Demonstration of Fuel Cell Auxiliary Power Unit (APU) to Power Truck Refrigeration Units (TRUs) in Refrigerated Trucks

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Gus Block, Nuvera Fuel Cells
Mauricio Blanco, Ballard Power Systems

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Project ID# MT014

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Overview

Timeline
- Project Start: April 2013
- Project End: March 2018
- Percent complete: 70%

Barriers Addressed by This Project
- B. High hydrogen fuel infrastructure capital costs
- E. Lack of life cycle cost and performance data to demonstrate low investor risks
- F. Inadequate user experience for fuel cell applications

Budget
- FY16/17 DOE Funding: $0K
- Previous DOE Funding: $2M

<table>
<thead>
<tr>
<th>Allocation of Funding</th>
<th>Spent to Date</th>
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</thead>
<tbody>
<tr>
<td>DOE Funding for Subcontracts</td>
<td>$986K</td>
</tr>
<tr>
<td>Contractor In-Kind Cost Share</td>
<td>$795K</td>
</tr>
<tr>
<td>Remaining Commitments</td>
<td>$108K</td>
</tr>
<tr>
<td>PNNL Expenditures</td>
<td>$212K</td>
</tr>
</tbody>
</table>

Partners

<table>
<thead>
<tr>
<th>Role</th>
<th>Nuvera Team</th>
<th>Ballard Team</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell/Integration</td>
<td>Nuvera</td>
<td>Ballard</td>
</tr>
<tr>
<td>TRU Producer</td>
<td>Thermo King</td>
<td>Carrier</td>
</tr>
<tr>
<td>Business Case</td>
<td>Thermo King</td>
<td>Zen</td>
</tr>
<tr>
<td>Demonstration</td>
<td>TBD</td>
<td>Walmart</td>
</tr>
</tbody>
</table>
Relevance: Project Purpose

Overall Objective: To demonstrate the viability of fuel cell-based Transport Refrigeration Units (TRUs) for refrigerated Class 8 trucks using demonstrations and business case development.

Barriers Addressed on This Project

B. High hydrogen fuel infrastructure capital costs
   ● Provide DOE funding with 50% cost share to support the demonstrations

E. Lack of life cycle cost and performance data to demonstrate low investor risks
   ● Develop business case with value proposition analysis and total cost of ownership modeling
   ● Evaluate demonstration results and share with industry

F. Inadequate user experience
   ● Perform demonstration in real world application
   ● Develop safety plan to address operations and refueling
   ● Involve primary TRU companies—Thermo King/Carrier
Relevance: Where does it make most sense?

- “Hub and Spoke” Distribution Centers where single H₂ source can supply all vehicles
  - Return to same distribution center to refuel (preferably every day)
- Hydrogen already on site for refueling fuel cell forklifts—safety and regulatory issues addressed
  - Larger H₂ usage does not require major infrastructure modifications
- Government regulations and incentives drive the need for alternatives to diesel TRUs (e.g. anti-idling laws, noise, emissions)
- Successful replacement of diesel engine (power, mass, volume)
- Acceptable Economics
Approach

- Develop and demonstrate two fuel cell systems in commercial operations
- Assess the system performance
- Analyze its market viability

<table>
<thead>
<tr>
<th>Compete &amp; Place Subcontracts</th>
<th>Develop Business Case</th>
<th>Size the System</th>
<th>Design &amp; Test APU</th>
<th>Perform testing and demonstration</th>
<th>Analyze Demo Results &amp; Report</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>2017</td>
<td>2017</td>
<td>2017</td>
<td>2017</td>
<td>2017</td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td></td>
<td>800-1000 hr Demo</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Acquire Fuel-Cell based system for demonstration:
- Acquisitions through open competition
- Team with manufacturers and end-users

Develop a business case:
- Voice of the customer
- Market assessment
- Value proposition analysis

Design the system:
- Develop fuel cell system with rated power
- Provide power conversion
- Address safety and compliant issues with TRU
- Make road-worthy
- Must be comparable to current diesel

Perform testing and demonstration:
- Site H₂ infrastructure preparation
- Perform intermediate tests: vibration, etc.
- Install system and commission APU
- Perform 800-1000 hour tests with actual deliveries and varying routes

Analyze Demo Results:
- PNNL will collect real time data and perform independent Technical / Economic Assessment
- Evaluate relative to DOE Technical Targets
- Update business case based on demonstration results
- Prepare final report
Accomplishments

Nuvera System Packaging Complete

- Nuvera—Phase II Completion in May
  - DOE/PNNL/Nuvera decision to restart project
  - Nuvera finalized system packaging, wiring, controls, software, communication
  - Thermo King designed new Power Distribution Unit:
    - DC/DC for auxiliaries, updated control software, integration

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Accomplishments

Nuvera’s Successful Low Power Integrated Test

- Nuvera results of test of new Power Distribution Unit (PDU) from Thermo King
- Successfully demonstrated integration.

Next Steps:
Integrate inverter and TRU into system for full 8 hour laboratory demonstration
Accomplishments

Ballard Sized FC Power: Walmart TRU Data

- Typical Walmart Data from one of 16 TRUs evaluated
- High ambient temperature in Winter Haven, FL
- Decision: Requires 18 kW maximum power

The peak power is \( \sim 18 \text{ kW} \)
Accomplishments

Ballard Sized H₂ Fuel Tank: Walmart TRU Data

- 83% of TRUs would require < 10 kg H₂/day
- Highest H₂ usage for 22 hrs = 19 kg H₂/day
- Design with 20 kg H₂ Tank for 2 days operation or 24 hours of freezer load operation

H₂ Consumed = 19.1 kg (22 hours of operation)
Accomplishments

Walmart ORBCOMM location data used to observe the trailer routes followed

- Trailers did not always return to the same distribution center
- One reefer traveled between Brundige, AL and Winter Haven, FL, the other worked exclusively out of one DC
Accomplishments

Ballard System Design Work

- Hybrid vs. non-hybrid
  - Decision non-hybrid: runs at maximum power for hours and transients are relatively slow

- Location of System on the Trailer
  - Bottom of the trailer challenging but preferred

- System BOM and Packaging
  - Commercially available components identified with modeling tool
  - Initial layout of main fuel cell system
Accomplishments

Ballard Business Case Challenges

**Total Cost of Ownership Model**

- Low Diesel Cost and High H₂ Cost

<table>
<thead>
<tr>
<th>Hydrogen Cost [$/kg]</th>
<th>$2.00</th>
<th>$3.00</th>
<th>$4.00</th>
<th>$5.00</th>
<th>$6.00</th>
<th>$7.00</th>
<th>$8.00</th>
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</thead>
<tbody>
<tr>
<td>Diesel Cost [$/gallon]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$2.00</td>
<td>(23,606)</td>
<td>(38,967)</td>
<td>(54,328)</td>
<td>(69,690)</td>
<td>(85,051)</td>
<td>(100,413)</td>
<td>(115,774)</td>
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<td>$3.00</td>
<td>(10,548)</td>
<td>(25,910)</td>
<td>(41,271)</td>
<td>(56,633)</td>
<td>(71,994)</td>
<td>(87,356)</td>
<td>(102,717)</td>
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<tr>
<td>$4.00</td>
<td>2,509</td>
<td>(12,853)</td>
<td>(28,214)</td>
<td>(43,575)</td>
<td>(58,937)</td>
<td>(74,298)</td>
<td>(89,660)</td>
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<td>$5.00</td>
<td>15,566</td>
<td>(205)</td>
<td>(15,157)</td>
<td>(30,518)</td>
<td>(45,880)</td>
<td>(61,241)</td>
<td>(76,603)</td>
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<td>$6.00</td>
<td>28,623</td>
<td>13,262</td>
<td>(2,100)</td>
<td>(17,461)</td>
<td>(32,822)</td>
<td>(48,184)</td>
<td>(63,545)</td>
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<td>$7.00</td>
<td>41,680</td>
<td>26,319</td>
<td>10,958</td>
<td>(4,404)</td>
<td>(19,765)</td>
<td>(35,127)</td>
<td>(50,488)</td>
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<tr>
<td>$8.00</td>
<td>54,738</td>
<td>39,376</td>
<td>24,015</td>
<td>8,653</td>
<td>(6,708)</td>
<td>(22,069)</td>
<td>(37,431)</td>
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<tr>
<td>$9.00</td>
<td>67,795</td>
<td>52,433</td>
<td>37,072</td>
<td>21,711</td>
<td>6,349</td>
<td>(9,012)</td>
<td>(24,374)</td>
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<td>$10.00</td>
<td>80,852</td>
<td>65,491</td>
<td>50,129</td>
<td>34,768</td>
<td>19,406</td>
<td>4,045</td>
<td>(11,316)</td>
</tr>
</tbody>
</table>

TCO = ($37,746) @ $3.27/gallon diesel
Ballard Business Case Challenges

- Total Cost of Ownership Model
  - Low Diesel Cost and High H₂ Cost
  - High Fuel Cell System Capital Cost (~2X diesel engine)
    - Power Electronics (24% of total) needed to match TRU’s 480VDC 3 phase requirement
    - Cost of 20 kg H₂ Tank (34% of total)
    - Cost based on only 500 units/year

H₂ storage assumes 20kg storage capacity at 350 bar (for reference, FC car tank stores 5-6kg at 700 bar)

May be potential to further reduce power electronics cost by closer design integration with TRU; cost assumes integrated DC/AC converter (vs separate DC/DC and inverter)
Accomplishments

Business Case Challenges

- Total Cost of Ownership Model
  - Low Diesel Cost and High H₂ Cost
  - High Fuel Cell System Capital Cost (2X diesel engine)

- Government Regulations/Incentives
  - Loss of 30% Federal Business Energy Investment Tax Credit (expired 12/2016)
  - Alternatives to Federal and California Regulations

<table>
<thead>
<tr>
<th>Technology</th>
<th>12/31/16</th>
<th>12/31/17</th>
<th>12/31/18</th>
<th>12/31/19</th>
<th>12/31/20</th>
<th>12/31/21</th>
<th>12/31/22</th>
<th>Future Years</th>
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</thead>
<tbody>
<tr>
<td>PV, Solar Water Heating, Solar Space Heating/Cooling</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>26%</td>
<td>22%</td>
<td>10%</td>
<td>10%</td>
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<tr>
<td>Solar Process Heat</td>
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<td></td>
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<tr>
<td>Hybrid Solar Lighting, Fuel Cells, Small Wind</td>
<td>30%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>Geothermal Heat Pumps, Microturbines, Combine Heat</td>
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<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td>and Power Systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geothermal Electric</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Large Wind</td>
<td>30%</td>
<td>24%</td>
<td>18%</td>
<td>12%</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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</tbody>
</table>
Ballard Phase I Decision

- Ballard No-Go into Phase II
- Lessons Learned
  - System cost needs to be more competitive
    - This is due mainly to the high costs for the power electronics and hydrogen tanks needs for this application
  - System mass too high--leave ~1000 lbs product on the dock
    - This includes the added shielding/packaging needed to protect the hydrogen tanks and FC system when mounted to the trailer
  - Disparity between diesel and H₂ cost
  - Loss of range--niche market needs to have systems return daily
  - Federal and local incentives/regulations need to be more favorable
  - Insufficient hydrogen and infrastructure
    - Challenge even at locations with MH equipment
  - Major development effort to create a product
    - Cost effective off-the-shelf system needed
## Responses to Previous Year Reviewer’s Comments

<table>
<thead>
<tr>
<th>FY16 Reviewer Comment</th>
<th>FY17 Response to Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customer test locations are not tied into any other existing infrastructure making it more expensive and higher risk.</td>
<td>Ballard demonstration location is to use existing H₂ infrastructure. Nuvera identifying new demonstration partners includes those with existing H₂ infrastructure.</td>
</tr>
<tr>
<td>It is unclear what the Nuvera fuel cell status is.</td>
<td>Provided details of the current fuel cell system and what still needs to be completed before the demonstration.</td>
</tr>
<tr>
<td>A definition of “sized appropriately” for the developing system is needed.</td>
<td>Data is provided for sizing of Ballard’s fuel cell and H₂ tank.</td>
</tr>
<tr>
<td>One of the main goals of the project could be development of a working business case model for an early fuel cell based TRU market.</td>
<td>Thermo King (Nuvera Team) and Zen Energy Solutions (Ballard Team) developed a business case with TCO model.</td>
</tr>
</tbody>
</table>
## Collaborations

<table>
<thead>
<tr>
<th>Partner</th>
<th>Project Roles</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE</td>
<td>Sponsorship, Steering</td>
</tr>
<tr>
<td>PNNL</td>
<td>Management and Coordination, Data Collection and Analysis, Business Case Development</td>
</tr>
<tr>
<td>Nuvera</td>
<td>Fuel Cell Supplier, System Integrator</td>
</tr>
<tr>
<td>Thermo King</td>
<td>Integration of APU with TRU</td>
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<tr>
<td>Thermo King</td>
<td>Business Case Development</td>
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<tr>
<td>None</td>
<td>Demonstration Partner</td>
</tr>
<tr>
<td>Walmart</td>
<td></td>
</tr>
</tbody>
</table>

### Special Thanks

- Pete Devlin, DOE-EERE Fuel Cells Technology Office
Remaining Challenges and Barriers

► Identify a Demonstration Site for Nuvera Team
  ▪ Must return nightly to the distribution center
  ▪ California is the preferred site

► Finalize Nuvera cell based APU that:
  ▪ Is capable of on-road operation (vibration, safety, on-road projectiles)

► Need Market Pull
  ▪ Generate the required interest to bring the system to market
Future Work

Phase III Nuvera Scope Before Demo

- Prepare system for on-road operations
  - Install stack cover
  - Design external enclosure
  - Address vibration issues and test
  - Final safety assessment
## Milestones and Deliverables

<table>
<thead>
<tr>
<th>Milestone Description</th>
<th>Owner</th>
<th>Milestone Type</th>
<th>% Complete</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Pause</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>Feb. 2015 to Sept. 2016</td>
</tr>
<tr>
<td>Complete Phase II: System Development</td>
<td>Nuvera</td>
<td>Go/No-Go</td>
<td>70%</td>
<td>May 2017</td>
</tr>
<tr>
<td>Phase III Go/No-Go</td>
<td>Nuvera</td>
<td>Standard</td>
<td>Not started</td>
<td>Nov. 2017</td>
</tr>
<tr>
<td>System Safety Assessment &amp; Integration with Trailer</td>
<td>Ballard</td>
<td>Go/No-Go</td>
<td>Not started</td>
<td>Dec. 2017 to Mar. 2018</td>
</tr>
</tbody>
</table>

## Future Work

<table>
<thead>
<tr>
<th>Milestone Description</th>
<th>Owner</th>
<th>Milestone Type</th>
<th>% Complete</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>Phase I: System Design and Market Assessment</td>
<td>Ballard</td>
<td>Go/No-Go</td>
<td>100%</td>
<td>April 2017</td>
</tr>
</tbody>
</table>
Technology Transfer Activities

- Share Results
  - Press Releases, Interviews, Presentations, Publications

- Develop Business Cases and Commercialization Plans
  - Working with largest TRU manufacturers in the U.S.
  - Working with potential customers for demonstrations

- Look for Potential Future Funding for Follow-On Demonstrations
## Project Summary

<table>
<thead>
<tr>
<th>Relevance</th>
<th>Demonstrate the technical and commercial viability of fuel cell-based Transport Refrigeration Units (TRUs) for refrigerated Class 8 trailers.</th>
</tr>
</thead>
</table>
| **Approach** | • Demonstrate fuel cell system in commercial applications  
• Assess the system performance  
• Analyze its market viability |
| **Technical Accomplishments and Progress** | • Nuvera successfully integrated and tested system in the laboratory at low power  
• Zen developed business case with Carrier/Ballard  
• Ballard developed system design and completed the Phase I Go/No-Go Decision |
| **Collaborations** | • Nuvera and its team: Thermo King  
• Ballard and its team: Carrier, Zen Energy Solutions, Walmart |
| **Proposed Future Research** | • Continue to oversee project  
• Perform multiple demonstrations and analyze results |

Project ID# MT014

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Questions?

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