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>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2016 Target</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Levelized Cost$^d$ (Production Only)</td>
<td>$/kg$</td>
<td>4.20$^d$</td>
<td>3.90$^d$</td>
<td>2.30$^d$</td>
</tr>
<tr>
<td>Electrolyzer System Capital Cost</td>
<td>$/kg$</td>
<td>0.70</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>$/kW$</td>
<td>430$^{a,f}$</td>
<td>300$^f$</td>
<td>300$^f$</td>
</tr>
<tr>
<td>System Energy Efficiency$^g$</td>
<td>% (LHV)</td>
<td>67</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>kWh/kg</td>
<td>50</td>
<td>46</td>
<td>44</td>
</tr>
<tr>
<td>Stack Energy Efficiency$^h$</td>
<td>% (LHV)</td>
<td>74</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>kWh/kg</td>
<td>45</td>
<td>44</td>
<td>43</td>
</tr>
<tr>
<td>Electricity Price</td>
<td>$/kWh</td>
<td>From AEO 2009$^j$</td>
<td>From AEO 2009$^j$</td>
<td>0.037$^j$</td>
</tr>
</tbody>
</table>
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
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

Giner/Parker Electrolyzer
100 Hour Test for Joule Milestone

Accumulated Test Time: 100.5 hours

Scheduled shutdown
Restart w/ add'l cooling
Lightning strike, power outage.
Wildfire evac.
Faulty Press. Trans.
Detailed Analysis Period
# System Efficiency

## Production & Losses

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>1500 mA/cm²</th>
<th>1600* mA/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stack H2-Production</td>
<td>kg-H₂/hr</td>
<td>0.445</td>
<td>0.468</td>
</tr>
<tr>
<td>Membrane permeation losses (-0.6%)</td>
<td></td>
<td>-0.003</td>
<td>-0.005</td>
</tr>
<tr>
<td>Phase-Seperator (-0.14%)</td>
<td></td>
<td>-0.0006</td>
<td>-0.0007</td>
</tr>
<tr>
<td>H₂-Dryer (3 to 4%)</td>
<td></td>
<td>-0.018</td>
<td>-0.015*</td>
</tr>
<tr>
<td>Total H2-Production</td>
<td></td>
<td>0.424</td>
<td>0.43*</td>
</tr>
</tbody>
</table>

## Power Consumption

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

## Overall Efficiencies

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>1500 mA/cm²</th>
<th>1600* mA/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer Stack (includes permeation)</td>
<td>kWh/kg</td>
<td>46.6</td>
<td>46.7</td>
</tr>
<tr>
<td>System ( No Dryer)</td>
<td>50.5</td>
<td>60.9</td>
<td></td>
</tr>
<tr>
<td>System ( w/Dryer)</td>
<td>54.0</td>
<td>64.8*</td>
<td></td>
</tr>
</tbody>
</table>
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)

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2015</th>
</tr>
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<tbody>
<tr>
<td>Status</td>
<td>74</td>
<td>76</td>
</tr>
<tr>
<td>Target</td>
<td></td>
<td></td>
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</tbody>
</table>

NREL Data

Stack

- 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.

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

Graph showing data points for two test periods: Jan 7, 2011 and Sep 25, 2012.
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...

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