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 CO₂ 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).
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.
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 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  

**Cathode**

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

**Electrolyte**

**Today’s Tech (4 volt)**  
- Liquid organic solvents & gels  

**Next Generation (5 volt)**  
- High voltage electrolytes  
- Electrolytes for Li metal  
- Non-flammable electrolytes
Current R&D Focus and Associated 2011 Technology Readiness Levels

**Energy**

- **ARPA E**
  - TRL 0/1 (BES)
  - New Battery Concepts, New Materials

- **EERE**
  - Graphite & Ni, Mn, Fe cathodes
    - Theoretical: 400 Wh/kg, 1400 Wh/l

- **VTP**
  - Graphite & Higher-Voltage/higher capacity cathodes
    - Theoretical Energy: 560 Wh/kg, 1700 Wh/l

- **BES**
  - Nanostructure, Characterization, Interfaces, Chemistry related to Energy Storage; EFRCs & Batteries and Energy Storage HUB (2012)

**Technology Readiness Levels**

- **TRL 2**
  - Lithium Sulfur/air; Non lithium systems
    - Theoretical Energy: 3000 Wh/kg, >3000 Wh/l

- **TRL 2**
  - Lithium metal polymer/solid state battery
    - Theoretical Energy: 990 Wh/kg, 3000 Wh/l

- **TRL 3**
  - Silicon/metal alloy anodes & High-Voltage cathode
    - Theoretical: 880 Wh/kg, 3700 Wh/l

- **TRL 3-4**
  - Graphite & Higher-Voltage/higher capacity cathodes
    - Theoretical Energy: 560 Wh/kg, 1700 Wh/l

**Time**
## Attributes of Battery Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Energy (Wh/kg)</th>
<th>Power (W/kg)</th>
<th>Life (cycles)</th>
<th>Energy Efficiency</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium-ion (current status)</td>
<td>80</td>
<td>500-1000</td>
<td>&gt;3,000</td>
<td>&gt; 90%</td>
<td>Meets SAE J2929</td>
</tr>
<tr>
<td>Lithium-ion (future generations)</td>
<td>200+</td>
<td>2,000</td>
<td>&gt;3,000</td>
<td>&gt; 90%</td>
<td>Meet SAE J2929</td>
</tr>
<tr>
<td>Lithium metal polymer</td>
<td>150-200</td>
<td>&lt;100</td>
<td>~1000</td>
<td>85%</td>
<td>Concern</td>
</tr>
<tr>
<td>Lithium metal / Sulfur</td>
<td>250-400</td>
<td>&lt;300</td>
<td>~100</td>
<td>85%</td>
<td>Concern</td>
</tr>
<tr>
<td>Lithium metal / Air</td>
<td>400-800</td>
<td>Poor</td>
<td>~10</td>
<td>&lt;70%</td>
<td>Concern</td>
</tr>
<tr>
<td>DOE 2020 Goals</td>
<td>250</td>
<td>2,000</td>
<td>500-3,750</td>
<td>&gt;90%</td>
<td>Meet SAE J2929</td>
</tr>
</tbody>
</table>
VTP Battery R&D Activities and Targets

Advanced Materials Research

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

High Energy & High Power Cell R&D

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

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

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 Performance Targets

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent Electric Range (miles)</td>
<td>N/A</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Discharge Pulse Power: 10 sec (kW)</td>
<td>25</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>Regen Pulse Power: 10 sec (kW)</td>
<td>20</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Recharge Rate (kW)</td>
<td>N/A</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Cold Crank Power: -30 ºC/2sec (kW)</td>
<td>5</td>
<td>7</td>
<td>N/A</td>
</tr>
<tr>
<td>Available Energy (kWh)</td>
<td>0.3</td>
<td>3.4</td>
<td>11.6</td>
</tr>
<tr>
<td>Calendar Life (year)</td>
<td>15</td>
<td>10+</td>
<td>10</td>
</tr>
<tr>
<td>Cycle Life (cycles)</td>
<td>300,000 (shallow)</td>
<td>3,000-5,000 (deep)</td>
<td>1,000 (deep)</td>
</tr>
<tr>
<td>Maximum System Weight (kg)</td>
<td>40</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Maximum System Volume (l)</td>
<td>32</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>Operating Temperature Range (ºC)</td>
<td>-30 to +52</td>
<td>-30 to +52</td>
<td>-40 to +85</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>DOE Energy Storage Targets</th>
<th>PHEV (10 mile AER)</th>
<th>PHEV (40 mile AER)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Target</td>
<td>Status (2011)</td>
</tr>
<tr>
<td>Discharge Pulse Power: 10 sec (kW)</td>
<td>45</td>
<td>~70</td>
</tr>
<tr>
<td>Regen Pulse Power: 10 sec (kW)</td>
<td>30</td>
<td>~40</td>
</tr>
<tr>
<td>Available Energy (kWh)</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Calendar Life (year)</td>
<td>10+</td>
<td>8-10</td>
</tr>
<tr>
<td>Cycle Life (deep cycles)</td>
<td>5000</td>
<td>3000-5000</td>
</tr>
<tr>
<td>Maximum System Weight (kg)</td>
<td>60</td>
<td>~57</td>
</tr>
<tr>
<td>Maximum System Volume (l)</td>
<td>40</td>
<td>~45</td>
</tr>
<tr>
<td>System Production Price @ 100k units/yr</td>
<td>$1,700</td>
<td>~2600</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th>AEV (2020)</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent Electric Range, miles</td>
<td>200-300</td>
<td>✓</td>
</tr>
<tr>
<td>Discharge Pulse Power (10 sec), kW</td>
<td>80-120</td>
<td>✓</td>
</tr>
<tr>
<td>Regenerative Pulse Power (10 sec), kW</td>
<td>40</td>
<td>✓</td>
</tr>
<tr>
<td>Available Energy, kWh</td>
<td>40-60</td>
<td>✓</td>
</tr>
<tr>
<td>Recharge Rate, kW</td>
<td>120</td>
<td>50</td>
</tr>
<tr>
<td>Calendar Life, years</td>
<td>10+</td>
<td>tbd</td>
</tr>
<tr>
<td>Cycle Life, cycles</td>
<td>1000 deep cycles</td>
<td>tbd</td>
</tr>
<tr>
<td>Operating Temperature Range, C</td>
<td>-40 to 60</td>
<td>0 to 40</td>
</tr>
<tr>
<td>System Weight, kg</td>
<td>160-240</td>
<td>500-750</td>
</tr>
<tr>
<td>System Volume, liters</td>
<td>80-120</td>
<td>200-400</td>
</tr>
<tr>
<td>Production Cost at 100,000 units/year</td>
<td>$125/kWh</td>
<td>&lt; $600</td>
</tr>
</tbody>
</table>
Historic Trends of Commercial Lithium Ion Batteries

TRENDS FOR 18650 LI-ION CELLS

H. Takeshita, 2006 International Power Sources Conference
Increasing energy density cuts the number of cells. Cell count reduction directly results in packaging efficiencies.

Higher energy materials reduce cell size resulting in cell hardware reduction.

Higher speed coating techniques, non-NMP solvent, higher speed cell stacking

Increasing material capacities significantly reduces cell size (material requirements), reduces amount of electrode needed per cell (increased processing speed), additional savings through low cost synthesis.
Path Forward for Lithium Based Batteries

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).

Source: Argonne National Laboratory
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**

<table>
<thead>
<tr>
<th>Year</th>
<th>Battery Cost ($ per kWh)</th>
<th>Battery Production Capacity (10 kWh packs)</th>
<th>Vehicle Production (announced, cumulative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>$1,000-$1,200</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2009</td>
<td>$600-$700</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2010</td>
<td>$600-$700</td>
<td>50,000</td>
<td>0</td>
</tr>
<tr>
<td>2011</td>
<td>Goal = $500</td>
<td>150,000</td>
<td>0</td>
</tr>
<tr>
<td>2012</td>
<td>Goal = $500</td>
<td>500,000</td>
<td>1,222,200</td>
</tr>
<tr>
<td>2013</td>
<td>Goal = $300</td>
<td>488,000</td>
<td>&gt;8M kWh per year capacity demand in 2015</td>
</tr>
<tr>
<td>2014</td>
<td>Goal = $300</td>
<td></td>
<td>&gt;8M kWh per year capacity demand in 2015</td>
</tr>
<tr>
<td>2015</td>
<td>Goal = $300</td>
<td></td>
<td>1,222,200</td>
</tr>
</tbody>
</table>

- 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.
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