# 2013 DOE Hydrogen and Fuel Cells Program Review

## Renewable Electrolysis Integrated System Development & Testing

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**Project ID: PD031**

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# Overview

## Timeline

Project start date: Sep. 2003

Project end date: Oct. 2013*

## Budget

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

## Barriers (2012 MYRDD)

G. System Efficiency

I. Grid Electricity Emissions (Distributed)

J. Renewable Electricity Generation Integration (Central)

L. Operations and Maintenance

## 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 | $/kg<br>$/kW | 0.70<br>430 [e, f] | 0.50<br>300 [f] | 0.50<br>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] |

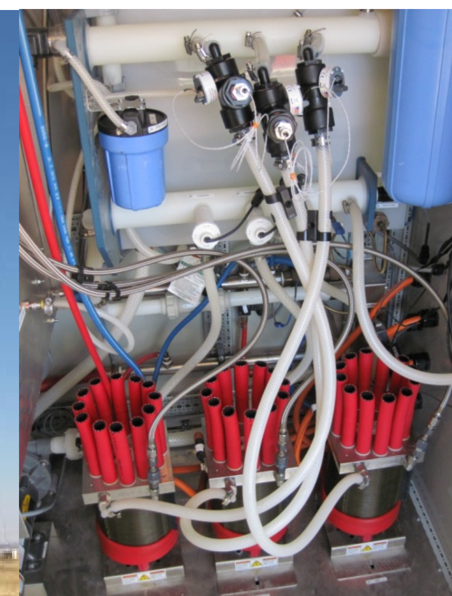
# Technical Accomplishments

## 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

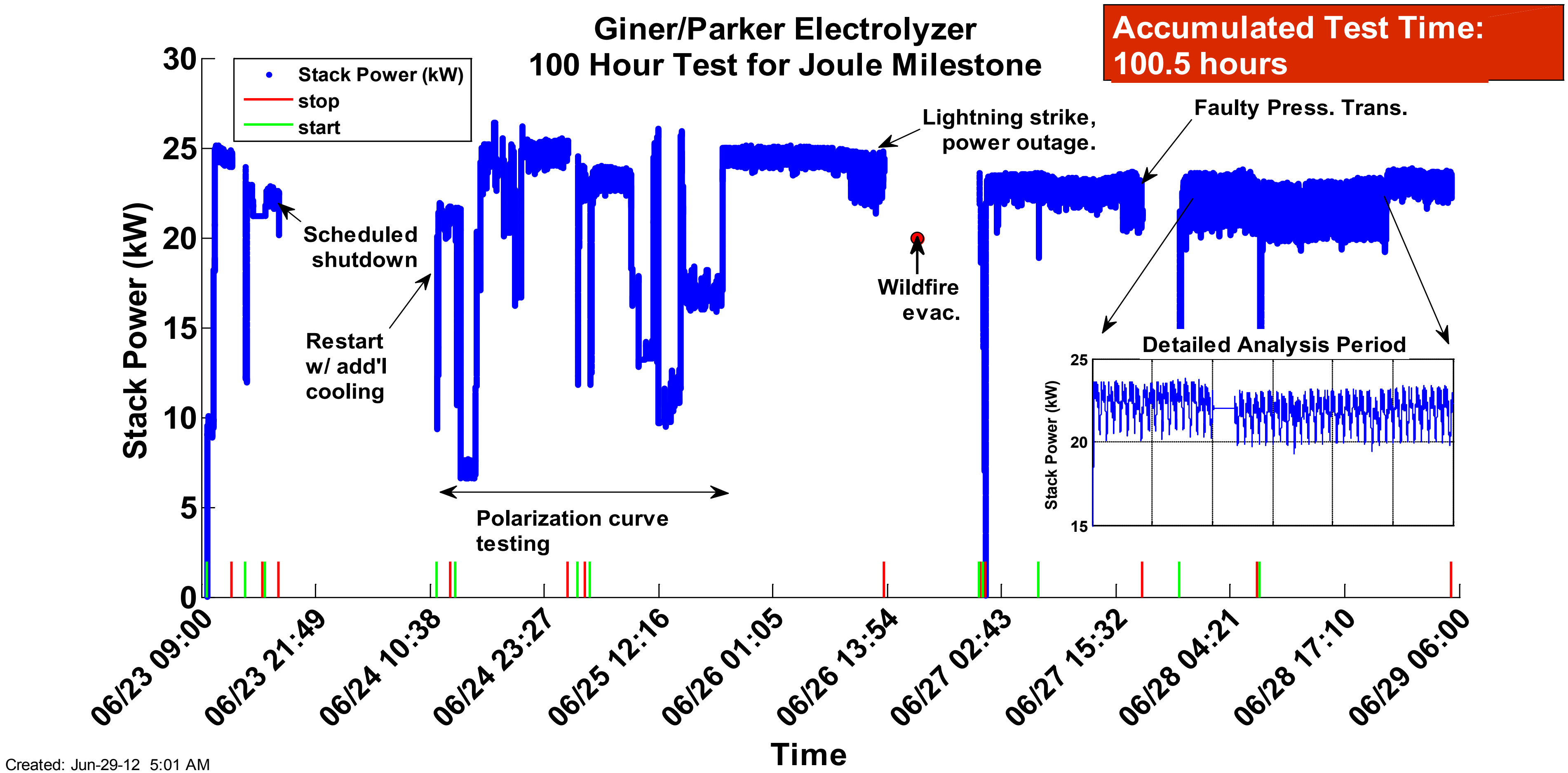
**Approach– Gather 200 hours of data to verify against DOE stack and system efficiency targets.**

## 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



# System Efficiency

| Production & Losses | Units | Giner Prediction 1500 mA/cm² | NREL DATA* 1600* mA/cm² |
|---|---|---|---|
| Stack H2-Production | $kg\text{-}H_2/hr$ | 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 $kg\text{-}H_2/hr$**

**Off-the-shelf Power Supply Efficiency was Low**

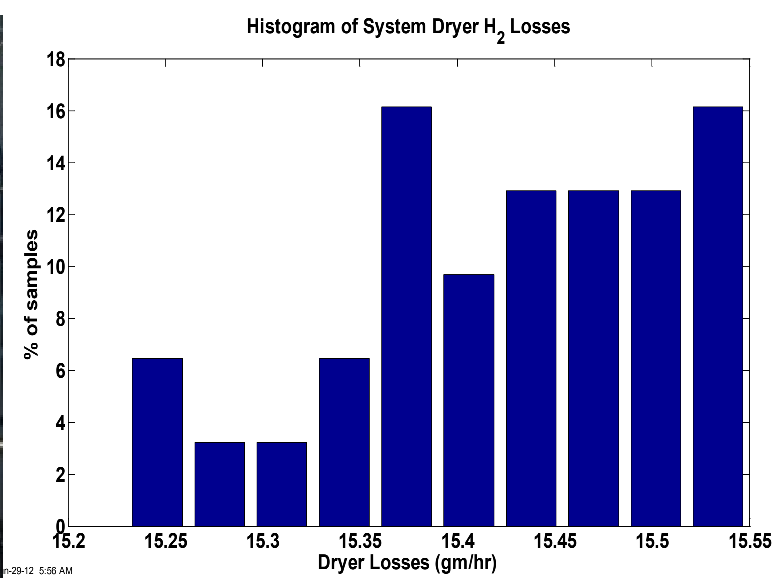
**Includes 0.7kW for Safety Ventilation Fans (+0.7kW or 1.6 kWh/kg)**

**~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

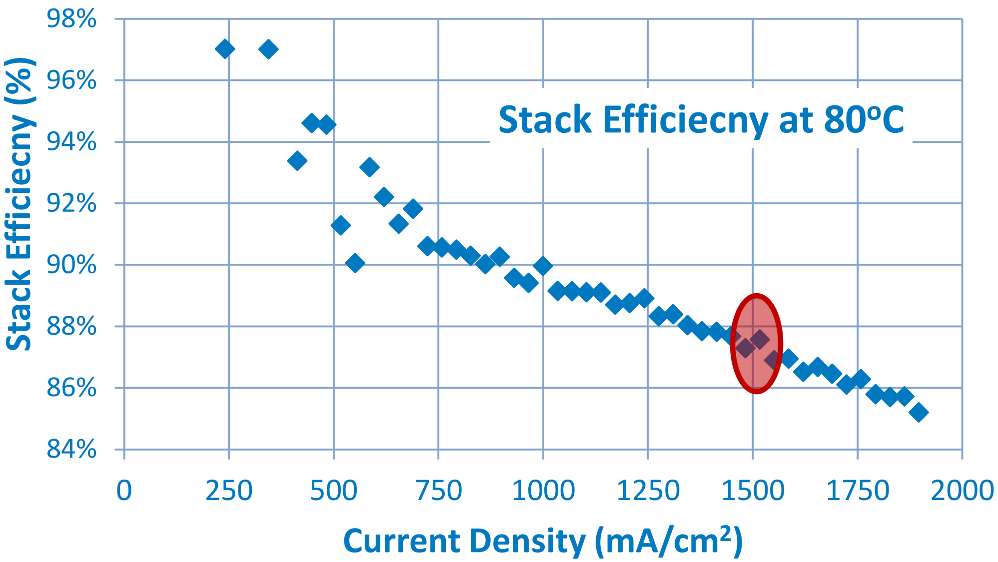



# Stack Efficiency Details

## Efficiencies on track to achieve DOE Targets (2012 MYRDD)

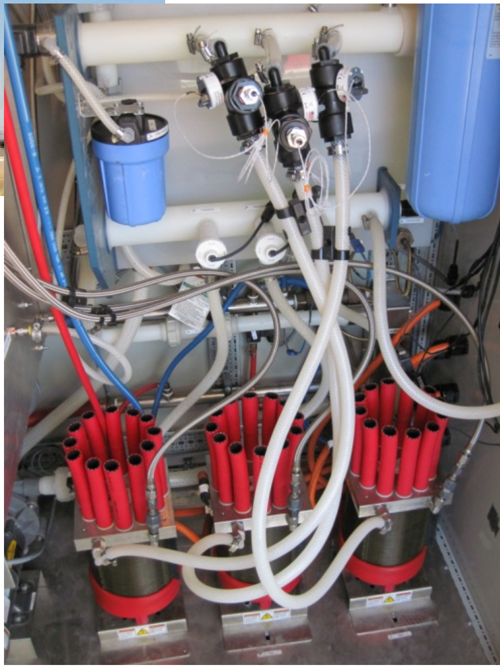
| | 2011 Status | 2015 Target | NREL Data | |
|---|---|---|---|---|
| Stack | 74 | 76 | **73.6** | % LHV |

- Stack current density range: 1300 – 1800 $mA/cm^2$
- Cell voltage (avg): 1.757V @ 1500 $mA/cm^2$ (80°C)
- High Stack voltage efficiency
  - 87% HHV (**73.6% LHV**) @ 1500 $mA/cm^2$
- 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

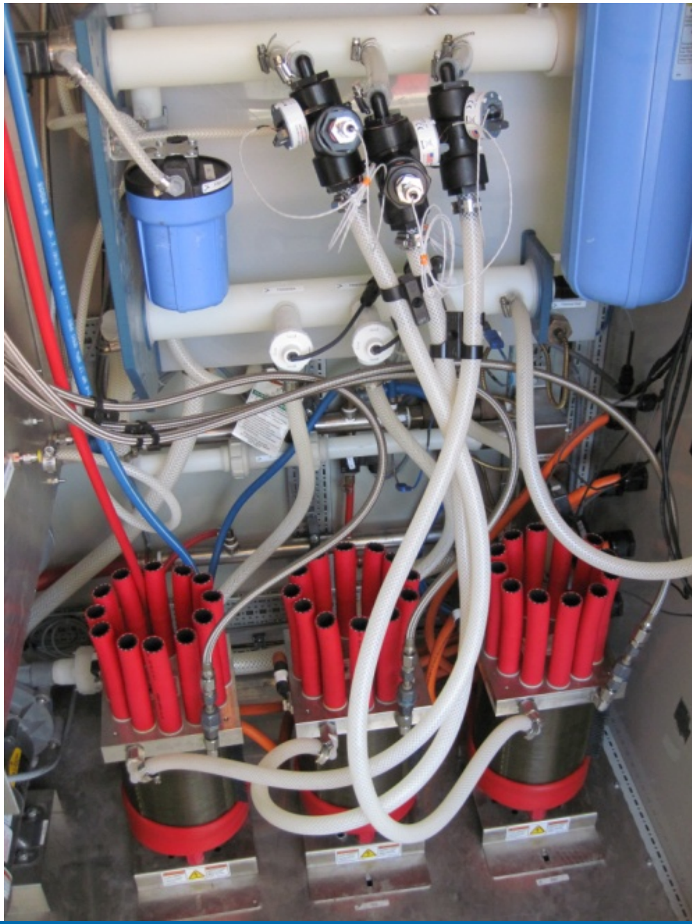
- Stack input and output temperature
- Stack voltage and current

## Control

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

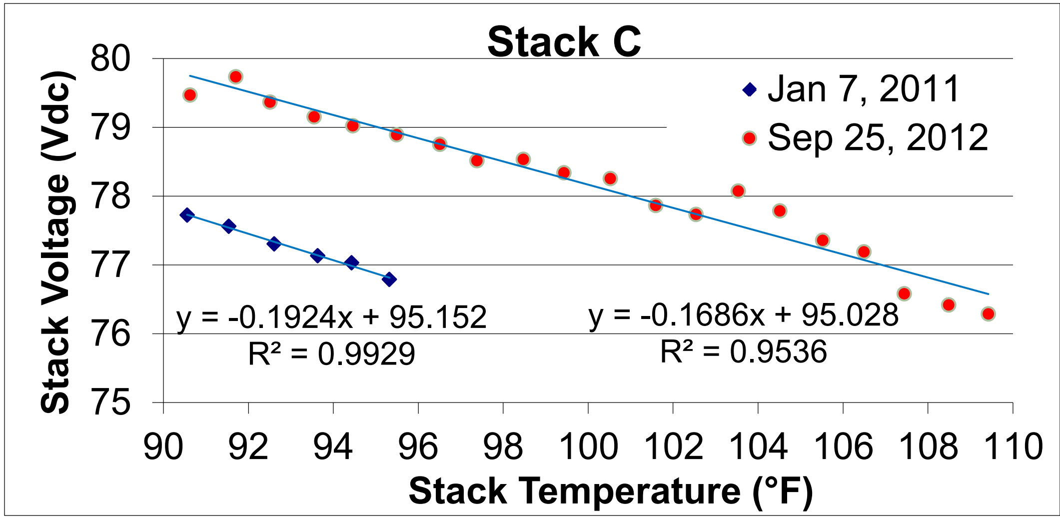
## Benefits

- 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