Battery Choices for Different Plug-in HEV Configurations

Plug-in HEV Forum and Technical Roundtable
South Coast Air Quality Management District
Diamond Bar, CA

July 12, 2006

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National Renewable Energy Laboratory

With support from
FreedomCAR and Vehicle Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
NREL’s Plug-in HEV R&D Activities

• Battery Level
  — R&D support to developers
  — Testing and evaluation – Sprinter PHEV testing
  — Thermal characterization and design
  — Supporting requirement analysis and development

• Vehicle Level
  — Real-world PHEV simulations - fuel economy and recharging
  — Support development of test procedures for PHEVs and MPG reporting
  — Evaluation of alternative PHEV design strategies
    » all-electric vs. blended operation
  — PHEV design cost-benefit analysis

• Utility Level
  — Assessment of PHEV impacts on utilities
  — Exploring synergies between PHEVs and wind power
  — V2G opportunities for PHEVs in regulation services

• National Level
  — Benefits assessment - oil use and emissions
  — Renewable community – linking PHEV to renewable

• Analysis support to DOE, OEMs, and others
  — Working to identify and overcome barriers to PHEV adoption

Secretary of Energy visiting NREL on 7/7/06 for ribbon cutting of the new S&T Facility and then discussing plug-in hybrids with EnergyCS & Hymotion
Topics of the Presentation

• Battery Technologies for PHEVs
  — State-of-the-art
  — Advances
• Impact of Vehicle Attributes on Battery
  — EV Range
  — System Architecture
  — Driving cycles and profiles
• Concluding Remarks and a Few Thoughts
Key Messages

• There is a broad spectrum of HEV-PHEV designs leading to different battery requirements.
• Batteries are available that could meet the energy and power demands for PHEVs, but cost and limited cycle/calendar life are major barriers for affordable PHEV introduction.
  • NiMH could do the job
  • Li-ion are potentially best candidates
  • All Li-ions are not “created equal”
• There are emission benefits with PHEVs, but the difference between pure EV range and blended EV range impacts may need to be understood
• PHEVs are the most cost-effective choice in a scenario of projected (low) battery costs and high fuel costs.
Batteries in Current PHEVs

- Varta: NiMH
- Electro Energy Inc.: Co/Ni based Li-Ion
- Johnson Controls/SAFT: Co/Ni based Li-Ion
- Kokam: Iron phosphate based Li-Ion
- Valence Technology: Iron phosphate based Li-Ion
- A123 Systems: Iron phosphate based Li-Ion
# High Power Battery and Ultracapacitor Characteristics for Hybrid Vehicles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VRLA</th>
<th>NiMH</th>
<th>Li Ion</th>
<th>Ultracap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell configuration</td>
<td>Parallel plates; spirally wound cylindrical</td>
<td>Spirally wound cylindrical; parallel plates</td>
<td>Spirally wound cylindrical &amp; elliptic</td>
<td>Spirally wound cylindrical &amp; elliptic</td>
</tr>
<tr>
<td>Nominal cell voltage (V)</td>
<td>2</td>
<td>1.2</td>
<td>3.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Battery electrolyte</td>
<td>Acid</td>
<td>Alkaline</td>
<td>Organic</td>
<td>Organic</td>
</tr>
<tr>
<td>Specific energy, Wh/kg</td>
<td>25</td>
<td>40</td>
<td>60 to 80</td>
<td>5</td>
</tr>
<tr>
<td>Battery/Module specific power, 10 sec, W/kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23°C, 50% SOC</td>
<td>400</td>
<td>1300</td>
<td>3000</td>
<td>&gt;3000</td>
</tr>
<tr>
<td>-20°C, 50% SOC</td>
<td>250</td>
<td>250</td>
<td>400</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Charge acceptance, 10 sec. W/kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23°C, 50% SOC</td>
<td>200</td>
<td>1200</td>
<td>2000</td>
<td>&gt;3000</td>
</tr>
<tr>
<td>2010 Projected Cost &gt;100,000 per year</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$/kWh, Module</td>
<td>100.00</td>
<td>500.00</td>
<td>700.00</td>
<td>20,000.00</td>
</tr>
<tr>
<td>$/kWh, Full pack</td>
<td>140</td>
<td>600</td>
<td>1100</td>
<td>25000</td>
</tr>
<tr>
<td>$/kW, pack</td>
<td>9.00</td>
<td>18.00</td>
<td>22.00</td>
<td>40.00</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>Good</td>
<td>Moderate</td>
<td>Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>Thermal managements requirements</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
<td>Light</td>
</tr>
<tr>
<td>Electrical control</td>
<td>Light</td>
<td>Light</td>
<td>Tight</td>
<td>Tight</td>
</tr>
</tbody>
</table>

Source: M. Anderman, AABC-04 Tutorial, San Francisco, CA June 2004
## Qualitative Comparison of Large-Format Battery Technologies for PHEVS

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Lead Acid</th>
<th>NiMH</th>
<th>Li-Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Volume (lit)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Capacity/Energy (kWh)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Discharge Power (kW)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Regen Power (kW)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Cold-Temperature (kWh &amp; kW)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Shallow Cycle Life (number)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Deep Cycle Life (number)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Calendar Life (years)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Cost ($/kW or $/kWh)</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Safety- Abuse Tolerance</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Maturity - Technology</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Maturity - Manufacturing</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
</tbody>
</table>

### Key
- Poor
- Fair
- Good

- **Qualitative Comparison of Large-Format Battery Technologies for PHEVS**

United States Department of Energy
National Renewable Energy Laboratory

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- **NREL**
  - National Renewable Energy Laboratory
NiMH has Matured in Power and Energy

Specific energy ranging from 45 Wh/kg to 80 Wh/kg depending on the power capability.

Source: Reproduced from A. Fetcenko (Ovonic Battery Company) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.
NiMH batteries are forecasted to dominate the HEV market for a while

Panasonic
6.5 Ah Battery for Toyota

Sanyo
6.5 Ah HEV cells in Ford Escape HEV
Source: Sanyo website news

Cobasys
EV module (left) and 42V HEV batteries

Electro Energy
Pack with bipolar Cells/Modules
Bipolar pack in a Plug-In Prius

Source: C. Pillot (Avicenne) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

Source: Images provided by James Landi of Electro Energy Inc.
Li Ion Technology – Diverse Chemistry & Opportunity

Many anodes are possible
- Carbon/Graphite
- Titanate (Li_4Ti_5O_12)
- Titanium oxide based
- Thin Oxide based
- Tungsten oxide

Many electrolytes are possible
- LiPF_6 based
- LiBF_4 based
- Various solid electrolytes
- Polymer electrolytes

Many cathodes are possible
- Cobalt oxide
- Manganese oxide
- Mixed oxides with Nickel
- Iron phosphate
- Vanadium oxide based

Voltage ~3.2-3.8 V
Cycle life ~1000-3000 Wh/kg >150
Wh/l >400
Discharge -30 to 60°C
Shelf life <10%/year

Characteristics of Cathode Materials

Theoretical values for a battery system relative to graphite anode and LiPF₆ electrolyte

<table>
<thead>
<tr>
<th>Material</th>
<th>Δx</th>
<th>mAh/g</th>
<th>avg V</th>
<th>Wh/kg</th>
<th>Wh/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCoO₂</td>
<td>0.55</td>
<td>151</td>
<td>4.00</td>
<td>602</td>
<td>3073</td>
</tr>
<tr>
<td>LiNi₀.₈Co₀.₁₅Al₀.₅O₂</td>
<td>0.7</td>
<td>195</td>
<td>3.80</td>
<td>742</td>
<td>3784</td>
</tr>
<tr>
<td>LiMn₂O₄</td>
<td>0.8</td>
<td>119</td>
<td>4.05</td>
<td>480</td>
<td>2065</td>
</tr>
<tr>
<td>LiMn₁/₃Co₁/₃Ni₁/₃O₂</td>
<td>0.55</td>
<td>153</td>
<td>3.85</td>
<td>588</td>
<td>2912</td>
</tr>
<tr>
<td>LiFePO₄*</td>
<td>0.95</td>
<td>161</td>
<td>3.40</td>
<td>549</td>
<td>1976</td>
</tr>
</tbody>
</table>

*Typically diluted with 10% carbon for electronic conductivity

Lower potential can provide greater stability in electrolyte
Cobalt oxide most widely used in consumer cells but recently too expensive
LiMn₁/₃Co₁/₃Ni₁/₃O₂ newer than LiNiCoO₂
Mn₂O₄ around for many years – not competitive for consumer – good for high power
LiFePO₄* – very new – too low energy density for consumer electronics
  - safe on overcharge but need electronics to prevent low voltage
  - may require larger number of cells due to lower voltage

Nano-materials in Li-Ion Batteries Improve Performance & Life

- Easier diffusion of Li-ion into and out of the host
  - High specific capacity at high rate
- Increased electrode surface area and thus higher rates
- Stable 3 dimensional host materials
- Small dimensional change as Li-ions are cycled in and out
  - Improved cycling life due to less structural change
  - Low irreversible capacity loss
- Exhibit of both faradaic and non-faradaic capacity
  - Higher capacity retention
- Enabling new materials

Source: Excerpts A. Singhal (NEI Corporation) and E. House (Altair Nanotechnologies) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.
Many Oxide Based Li-Ion Batteries are Available

- Johnson Control
- Saft
- LG Chem
- Kokam
- Sony
- Sanyo
- Samsung
- Panasonic
- Electrovaya
- NEC Lamilion Energy
- Nissan
- Lishen
- Pionics
- SK Corp
- GS Yuasa
- Altair Nanotechnologies
Lithium Iron Phosphate (LiFePO$_4$) Cathodes

+ High stability and non-toxic
+ Good specific capacity
+ Flat voltage profile
+ Cost effective (less expensive cathode)
+ Improved safety
- Lower voltage than other cathodes
- Poor Li diffusion ($D_{Li} \sim 10^{-13}$ cm$^2$/Sec)
- Poor electronic conductivity ($\sim 10^{-8}$ S/cm)

• Approach many use to overcome poor characteristics
  — Use nano LiFePO$_4$ – carbon composite
  — Use larger number of cells
  — Nano structured materials

Source: Various papers from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.
Improvements in Iron Phosphate Li-ion Batteries

Valence Technology 18650 Cells
100 Wh/kg in cell 84 Wh/kg in U Charge module

The battery with standard lead acid battery form factor includes a battery management system.


<table>
<thead>
<tr>
<th>Specifications</th>
<th>U1-12XP</th>
<th>U24-12XP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>12.8 V</td>
<td>12.8 V</td>
</tr>
<tr>
<td>Capacit (C/5)</td>
<td>40 Ah</td>
<td>100 Ah</td>
</tr>
<tr>
<td>Specific energy</td>
<td>84 Wh/kg</td>
<td>82 Wh/kg</td>
</tr>
<tr>
<td>Energy density</td>
<td>110 Wh/l</td>
<td>126 Wh/l</td>
</tr>
<tr>
<td>Standard Discharge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. cont. current</td>
<td>80 A</td>
<td>150 A</td>
</tr>
<tr>
<td>Max. 30 sec. pulse</td>
<td>120 A</td>
<td>300 A</td>
</tr>
<tr>
<td>Cut-off voltage</td>
<td>10 V</td>
<td>10 V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Density</th>
<th>Weight to discharge @1500W</th>
<th>Safety</th>
<th>Life at 100% DoD 1C rate</th>
<th>Environmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>3600 W/Kg</td>
<td>0.9 lbs</td>
<td>✓</td>
<td>~7000</td>
<td>✓</td>
</tr>
</tbody>
</table>

Based on: Novel nano scale doped phosphate active materials (pat. pending)
Low impedance cell design and electrolyte (pat. pending)

A123 Systems
with 26650 Cells
100 Wh/kg

Source: Andrew Chu (A123 Systems) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

100%DOD 1C charge, 1C discharge cycling data. Using first 1000 cycles, extrapolated cycle life: ~7000 cycles.
Improving Li-Ion Batteries with Titanate Anode

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Traditional Li Ion Batteries</th>
<th>Li Ion Batteries Using Altairnano materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>Graphite</td>
<td>Lithium titanate spinel Nano-Structured oxides</td>
</tr>
<tr>
<td>Cathode</td>
<td>Cobaltate</td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge rate</td>
<td>½ C</td>
<td>20 C and greater</td>
</tr>
<tr>
<td>Discharge rate</td>
<td>4 C</td>
<td>40 C and greater</td>
</tr>
<tr>
<td>Cycle life</td>
<td>300-500 cycles</td>
<td>9,000 cycles (full DOD)</td>
</tr>
<tr>
<td>Calendar life</td>
<td>2-3 years</td>
<td>10-15 years</td>
</tr>
</tbody>
</table>

Source: E. House (Altair Nanotechnologies) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

Altaire Nanotechnologies Inc.
- Improved low temperature performance
- Faster charge acceptance
- Longer cycle life
- 80-100 Wh/kg
- 2000-4000 W/kg

~90% SOC of RT Cell at -30°C and 1-2C Charge Rate!
PHEV Battery Options

Need for higher energy than HEVs, so P/E lower

Available specific energy (Wh/kg)

Specific power (W/kg)

P/E = Power/ Energy (W/Wh)

Expanded PHEV design space

Battery Cycle Life Depends on State of Charge Swing

- PHEV battery likely to deep-cycle each day driven: 15 yrs equates to 4000-5000 deep cycles
- Also need to consider combination of high and low frequency cycling

Source: Christian Rosenkranz (Johnson Controls) at EVS 20, Long Beach, CA, November 15-19, 2003
Summary: Exciting Times for Li-Ion Batteries

- **New Cathodes**
  - Lower cost
  - Higher power
  - Better safety
  - Improved life
- **New Anodes**
  - Faster charge rate
  - Improved life
- **New Electrolyte**
  - Improved safety
  - Improved low temperature performance
- **New Separator**
  - Lower cost
  - Improved safety
Battery Definition as Key Input to Simulation

Input parameters that define the battery in **BLUE**

- **PHEV range**
- **kWh/mi** (from simulation) → **kWh usable**
- **SOC window** → **kWh total**
- **P/E ratio** → **kWmotor**
- **Performance constraints** → **kWengine**

**DOH** = degree of hybridization

**Benefit of plugging-in**

**Total MPG Benefit**

**Benefit of hybridization**

Alternative PHEV Design Strategies: All-Electric vs Blended

- Engine turns on when battery reaches low state of charge
- Requires high power battery and motor

*All-Electric (Pure EV or ZEV)*

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
Alternative PHEV Design Strategies:
All-Electric vs Blended

- Engine turns on when power exceeds battery power capability
- Engine only provides load that exceeds battery power capability

**Blended**

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
Blended vs. AER Consumption Tradeoff

- Reducing ESS power should reduce cost, mass, volume
- 50% reduction in power still provides almost all of the fuel consumption benefit

* CD = Charge Depleting

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
PHEV Battery Sizing Alternatives

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
Battery Cost Model based on P/E Ratio

Lower power to energy ratio leads to lighter, smaller, and less expensive energy storage system.

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
Battery Model (cont.) – SOC Window

Battery SOC Operating Window vs. Specified All-Electric Range

SOC operating window

Source: Andrew Simpson (NREL), Presented to FreedomCAR Vehicle System Analysis Team, March 1 2006
Real Driving Survey Data

- Provides valuable insight into travel behavior
- GPS augmented surveys supply details needed for vehicle simulation

Source: Tony Markel, Presentation at Clean City Congress and Expo, (NREL), Phenoix, AZ, May 8, 2006
• St. Louis data set includes 227 vehicles from 147 households
• Complete second by second driving profile for one day
• 8650 miles of travel
• St. Louis data set is a small sample of real data
• NPTS data is generated from mileage estimates

Source: Tony Markel, Jeff Gondor, and Andrew Simpson (NREL), Presented to FreedomCAR Vehicle System Analysis Team, June 14 2006
PHEVs Reduce Fuel Consumption By >50% On Real-World Driving Cycles

227 vehicles from St. Louis each modeled as a conventional, hybrid and PHEV

- 8647 total miles driven
- 100% replacement of sample fleet

Average Daily Costs

<table>
<thead>
<tr>
<th></th>
<th>Gas.</th>
<th>Elec.</th>
<th>¢/mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>$3.45</td>
<td>---</td>
<td>9.1</td>
</tr>
<tr>
<td>HEV</td>
<td>$2.48</td>
<td>---</td>
<td>6.5</td>
</tr>
<tr>
<td>PHEV20</td>
<td>$1.58</td>
<td>$0.48</td>
<td>5.4</td>
</tr>
<tr>
<td>PHEV40</td>
<td>$1.21</td>
<td>$0.72</td>
<td>5.1</td>
</tr>
</tbody>
</table>

Assumes $2.41/gal and 9¢/kWh

PHEVs:
>40% reduction in energy costs
>$500 annual savings

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
Fuel Economy and All Electric Range Comparison

• Difference between rated (EPA drive cycles) and Real median values are significant for the PHEVs
  — Consumers likely to observe fuel economy higher than rated value in typical driving
  — Vehicles designed with all electric range likely to operate in a blended mode to meet driver demands

<table>
<thead>
<tr>
<th></th>
<th>Fuel Economy (mpg) **</th>
<th>All Electric Range (mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rated</td>
<td>Median</td>
</tr>
<tr>
<td>Conventional</td>
<td>26</td>
<td>24.4</td>
</tr>
<tr>
<td>HEV</td>
<td>39.2</td>
<td>35.8</td>
</tr>
<tr>
<td>PHEV20</td>
<td>54</td>
<td>70.2</td>
</tr>
<tr>
<td>PHEV40</td>
<td>67.4</td>
<td>133.6</td>
</tr>
</tbody>
</table>

** Fuel economy values do not include electrical energy consumption

Source: Tony Markel, Jeff Gondor, and Andrew Simpson (NREL), Presented to FreedomCAR Vehicle System Analysis Team, June 14 2006
Concluding Remarks – Vehicle Simulations

• Simulations on sample real-world drive cycles suggests PHEV technology can dramatically reduce petroleum consumption.

• Benefits of a PHEV over a conventional vehicle or HEV are tied to travel behavior.

• A vehicle designed for all electric range in urban driving will likely provide only limited electric operation in real world applications
  — Still provides significant fuel displacement

• Plug-in hybrid technology can reduce petroleum consumption beyond that of HEV technology.
Concluding Remarks - Battery

• Batteries with low power to energy ratios would be needed for PHEVs

• Expansion of the energy storage system usable state of charge window while maintaining life will be critical for reducing system cost and volume

• A blended operating strategy as opposed to an all electric range focused strategy may provide some benefit in reducing cost and volume while maintaining petroleum consumption benefits

• The key remaining barriers to commercial PHEVs are battery life, packaging and cost.
Some Final Thoughts

- PHEVs reduce emissions and displace petroleum
  - Is there a need to require ZEV (pure EV) range?
  - Does blended EV range achieve both objectives?
- Does AER or ZEV need to be over a “standard” drive cycle or “real” drive cycles?
- DOE and others are focusing R&D to reduce battery cost and to improve performance and life.
- Incentives for PHEVs with larger EV range (larger battery pack) may be needed.
- Learning demonstrations are key in the short term – a good role for AQMD.
Acknowledgments

• DOE Program Support
  – Dave Howell
  – Tien Duong

• NREL Technical Support
  – Tony Markel
  – Andrew Simpson
  – Jeff Gonder