II.B.4 Renewable Electrolysis Integrated System Development and Testing

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- Spectrum Automation, Denver, CO
- Polyphotonics, Rochester, NY

Project Start Date: September, 2003
Project End Date: October, 2009

Objectives

- Work closely with industry to provide independent testing, validation, and feedback of system performance, potential areas for improvement with regard to integrating renewable sources and advanced hardware, and control strategies.
- Quantify system-level efficiency improvements and cost reductions by designing, building, and integrating dedicated wind- and photovoltaic (PV)-to-electrolyzer stack power electronics to enable closer coupling of renewably-generated electricity and electrolyzer stack.
- Model, simulate, and optimize the renewable electrolysis system performance for dedicated hydrogen production and electricity/hydrogen cogeneration.
- Characterize and determine system impacts on commercial electrolyzer technology to accommodate the varying energy input from wind turbines and photovoltaics coupled directly to the hydrogen-producing electrolyzer stack.
- Explore system-level integration issues surrounding multiple electrolyzers of polymer electrolyte membrane (PEM) and alkaline technologies to gauge their efficiencies, responsiveness, and performance to varying renewable energy sources.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(G) Capital Cost
(H) System Efficiency
(I) Grid Electricity Emissions (for distributed)
(J) Renewable Electricity Generation Integration (for central)

Technical Targets

By addressing the technical barriers of integration with renewable energy sources, this project works to achieve the DOE cost targets for distributed and central electrolytic hydrogen production. One of the primary objectives of this work includes the development of integrated power electronics and control theory to couple renewable energy sources with the electrolyzer stack. This work can reduce the capital cost and improve the efficiency to 81% (higher heating value, HHV) of the renewable electrolysis system by 2012.

Distributed Electrolysis

- By 2012, reduce the cost of distributed production of hydrogen from distributed electrolysis to $3.70/gasoline gallon equivalent (gge) of H_2 (delivered) at the pump.

Central Electrolysis

- By 2012, reduce the capital cost of wind-coupled electrolyzer system to $350/kW.
- By 2012, reduce the cost of central production of hydrogen from wind electrolysis to $3.10/gge of H_2 at the plant gate ($4.80/gge delivered).

The 2012 electrolyzer capital costs assume a 12.5% savings on a standard H2A assumption for an advanced electrolyzer cost of $400/kW [1].

Accomplishments

- Designed, built, and tested direct current (DC)/DC power converter with maximum power point tracking (MPPT), which enables comparison of PV direct-connected and other configurations utilizing power electronics with MPPT.

- Provided independent verification of stack efficiency towards the Department of Energy's Joule Milestone EE GG 1.1.01.1. The electrolyzer module (EM), from Giner Electrochemical Systems, achieved a stack voltage efficiency of 67% (HHV) with 1,000 psig H_2 output pressure.
- Conducted analysis of using hydrogen as a mechanism for energy storage for use by electric utilities to better integrate variable wind energy resources and levelize demand.
- Attained approval to conduct daily operations on the wind to hydrogen (Wind2H2) demonstration project. Baseline (grid-connected), 10 kW PV and 10 kW wind turbine sources are now being tested using NREL's power converters.

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Introduction

One issue that limits greater penetration of renewable energy sources (e.g. wind and solar) is their variable and seasonal energy production. One solution may be to produce hydrogen through water electrolysis and use that hydrogen in a fuel cell, either to fuel vehicles or to produce electricity during times of low power production or peak demand. Most electrolyzers commercially available today are designed for grid-connected operation; therefore, they incorporate power electronics to convert alternating current (AC) from the grid to DC power required by the cell stack. These power converters can represent 25% to 30% of the total cost of the electrolyzer. Power converters are also required for the renewable energy source. For example, when variable-speed wind turbines use wind energy they rely on power electronics to convert the variable frequency–variable voltage that is produced at the generator to DC. When connected to the grid, this voltage must be converted back to AC at grid frequency (60 Hz).

Approach

This project examines the design and optimization of electrolyzers, power electronics, and system components to integrate renewables and electrolyzers to improve the efficiency, cost, and robustness of these systems. Hydrogen production via electrolysis is heavily dependent on the cost of electricity. System integration research aims to reduce the cost of hydrogen production by:

- Developing and optimizing advanced controls, subsystems, and power electronics to reduce capital cost and improve system efficiency.
- Testing and validating the performance of next generation electrolyzer systems awarded under DOE contracts.
- Characterizing stack and system performance of commercially available electrolyzer systems with varying renewable energy sources.
- Analyzing energy storage to optimize the system.
- Developing models of the electrolyzer system.
- Optimizing the system for dedicated hydrogen production by stack sequencing or for combined hydrogen/electricity production.

Results

Hydrogen-Based Energy Storage Analysis

During Fiscal Year 2008, a scoping analysis was conducted using hydrogen as a mechanism for energy storage for use by electric utilities to better integrate variable wind energy resources and levelize demand. Analysis modeled three different system topologies over three timeframes, characterizing capital costs, replacement costs, operating and maintenance (O&M) costs, system efficiencies, cost of input energy, etc.

Costs used to predict a $/kWh cost for energy storage: A system consisting of electrolyzers (for hydrogen production), geologic hydrogen storage, and fuel cells (for conversion of stored hydrogen back into electricity) showed to be the most promising, with future optimized systems predicted to provide stored electricity at a cost of $0.16/kWh.

To provide the necessary energy storage to meet these presumed electrical demands, the NREL study modeled a hydrogen-based storage system consisting of electrolyzers to produce the necessary hydrogen, fuel cells to convert the hydrogen back into electricity, and hydrogen storage based on either steel tanks or underground geologic caverns. To understand how these system elements would affect the cost of electricity from hydrogen-based energy storage, the NREL study made a number of assumptions, which include predicted capital costs, replacement costs, and O&M costs for all of the subsystems, as well as fuel and electricity costs. In general, these assumptions were based on previous modeling efforts conducted by NREL and on the projections from U.S. Department of Energy hydrogen and fuel cell programs.

DC/DC Power Converter

NREL has designed, constructed, and begun testing a DC/DC power converter (Figure 1) to be utilized with the 10 kW of PV at NREL's Distributed Energy Resources Test Facility. The focus of this power converter design is to reduce cost, increase flexibility

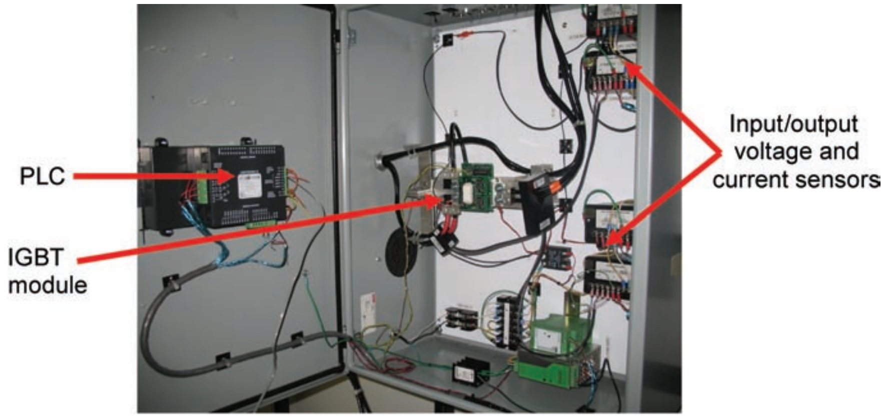

FIGURE 1. NREL's DC to DC Power Converter

of energy input, and to bring the system towards commercial viability more than previous designs utilizing unique controllers and expensive software.

An off-the-shelf programmable logic controller is interfaced with an off-the-shelf insolated gate bipolar transistor-based power electronics module to step-down the DC voltage from the PV array to that required by the electrolyzer stack. The system was designed to be low-cost and easily programmable/tuned using commercially available components. The new design will take advantage of many of the recent advances in semiconductor power electronics including higher power density and reduced thermal resistance. Closed-loop current-control to the electrolyzer stacks and MPPT of the PV array will provide improved performance and efficiency.

Integrating the stack power (I_{STACK} * V_{STACK}) for the 7-hour test period shows that it captured 24.8 kWh or 8% of the total solar insolation. The main disadvantage of running the stack directly from the PV array is the inability to track the maximum power point of the PV array (V_{MAX}, I_{MAX}) to make more efficient use of available power. It should be noted that while the stack energy needs were met with the PV array (a DC to DC coupling) the electrolyzer system also requires an average of 612 W of power from the grid to support onboard ancillary loads.

Test and Validation

The EM is designed and built by Giner Electrochemical Systems, based in Newton, Massachusetts, to demonstrate differential high-pressure (~1,000 psig) PEM electrolysis with improved stack efficiency and cost. The EM is being tested at NREL's High-Temperature Facility to provide independent verification of stack efficiency towards the Department of Energy's Joule Milestone EE GG 1.1.01.1 which states, "Complete lab-scale electrolyzer, test to determine whether it achieves 64% energy efficiency and evaluate systems capability to meet $5.50/gge hydrogen cost target, untaxed at the station, and with large equipment production volumes (e.g., 500 units/year)."

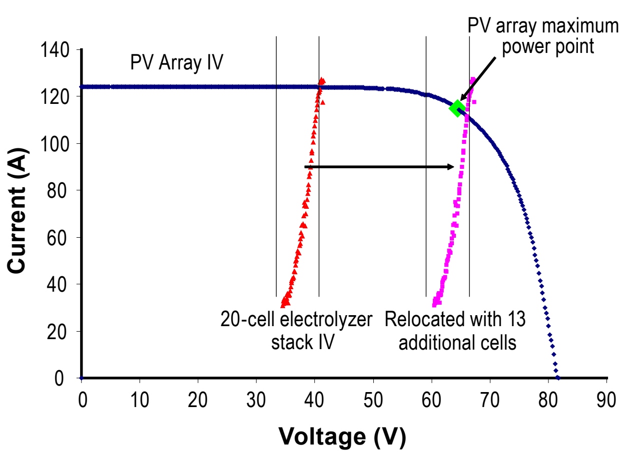

FIGURE 2. Impacts of Adding 13 Additional Electrolyzer Cells to the 20-Cell Stack

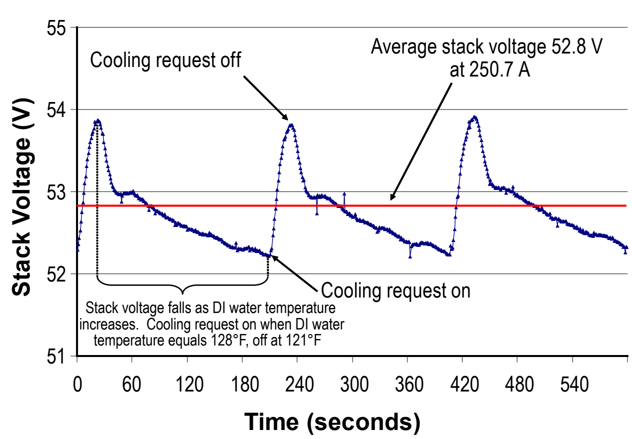

FIGURE 3. Variations in Stack Voltage due to Dionized Water Temperature Variations

The EM stack contains 23 cells connected in series. The average stack voltage was found to be 52.8 V resulting in an average cell voltage of 1.89 V (see Figures 2 and 3).

$$\text{Stack Efficiency} = \frac{\text{Ideal Stack Potential}}{\text{Actual Stack Potential}} = \frac{1.27}{1.89}(100) = 67\%$$

The EM stack is operated at a nominal 250 A_{dc} resulting in an average stack voltage of 52.8 V_{dc}. Excellent agreement of these values are found between the voltage and current transducers, hand-held meters, and the EM internal monitoring. The stack voltage efficiency was determined to be 67% (HHV) or 56% (lower heating value, LHV) when the pressure and temperature compensated Nernst potential equal to 1.27 V/cell (HHV) or 1.05 V/cell (LHV) (50.8°C, 65 atm) was divided by the actual cell voltage 1.89 V.

Conclusions and Future Directions

The project is relevant to the DOE targets by addressing capital cost, efficiency, and renewable energy source integration to reduce the cost per kg of H_2. The approach includes demonstrating advanced controls, system-level improvements, and integration of renewable energy sources to commercially available electrolyzer stacks via NREL-designed-and-built power electronic controllers. The technical accomplishments include:

- Verified stack voltage efficiency 67% (HHV) or 56% (LHV) of high-pressure (1,000 psig) hydrogen output electrolyzer to help meet DOE Joule milestone.
- Integrated wind and PV functionality into power electronics modules coupled directly to the hydrogen-producing electrolyzer stacks to reduce capital cost.
- Conduced analysis using hydrogen as a mechanism for energy storage for use by electric utilities to better integrate a system consisting of electrolyzers, geologic hydrogen storage, and fuel cells to provide stored electricity at a cost of $0.16/kWh.

The NREL team will continue to work to transfer technology and foster collaborative relationships with industry. One promising opportunity in FY 2009 includes a collaborative project with multiple industry partners to design, build, and test a high-pressure phase separator. This work will enhance the existing active and informal partnerships with industry, academia, and domestic/international researchers.

Additionally, the team will be working to complete the following;

- Giner electrolyzer testing
- Baseline and renewable energy source testing for the wind to hydrogen demonstration project
- Cost and performance modeling/simulation of renewable electrolysis systems
- Installation of the hydrogen (5,000 psig) refueling station
- Testing of the 3rd generation 10 kW wind turbine to electrolyzer stack power electronics
- Transfer small wind, PV, and grid integrated power electronics results to industry
- Update renewable electrolysis test protocol draft
- Verify automated operation of wind to hydrogen project
- Analyze hydrogen product quality using ion chromatography
- Test and validate electrolyzer systems from DOE-sponsored projects
- Compare the ability of PEM and alkaline electrolyzers to accommodate the varying energy input from wind and PV

FY 2008 Publications/Presentations

1. Harrison, K. *Preliminary Test Report on Giner EP1 PEM Electrloyzer.* DOE Deliverable Report 3.7.12, September, 2007.

2. Duffy, M.; Harrison, K.; Sheahen, T. *Measurement of Hydrogen Production Rate Based on Dew Point Temperatures: Independent Review.* NREL /MP-150-42237. Golden, CO: National Renewable Energy Laboratory 2007.

3. Harrison, K. “Renewable Electrolysis: Integration, Validation and Demonstration, Conference “The Challenge of Deploying Hydrogen Technologies in Islands.” Presented to Canary Islands Institute of Technology. Gran Canaria, Spain. October 26, 2007.

4. Harrison, K.; Martin. G. “Renewable Electrolysis: Integration, Validation and Demonstration.” Presented at the National Hydrogen Association Conference. Sacramento, CA. March 31, 2008.

5. Harrison, K.; Martin. G. “Renewable Electrolysis: Integration, Validation and Demonstration.” Presented to the American Wind Energy Association. Austin, TX, June 3, 2008.

References

1. Short, W.; Blair, N.; Heimiller, D. *Modeling the Market Potential for Hydrogen from Wind and Competing Sources.* NREL/CP-620-38183. Golden, CO: National Renewable Energy Laboratory, May 2005.