Energy Storage Requirements for Hybrid Fuel Cell Vehicles

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www.ctts.nrel.gov/BTM
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Presentation Outline

- Objectives
- Previous Studies
- Current Approach
- Results
  - Technical Results
  - Cost Analysis
- Conclusions
Objectives

• Extend previous studies to determine how the fuel cell and battery sizing choices can impact not only efficiency but also cost, mass, and volume constraints.
• Analyze the fuel cell and energy storage system demands under drive cycle and performance tests for two vehicle platforms using ADVISOR™.
• Consider several sizing scenarios and energy storage technologies.
• Support the FreedomCAR technical teams in defining energy storage requirements for fuel cell vehicles.
Previous Studies

• Hybridization of a fuel cell vehicle with energy storage improves fuel economy and make it practical (UCD, VTech, NREL)
  – Smaller fuel cell - lower cost
  – Fuel cell or reformer warm up
  – Improving transient response
  – Capturing regenerative breaking

• Pre-production prototype fuel cell vehicles are hybrids
  – Toyota FCHV – (NiMH)
  – Honda FCX – (ultra-capacitors)
Optimization of Fuel Cell Vehicle Design Provides Insight into System Trade-offs

- Derivative-free optimization algorithms necessary for complex design space of HEVs
- Drive cycle influences optimal degree of hybridization and control parameters
  - NEDC provides robust design
- Fuel cell transient response capability critical for “pure” fuel cell vehicle
- An optimized hybrid design can nullify the effects of fuel cell transient response
- Fuel economy impact of gasoline reformer warm-up may be substantial
- Relatively small energy storage system can overcome warm-up limitations of reformer
Approach for This Study

- Summarize Study Assumptions
- Determine the Potential Roles of the Battery
- Run Simulations to Quantify Requirements Associated with Individual Roles
- Compile the Battery Requirements
- Compare Requirements to Existing Technology
### Vehicle Characteristics

<table>
<thead>
<tr>
<th>Assumption Description</th>
<th>Units</th>
<th>mid-size SUV</th>
<th>mid-size Car</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle Description</strong></td>
<td></td>
<td>Rear wheel drive</td>
<td>Front wheel drive</td>
</tr>
<tr>
<td>Base Conventional Vehicle Mass</td>
<td>kg</td>
<td>1865</td>
<td>1480</td>
</tr>
<tr>
<td>Base Vehicle Glider Mass</td>
<td>kg</td>
<td>1276</td>
<td>1074</td>
</tr>
<tr>
<td>Cargo Mass</td>
<td>kg</td>
<td>136</td>
<td>136</td>
</tr>
<tr>
<td>Fuel Cell Vehicle Mass</td>
<td>kg</td>
<td>1923</td>
<td>1553</td>
</tr>
<tr>
<td>Aero. Drag Coef.</td>
<td></td>
<td>0.41</td>
<td>0.33</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>m^2</td>
<td>2.6</td>
<td>2</td>
</tr>
<tr>
<td>Rolling Resistance Coef.</td>
<td></td>
<td>0.012</td>
<td>0.009</td>
</tr>
<tr>
<td>Wheel Radius (effective)</td>
<td>m</td>
<td>0.343</td>
<td>0.314</td>
</tr>
<tr>
<td>Vehicle Range</td>
<td>mi (km)</td>
<td>300 (483)</td>
<td>300 (483)</td>
</tr>
</tbody>
</table>

### Performance

<table>
<thead>
<tr>
<th>Assumption Description</th>
<th>Units</th>
<th>mid-size SUV</th>
<th>mid-size Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-60 mph (0-97 kph)</td>
<td>s</td>
<td>&lt;=11.2</td>
<td>&lt;=12</td>
</tr>
<tr>
<td>40-60 mph (64-97 kph)</td>
<td>s</td>
<td>&lt;=4.4</td>
<td>&lt;=5.3</td>
</tr>
<tr>
<td>0-85 mph (0-137 kph)</td>
<td>s</td>
<td>&lt;=20.0</td>
<td>&lt;=23.4</td>
</tr>
<tr>
<td>Grade @ 65mph (105kph) for 20min. @ Curb Mass + 408kg</td>
<td>%</td>
<td>&gt;=6.5</td>
<td>&gt;=6.5</td>
</tr>
<tr>
<td>Drive Cycle Tolerance</td>
<td>mph (kph)</td>
<td>&lt;=2 (3.2)</td>
<td>&lt;=2 (3.2)</td>
</tr>
<tr>
<td>SOC Balancing</td>
<td>%</td>
<td>&lt;=0.5%</td>
<td>&lt;=0.5%</td>
</tr>
</tbody>
</table>
# Energy Storage System Assumptions

<table>
<thead>
<tr>
<th>Assumption Description</th>
<th>Units</th>
<th>PbA</th>
<th>NiMH</th>
<th>Li-Ion</th>
<th>Ultra-capacitor</th>
</tr>
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<tbody>
<tr>
<td>Energy Storage Energy Density</td>
<td>Wh/L</td>
<td>75</td>
<td>100</td>
<td>190</td>
<td>5</td>
</tr>
<tr>
<td>Energy Storage Specific Energy</td>
<td>Wh/kg</td>
<td>35</td>
<td>55</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>Energy Storage Energy Density</td>
<td>W/L</td>
<td>1600</td>
<td>2000</td>
<td>2800</td>
<td>4500</td>
</tr>
<tr>
<td>Energy Storage Specific Energy</td>
<td>W/kg</td>
<td>550</td>
<td>1000</td>
<td>1300</td>
<td>3500</td>
</tr>
<tr>
<td>Energy Storage Cost (power)</td>
<td>$/kW</td>
<td>$10.00</td>
<td>$40.00</td>
<td>$60.00</td>
<td>$15.00</td>
</tr>
</tbody>
</table>

## DOE-OTT High-Power Vehicle Energy Storage Target

<table>
<thead>
<tr>
<th>Assumption Description</th>
<th>Units</th>
<th>DOE-OTT High-Power Vehicle Energy Storage Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Storage Cost (energy)</td>
<td>$/kWh</td>
<td>$1,666.67</td>
</tr>
<tr>
<td>Energy Storage Cost (power)</td>
<td>$/kW</td>
<td>$20.00</td>
</tr>
</tbody>
</table>
## Fuel Cell and Hydrogen Storage Assumptions

### Fuel Cell System

<table>
<thead>
<tr>
<th>Assumption Description</th>
<th>Units</th>
<th>2005</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Type</td>
<td>--</td>
<td>hydrogen</td>
<td>hydrogen</td>
</tr>
<tr>
<td>Fuel Cell Peak Efficiency</td>
<td>%</td>
<td>62.9</td>
<td>62.9</td>
</tr>
<tr>
<td>Fuel Cell Efficiency at 25% Power</td>
<td>%</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Fuel Cell Efficiency at Rated Power</td>
<td>%</td>
<td>53.6</td>
<td>53.6</td>
</tr>
<tr>
<td>Fuel Cell System Specific Power</td>
<td>W/kg</td>
<td>500</td>
<td>650</td>
</tr>
<tr>
<td>Fuel Cell System Power Density</td>
<td>W/L</td>
<td>500</td>
<td>650</td>
</tr>
<tr>
<td>Fuel Cell System Cost</td>
<td>$/kW</td>
<td>96</td>
<td>27</td>
</tr>
<tr>
<td>Fuel Cell System 10-90% Power Transient Response Capability</td>
<td>s</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

### Hydrogen Storage

<table>
<thead>
<tr>
<th>Assumption Description</th>
<th>Units</th>
<th>2005</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2 Storage Energy Density</td>
<td>kWh/L</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>H2 Storage Specific Energy</td>
<td>kWh/kg</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>H2 Storage Cost</td>
<td>$/kWh</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>
Roles of the Energy Storage System

- Traction power during fuel cell startup
- Power-assist during drive cycles
- Regenerative braking recapture
- Gradeability performance
- Acceleration capability
- Electrical accessory loads
- Fuel cell startup and shutdown
Pictorial Description of Roles of the Energy Storage System

- Reduced FC Power During FC Startup
- Lagging FC Power Due to FC Ramp Rate
- Acceleration, Grade, and Peak Pulse Power Shaving from FC Downsizing
- Regen Capability
Drawing Power Envelope during a Drive Cycle
Traction Power During Fuel Cell Startup

Energy Mid Car 2005

Power Mid Car 2005
Traction Power During Fuel Cell Startup

Energy Mid SUV 2005

Power Mid SUV 2005
100kW Example - Energy Storage Traction

Power/Energy During Fuel Cell Startup

Energy

SUV requirements during the US06 assuming limited fuel cell performance

Cumulative Energy (Wh)

Time (s)

Power (kW)

midSUV_2005_US06

Fuel Cell
Energy Storage

NREL, Center for Transportation Technologies and Systems
Traction Power Assist During US06 Drive Cycle

**Energy**

Battery provides peak shaving capability during the US06 drive cycle.

**Power**
Traction Power/Energy Requirements Due to 2s Fuel Cell Power Response Capability

Battery provides ramp rates greater than fuel cell’s ramp capability

**Energy**

- Required Energy Storage Assist Power (kW)
- Required Energy Storage Assist Energy (Wh)

**Power**

- FC Power (kW)
- Battery provides ramp rates greater than fuel cell’s ramp capability
Total Available Regenerative Braking Energy possible for Recapture

Car

Available Regenerative Energy (kWh)

Time (s)

0 500 1000 1500 2000 2500 3000

0 0.5 1 1.5

midCar_2005_2UDDS
midCar_2005_HWFET
midCar_2005_US06

SUV

Available Regenerative Energy (kWh)

Time (s)

0 500 1000 1500 2000 2500 3000

0 0.5 1 1.5

midSUV_2005_2UDDS
midSUV_2005_HWFET
midSUV_2005_US06
Regenerative Braking Event Analysis

Car

SUV
Acceleration Performance – Power Demanding

Energy

During 0-60 (0-97kph) mph maximum acceleration

Power

NREL, CENTER FOR TRANSPORTATION TECHNOLOGIES AND SYSTEMS
Gradeability Performance – Energy Demanding

**Energy**

6.5% Grade @ 65 mph (105kph) for 20 minutes
At curb mass + 408kg

**Power**

NREL, CENTER FOR TRANSPORTATION TECHNOLOGIES AND SYSTEMS
Accessory Loads

- FTP
  - 750 W for 2738 s
    - 570 Wh
- HWFET
  - 750 W for 765 s
    - 159 Wh
- US06
  - 1500 W for 600 s
    - 250 Wh
- SC03
  - 3000 W for 600 s
    - 500 Wh
### Summary of Energy Storage Requirements for SUV (for 100kW Fuel Cell Case)

<table>
<thead>
<tr>
<th>Event Description</th>
<th>Peak Power (kW)</th>
<th>Duration (s)</th>
<th>Cumulative Energy (kWh)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Startup Traction Loads</td>
<td>46.4</td>
<td>&lt;11</td>
<td>0.15</td>
<td>50% rated power, 120s warm-up over 2UDDS, HWFET, &amp; US06</td>
</tr>
<tr>
<td>B Power-assist (response)</td>
<td>70.0</td>
<td>&lt;3</td>
<td>0.08</td>
<td>2 second 10%-90% FC response (ramp rate) during 2UDDS, HWFET, &amp; US06</td>
</tr>
<tr>
<td>C Power-assist (downsize)</td>
<td>43.3</td>
<td>&lt;3</td>
<td>0.05</td>
<td>During 2UDDS, HWFET, &amp; US06. US06 is limiting case</td>
</tr>
<tr>
<td>D Gradeability (see Table 2)</td>
<td>0.0</td>
<td>1200</td>
<td>0.00</td>
<td>81.4 kW sustained load for 1200s</td>
</tr>
<tr>
<td>E Acceleration</td>
<td>40.0</td>
<td>20</td>
<td>0.22</td>
<td>140 kW sustained load for 20s</td>
</tr>
<tr>
<td>F Accessory Loads</td>
<td>1.5</td>
<td>600-2800</td>
<td>0.10</td>
<td>US06 peak power, energy is for US06 4 min, or FTP 8 min</td>
</tr>
<tr>
<td>G Fuel Cell Shutdown</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>H Regenerative Braking</td>
<td>70.0</td>
<td>&lt;30</td>
<td>1.50</td>
<td>P_max is during US06, energy is FTP cycle max</td>
</tr>
</tbody>
</table>

- Power Requirement = max(A,B,C,D,E) + aux. load if applicable
- Energy Requirement = greatest of four cases

**Case(1)** The energy required to sustain the continuous grade power, plus a 750W accessory power for 20 minutes;

**Case(2)** The energy required to sustain the energy storage power requirement over six consecutive acceleration tests;

**Case(3)** The energy required to sustain the Highway or FTP accessory load for eight minutes, or the US06 accessory load for 4 minutes;

**Case(4)** The summation of the energies in A, B, and C. Minus overlap in cases A and C, cases A and B are additive (neglecting slight overlap).

**Required:**
- Power = 71.5kW, Energy = 1.33kWh (from Case 2 below)
Summary of Energy Storage Requirements for SUV (for varying Fuel Cell Size)

- Energy storage power (P), energy (E), and P/E ratio are compiled for many fuel cell sizes.
- Plot illustrates how P, E, and P/E change while the fuel cell is downsized.
Fuel Cell Cost and Volume - 2010

Cost

Volume

NREL, Center for Transportation Technologies and Systems
Chemistry Dependent Energy Storage System Cost and Volume

**Cost**

- Cost of Required Battery Pack ($)
- Fuel Cell Power (kW)

**Volume**

- Required Energy Storage Volume (Liters)
- Fuel Cell Power (kW)
Powertrain System Cost and Volume - 2005

Cost

Volume

NREL, Center for Transportation Technologies and Systems
Conclusions

• A methodology has been developed for determining the requirements of an energy storage system to be included in a fuel cell hybrid vehicle.

• Requirements depends on the energy storage system’s expected roles.

• This study’s energy storage system requirements for a mid-size SUV ranged from 40-85 kW and 0.05-7 kWh depending on fuel cell system size and the role of the energy storage system.

• The best choice for energy storage chemistry may be different depending on the level of fuel cell downsizing.

• Downsizing fuel cell beyond the power level required for continuous gradeability led to dramatically increased energy requirements (and thus predicted cost) for the energy storage system.

• Short term costs drive design toward smaller fuel cell and larger battery while cost is less influential in long-term design scenarios.
Future Work

• Refine vehicle and components assumptions to support identifying energy storage requirements for fuel cell vehicles
• Perform more detailed startup and shutdown load data for present/future fuel cell systems.
• Investigate use of ultracapacitors for hybrid fuel cell vehicles.
• Define the bounds for future optimization problems in which cost, volume, and mass constraints can all be evaluated simultaneously while maximizing fuel economy.
Acknowledgements

• This study was sponsored by U.S. Department of Energy’s Office of FreedomCAR and Vehicle Technologies.
• We appreciate the technical discussions we had with several FreedomCAR Technical Teams during the course of this study.

www.ctts.nrel.gov/BTM