Battery Choices and Potential Requirements for Plug-In Hybrids

Plug-In Hybrid Electric Truck Workshop
Hybrid Truck Users Forum
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National Renewable Energy Laboratory

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

- **Battery Level**
  - R&D support to developers
  - Testing and evaluation – Sprinter PHEV testing
  - Thermal characterization and design
  - Requirement analysis in support of EES Tech Team

- **Vehicle Level**
  - Simulated real-world PHEV fuel economy
  - Support development of test procedures and MPG reporting
  - Route-based control
  - 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 homes/communities

- **Analysis support to DOE, OEMs, and others**
  - Working to identify and overcome barriers to PHEV adoption
NREL’s Heavy Hybrid Vehicle Activities

• Technical Monitor of DOE’s Advanced Heavy Hybrid Propulsion System Program
  — GM – Allison Transmission (Heavy hybrid transit bus application & prototype validation) – parallel hybrid
  — Eaton/International (Class 4-6 vehicle applications & prototype validations) – parallel hybrid
  — Oshkosh (Class 7-8 vehicle application & prototype validation) – Series hybrid; extremely demanding duty-cycle
  — Caterpillar (Focus on thermoelectric waste heat recovery)

• Technical Contributions
  — ReFUEL Lab (Chassis and engine dynamometers)
    » Vehicle fuel economy and emissions testing
    » Vehicle drive cycle characterization and analysis
  — Thermal testing, analysis, and management
    » Power electronics
    » Batteries and ultracapacitors
Topics of This 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
Key Messages

- There is a broad spectrum of 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 – volume and weight are concerns
  - Li-ion are potentially best candidates
  - All li-ions are not “created equal”

- For heavy-duty PHEV, combining low-cost, high-energy batteries (such as NaNiCl or ZnAir) with high power ultracapacitors may have potential

- There is a trade of between high fuel economy and emissions benefits
  - Engine-off during EV operation reduces the petroleum consumption
  - Too many engine-off cycles lead to cold starts and higher emissions

- PHEVs are the most-cost-effective choice in a scenario of projected low battery costs and high fuel costs.
Batteries in Current PHEVs

- **Johnson Controls / Varta**
- **Johnson Controls / SAFT**
- **Valence Technology**

**NiMH**

- **Electro Energy Inc.**
- **Kokam**

**Co/Ni based Li-Ion**

- **A123 Systems**

**Iron phosphate based Li-Ion**
# High Power Battery and Ultracapacitor Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VRLA</th>
<th>NiMH</th>
<th>Li Ion</th>
<th>Ultracap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell configuration</strong></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><strong>Nominal cell voltage (V)</strong></td>
<td>2</td>
<td>1.2</td>
<td>3.6</td>
<td>1.8</td>
</tr>
<tr>
<td><strong>Battery electrolyte</strong></td>
<td>Acid</td>
<td>Alkaline</td>
<td>Organic</td>
<td>Organic</td>
</tr>
<tr>
<td><strong>Specific energy, Wh/kg</strong></td>
<td>25</td>
<td>40</td>
<td>60 to 80</td>
<td>5</td>
</tr>
<tr>
<td><strong>Battery/Module specific power, 10 sec, W/kg</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>23°C, 50% SOC</strong></td>
<td>400</td>
<td>1300</td>
<td>3000</td>
<td>&gt;3000</td>
</tr>
<tr>
<td><strong>-20°C, 50% SOC</strong></td>
<td>250</td>
<td>250</td>
<td>400</td>
<td>&gt;500</td>
</tr>
<tr>
<td><strong>Charge acceptance, 10 sec. W/kg</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>23°C, 50% SOC</strong></td>
<td>200</td>
<td>1200</td>
<td>2000</td>
<td>&gt;3000</td>
</tr>
<tr>
<td><strong>2010 Projected Cost &gt;100,000 per year</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$/kWh, Module</strong></td>
<td>100.00</td>
<td>500.00</td>
<td>700.00</td>
<td>20,000.00</td>
</tr>
<tr>
<td><strong>$/kWh, Full pack</strong></td>
<td>140</td>
<td>600</td>
<td>1100</td>
<td>25000</td>
</tr>
<tr>
<td><strong>$/kW, pack</strong></td>
<td>9.00</td>
<td>18.00</td>
<td>22.00</td>
<td>40.00</td>
</tr>
<tr>
<td><strong>Energy efficiency</strong></td>
<td>Good</td>
<td>Moderate</td>
<td>Good</td>
<td>Very Good</td>
</tr>
<tr>
<td><strong>Thermal managements requirements</strong></td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
<td>Light</td>
</tr>
<tr>
<td><strong>Electrical control</strong></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 Existing Energy 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>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Volume (lit)</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Capacity/Energy (kWh)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Discharge Power (kW)</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Regen Power (kW)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Cold-Temperature (kWh &amp; kW)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Shallow Cycle Life (number)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Deep Cycle Life (number)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Calendar Life (years)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Cost ($/kW or $/kWh)</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Safety- Abuse Tolerance</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Maturity - Technology</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Maturity - Manufacturing</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

**Key**
- **Poor**
- **Fair**
- **Good**
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, 2006, Ft. Lauderdale, FL.
NiMH technology is forecasted to have a major market share in hybrid market until Li-Ion takes off

Panasonic

6.5 Ah Battery for Toyota Prius

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: Images provided by James Landi of Electro Energy Inc.

Forecast

Source: C. Pillot (Avicenne) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.
Li-Ion Technology – Diverse Chemistry & Opportunity

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

Many anodes are possible
- Carbon/Graphite
- Titanate (Li$_4$Ti$_5$O$_{12}$)
- Titanium oxide based
- Tin Oxide based
- Tungsten oxide

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

Many electrolytes are possible
- LiPF$_6$ based
- LiBF$_4$ based
- Various solid state electrolytes
- Polymer electrolytes
  (+ some salts)

## Characteristics of Cathode Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Delta x$</th>
<th>mAh/g</th>
<th>avg V</th>
<th>Wh/kg</th>
<th>Wh/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCoO$_2$</td>
<td>0.55</td>
<td>151</td>
<td>4.00</td>
<td>602</td>
<td>3073</td>
</tr>
<tr>
<td>LiNi$<em>{0.8}$Co$</em>{0.15}$Al$_{0.05}$O$_2$</td>
<td>0.7</td>
<td>195</td>
<td>3.80</td>
<td>742</td>
<td>3784</td>
</tr>
<tr>
<td>LiMn$_2$O$_4$</td>
<td>0.8</td>
<td>119</td>
<td>4.05</td>
<td>480</td>
<td>2065</td>
</tr>
<tr>
<td>LiMn$<em>{1/3}$Co$</em>{1/3}$Ni$_{1/3}$O$_2$</td>
<td>0.55</td>
<td>153</td>
<td>3.85</td>
<td>588</td>
<td>2912</td>
</tr>
<tr>
<td>LiFePO$_4$</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

- Cobalt oxide most widely used in consumer cells but recently too expensive
- LiMn$_{1/3}$Co$_{1/3}$Ni$_{1/3}$O$_2$ newer than LiNiCoO$_2$
- Mn$_2$O$_4$ around for many years – not competitive for consumer – good for high power
- Oxide cathodes with cobalt are more energetic
- LiFePO$_4$ – very new – too low energy density for consumer electronics
  - safe on overcharge but need electronics to prevent under-voltage
  - may require larger number of cells due to lower cell voltage

Many Commercial Oxide Based Li-Ion Batteries are Available

- Johnson Control - Saft
- LG Chem
- Electrovaya
- Kokam
- SK Corp
- NEC Lamilion Energy
- GS Yuasa
- Sony
- Sanyo
- Samsung
- Panasonic
- Nissan
- Lishen
- Pionics
- Altair Nanotechnologies
- Chinese companies
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 (\(D_{Li} \approx 10^{-13} \text{ cm}^2/\text{Sec}\))
  – Poor electronic conductivity (\(\approx 10^{-8} \text{ S/cm}\))

• 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, 2006, Ft. Lauderdale, FL.

Source: On line brochures from Valence Technolo http://www.valence.com/ucharge.asp
Improvements in Iron Phosphate Li-ion Batteries

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

<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>

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


A123 Systems with 26650 Cells
100 Wh/kg

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

Source: Andrew Chu (A123 Systems) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.
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</td>
</tr>
<tr>
<td>Cathode</td>
<td>Cobaltate</td>
<td>Nano-Structured oxides</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>


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Altair 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!
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

Main barrier is cost!
Other Energy Storage Potential Choices for Plug-In Hybrid Electric Trucks (PHET)

- Sodium Nickel Chloride battery (NaNiCl) – Zebra
  - High energy density
  - Low power density
  - Inexpensive
- Zinc Air battery/fuel cell (ZnAir)
  - Types
    » The “Refuellable” ZnAir Fuel Cell
    » The “Mechanically Rechargeable” ZnAir Fuel Cell
    » The Electrically Rechargeable ZnAir Battery
  - High energy density
  - Low power density
  - Inexpensive
- Ultracapacitors
  - High power density
  - Low energy density
  - Expensive now, could become lower in cost
- Combination of ultracapacitors with NaNiCl or ZnAir
  - The need for DC/DC converter may increase cost, volume/mass
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

Need to obtain similar data for state-of-the-art batteries

Source: Christian Rosenkranz (Johnson Controls) at EVS 20, Long Beach, CA, November 15-19, 2003
Battery Sizing Depends on:
EV range, vehicle (mass, aerodynamic, etc.), drive cycle, strategy

Equi EV range

- kWh/mi (from simulation)
- kWh usable
- SOC window
  - kWh total
- kW_{motor} (from simulation)
- Performance constraints
  - kW_{engine}

kWh usable → kWh total
SOC window → kWh total
KWh/mi → kWh usable

Benefit of plugging-in

Total MPG Benefit

Benefit of hybridization

DOH = degree of hybridization

Battery Usage in EVs, HEVs, and PHEVs

- **HEV**
  - Charged, not used
  - Used frequently in CS
  - Used sometimes in CS
  - 0.2-0.4 kWh CS
  - 1-2 kWh total
  - Uncharged capacity

- **PHEV**
  - Charged and used (CD)
  - 5-10 kWh
  - 30-40 kWh

- **EV**
  - Charged and used (CD)

**kWh**: Battery energy for midsize car

**CS**: Charge Sustaining

**CD**: Charge Depleting

NREL National Renewable Energy Laboratory
Alternative PHEV Design Strategies: Charge Depleting EV vs. Charge Depleting HEV

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

**Charge-Depleting EV (All-Electric)**

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
Alternative PHEV Design Strategies: Charge Depleting EV vs. Charge Depleting HEV

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

**Charge Depleting HEV (Blended)**

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006
## Example of Battery Requirements for Plug-in Hybrid Vehicles

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum System Production Price @ 100k units/yr</td>
</tr>
<tr>
<td>Calendar Life, 40°C</td>
</tr>
<tr>
<td>Maximum System Weight</td>
</tr>
<tr>
<td>Maximum System Volume</td>
</tr>
<tr>
<td>SOC Range</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charge Depleting HEV Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Equivalent Electric Range</td>
</tr>
<tr>
<td>Available Energy for CD Mode, 10 kW Rate</td>
</tr>
<tr>
<td>CD Life / Discharge Throughput</td>
</tr>
<tr>
<td>Suggested Total Energy (at 10 kW rate)</td>
</tr>
<tr>
<td>Maximum System Recharge Rate at 30°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Charge Sustaining HEV Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Pulse Discharge Power (10 sec)</td>
</tr>
<tr>
<td>Peak Regen Pulse Power (10 sec)</td>
</tr>
<tr>
<td>Available Energy for CS (Charge Sustaining) Mode</td>
</tr>
<tr>
<td>Minimum Round-trip Energy Efficiency (USABC HEV Cycle)</td>
</tr>
<tr>
<td>Cold cranking power at -30°C, 2 sec - 3 Pulses</td>
</tr>
<tr>
<td>CS HEV Cycle Life, 50 Wh Profile</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Battery Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Current (10 sec pulse)</td>
</tr>
<tr>
<td>Maximum Operating Voltage</td>
</tr>
<tr>
<td>Minimum Operating Voltage</td>
</tr>
<tr>
<td>Maximum Self-discharge</td>
</tr>
<tr>
<td>Survival Temperature Range</td>
</tr>
<tr>
<td>Unassisted Operating &amp; Charging Temperature Range</td>
</tr>
</tbody>
</table>
Battery Energy Requirements for Heavy-Duty PHET

- The energy efficiency of light-duty vehicles are about 200 to 400 Whr/mile
  - 5 to 12 kWhr battery for 30 mile
  - 2 Second power: 30 to 60 kW
  - Power to energy ratio (P/E) from 2 to 15

- Sprinter van delivery PHEV is estimated to consume about 600 Whr/mile in charge depleting (CD) mode

- Heavy-duty trucks could consume from 1000 to 2000 Whr/mile
  - 30 to 60 kWh battery for 30 mile range
  - Some may require additional kWh energy during idling or vocational operation
  - Power need: 50 to 150 kW or even more
  - Volume, weight, and cost are big issues
  - Thermal management is a concern
Battery Pack Packaging?

• Many small cells
  — Low cell cost (commodity market)
  — Improved safety (faster heat rejection)
  — Many interconnects
  — Low weight and volume efficiency
  — Reliability (many components, but some redundancy)
  — Higher assembly cost
  — Electrical management (costly)
  — Life?

• Fewer large cells
  — Higher cost
  — Increased reliability
  — Lower assembly cost
  — Higher weight and volume efficiency
  — Thermal management (tougher)
  — Safety ??
  — Better Reliability (lower number of components)
  — Life?
Concluding Remarks

• Batteries with low power to energy ratios are needed for PHEVs and PHETs

• Widening of the energy storage system usable state of charge window while maintaining life will be critical for reducing system cost and volume, but could decrease the life

• 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 barrier to commercialization of PHEVs and PHETs are battery life, packaging, and cost.
Acknowledgments

• DOE Program Support
  – Dave Howell
  – Tien Duong

• Technical Support
  – Tony Markel (NREL)