Battery Requirements and Cost-Benefit Analysis for Plug-In Hybrid Vehicles

Ahmad Pesaran
Tony Markel

National Renewable Energy Laboratory
Golden, CO, USA
ahmad_pesaran@nrel.gov, Tel: 303 275-4441

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Outline

• Why Plug-In Hybrids?
• What is a Plug-In Hybrid?
• Definitions and Terminologies
• Current Plug-in Hybrid Conversions
• Battery Requirements
• Analysis – Benefits and Costs
• Summary
Why are Alternative Fuel and Efficient Vehicles Needed?

- Petroleum consumption has steadily increased while domestic production has continued to decline
- Energy security and oil independence are major concerns in US
- World oil production will likely peak within the next 5-15 years
- Recent increase in gasoline price is an indicator of growing tension between supply and demand
- Greenhouse gas emission and global warming concerns
Why are Plug-In Hybrids Getting a lot of Attention?

• Most hybrid vehicles still consume petroleum.
• Alternative fuel vehicles such as E85 are available, but fuel and required infrastructure are not ready.
• Mass production of hydrogen fuel cell vehicles is not likely in the next 15 years.
• Electric vehicles are not likely to be mass produced in the next 20 years due to battery cost, charging time and fast charging infrastructure requirements.
• Plug in hybrids offer potential for both energy efficiency and use of domestic energy (electricity) without paradigm shift in a new fueling infrastructure.
• A majority of US drivers travel fewer than 40 miles a day, so a vehicle with short EV range and long petroleum range is very attractive.
• The President’s State of Union Address in 2006 & 2007
Plug-in Hybrid Stakeholder Objectives

- **US Gov./DOE**
  - Reduced petroleum use; Use alternative energy

- **State Gov.**
  - Reduced air pollution; Use renewable energy

- **Auto Manufacturers**
  - Sell cars

- **Consumers**
  - Drive affordable, functional, fun, and feel good cars

- **Electric Utilities**
  - Sell electricity

- **Battery Manufacturers**
  - Sell batteries

- **Security advocates, Environmentalists, Consortiums**
  - Conversion companies, Component suppliers
What is a Plug-In Hybrid Electric Vehicle
An HEV with an energy storage system that could be charged with off-board electricity

Fuel Flexibility
- PETROLEUM
- ELECTRICITY
- ADVANCED ENGINE
- ENGINE DOWNSIZING
- ENGINE IDLE-OFF
- REGENERATIVE BRAKING
- ELECTRIC ACCESSORIES
- BATTERY RECHARGE

AND/OR

PETROLEUM
ELECTRICITY

NREL
Some PHEV Definitions

**Charge-Depleting (CD) HEV Mode:** Vehicle operation on the electric drive, engine subsystem or both with a net decrease in battery state-of-charge.

**Charge-Sustaining (CS) HEV Mode:** Vehicle operation on the electric drive, engine subsystem or both at ‘relatively constant’ battery state-of-charge (i.e. within a narrow range).

**All-Electric Range (AER):** After a full recharge, the total miles driven electrically (engine-off) before the engine turns on for the first time.

**Charge-Depleting Range (CDR):** After a full recharge, the total miles driven before the vehicle reaches charge-sustaining mode.

**PHEV20:** A PHEV with useable energy storage equivalent to 20 miles of driving energy on a reference driving cycle. A PHEV20 can displace petroleum energy equivalent to 20 miles of driving on the reference cycle with off-board electricity.

**NOTE:** PHEV20 does not imply that the vehicle will achieve 20 miles of AER or CDR on the reference cycle nor any other driving cycle. Operating characteristics also depend on the power ratings of components, the powertrain control strategy and the nature of the driving cycle.
Operating Strategy Options
All-Electric or Blended/Hybrid

Charge Depleting Electric

- Engine is off during the electric range
- Engine turns on when battery reaches low state of charge
- Requires high power battery and motor

Charge Depleting Hybrid (Blended)

- Engine turns on when power exceeds battery power capability
- Engine only provides load that exceeds battery power capability
How Do PHEVs Reduce Petroleum Consumption?

- **PHEV Benefits**
  - **Efficiency in Charge-Sustaining Mode**
  - **Petroleum Displacement in Charge-Depleting Mode**

**Conventional Vehicle**
- Consumption Benefits of PHEV
- Technology Tied to Usage Pattern

**Hybrid Vehicle**
- ~10-35%
- ~50-80%

**Plug-In Hybrid Vehicle**
- ~35-50%

**Distance**

Charge-Depleting Mode

Charge-Sustaining Mode
Some of PHEV Prototypes

EnergyCS Plug-In Prius
Hymotion Escape PHEV
AFS Trinity Extreme Hybrid™

DaimlerChrysler Sprinter Van PHEV
AC Propulsion Jetta PHEV
Renault Kangoo Elect’road
Batteries in Current PHEVs

Johnson Controls / Varta

Electro Energy Inc.

Johnson Controls / SAFT

Kokam

Valence Technology

A123 Systems
Battery Usage in EVs, HEVs, and PHEVs

- **HEV**
  - Charged capacity, not used: 0.2-0.4 kWh CS
  - Charged and used (CD): Total Battery Capacity*
  - Uncharged capacity: 1-2 kWh

- **PHEV**
  - Charged, not used: 0.2-0.4 kWh CS
  - Charged and used (CD): 6-12 kWh

- **EV**
  - Charged, not used: 30-40 kWh
  - Charged and used (CD): 30-40 kWh

**SOC Range (%)**

**CD**: Charge Depleting

**CS**: Charge Sustaining

*Battery capacity for a midsize car
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
Battery Sizing Depends on:
EV range, vehicle (mass, aerodynamic, etc.), drive cycle, strategy

Equi EV range
kWh/mi → kWh usable (from simulation)
SOC window → kWh total
kW\text{motor} (from simulation) → P/E
Performance constraints → kW\text{engine}

DOH = degree of hybridization

kWh usable → Benefit of plugging-in
kWh total → Total MPG Benefit

# Example of Battery Requirements for Plug-in Hybrid Vehicles

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
<th>Long-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum System Production Price @ 100k units/yr</td>
<td>$3,500</td>
</tr>
<tr>
<td>Calendar Life, 40°C</td>
<td>Years</td>
</tr>
<tr>
<td>Maximum System Weight</td>
<td>kg</td>
</tr>
<tr>
<td>Maximum System Volume</td>
<td>Liter</td>
</tr>
<tr>
<td>SOC Range</td>
<td>%</td>
</tr>
<tr>
<td>Equivalent Electric Range</td>
<td>miles</td>
</tr>
<tr>
<td>Available Energy for CD Mode, 10 kW Rate</td>
<td>kWh</td>
</tr>
<tr>
<td>CD Life / Discharge Throughput</td>
<td>Cycles / MWh</td>
</tr>
<tr>
<td>Total Energy (at 10 kW rate)</td>
<td>kWh</td>
</tr>
<tr>
<td>Maximum System Recharge Rate at 30°C</td>
<td>kW</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power (10 sec)</td>
<td>kW</td>
</tr>
<tr>
<td>Peak Regen Pulse Power (10 sec)</td>
<td>kW</td>
</tr>
<tr>
<td>Available Energy for CS (Charge Sustaining) Mode</td>
<td>kWh</td>
</tr>
<tr>
<td>Minimum Round-trip Energy Efficiency (USABC HEV Cycle)</td>
<td>%</td>
</tr>
<tr>
<td>Cold Cranking Power at -30°C, 2 sec - 3 Pulses</td>
<td>kW</td>
</tr>
<tr>
<td>CS HEV Cycle Life, 50 Wh Profile</td>
<td>Cycles</td>
</tr>
<tr>
<td>Max. Current (10 sec pulse)</td>
<td>A</td>
</tr>
<tr>
<td>Maximum Operating Voltage</td>
<td>Vdc</td>
</tr>
<tr>
<td>Minimum Operating Voltage</td>
<td>Vdc</td>
</tr>
<tr>
<td>Maximum Self-discharge</td>
<td>Wh/day</td>
</tr>
<tr>
<td>Survival Temperature Range</td>
<td>°C</td>
</tr>
<tr>
<td>Unassisted Operating &amp; Charging Temperature Range</td>
<td>°C</td>
</tr>
</tbody>
</table>

1. These categories are similar to the ones proposed for USABC charge-depleting electric vehicles and FreedomCAR charge-depleting power-assist HEVs
PHEV Key Benefits and Challenges

**KEY BENEFITS**

**Consumer:**
- Lower “fuel” costs
- Fewer fill-ups
- Home recharging convenience
- Fuel flexibility

**Nation:**
- Less petroleum use
- Less greenhouse and regulated emissions
- Energy diversity/security

**KEY CHALLENGES**

- Energy Storage/Battery
  - Cost
  - Life
    - Shallow and deep cycles
    - Calendar
  - Safety
  - Packaging
  - Thermal Management
- Power Electronics
- Vehicle cost

*Cost-Benefit Analysis*
## Plug-In Hybrid Fuel Economy

Predicted fuel economy and operating costs for midsize sedan

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Gasoline Fuel Economy</th>
<th>Electricity Use</th>
<th>Annual Energy Use</th>
<th>Annual Energy Cost</th>
<th>Recharge Time$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>27 mpg</td>
<td>---</td>
<td>564 gal.</td>
<td>$1360</td>
<td>---</td>
</tr>
<tr>
<td>Hybrid-Electric</td>
<td>36 mpg</td>
<td>---</td>
<td>416 gal.</td>
<td>$1000</td>
<td>---</td>
</tr>
<tr>
<td>Plug-In Hybrid 20mi range</td>
<td>51 mpg</td>
<td>0.09 kWh/mi</td>
<td>297 gal. and 1394 kWh$^2$</td>
<td>$716 + $125</td>
<td>&lt; 4 hrs</td>
</tr>
<tr>
<td>Plug-In Hybrid 40mi range</td>
<td>69 mpg</td>
<td>0.16 kWh/mi</td>
<td>218 gal. and 2342 kWh$^2$</td>
<td>$525 + $211</td>
<td>&lt; 8 hrs</td>
</tr>
</tbody>
</table>

1) Assumes 15,000 miles annually, gasoline price of $2.40 per gallon, electricity price of 9c/kWh
2) Note that average US household consumes 10,700 kWh of electricity each year
3) Using 110V, 20A household outlet
Powertrain Costs Comparison – Long Term

From A. Simpson and T. Markel, 22nd Electric Vehicle Symposium, Yokohoma, Japan, October 2006

Powertrain Costs (incl. retail markups)

<table>
<thead>
<tr>
<th>Powertrain Type</th>
<th>Charging Plug</th>
<th>Battery</th>
<th>Motor/Inverter</th>
<th>Transmission</th>
<th>Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>$4,004</td>
<td>$1,998</td>
<td>$1,680</td>
<td>$2,876</td>
<td>$3,023</td>
</tr>
<tr>
<td>HEV0</td>
<td>$6,002</td>
<td>$2,523</td>
<td>$4,864</td>
<td>$2,930</td>
<td>$3,023</td>
</tr>
<tr>
<td>PHEV10</td>
<td>$9,073</td>
<td>$1,994</td>
<td>$2,006</td>
<td>$2,970</td>
<td>$3,023</td>
</tr>
<tr>
<td>PHEV20</td>
<td>$12,307</td>
<td>$2,013</td>
<td>$1,877</td>
<td>$3,023</td>
<td>$3,023</td>
</tr>
<tr>
<td>PHEV40</td>
<td>$14,438</td>
<td>$683</td>
<td>$683</td>
<td>$683</td>
<td>$683</td>
</tr>
</tbody>
</table>

UDDS AER PHEVs
Payback time of PHEVs Relative to HEVs depends on the initial battery cost and fuel cost

Cumulative Vehicle plus Energy (Fuel/Elec.) Costs

From A. Simpson and T. Markel, 22nd Electric Vehicle Symposium, Yokohoma, Japan, October 2006

Long-term scenario
LI-ION BATTERIES

$3.00/gal.
$0.09¢/kWh (2005 average, not off-peak)

Maintenance costs not included, no discount rate applied
Both Higher Gas Prices and Lower Battery Costs Required for PHEV to Payback Relative to HEV

Cumulative Vehicle plus Energy (Fuel/Elec.) Costs
From A. Simpson and T. Markel, 22\textsuperscript{nd} Electric Vehicle Symposium, Yokohoma, Japan, October 2006

$5.00/gal. (future?)

$0.09\,\text{¢/kWh} \,(2005\,\text{average,\,not\,off-peak})

\textit{Maintenance costs not included, no discount rate applied}
Concerns with Battery Packaging and Management
Concluding Remarks

• PHEVs could displace petroleum consumption with domestic and renewable electricity.

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

• Widening of the battery’s usable SOC 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.

• Battery requirements for PHEVs are demanding: low cost, wide T operation, wide SOC operation, both shallow and deep cycles.

• PHEVs make economic sense with lower battery cost and higher gasoline prices, otherwise other incentives or tax credits needed.

• The key barriers to commercialization of PHEVs are battery life, packaging, safety, and cost.