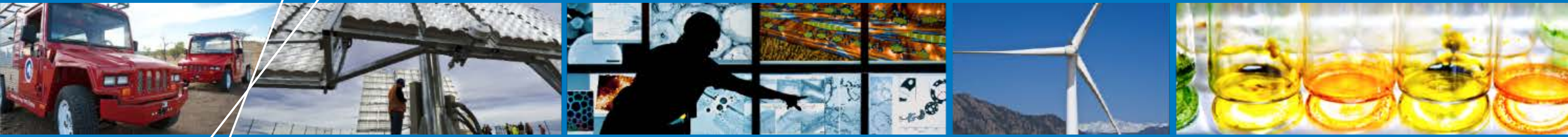
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

2016 DOE Hydrogen and Fuel Cells Program Review



Renewable Electrolysis Integrated System Development & Testing

Mike Peters*, Kevin Harrison, Huyen Dinh, Danny Terlip, Jennifer Kurtz, Josh Martin

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Project ID: PD031

***Presenter**

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

TIMELINE

- Start date: September, 2003
- End date: October, 2016*

* Project continuation and direction determined annually by DOE

BARRIERS

G. System Efficiency
I. Grid Electricity Emissions (Distributed)
J. Renewable Electricity Generation Integration (Central)
L. Operations and Maintenance

BUDGET

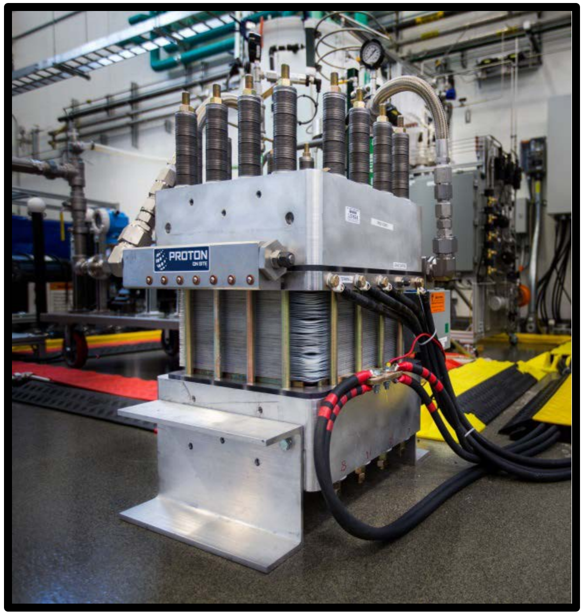
- FY15: $200K
- FY16: $200k
- Total Project Value: $6,100k

PARTNERS

- Xcel Energy
- Proton OnSite
- Giner Inc.

Relevance: Renewable Electrolysis

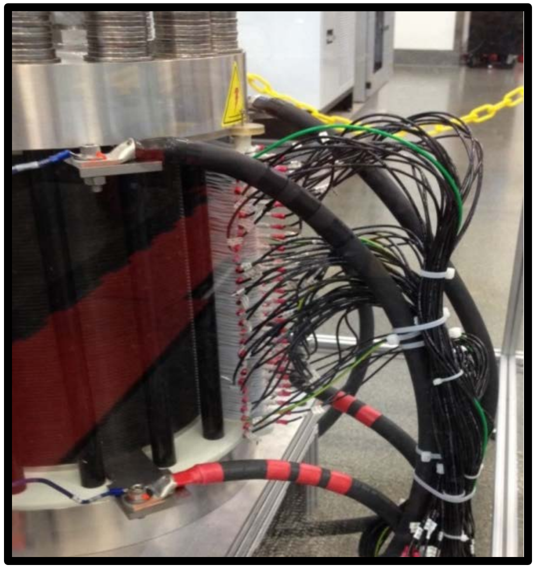
Hydrogen is a versatile energy carrier that can be used for many applications, however, hydrogen must be produced renewably to make a significant impact on CO_2 reductions worldwide.



Impact: System and Stack Testing

Validate

- Cell: Individual cell voltage measurements
- Stack Capacity: < 1 kW – 1 MW
- System: Independent verification of system efficiency



Develop and Optimize

- System efficiency, performance, and durability under varying power operation
  - Solar, wind, grid services
- Integration with hydrogen infrastructure components
  - Compressors, storage, dispensing

Approach: Trackable progress – FY15 & FY16

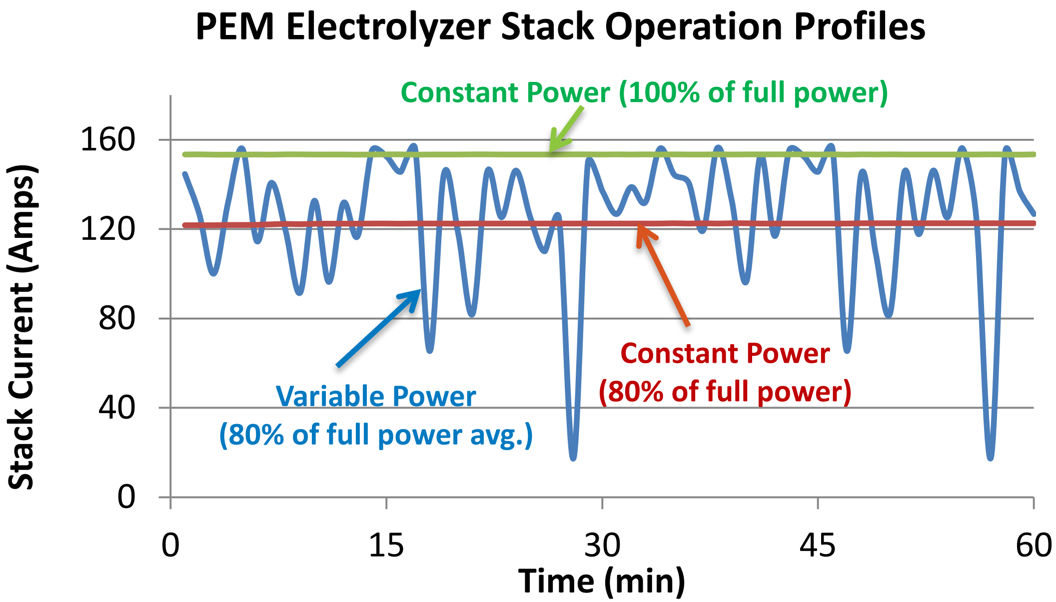
Milestone Description	Type	Due Date	Status
Collect 40 hours each on 3 different pressure swing adsorption drying techniques comparing the fixed flow (orifice) approach with two new linear actuated valves (variable flow) that vary in performance and price.	Annual Milestone (Regular)	30-Jun-15	Complete
Complete cumulative testing of 7500 h for two PEM electrolyzer stacks and 4500 h for a new stack under constant- and variable-powered operating conditions and compare stack decay rates of the two operational modes with results from FY14.	Quarterly Progress Measure (Regular)	30-Sep-15	Complete
Complete general design of equipment located inside an electrolyzer which operates entirely off of Direct Current (DC) with the goal of direct coupling with a renewable energy source (PV or Wind). The general design should include a first draft of the equipment Bill of Materials (BOM), data sheets with efficiency curves and a system P&ID labelled with individual components.	Quarterly Progress Measure (Regular)	12/31/2015	Complete
Perform a critical design review to ensure functionality of design. Perform PHA to review the safety implications of the design.	Quarterly Progress Measure (Regular)	3/31/2016	Complete
Specify and create a final BOM with the design and PHA results from Q1 and Q2 implemented in the final design. Provide a cost estimate and timeline to build such an electrolyzer for future work.	Annual Milestone	6/30/2016	On Track
Design, procure, install, and test a differential voltage data collection system capable of measuring individual cell voltages on an electrolyzer stack. The data collection system will include 100 channels capable of measuring 0 – 2.5 differential voltage. The Q4 milestone report will analyze how cell voltage is shared within a stack under variable conditions, furthering understanding of variable (renewable) operation of electrolyzer stacks.	Quarterly Progress Measure (Regular)	9/30/2016	On Track

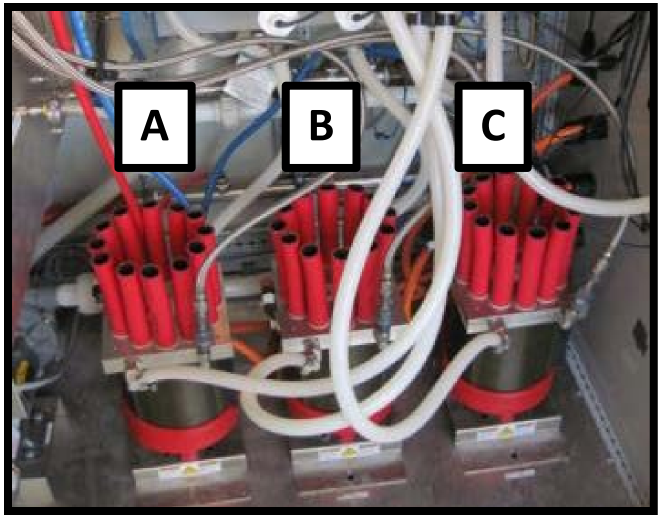
Relevance: System Capital Cost

For renewable electrolysis to be successful, electrolyzer stacks operating under variable loads need to have a lifetime equivalent to electrolyzer stacks operating under constant loads.

Approach: Long Duration Testing

- Conduct long-duration (thousands of hours) side-by-side testing on 10 kW PEM stacks comparing stack voltage decay rates between constant and variable power operation
- Collaborate with electrolyzer manufacturer, Proton OnSite, when issues with stacks and balance-of-plant arise
- Develop data collection and analysis tools to capture decay rates and upset conditions over time





Approach: Analyzing Data

Original Method – measure stack voltage at full power and normalize to a common temperature for comparison (155 Amps, 104 ^{o}F)

- Pros: Relatively simple and quick data analysis (can do it in Excel), gives good overall picture of the health of the stacks
- Cons: Only provides information at one temperature, sometimes relies on extrapolation, easy to miss bigger issues with the stacks/system

Technology Validation Method – track Current-Voltage curve behavior over duration of testing and use numerous curve fits over the duration regardless of power and temperature

- Pros: Able to analyze entirety of data sets at once, leverages fuel cell model developed in technology validation program, clearly shows when stack or system issues are present
- Cons: Needs special software license to work (MATLAB), does not normalize by stack temperature

Accomplishment: Decay Comparison

- A total of six 10 kW PEM stacks were tested from November, 2010 to October, 2015
  - Phase 1: received used system from U.S. Army, original hours unknown, Stacks A1, B1, C1
  - Phase 2: Same electrolyzer balance of plant with three new stacks from Proton, Stacks A2, B2, C2
- **The electrolyzer was operated for over 17,000 hours during the 5 years of testing resulting in a 39% utilization**

Stack Identifier	Profile Type	Total Hours	Comparison Hours	Original Method Decay Rate [µV/cell-hr]	**Tech Val Method Decay Rate [µV/cell-hr]**	Tech Val Method (All data) Decay Rate [µV/cell-hr]
A1	Variable	10014	5401	16.7	**0.1**	9.1
B1	Variable	10112		9.7	**1.0**	23.6
C1	Constant	12069		9.2	**2.1**	22.7
A2	Variable	7257	5226	4.4	**13.3**	19.3
B2	Constant	7257	4127	14.3	**30.2**	56.8
C2	Variable	4330	3999	-7.2	**-10.1**	-10.1

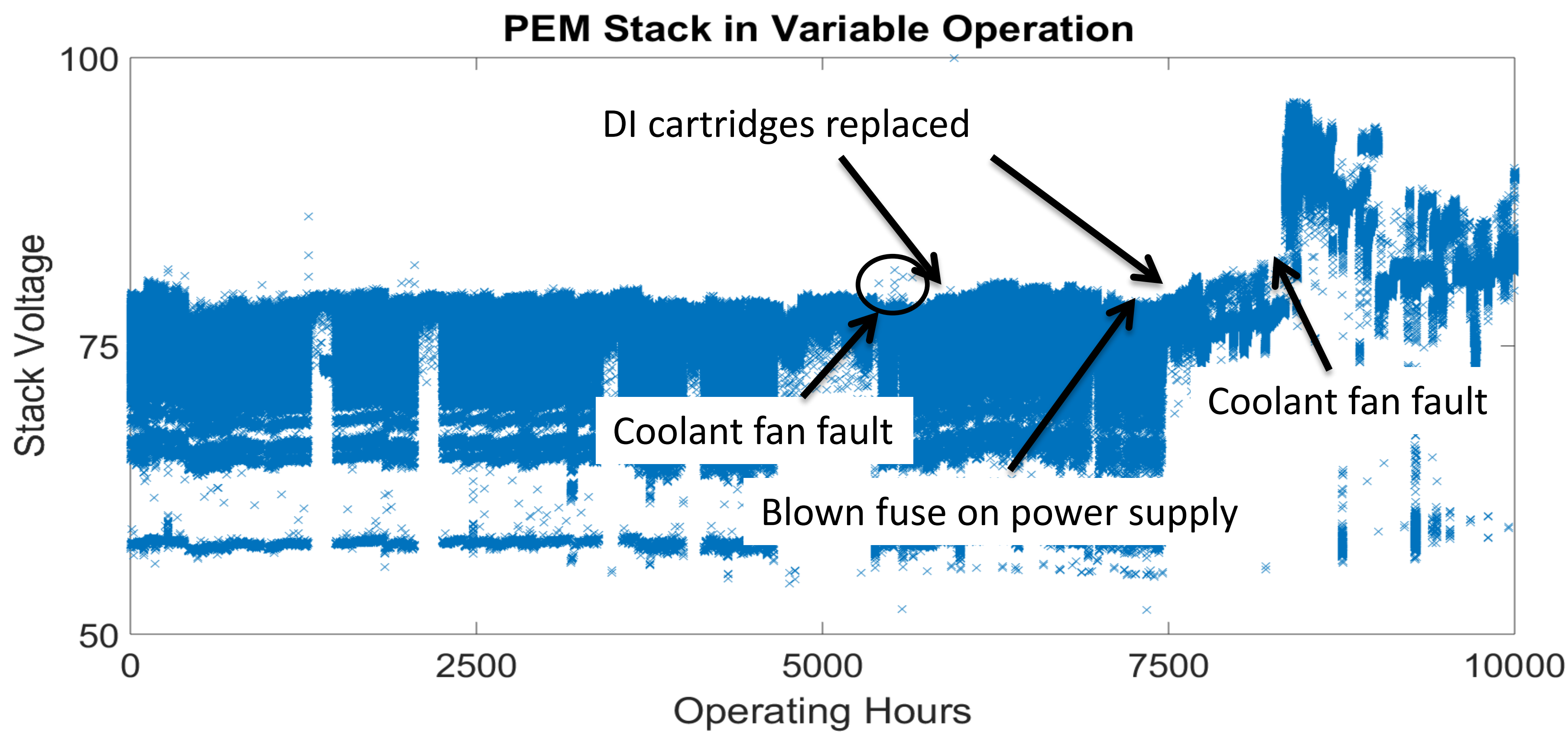
Accomplishment: Decay Comparison

- **Variable versus constant power operation did not affect the decay rate of the electrolyzer stacks**
- The stacks showed a fairly consistent decay rate throughout operation until an unrelated system disruption caused irreversible damage (example on next slide)
- Balance of plant issues more likely to push stacks to failure than how the stacks are operated
  - Power quality issues
  - DI water contamination

Profile Type	Tech Val Method Decay Rate [μV/cell-hr]	Tech Val Method (All data) Decay Rate [μV/cell-hr]
Variable	0.1	9.1
	1.0	23.6
	13.3	19.3
	-10.1	-10.1
Constant	30.2	56.8
	2.1	22.7

Accomplishment: System Performance

- The significant changes in decay rates most likely related to balance of plant issues
- Although electrolyzers have proven to be capable of responding quickly to variable loads or grid services, power quality can cause issues with non-stack components



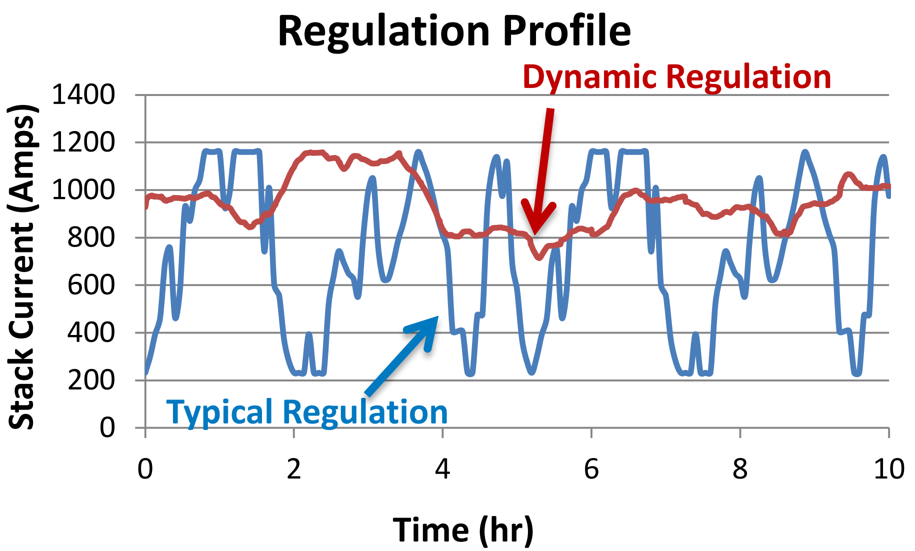
Collaboration: Resolving Issues with Proton

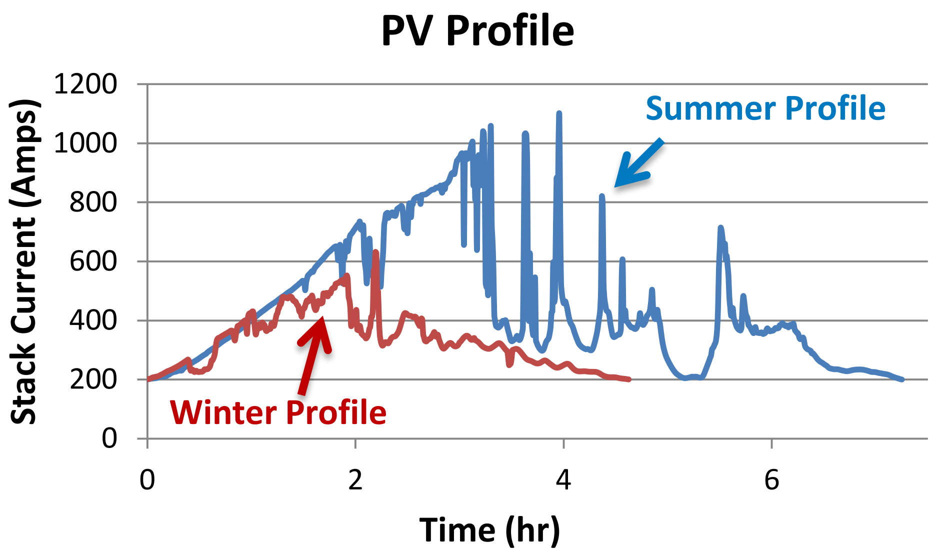
Proton recently provided detailed analysis on two stacks showing higher than usual decay rates

- Stacks were determined within acceptable tolerance for:
  - Cell AC Resistance
  - Electrical Short Test
  - Cross-Cell Nitrogen Diffusion Rate
  - Overall integrity
- Proton found high silica concentration in stack water

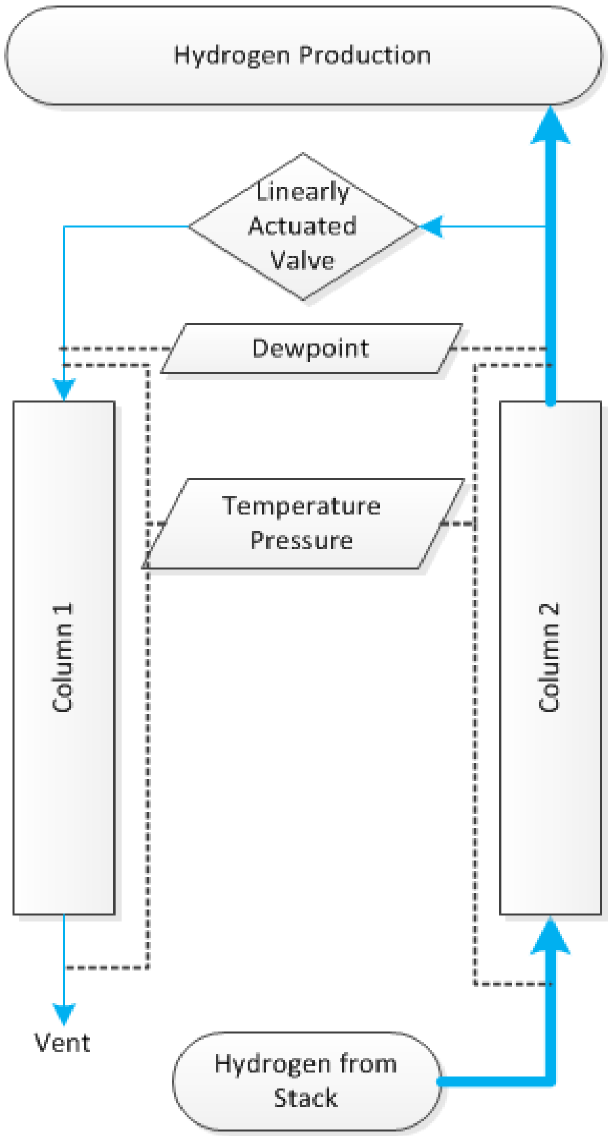
Relevance: System Efficiency Improvements

An electrolyzer's balance of plant needs to adjust to variable load operation to keep system efficiency high.





Approach: Variable Drying



Problem

- Traditional H_2 drying systems are designed to operate at full power with a fixed amount of H_2 loss regardless of operating conditions
- Under variable loads drying losses as a percentage of flow become very high

Concept

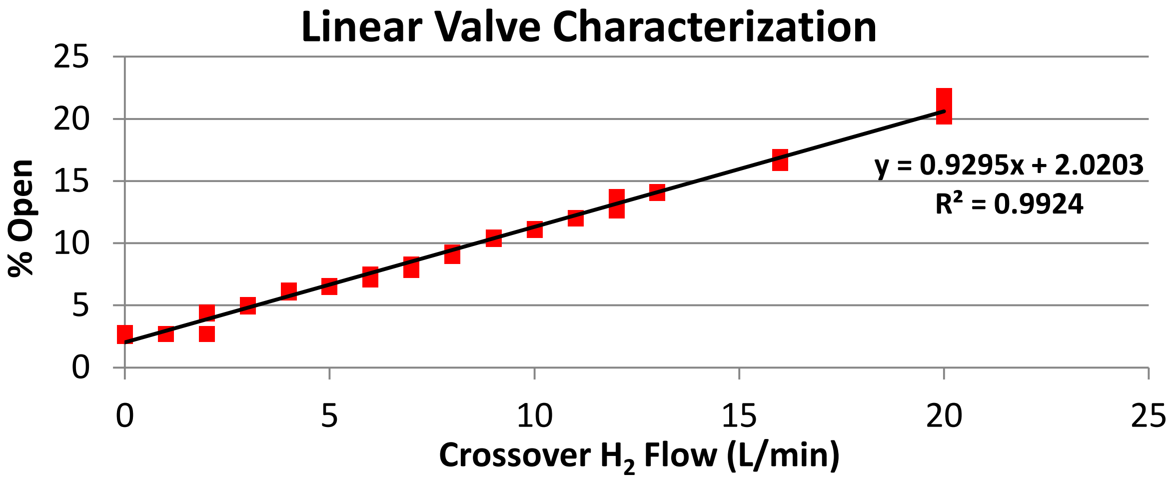
- Use a linear actuated valve to control the amount of hydrogen lost during pressure swing adsorption (PSA) drying
- Aim to lose 3.5% of total hydrogen produced – not of rated capacity

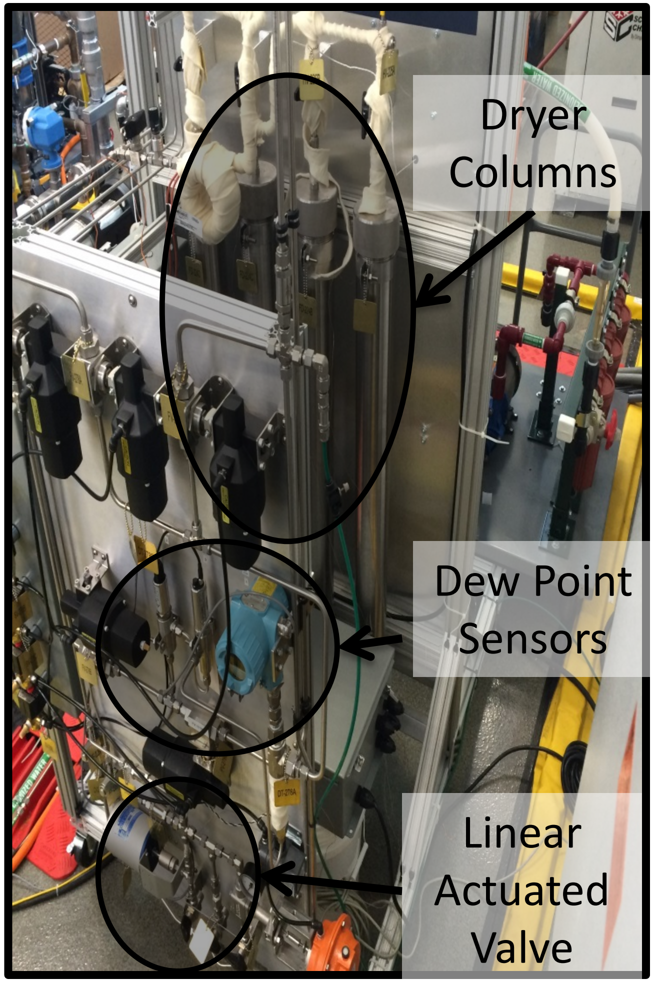
Measure

- Hydrogen loss (Volumetric bubble test)
- Hydrogen quality (Dew point sensor, SAE J2719)

Accomplishment: Demonstrated H_2 Savings

- Operated a 120 kW PEM electrolyzer with variable profiles comparing the two drying techniques (fixed vs. variable)
  - 3.5% fixed approach: Drying losses fixed at 76 g/h regardless of hydrogen flow
  - 3.5% variable approach: Drying losses set to 3.5% of hydrogen flow (based on stack current)
- **Each method was tested for 40 hours with 5 different variable profiles**
  - Wind, (2) Solar, (2) Regulation





Progress: Continuous Improvement

- The hydrogen quality in both cases was equal and below the 5 parts per million target of SAE J2719 (H_2O in H_2) – Independently validated
- **A hydrogen savings of 1 kg per 40 kg produced was demonstrated**
  - Savings highly dependent on type of profile the system is operated under
- **Hydrogen savings were demonstrated but in both scenarios the dryer beds became saturated quickly (< 40 hours)**
- **Hardware in place allows dryer optimization to continue with operations and partnerships**
  - Other variables, like crossover time, heating, pre-cooling to be optimized

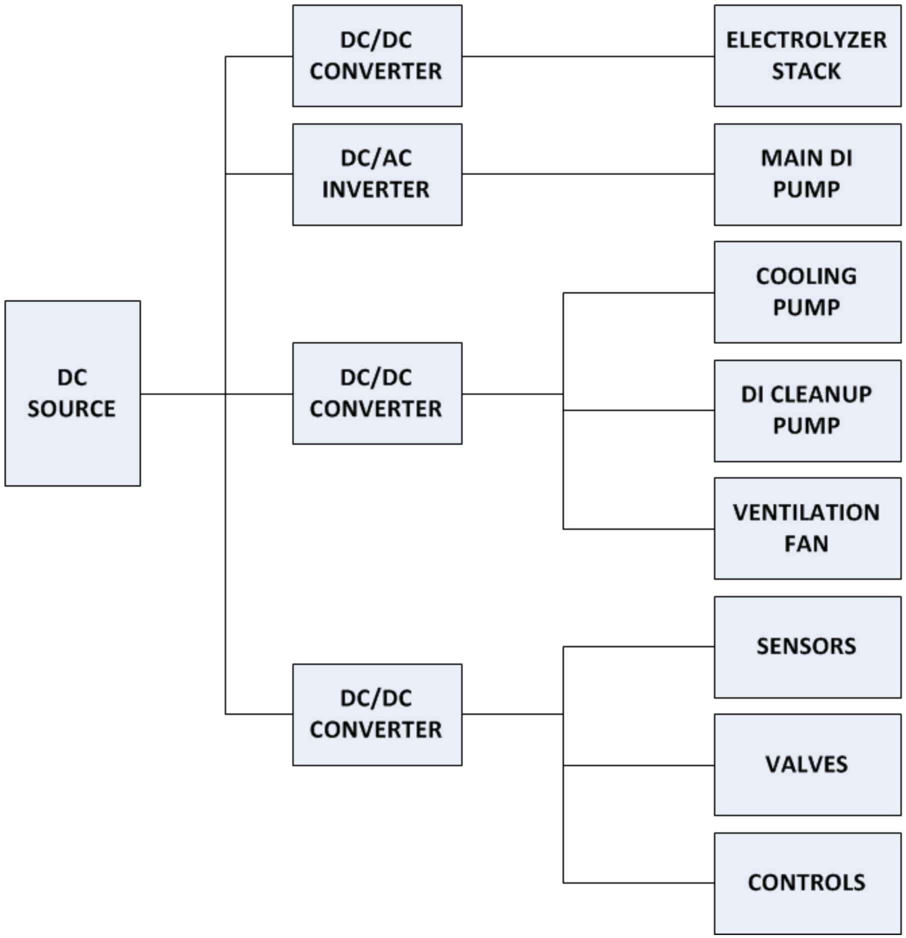
Progress: All DC BoP Design

Goal

- Design an electrolyzer balance of plant that is capable of operating off-grid with inputs only from renewable energy

Approach

- Determine system constraints and realistic design strategy
- Conduct trade study on power conversion architecture
- Create a design basis for the system and identify balance of plant components that differ from typical electrolyzer systems



Accomplishments

- General system requirements and draft bill of materials identified
- Conducted design reviews with power electronics experts

Future Work: Integrating with Renewables

FY16

- Finalize design for direct current balance of plant for a standalone renewable electricity to electrolyzer system
- Identify and specify essential balance of plant components that would change in this standalone system
- Analyze individual cell voltages under variable conditions

Potential Future Topics

- Explore power quality issues
- Look into different power conversion technologies
- Test different dryer materials

Responses to Previous Year Reviewer Comments

The issues with the dew-point sensors seemed to resonant with the members of the audience. I question, though, the lack of collaborations and coordination with experts in this field. Clearly, the data collected from these critical instruments affects resultant conclusions, etc. I recommend that subject matter experts be brought in to address this, apparently, long-term problem.

Response: NREL sought advice from their metrology laboratory and has implemented dew point sensor calibration schedules. A high performance dew point sensor was installed on the system and results have been more consistent.

Not likely to dramatically lower the carbon footprint of H2.

Response: Since the Xcel Energy/NREL CRADA in 2005, the project has worked closely with industry on hardware optimization and validation of their systems. This project was the first to demonstrate electrolyzers (in a microgrid) performing fast response to mitigate frequency disturbances. It was also a pioneer in demonstrating the efficiency improvements of direct- versus closely-coupled PV-to-stack operations. These successes have shifted the industry to focus more on integration and scale-up with renewables to reduce the carbon footprint of the resulting hydrogen product.

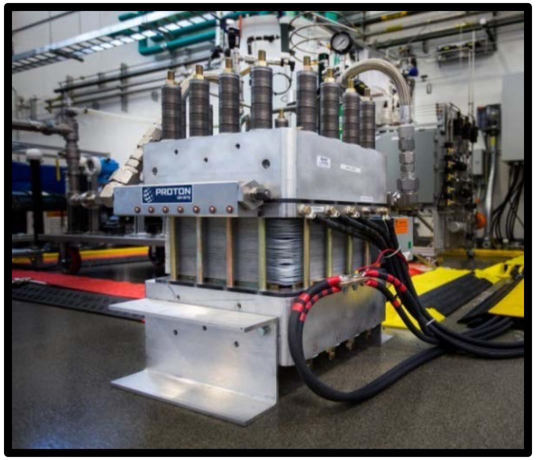
Collaborations

Industry

- Proton OnSite
  - Long duration stack testing
  - 120 kW stack operation
  - BoP improvements
- Giner Inc.
  - Stack FAT testing
  - BoP improvements
- Xcel Energy (CRADA)
  - Wind2H2 Project

Internal to NREL

- Technology Validation
  - Data analysis
- 700 bar hydrogen station
  - Hydrogen production
  - Fuel quality
- INTEGRATE
  - Grid profiles and revenue streams
- Calibration Department
  - Dew point sensor performance tracking



Publications and Presentations

- Presentation at the ACT Expo, “Renewable Hydrogen Production for Use in Hydrogen Fuel Cell Vehicles,” Dallas, Texas, May 2015
- 228th Electrochemical Society Meeting, “Large Active Area Electrolyzer Stack Test Bed – Design, Data and Development”, Phoenix, Arizona, October 2015
- 2nd International Workshop, Durability and Degradation Issues in PEM Electrolysis Cells and its Components, “Lifetime Prediction of PEM Water Electrolysis Stacks Coupled with RES”, Freiburg, Germany, February 2016
- Solar Fuels Generation - PV and Electrolysis Workshop, “Renewable Electrolysis – Systems Integration and Optimization”, Institute of Energy Conversion, University of Delaware Energy Institute, February 2016

Summary

Relevance:

- Hydrogen is a versatile energy carrier that can be used for many applications, however, hydrogen must be produced renewably to make a significant impact on CO2 reductions worldwide
- Electrolyzer stacks operating under variable loads need to have a lifetime equivalent to electrolyzer stacks operating under constant loads.
- Electrolyzer's balance of plant needs to adjust to variable load operation to keep system efficiency high

Approach:

- Validate: Cell, stack, or system performance
- Explore and optimize: System efficiency and performance under varying power operation, integrate with hydrogen infrastructure components
- Track progress through milestones and deliverables: long duration testing

Technical Accomplishments:

- Decay Rate Comparison
  - Electrolyzer was operated for over 17,000 hours during the 5 years of testing
  - Variable versus constant power operation did not affect the decay rate of the electrolyzer stacks
  - Electrolyzer balance of plant can cause issues with non-stack components
- Variable Drying
  - Tested variable versus fixed approach for 40 hours each
  - No difference in hydrogen quality between the two methods
  - 3.5% drying losses may be too optimistic

Collaborations:

- Industry – Proton OnSite, Giner, Xcel Energy
- Internal - 700 bar station, INTEGRATE

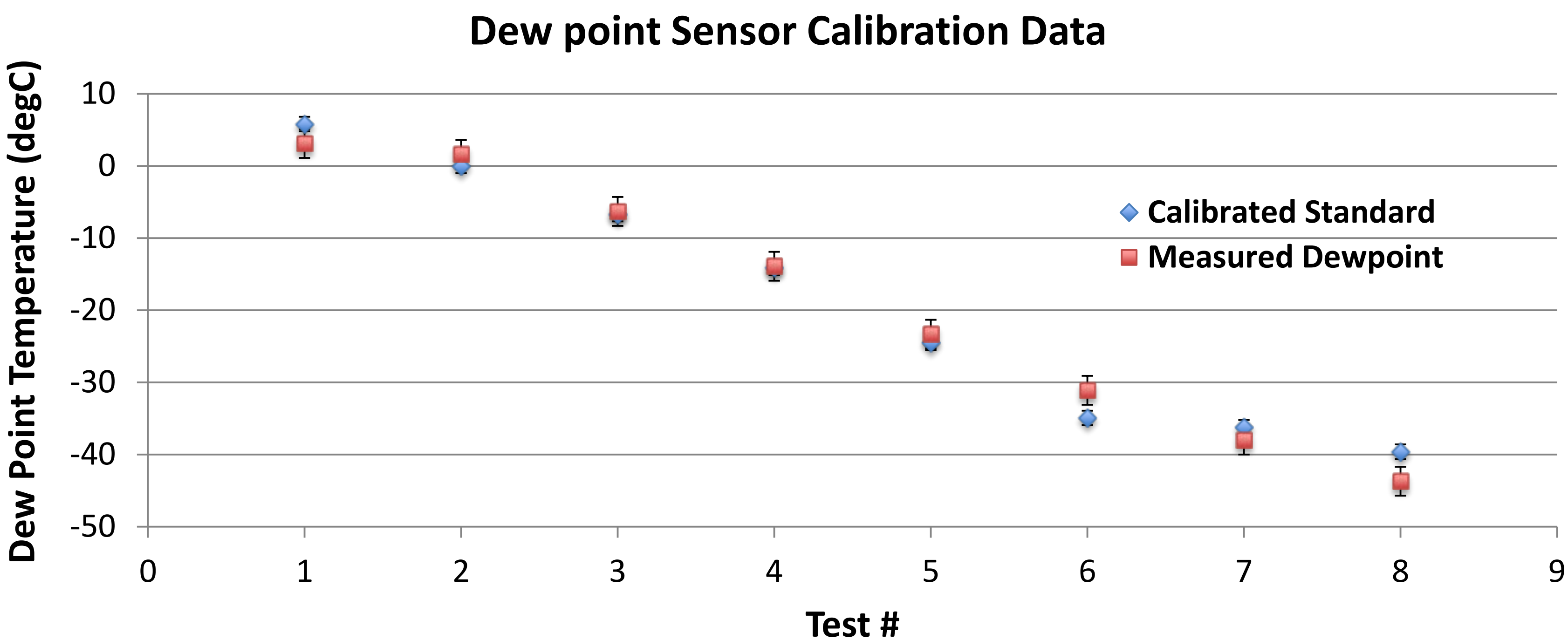
Proposed Future Research:

- Design a direct current balance of plant for a standalone renewable system
- Power quality, voltage regulation, power conversion, dryer materials

Technical Backup Slides

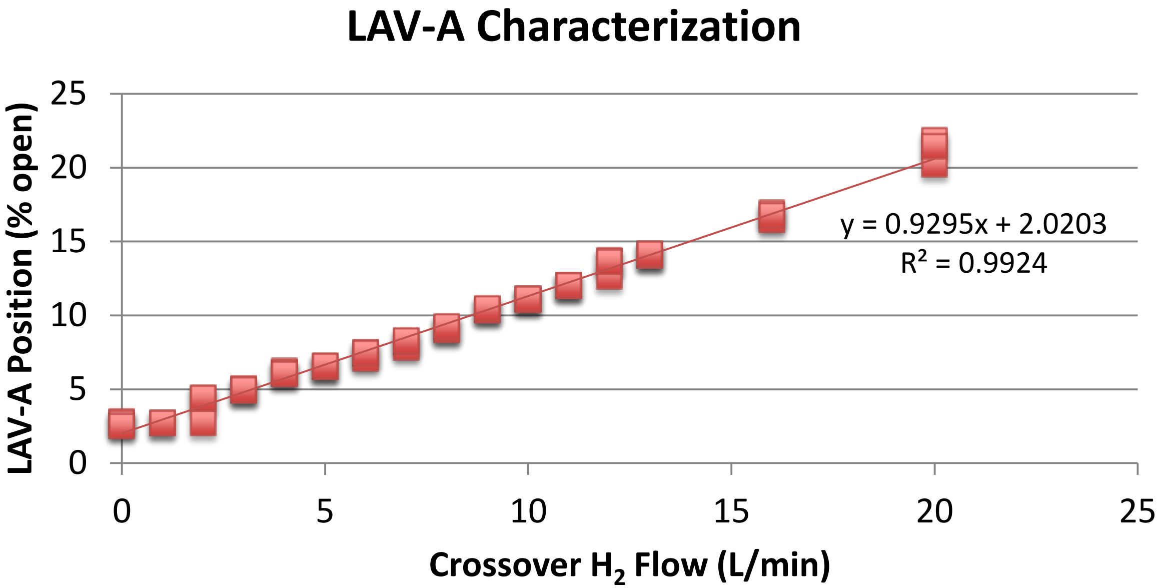
Dew Point Sensor Calibration

- **NREL Metrology Calibration Process**
  - Dew point standard is produced in N_2 at varying gas temperatures
  - Standard is calibrated with a high precision dew point analyzer
    - +/- 0.1°C
  - Standard flows past our sensor to obtain calibration curve
  - Requires removal of dew point sensor from stack test bed



Accomplishment: Linear Valve Characterization

- Characterized electrically driven linear control valve (4 – 20 mA signal)
- Valve showed good linearity in measured range
  - 0 – 20 L/min
  - 0 – 0.108 kg/hr
  - 0 – 5% of full stack current



Dew Point Sensor Data

Dewpoint Sensor	Sensor Type	Range	Stated Accuracy
Vaisala DMT152	Polymer	-100 to 0°C	+/-2°C
GE Dewpro MMY31	Ceramic	-90 to 10°C	+/-2°C
Kahn Easydew	Ceramic	-100 to 20°C	+/-2°C

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