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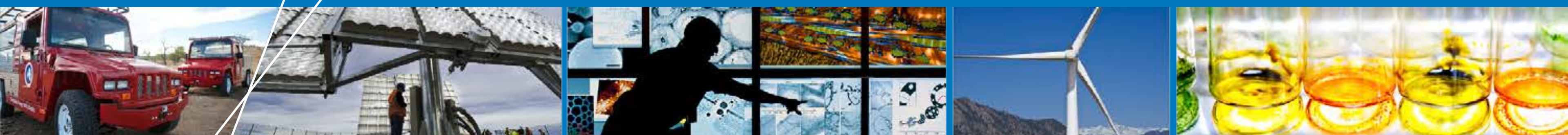
NATIONAL RENEWABLE ENERGY LABORATORY

2012 DOE Hydrogen and Fuel Cells Program Review



Renewable Electrolysis Integrated System Development & Testing

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Project ID: TV015

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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

Project start date: Sep. 2003

Project end date: Oct. 2012*

Barriers

G. Cost

H. System efficiency

J. Renewable integration

Budget

- Project Funding (2009-2011): $950k
- Funding received in FY11: $425k
- Planned Funding for FY12: $450k**

Partners

- CA Dept. of Food and Agriculture
- Xcel Energy
- All U.S. electrolyzer manufacturers
- Univ. of North Dakota/EERC
- DOE Wind/Hydro Program

* Project continuation and direction determined annually by DOE

**$265k from Technology Validation, remaining from Production and Delivery

Relevance – Main Objectives

Testing – Performance

- Perform characterization and performance testing on electrolysis systems developed from DOE awarded projects
- Test electrolyzer stack and system response with typical renewable power profiles
- Develop and validate system to characterize hydrogen mass flow

Demonstration – Renewable Resources Integration

- Identify opportunities for system cost reduction and optimization as they pertain to electric utilities
- Characterize, evaluate, and model integrated renewable energy systems (IRES)
- Evaluate reliability growth of IRES
- Characterize electrolyzer performance with variable stack power
- Design, build, and test shared power electronics and direct-coupled renewable-to-stack configurations

Relevance – Barriers Addressed

Capital Costs: R&D is needed to lower capital and improve the efficiency and durability of the system. Cost reductions can be realized with electrochemical compression enabling the elimination of a mechanical compression stage.

System Efficiency: In large production facilities even slight increases in efficiency enable significant reductions in hydrogen cost.

Renewable Electricity Generation Integration: More efficient integration with renewable electricity generation is needed to reduce costs and improve performance.

Integrated Renewable Electrolysis Systems: These need to be developed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production.

Table 3.1.4. Technical Targets: Distributed Water Electrolysis Hydrogen Production [a, b, c]
(Technical targets are being reevaluated and will be updated in the next release)

Characteristics	Units	2003 Status	2006 Status [c]	2012 Target	2017 Target
Hydrogen Cost	$/gge	5.15	4.80	3.70	<3.00
Electrolyzer Capital Cost [d]	$/gge $/kW	N/A N/A	1.20 665	0.70 400	0.30 125
Electrolyzer Energy Efficiency [f]	% (LHV)	N/A	62	69	74

MYPP 2011 Interim Update – Technical Plan - Production

Approach

Test, evaluate, model, and optimize the renewable electrolysis system performance for dedicated hydrogen production and electricity/hydrogen cogeneration

System Integration and Component Development

Work with industry to develop new advanced hardware and control strategies to couple renewable and electrolyzer systems.

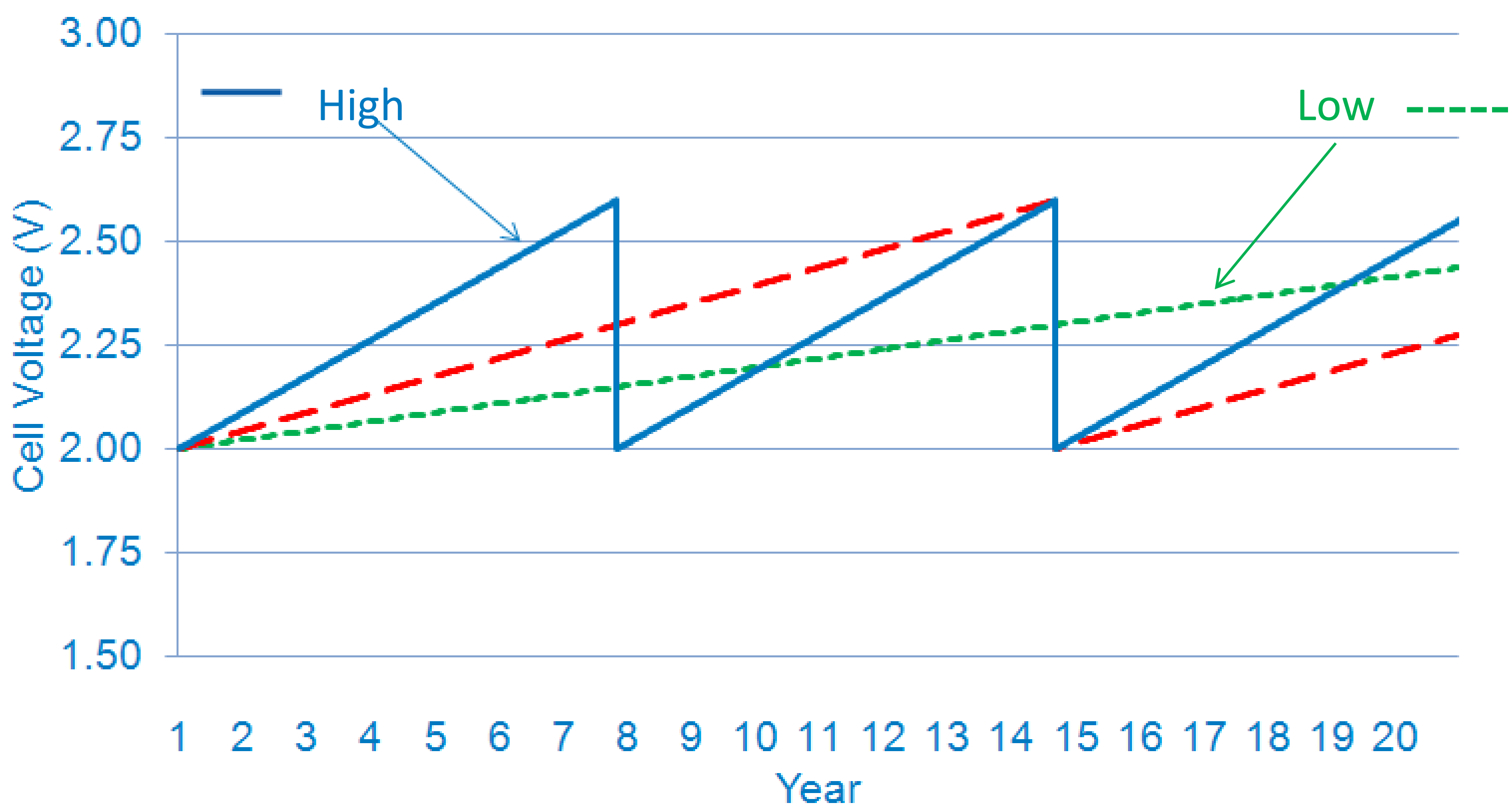
Characterization Testing and Protocol Development

Install equipment, characterize performance, and develop standardized test procedures.

Stack Performance – Varying Current

Purpose

- Low 2.5, mid 5 and high 10 µV/cell/hr decay rate
- Means the difference between 0, 1, and 2 stack replacements in 20 years
- Lower decay rate reduces power supply and cooling system overhead



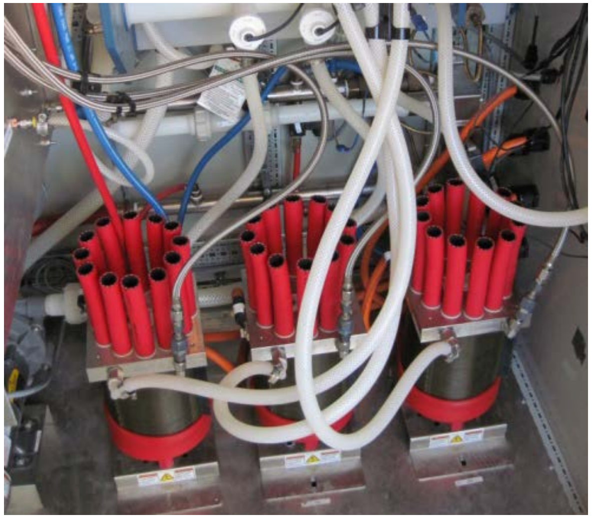
Stack Performance – Varying Current

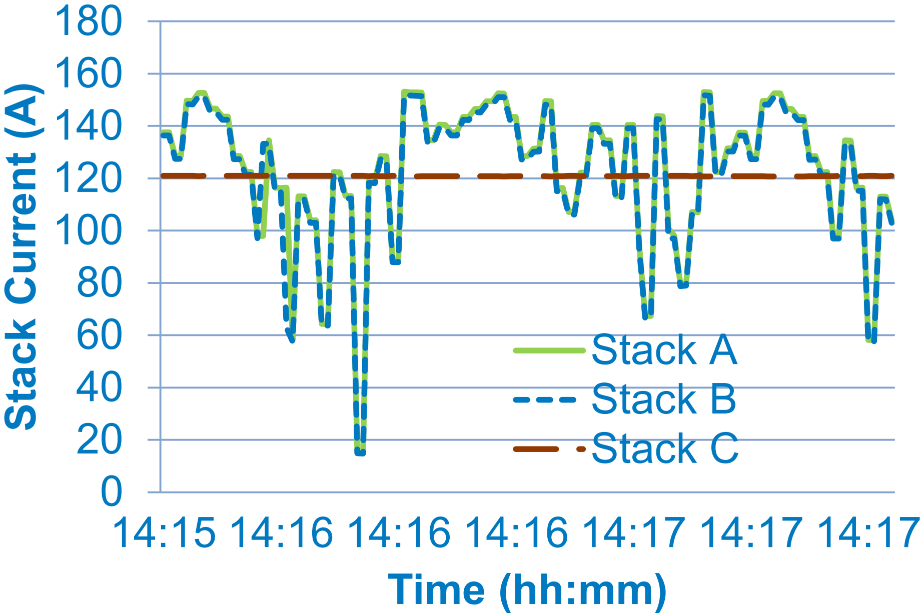
Monitoring all 3 stacks

- Input water temperature
- Output water temperature
- Stack current
- Stack voltage

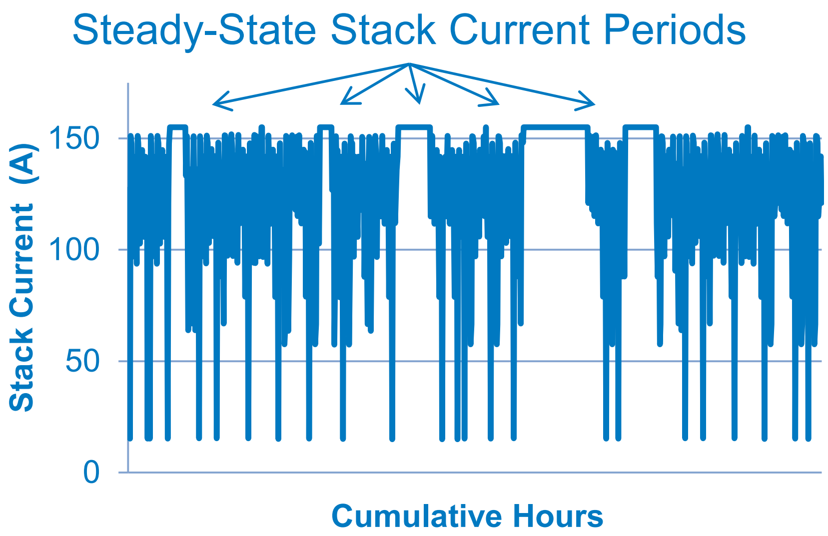
Controlling Stack Currents

- Two stacks operating on varying wind energy profile (Stacks A, B)
- Third stack operating at constant current (Stack C, Steady-state operation)
- All three have same average stack current (121 A)





Stack Performance – Varying Current



Mode	Average Decay µV / cell-hr	% Difference Relative to Constant Current
Variable	11.6	30%
Variable	10.5	18%
Constant	8.9	-
Hours	5474	

Steady-State Methodology

- All three stacks operated at full stack current (~155A)
- 1 minute sample rate
- Stack input and output water temperatures are averaged to normalize different stack operating temperatures
- Linear fit – cell membrane resistance f(T)
- All steady-state voltage data extrapolated to 40°C (104°F) for fair comparison

Diagnostics Laboratory for Prototypes

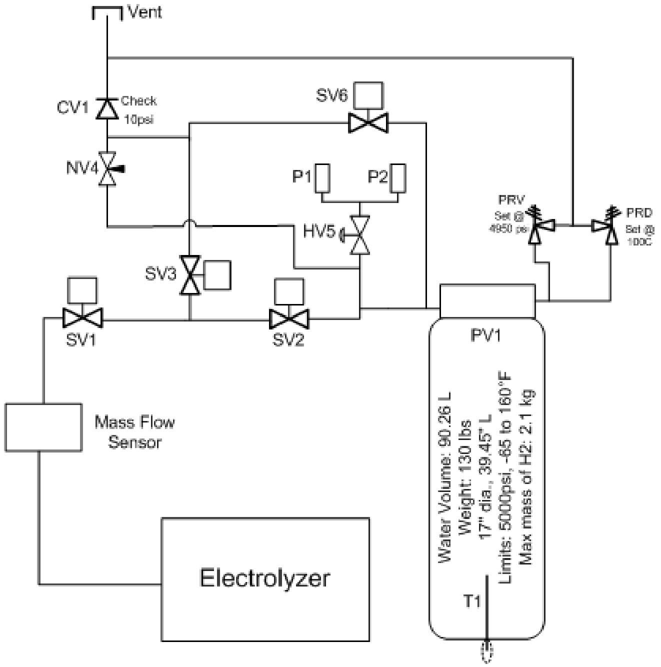
- PDL – Class 1, Div. 2, Group B (12’x14’x10’)
- Hydrogen product, vent and heating from adjacent Wind-to-Hydrogen Production Building
- 75 kVA, 480Δ:208Y/120V, 3p Supports testing of GES, Avalence and WFO H_2-systems
- 480V, 100A service available
- Safety, monitoring and control
- Product can be compressed or vented

Mass Flow Measurements

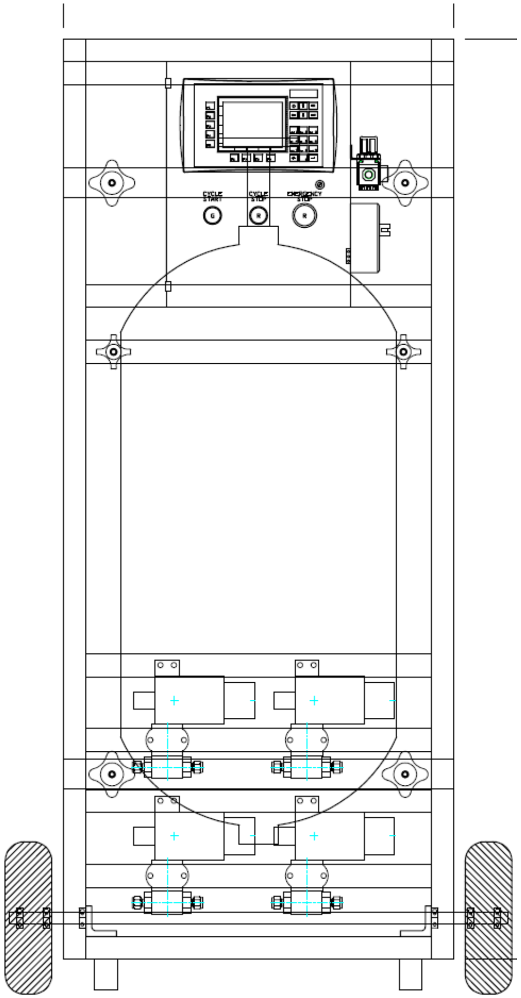
Prototype for 10,000 psig system for California Department of Food and Agriculture (CDFA) , Division of Measurement Standards (DMS)

The CDFA through the DMS has entered into a two year contract with the California Energy Commission to **develop standards suitable for the commercial measurement of gaseous hydrogen for vehicle and other refueling applications** which include device accuracy, installation, field testing and use.

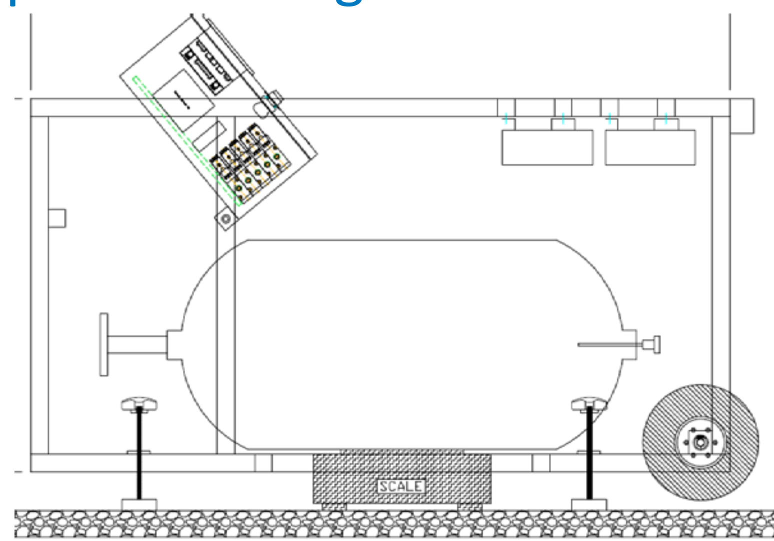
- NIST monitoring progress



Mass Flow Measurements



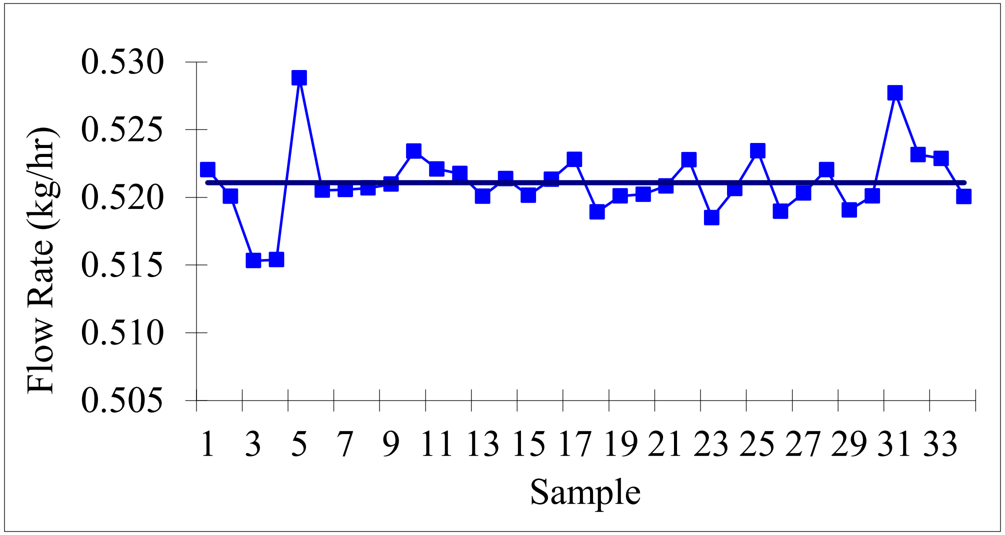
- System designed with industry input
- Intended to be shippable
- Volumetric measurements of mass flow for
  - Electrolyzer
  - Dispenser (Today, up to 350 bar)
  - Fuel Cell
  - Compressor
- Designed to accomplish 3 testing methods with one assembly
  - ✓Volumetric
  - ✓Master meter
  - Gravimetric

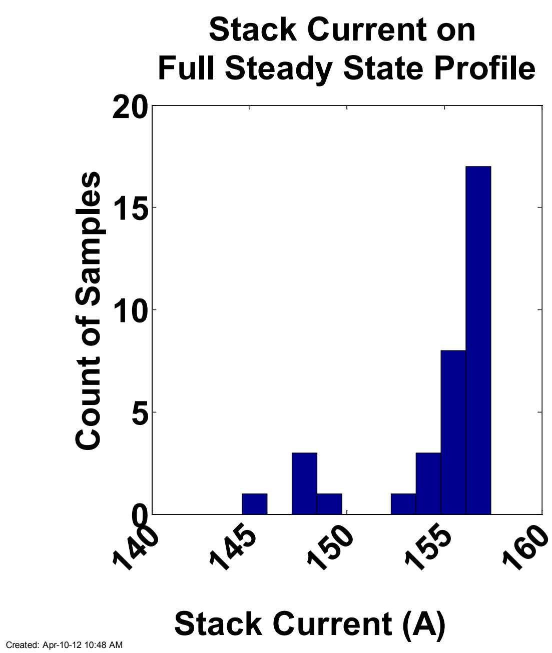


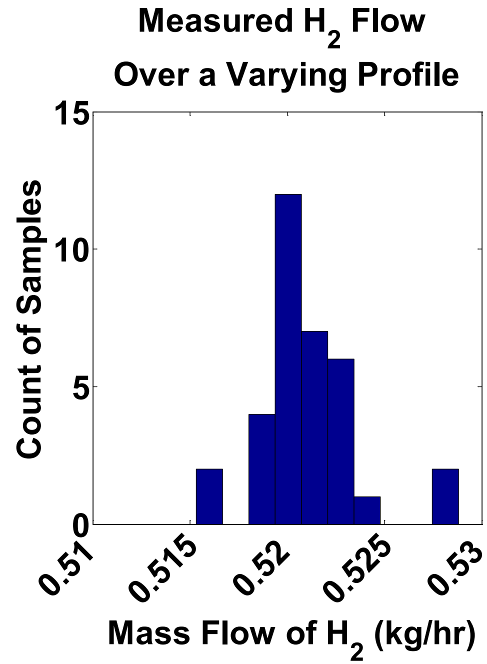
Mass Flow Measurements

Full Constant Stack Current

- 34 trials spread across 3 days
- Each lasting about 9 minutes
- P initial = 20 psig
- P final = 180 psig
- Flow (avg) = 0.521 kg/hr
- Std Dev = 0.003 kg/hr



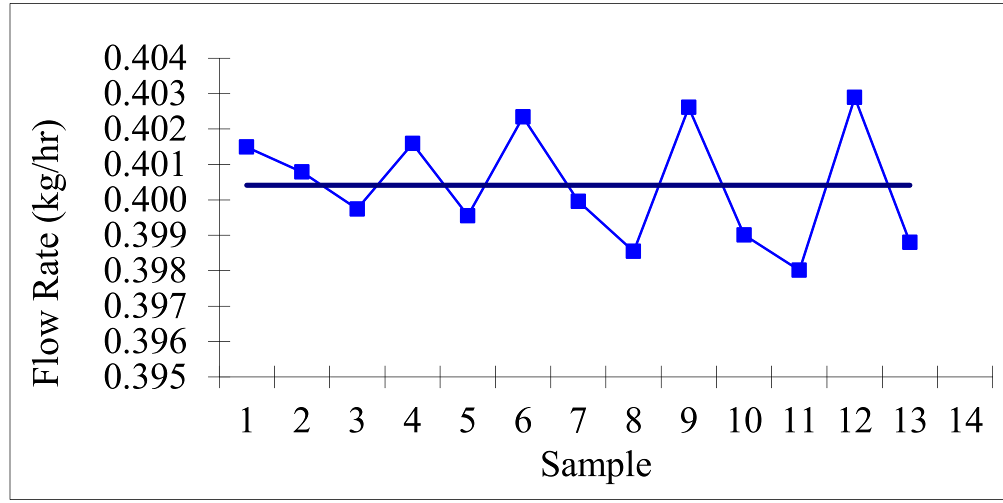


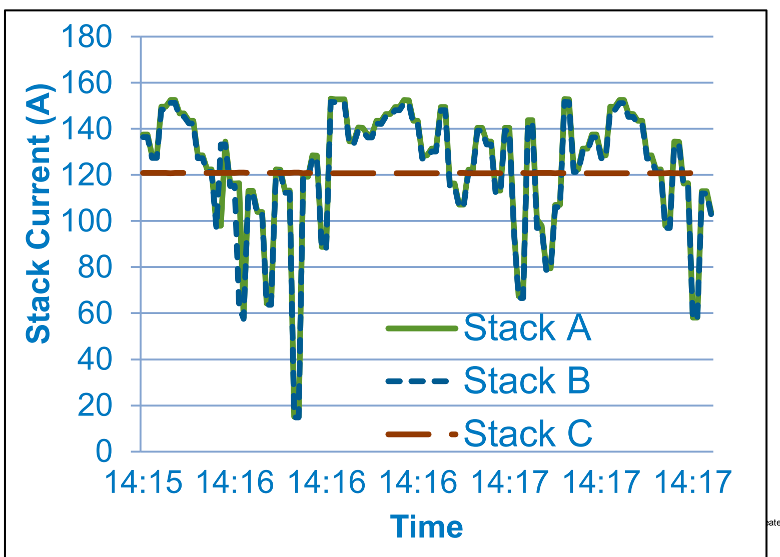


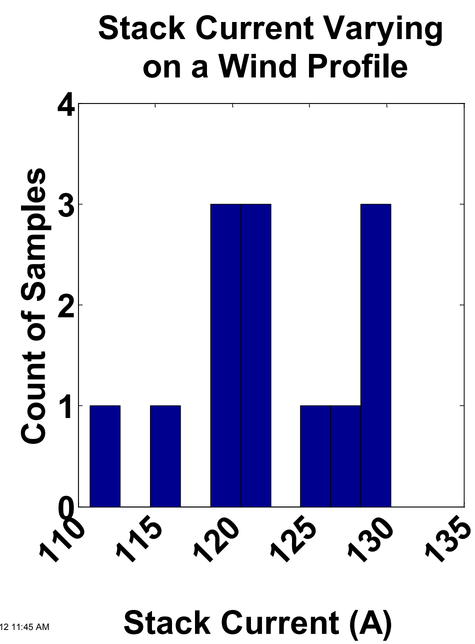
Mass Flow Measurements

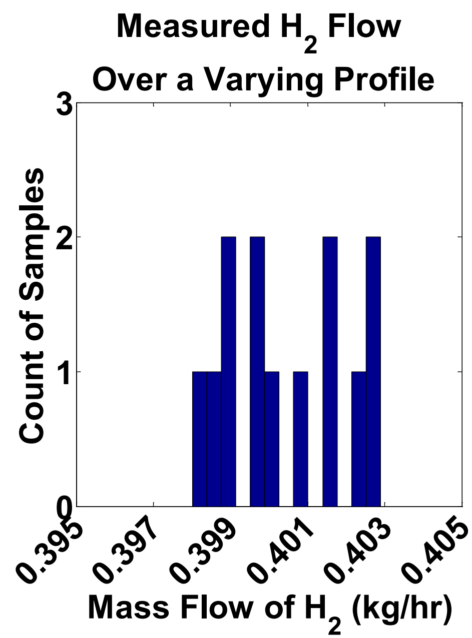
Variable Stack Current

- Each lasting about 11 minutes
- Flow (avg) = 0.400 kg/hr
- Std Dev = 0.002 kg/hr
- Although varying current, volumetric accumulation evens out flow variations









Electrolyzer – Grid Frequency Support

Experimental Setup showing AC micro-grid configuration to test frequency response of PEM and alkaline electrolyzers

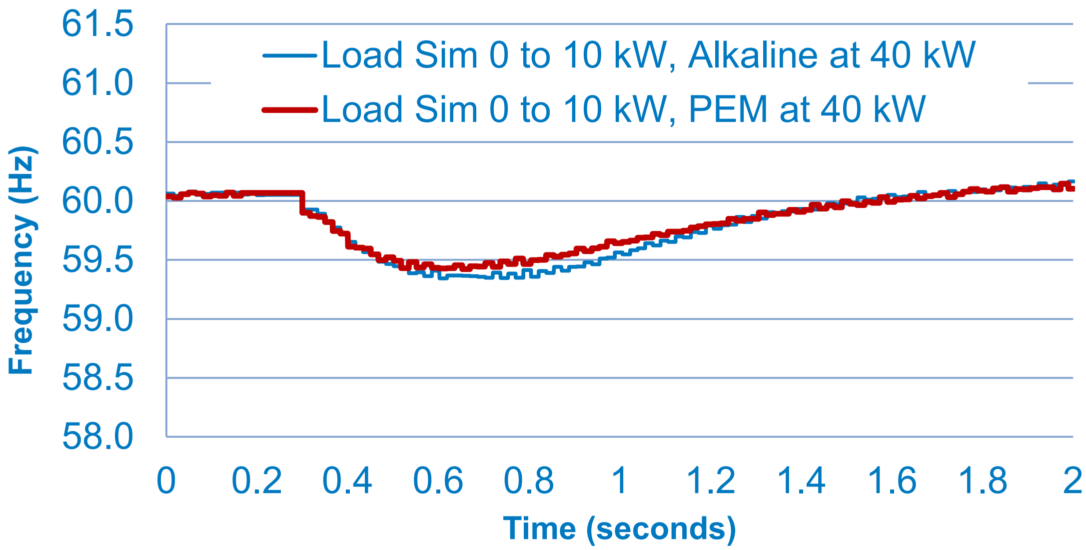
Electrolyzers have the potential to realize an additional revenue stream by providing ancillary grid support services.

Methodology

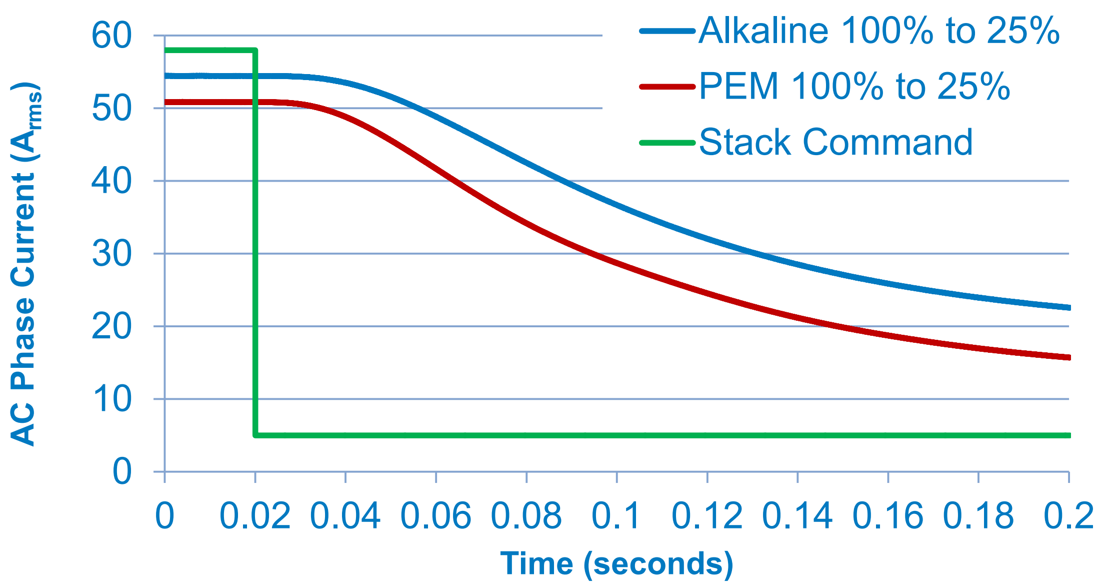
- 120 kW diesel generator powering electrolyzers
- Load simulator adding or shedding load to induce frequency disturbances
- Electrolyzers commanded to shed or add stack power
  - Micro-grid monitored and electrolyzer command initiated when frequency exceeded ± 0.2 Hz

Electrolyzer – Grid Frequency Support

'Natural' un-mitigated frequency disturbances on AC micro-grid caused by 10 kW resistive load step while powering the alkaline and PEM electrolyzer

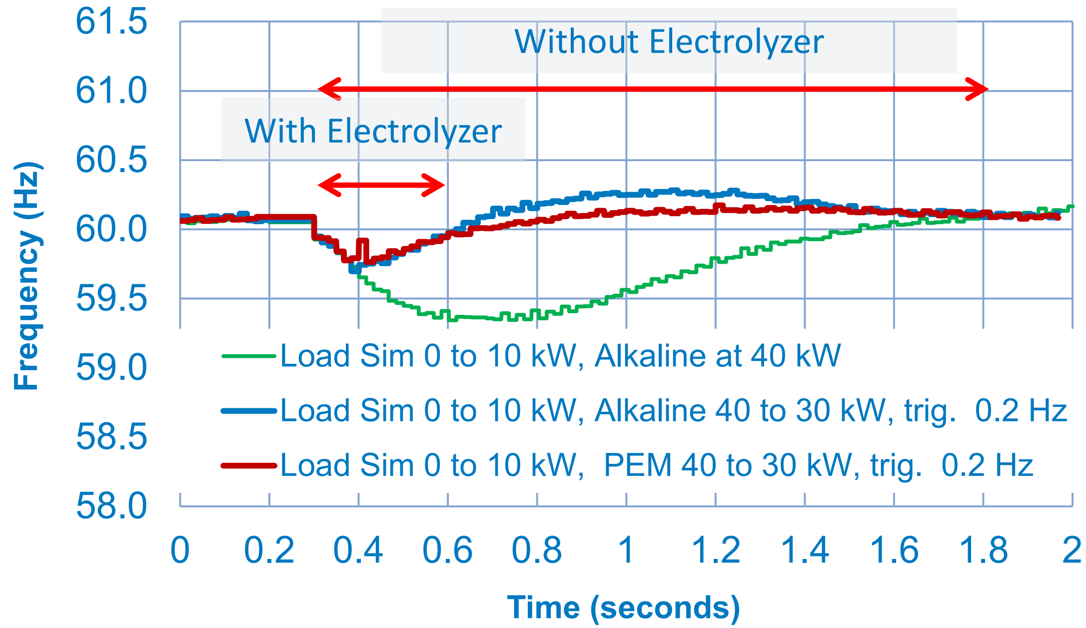


PEM and alkaline system-level response showing AC phase current (rms) to command to shed stack power (100% down to 25% of their rated power)

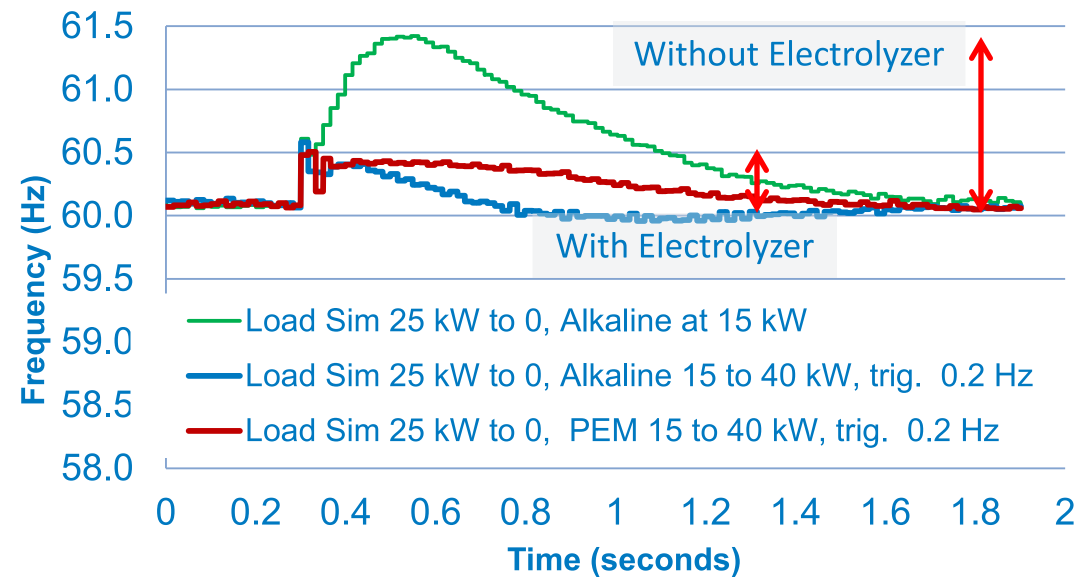


Electrolyzer – Grid Frequency Support

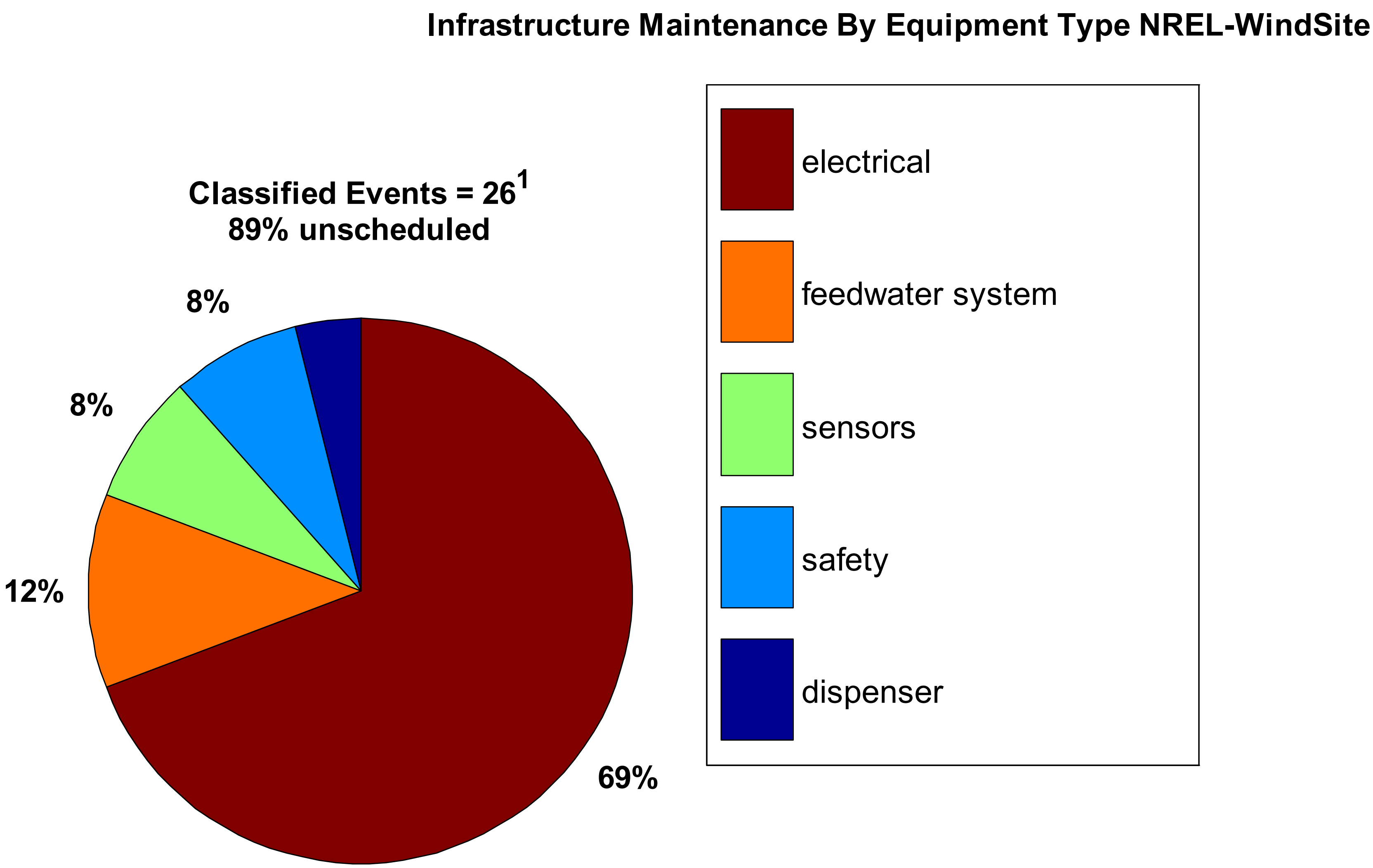
10 kW steps -PEM and alkaline systems shorten magnitude and duration of under-frequency disturbance on AC micro-grid



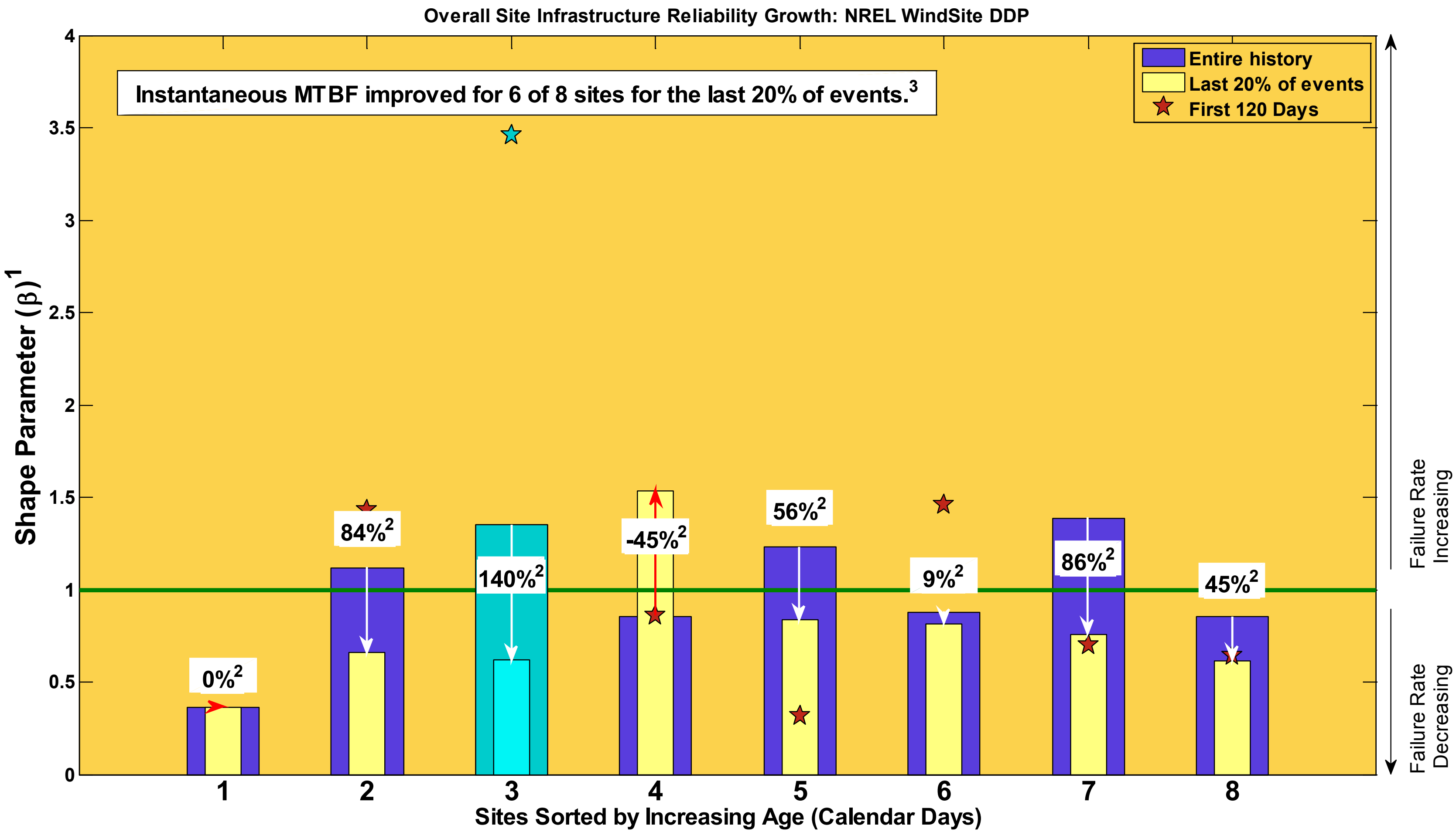
25 kW steps - PEM and alkaline systems shorten and reduce magnitude of over-frequency disturbance on AC micro-grid



Maintenance by Equipment Type



NREL Performance Comparison



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NREL WindSite DDP

1. IEC 61164:2004(E)., Reliability Growth - Statistical Test and Evaluation Methods, IEC. 2004.

2.% change in instantaneous MTBF

3. Some sites are no longer active. Final results are shown for those sites.

Collaborations

DOE, CRADA, NCAP and TSA

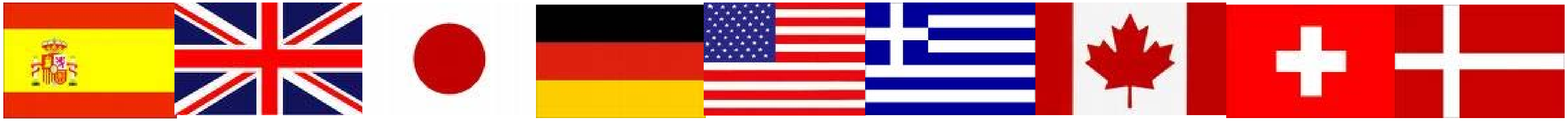
- California Department of Food and Agriculture
- NREL Technology Validation Team
- Xcel Energy – Wind-to-Hydrogen demonstration project since 2005
- Next Hydrogen – Performing market analysis (CAN)
- MAETEC – Preparing to test electrolyzer (UT)
- Electrolyzer manufacturers (GES, Avalence, Proton, Teledyne)

Information sharing

- Hydrogen Utility Group – Led by Xcel Energy
- California Fuel Cell Partnership (H2 Capacity & Storage Data)
- Electrolyzer manufacturers (GES, Avalence, Proton, Teledyne)
- University of North Dakota/Energy & Environmental Research Center
- Ft. Collins Utility (CO)

International

- International Energy Agency, Annex 24 “Wind Energy and Hydrogen Integration” (Ending 2012)
- Risø-DTU (Denmark) – Modeling and experimental verification of enhanced energy storage systems



Future Work

- Validate improved stack and system efficiency
  - May 2012 delivery – Giner
- Validate medium pressure from alkaline stack
  - FY13 delivery – Avalence
- Utilize test facilities and equipment to support industry
  - NCAP activities – NREL funded
- Complete variable stack testing
- Develop Renewable Electrolysis System Integration Simulation Tool (RESIST)
- Analysis of variance (ANOVA) analysis of mass flow equipment
  - Improve volumetric mass flow accuracy
  - Demonstrate improved master meter calibration
- Demonstrate Bi-polar multi-stack operation

Summary

Relevance: Addressing capital cost, efficiency, and renewable energy source integration to reduce the cost per kilogram of hydrogen

Approach: Demonstrating advanced controls, system-level improvements and integration of renewable energy sources to electrolyzer stack

Technical Accomplishments:

- Designed and installed new test facility and infrastructure to support validation and performance testing of DOE-awarded systems
- Operating 2 (of 3) stacks with wind profile for stack decay comparison. Total ~ 5500 hrs
  - Comparison of voltage decay rates of steady-state and variable stack current operation to better understand long-term impacts of variable stack operation
  - Improving understanding of short-term voltage transients
- Completed frequency mitigation testing of alkaline and PEM electrolyzers on AC grid
  - Both provided sub-second response to reduce magnitude and duration of disturbance
- Designed, built and began testing with volumetric mass flow system

Technology Transfer & Collaborations: Validating system performance and disseminating results to industry to enable improved renewable and electrolyzer integration. Active and informal partnerships with industry, academia and domestic/international researchers.

Proposed Future Research:

- Validation of stack/system efficiency and higher-pressure operation of DOE-awarded systems
- RESIST modeling of electrolyzer performance
- ANOVA and performance improvements of mobile volumetric mass flow system
- Demonstrate bi-polar stack operation