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

Kriston Brooks, PNNL (PM, Presenter)
Gus Block, Nuvera Fuel Cells
Mauricio Blanco, Ballard Power Systems

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Project ID# MT014

PNNL-SA-125673

Overview

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

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

Allocation of Funding	Spent to Date
DOE Funding for Subcontracts	$986K
Contractor In-Kind Cost Share	$795K
Remaining Commitments	$108K
PNNL Expenditures	$212K

- 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	TBD	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" 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 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**

Fuel Cell Lift Truck

H_2 Refueling

Truck APU

Grocers and other Food Customers

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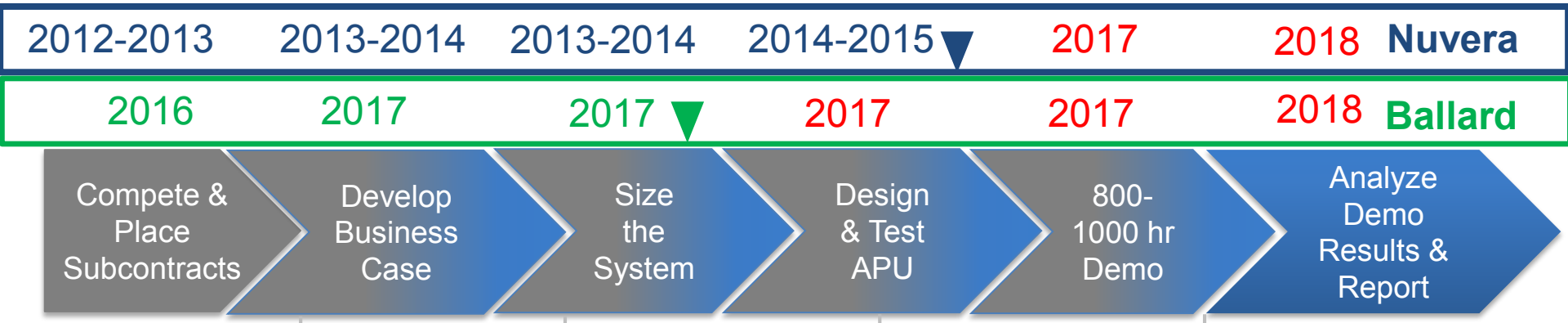
Approach

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



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:

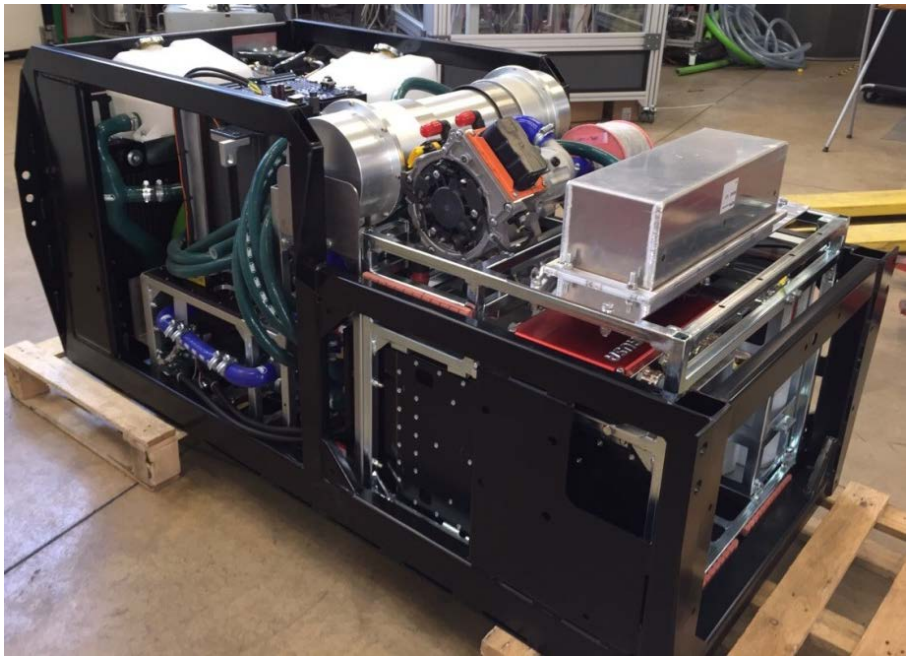
- Site H_2 infrastructure preparation
- Perform intermediate tests: vibration, etc.
- Install system and commission APU
- Perform 800-1000 hour tests with actual deliveries and varying routes

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

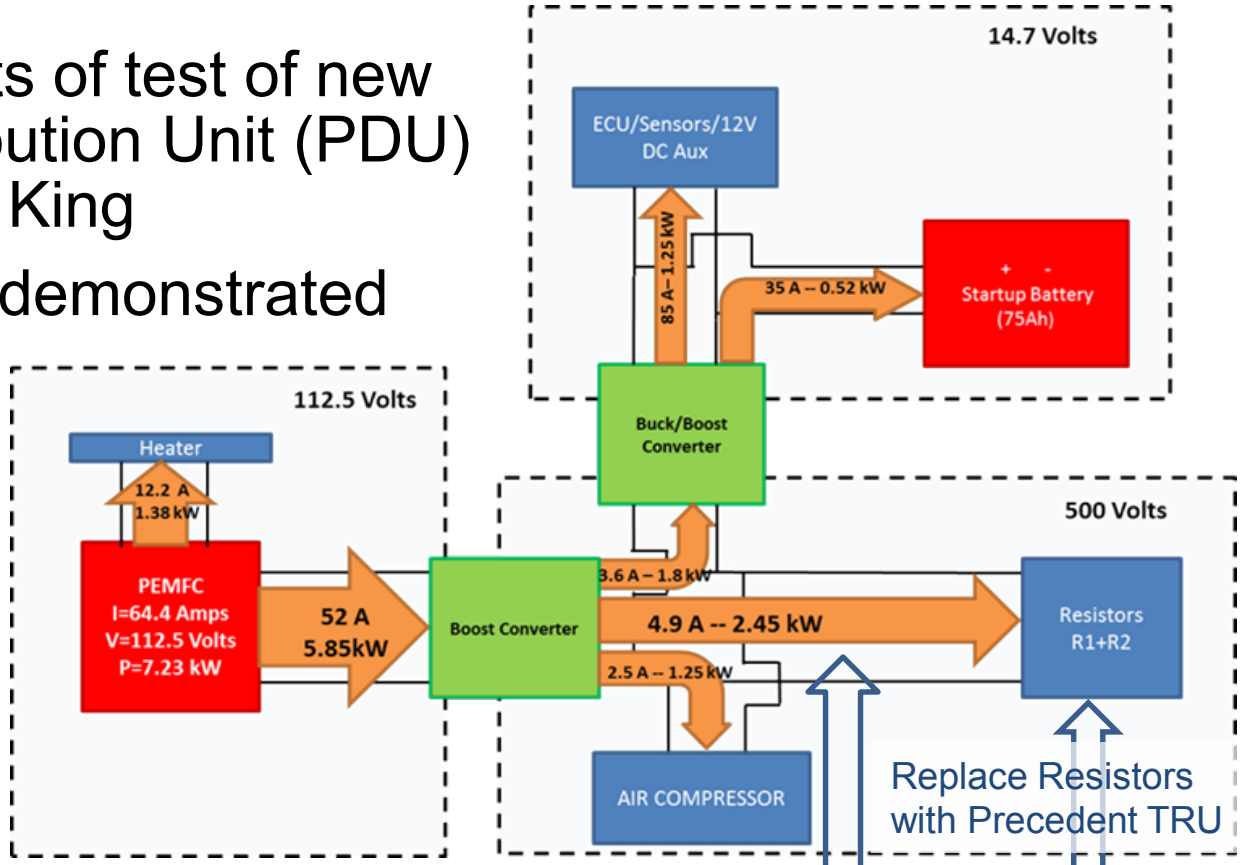
Nuvera System Packaging Complete

- 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



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**:

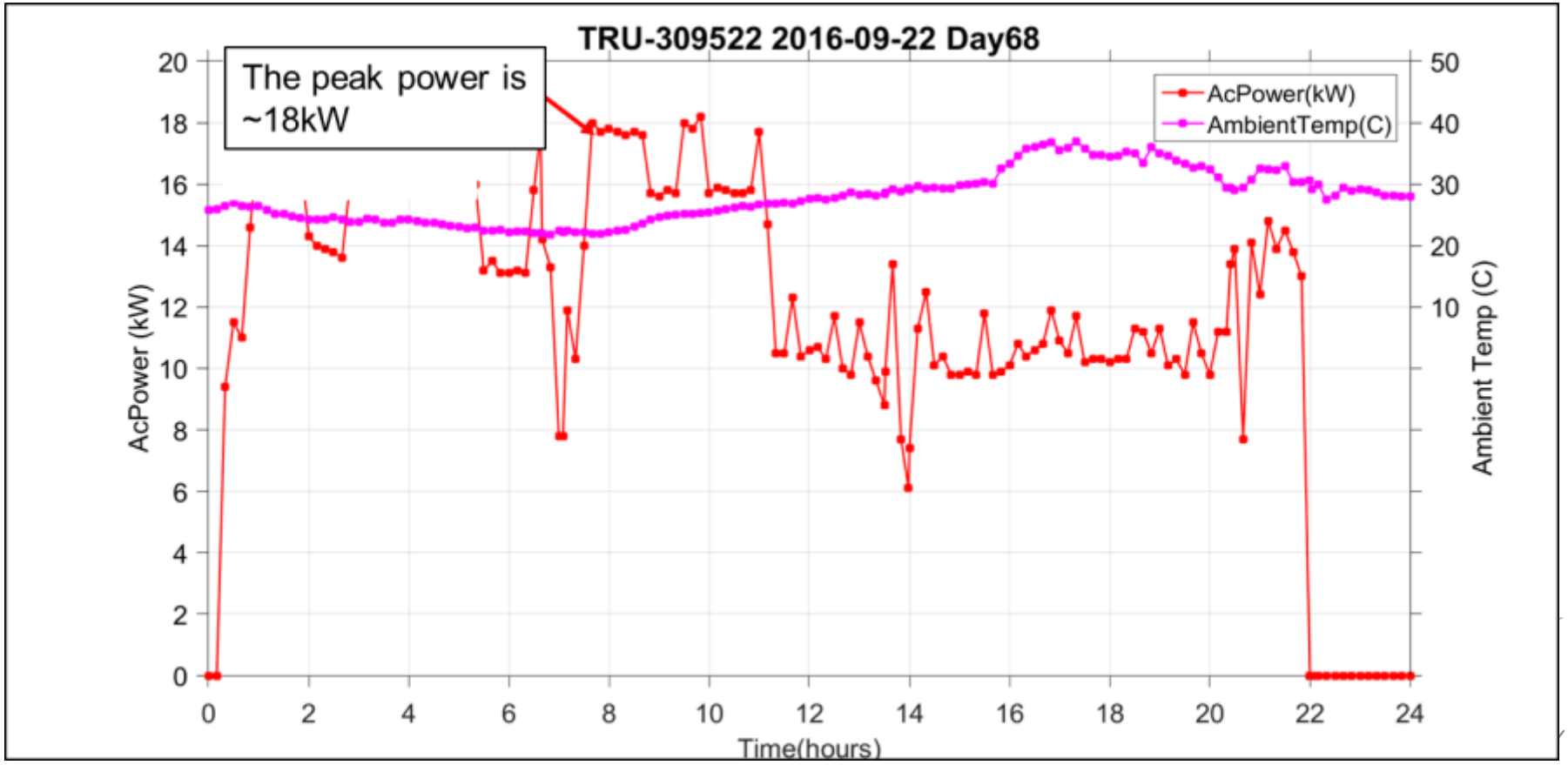
Integrate inverter and TRU into system for full 8 hour laboratory demonstration

Inverter Installation

Produces AC Power

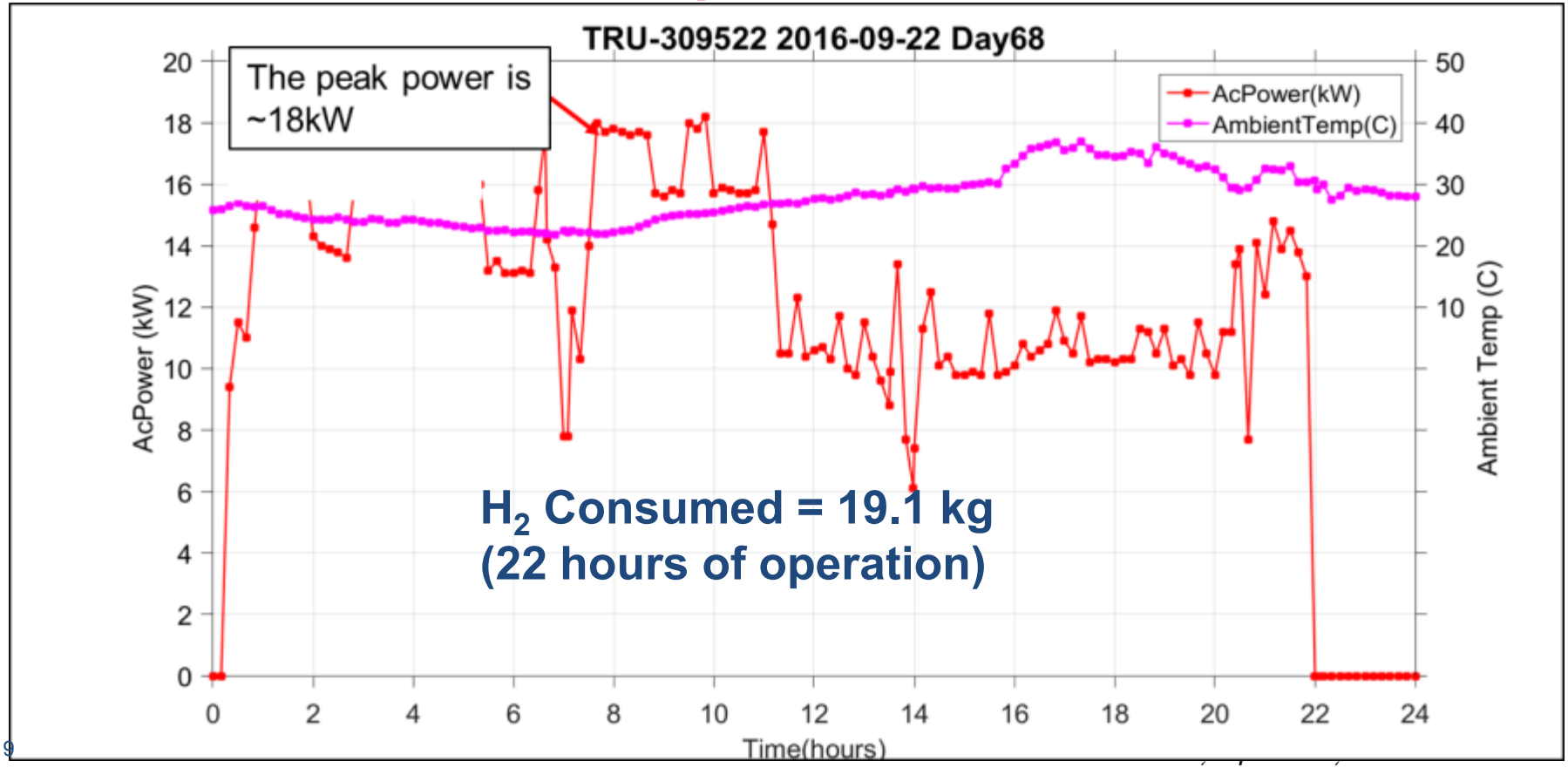
Ballard Sized FC Power: Walmart TRU Data

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



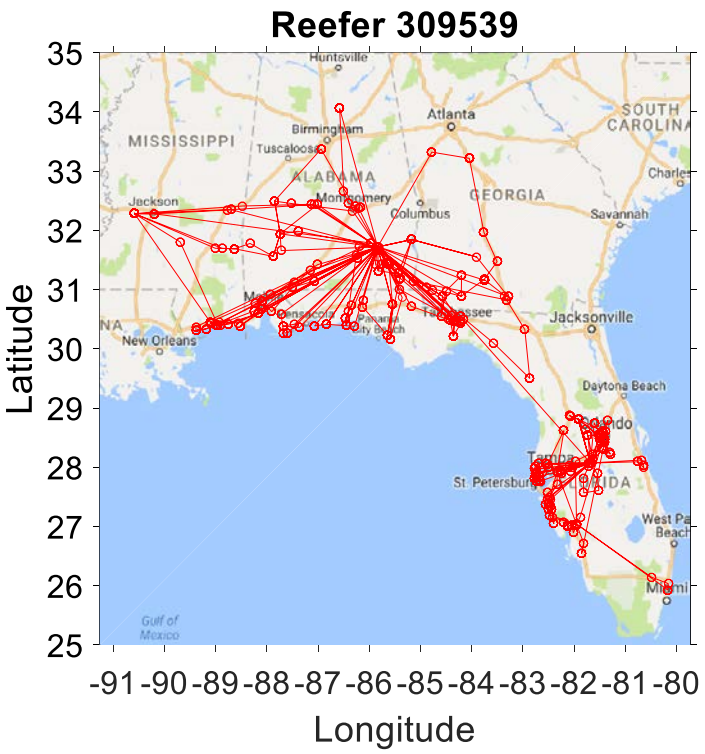
Ballard Sized H_2 Fuel Tank: Walmart TRU Data

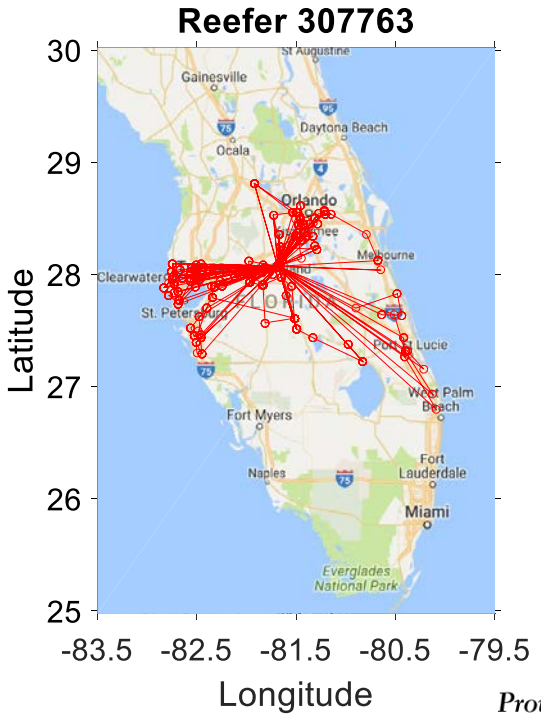
- 83% of TRUs would require < 10 kg H_2/day
- Highest H_2 usage for 22 hrs = 19 kg H_2/day
- **Design with 20 kg H_2 Tank for 2 days operation or 24 hours of freezer load operation**



Walmart ORBCOMM location data used to observe the trailer routes followed

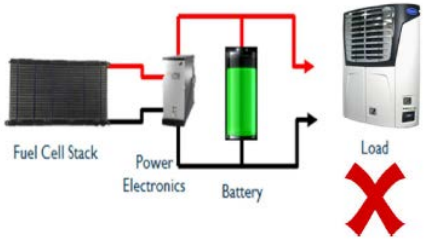
- Trailers did not always return to the same distribution center
- One reefer traveled between Brundige, AL and Winter Haven, FL, the other worked exclusively out of one DC

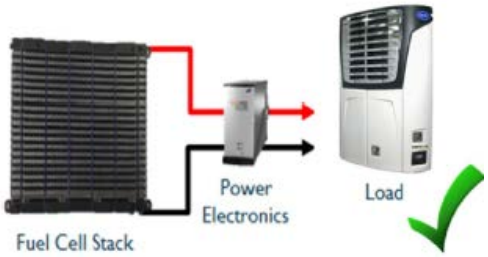


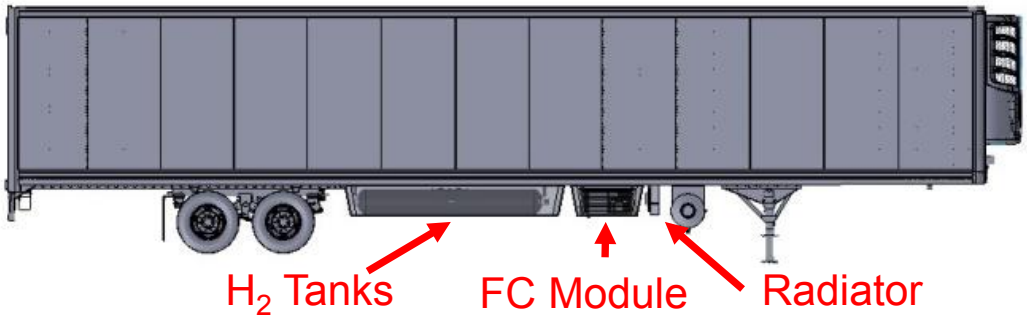


Ballard System Design Work

- 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







Ballard Business Case Challenges

- Total Cost of Ownership Model
  - Low Diesel Cost and High H_2 Cost

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

TCO = ($37,746) @ $3.27/gallon diesel

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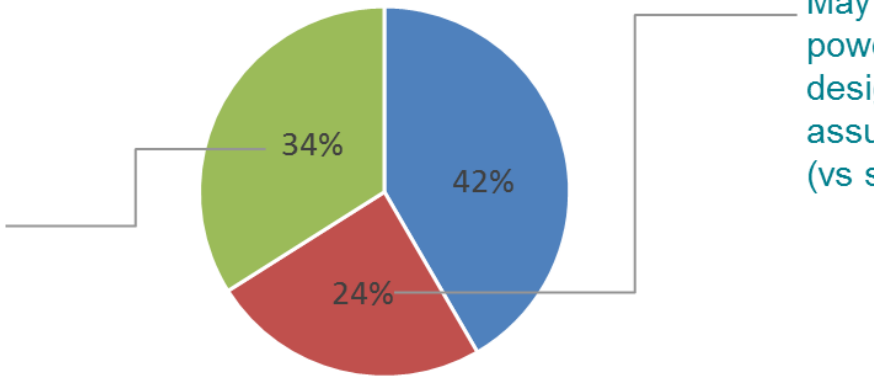
Ballard Business Case Challenges

- Total Cost of Ownership Model
  - Low Diesel Cost and High H_2 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 H_2 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)

Business Case Challenges

- Total Cost of Ownership Model
  - Low Diesel Cost and High H_2 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

Technology	12/31/16	12/31/17	12/31/18	12/31/19	12/31/20	12/31/21	12/31/22	Future Years
PV, Solar Water Heating, Solar Space Heating/Cooling, Solar Process Heat	30%	30%	30%	30%	26%	22%	10%	10%
Hybrid Solar Lighting, Fuel Cells, Small Wind	30%	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Geothermal Heat Pumps, Microtubines, Combine Heat and Power Systems	10%	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Geothermal Electric	10%	10%	10%	10%	10%	10%	10%	10%
Large Wind	30%	24%	18%	12%	N/A	N/A	N/A	N/A

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 H_2 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

FY16 Reviewer Comment	FY17 Response to Comment
Customer test locations are not tied into any other existing infrastructure making it more expensive and higher risk.	Ballard demonstration location is to use existing H_2 infrastructure. Nuvera identifying new demonstration partners includes those with existing H_2 infrastructure.
It is unclear what the Nuvera fuel cell status is.	Provided details of the current fuel cell system and what still needs to be completed before the demonstration.
A definition of "sized appropriately" for the developing system is needed.	Data is provided for sizing of Ballard's fuel cell and H_2 tank.
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	Thermo King (Nuvera Team) and Zen Energy Solutions (Ballard Team) developed a business case with TCO model

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

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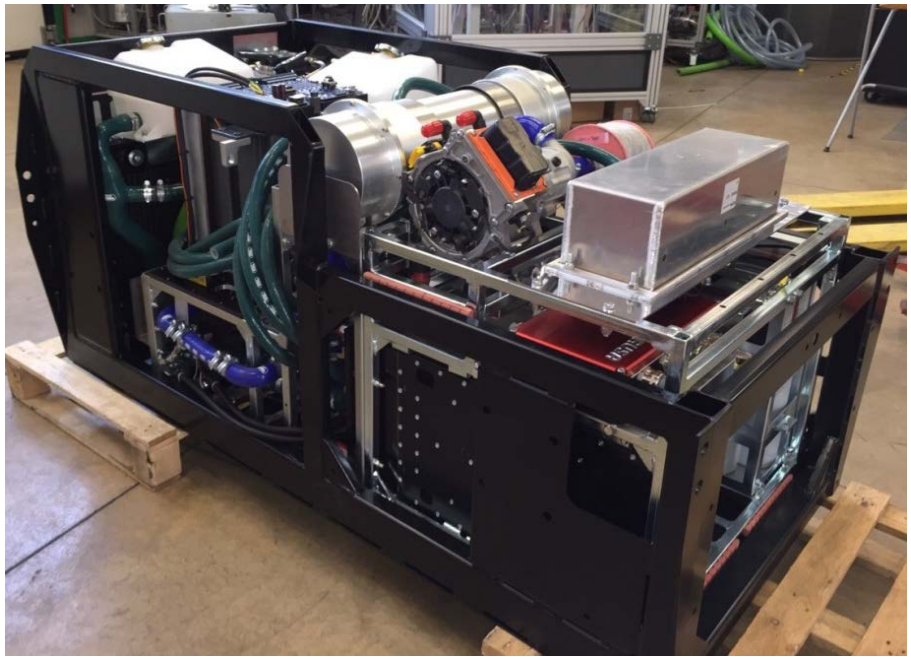
Remaining Challenges and Barriers

- 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

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



Future Work

Milestones and Deliverables

Milestone Description	Owner	Milestone Type	% Complete	Notes
Project Pause	Nuvera	**N/A**	N/A	**Feb. 2015 to Sept. 2016**
Complete Phase II: System Development Phase III Go/No-Go		**Go/No-Go**	70%	**May 2017**
System Safety Assessment & Integration with Trailer		Standard	Not started	**Nov. 2017**
Demonstration			Not started	**Dec. 2017 to Mar. 2018**

Milestone Description	Owner	Milestone Type	% Complete	Notes
Phase I: System Design and Market Assessment	**Ballard**	**Go/No-Go**	100%	**April 2017**

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

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 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

Kriston Brooks
(509) 372-4343
kriston.brooks@pnnl.gov

Questions?

Contact:

Kriston P Brooks ☎: 509-372-4343 ✉: kriston.brooks@pnnl.gov