Characterizing Electrolyzer Performance for Use in Wind Energy Applications

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Presented at the American Wind Energy Association’s (AWEA) WINDPOWER Annual Conference in Pittsburgh, Pennsylvania, June 4-7, 2006.

NREL/PR-560-40100
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Presentation Outline

• Background
• Characterization, Testing and Modeling
• Economic Analysis
• Large-scale R&D
The “Solar and Wind Technologies for Hydrogen Production” report was submitted to Congress as required by Section 812 of the 2005 Energy Policy Act.

The report shows that wind and solar energy sources for producing hydrogen are present in many parts of the country.

The report is available at www.hydrogen.energy.gov/congress_reports.html.
Definition:
A Gallon of Gasoline vs. a Kilogram of Hydrogen

- Gasoline
  - 108,000 – 123,500 BTU/gal
- Hydrogen
  - 116,000 BTU/kg
- 1 kilogram of hydrogen ≈ 1 gallon of gasoline
- One caveat, if fuel cells are twice as efficient as gasoline internal combustion engines then only half the amount of hydrogen would be needed
  - Twice the mileage with hydrogen
How to produce hydrogen RE? Electrolysis.

Focus of this research is on renewable H$_2$ production because it is the only way (today) to produce the gas without emissions.
Electricity Costs are Key

Hydrogen costs via electrolysis with electricity costs only

DOE: $2.00 - 3.00 kg$^{-1}$ delivered, untaxed, 2005$ by 2015
Technology Characteristics

• **Alkaline**
  - Cheaper catalyst (Ni v. Pt)
  - Low current density (↑ efficiency)
  - Largest system < $10^3 \, \text{kW}^{-1}$

• **PEM**
  - Pure water input requires $H_2O$ vapor removal
  - Higher differential output pressure
  - Solid (not corrosive) electrolyte
  - $10^3 – 10^4 \, \text{kW}^{-1}$

• **Solid Oxide**
  - R&D
Characterization Testing and Protocol Development

• Completed initial characterization of 6 kW PEM electrolyzer for power electronics design

• Completed testing with simulated PV and wind using power supplies

• Completed testing with 5 kW PV array

• Continued testing with 10 kW wind turbine
Electrolyzer Requirements

- Ideally ~1.2 V cell$^{-1}$ → $f(I,T,P)$
- Practical cells ~ 2.0 – 2.5 V cell$^{-1}$
- N series-connected cells $\uparrow$ V

System Efficiency:

$$\text{System Efficiency} = \frac{\text{HHV} \left( \frac{\text{kWh}}{\text{kg}} \right) \left( \frac{\text{kWh}}{\text{kWh}} \right)}{\left( \frac{\text{Stack Input Energy}(\text{kWh})}{\text{Power Supply Efficiency}} \right) + \text{Ancillary Losses}(\text{kWh}) \div \text{Hydrogen Produced}(\text{kg})}$$

Stack Efficiency:

$$\text{Stack Efficiency} = \frac{\text{Ideal Stack Potential}}{\text{Actual Stack Potential}}$$
System Integration and Component Development

Completed Power Electronic Interface Modifications

10 kW Bergey Excel

Modified VCS-10

Step Down Transformer

40 VDC Battery Bank

Half-bridge Controlled SCR Bridge

ELECTROLYZER

40 VDC
Variable Input Power

- Wind energy to stack and PV to DC/DC converter

- Programmable power supplies to vary input power to stack
Monitor Performance

- Stack and system energy
- Hydrogen pressure, flow and quality
- Water temp., flow and quality

- Impacts on grid (pf, THD)
Modeling

- IV data and electrochemistry to extract stack characteristics

\[
E = 1.20 + \frac{RT(I)}{F} \left\{ \text{Sin}^{-1} \left( \frac{j}{2c_1} \right) + \text{Sin}^{-1} \left( \frac{j}{2c_2} \right) \right\} + \frac{\phi}{c_3} j
\]

(12)

\[c_1 = j_{A,o} = 1.65 \times 10^{-8}\]

(13)

\[c_2 = j_{C,o} = 0.09\]

(14)

\[c_3 = \sigma = 0.075\]

(15)
Analysis of Performance

- System efficiency of PEM system at various levels of current and temperature
Economic Analysis Purpose

Hydrogen Production

– How much does it cost to produce hydrogen for use as a transportation fuel?
– System uses wind electricity to produce hydrogen for transportation purposes
– Results in $/kg of hydrogen
– Whether wind at site can compete with distributed H₂ production
Case 1: Hydrogen Production at the Wind Site

Vestas V82 turbine
- 1.65 MW
Evaluated two wind sites
- Minnesota WROC Site
- Gobblers’ Knob

- Electrolyzer
  - Produces hydrogen whenever the turbine produces electricity, except during peak electricity demand hours

Hydrogen delivery costs are not included

Electricity → Electrolyzer → Hydrogen
Case 2: Distributed Hydrogen Production Using Xcel Aggregate Wind Power

Lamar

Peetz

Ponnequin

Xcel Aggregate Wind

Wind Sites

Grid

Signal

Electrolyzer

Must meet a filling station demand

Hydrogen for transportation fuel use

Hydrogen Storage Tanks

Hydrogen Fueling Station

Hydrogen
Model Results

- Good wind resource is a key to producing low price hydrogen
  - 12-16% price reduction in hydrogen production
- Production at the wind site makes fiscal sense if cost reductions offset delivery cost
- Cost reductions and efficiency improvements must be obtained by electrolyzer manufacturers to obtain low price hydrogen
- If aggregate wind electricity is available at the filling station for $0.038/kWh, the potential exists for hydrogen production, compression and storage from wind below the DOE cost target of $2-3/kg delivered

∴ Xcel Decides Go!

National Renewable Energy Laboratory
Project Objectives

This project examines the issues with using renewable energy to produce hydrogen by electrolyzing water:

- Characterize electrolyzer performance under variable input power conditions
- Design and develop shared power electronics packages and controllers to reduce cost and optimize system performance and identify opportunities for system cost reduction through breakthroughs in component integration
- Test, evaluate and optimize the renewable electrolysis system performance for both
  - Dedicated hydrogen production
  - Electricity/hydrogen cogeneration
Wind2H2E Wind Testing Configurations

- Northern Power Systems 100 kW WT
- DC BUS
- Excess AC Power
- DC-DC Converters
- H₂ Storage 3,500 PSI
- H₂ Output
- Hydrogen IC Engine/Generset 60kW
- AC Power
- Utility Grid
- (Future) H₂ Filling Station

*Image of a wind turbine, DC-DC converters, H₂ compression, H₂ output, H₂ storage, and a hybrid vehicle.*
Wind2H2E Grid Testing Configurations

Utility Grid

AC Power

Proton Energy HOGEN 40RE

H₂ Compression

H₂ Output

H₂ Storage 3,500 PSI

AC Power

Teledyne HM-100

Hydrogen IC Engine/ Genset 60kW

(Future) H₂ Filling Station

National Renewable Energy Laboratory
Acknowledgements and References

• Thanks to:
  – Johanna Levene, Ben Kroposki, Bill Kramer and Chris Pink
  – Peter Lilienthal and Tom Lambert for HOMER development and enhancements
  – H2A team for hydrogen equipment assumptions
  – Team of Xcel, NREL, EPRI and John Cornish
  – Specifically Frank Novachek and Vicki McCarl of Xcel Energy for their invaluable assistance and support during this project.

• References:
  – www.nrel.gov/homer
  – WindPower paper and presentation, An Economic Analysis of Hydrogen Production from Wind
  – www.hydrogen.energy.gov/h2a_analysis.html
Backup Slides
### Key Common Assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
</table>
| Electrolyzer               | • Costs are assumed to be $740/kW, $400/kW, and $300/kW in near, mid and long term  
                            • Electrolyzer and compression efficiencies are 70, 78 and 83% (based on 39 kWh/kg HHV) in short, mid and long term  
                            • Uses AC power                                                                                                                                 |
| Compressor                 | • $600,000, $300,000 and $100,000 for a 1500 kg compressor in near, mid and long term  
                            • Includes compressor energy requirements of 2.09 kWh/kg                                                                                                                                               |
| Annual Real Interest Rate  | • Discount rate used to convert between one-time costs and annualized costs  
                            • Study uses 10%                                                                                                                                                                                      |
| Hydrogen Dispensing        | • No hydrogen dispensing costs included                                                                                                                                                                    |

Detailed assumptions are available in Appendix A of Power-Gen paper.
## Key Common Assumptions (cont…)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Electricity</td>
<td>• Peak electricity usage is from 4-7 p.m. on weekdays, so no hydrogen can be produced during those three hours</td>
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<td></td>
<td>• There are no peak hours during the weekend, so electrolyzer can run 24 hours a day</td>
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<tr>
<td>System Pressure</td>
<td>• Hydrogen is compressed after production to 6500 psi</td>
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<tr>
<td></td>
<td>• Storage is provided at 6500 psi</td>
</tr>
<tr>
<td>Wind Turbine Capital and Operating</td>
<td>• Turbine costs are not specifically used in analyses, rather the cost of wind generated electricity is used</td>
</tr>
<tr>
<td>Costs</td>
<td>• Assumes this cost includes capital, replacement and operating costs of the wind turbines</td>
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<tr>
<td></td>
<td>• Xcel Energy purchases wind generated electricity at a rate of $0.038/kWh</td>
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Detailed assumptions are available in Appendix A of Power-Gen paper
## Wind2H2E Project Features

<table>
<thead>
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<th>Feature</th>
<th>Importance</th>
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<tbody>
<tr>
<td>Direct DC feed to electrolyzer</td>
<td>Grid connected and isolated wind farm simulations, system efficiency gains &amp; future control system integration capital cost reductions</td>
</tr>
<tr>
<td>Concurrent AC feed to electrolyzer</td>
<td>Permits clear comparison to direct DC feed performance</td>
</tr>
<tr>
<td>Multiple commercial electrolyzers</td>
<td>Grid connected and isolated wind farm simulations and reduced operability risk, and system efficiency gains</td>
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<tr>
<td>Medium pressure range compression and storage</td>
<td>Reduced operability risk, reduced cost to compress hydrogen &amp; improved reliability</td>
</tr>
<tr>
<td>Hydrogen ICE generator set</td>
<td>H₂ or H₂/NG mixed fuel option</td>
</tr>
<tr>
<td>Initial siting at NREL controlled facility</td>
<td>World class R&amp;D practices and opportunity to learn H₂ handling practices from experienced practitioners</td>
</tr>
<tr>
<td>System transportability for redeployment</td>
<td>Utility value after R&amp;D testing</td>
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Analysis Tool

• The HOMER® Model was developed at NREL to allow users to optimize electric systems and make it easier to evaluate the many possible system configurations
  – Hydrogen added in 2004, enhanced in 2005

The Problem:
Case 2: You are trying to meet a hydrogen load (shown to the left)
  - How much electricity can aggregate grid provide?
  - Should you add more electrolyzers, or more storage to meet demand?
  - How much does the hydrogen cost?