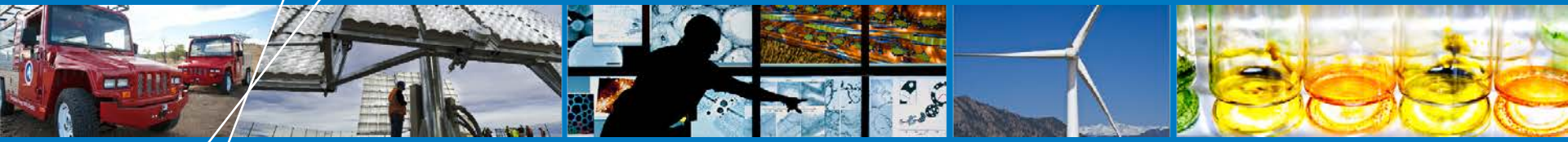
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

2013 DOE Hydrogen and Fuel Cells Program Review



Renewable Electrolysis Integrated System Development & Testing

Kevin Harrison, Michael Peters

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Project ID: PD031

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Overview

Timeline

Project start date: Sep. 2003
Project end date: Oct. 2013*

Barriers (2012 MYRDD)

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

Budget

- Project Funding (2009-2011): $1375k
- Planned Funding for FY13: $495k**

Partners

- Xcel Energy (CRADA)
- Proton OnSite (CRADA)
- Giner Electrochemical Systems
- Univ. of North Dakota/EERC
- DOE Wind/Hydro Program

* Project continuation and direction determined annually by DOE

**$230k from Production and Delivery, remaining from Technology validation

Relevance & Approach

- Provide independent testing of state-of-the-art electrolyzer stacks and systems for DOE and Industry
- Quantify and feedback stack and system performance with grid and integration with renewable power systems
- Develop and optimize electrolyzer sub-systems, power conversion and test equipment for renewable hydrogen

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]

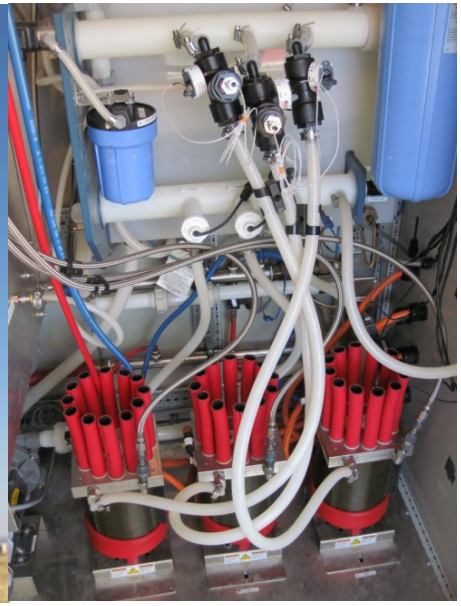
Technical Accomplishments

Demonstrated PEM Electrolyzer Efficiency

- Goal to achieve DOE 2015 targets for;
  - Stack efficiency
  - System efficiency
- 200 hours of operation
- Verified reduced drying losses
- FY12 EE-1 Joule Milestone completed

Compared Stack Performance on a Wind Power Profile

- 10,000 hour performance comparison between variable wind power and constant power operation
- Analyzed stack decay differences between constant and variable modes
- FY13 2Q Joule Milestone achieved



Electrolyzer Stack & System Efficiency

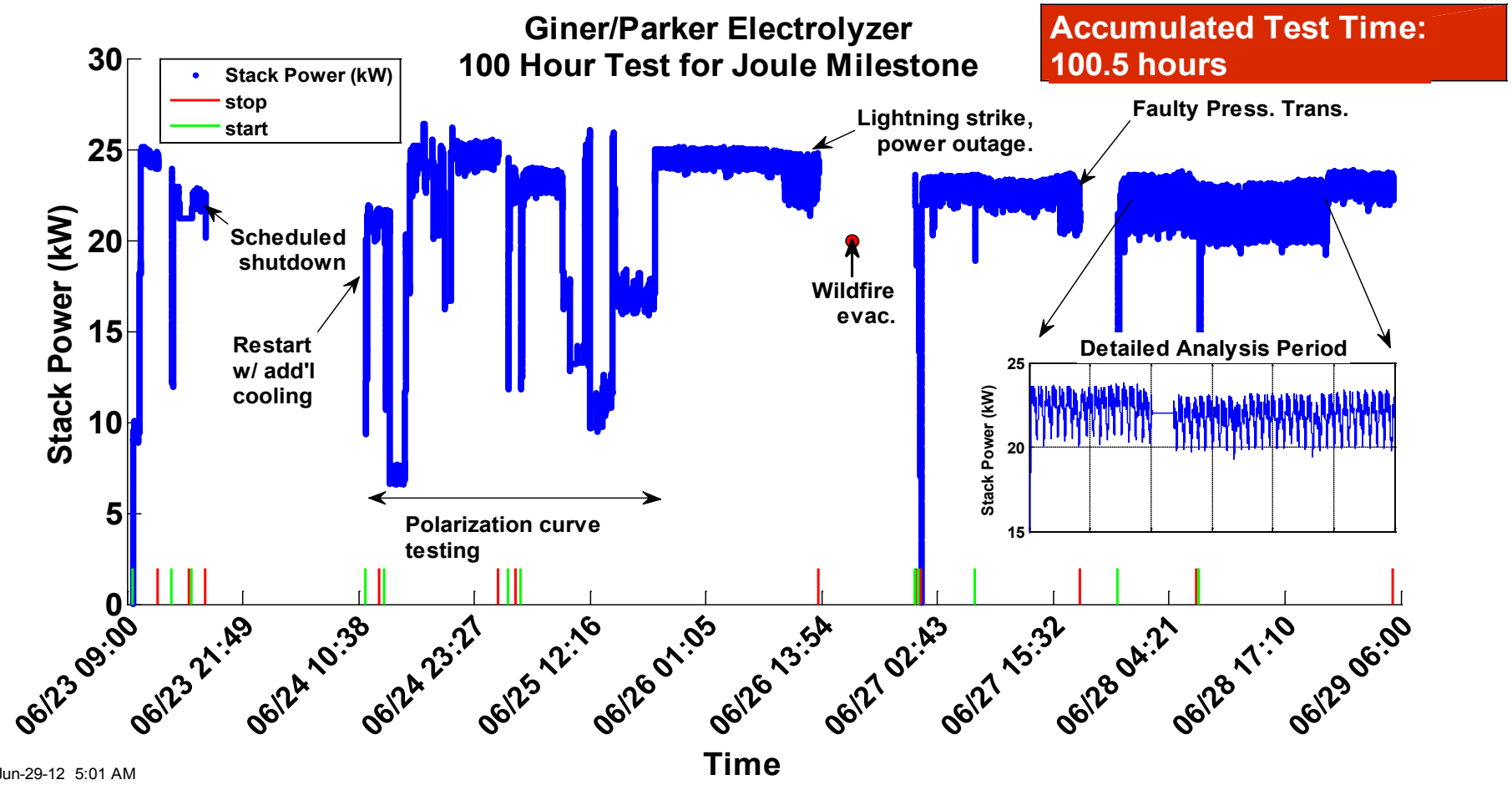
Approach– Gather 200 hours of data to verify against DOE stack and system efficiency targets.

System was instrumented to monitor;

- Stack DC Current
- Stack DC Voltage
- Stack in/output water Temperature
- AC input Voltage
- AC input Current
- AC input Power (calculated)
- Hydrogen production using NREL designed and built mass flow device

FY12 EE-1 Joule Milestone

Technical Accomplishment: June 2012 – Complete 100 hours of field testing of a prototype PEM electrolyzer system with the potential to provide 12 kg per day at 300 psig



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System Efficiency

Production & Losses	Units	Giner Prediction 1500 mA/cm²	NREL DATA* 1600* mA/cm²
Stack H2-Production	kg-H_2/hr	0.445	0.468
Membrane permeation losses (-0.6%)		-0.003	-0.005
Phase-Separator (-0.14%)		-0.0006	-0.0007
H_2-Dryer (3 to 4%)		-0.018	-0.015*
Total H2-Production		**0.424**	**0.43***

Power Consumption		Units	1500 mA/cm²	1600* mA/cm²
Electrolyzer Stack		kW	**20.6**	**21.9***
DC power supply & control (assuming 94% eff.)			+1.23	**+ 4.2**
PLC Rack			0.05	0.05
Electrolyzer Water Pump			0.30	0.30
Heat exchanger fans A & B			0.05	0.05
H2 sensor circuit pump			0.12	0.12
Total Power Consumption (No Dryer)			**22.3**	**26.22**
H_2-Dryer	Chiller (1.4kW Max)		0.46	0.52
	Heaters A & B		0.07	0.07
Total Power Consumption (w/Dryer)			**22.9**	**27.9***

Overall Efficiencies	Units	1500 mA/cm²	1600* mA/cm²
Electrolyzer Stack (includes permeation)	kWh/kg	**46.6**	**46.7**
System (No Dryer)		**50.5**	**60.9**
System (w/Dryer)		**54.0**	**64.8***

Stack Current Density Operating Range: 1300 - 1800 mA/cm²

H_2-Dryer Losses: 3.4%

Near Theoretical Calc. of 0.44 kg-H_2/hr

Off-the-shelf Power Supply Efficiency was Low

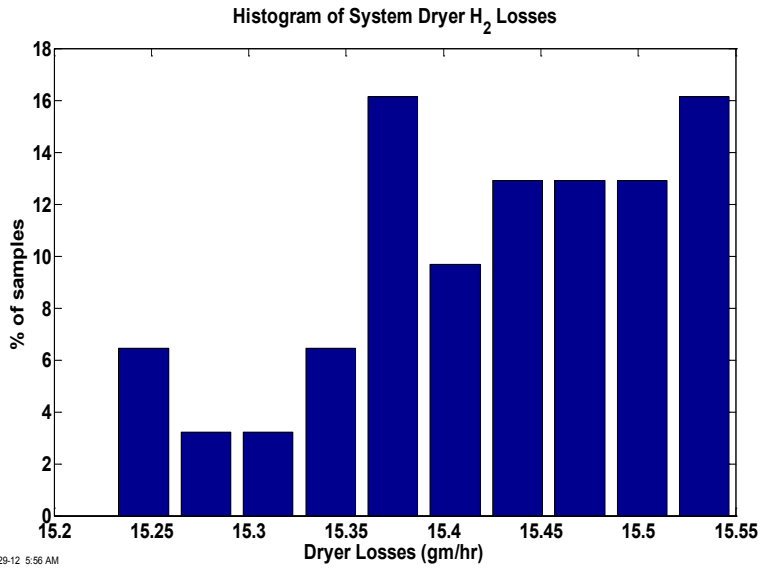
Includes 0.7kW for Safety Ventilation Fans (+0.7kW or 1.6 kWh/kg)

~10 kWh/kg loss due to power supply

System Efficiency – Drying Losses

Technical Accomplishment: NREL validated hydrogen losses from the electrolyzer dryer system

- Mass flow sensor: 11 – 12 grams/hr (In question)
- Volumetric: 15.2 – 15.6 grams/hr (reliable)
- Volumetric results better than predicted by Giner 18 grams/hr

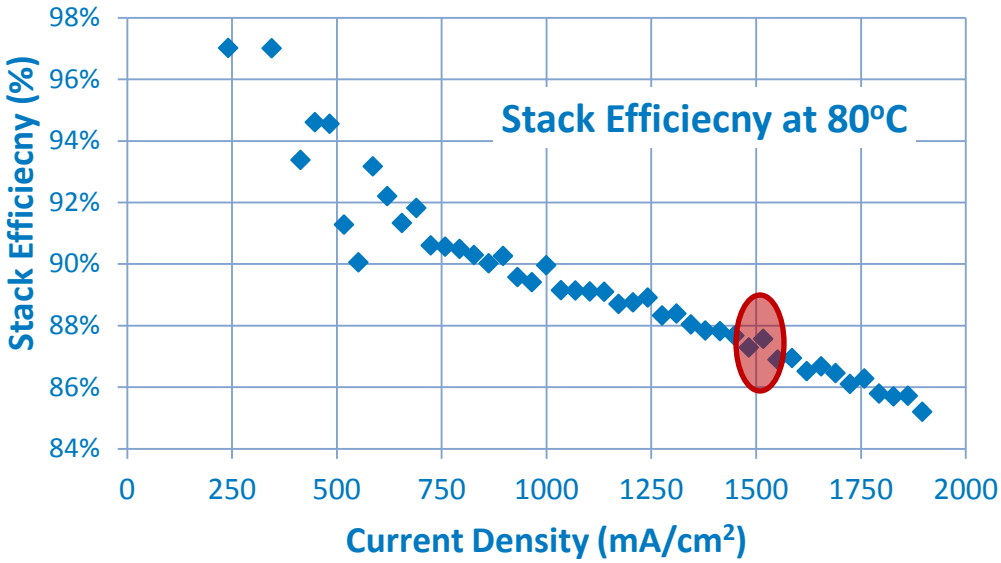


Stack Efficiency Details

Efficiencies on track to achieve DOE Targets (2012 MYRDD)

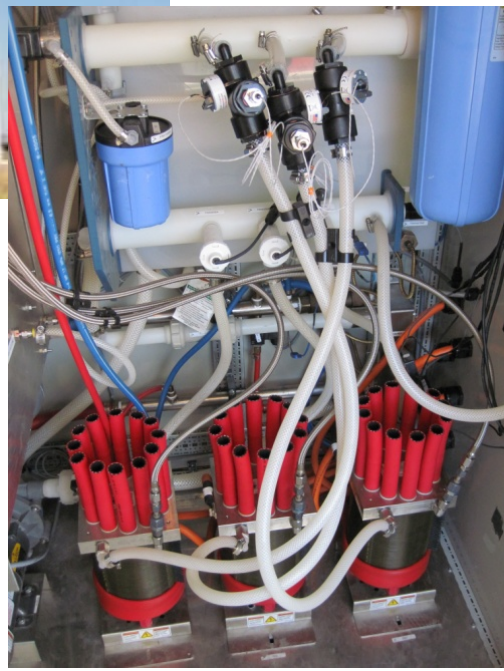
	2011 Status	2015 Target	NREL Data	
Stack	74	76	**73.6**	% LHV

- Stack current density range: 1300 – 1800 mA/cm²
- Cell voltage (avg): 1.757V @ 1500 mA/cm² (80°C)
- High Stack voltage efficiency
  - 87% HHV (**73.6% LHV**) @ 1500 mA/cm²
- Operating pressure: 390 psig



PEM Electrolyzer Stack Test Bed

Technical Accomplishment: Determined the impact of operating stacks with wind power



Proton Onsite (CRADA) – ~50 kW, 13 kg/day PEM electrolyzer on loan from U.S. Army

- **System installed at the Xcel Energy/NREL Wind-to-Hydrogen project**

PEM Electrolyzer Stack Test Bed

FY12 Technical Accomplishment: Instrumented Proton H-Series and took control of AC/DC power supplies to operate stacks in variable power mode

Monitoring

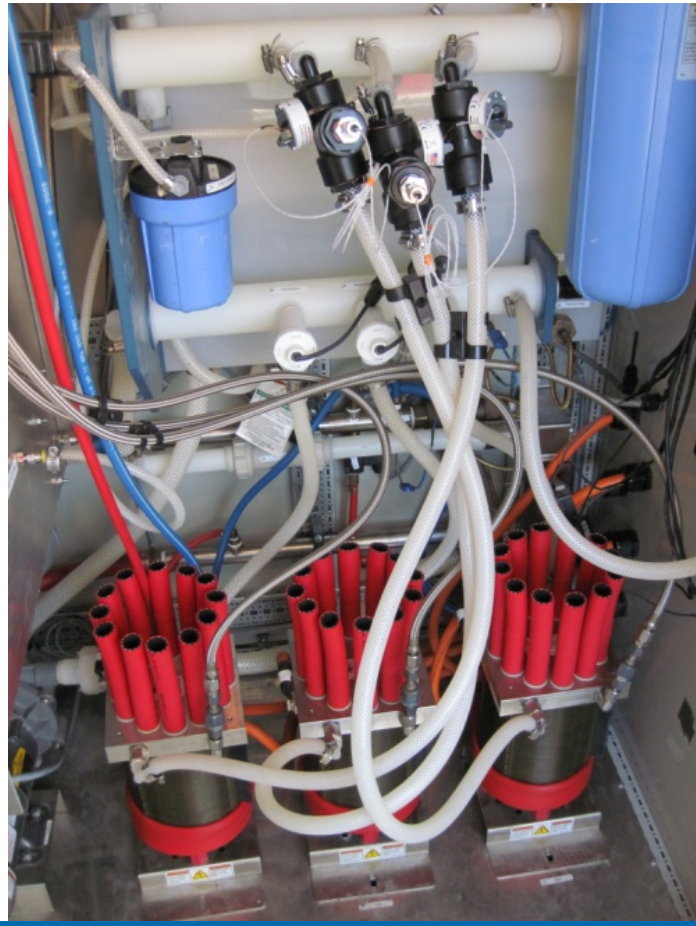
- Stack input and output temperature
- Stack voltage and current

Control

- Individual control over each of 3 stacks
- Programmable wind/solar profiles

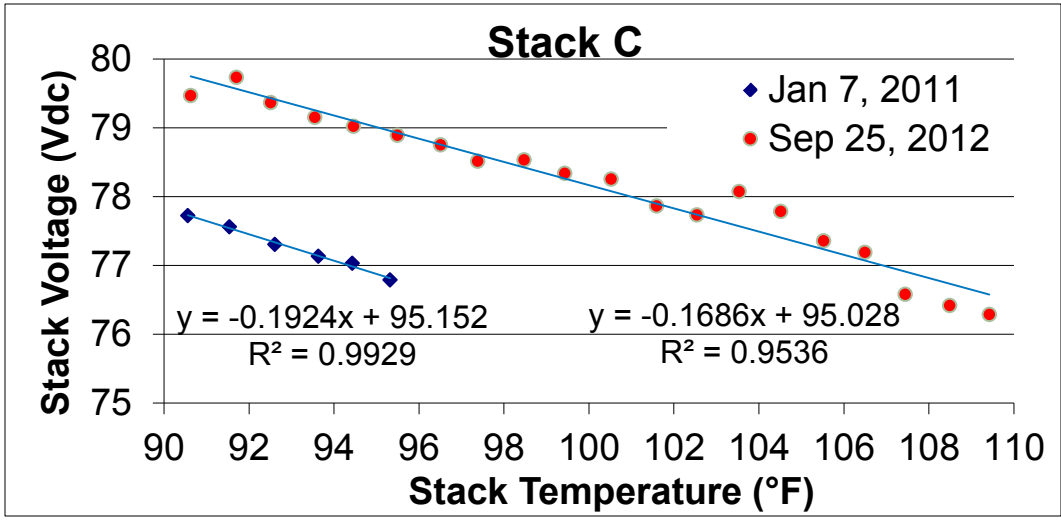
Benefits

- Stacks see same;
  - Ambient and input water temperature
  - Water quality
  - Cooling water cycles



Electrolyzer Life-Cycle Costs

Technical Accomplishment: 7500 hours of variable power operation – First stack decay rate showing signs of failure.



Stack Operating Mode	Decay Rate (µV/cell-hr)	Equation	Stack Voltage (104°F)	Test Period Hours
Variable	16.7	y = -0.1575x + 94.33	77.95	7538
		y = -0.1849x + 100.01	80.78	
Variable	9.7	y = -0.1691x + 93.298	75.71	7538
		y = -0.1546x + 93.08	77.00	
Constant	9.2	y = -0.1594x + 92.922	76.34	7538
		y = -0.1686x + 95.028	77.49	

Electrolyzer Life-Cycle Costs

Result: The storage without hydration and vintage of stacks has led to reduced life of these stacks

- Stack A failed shortly after 7500 hr test
- Stack B failed shortly after this additional 2500 hr
- Stack C hasn't failed but…

Stack Operating Mode	Decay Rate (µV/cell-hr)	Date	Equation	Stack Voltage (104°F)	Test Period Hours
Failed	**N/A**	7/25/2012	y = -0.1849x + 100.01	80.8	N/A
		N/A	N/A	N/A	
Constant	**240**	7/25/2012	y = -0.1546x + 93.08	77.0	2476
		3/21/2013	y = 0.7885x + 15.219	97.2	
Variable	**132**	7/25/2012	y = -0.1686x + 95.028	77.5	2476
		3/21/2013	y = 0.0088x + 87.686	88.6	

Collaborations

Formal

- Proton Onsite (CRADA) – Electrolyzer stack durability testing
- MAETEC (NCAP) – Preparing to test electrolyzer
- PDC Machines (CRADA) – Compressor reliability testing
- Xcel Energy (CRADA) – Wind-to-Hydrogen demonstration project since 2005

Information Sharing

- University of North Dakota/Energy & Environmental Research Center
- Worldwide electrolyzer and hydrogen component manufacturers

International

- ADvanced ELectrolyzer (ADEL) Workshop – (Foreign Payment)
- Risø-DTU (Denmark) – Modeling and experimental verification of enhanced energy storage systems

Future Work – RD&D Challenges

Analysis

- Analyze benefits of novel drying system to inform experimental device
- Analyze electrolyzer operation under variable wind power to take advantage of time-of-day electricity pricing

Experimental

- Develop prototype hydrogen drying system to improve electrolyzer system efficiency
  - Reduce drying system to achieve < 3% drying losses in a variable wind power mode of operation
- Long-duration testing of three (3) PEM electrolyzer stacks
  - 6000 hours, variable wind profile, stack decay
- Commission and operate prototype Giner electrolyzer at ESIF
  - Improve system design to enable long-duration operation

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:

- Verified stack and system efficiency of DOE-awarded system from Giner
  - Stack 73.6 % LHV
  - System 64.8 kWh/kg (~ 10 kWh/kg attributed to low power supply efficiency)
- Completed 10,000 hours of variable wind-profile stack testing
  - Compared voltage decay rates of steady-state and variable stack current operation
  - New stacks to be supplied from Proton

Collaborations: Two new CRADA's in 2013. Verification stack and system performance. Disseminating results to industry and stakeholders worldwide.

Proposed Future Research (Analysis/Experimental):

- Analyze time-of-day pricing scenario to reduce cost of hydrogen
- Novel drying approach to increase system efficiency
- Long-duration testing of new stacks from Proton under wind-profile mode
- Improve Giner system to enable extended operation at ESIF