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**

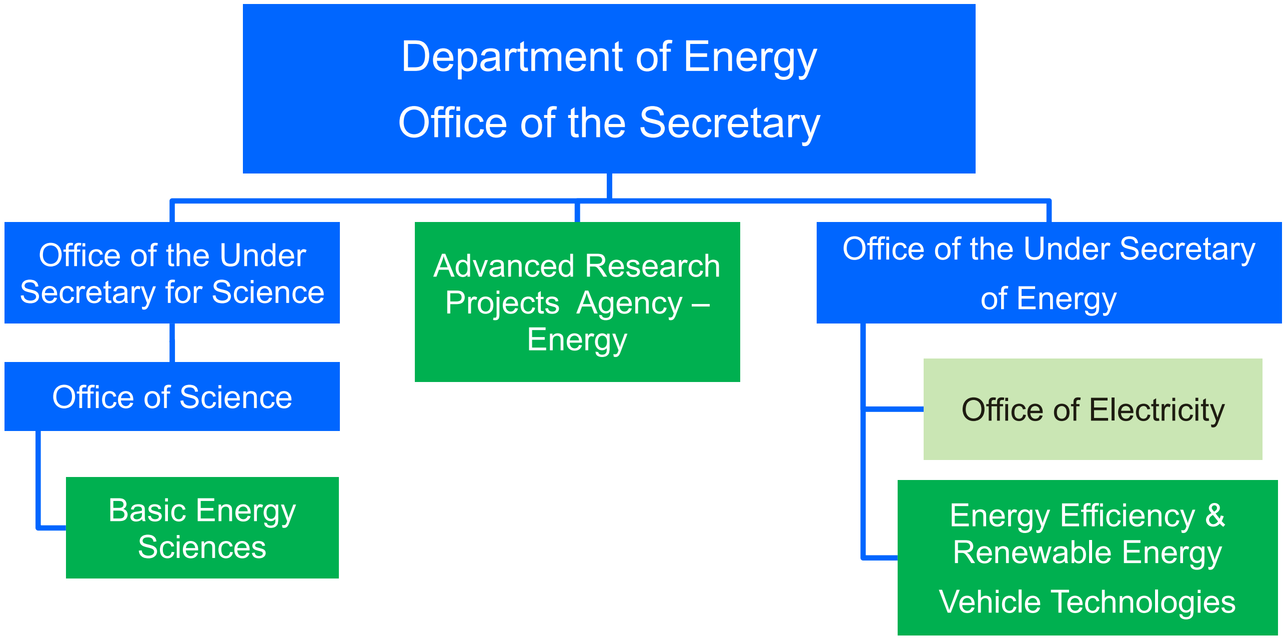
Nissan Leaf → All Electric
- ≥ 24 kWh battery
- Battery Power Rating: ≥ 110kW
- Battery Cost: about $15,000

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

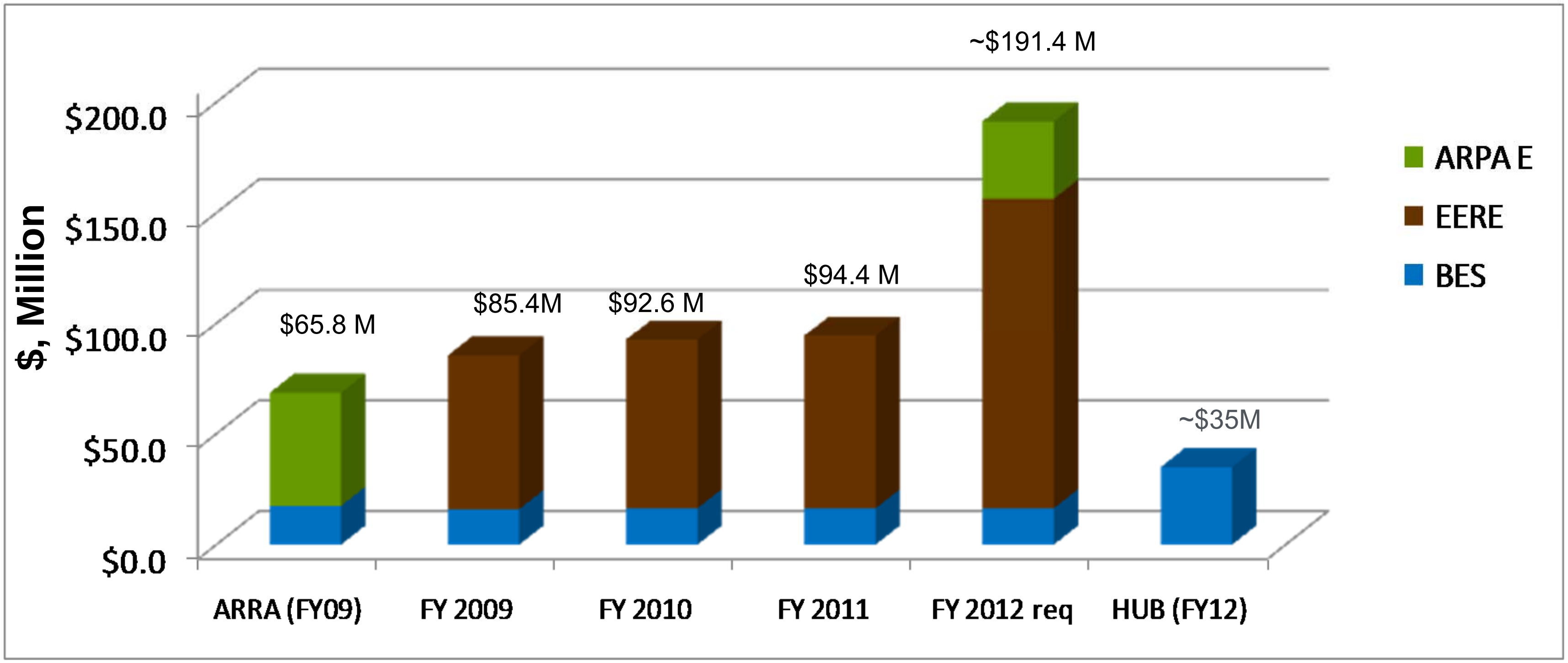
**Battery affordability and performance are the keys.**

# 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

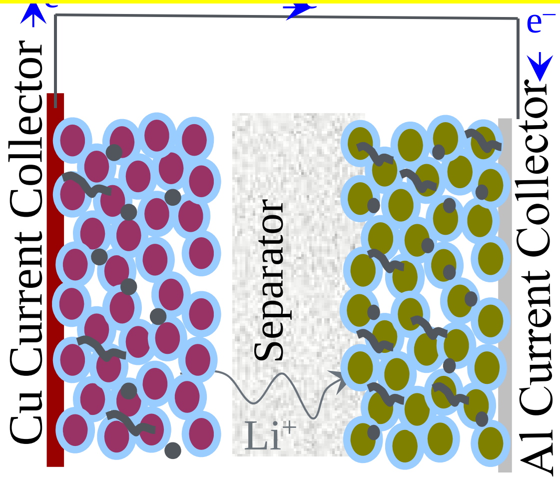
## DOE-funded Technologies Move to Commercial Applications

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

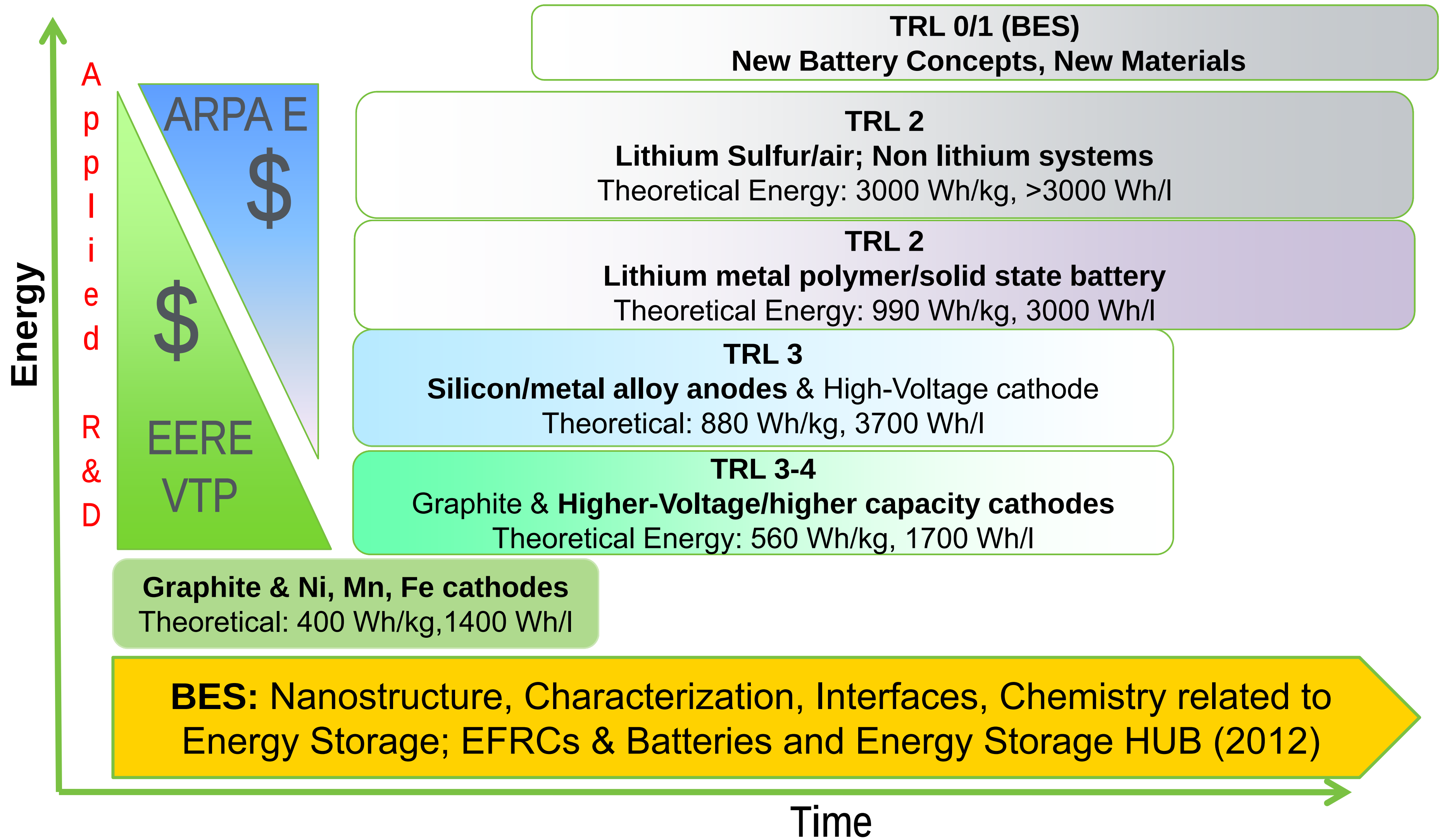
Next Generation (5 volt)
-High voltageelectrolytes
-Electrolytes for Li metal
-Non-flammable electrolytes

**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

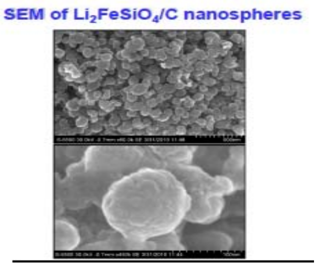


# Current & Future Technologies

| 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

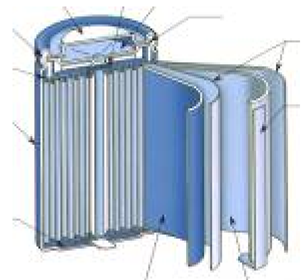



- ❑ High energy cathodes
- ❑ Alloy, lithium anodes
- ❑ High voltage electrolytes
- ❑ Lithium metal/ Li-air

**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

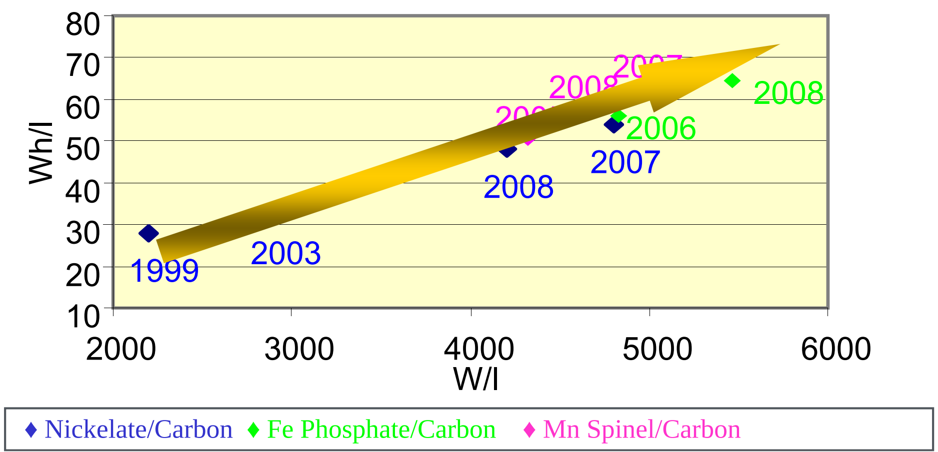
| USDRIVE Energy Storage Targets | HEV | PHEV (2015) | | EV (2020) |
|---|---|---|---|---|
| | | PHEV-10 | PHEV-40 | |
| Equivalent Electric Range (miles) | N/A | 10 | 40 | 200-300 |
| Discharge Pulse Power: 10 sec (kW) | 25 | 45 | 38 | 80 |
| Regen Pulse Power: 10 sec (kW) | 20 | 30 | 25 | 40 |
| Recharge 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

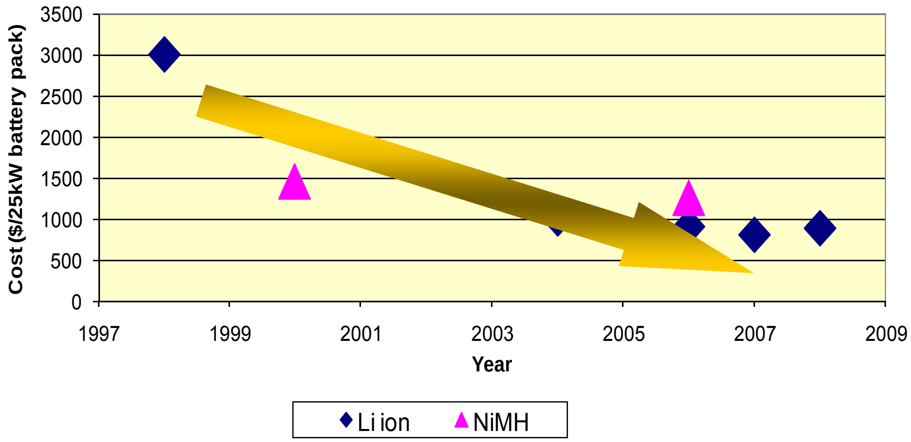
Most HEV performance targets met by Lithium-ion batteries.

- 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

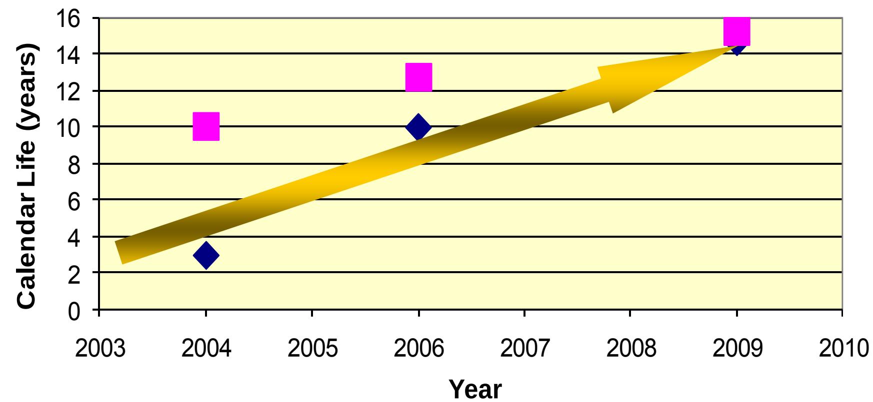
Energy and Power Density of USABC HEV Technologies - 3 Sample Data Sets




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 |

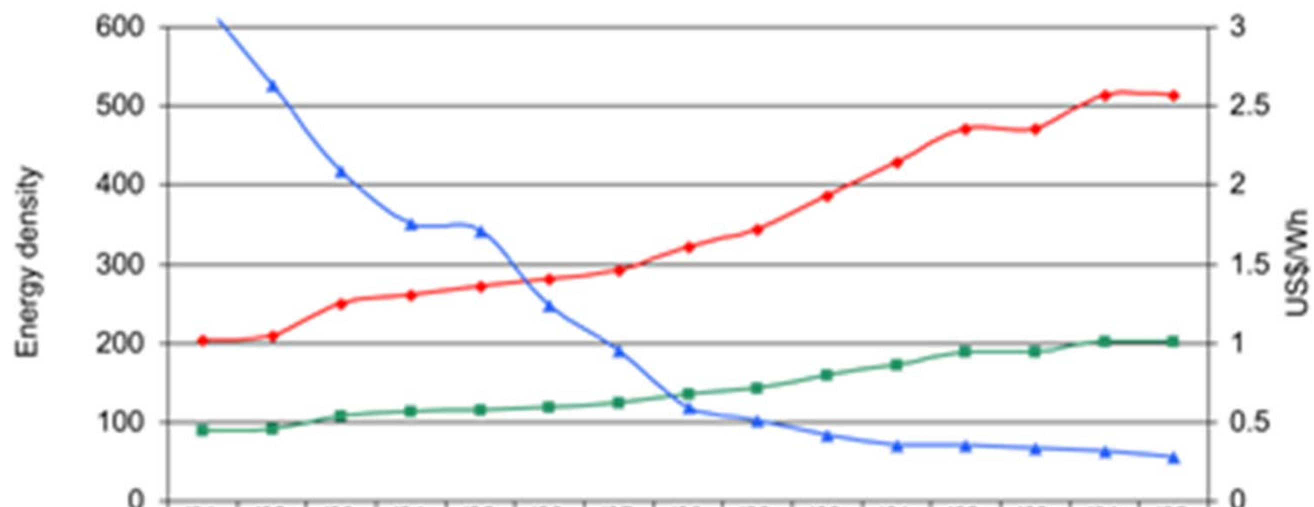
# Status of Conventional EV Battery Development

- 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

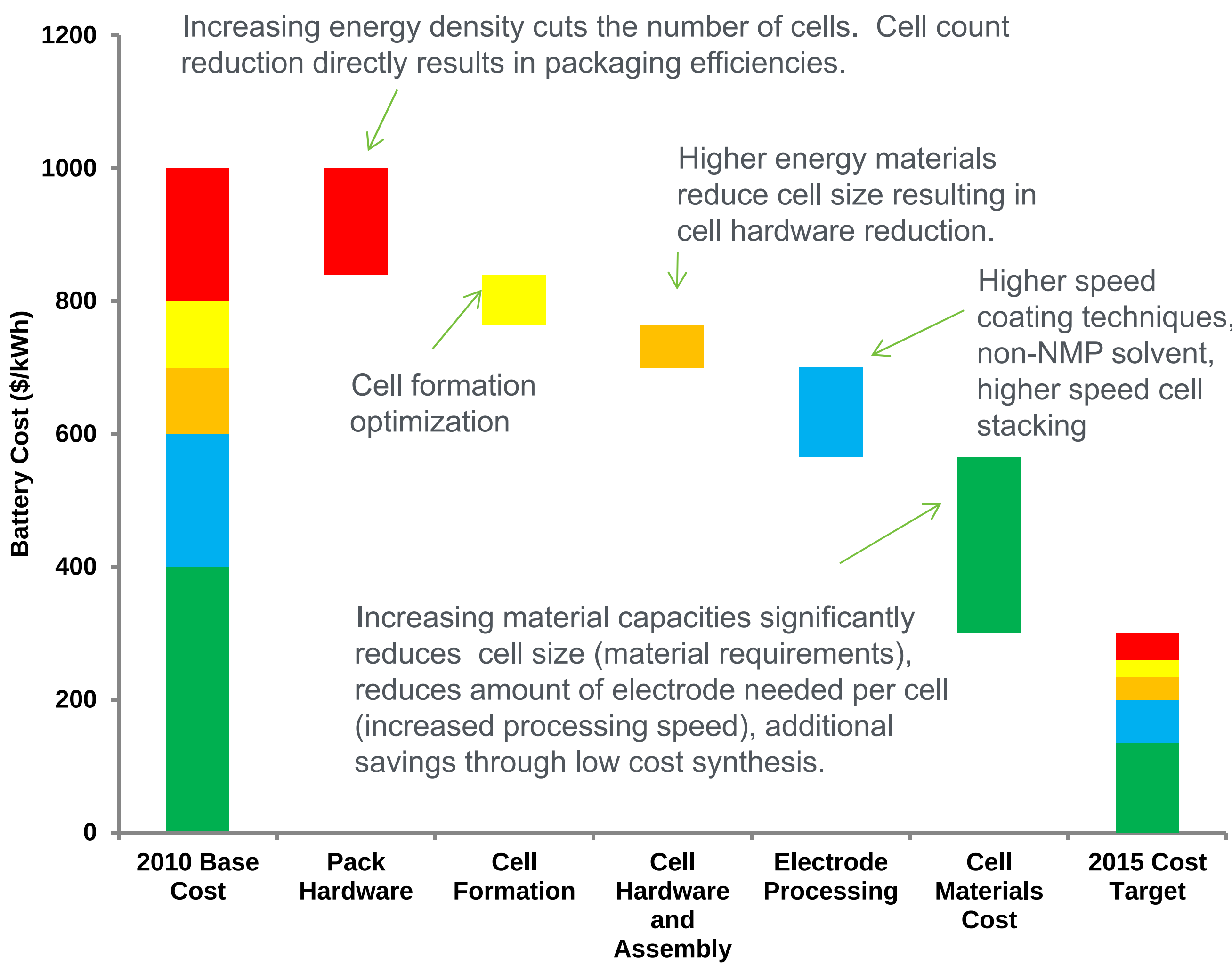


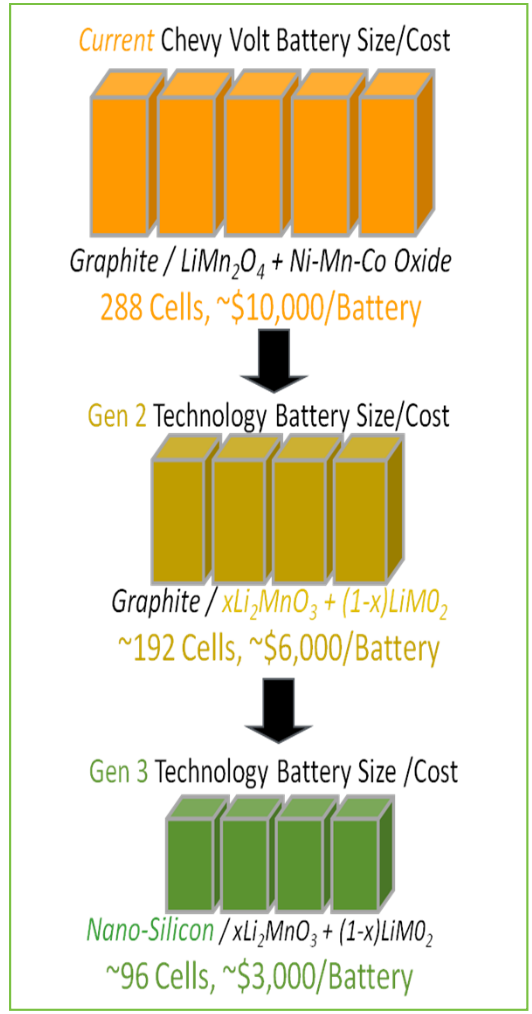

| | '91 | '92 | '93 | '94 | '95 | '96 | '97 | '98 | '99 | '00 | '01 | '02 | '03 | '04 | '05 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wh/l | 204 | 208 | 250 | 260 | 271 | 281 | 292 | 321 | 343 | 386 | 428 | 471 | 471 | 514 | 514 |
| Wh/kg | 88 | 90 | 108 | 113 | 114 | 119 | 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

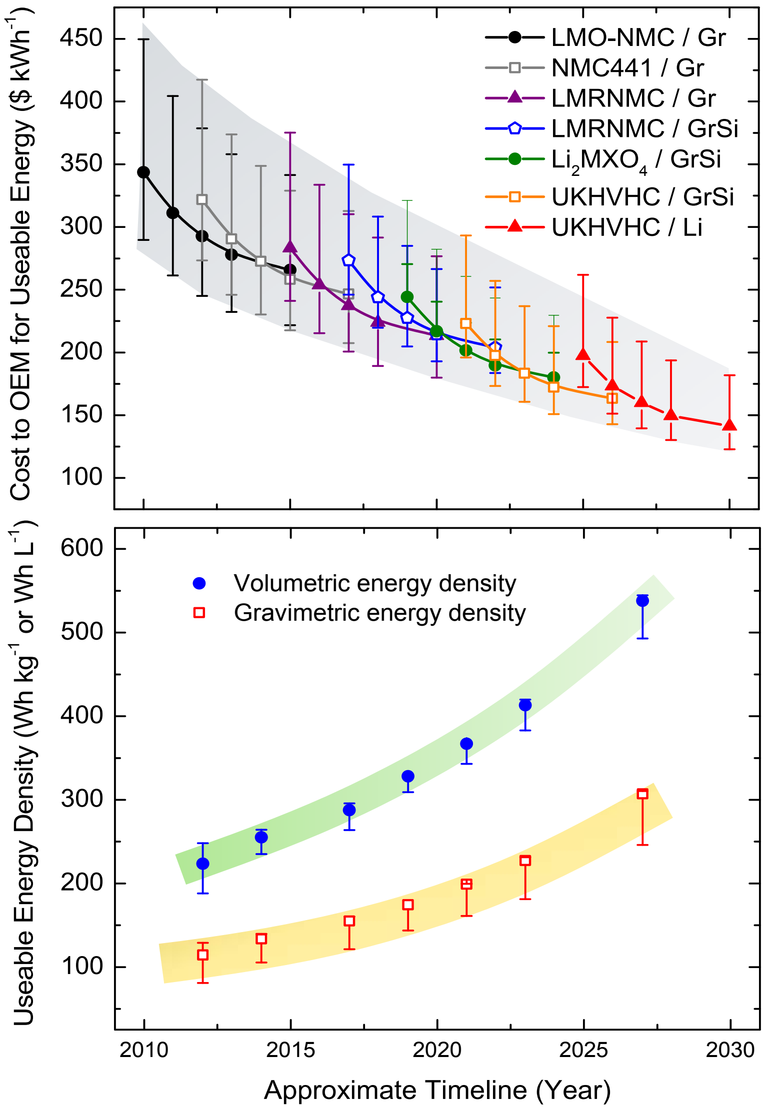
Beijing Li-Ion forum

# 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).

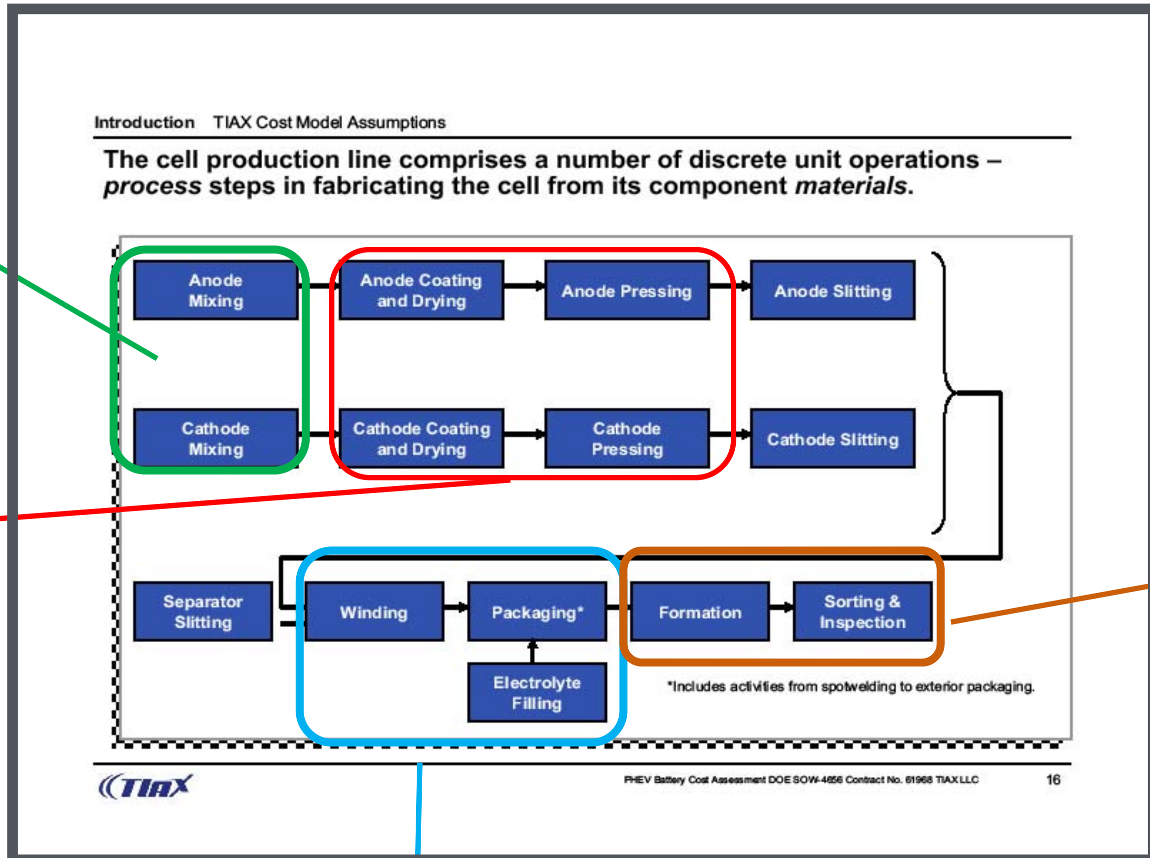
# New R&D Thrusts: Manufacturing Technology

**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




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

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

# Outlook for Battery Cost and EV Production Capacity

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

| Year | 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 | Goal = $300 | | | |
| 2015 | | 500,000 | 488,000 | 1,222,200 |

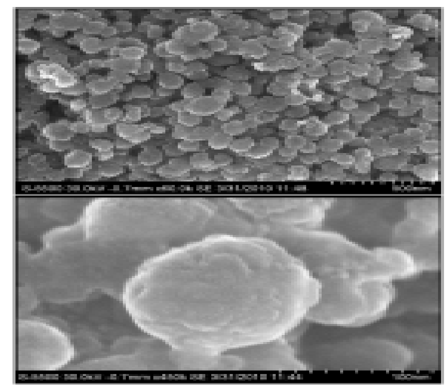
- Potential to reach 1.2 million cumulative Plug-In EV sales by 2015, based on announced production plans
- Chevy Volt & Nissan Leaf entered the market in late 2010 (~10,000 sold)
- Nine more models announced to enter during 2012-2013

***~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