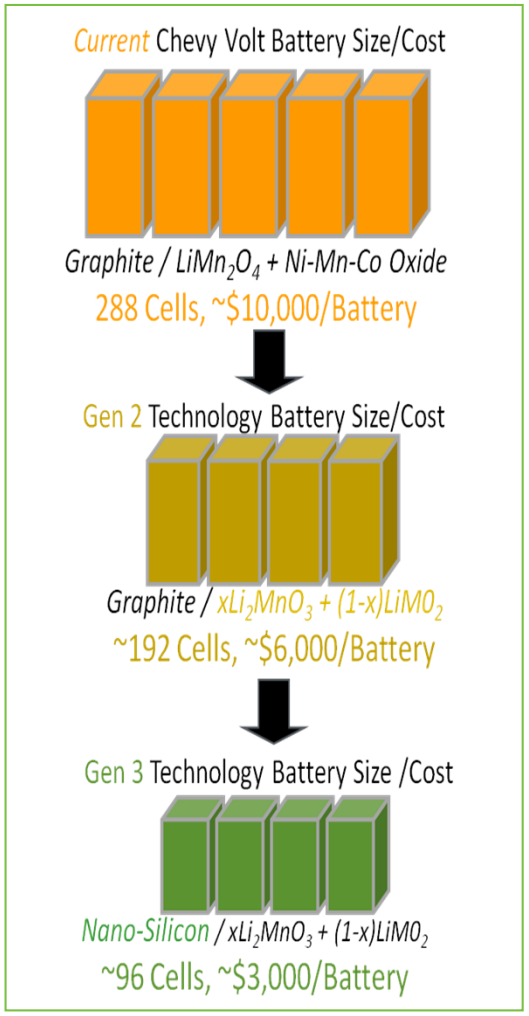


	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05
Wh/l	204	208	250	260	271	281	292	321	343	386	428	471	471	514	514
Wh/kg	88	90	108	113	114	119	123	135	143	159	172	189	189	202	202
US$/Wh	3.17	2.63	2.09	1.75	1.71	1.24	0.95	0.59	0.51	0.42	0.35	0.35	0.33	0.31	0.28

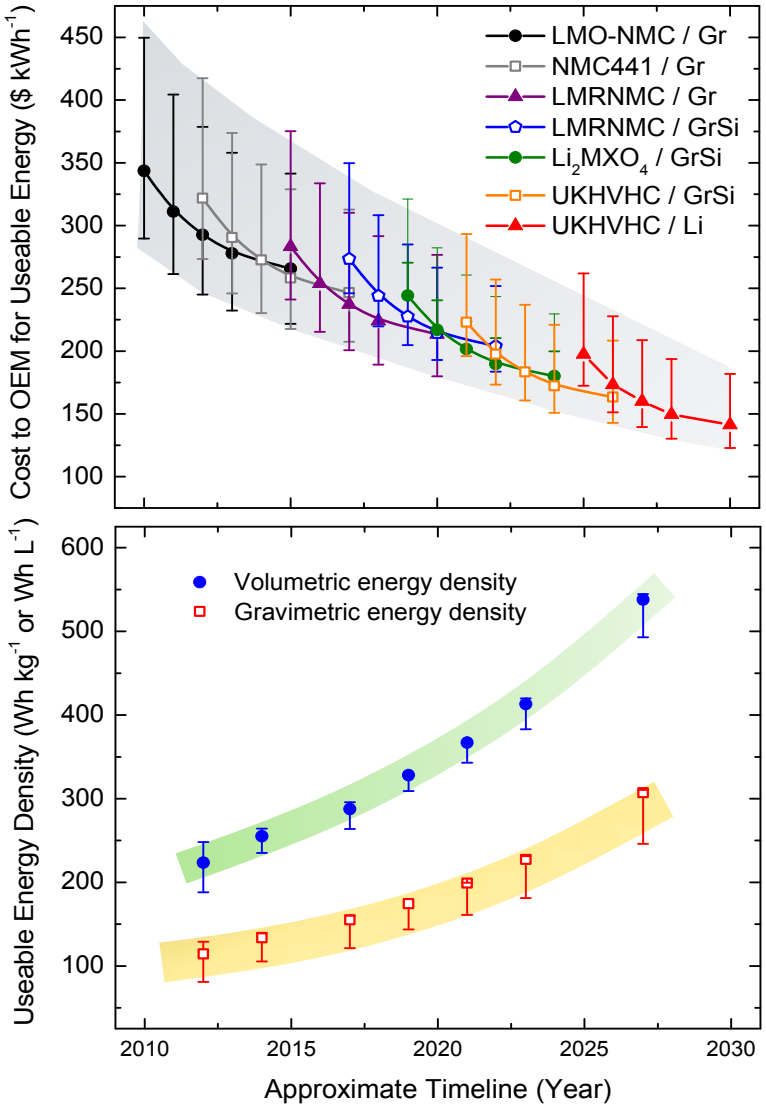
H. Takeshita, 2006 International Power Sources Conference

Battery Cost Reduction





Path Forward for Lithium Based Batteries



Source: Argonne National Laboratory

If high-risk research is successful, material advances may lead to a 60% reduction in cost and 250% increase in energy density

Calculations for a EV100: 30 kWh, 80 kW, 360V

- Smaller batteries will have higher costs for energy and lower energy densities. Larger energy batteries will have lower costs for energy and higher energy densities.
- Total cost to OEM includes purchased battery, battery management system, and liquid thermal management (w/o electric compressor) as calculated by BatPaC v1.0.
- Cases range from 70-150 μm maximum allowable electrode thickness and 40 – 80 Ah cell capacity (1P and 2P configurations).

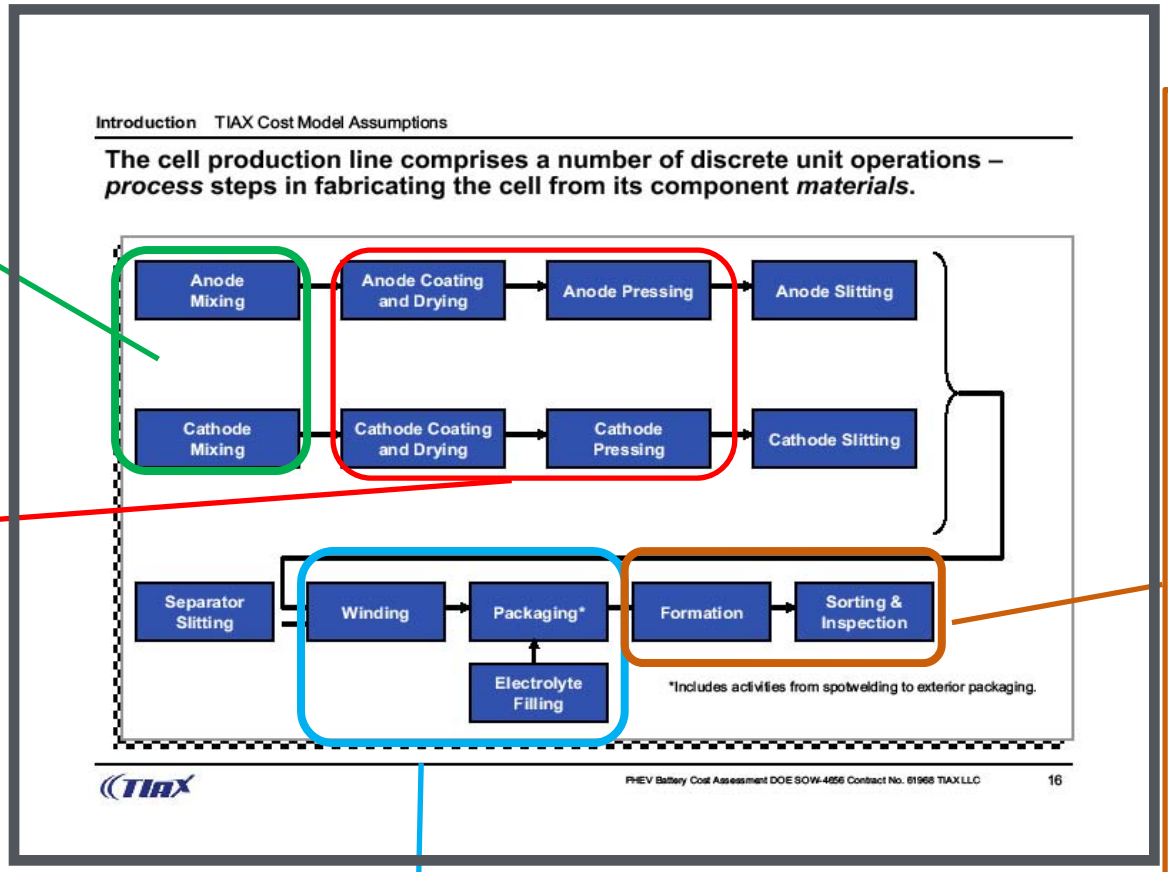
New R&D Thrusts: Manufacturing Technology

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

Outlook for Battery Cost and EV Production Capacity

On Track to Meet Administration's Goal of 1 Million EVs by 2015

	Battery Cost ($ per kWh)	Battery Production Capacity (10 kWh packs) ARRA	Battery Production Capacity (10 kWh packs) ATVM	Vehicle Production (announced, cumulative)
2008 2009	$1,000-$1,200	0	0	0
2010 2011	★ $600-$700	50,000		
2012	Goal = $500	150,000	144,000	
2013 2014				
2015	Goal = $300	500,000	488,000	1,222,200

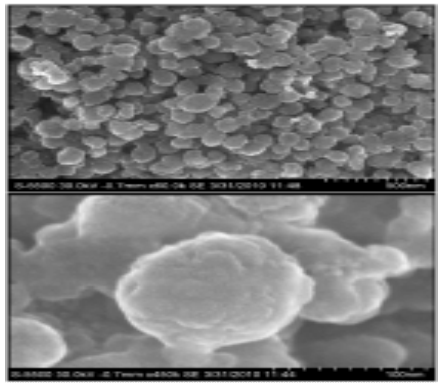
- Potential to reach 1.2 million cumulative Plug-In EV sales by 2015, based on announced production plans
- Chevy Volt & Nissan Leaf entered the market in late 2010 (~10,000 sold)
- Nine more models announced to enter during 2012-2013

~10M kWh per year production capacity in 2015

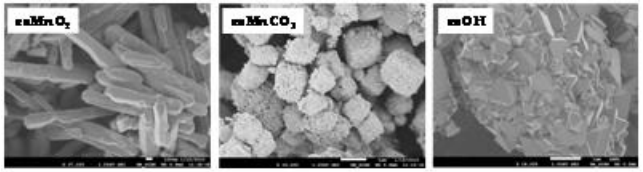
>8M kWh per year capacity demand in 2015

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