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

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Project ID# MT014

PNNL-SA-134031

Overview

Timeline

- Project Start: April 2013
- Project End: March 2018
- Percent complete: 100%

Budget

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

Allocation of Funding	Spent to Date
DOE Funding for Subcontracts	$1,018K
Contractor In-Kind Cost Share	$853K
Remaining Commitments	$0K
PNNL Expenditures	$230K

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

Partners

Role	Nuvera Team	Ballard Team
Fuel Cell/ Integration	Nuvera	Ballard
TRU Producer	Thermo King	Carrier
Business Case	Thermo King	Zen
Demonstration	--	Walmart

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" Food Distribution Centers where single H_2 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 H_2 usage and outdoor refueling 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 (cost of diesel, H2, fuel cell, power electronics**

Fuel Cell Lift Truck

H_2 Refueling

Truck APU

Grocers and other Food Customers

Approach

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

2012-2013	2013-2014	2013-2014	2014-2017	**Nuvera**
2016	2017	2017		**Ballard**

Compete & Place Subcontracts → Develop Business Case → Design the System → Fab & Test APU → 800-1000 Hr Demo & Report

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:
- Size the system components
- Provide power conversion
- Address safety and compliant issues with TRU
- Identify location for installation

Fabricate and Test System:
- Fabricate fuel cell system
- Integrate with power electronics and TRU
- Perform laboratory demonstration testing

Demonstration:
- Install system on trailer & commission APU
- Perform 800-1000 hour tests with actual deliveries and varying routes
- Collect real time data and perform PNNL Technical / Economic Assessment
- Prepare final report

Summary of Accomplishments

<table>
<tr><th>Phase</th><th>Accomplishment</th><th>Nuvera</th><th>Ballard</th></tr>
<tr><td rowspan="3">Phase 1</td><td>Finalized Business Case</td><td>Yes</td><td>FY17</td></tr>
<tr><td>Prepared Safety Evaluations</td><td>Yes</td><td>FY17</td></tr>
<tr><td>Finalized System Design</td><td>Yes</td><td>FY17</td></tr>
<tr><td colspan="2">Phase I Go/No-Go Decision</td><td>Yes</td><td>No</td></tr>
<tr><td rowspan="3">Phase 2</td><td>Fabricated Fuel Cell System</td><td>Yes</td><td rowspan="5">N/A</td></tr>
<tr><td>Integrated with Power Electronics</td><td>FY17</td></tr>
<tr><td>Performed 8 Hour Demonstration</td><td>FY18</td></tr>
<tr><td colspan="2">Phase II Go/No-Go Decision</td><td>No</td></tr>
<tr><td>Phase 3</td><td>800-1000 hour Commercial Demonstration</td><td>N/A</td></tr>
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Thermo King/Nuvera Business Case:

Net Present Value of fuel cell- vs. diesel-powered TRU

With ITC					
Hydrogen	TRU Incremental Cost	Diesel $3.00	Diesel $4.00	Diesel $6.00	Diesel $8.00
Hydrogen $2.50	$ 11,550	$ 2,567	$ 17,576	$ 47,594	$ 99,865
Hydrogen $4.00	$ 11,550	$ (19,575)	$ (3,967)	$ 26,051	$ 78,323
Hydrogen $6.00	$ 11,550	$ (34,090)	$ (34,090)	$ (4,072)	$ 48,199
Hydrogen $8.00	$ 11,550	$ (63,614)	$ (63,614)	$ (33,596)	$ 18,675
Hydrogen $10.00	$ 11,550	$ (93,167)	$ (92,923)	$ (62,905)	$ (10,634)
Hydrogen $12.00	$ 11,550	$ (122,687)	$ (122,687)	$ (92,669)	$ (40,398)
Hydrogen $2.50	$ 16,800	$ (2,683)	$ 16,568	$ 52,149	$ 87,730
Hydrogen $4.00	$ 16,800	$ (24,825)	$ 4,047	$ 39,628	$ 75,209
Hydrogen $6.00	$ 16,800	$ (39,340)	$ (27,240)	$ 8,342	$ 43,923
Hydrogen $8.00	$ 16,800	$ (68,864)	$ (58,526)	$ (22,945)	$ 12,637
Hydrogen $10.00	$ 16,800	$ (98,417)	$ (89,813)	$ (54,231)	$ (18,650)
Hydrogen $12.00	$ 16,800	$ (127,937)	$ (121,099)	$ (85,518)	$ (49,936)
Hydrogen $2.50	$ 22,050	$ (7,933)	$ 7,076	$ 37,094	$ 89,365
Hydrogen $4.00	$ 22,050	$ (30,075)	$ (14,467)	$ 15,551	$ 67,823
Hydrogen $6.00	$ 22,050	$ (44,590)	$ (44,590)	$ (14,572)	$ 37,699
Hydrogen $8.00	$ 22,050	$ (74,114)	$ (74,114)	$ (44,096)	$ 8,175
Hydrogen $10.00	$ 22,050	$ (103,667)	$ (103,423)	$ (73,405)	$ (21,134)
Hydrogen $12.00	$ 22,050	$ (133,187)	$ (133,187)	$ (103,169)	$ (50,898)

Higher diesel and lower H_2 cost provide positive NPV

Assumptions:

- 24 kW (net) fuel cell power system
- 100% efficiency improvement over diesel ICEs
- 12 year trade cycle
- Baseline Thermo King Precedent S-600 TRU price: $23,500
- 2000 operating hours per year
- 75% of hauling at fresh continuous cycle sentry (+35° F)
- 25% of hauling at deep frozen (-20° F)
- Diesel ICE maintenance costs: $6,566
- Fuel cell system maintenance costs: $2,144
- "Marginal" value proposition defined as $0 to -$30,000 NPV

Carrier/Walmart/Zen/Ballard Business Case:
Net Present Value of fuel cell- vs. diesel-powered TRU

Hydrogen Cost	TRU Incremental Cost	Diesel ($/gallon) (with ITC)								
($/kg)		$2.00	$3.00	$4.00	$5.00	$6.00	$7.00	$8.00	$9.00	$10.00
$2.00	$34,000	$ 2,820	$ 22,789	$ 42,759	$ 62,729	$ 82,699	$102,669	$122,639	$142,609	$162,578
$3.00	$34,000	$ (12,542)	$ 7,428	$ 27,398	$ 47,338	$ 67,339	$ 87,307	$107,277	$127,247	$147,217
$4.00	$34,000	$ (27,903)	$ (7,933)	$ 12,037	$ 32,006	$ 51,976	$ 71,946	$ 91,916	$111,886	$131,856
$5.00	$34,000	$ (43,265)	$ (23,295)	$ (3,325)	$ 16,645	$ 36,615	$ 56,585	$ 76,554	$ 96,524	$116,494
$6.00	$34,000	$ (58,626)	$ (38,656)	$ (18,686)	$ 1,284	$ 21,253	$ 41,223	$ 61,193	$ 81,163	$101,133
$7.00	$34,000	$ (73,987)	$ (54,018)	$ (34,048)	$ (14,078)	$ 5,892	$ 25,862	$ 45,832	$ 65,801	$ 85,771
$8.00	$34,000	$ (89,349)	$ (69,379)	$ (49,409)	$ (29,439)	$ (9,469)	$ 10,500	$ 30,470	$ 50,440	$ 70,410

<u>Assumptions:</u>

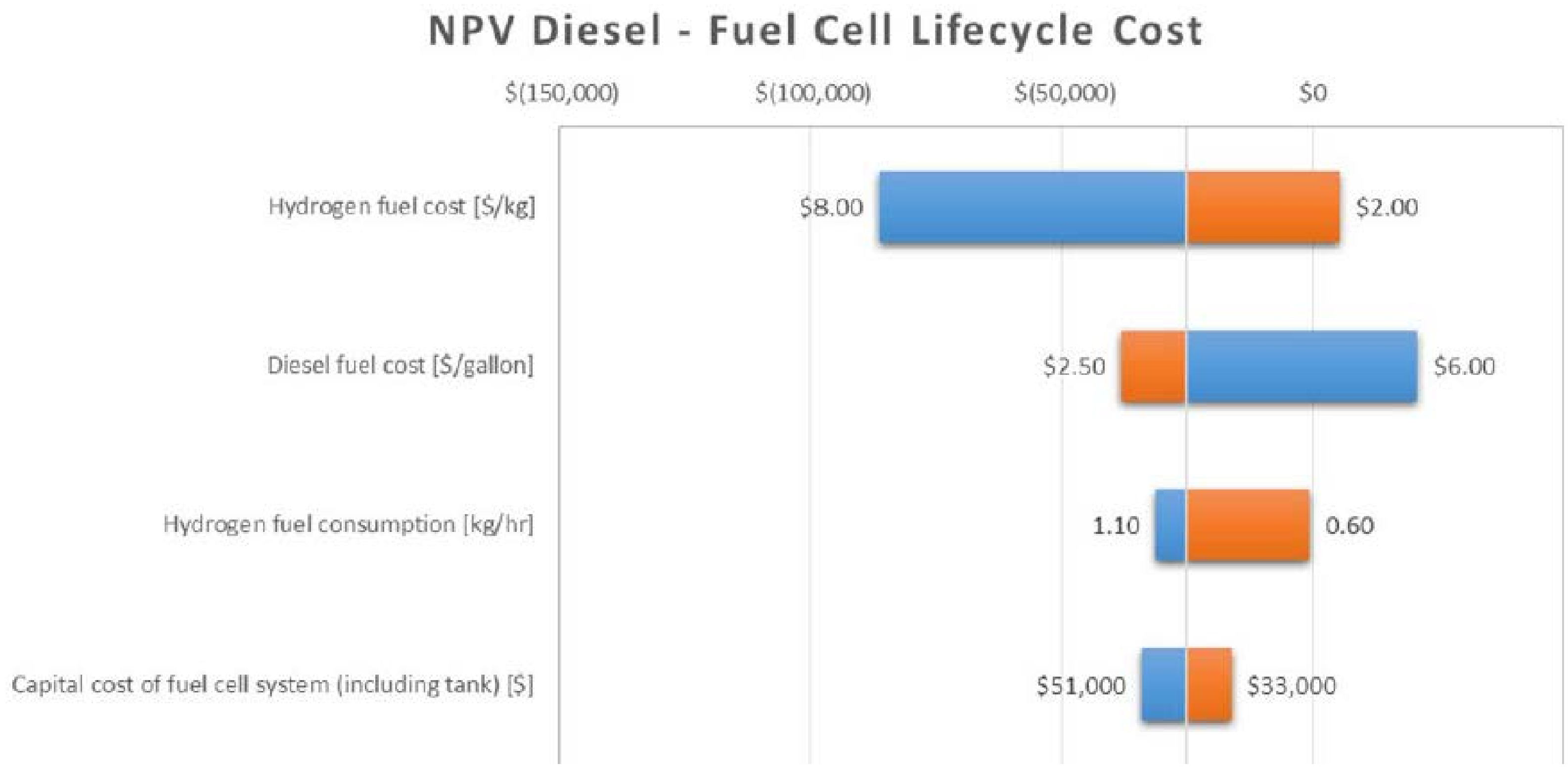
- 20 kg fuel tanks
- 10 year trade cycle
- 2500 operating hours per year
- Diesel ICE maintenance costs: $21,250
- Fuel cell system maintenance costs: $12,750
- Carbon credit price $13/tonne CO_2e

Although different assumptions, Nuvera and Ballard analyses are similar

Accomplishments

Carrier/Walmart/Zen/Ballard Business Case:

The two most significant contributors are capital cost and fuel cost.



Baseline Assumptions:

- $3.27/gallon diesel and $4/kg H2
- 1. kg/hr fuel consumption
- $42,000 FCS + tank

Business Case Common Outcomes

- Positives
  - Availability of hydrogen infrastructure at major grocery distribution centers
  - Technology shift towards all-electric TRUs
  - Federal, state and local emissions regulations of diesel engines
  - Noise restrictions in sensitive or densely populated areas
  - Diesel fuel prices and uncertainty of future diesel prices, coupled with increasing availability and economic viability of natural gas fuel for transportation
  - Environmental and sustainability initiatives of industry leaders

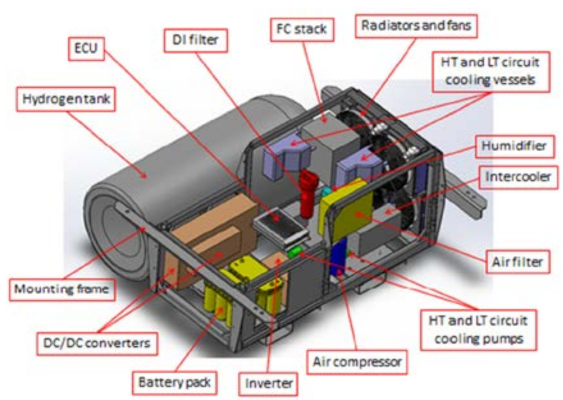
Business Case Common Outcomes

- Challenges
  - Need lower H_2 cost for positive NPV
  - Limited hydrogen infrastructure that does not accommodate Class 8 tractor trailers
  - Fuel cell TRU results in added system weight and volume
    - Ballard estimate ~600 lbs
  - Lack of regulatory drivers: Work-arounds are possible for federal and state emissions regulations of diesel engines
    - EPA: Stay below 25 hp cut-off for stringent PM-10 standards
    - California: Retire, add filter or sell out of state after 7 years

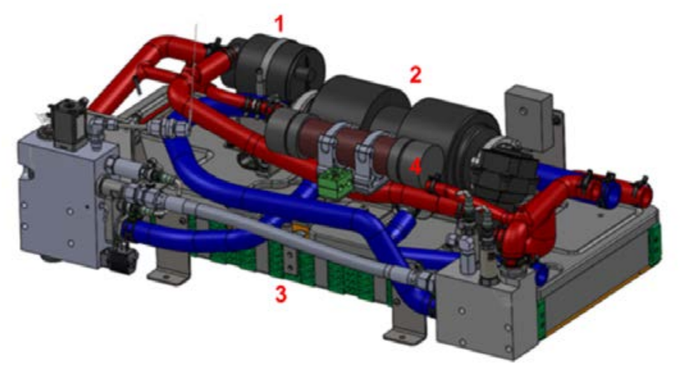
Accomplishments

System Designs

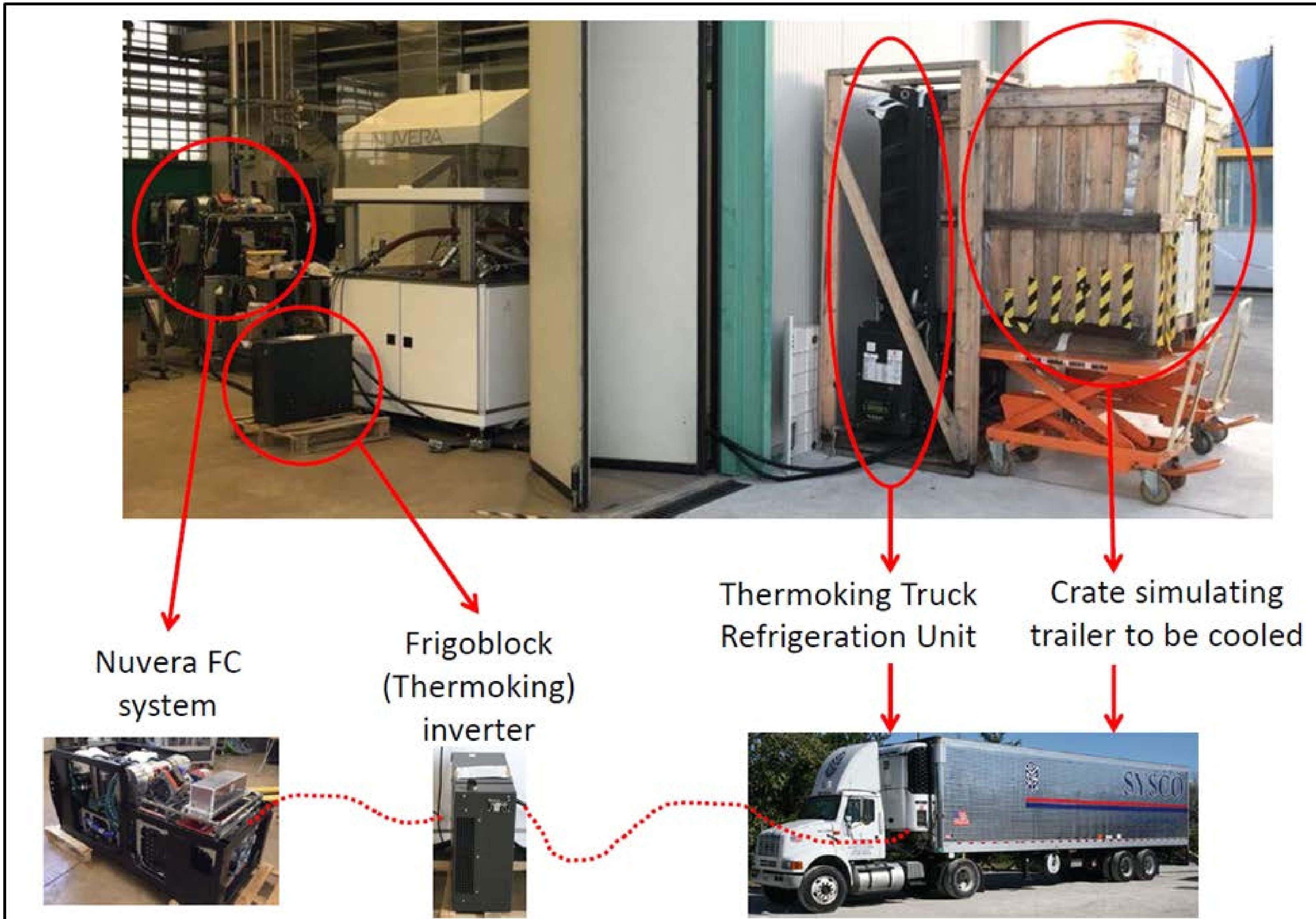
- Nuvera System
  - Orion Gen 2 fuel cell
  - 25 kW fuel cell
  - Minor hybridization
  - FC mounted under trailer
  - Diesel back-up during demo
  - 10 kg H_2 Tank
  - Power Electronics
    - DC-DC Boost Converter
    - Inverter



- Ballard System
  - FCvelocity-9SSL fuel cell
  - 20 kW fuel cell
  - Non-hybrid architecture
  - FC mounted under trailer
  - Diesel back-up during demo
  - 20 kg H_2 Tank
  - Power Electronics
    - DC-DC Boost Converter
    - VFD 480 VAC/3 phase



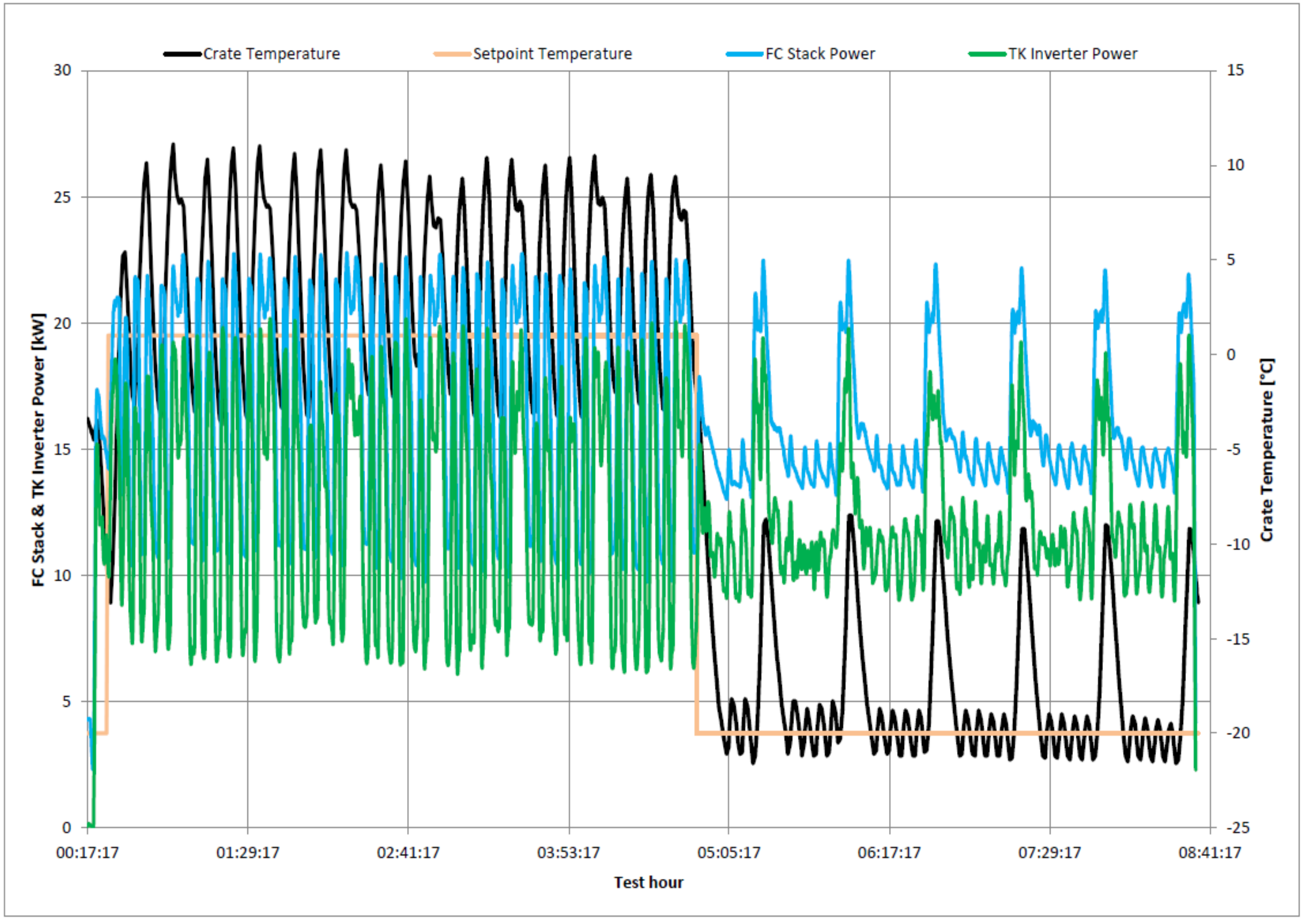
Nuvera System Laboratory Demonstration



Accomplishments

Eight Hour Demonstration Results:

Temperature/Power



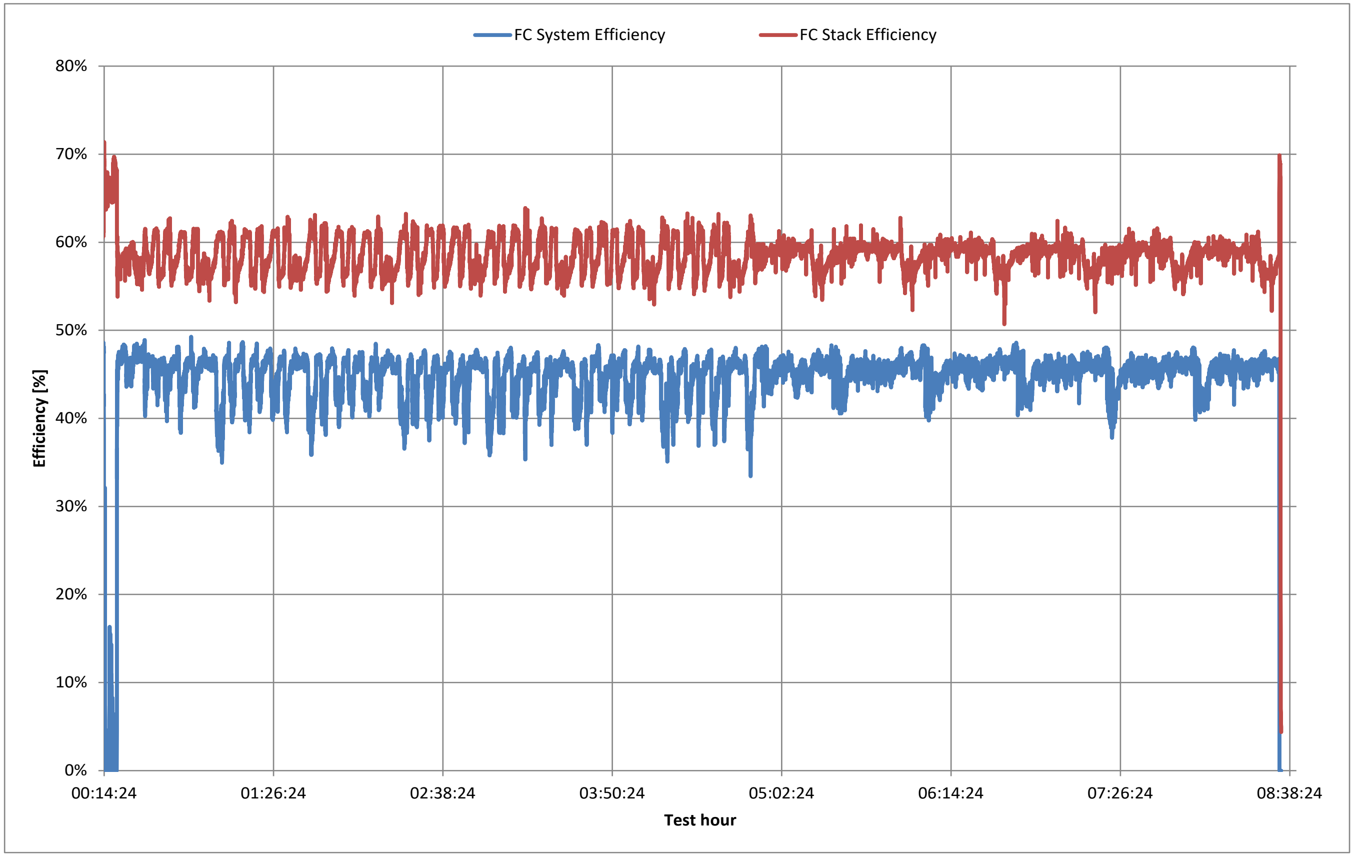
Results

Setpoint reached and maintained

Power within the range of previous Precedent C600 unit results at Thermo King

- Setpoints = 1ºC and -20ºC
- Average Inverter Power = 12.25 and 12.11 kW
- Peaks correspond to defrost cycles

Eight Hour Demonstration Results:
System and Stack LHV Efficiency



Results

DOE's 80 kWe fuel cell technical target 2020 is 65% peak energy efficiency.

Nuvera average FC efficiency is 58%.

- System efficiency includes air compressor, water pump, sensors, power electronics

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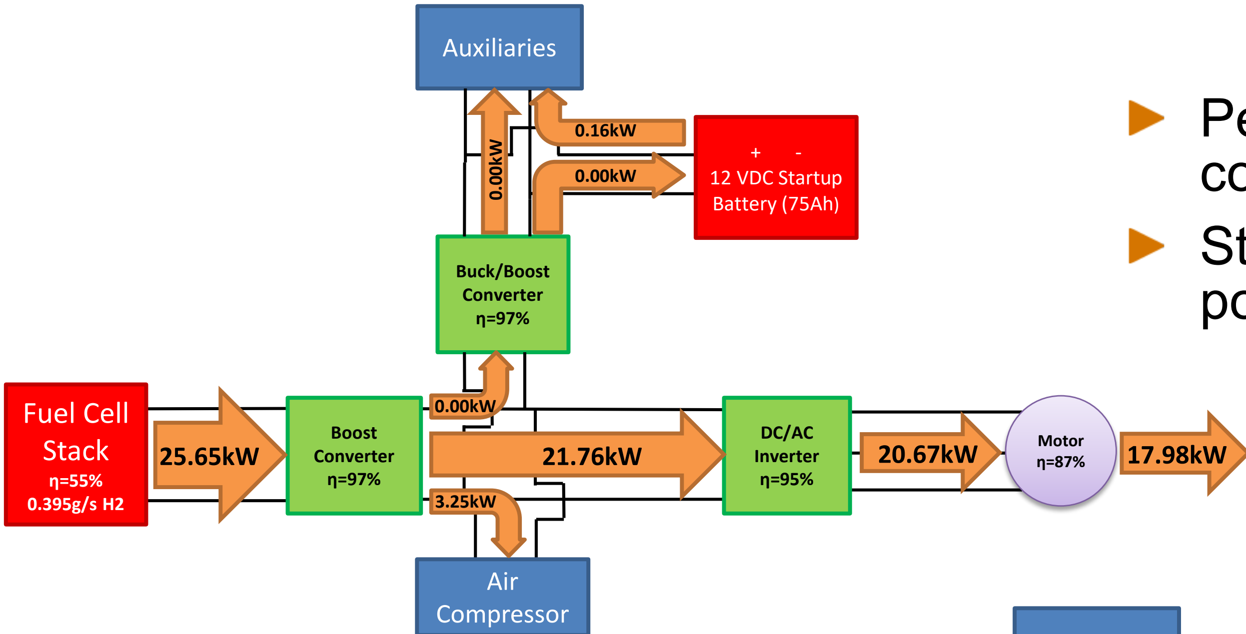
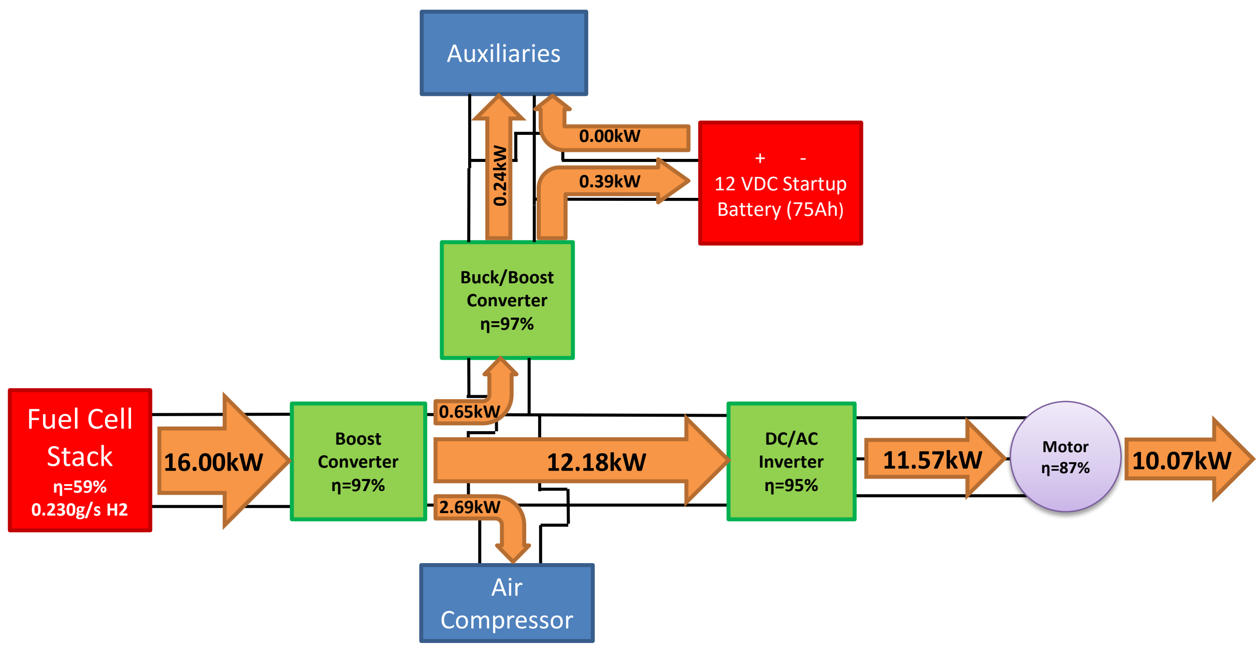
Accomplishments

Nuvera Power Electronics Integration



- Peak power demand condition
- Start-up battery powers auxiliaries

- Average power demand
- Fuel cell charges battery at low state-of-charge



Responses to Previous Year Reviewer's Comments

FY17 Reviewer Comment	FY18 Response to Comment
"need to produce 480V three phase power . . .is driving cost/mass into the system." "battery box replacement ... may have hurt cost and mass."	The power electronics for the DC to AC conversion has impacted the system mass and cost. OEMs agree that the commercial product would have a DC motor.
"an actual demonstration would have gone faster if the demonstration partner had been on board at the beginning."	HEB was the Nuvera demonstration partner during most of the development but withdrew from the project due to the unfavorable value proposition.
"More parametric measures are needed on the impact of several fuel costs."	Diesel TRUs are the incumbent technology. As a result, only diesel costs are compared to hydrogen.
"thought should be given to doing an emissions comparison with diesel. Perhaps there is also a low-carbon fuel standard opportunity."	Cost model included costs associated with emissions compliance for Tier IV diesel engines and carbon credit prices.

Collaborations

Partner		Project Roles
DOE		Sponsorship, Steering
PNNL		Management and Coordination, Data Collection and Analysis, Business Case Development
NUVERA	BALLARD	Fuel Cell Supplier, System Integrator
THERMO KING	Carrier	Integration of APU with TRU
THERMO KING	ZEN CLEAN ENERGY SOLUTIONS	Business Case Development
None	Walmart	Demonstration Partner

- Special Thanks
  - Pete Devlin, DOE-EERE Fuel Cells Technology Office

Remaining Challenges and Barriers

- Technology is viable but need market pull to bring the system to market
  - Need to identify a sufficiently large niche market to justify product development
  - Federal and local incentives/regulations need to be more favorable
  - System cost lifecycle needs to be more competitive
    - Fuel cell, power electronics, tankage
    - Diesel and H_2 prices
  - Challenges with hydrogen infrastructure
    - Current refueling stations do not accommodate tractor trailers
  - System mass may be too high
- Partners understand and remain interested in technology but waiting for more favorable commercialization conditions

Future Work—Remainder of FY18

- Complete final report summarizing Nuvera and Ballard results
- Identify niche markets and commercial partners with improved business case to sell the OEMs on the technology
- Any proposed future work is subject to change based on funding levels

Technology Transfer Activities

- Two major US OEMs for Transport Refrigeration Units understand the technology and participated in the development of the business cases
- Identify partners and niche markets that align with a favorable pathway to commercialization

Project Summary

Relevance	Demonstrate the technical and commercial viability of fuel cell-based Transport Refrigeration Units (TRUs) for refrigerated Class 8 trailers.
Approach	• Demonstrate fuel cell system in commercial applications • Assess the system performance • Analyze its market viability
Technical Accomplishments and Progress	• Nuvera successfully performed an 8 hour integrated test in the laboratory • Nuvera completed the Phase II Go/No-Go Decision • 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	• Complete final report • Identify niche markets with improved business case

Project ID# MT014

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Questions?

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