Technology Acceleration: Fuel Cell Bus Evaluations

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National Renewable Energy Laboratory
May 1, 2019

DOE Hydrogen and Fuel Cells Program
2019 Annual Merit Review and Peer Evaluation Meeting

Project ID # ta013

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

Timeline and Budget

• Project start date: 09/01/03
• FY18 DOE funding: $200K
• FY19 planned DOE funding: $150K
• Total DOE funds received to date: $4.25M (over 17 years)

Additional funding: U.S. Department of Transportation (DOT) Federal Transit Administration (FTA)

Barriers

• Lack of current fuel cell vehicle (bus) performance and durability data
• Lack of current hydrogen fueling infrastructure performance and availability data

Partners

• Transit fleets: Operational data, fleet experience
• Manufacturers: Vehicle specs, data, and review
• Fuel providers: Fueling data and review
Relevance

Current Targets\(^a\) | Units | 2016 Target | Ultimate Target
--- | --- | --- | ---
Bus lifetime | years/miles | 12/500,000 | 12/500,000
Powerplant lifetime | hours | 18,000 | 25,000
Bus availability | % | 85 | 90
Roadcall frequency (bus/fuel cell system) | miles between roadcall | 3,500/15,000 | 4,000/20,000
Operation time | hours per day/ days per week | 20/7 | 20/7
Maintenance cost | $/mile | 0.75 | 0.40
Fuel economy | miles per diesel gallon equivalent | 8 | 8

Data Collection/Analysis

NREL uses a standard protocol for collecting existing data from transit partners that:

• Provides a third-party analysis
• Includes comparisons to conventional-technology buses in similar service (diesel, CNG, diesel hybrid)

Individual Site Reports

• Documents performance results and experience for each transit agency
• Builds database of results
• Reports published and posted on NREL website

Annual FCEB Status Report (milestone)

• Crosscutting analysis comparing results from all sites
• Assesses progress and needs for continued success
• Provides input on annual status for DOE/DOT targets

CNG = compressed natural gas
## Approach: Data Summary for 2019

### Selected specifications for FCEBs included in data summary

<table>
<thead>
<tr>
<th>Bus Manufacturer</th>
<th>Van Hool</th>
<th>ENC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>A330</td>
<td>AFCB/Axcess</td>
</tr>
<tr>
<td>Bus length/height</td>
<td>40 ft/136 in.</td>
<td>40 ft/140 in.</td>
</tr>
<tr>
<td>Fuel cell OEM</td>
<td>UTC Power</td>
<td>Ballard</td>
</tr>
<tr>
<td>Model</td>
<td>PureMotion 120</td>
<td>FCvelocity–HD6</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>Hybrid system</td>
<td>Siemens ELFA, Van Hool integration</td>
<td>BAE Systems HybriDrive</td>
</tr>
<tr>
<td>Design strategy</td>
<td>Fuel cell dominant</td>
<td>Fuel cell dominant</td>
</tr>
<tr>
<td>Energy storage – OEM</td>
<td>EnerDel</td>
<td>A123</td>
</tr>
<tr>
<td>Type</td>
<td>Li-ion</td>
<td>Nanophosphate Li-ion</td>
</tr>
<tr>
<td>Capacity</td>
<td>17.4 kWh</td>
<td>11 kWh</td>
</tr>
<tr>
<td>Altoona tested</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

ENC = ElDorado National California
AFCB = American Fuel Cell Bus
OEM = original equipment manufacturer
## Approach: Data Summary for 2019

### FCEB fleets included in data summary

<table>
<thead>
<tr>
<th>Transit Agency</th>
<th>Abbreviation</th>
<th>Location</th>
<th>Bus Type</th>
<th># Buses</th>
<th>Data Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Transit</td>
<td>ACT</td>
<td>Oakland, CA</td>
<td>Van Hool</td>
<td>13</td>
<td>Fuel cell hours and fuel cost only</td>
</tr>
<tr>
<td>SunLine Transit Agency</td>
<td>SL</td>
<td>Thousand Palms, CA</td>
<td>AFCB</td>
<td>4</td>
<td>All, prototype bus removed</td>
</tr>
<tr>
<td>Orange County Transportation Authority</td>
<td>OCTA</td>
<td>Santa Ana, CA</td>
<td>AFCB</td>
<td>1</td>
<td>All</td>
</tr>
<tr>
<td>Stark Area Regional Transit Authority</td>
<td>SARTA</td>
<td>Canton, OH</td>
<td>AFCB</td>
<td>5</td>
<td>All</td>
</tr>
</tbody>
</table>

![AC Transit](image1.png)

![SunLine](image2.png)

![OCTA](image3.png)

![SARTA](image4.png)
Accomplishments and Progress
Top Fuel Cell Powerplant Exceeds 31,000 Hours

- Top fuel cell powerplant (FCPP) >31,200 hours
- Six FCPPs have surpassed DOE/DOT ultimate target

FCPP retired (9) and replaced with spare (10)

Total hours accumulated on each FCPP as of 12/31/18
Accomplishments and Progress
Summary of Fuel Cell Powerplant Hours Data

- Data from 29 FCPPs
- 31,210: high-hour FCPP
- 10 new buses added to the data set over the last 2 years
- 13,218: average hours for all FCPPs
- 23,954: average hours for buses 7 years or older
- 6 FCPPs surpassed ultimate target of 25,000 hours
- 12 FCPPs surpassed interim target of 18,000 hours
- 1 FCPP retired in late 2018 at 25,969 hours
  - FCPP no longer provided enough power to keep schedule
  - Replaced with spare FCPP that was part of original purchase
Accomplishments and Progress
Reliability: Miles Between Roadcall (MBRC)

- Data from newer buses (in service from July 2014)
- Fuel cell system roadcalls are caused by balance of plant components, not stack issues
### Accomplishments and Progress

#### Hydrogen Cost Data Summary, $/mi

<table>
<thead>
<tr>
<th></th>
<th>AC Transit&lt;sup&gt;a&lt;/sup&gt;</th>
<th>SunLine&lt;sup&gt;b&lt;/sup&gt;</th>
<th>OCTA&lt;sup&gt;c&lt;/sup&gt;</th>
<th>SARTA&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data period</td>
<td>2/13–7/17</td>
<td>3/12–12/18</td>
<td>3/16–12/18</td>
<td>2/18–12/18</td>
</tr>
<tr>
<td>Number of months</td>
<td>54</td>
<td>82</td>
<td>34</td>
<td>11</td>
</tr>
<tr>
<td>Average H&lt;sub&gt;2&lt;/sub&gt; cost, $/kg</td>
<td>8.39</td>
<td>10.17</td>
<td>13.95</td>
<td>5.14</td>
</tr>
<tr>
<td>Maximum H&lt;sub&gt;2&lt;/sub&gt; cost, $/kg</td>
<td>10.26</td>
<td>26.02</td>
<td>16.99</td>
<td>5.88</td>
</tr>
<tr>
<td>Minimum H&lt;sub&gt;2&lt;/sub&gt; cost, $/kg</td>
<td>6.49</td>
<td>2.53</td>
<td>12.99</td>
<td>5.00</td>
</tr>
<tr>
<td>Overall FCEB fuel cost, $/mile</td>
<td>1.41</td>
<td>1.83</td>
<td>2.21</td>
<td>1.04</td>
</tr>
<tr>
<td>Baseline technology</td>
<td>Diesel</td>
<td>CNG</td>
<td>CNG/diesel hybrid</td>
<td></td>
</tr>
<tr>
<td>Average fuel cost, $/gal or $/gge</td>
<td>2.43</td>
<td>0.96</td>
<td>1.15</td>
<td>1.89/2.30</td>
</tr>
<tr>
<td>Overall baseline fuel cost, $/mile</td>
<td>0.57</td>
<td>0.32</td>
<td>0.32</td>
<td>0.45/0.51</td>
</tr>
</tbody>
</table>

Fuel cost is based on data provided by agencies; not all are equal comparisons

<sup>a</sup> Delivered cost

<sup>b</sup> Includes station operating and maintenance (O&M) costs

<sup>c</sup> Retail cost from local public stations

<sup>d</sup> Delivered cost
Accomplishments and Progress

Fueling Cost Data Summary, $/mi

- **FCEB:**
  - Feb-13: 3.50
  - Jul-13: 3.00
  - Dec-13: 2.50
  - Mar-14: 2.00
  - May-14: 1.50
  - Oct-14: 1.00
  - Mar-15: 0.50
  - Aug-15: 0.00
  - Jun-16: 3.50
  - Sep-16: 3.00
  - Dec-16: 2.50
  - Feb-17: 2.00
  - May-17: 1.50
  - Oct-17: 1.00
  - Mar-18: 0.50
  - Jun-18: 0.00
  - Sep-18: 3.50
  - Dec-18: 3.00

- **CNG:**
  - Sep-15: 0.32
  - Apr-16: 0.32
  - Nov-16: 0.32
  - Jun-17: 0.32
  - Jan-18: 0.32
  - Aug-18: 0.32

- **Diesel:**
  - Mar-12: 0.57
  - Oct-12: 0.57
  - May-13: 0.57
  - Dec-13: 0.57
  - Jul-14: 0.57
  - Feb-15: 0.57
  - May-15: 0.57
  - Dec-15: 0.57
  - Jul-16: 0.57
  - Feb-17: 0.57
  - May-17: 0.57
  - Dec-17: 0.57
  - Jul-18: 0.57
  - Feb-18: 0.57
  - May-18: 0.57
  - Oct-18: 0.57
  - Jan-19: 0.57
  - Apr-19: 0.57
  - May-19: 0.57
  - Jun-19: 0.57
  - Jul-19: 0.57
  - Aug-19: 0.57
  - Sep-19: 0.57
  - Oct-19: 0.57
  - Nov-19: 0.57
  - Dec-19: 0.57

- **Retail cost from local public stations:**
  - AC Transit
  - SunLine
  - OCTA
  - SARTA
Accomplishments and Progress
Maintenance Cost by System

- Cost for propulsion system repairs highest for AFCBs
- Propulsion issues include:
  - Cooling system leaks
  - Low-voltage batteries
  - Fuel cell BOP
- Other issues:
  - Air compressor
  - Suspension

- Cumulative cost from in-service date
- Labor @ $50/h

BEB = battery electric bus
BOP = balance of plant
PMI = preventive maintenance inspection
HVAC = heating, ventilation, and air conditioning
Accomplishments and Progress
Maintenance Cost Trends

Cumulative maintenance cost from start of service

1. Low miles and introduction of new technology leads to higher cost in early stage of FCEB introduction
2. Cost drops and stabilizes as miles increase—most repairs handled under warranty
3. Cost trends up with learning curve for troubleshooting and repair as agency staff take on more maintenance work
4. BEB maintenance work handled by on-site OEM staff
5. BEB costs increase as agency takes over and warranty period ends
Accomplishments and Progress

Technical Issues Affecting Cost

- Fuel cell system issues—majority due to balance of plant
  - Air handling—blowers, compressors, controller
  - Cooling—pumps, plumbing
- Electrical system: low-voltage batteries
  - Electric accessories can cause a continual drain that shortens battery life (includes IT equipment such as cameras and fareboxes)
  - Issue also affects BEBs
- Cooling system leaks
  - Significant labor to locate
- Bus air compressor
- Added labor hours for troubleshooting problems
Accomplishments and Progress: Responses to Previous Year Reviewers’ Comments

• While the project provides value in tracking long-term reliability and life of the fuel cell system and buses, that presents a weakness in that the technology being examined is increasingly obsolete—and in some cases, technology from companies that are no longer in business is being used. It could be useful to separate out newer FCEBs from the older-generation FCEBs in the analysis.
  – Response: The primary analysis in this presentation is for the newest buses that began service in July 2014. The AFCB prototype was removed from the analysis and the data from the AC Transit buses are limited to FCPPP hours and fuel cost.

• Recommended the project team also indicate which buses are tested by the Altoona Bus Research and Testing Center
  – Response: This has been added to the bus specifications slide. The AFCB and New Flyer FCEBs have completed Altoona testing.
Collaboration and Coordination

- Transit agencies (1) provide data on buses, fleet experience, and training and (2) review reports
  - California: AC Transit, SunLine, OCTA
  - Ohio: SARTA
- Manufacturers provide some data on buses and review reports
  - Bus OEMs: New Flyer, ElDorado National
  - Fuel cell OEMs: Ballard, Hydrogenics, US Hybrid
  - Hybrid system OEMs: BAE Systems, New Flyer
- FTA provides funding to cover evaluations of both FCEBs and BEBs (follows same protocol)
- Other organizations share information and analysis results
  - California Air Resources Board, Center for Transportation and the Environment, CALSTART
Remaining Challenges and Barriers

• For technology acceleration and data collection project:
  – Continue data collection to track progress of newer-generation designs
  – Establish good relationships with additional transit agencies to add to the data set

• For industry to commercialize FCEBs:
  – Deploy larger fleets
    • Lower per-bus price: OEMs estimate ~$1M/bus for higher volumes
    • Accelerate learning curve for staff
    • Combine orders for multiple agencies
  – Incorporate training for FCEBs into standard maintenance training
  – Install hydrogen stations
    • High capital cost to install, but easier to scale up compared to battery fleet
    • Turn-key stations where fuel provider owns, operates, and maintains station can help with stabilizing cost for long-term budget planning
    • Long-term fuel contracts can lock in lower cost
    • Station utilization—higher volumes can mean lower per-unit cost
Proposed Future Work

• Remainder of FY 2019
  – Complete the following data analyses/reports:
    • SunLine AFCB Report, May 2019
    • 2019 Annual Status Report, September 2019
    • Preliminary reports on SARTA and OCTA (FTA-funded)
  – Provide feedback to DOE on technical issues with systems and components
  – Analyze fuel cell truck projects

• FY 2020
  – Kick off new FCEB evaluations as buses go into service—target new designs from different OEMs
  – Complete annual crosscutting analysis across sites

Any proposed future work is subject to change based on funding levels.
Proposed Future Work

<table>
<thead>
<tr>
<th>Demonstration</th>
<th>State</th>
<th>City</th>
<th>Bus Length</th>
<th># Buses</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEBA Demonstration</td>
<td>CA</td>
<td>Oakland</td>
<td>40</td>
<td>13</td>
<td>AC Transit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>American Fuel Cell Bus (AFCB)</td>
<td>CA</td>
<td>Thousand Palms</td>
<td>40</td>
<td>1</td>
<td>SunLine</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OH</td>
<td>Canton, Cleveland</td>
<td>40</td>
<td>2</td>
<td>OCTA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFCB (TIGGER)</td>
<td>CA</td>
<td>Thousand Palms</td>
<td>40</td>
<td>3</td>
<td>SunLine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery Dominant AFCB</td>
<td>CA</td>
<td>Thousand Palms</td>
<td>40</td>
<td>1</td>
<td>SunLine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AFCB (Low-No)</td>
<td>CA</td>
<td>Thousand Palms</td>
<td>40</td>
<td>5</td>
<td>SunLine</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>OH</td>
<td>Canton</td>
<td>40</td>
<td>5</td>
<td>SARTA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCEB Commercialization Consortium</td>
<td>CA</td>
<td>Oakland</td>
<td>40</td>
<td>10</td>
<td>AC Transit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CA</td>
<td>Orange County</td>
<td>40</td>
<td>10</td>
<td>OCTA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SunLine FCEB &amp; H2 generation</td>
<td>CA</td>
<td>Thousand Palms</td>
<td>40</td>
<td>5</td>
<td>SunLine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Generation FCEB</td>
<td>CA</td>
<td>Oakland</td>
<td>60</td>
<td>1</td>
<td>AC Transit</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Color coded by Technology:
- **Fuel cell dominant electric**
- **Battery dominant fuel cell electric**

- Current data collection includes a total of 29 FCEBs at six transit sites
- New sites could add 26 buses from a third OEM

Any proposed future work is subject to change based on funding levels.
Technology Transfer Activities

• Project provides non-biased evaluation of technology developed by industry

• Project documents performance results and lessons learned to aid market in understanding needs for full commercialization
  – Manufacturers
  – Transit agencies
  – Policymaking organizations
  – Funding organizations

• No technology (hardware/software) is developed through this project
## Summary: Progress Toward Targets

### Summary of FCEB data through December 2018

<table>
<thead>
<tr>
<th></th>
<th>2017 Fleet Average</th>
<th>2018 Fleet Max</th>
<th>2018 Fleet Average</th>
<th>2016 Target</th>
<th>Ultimate Target</th>
<th>Target Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus lifetime (years)</td>
<td>5.5</td>
<td>8.4</td>
<td>4.6</td>
<td>12</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Bus lifetime&lt;sup&gt;a&lt;/sup&gt; (miles)</td>
<td>128,656</td>
<td>237,483</td>
<td>125,613</td>
<td>500,000</td>
<td>500,000</td>
<td></td>
</tr>
<tr>
<td>Powerplant lifetime&lt;sup&gt;a&lt;/sup&gt; (hours)</td>
<td>13,041</td>
<td>31,210</td>
<td>13,218</td>
<td>18,000</td>
<td>25,000</td>
<td>Ultimate</td>
</tr>
<tr>
<td>Bus availability (%)</td>
<td>71</td>
<td>100</td>
<td>73</td>
<td>85</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Roadcall frequency&lt;sup&gt;b&lt;/sup&gt; (bus)</td>
<td>4,516</td>
<td>4,375</td>
<td>3,997</td>
<td>3,500</td>
<td>4,000</td>
<td>2016</td>
</tr>
<tr>
<td>Roadcall frequency (fuel cell system)</td>
<td>18,026</td>
<td>43,806</td>
<td>15,449</td>
<td>15,000</td>
<td>20,000</td>
<td>2016</td>
</tr>
<tr>
<td>Maintenance cost ($/mi)</td>
<td>0.53</td>
<td>0.62</td>
<td>0.42</td>
<td>0.75</td>
<td>0.40</td>
<td>2016</td>
</tr>
<tr>
<td>Fuel economy (mpdge)&lt;sup&gt;c&lt;/sup&gt;</td>
<td>7.01</td>
<td>7.82</td>
<td>7.01</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Range (miles)&lt;sup&gt;d&lt;/sup&gt;</td>
<td>300</td>
<td>360</td>
<td>277</td>
<td>300</td>
<td>300</td>
<td>Ultimate</td>
</tr>
</tbody>
</table>

<sup>a</sup> Bus miles or fuel cell hours accumulated to date. Does not indicate end of life.

<sup>b</sup> MBRC: average for current designs.

<sup>c</sup> Miles per diesel gallon equivalent.

<sup>d</sup> Estimated range based on fuel economy and 95% tank capacity. Transit agencies report lower real-world range.
Thank You

www.nrel.gov

NREL/PR-5400-73407

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.
Backup Slides
Accomplishments and Progress
Maintenance Cost: Parts and Labor

- Majority of FCEB cost is from labor—troubleshooting and training increase labor hours
- Parts costs are low while the buses are under warranty

Cumulative cost from in-service date
Labor @ $50/h
## Accomplishments and Progress

### Electric Cost Data Summary for BEBs

<table>
<thead>
<tr>
<th>Agency</th>
<th>Data period</th>
<th>Number of months</th>
<th>Average energy cost, $/kWh</th>
<th>Summer cost, $/kWh</th>
<th>Winter cost, $/kWh</th>
<th>Overall cost comparison to baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foothill Transit</td>
<td>4/14–7/18</td>
<td>51</td>
<td>0.18</td>
<td>0.21</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>County Connection</td>
<td>6/17–5/18</td>
<td>12</td>
<td>0.22</td>
<td>0.25</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>King County Metro</td>
<td>4/16–3/17</td>
<td>12</td>
<td>0.20</td>
<td>0.19</td>
<td>0.21</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall BEB energy cost, $/mile</th>
<th>0.46</th>
<th>0.73</th>
<th>0.57</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline technology</td>
<td>CNG</td>
<td>Diesel</td>
<td>Diesel/Hybrid</td>
</tr>
<tr>
<td>Average fuel cost, $/gal or $/gge</td>
<td>0.95</td>
<td>2.02</td>
<td>1.59</td>
</tr>
<tr>
<td>Overall baseline fuel cost, $/mile</td>
<td>0.24</td>
<td>0.54</td>
<td>0.30/0.25</td>
</tr>
</tbody>
</table>
Accomplishments and Progress
Electric Cost Data Summary for BEBs

Foothill Transit

Cost, $/mile
Apr-14 | Aug-14 | Dec-14 | Apr-15 | Aug-15 | Dec-15 | Apr-16 | Aug-16 | Dec-16 | Apr-17 | Aug-17 | Dec-17 | Apr-18
BEB (35 ft) | CNG

County Connection

Cost, $/mile
Jun-17 | Jul-17 | Aug-17 | Sep-17 | Oct-17 | Nov-17 | Dec-17 | Jan-18 | Feb-18 | Mar-18 | Apr-18 | May-18
BEB | Diesel Trolley | Diesel

King County Metro

Cost, $/mile
Apr-16 | May-16 | Jun-16 | Jul-16 | Aug-16 | Sep-16 | Oct-16 | Nov-16 | Dec-16 | Jan-17 | Feb-17 | Mar-17
BEB | Diesel | Hybrid