Lower-Energy Requirements for Power-Assist HEV Energy Storage Systems—Analysis and Rationale

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Executive Summary

• Performed simulations and analyzed test data in conjunction with an EES TT Workgroup in response to a USABC request

• Results suggested power-assist (PA) HEVs can still achieve high fuel savings with lower energy requirements and potentially lower cost

• Clarified energy definition
  – “Available” energy where power requirements simultaneously met, vs.
  – Energy window for vehicle use

• USABC/EES TT established new set of ESS targets and issued a Request for Proposal Information (RFPI)
  – The goal is to reduce the cost of fuel-saving HEV systems
  – Open to any ESS technology (very high power batteries, electrochemical double layer capacitors, or asymmetric supercapacitors)

EES TT = The FreedomCAR Electrochemical Energy Storage Technical Team
USABC = United States Advanced Battery Consortium
HEV, ESS = hybrid electric vehicle, energy storage system
Background

• Historic PNGV, FreedomCAR, and/or USABC targets
  – For the energy storage system (ESS) in a power-assist (PA) hybrid electric vehicle (HEV)
  – Established in the late 1990s and early 2000s
  – Call for 0.3-0.5 kWh of “available” energy

• Limitations of NiMH batteries result in large design margins
  – To achieve at least 8-10 year life
  – Lead to **high-cost** battery packs with total energy of 1.2 to 1.5 kWh

• Pursuing more cost-effective energy storage
  – EES TT and USABC assembled a workgroup to re-evaluate the energy required for PA-HEVs and milder hybrids
  – NREL was asked to provide analysis support

PNGV = Partnership for a New Generation of Vehicles
USABC = United States Advanced Battery Consortium
NiMH = Nickel metal hydride
EES TT = The FreedomCAR Electrochemical Energy Storage Technical Team
**Motivation for this work:**
Could required energy be reduced to save $ and expand technologies?


<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>Power-Assist (Minimum)</th>
<th>Power-Assist (Maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse discharge power (10s)</td>
<td>kW</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Peak regenerative pulse power (10s)</td>
<td>kW</td>
<td>20 (97-Wh pulse)</td>
<td>(55-35)</td>
</tr>
<tr>
<td>Total available energy (over DOD range where power goals are met)</td>
<td>KWh</td>
<td>0.3 (at C1/1 rate)</td>
<td>0.5 (at C1/1 rate)</td>
</tr>
<tr>
<td>Minimum round-trip energy efficiency</td>
<td>%</td>
<td>90 (25-Wh cycle)</td>
<td>90 (50-Wh cycle)</td>
</tr>
<tr>
<td>Cold cranking power at -30°C (three 2-s pulses, 10-rests between)</td>
<td>kW</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Cycle life for specified SOC increments</td>
<td>cycles</td>
<td>300,000 Wh cycles (7.5MWh)</td>
<td>300,000 Wh cycles (15 MWh)</td>
</tr>
<tr>
<td>Calendar Life</td>
<td>years</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Maximum weight</td>
<td>kg</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Maximum volume</td>
<td>l</td>
<td>32</td>
<td>45</td>
</tr>
<tr>
<td>Operating Voltage limits</td>
<td>Vdc</td>
<td>max&lt;400 min&gt;(0.55 x Vmax)</td>
<td>max&lt;400 min&gt;(0.55 x Vmax)</td>
</tr>
<tr>
<td>Maximum allowable self-discharge rate</td>
<td>Wh/day</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Temperature range:</td>
<td>°C</td>
<td>-30 to +52</td>
<td>-30 to +52</td>
</tr>
<tr>
<td>Equipment operation</td>
<td></td>
<td>46 to +66</td>
<td>46 to +66</td>
</tr>
<tr>
<td>Equipment survival</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production Price @ 1,000,000 units/year</td>
<td>$</td>
<td>500</td>
<td>800</td>
</tr>
</tbody>
</table>

Total available energy (over DOD range where power goals are met) = 0.3-0.5 kWh
Approach Outline
Supporting FreedomCAR/USABC Workgroup’s re-evaluation of HEV ESS requirements/goals per DOE’s funding

• HEV simulations
  – ESS energy vs. fuel use trends
  – Various degrees of hybridization and drive cycles

• Analysis of vehicle ESS test data
  – Production HEV dyno runs
  – Sanity check on ESS use over standard cycles

• Reprocessing of simulations for power analysis
  – Characterize power pulses

• (More closely examine energy definition)
  – “Available” energy over which pulse power goals met, vs.
  – Energy window for vehicle use

Dis. reqmt. (25 kW * 10 s) met: 300 + 56 = 356 Wh
Chg. reqmt. (20 kW * 10 s) met: 300 + 69 = 369 Wh

Goals Both Met = 300 Wh
Dis. reqmt. (25 kW * 10 s) met: 300 + 56 = 356 Wh
Chg. reqmt. (20 kW * 10 s) met: 300 + 69 = 369 Wh

Energy Window for Vehicle Use = 425 Wh

Workgroup
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J. Deppe
Base modeling process/assumptions
Used Powertrain System Analysis Toolkit (PSAT) simulation software

- Midsize parallel HEV

- Multiple degree of hybridization (DOH) cases
  - Based on consistent 0-60 mph acceleration

  \[
  \text{DOH} = \frac{\text{Motor Power}}{\text{(Engine + Motor)Power}}
  \]

  - \text{DOH} = 10%: 15 kW motor, 135 kW eng
  - \text{DOH} = 19%: 25 kW motor, 110 kW eng
  - \text{DOH} = 38%: 45 kW motor, 75 kW eng

- Multiple drive cycles (UDDS, US06 & Colorado foothills)

Platform assumptions -- held constant
(Technology-neutral assessment of ESS capability)

- \(FA = 2.27\ m^2\)
- \(CD = 0.30\)
- \(Crr1 = 0.008\)
- \(Crr2 = 0.00012\)
- Test mass = 1675 kg
- Accessory power:
  - Electrical = 500 W
  - Mechanical = 230 W
Simulate and analyze ESS in all base cases
Identify actual energy window used to support HEV functions

• Investigate range of ESS energy content
  – ESS power limited by lesser of motor power or driving demand

• Constant SOC-based controls → changing Wh control window

• Capture in-use energy window for each simulation (charge sustaining)

In-use “Energy Window” defined by (max – min) for the particular cycle
Example in-use ESS energy comparison

Comparison of large and small ESS cases over US06 cycle

Energy window = 125 and 27 Wh, respectively

Launch Assist

“Idle-off” accessory power

Regen Capture
Simulation Results: Trends from fuel consumption results:
* Fuel savings increase with higher DOH (engine downsizing)
* Fuel savings increase, but taper with larger energy window

UDDS Cycle Results

DOH = 10%
DOH = 19%
DOH = 38%

Significant benefit with energy window out to $\approx 50$ Wh.
Most additional benefit with energy window out to $\approx 150$ Wh or so.

10% decrease
14% decrease
29% decrease
13% decrease

Fuel Consumption (L/100 km)

ESS Energy Window (Wh)
Simulation Results: Similar trends for other drive cycles

US06 Cycle Results

DOH = 10%
DOH = 19%
DOH = 38%

3% decrease
3% decrease
12% decrease
6% decrease

Fuel Consumption (L/100 km)
ESS Energy Window (Wh)
Simulation Results: Some additional, limited benefit for higher energy window use in foothills-type driving
Actual driving data from existing commercial HEVs
Used to complement and provide a sanity check on the simulation results
Consistent findings from analysis of production HEV dyno data*

Results adjusted for round-trip efficiency (to provide actual ESS energy state)

* In-use energy window for charge-sustaining tests: same range as simulation results
* Total "nominal" battery energy much larger, some of it used occasionally

* Thanks to ANL for providing access to some of the raw dynamometer test data
Summary of in-use ESS energy window analysis

• Even small energy windows can provide HEV fuel savings

• Significant fuel savings can be achieved with a ≈150-200 Wh energy window (less than the previous 425 Wh minimum goal)

• Reasons for large total “nominal” energy in current-production HEVs
  – Infrequent drive cycle use (e.g., long uphill/downhill grades)
  – Achieving longer cycle life from reduced SOC swings
  – Energy comes along with sizing for power capability (particularly at cold temperatures)
    – Note that power dominates cost in HEV batteries (high P/E ratio)

Next question: What goals for ESS power capability tests should be combined with a reduced in-use energy goal?
Power pulse analysis considerations/approach

• **Standard lab test** vs. **in-vehicle ESS capability**
  – Actual use depends on DOH, drive cycle, engine vs. motor control decisions, etc.

• Analyze pulses from past simulation cycles, observe trends

**Process for translating complex pulse profiles into “standard pulse test” equivalents**
Example complex in-vehicle power profile*

* From aforementioned ANL dyno testing
Quantifying pulse characteristics - 1

ESS Power Profile
Camry HEV - US06 Data

- Peak
- Average Power at Pulse Duration
- Pulse energy /time
- 1 kW Filter
- -1 kW Filter
- Discharge Pulses
- Charge Pulses

Cycle Time (s)
Quantifying pulse characteristics - 2
Quantifying pulse characteristics - 3

ESS Power Profile
Camry HEV - US06 Data

- Discharge Pulses
- Charge Pulses

Peak
X Sec Power Capability
Pulse energy / X Sec

1 kW Filter
-1 kW Filter

Cycle Time (s)
ESS Power (kW)
Example results from power pulse analysis

• Bound observations for in-use power pulses
  – Max discharge
  – Max charge/regen
Summarized pulse power bounds for multiple cases

Each DOH configuration
- DOH = 10%
- DOH = 19%
- DOH = 38%

Two in-use energy window cases
- Smallest energy: 
- Largest energy: 

- EES TT Workgroup: Use 2 sec and 10 sec values from highest ESS power and energy case on US06 as basis for power goals
Proposed method to obtain value for battery testing from an “energy window for vehicle use”

1) Begin with the stated “energy window for vehicle use” (e.g., 165 Wh)

2) Calculate energy for pulse requirements
   a) Discharge (e.g., 10 sec x 20 kW → 56 Wh)
   b) Charge (e.g., 10 sec x 30 kW → 83 Wh)

3) Subtract pulse energy from ends of vehicle use energy (e.g., 165 Wh – 83 Wh – 56 Wh = 26 Wh)

4) This gives “available energy over which pulse power requirements must be met” (e.g., perform size factor analysis with ≥ 26 Wh bounded by 10 s power requirements)

5) Repeat if needed for other pulse power levels (e.g., if energy from 2 sec power requirements happens to be greater than that from the 10 sec power requirements)

6) Note: restrict “energy over which pulse power requirements must be met” to ≥ 0

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Energy Window = 165 Wh

<table>
<thead>
<tr>
<th>Dis.</th>
<th>Chg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>165 - 56 = 109 Wh</td>
<td>Chg reqmt met: 165 - 83 = 82 Wh</td>
</tr>
<tr>
<td>Reqmts both met</td>
<td>26 Wh</td>
</tr>
</tbody>
</table>

(“Available Energy”)
Comparing New Proposed Lower Energy ESS requirements with other existing requirements

<table>
<thead>
<tr>
<th>End of Life Characteristics</th>
<th>Unit</th>
<th>FSS (42V Start-Stop)</th>
<th>PA (Lower Energy)</th>
<th>PA - Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Reference UC</td>
<td>New</td>
<td>Reference Battery</td>
</tr>
<tr>
<td>2 sec Discharge / Regen Pulse Power</td>
<td>kW</td>
<td>6 (Dis) / NA (Rgn)</td>
<td>55 (Dis) / 40 (Rgn)</td>
<td>NA</td>
</tr>
<tr>
<td>10 sec Discharge / Regen Pulse Power</td>
<td>kW</td>
<td>NA</td>
<td>20 (Dis) / 30 (Rgn)</td>
<td>25 (Dis) / 20 (Rgn)</td>
</tr>
<tr>
<td>Energy from pulse requirements</td>
<td>Wh</td>
<td>3</td>
<td>56</td>
<td>69</td>
</tr>
<tr>
<td>Energy over which requirements both met</td>
<td>Wh</td>
<td>30</td>
<td>26</td>
<td>300</td>
</tr>
<tr>
<td>Energy window for vehicle use</td>
<td>Wh</td>
<td>33</td>
<td>165</td>
<td>425</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>%</td>
<td>95</td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>Cycle-life</td>
<td>Cycles</td>
<td>750,000 (UC)</td>
<td>300,000 (HEV)</td>
<td>300,000 (HEV)</td>
</tr>
<tr>
<td>Cold-Cranking Power at -30°C (after 30-day stand at +30°C)</td>
<td>kW</td>
<td>8/21V_{min}</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Calendar-life, Years</td>
<td>Years</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Maximum System Weight</td>
<td>kg</td>
<td>10</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Maximum System Volume</td>
<td>Liter</td>
<td>8</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Selling Price/System @ 100k/yr</td>
<td>$</td>
<td>80</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Maximum Operating Voltage</td>
<td>Vdc</td>
<td>48</td>
<td>≤ 400</td>
<td>≤ 400</td>
</tr>
<tr>
<td>Minimum Operating Voltage</td>
<td>Vdc</td>
<td>27</td>
<td>≥ 0.55 V_{max}</td>
<td>≥ 0.55 V_{max}</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>°C</td>
<td>-30 to +52</td>
<td>-30 to +52</td>
<td>-30 to +52</td>
</tr>
<tr>
<td>Survival Temperature Range</td>
<td>°C</td>
<td>-46 to +66</td>
<td>-46 to +66</td>
<td>-46 to +66</td>
</tr>
</tbody>
</table>

Proposed requirements

Previous USABC requirements
From Analysis to New Requirements

• New set of targets/goals established for PA-HEVs
  – Selected by EES TT and USABC
  – Based on the analysis and discussions of the Workgroup
  – Referred to as lower-energy energy storage system (LEESS) goals

• USABC announces a Request for Proposal Information (RFPI)
  – Asking for proposals for technologies meeting the LEESS requirements
  – Systems satisfying the requirements could be based on batteries, symmetric or asymmetric capacitors, or some other device
Summary

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• Results suggested power-assist HEVs can still achieve high fuel savings with lower energy requirements and potentially lower cost

• Clarified energy definition
  – “Available” energy where power requirements simultaneously met, vs.
  – Energy window for vehicle use

• USABC/EES TT established new set of ESS targets and an RFPI
  – With goal of reducing cost for fuel-saving HEV systems
  – Open to any ESS technology (batteries, ultracapacitors, hybrid battery-ultracapacitors)
Acknowledgments

• Funded by DOE Energy Storage Program Manager
  – David Howell, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program

• Direction provided by USABC Managing Committee

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  – H. Tataria; R. Elder; C. Ashtiani; J. Belt; V. Bataglia;
  – C. Bae; R. Spotnitz; K. Snyder; J. Deppe