2014 DOE Hydrogen and Fuel Cells Program Review

Renewable Electrolysis Integrated System Development & Testing

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Project ID: PD031

Overview

Timeline

Project start date: Sep. 2003

Project end date: Oct. 2014*

Barriers

G. System Efficiency

I. Grid Electricity Emissions (Distributed)

J. Renewable Electricity Generation Integration (Central)

L. Operations and Maintenance

Budget

FY13 DOE Funding: $460k

Planned FY14 DOE Funding: Forward funded with FY13 funds

Proton Contribution: $35k

Total Project Value: $5,700k

Partners

- Xcel Energy (CRADA)
- Proton OnSite
- Giner Inc.
- DOE Wind/Hydro Program

* Project continuation and direction determined annually by DOE

Relevance

- Hydrogen is a storage fuel enabling higher penetrations of renewable electricity sources
- Electrolyzer systems can help stabilize the utility grid
- Renewable hydrogen production can provide a near-zero carbon transportation fuel

Approach to Achieving DOE Targets

- Provide independent performance testing of advanced electrolyzer stacks and systems for DOE and Industry
- Develop and optimize electrolyzer stack and sub-system performance using grid and renewable power systems
- Quantify and report improvements of integrated system performance towards DOE and Industry efficiency and cost targets

Table 3.1.4 Technical Targets: Distributed Forecourt Water Electrolysis Hydrogen Production [a, b, c]

Characteristics	Units	2011 Status	2015 Target	2020 Target
Hydrogen Levelized Cost [d] (Production Only)	\$/kg	4.20 [d]	3.90 [d]	2.30 [d]
Electrolyzer System Capital Cost	\$/kg \$/kW	0.70 430 [e, f]	0.50 300 [f]	0.50 300 [f]
System Energy Efficiency [g]	% (LHV)	67	72	75
	kWh/kg	50	46	44
Stack Energy Efficiency [h]	% (LHV)	74	76	77
	kWh/kg	45	44	43
Electricity Price	\$/kWh	From AEO 2009 [i]	From AEO 2009 [i]	0.037 [j]

Technical Accomplishments

Compared Stack Lifetime

Wind vs. Constant Power

- **Goal:** Analyze stack decay differences between constant- and variable-powered stack operation
- Two new stacks provided by Proton
- Initial 2,000 hour operation completed
- Comparing stack decay rates under constant, full-power operation

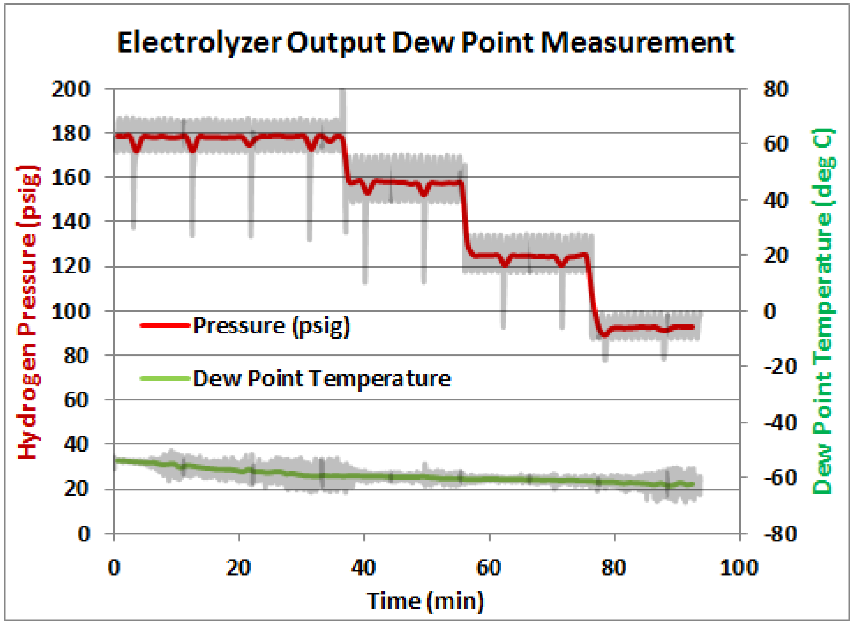
Electrolyzers Providing Grid Support Services

- **Goal:** Decrease the cost of hydrogen production by adding multiple revenue streams
  - End-user energy management
  - Transmission and distribution support
  - Wholesale market services
- Small-scale demonstration and technical paper completed

Technical Accomplishments

Improve Electrolyzer Efficiency by Reducing Drying Losses

- **Goal:** Reduce drying losses in electrolyzers to less than 3.5% by using innovative variable flow approach
- Measure moisture content of the gas output to validate approach
- SAE J2719 requires less than 5 ppm (by volume) water vapor in hydrogen for transportation
- Variable flow approach compliments variable stack powered operation of the electrolyzer



PEM Electrolyzer Stack Test Bed

- **Proton Onsite (H-Series)** – 40 kW, 13 kg/day PEM electrolyzer
- System installed at the Xcel Energy/NREL Wind-to-Hydrogen project
- Instrumented electrolyzer and took control of AC/DC power supplies to operate stacks in variable power mode (a.k.a., wind simulator profile)

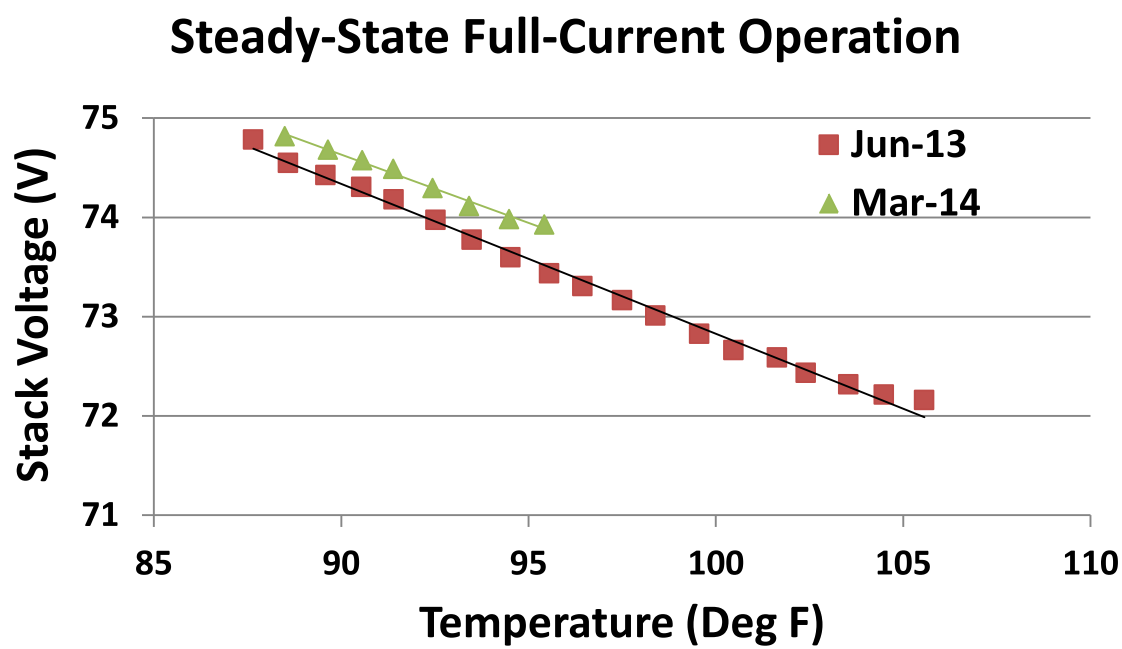
PEM Electrolyzer Stack Test Bed

Technical Accomplishment

- First 500 hours of operation provided significantly different decay rates (break-in period)
- Next 1,500 hours (2,000 hour total) enough to baseline stack decay and provide fair starting point for long-duration testing

Operating Mode	Stack Identifier	Decay Rate (µV/cell-h)
Constant Power	Stack A	9.5
Constant Power	Stack B	9.5

Next Step: Run one stack with variable-power based on wind turbine power profile; the other will stay in constant-power mode



Electrolyzer Grid Integration

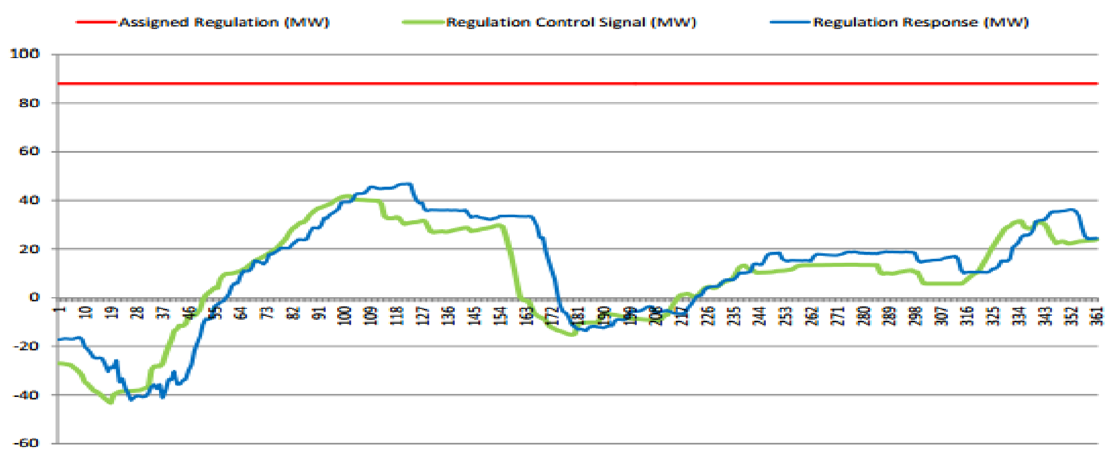
Approach – Test electrolyzer's ability to participate in grid ancillary services to reduce the overall cost of hydrogen production by adding multiple value streams.

- Electricity generator and dispatchable loads participating in grid services must meet ramping requirements
- Tested electrolyzer using standard utility ramping power profiles
  - Collected electrolyzer system AC power
  - Only have control of the electrolyzer stacks
    - Balance of plant is another opportunity
- **Previous Work:** Intentionally disturbed diesel-powered micro-grid and compared response time of PEM and Alkaline electrolyzer systems using stack load to stabilize frequency.

Regulation Market Test

- PJM Regulation Testing: Resources need to achieve total performance score > 75%
- Performance score calculated with a weighted average between:
  - Accuracy - Correlation of control signal and regulating units response
  - Delay - Time delay between control signal and point of highest correlation from Step 1
  - Precision - Difference between the areas under the curve for the control signal and the regulating units response

Performance Score Example – Combined Cycle



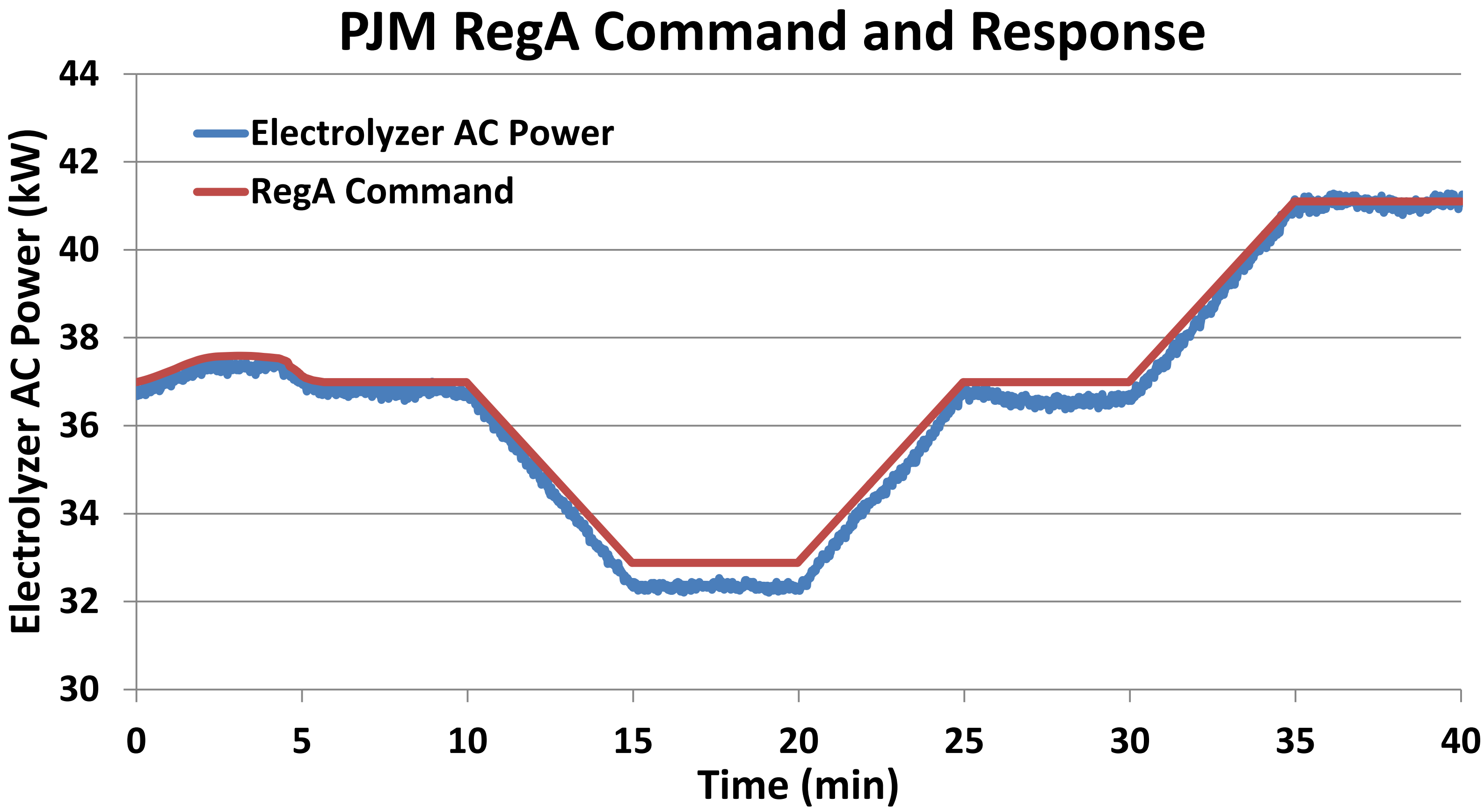
Correlation: 0.95 Delay: 0.66 Precision: 0.74

Total Performance Score: 0.78

Regulation Market Test

Technical Accomplishment:

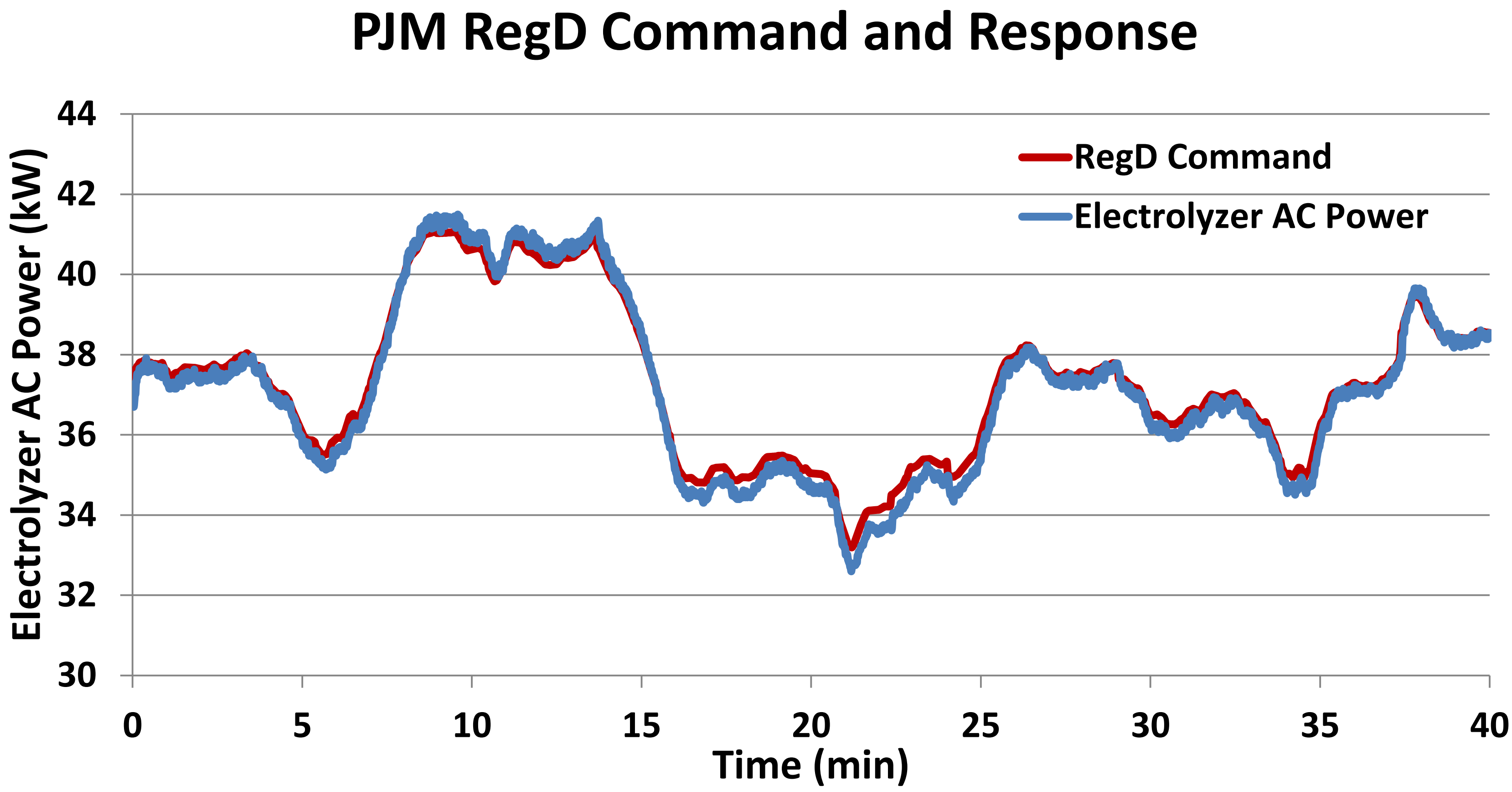
- PJM RegA Test: used for traditional regulation
- For regulating resources with physical characteristics that limit ramp rate
- Results show strong correlation between command and response which would allow the electrolzyer to bid in to the regulation market



Regulation Market Test

Technical Accomplishment:

- PJM RegD Test: dynamic regulation signal testing
- For regulating resources with no physical characteristics that limit ramp rate
- Results show strong correlation between command and response which would allow the electrolzyer to bid in to the regulation market



System Efficiency

Approach: Validated electrolyzer mass flow and system efficiency using NREL-designed device

- Validated Proton H-Series mass flow
- Varied stack current to look at different flow rates
- Unit showed good precision, all three trials less than ± 1 gram with 95% confidence

	Trial 1 (n = 75) 96% of rated power	Trial 2 (n = 24) 77% of rated power	Trial 3 (n = 61) 71% of rated power
Stack Current (A)	148.4	119.8	110.0
Measured Flow (kg/hr)	0.520	0.410	0.373
Rated Flow* (kg/hr)	0.516	0.417	0.383

* Rated flow of 0.539 kg/hr (Proton) multiplied by % of stack current

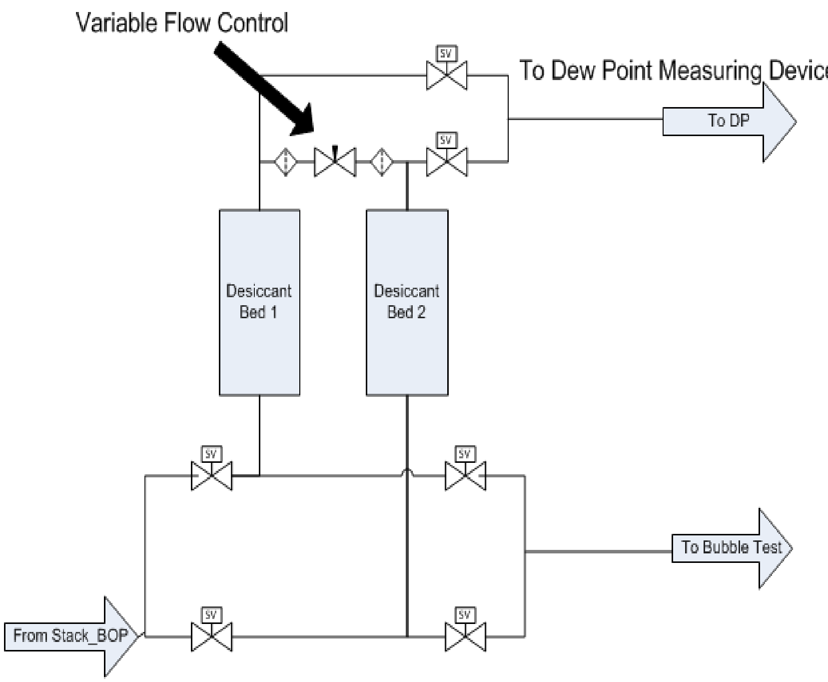
System Efficiency – Drying Losses

Technical Accomplishment: Confirmed dew point and hydrogen loss due to drying system with varying stack power, without variable flow drying technique

- Found drying losses to be between 11-18% of electrolyzer flow
- As stack current decreased the percentage of hydrogen lost increased
- Variable flow drying technique will maintain the percentage of hydrogen lost based on hydrogen output (stack power) instead of losing a higher percent as stack power is decreased

Drying Losses	100% Stack Power	80% Stack Power	60% Stack Power
Flow (kg/hr)	0.07	0.07	0.07
% of Rated Flow	**11%**	**14%**	**18%**

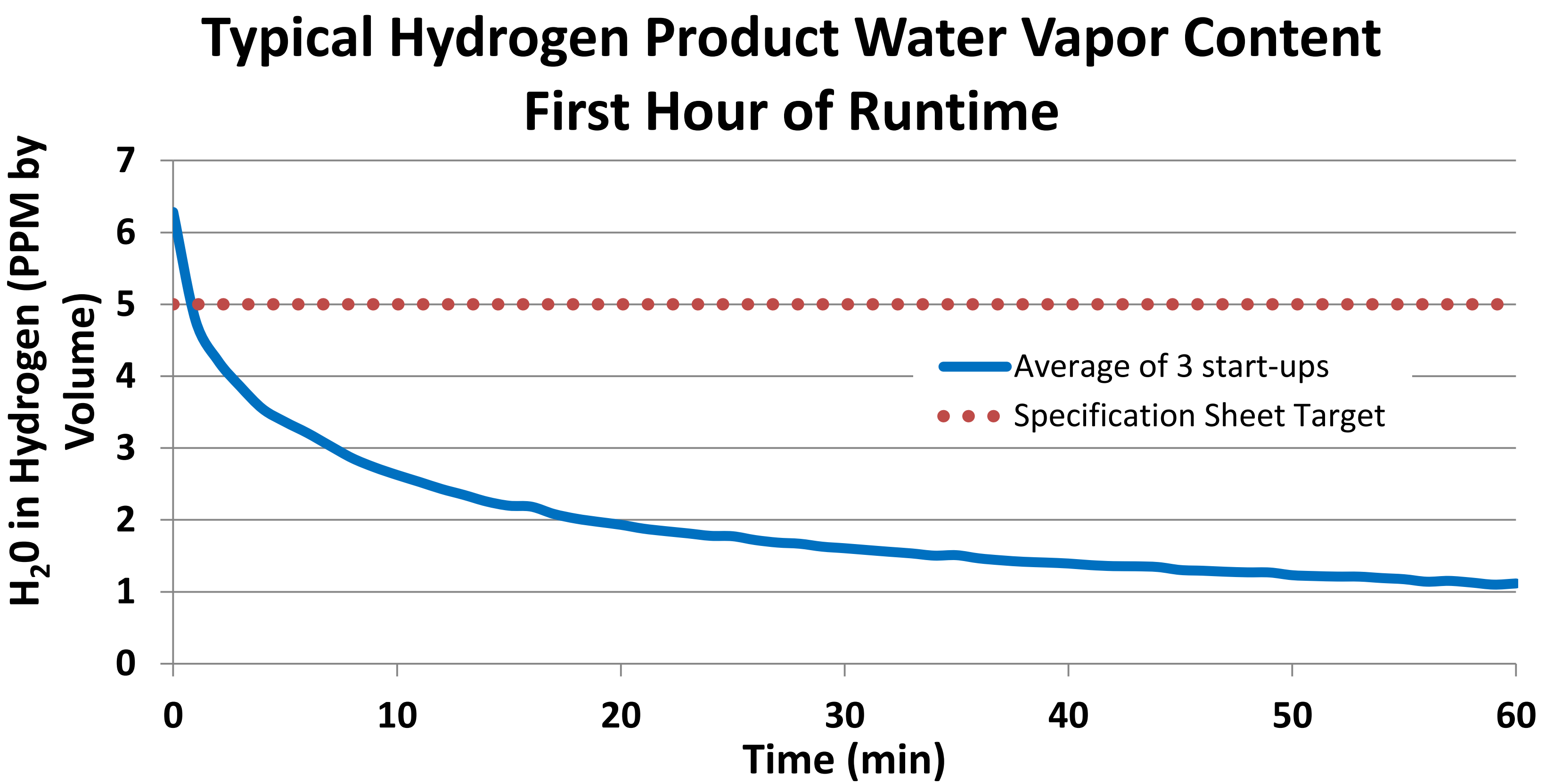
*** Sample size n = 5 for each test**



System Efficiency – Drying Losses

Technical Accomplishment:

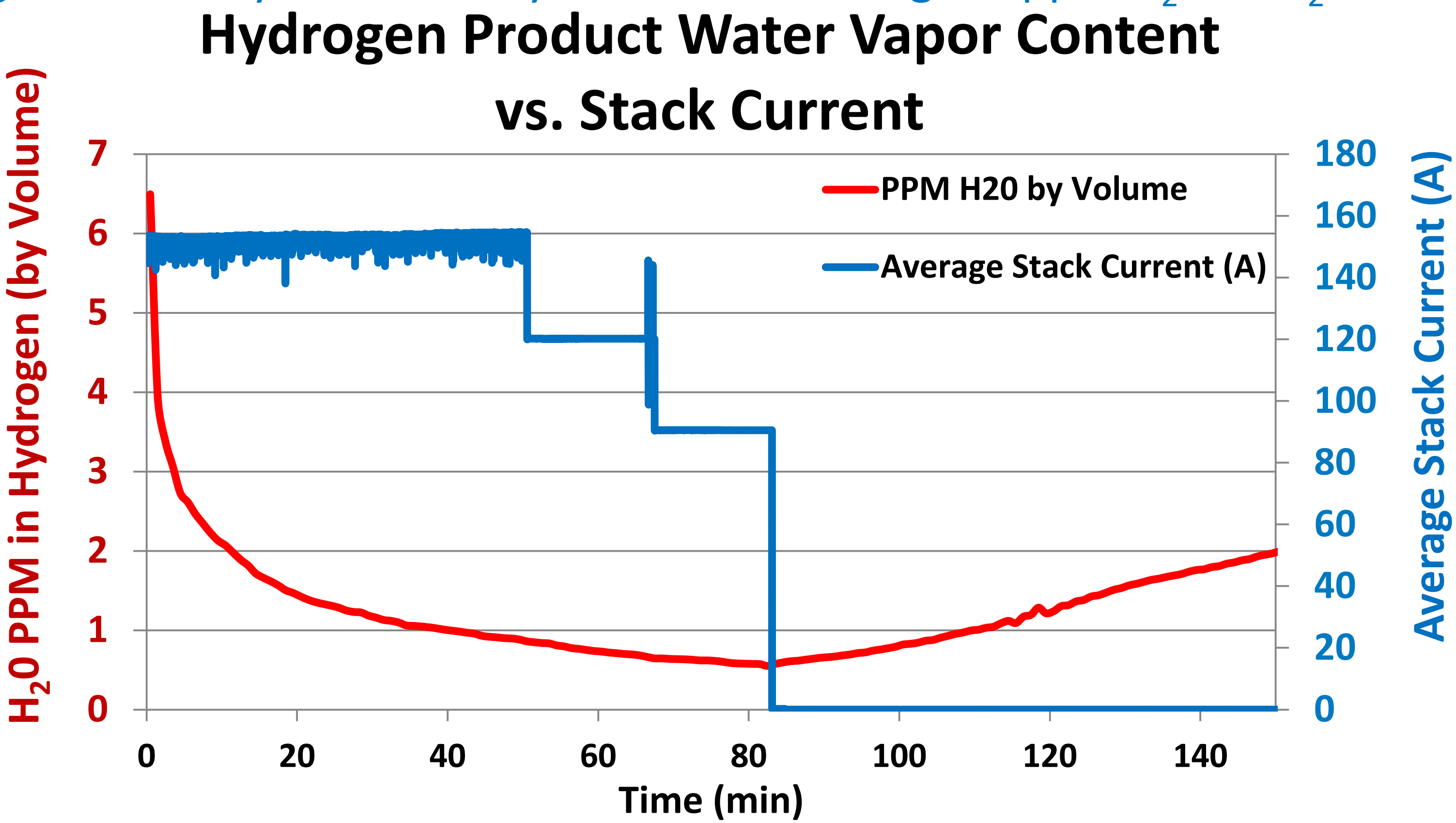
- Proton H-Series specification sheet and SAE J2719 look for H_2O in H_2 < 5 ppm
- Typical startup shows ppm below standard in less than 5 minutes
- Current electrolyzer drying technologies exceed SAE J2719 in a short amount of time, variable flow drying will allow less hydrogen to be lost while still staying under 5 ppm



System Efficiency – Drying Losses

Technical Accomplishment:

- Varied stack power:
  - ppm H_2O in H_2 was unaffected by the variation
  - Drying losses as a percentage of H_2 output increased (previous slides)
- Variable flow drying technique combined with variable stack power will allow higher electrolyzer efficiency while maintaining < 5 ppm H_2O in H_2



Collaborations

Formal

Giner Inc.

- Work for Others

Xcel Energy (CRADA)

- Wind-to-Hydrogen demonstration project since 2005

Proton Onsite

- Provided (2) PEM stacks for variable power testing
- Hydrogen drying test bed

International

Presented results at;

- ADvanced ELectrolysers (ADEL) International Workshop, Corsica, France
- F-Cell World of Energy Solutions, Stuttgart, Germany

Internal to NREL

Hydrogen Component Validation

- TV19 – Presented by Danny Terlip

700 bar Hydrogen Hose Reliability & Improvement

- PD100 – Presented by Kevin Harrison

INTEGRATE

- Integrated Network Test-bed for Energy Grid Research and Technology Experimentation
- FCTO - Large active area stack testing and balance of plant optimization
- Investigate and demonstrate how EE and RE technologies can work together holistically to provide grid services and increase their hosting capacity

Future Work

- Complete testing and economic analysis of novel drying technique to optimize drying losses in a renewable (variable) powered system
- Automate inline hydrogen drying monitoring system to quantify drying losses, production flow and dew point over long durations
- Replace 3rd (of 3) ~10 kW PEM stacks
  - 6000 hours (milestone), variable wind profile to determine stack decay

Summary

Relevance: Goals consistent with reducing capital cost, improving stack and system efficiency and integrating systems with renewable energy sources

Approach: Develop and demonstrate advanced controls, novel sub-systems, system-level improvements and integrate with renewable energy sources to reduce the cost of hydrogen

Technical Accomplishments:

- Installed two new PEM stacks and collected 2,000 hours of constant power data to baseline early stack decay rate
  - Both stacks showed a decay rate of 9.5 μV/cell-h
- Tested smaller scale electrolyzers ability for grid integration
  - Exploring added value streams to reduce production costs
- Baseline commercially available electrolyzer water vapor
  - Electrolyzer reaches <5 ppm in under 5 minutes
  - Stack Current does not affect ppm

Collaborations:

- Proton Onsite – Electrolyzer stack variable power testing and large active area stack testing
- Giner Inc. – Large active area stack testing
- Internal: INTEGRATE, Component Validation and Hose Reliability

Proposed Future Research:

- Continue testing novel drying technique to optimize drying losses versus output hydrogen
- 6,000 hours variable wind profile to determine stack decay on Proton stacks
- Design and build hydrogen drying cart to allow autonomous collection of drying losses, production flow and dew point

Backup Slides

Example of Variable-Power Profile