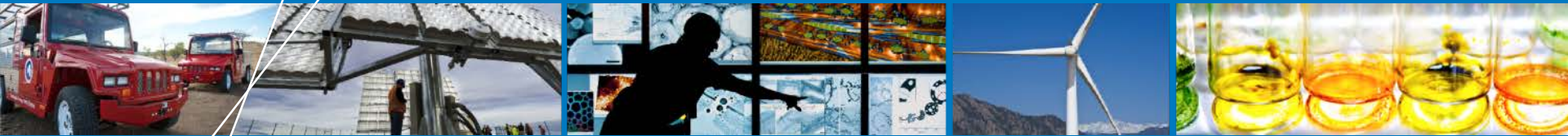


2016 DOE Hydrogen and Fuel Cells Program Review



Renewable Electrolysis Integrated System Development & Testing

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Project ID: PD031

***Presenter**

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Overview

T I M E L I N E

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

* Project continuation and direction determined annually by DOE

B A R R I E R S

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

B U D G E T

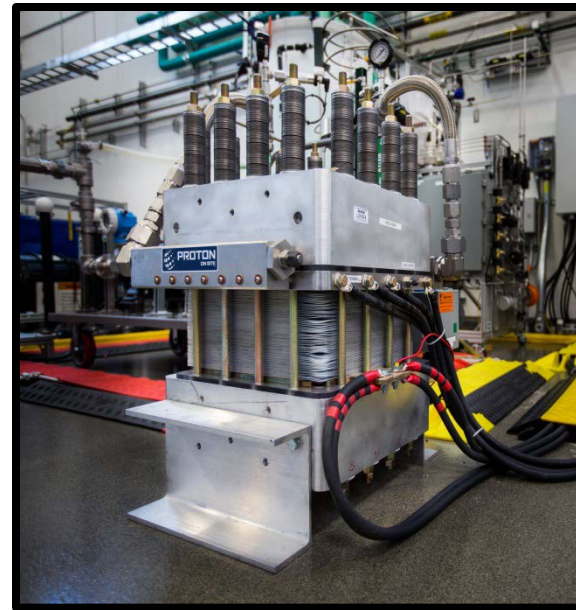
- FY15: \$200K
- FY16: \$200k
- Total Project Value: \$6,100k

P A R T N E R S

- 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 CO₂ 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

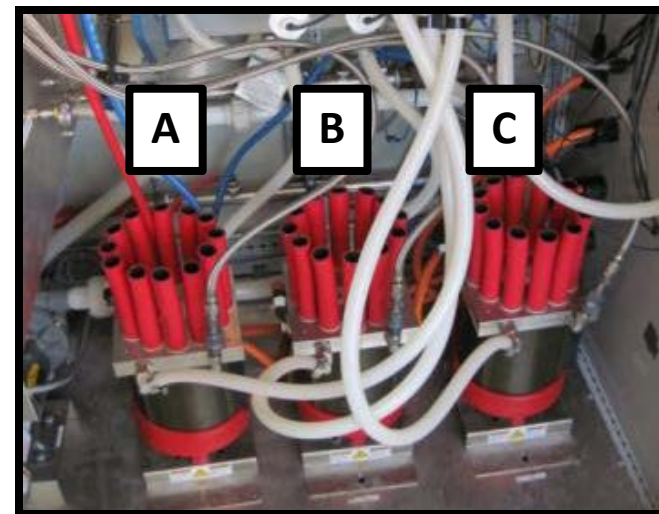
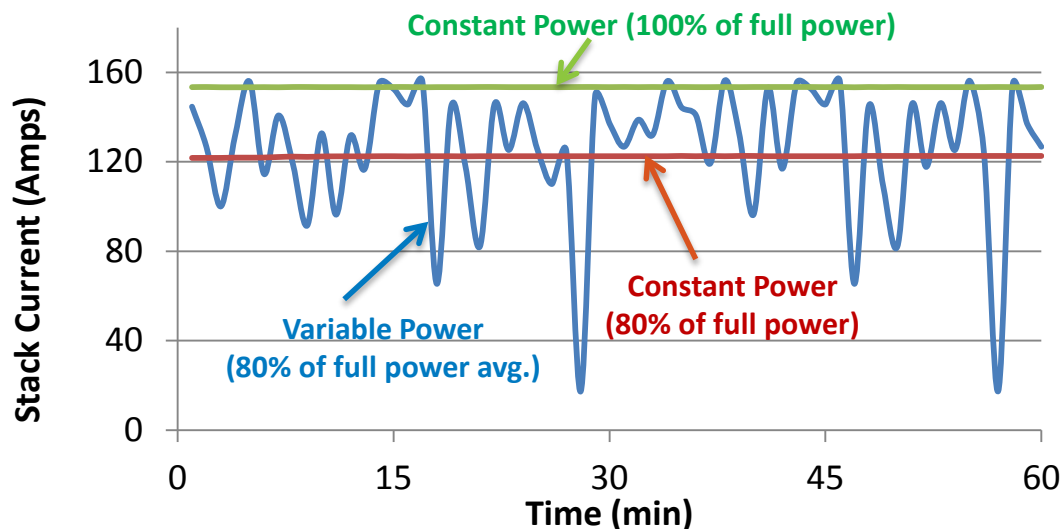
For renewable electrolysis to be successful, electrolyzer stacks operating under variable loads need to have a lifetime equivalent to electrolyzer stacks operating under constant loads.



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

PEM Electrolyzer Stack Operation Profiles



Approach: Analyzing Data

Original Method – measure stack voltage at full power and normalize to a common temperature for comparison (155 Amps, 104 °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 [$\mu\text{V}/\text{cell-hr}$]	Tech Val Method Decay Rate [$\mu\text{V}/\text{cell-hr}$]	Tech Val Method (All data) Decay Rate [$\mu\text{V}/\text{cell-hr}$]
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

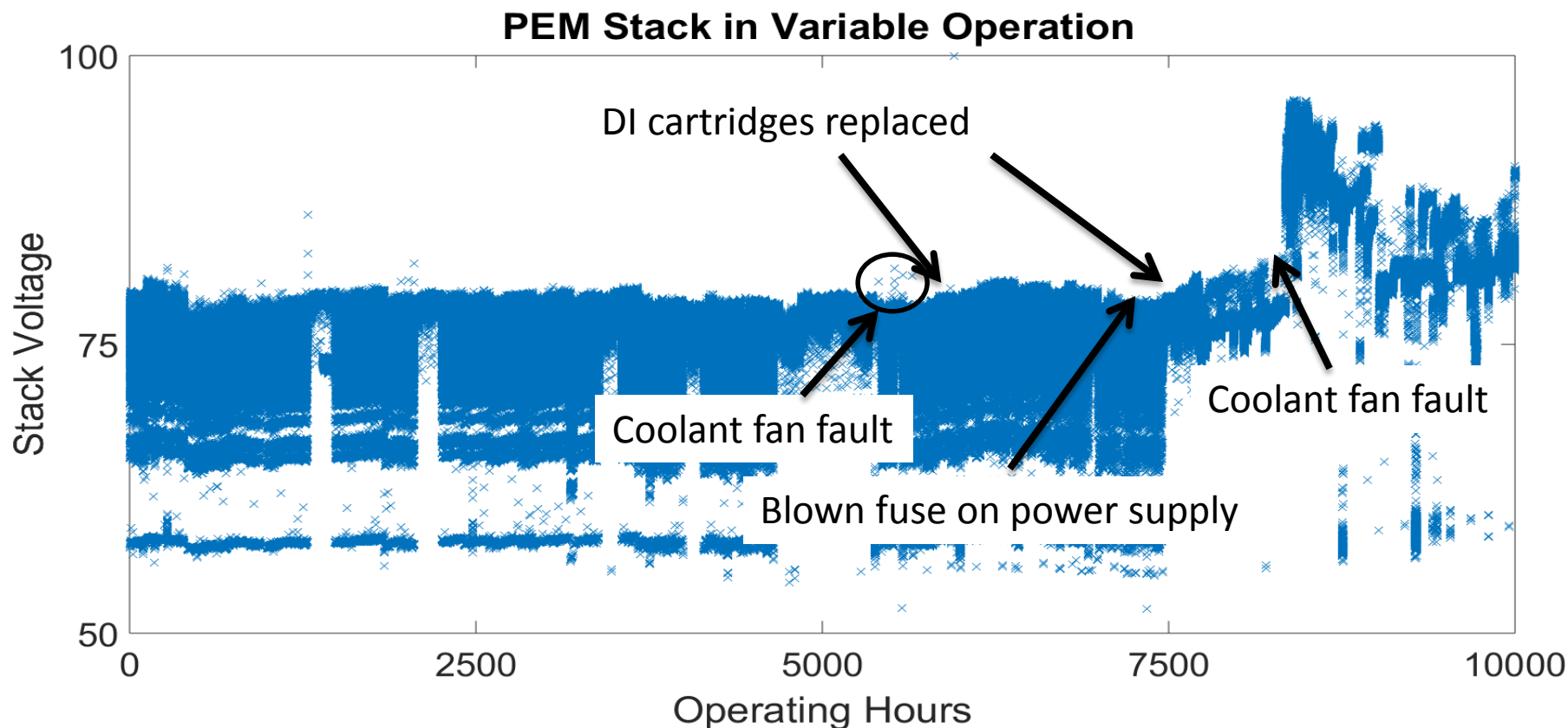
- Variable versus constant power operation did not affect the decay rate of the electrolyzer stacks
- The stacks showed a fairly consistent decay rate throughout operation until an unrelated system disruption caused irreversible damage (example on next slide)
- Balance of plant issues more likely to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



Profile Type	Tech Val Method Decay Rate [$\mu\text{V}/\text{cell}\text{-hr}$]	Tech Val Method (All data) Decay Rate [$\mu\text{V}/\text{cell}\text{-hr}$]
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

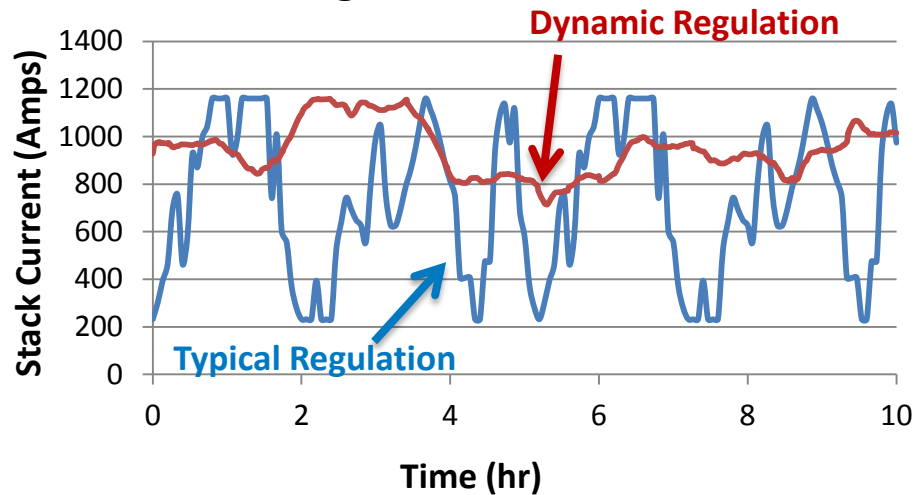
Proton recently provided detailed analysis on two stacks showing higher than usual decay rates

- 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

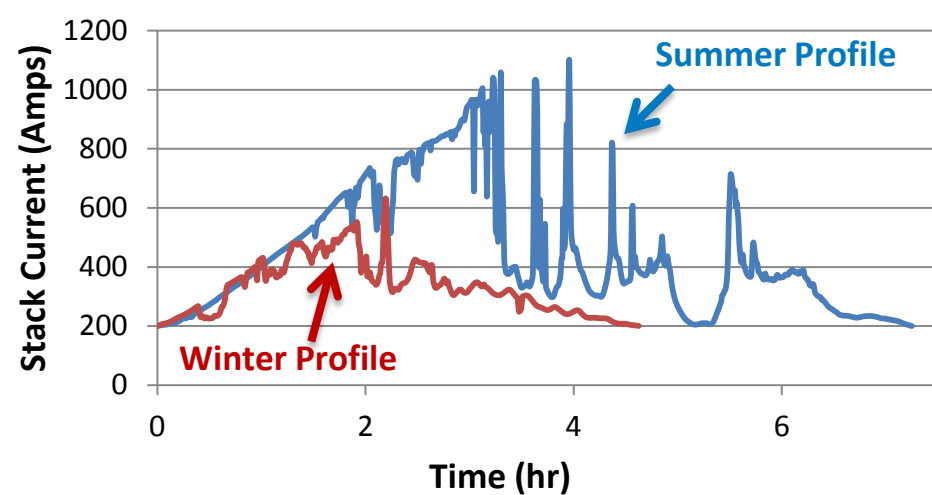
Relevance: System Efficiency Improvements

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

Regulation Profile



PV Profile



Approach: Variable Drying

Problem

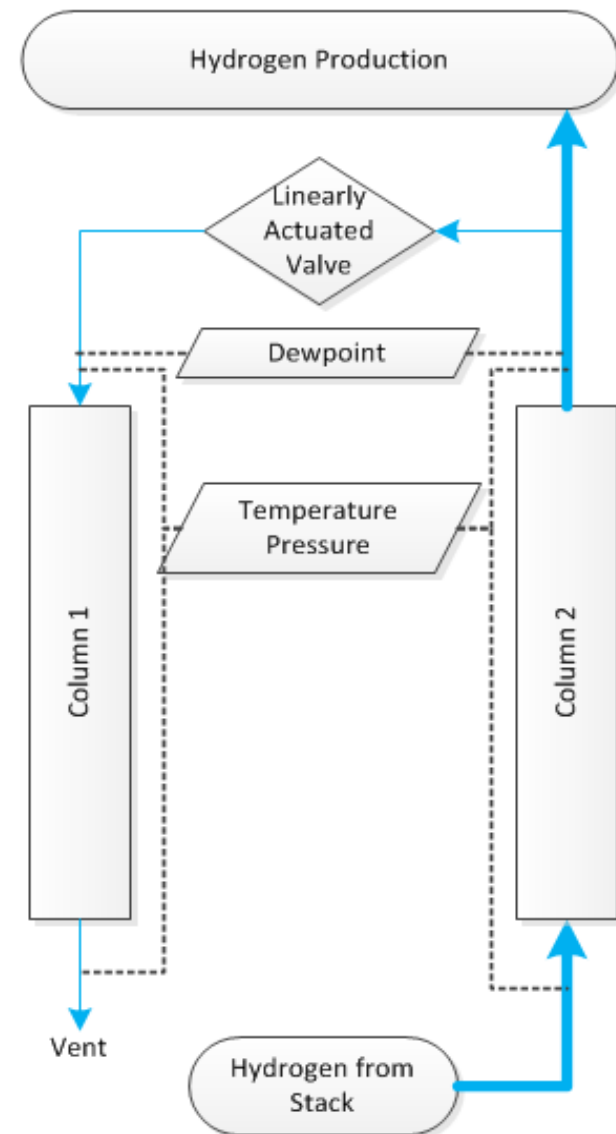
- Traditional H₂ drying systems are designed to operate at full power with a fixed amount of H₂ loss regardless of operating conditions
- Under variable loads drying losses as a percentage of flow become very high

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

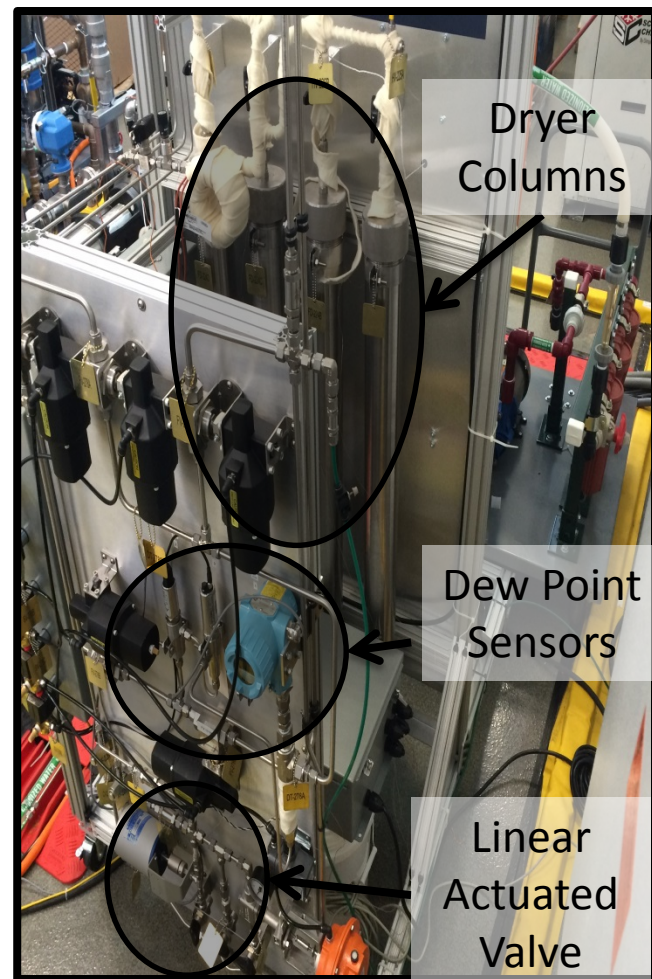
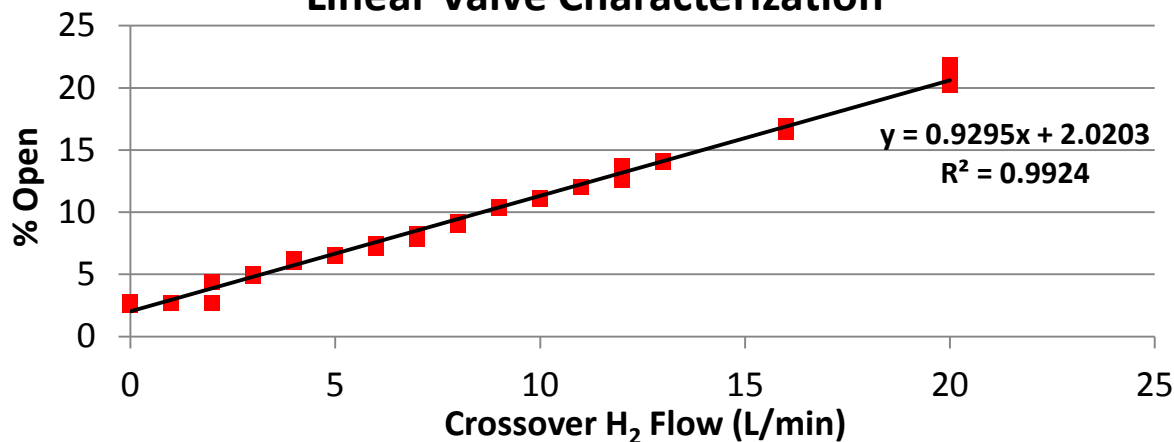
- Hydrogen loss (Volumetric bubble test)
- Hydrogen quality (Dew point sensor, SAE J2719)



Accomplishment: Demonstrated H₂ 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

Linear Valve Characterization



Progress: Continuous Improvement

- The hydrogen quality in both cases was equal and below the 5 parts per million target of SAE J2719 (H₂O in H₂) – 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

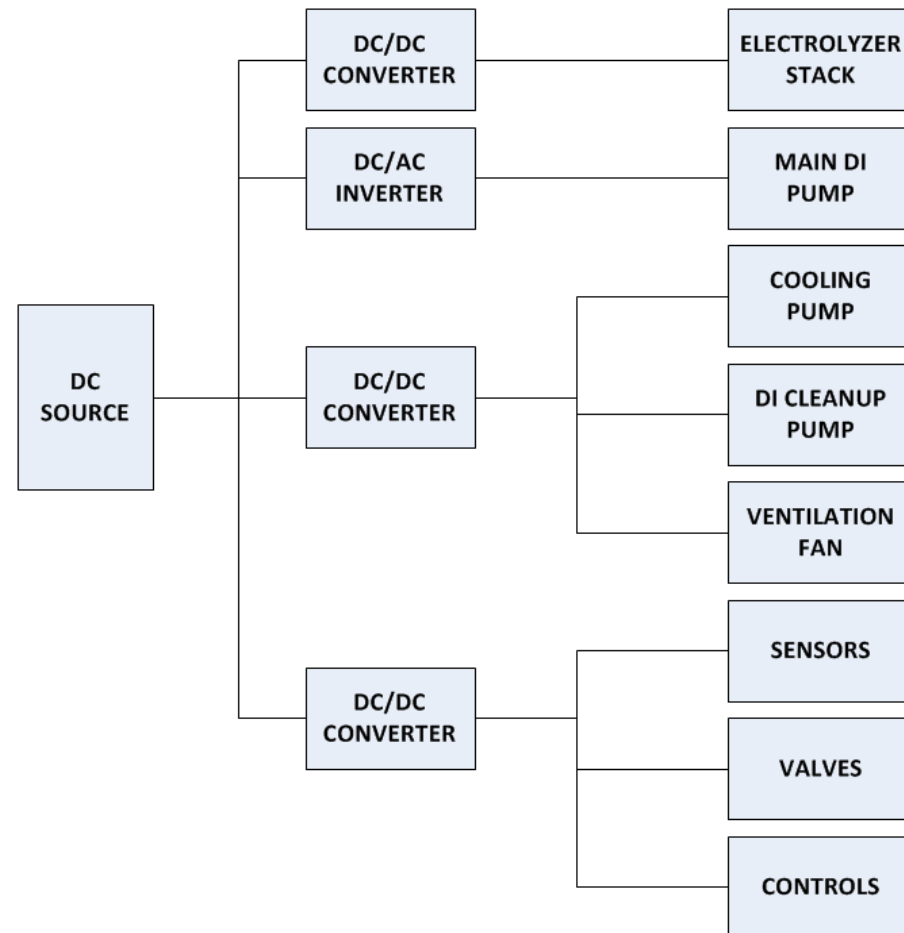
- Design an electrolyzer balance of plant that is capable of operating off-grid with inputs only from renewable energy

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

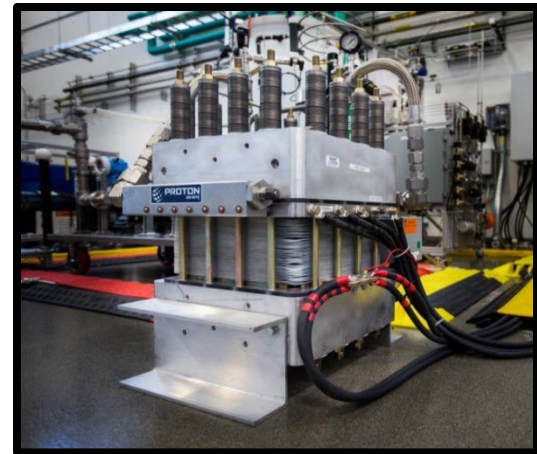
Industry

- 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

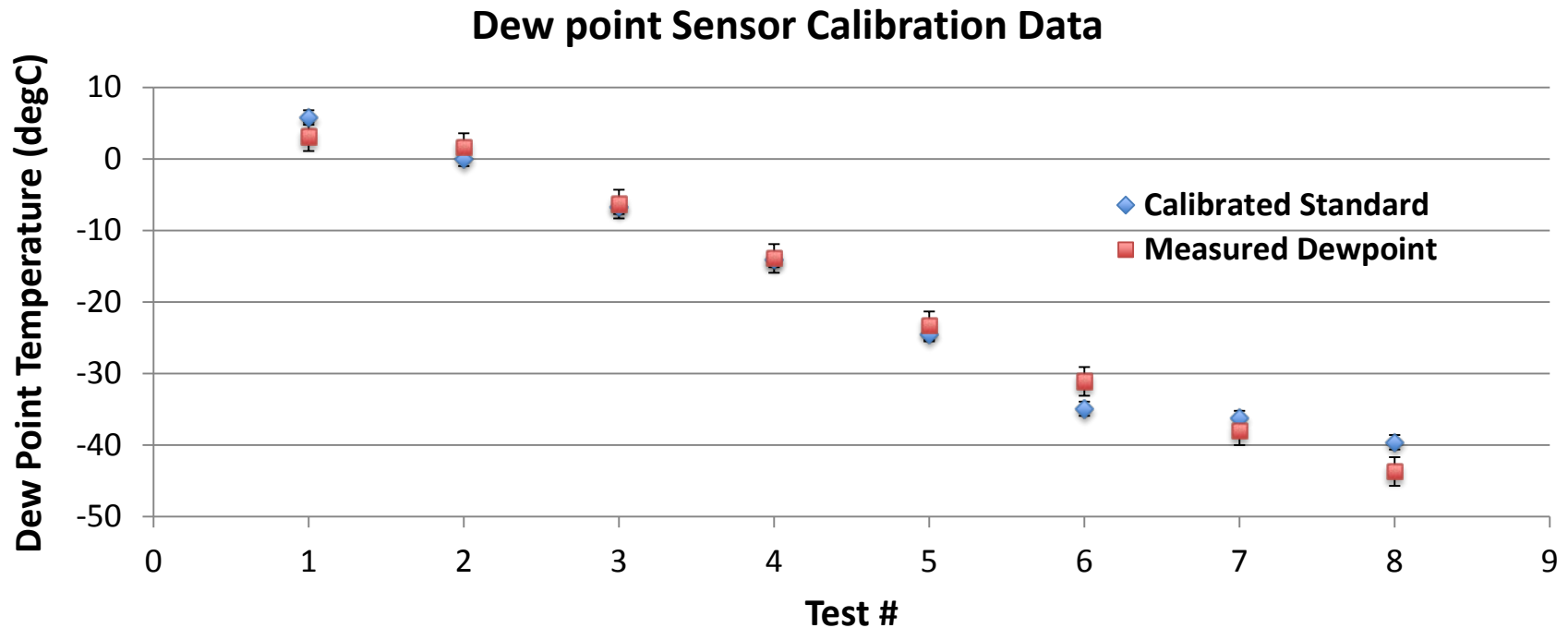
Proposed Future Research:

- 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 N₂ 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

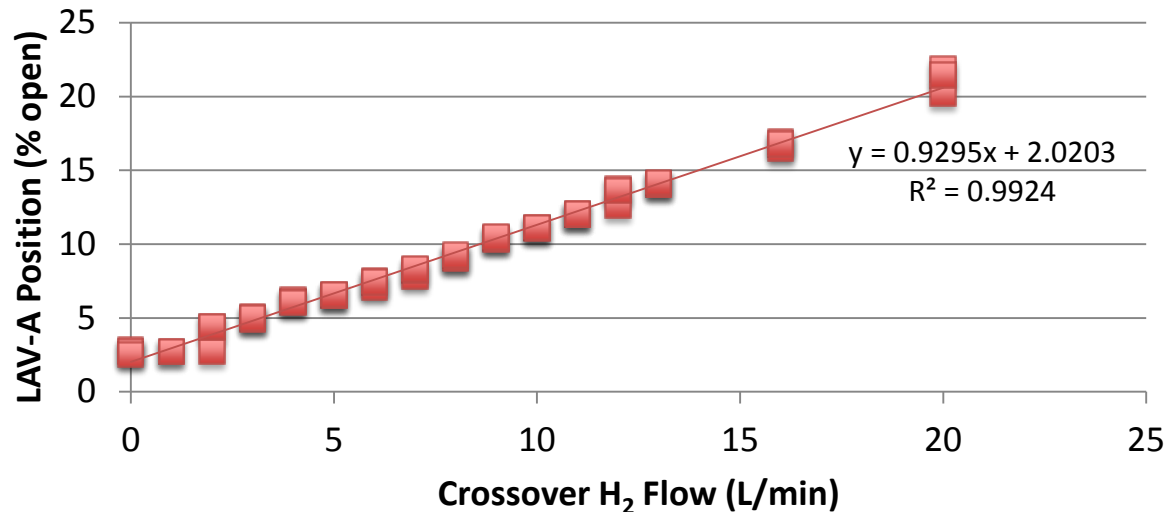


Accomplishment: Linear Valve Characterization

- 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



LAV-A Characterization



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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