Estimates of BEV and PHEV market penetration potential

Presented to the
Hydrogen and Fuel Cell Technical Advisory Committee (public comment session)
Washington, D.C.
November 4, 2011

by C. E. (Sandy) Thomas, Ph.D.,
Clean Energy Consultant
former-President H₂Gen Innovations, Inc. (ret.)
Alexandria, Virginia

www.CleanCarOptions.com
Outline

- Market Penetration Potential
  - BEV size and range limitations
  - BEV Sales Potential in US
Why not longer range BEVs?

• Low Specific Energy (kWh/kg)
• Low Energy Density (kWh/liter)
• MASS COMPOUNDING
Nissan Leaf Battery Parameters compared to USABC long-term goals

<table>
<thead>
<tr>
<th></th>
<th>Specific Energy</th>
<th>Specific Power</th>
<th>Power Density</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wh/kg</td>
<td>kW/kg</td>
<td>kW/L</td>
<td>kWh/L</td>
</tr>
<tr>
<td>Nissan Leaf Battery</td>
<td>80</td>
<td>0.3</td>
<td>0.3</td>
<td>0.0261</td>
</tr>
<tr>
<td>USABC long-term commercialization goals</td>
<td>150</td>
<td>0.46</td>
<td>0.46</td>
<td>0.230</td>
</tr>
</tbody>
</table>

Nissan Leaf Battery: 24 kWh useable energy; 300 kg mass, 90 kW power & 918 liters volume (estimated from two orthogonal photos)
Useful Specific Energy

Useful Specific Energy (Wh/kg)

- Pb-A: 35
- NiMH: 75
- Nissan Leaf: 80
- USABC Goal: 150
- 35 MPa: 544.9
- 70 MPa: 482.3

Batteries

H2 Tank, Battery & Fuel Cell System
Mass Compounding

• Adding batteries to increase range requires:
  • Slightly larger mechanical structure
  • Slightly larger suspension systems
  • Slightly larger brakes
• Which requires still more batteries to provide range and acceleration required
Mass Compounding of Late Model US cars

- Malen & Reddy (U. of Michigan) determined that adding 100 kg of batteries to a vehicle requires 59.8 kg of added mass to non-powertrain vehicle subsystems*.

- The **EV motor mass** increases with increased vehicle mass

- **Battery mass** increases with increased vehicle mass to maintain safe acceleration and to achieve the desired range

Energy per mile required from battery or FC

Energy Required to Motor/Controller (kWh/mile)

Vehicle Test Mass (kg)

Vehicle Model Results; 1.25X EPA combined

Edmund's road test of Nissan Leaf, California Speedway, (0.343 kWh/mile) 11/16/2010
BEV test mass estimation with and without mass compounding

Without mass compounding: to increase range from 65 miles to 100 miles requires the addition of 35miles x .367 kWh/mile = 12.8 kWh / .08 kWh/kg = 161 kg of extra battery for a total test mass of 1921 +161= **2,082 kg**

With mass compounding, the final BEV test mass for 100 miles range is **3,236 kg**, a 55% increase over the simple linear calculation!

<table>
<thead>
<tr>
<th>Battery capacity:</th>
<th>Est Range</th>
<th>kWh/mile</th>
<th>Miles</th>
<th>24 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>people</td>
</tr>
<tr>
<td>Model</td>
<td>0.337</td>
<td>71.2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Edmund's road test</td>
<td>0.343</td>
<td>70.0</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Model</td>
<td>0.367</td>
<td>65.4</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

Leaf curb mass: 1521 kg

---

work/vehicles/battery/Vehicle.XLS; Tab 'FUDS'; AC 654 - 10 / 11

---
Deloitte survey “Unplugged: electric vehicle realities versus consumer expectations”

- 63% of potential EV buyers expect greater than 300 miles range on one charge
- 23% expect charging in less than 30 minutes

*Deloitte Survey “Unplugged: Electric vehicle realities versus consumer expectations”
Vehicle Test Mass with Mass Compounding for BEVs & FCEVs

Nissan Leaf BEV (80 Wh/kg)
5 people & No A/C

Adv Li-ion BEV (150 Wh/kg)

700-bar FCEV

350-bar FCEV

"Adv Li-ion battery” assumes that the USABC long-term commercialization goals are achieved (150 Wh/kg; 230 Wh/Liter).
BEV Mass Compounding Elements

**Vehicle Test Mass (kg)**

Range (miles)

- 70
- 100
- 150
- 200

Leaf BEV- 5 passengers & No A/C

- Motor/controller
- Battery
- Passengers
- Glider

BPEV mass, vol, cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; Q-163 - 10 / 10
FCEV Mass Compounding Elements

Vehicle Test Mass (kg) vs Range (miles) for FCEV- 5 passengers & No A/C (700-bar hydrogen storage)

- Fuel cell
- Motor/controller
- Battery
- H2 Tank
- Hydrogen
- Passengers
- Glider

BPEV mass, vol, cost vs range charts RevB.XLS; Tab 'Equation-Leaf'; I163 - 10 / 11
Useful Energy Density
Energy Storage Volumes for Nissan Leaf size BEVs and FCEVs

Energy storage volume (Liters)

Nissan Leaf BEV (80 Wh/kg)

Nissan Leaf Internal volume

Adv Li-ion BEV (150 Wh/kg)

350-bar FCEV

700-bar FCEV

Vehicle Range (miles)
Energy storage volume (expanded scale)

Nissan Leaf BEV (80 Wh/kg)

Adv Li-ion BEV (150 Wh/kg)

350-bar FCEV

700-bar FCEV

Advanced Li-Ion assumes USABC Long-Term Commercialization Goals are Achieved
Boston Consulting Group* Battery Cost Estimates

<table>
<thead>
<tr>
<th></th>
<th>Battery cost ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Current Cost</td>
<td>$990</td>
</tr>
<tr>
<td>2020 costs</td>
<td>260</td>
</tr>
</tbody>
</table>

BEV Battery Pack OEM cost estimates vs. range

BEV battery Cost estimated by Boston Consulting Group

Current cost - High
Current cost - Low
2020- High
2020-Low

BEV Range (miles)

$200,000
$180,000
$160,000
$140,000
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$-

$20,000
$40,000
$60,000
$80,000
$100,000
$120,000
$140,000
$160,000
$180,000
$200,000

70 100 150 200 250 300

BEV Range (miles)
BEV Market Penetration
Market Potential for BEVs

• Assuming that BEVs can only be sold for small vehicles, how many small vehicles are in the current US car fleet?
• And what % of GHGs and oil consumption do these small cars represent?
• (McKinsey & Company estimated that 50% of all vehicles in the EU that generate 75% of all GHGs are too big or travel too far to be affordably powered by batteries.
Distribution of US Car sizes

<table>
<thead>
<tr>
<th>Car Size</th>
<th>% on the road</th>
<th>% of 2010 Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td>two-seaters</td>
<td>0.9%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Minicompact</td>
<td>0.5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>subcompact</td>
<td>8.2%</td>
<td>7.8%</td>
</tr>
<tr>
<td>Compact</td>
<td>16.7%</td>
<td>14.6%</td>
</tr>
<tr>
<td>Small wagons</td>
<td>1.8%</td>
<td>4.5%</td>
</tr>
<tr>
<td>All Small cars</td>
<td>28.1%</td>
<td>28.1%</td>
</tr>
<tr>
<td>Small vans</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Small pickups</td>
<td>1.1%</td>
<td>0.0%</td>
</tr>
<tr>
<td>All Small Vehicles</td>
<td>30.9%</td>
<td>28.7%</td>
</tr>
<tr>
<td>Midsize sedans</td>
<td>17.6%</td>
<td>21.9%</td>
</tr>
<tr>
<td>Midsize vans</td>
<td>7.2%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Medium wagon</td>
<td>1.2%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Large wagon</td>
<td>0.2%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Midsize pickups</td>
<td>3.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Midsize SUVs</td>
<td>12.0%</td>
<td>14.0%</td>
</tr>
<tr>
<td>Large cars</td>
<td>8.5%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Large vans</td>
<td>0.7%</td>
<td>0.1%</td>
</tr>
<tr>
<td>all pickups</td>
<td>10.2%</td>
<td>11.2%</td>
</tr>
<tr>
<td>Large SUVs</td>
<td>8.0%</td>
<td>10.4%</td>
</tr>
</tbody>
</table>
Previous Assumption for GHG reductions:

- 100% replacement of ICVs with BEVs
New Assumption

- BEVs will replace:
  - All small cars,
  - All small pickup trucks
  - All small SUVs
  - All small vans
  - And 50% of all midsize sedans

<table>
<thead>
<tr>
<th>Type</th>
<th>EPA range</th>
<th>Charging Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(km)</td>
<td>120-V</td>
</tr>
<tr>
<td>Nissan Leaf</td>
<td>117.5</td>
<td>21</td>
</tr>
<tr>
<td>Ford Transit</td>
<td>128.7</td>
<td>27</td>
</tr>
<tr>
<td>Connect</td>
<td>129-193</td>
<td>28*</td>
</tr>
<tr>
<td>Toyota RAV4</td>
<td>113-161</td>
<td>3.5**</td>
</tr>
<tr>
<td>Smart Fortwo</td>
<td>113-161</td>
<td>3.5**</td>
</tr>
<tr>
<td>Wheego Life</td>
<td>160.9</td>
<td>5***</td>
</tr>
<tr>
<td>Mitsubishi i-MiEV</td>
<td>99.8</td>
<td>14</td>
</tr>
<tr>
<td>Think City</td>
<td>160.9</td>
<td>18</td>
</tr>
</tbody>
</table>

*RAV4 charging times for prototype; production unit charging time expected to be shorter

**Smart Fortwo charging from 20% to 80% SOC; 8 hours for full charge

***Wheego charging time for 50% to 100% SOC
AEO 2011 US Grid Mix Projections through 2035 assuming no carbon constraints

<table>
<thead>
<tr>
<th>No Carbon constraints</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>44.8%</td>
<td>42.3%</td>
<td>43.5%</td>
<td>45.5%</td>
<td>45.5%</td>
<td>45.2%</td>
</tr>
<tr>
<td>Oil</td>
<td>1.1%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>1.0%</td>
<td>0.9%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Natural gas</td>
<td>24.6%</td>
<td>23.8%</td>
<td>22.3%</td>
<td>20.8%</td>
<td>22.1%</td>
<td>23.4%</td>
</tr>
<tr>
<td>All fossil fuels</td>
<td>70.6%</td>
<td>67.1%</td>
<td>66.7%</td>
<td>67.2%</td>
<td>68.5%</td>
<td>69.5%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>19.4%</td>
<td>19.8%</td>
<td>19.7%</td>
<td>18.6%</td>
<td>17.5%</td>
<td>16.7%</td>
</tr>
<tr>
<td>renewables</td>
<td>10.0%</td>
<td>13.1%</td>
<td>13.6%</td>
<td>14.2%</td>
<td>14.0%</td>
<td>13.8%</td>
</tr>
</tbody>
</table>

work/electric utilities/AEO-2011 alternative scenarios.XLS, DD 382;10/24/2011
## Impact of small BEVs* on US GHGs and Oil Consumption in 2015

<table>
<thead>
<tr>
<th></th>
<th># of LDVs on the road</th>
<th>% VMT</th>
<th>% gasoline</th>
<th>% GHGs</th>
<th>% ICV GHG savings</th>
<th>% BEV grid GHGs</th>
<th>Net GHG Savings (2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cars &amp; trucks suitable for BEVs:</td>
<td>39.6%</td>
<td>27.2%</td>
<td>24.9%</td>
<td>25.2%</td>
<td>-25.2%</td>
<td>17.3%</td>
<td>-7.91%</td>
</tr>
<tr>
<td>Larger cars &amp; trucks:</td>
<td>60.4%</td>
<td>72.8%</td>
<td>75.1%</td>
<td>74.8%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Includes all two-seaters, all mini-compact, subcompact, all compact, all small sedans, all small wagons, all small vans, all small pickup trucks, all small SUVs & 50% of all midsize sedans.
Maximum GHG Reductions for BEVs, PHEVs through 2035

- **BEV + PHEV**
  - 2015: 20.6%, 26.6%
  - 2020: 20.6%, 25.5%

- **PHEV-only**
  - 2015: 18.1%, 25.0%
  - 2020: 18.1%, 23.7%

- **BEV-only**
  - 2015: 7.9%, 7.8%
  - 2020: 7.9%, 7.0%

- **FCEV**
  - 2015: 51.2%, 51.3%
  - 2020: 51.2%, 51.2%
  - 2035: 51.2%, 51.3%

% Reduction in GHGs
Maximum Reductions in Oil Consumption for BEVs & PHEVs Through 2035

- **BEV + PHEV**: 64.7% (2015), 64.6% (2020), 66.7% (2035)
- **PHEV-only**: 53.5% (2015), 53.4% (2020), 56.1% (2035)
- **BEV-only**: 24.5% (2015), 24.5% (2020), 24.5% (2035)
- **FCEV**: 99.6% (2015), 99.6% (2020), 99.6% (2035)

% Reduction in Petroleum consumption
Thank You

• Contact Information:

  C.E. (Sandy) Thomas, former-President (ret.)
  H2Gen Innovations, Inc.
  Alexandria, Virginia 22304
  703-507/8149
  thomas@cleancaroptions.com

• Simulation details at:

• [http://www.cleancaroptions.com](http://www.cleancaroptions.com)