Energy Storage System Considerations for Grid-Charged Hybrid Electric Vehicles

presented at
IEEE Vehicular Power and Propulsion Conference

by
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September 8, 2005
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Overview

• Study objectives
• Case study: plug-in HEV energy storage requirements and options for a mid-sized sedan
• Battery/engine sizing tradeoffs
• Conclusion
Motivation for this Study

• Traditional ZEV-range concept for plug-in HEV’s requires ESS capable of high energy storage AND power capability = bigger, more-expensive battery
  
  \((high\ power,\ high\ energy,\ low\ annualized\ cost* \rightarrow\ pick\ any\ 2)\)
  
  \((high\ power,\ high\ energy,\ low\ volume \rightarrow\ pick\ any\ 2)\)

• Other HEV control strategy concepts (e.g. electric-assist) can still provide net-discharge, but with reduced battery power requirements.
  
  ➔ This might facilitate the use of cheaper and/or smaller batteries

* Annualized cost = battery replacement cost / lifetime
Purpose of this Study

1. Calculate ESS power and energy requirements for plug-in HEV’s with different control strategies

2. Consider implications for rest of system (in particular, engine efficiency and fuel economy)
Some Definitions

Degree of Hybridization (DOH):

\[
DOH = \frac{\frac{\text{battery} / \text{motor} (kW)}{\text{battery} / \text{motor} (kW) + \text{engine} / \text{generator} (kW)}}
\]

Power-to-Energy Ratio (P2E):

\[
P2E\left(\frac{1}{h}\right) = \frac{\text{power} (kW)}{\text{energy} (kWh^*)} = \frac{\frac{\text{specific power} (\frac{W}{kg})}{\text{specific energy} (\frac{Wh^*}{kg})}}{\text{energy density} (\frac{Wh^*}{L})}
\]

- relates suitability of energy storage to power events with different timescales

*useable Wh
Case Study – Vehicle Specifications

Mid-size car from EPRI study:
• $C_{DA} = 0.71m^2$
• $C_{RR} = 0.008$
• $P_{acc} = 500W$
• Test mass $\approx 1700kg$

Peak motive power $\approx 115kW$
Continuous power requirement $\approx 45kW$
• Top speed @ 90mph
• 7.2% gradeability @ 50mph

Electric energy consumption $\approx 300Wh/mile$
## Case Study – Battery Specifications

<table>
<thead>
<tr>
<th></th>
<th>No ICE help</th>
<th></th>
<th>With ICE help (45kW)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power (kW)</td>
<td>Energy (kWh)</td>
<td>P2E (1/h)</td>
<td>Power (kW)</td>
</tr>
<tr>
<td>HEV10</td>
<td>115</td>
<td>3</td>
<td>38.3</td>
<td>70</td>
</tr>
<tr>
<td>HEV20</td>
<td>115</td>
<td>6</td>
<td>19.2</td>
<td>70</td>
</tr>
<tr>
<td>HEV60</td>
<td>115</td>
<td>18</td>
<td>6.4</td>
<td>70</td>
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</tbody>
</table>
plugHEVs in this range
# Battery Products for Comparison

<table>
<thead>
<tr>
<th>Battery</th>
<th>Wh/kg</th>
<th>Wh/L</th>
<th>W/kg</th>
<th>W/L</th>
<th>Useable SOC</th>
<th>P2E</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Energy (for EVs)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAFT VLE 45 cell</td>
<td>149</td>
<td>313</td>
<td>664</td>
<td>1392</td>
<td>~ 80%</td>
<td>5.6</td>
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<tr>
<td>Cobasys 9500 module</td>
<td>60</td>
<td>155</td>
<td>250</td>
<td>650</td>
<td>~ 80%</td>
<td>5.2</td>
</tr>
<tr>
<td><strong>Mid Range (for plugHEVs?)</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SAFT VLM 27 cell</td>
<td>124</td>
<td>252</td>
<td>987</td>
<td>2000</td>
<td>~ 80%</td>
<td>9.9</td>
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<tr>
<td>Cobasys 4500 module</td>
<td>45</td>
<td>87</td>
<td>605</td>
<td>1180</td>
<td>~ 80%</td>
<td>16.8</td>
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<tr>
<td><strong>High Power (for HEVs)</strong></td>
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<tr>
<td>SAFT VLP 20 cell</td>
<td>89</td>
<td>187</td>
<td>1413</td>
<td>2973</td>
<td>&lt; 20%</td>
<td>&gt;79</td>
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<tr>
<td>Cobasys 1000 module</td>
<td>43</td>
<td>83</td>
<td>1100</td>
<td>2200</td>
<td>&lt; 20%</td>
<td>&gt;128</td>
</tr>
</tbody>
</table>

Match with HEV60

Match with HEV20
Battery/Engine Sizing Tradeoffs

45kW is only a lower constraint, engine can be larger than this.

This allows a smaller battery to be used... HEV20 example:

<table>
<thead>
<tr>
<th>Battery</th>
<th>Total Power (kW)</th>
<th>Battery Energy (kWh)</th>
<th>Battery Mass (kg)</th>
<th>Battery Volume (L)</th>
<th>Battery Power (kW)</th>
<th>Engine Power (kW)</th>
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</thead>
<tbody>
<tr>
<td>Lithium-Ion</td>
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<tr>
<td>SAFT VLM 27 cell</td>
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<td>6.0</td>
<td>61</td>
<td>30</td>
<td>60</td>
<td>55</td>
</tr>
<tr>
<td>SAFT VLE 45 cell</td>
<td>115</td>
<td>6.0</td>
<td>50</td>
<td>24</td>
<td>33</td>
<td>82</td>
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<tr>
<td>Nickel-Metal-Hydride</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobasys 4500 module</td>
<td>115</td>
<td>6.0</td>
<td>167</td>
<td>86</td>
<td>101</td>
<td>45</td>
</tr>
<tr>
<td>Cobasys 9500 module</td>
<td>115</td>
<td>6.0</td>
<td>125</td>
<td>49</td>
<td>31</td>
<td>84</td>
</tr>
</tbody>
</table>
Component Sizing and Control Options

HEV10 Mid-Size Sedan

60 mpg

Battery power sufficient to provide EV-only operation

$1800

P/E = 20

Battery Cost

NREL National Renewable Energy Laboratory
Component Sizing and Control Options

Only a few EV miles but many more blended miles

Battery Cost

$1500

5 mpg
Component Sizing and Control Options

Battery < half the original and fuel economy drop less than 10%

HEV10 Mid-Size Sedan

Battery Cost: $1250

Distance (miles)

Fuel Consumption (gallons)

89 kW, 25 kW, 52 kW, 63 kW

P/E = 8
Below 20kW battery, lost regen impacts consumption.
Component Sizing and Control Options

Cylinder deactivation in large engine could be used to regain efficiency.
So what’s the catch? 1) Lower engine efficiency!

Battery/Engine Sizing Tradeoffs

Reduced DOH widens this envelope
Battery/Engine Sizing Tradeoffs

2) Sacrificed all-electric operation and regenerative braking

![Distribution plots for different driving cycles: UDDS, HWFET, and US06. Each plot shows the probability distribution of power demand with dashed lines indicating the nominal power levels of 30kW.](image-url)
Conclusions

• P2E ratios for existing high-energy and mid-range battery products match with P2E requirements for plug-in HEVs
  – However, mid-range batteries may be bigger, more expensive due to simultaneous power and energy requirements
  – Note that high-value V2G services (i.e. regulation events) have high P/E ratios – does this affect ESS requirements?
  – *Do dual-source ultracaps & EV batteries make a good alternative to mid-range batteries?*
Conclusions (cont.)

• Engine size (power) can be increased to facilitate the use of smaller batteries with lower P2E ratios (i.e. EV types)
  – However, this incurs the cost of:
    • Reduced engine efficiency
    • Sacrificed all-electric capability and maybe some loss of regenerative braking
    • Potential reduction in vehicle fuel economy during both charge-depleting and –sustaining operation
  – Reduced mass/volume of ESS & motor must be traded against increased mass/volume of ICE
  – *These issues should be explored further with dynamic simulation (including consideration of control strategy practicalities)*