Prototype Integrated Hydrogen Fuel Cell Powered Data Center

Cooperative Research and Development Final Report

CRADA Number: CRD-17-00709

NREL Technical Contact: Genevieve Saur

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Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5400-82486
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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

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Cooperative Research and Development Final Report

Report Date: March 17, 2022

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement:

- Hewlett Packard Enterprise Company— "HPE"
- Lab 1886 USA, LLC (successor participant of Mercedes Benz Research and Development North America – "MBRDNA")
- Power Innovations International, Inc. — "PI"

CRADA Number: CRD-17-00709

CRADA Title: Prototype Integrated Hydrogen Fuel Cell Powered Data Center

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

Genevieve Saur | genevieve.saur@nrel.gov

Co-Authors/Previous Technical Contacts:

Steve Hammond | steven.hammond@nrel.gov

Jennifer Kurtz | jennifer.kurtz@nrel.gov

Name and Email Address of POC at Company:

Joachim Ladra* | joachim.ladra@daimler.com

Peter Muench | peter.muench@daimler.com

Stefan Ecker | stefan.ecker@daimler.com

Tahir Cader* | tahir.cader@hpe.com

Javier Izquierdo | javier.izquierdo@hpe.com

Vijay Arokia-Raj | vijay-joe.arokia-raj@hpe.com

Robert L. Mount* | bob@power-innovations.com

Craig Skidmore | craig@power-innovations.com

Robert S. Mount | RMount@power-innovations.com

*primary contact

<u>Sponsoring DOE Program Office(s)</u>:

Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies (HFCT)

<u>Joint Work Statement Funding Table showing DOE commitment</u>:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$200,000.00
Year 2, Modification #1	$0.00
Year 3, Modification #2	$0.00
Year 4, Modification #3	$0.00
TOTALS	$200,000.00

NREL received a total of $100k to support the experimental work and a workshop.

<u>Executive Summary of CRADA Work</u>:

Data centers are the backbone of the modern economy—from the server rooms that power small- to medium-sized organizations, to the enterprise-class data centers that support American corporations, and the server farms that run cloud computing services. Rather than a traditional grid-centric data center approach, work under the CRADA will be directed towards implementing a proof-of-concept "hydrogen-based" data center utilizing hydrogen fuel cells, electrolyzers, and solar photovoltaics as key building blocks. This integrated proof-of-concept builds on preliminary work done by HPE and its partners Mercedes-Benz Research & Development North America, Inc. (MBRDNA) and Power Innovations, to dramatically simplify the electrical infrastructure in the data center, leverage the latest automotive-scale hydrogen fuel cell technologies, and tightly couple renewably generated DC power directly to the Information Technology (IT).

While some limited aspects of this concept have been demonstrated previously the entire integrated proof of concept proposed here has not yet been realized.

Summary of Research Results:

The result of this CRADA was to:

- Develop and install a novel carbon-free data center proof-of-concept, based upon an integrated approach using automotive-scale hydrogen fuel cells and renewables for power
- Drive advances in fuel cell deployment and adoption in diverse applications beyond the transportation sector by showcasing in the NREL High Performance Computing Center (HPC) a fuel cell-integrated IT rack
- Initiate development of codes and standards for safety and reliability of hydrogen fuel cells in data centers by documenting the Safe Operating Procedures (SOP) in place at NREL for installing the fuel cell system inside an area not dedicated to hydrogen infrastructure
- Explore waste heat capture and re-use from both the IT racks and fuel cells for space heating applications or to drive adsorption chillers to generate chilled water, depending on site-specific needs, by connecting the prototype fuel cell system into the HPC's warm water liquid cooling system.

The concept is encapsulated in the following process diagram envisioning the carbon free data center integrated with hydrogen fuel cells.

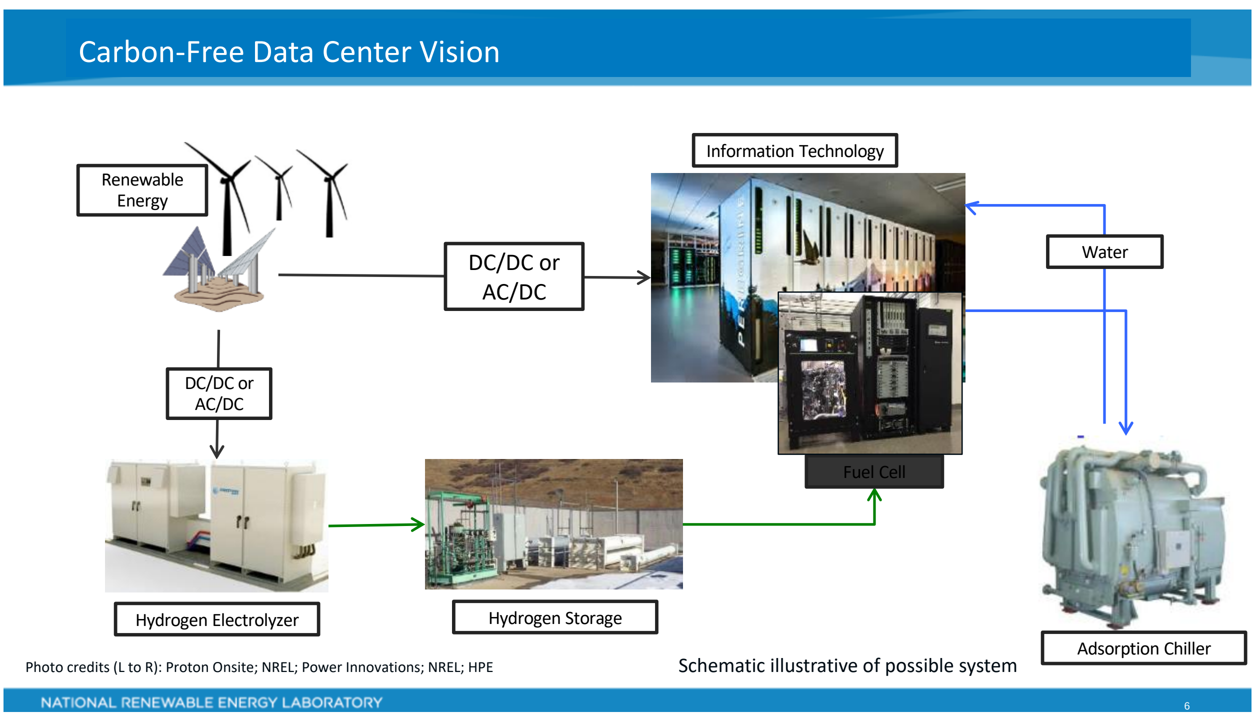

Figure 1. Schematic illustrating possible system (J. M. [National R. E. L. (NREL) Kurtz Golden, CO (United States)] (ORCID:0000000229277877) et al. 2017)

Task 1. Participants' work

The Participants will conduct the following activities under the CRADA Joint Work Statement:

Tasks 1.1 Delivery:

Deliver the fuel cell component of the FCCR system to NREL first; followed by delivery of the IT equipment component. The fuel cell and IT equipment will be integrated with the power electronics and associated controls onsite at NREL to re-create the fully functional FCCR system built and tested offsite and independent from NREL by Participants under the Participants' Independent Project.

The following equipment was loaned to NREL for the CRADA contract:

- (HPE) Roadrunner and Cloud Server racks
- (PI) Double conversion UPS, QLS60 with custom rail for connection to fuel cell1; Custom fuel cell rack enclosure2,3; High voltage prototype lithium ion battery including cables4

Tasks 1.2 ESIL Install & Commission:

Provide support to NREL's efforts to install and commission the fuel cell component in NREL's Energy System Integration Laboratory (ESIL) facility.

A fuel cell enclosure and system was developed by Power Innovations to provide an environment for the Daimler provided automotive FC. The enclosure was designed to be in negative pressure thereby sweeping out any potential hydrogen into the exhaust rather than the inside environment. The control systems included EPO/EMO switches and other monitoring controls for safe operation of the fuel cell inside of a building (Figure 2). The negative pressure enclosure and safety control systems allowed to fuel cell to be placed safely inside an area not generally dedicated to hydrogen infrastructure and use and illustrates how the prototype could be safely deployed inside a building.

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[1] Referenced Double Conversion UPS was developed at Power Innovations' sole expense and the title to the Double Conversion UPS will remain vested with Power Innovations

[2] Includes fuel cell system, cooling pumps, cooling connections and expansion tank, SIV module, TCU emulator box, CPC controller, H2 sensor exhaust, VCI controller, HSX multibus VC1 controller, and connecting hardware and software all of which have been loaned to PI under a separate written loan agreement with Mercedes Benz Research and Development North America. Right, title, and ownership of items is set forth in such written agreement between PI and MBRDNA.

[3] Also includes custom fuel cell support system, high and low temperature heat exchangers, low voltage battery module and cables, battery management system, charger, control hardware, firmware, and application software. These items plus integration of the Custom Fuel Cell Rack system were developed at Power Innovations' sole expense and the title to these items remains vested with Power innovations.

[4] Item has been loaned to PI under a separate written loan agreement with Mercedes Benz Research and Development North America. Right, title, and ownership of items is set forth in such written agreement between PI and MBRDNA.

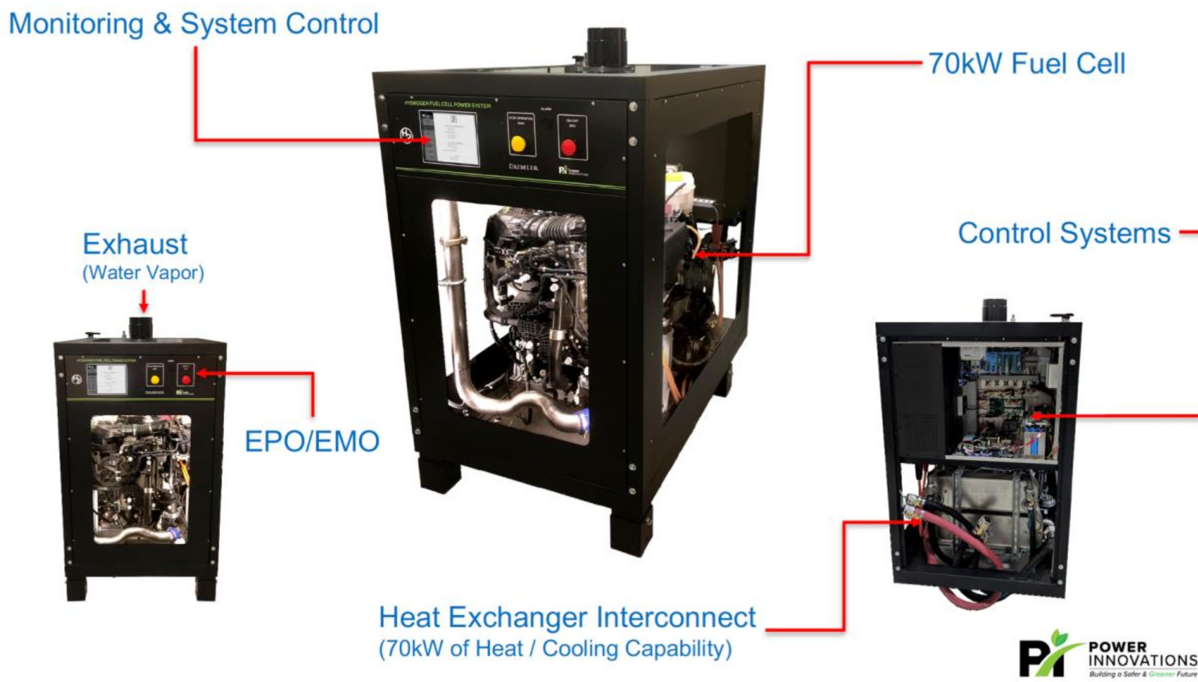

Figure 2. Power Innovations FC system integration of an automotive FC designed to be used inside of a building. (Saur et al. 2020)

Tasks 1.3 Initial Testing:

Support and collaborate with NREL during the fuel cell component bring-up and testing in the ESIL facility.

Initial testing, safety checks, and shake-out was performed in the ESIL part of the Energy Systems Integration Facility (ESIF) at NREL (Figure 3). This area is a dedicated hydrogen technologies testing lab. The tests were performed to verify how the system would operate once placed in the HPC, an active data center.

Figure 3. Experimental setup in ESIL for shake-out testing (Saur et al. 2020)

Task 1.4 Data Center Standup and Integrate:

Subsequent to ESIL testing, Participants will also support NREL during the bring-up and testing of the FCCR system as the fuel cell component is moved to the ESIF HPC data center and integrated with the IT equipment component.

With oversight from Power Innovations, ESIF operations, Hydrogen and Fuel Cells research group, and the HPC support group the FC integrated rack system was moved from the ESIL laboratory and placed in the HPC in ESIF. The testing units were positioned near the front of the room with good visibility from the corridor. Many tours of the facilities where it was used for both promotion of research and testing.

The hydrogen support infrastructure (Figure 4) included H2 production from electrolysis, compression and storage systems, a rooftop H2 line crossing the roof and dropped into the HPC room, and an exhaust vent and fan for the FC. The rooftop pipeline and drop into the HPC extended the established hydrogen infrastructure into a non-H2 laboratory area and demonstrated how H2 and fuel cell technologies could be deployed inside of buildings.

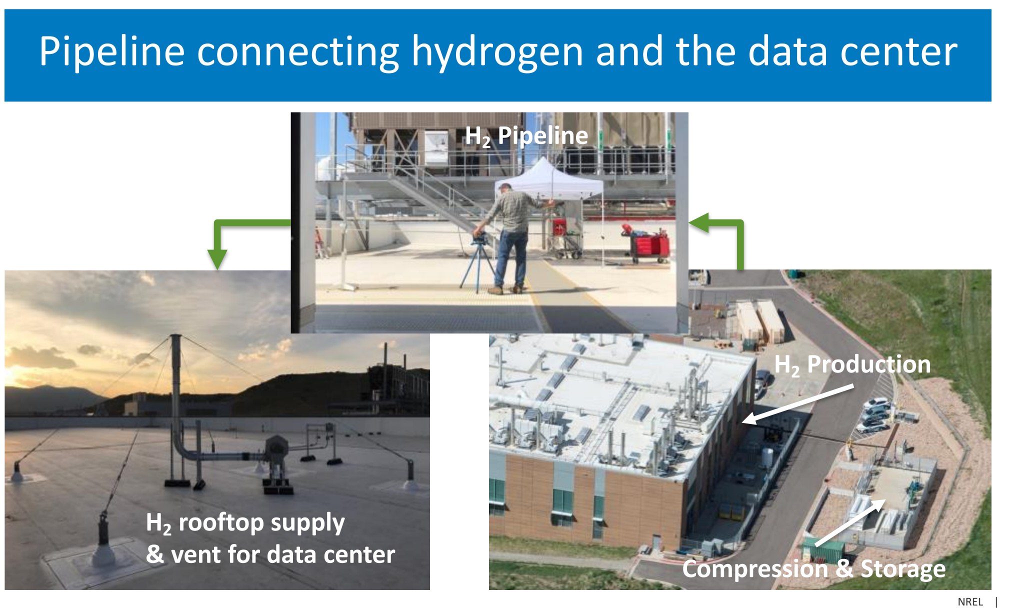

Figure 4. Hydrogen infrastructure to support data center FC integration

During integration, the IT load racks failed to function adequately. Because these were older models, parts replacement became difficult. A solution was devised by the team to use NREL's recently decommissioned supercomputer, Peregrine. This IT rack was capable of meeting a 45+ kW load which was a better matched to the 70 kW FC than the previous 5 kW IT racks. The fuel cell was limited to 45 kW max due to wiring limitations. The wiring was identified as a future upgrade if the project had continued. This adaptation to the plan allowed the system to be more fully tested than the original plan.

During re-commissioning testing in the HPC a condensation problem was identified which had not been a problem in the ESIL configuration. The long, vertical exhaust pipe going to the ESIF roof from the HPC (Figure 5) caused significant backflow water condensation and the FC enclosure started flooding. All safety systems functioned but the FC had to be turned off until a condensate solution could be devised. Insulating the exhaust pipe, adding a water sensor, and including some drip pans solved the problem. The condensate issue helped identify some future design work that might be done around water recovery and improved exhaust systems for different configurations. This was a valuable lesson from the prototype installation that will inform future versions of the system.

Figure 5. FC system in the HPC prior to the exhaust vent being insulated (Saur et al. 2020)

Task 1.5 Data Center Testing:

Support and collaborate with NREL during the FCCR system bring-up and testing in the NREL ESIF HPC data center. Testing will occur during normal business hours. It is anticipated that the duration of the test will be 3 to 6 months. Testing can continue for a longer period if agreed to in writing by all Parties.

Nine tests were developed by the Team to generate good test data for a number of situations and help de-risk the design; see Table 1.

Table 1. Excerpt from testing log spreadsheet

Test name	**Test time (include start/stop)**	**Run time**	**Attended Op**	**Estimated hydrogen**	**Load profile**	**Purpose**
High power	6 hrs	5 hrs	Yes	10.4	Initiate start up ramp up to 70 % max power and hold for 1 hour ramp up to 80% max power and hold for 1 hour ramp up to 90% max power and hold for 1 hour ramp up to 100% max power and hold for 1 hour ramp down to 80% and hold for 30 minutes shut down	The high power test examines high power operation of fuel cell over longer time periods than normal light-duty vehicle drive cycles. It ramps between several high power load points and shows that it can provide consistent, reliable power.
Transient	6 hrs	5 hrs	Yes	9.0	Beginning of test ramp test high transient square wave idle to 90% power, 3 second duration, 2 hours (700 cycles) medium transient square wave idle to 50% power, 3 second duration, 2 hours (700 cycles) end of test ramp test https://www.energy.gov/sites/prod/files/2017/05/f34/fcto_myrdd_fuel_cells.pdf (p46 table p.1)	The transient test examines ability of system to follow very transient behavior at high and medium power ranges. It shows that system can provide reliable power to changing IT load behavior.
Low power	4 hrs	3 hrs	Yes	2.3	Initiate start up ramp up to 33.3% (idle) max power and hold for 1 hour ramp up to 45% max power and hold for 1 hour ramp down to 33.3% and hold for 1 hour shut down	The low power test examines low power operation. Some IT loads may operate at points much lower than peak capacity. This examines the system operation over an extended time at low power.
Ramp	2 hr	1.5hr	Yes	2.6	See Ramp Test Spec tab. Adapted from polarization curve at https://www.energy.gov/sites/prod/files/2015/08/f25/fcto_dwg_usdrive_fctt_accelerated_stress_tests_jan2013.pdf	The ramp test provides a baseline operation over the entire range of load points to show how the system can function.

Test name	Test time (include start/stop)	Run time	Attended Op	Estimated hydrogen	Load profile	Purpose
Start/stop	7.5 hr	6.5 hr	Yes	7.9	Beginning of test ramp test start and operate at 50% max power and hold for 15 minutes then shutdown, wait 15 minutes and repeat 4 times start and operate at 50% max power and hold for 15 minutes then shutdown, wait 3 minutes and repeat 4 times ending of test ramp test	The stop start test examines the reliability of the system to stop and start in backup or other situations in which other power is unreliable.
Soak Test I - Weekend	5 hr	4 hr	Yes	8.2	After 2 days of shutdown (weekend) Initiate start-up (run level 3) Ramp load to 75% power (~33 kw) Hold 2 hours Shutdown FC (runlevel 3, turn on house power) and hold 15 min Initiate start-up (run level 3) Ramp load to 75% power (~33 kw) Hold 2 hours Shutdown	The soak examines the fuel cell's ability to perform after extended weekend shutdown. In the event the fuel cell available power is less than the load momentarily, the battery will supplement. This would be especially important for backup use cases in which the fuel cell may only operate a few times a year or in other intermittent operation uses cases such as peak shaving.
Soak Test II - 2 week	5 hr	4 hr	Yes	8.2	After 2 weeks of shutdown Initiate start-up (run level 3) Ramp load to 75% power (~33 kw) Hold 2 hours Shutdown FC (runlevel 3, turn on house power) and hold 15 min Initiate start-up (run level 3) Ramp load to 75% power (~33 kw) Hold 2 hours Shutdown	The soak test examines the fuel cell's ability to perform after extended two week shutdown. In the event the fuel cell available power is less than the load momentarily, the battery will supplement. This would be especially important for backup use cases in which the fuel cell may only operate a few times a year or in other intermittent operation uses cases such as peak shaving.

Test name	Test time (include start/stop)	Run time	Attended Op	Estimated hydrogen	Load profile	Purpose
Endurance Test I - Low Power	18 hr	17 hr	Yes	16.8	Beginning of test ramp test ramp up to 33.3% (idle) max power and hold for 1 hour ramp up to 45% max power and hold for 1 hour ramp down to 33.3% and hold for 1 hour repeat steps 2-4 5 times (total) ending of test ramp test	The endurance test shows the durability of the fuel cell to perform in extended operation at low power points. The automotive fuel cell has not been tested extensively in such long duration tests. It is currently required to restart after a certain time interval. This test would provide data to its durability and the ability to maintain power during the fuel cell restart cycle by use of the battery.
Endurance Test II - High Power	18 hr	17 hr	Yes	39.3	Beginning of test ramp test ramp up to 80% (idle) max power and hold for 1 hour ramp up to 90% max power and hold for 1 hour ramp down to 80% and hold for 1 hour repeat steps 2-4 5 times (total) ending of test ramp test	The endurance test shows the durability of the fuel cell to perform in extended operation at high power points. The automotive fuel cell has not been tested extensively in such large duration tests. It is currently required to restart after a certain time interval. This test would provide data to its durability and the ability to maintain power during the fuel cell restart cycle by use of the battery.

In all 11 tests runs were performed between 6/13/2019 and 3/2/2020. Four tests were incomplete, but all resulted in valuable lessons and data. Four of the test protocols were successfully run—ramp, low power, high power, and start/stop—before Covid and lack of funding caused the system to be decommissioned.

The first test performed was the ramp test which ended prematurely due to a separate hydrogen experiment shutting down the supporting hydrogen infrastructure. The prototype system handled unexpected scenario well. The battery took over as load was shed and then house power (future improvement: redundant fuel cell) took over the electric IT load, Figure 6. A problem with the wireless remote watchdog was also identified at this time. The watchdog system allows safety coordination of the hydrogen infrastructure and experimental setups in the laboratory environment. RF interference in data center was causing wireless systems to intermittently time-out. A time-out and loss of communication would cause the prototype system to automatically shutdown as part of the safety protocols. The solution was to move the signal antenna outside to the roof which resolved the problem for the remainder of the project but it was determined that a wired system would be better suited for the future especially in an environment with a lot of FCs and interference.

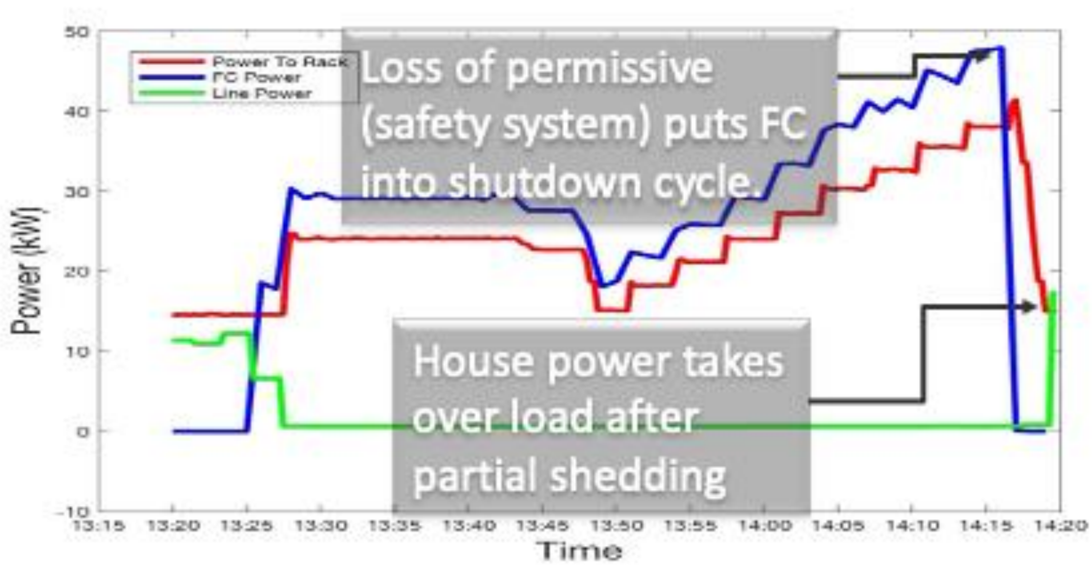

Figure 6. Loss of permissives due to another experiment causes experiment to shutdown unexpectedly (Saur et al. 2020)

A successful ramp test was conducted where the FC ramped about 6.6% of max every 3 minutes, Figure 7.

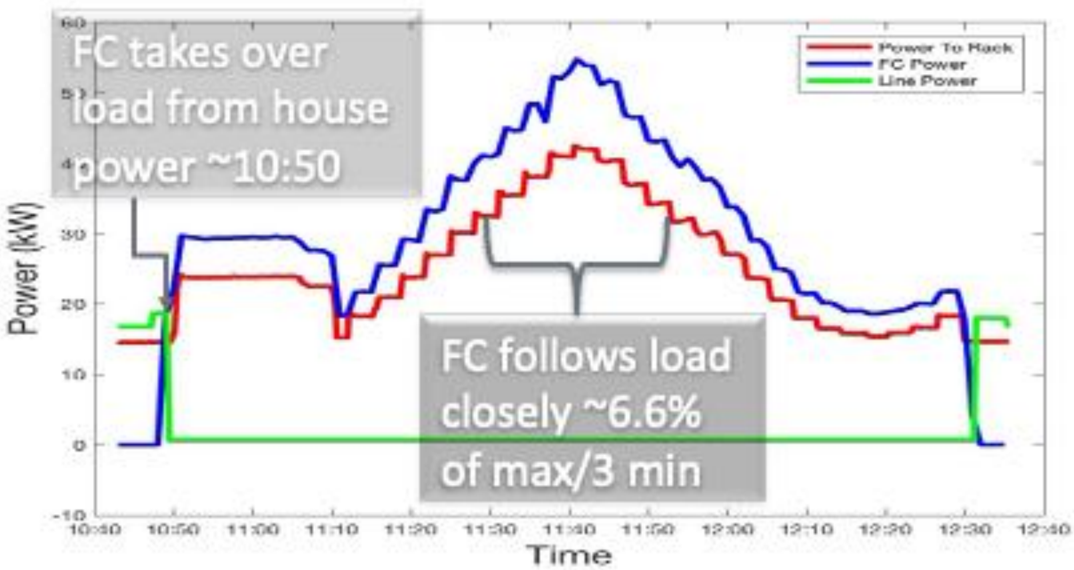

Figure 7. Successful ramp test (Saur et al. 2020)

Task 1.6 Analysis & Interpretation:

Support NREL to analyze and interpret all test data, and to ensure proper operation of the FCCR system.

Four of the nine test protocols were successfully run (Ramp, High Power, Low Power, Start/Stop) and test data has been generated as well as lessons learned regarding design and future improvements. Power Innovations has incorporated and improved the system through a parallel effort in designing a 250 kW system with plans to scale to 3 MW. Further testing and analysis were cut short when the project was decommissioned in July 2020 due to Covid and lack of secured funding to operate it further.

Task 1.7 Demonstration:

Assist NREL with the preparation for, and execution of, a demonstration of the FCCR system for the Super Computer Conference (SC'17). The demonstration will include showcasing the FCCR system to SC'17 attendees who will be bused over from the conference location for this purpose.

The system was not ready for the intended SC'17 conference, but it was subsequently promoted at a number of events and audiences including the 2019 TechConnect World Innovation Conference, 2017&2019 Fuel Cell Seminar & Energy Exposition, DOE's 2019 Hydrogen and Fuel Cell R&D for Datacenter Applications Workshop, DOE's Energy Hydrogen Carriers Workshop: Novel Pathways for Optimized Hydrogen Transport and Stationary Storage and several webinars.

Kurtz, Jennifer. "Hydrogen and Fuel Cells for IT Equipment." United States, 2016. https://www.osti.gov/biblio/1262195.

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Saur, Genevieve [National Renewable Energy Laboratory (NREL), Golden, CO (United States)] (ORCID:0000000282447302), Vanessa [U.S. Department of Energy Fuel Cell Technologies Office] Arjona, Amberlie [U.S. Department of Energy Fuel Cell Technologies Office] Clutterbuck, and Eric [U.S. Department of Energy Fuel Cell Technologies Office] Parker. "Hydrogen and Fuel Cells for Data Center Applications Project Meeting: Workshop Report." United States, December 5, 2019. https://doi.org/10.2172/1578270.

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Task 1.8 Decommission & Remove:

Assist NREL to decommission and remove the FCCR system at the completion of all testing and demonstration.

System was decommissioned in July 2020. It was boxed and sent back to the Power Innovations facility in Utah at the request of Daimler.

Task 1.9 Operation:

The Parties agree and acknowledge that Participants' Independent Project FCCR system is a prototype system. It is strictly meant for periodic, experimental use. Participants make no commitment to number of operating hours.

Task 2. Contractor work under the CRADA:

NREL will conduct the following activities under the CRADA Statement of Work:

Facility preparation of the ESIL and ESIF HPC data center to enable the safe delivery of H2 to the fuel cell (when in the ESIL) and the FCCR system (when in the ESIF), including safe operation of the fuel cell in the ESIL then eventually the FCCR system in the ESIF.

This preparation will include ensuring the following safe operations:

- Providing adequate sensing;
- Providing adequate ventilation;
- Providing adequate cooling of the fuel cell, then of the complete FCCR;
- Delivering adequate Power;
- Monitoring and controlling of the fuel cell in ESIL and FCCR system in ESIF;
- Properly integrating of the FCCR system into ESIF HPC data center;
- Conducting a hazard analysis; and
- Developing safe operating procedures for startup, operation, and shutdown of the FCCR system and associated infrastructure.

Hydrogen and fuel cell researchers. ESIF operations and HPC support personnel collaborated extensively in the set-up, shake-out and testing of the system. The system was operated successfully both in the lab and in a demonstration environment in the HPC.

Subject Inventions Listing:

None

ROI #:

None