II.E.3 Renewable Electrolysis Integrated System Development and Testing

Kevin W. Harrison (Primary Contact),
Todd Ramsden, Gregory Martin,
Genevieve Saur
National Renewable Energy Laboratory (NREL)
1617 Cole Blvd.
Golden, CO 80401
Phone: (303) 384-7091
E-mail: Kevin.Harrison@nrel.gov

DOE Technology Development Manager:
Roxanne Garland
Phone: (202) 586-7260
E-mail: Roxanne.Garland@ee.doe.gov

Subcontractors:
- Engineering Procurement & Construction, Denver, CO
- Spectrum Automation, Denver, CO

Project Start Date: September, 2003
Project End Date: September 30, 2012

Objectives

- Model and evaluate the potential of using hydrogen as an energy storage mechanism when coupled to renewable electricity sources at utility scales.
- Quantify efficiency and capital cost improvements achieved by designing and building integrated power electronics to more closely couple wind turbines and photovoltaic arrays to the electrolyzer stacks.
- Test and characterize the impacts on commercial electrolyzer systems to accommodate the varying energy from wind turbines and photovoltaic arrays coupled directly to the hydrogen-producing electrolyzer stack.
- Work closely with industry to provide independent testing and validation of system performance of next generation electrolyzer systems awarded under DOE contracts, and provide feedback on potential areas for improvement.
- Characterize and evaluate performance improvements of system-level integration and optimization opportunities for renewable-energy-based electrolysis production facilities.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration (RD&D) Plan:

(G) Capital Cost
(H) System Efficiency
(I) Grid Electricity Emissions (distributed)
(J) Renewable Electricity Generation Integration (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 objectives of this work includes the development of integrated power electronics and control theory to couple renewable electricity sources with the electrolyzer stack. This work can help reduce the capital cost and improve the efficiency to reduce the cost of renewable hydrogen production 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.

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

- Completed the hydrogen-based energy storage analysis and companion energy storage benchmarking study.
- Installed, commissioned and operated 13 kg/day polymer exchange membrane (PEM) electrolyzer at the wind-to-hydrogen demonstration project (loan from the U.S. Army):
  - Relocated both small (2.2 kg/day) PEM electrolyzers to adjacent Hydrogen Test Facility to upgrade with additional 10-cell stack for further testing.

- Completed the extensive process to obtain approval to run in unattended mode of operation:
  - Operated both the PEM and alkaline systems for longer duration run-times in unattended mode.
  - In March alone achieved about 120 hours of operation of the integrated energy system test bed producing over 40 kg of hydrogen.
  - Product fuel from testing used in hydrogen-powered vehicles.
- Installed and began testing upgraded PEM electrolyzer with additional 10-cell stack electrically in series with original 20-cell stack:
  - Conducted comparison testing of 10 kW photovoltaic (PV) array directly coupled with electrolyzer stack with power converter between array and stack.
- Authors from NREL and Natural Resources Canada published book chapter as part of the 18th World Hydrogen Energy Conference.
- Installed, commissioned and began operating 5 kW PEM fuel cell in the integrated renewable energy system.

✧ ✧ ✧ ✧ ✧

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 peak demand. Xcel Energy and NREL have collaborated to design, install, and operate the Wind-to-Hydrogen (Wind2H2) project, which demonstrates how to make and use hydrogen with renewable energy without producing greenhouse gases or other harmful by-products.

The Wind2H2 project is helping industry understand the hurdles and potential areas for improvement in emerging renewable electrolysis technologies. By allowing engineers to operate and configure an integrated electrolysis facility, this project has enabled the investigation and analysis of hydrogen production, compression, storage, and electricity generation that will provide valuable data, which can be used to improve the designs of future renewable electrolysis systems. A significant focus of the Wind2H2 project is to explore integration issues and opportunities for performance and cost improvements resulting from system-level optimization. NREL engineers are investigating how to maximize renewable energy use and optimize energy transfer within the Wind2H2 system.

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 direct current (DC) power required by the cell stack. These power converters can represent 14% to 22% of the total cost of the electrolyzer. Power converters are also required for the renewable energy source. By designing and incorporating dedicated power converters that allow wind turbines and photovoltaic arrays to be more closely coupled to electrolyzer stacks, energy transfer within the system can be improved and costs lowered.

Approach

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

- Exploring system-level integration and optimization opportunities for renewable-energy-based electrolysis production and storage facilities.
- Quantifying system-level efficiency improvements, system impacts, and cost reductions achieved by designing and building integrated power electronics to more closely couple varying energy from wind turbines and PV arrays to the electrolyzer stacks.
- Gaining operational experience of a hydrogen production facility, evaluating appropriate safety systems and system controls for safe unattended operation, and identifying areas for cost and efficiency improvements.
- Evaluating the potential of using hydrogen as an energy storage mechanism to help integrate variable output renewable energy on large MW-scale systems for utilities.
- Developing and optimizing advanced controls, subsystems, and power electronics to reduce electrolyzer capital cost and improve system efficiency.

Results

Experimental Findings

Direct Coupling versus Power Converter: NREL designed, installed and tested an additional 10-cell stack in a system with an existing 20-cell PEM stack. The original 7 kW rated electrolyzer could produce 2.2 kilograms of hydrogen per day. After the 10-cell upgrade, the modified PEM system requires 10 kW of electricity and produces 50% more product. More importantly, the added ½-stack shifted the electrical operating point of the combined stacks to better align with the maximum power point of NREL's 10 kW PV array. The improved alignment allowed for a more optimal direct coupling of the array to the stack pitted against the NREL-designed power converter utilizing an algorithm for maximum power point tracking (MPPT).

NREL produced hydrogen with power provided from the 10 kW PV array, comparing power transfer from a directly-coupled array to power transfer to the stack using NREL's MPPT power converter. This testing showed that direct-coupling outperformed power electronics utilizing MPPT when irradiances were below 500 W/m^2 (see Figure 1).

These findings provide useful insight into future integrated system designs. Electrolyzer stack voltage is a function of temperature, stack current and age. While the PV array maximum power point varies with temperature, irradiance and age. Passively keeping these two operating points aligned and optimal would be challenging as both systems vary over their normal operating ranges. Finally, time-of-day influences irradiance from the sun and configurations can be selected based on their performance for that irradiance level. As all of these parameters drive the operating points of the source and stack it seems reasonable to employ a situational approach to energy transfer. In this case, during the morning and evenings when the irradiance is below 500 W/m^2 switch to the direct coupling configuration. Also, during cloudy or stormy periods when the irradiance drops below the transition point power the stack in a direct-coupled mode. All other times when the irradiance is greater than 500 W/m^2 the power converter utilizing MPPT will transfer more energy from the array to the electrolyzer stack.

Long Duration Testing: NREL completed the installation, commissioning and started operation of an H-series (13 kg/day) PEM electrolyzer on loan from the U.S. Army. This will enable the side-by-side comparison testing of similarly sized alkaline and PEM electrolyzer technologies. Both smaller S-series system were relocated from the wind-to-hydrogen demonstration project to NREL's Hydrogen Test Facility. One of the two smaller PEM systems is the source of the previously described direct coupling versus MPPT power converter testing.

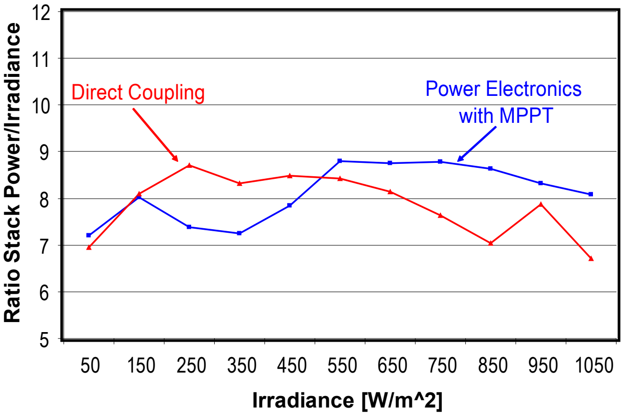

FIGURE 1. Direct Coupling and MPPT Power Converter Performance based on Irradiance

The NREL and Xcel Energy wind-to-hydrogen demonstration project has been conducting daily operations since 2006. Originally developed as a platform for research, demonstration, evaluation, and testing, the Wind2H2 system has recently undergone significant modifications to enable operations in an unattended mode, thereby allowing longer duration system testing. To run the Wind2H2 system in an unattended mode, new monitoring and control systems were developed and an extensive safety review and verification of these new systems was completed.

Since March 2010 (Figure 2) the wind-to-hydrogen system has been approved for long-duration unattended operation. However, also in March 2010 the alkaline electrolyzer, from Teledyne Energy Systems, displayed symptoms of severe gas cross-over within the stack. A replacement stack has been ordered and the existing stack will be returned for failure analysis. The PEM system is now being operated overnight and all the way through weekends to keep up with the demand of NREL's leased 12-passenger hydrogen-fueled internal combustion engine shuttle.

Long-duration testing showed the system could operate safely without operator attendance. Long-duration operation will continue for demonstration purposes while the wind-to-hydrogen system will also continue to be used for research and evaluation.

Analysis

NREL conducted a study of the life-cycle costs associated with hydrogen-based energy storage systems, and benchmarked these costs against competing energy storage systems including pumped hydro energy storage, compressed air energy storage, and battery storage. The study included full sets of analyses of hydrogen-based energy storage systems, including PEM fuel cell-based systems and hydrogen expansion-combustion turbine based systems. The study found that hydrogen-based systems were competitive with battery-based systems, with hydrogen expansion-combustion turbine systems providing stored electricity for as little as 17 cents/kWh (Figure 3).

The goal of this analysis was to develop a cost survey of the most-promising and/or mature energy storage technologies and compare them with several configurations employing hydrogen as the energy carrier. A simple energy arbitrage scenario was developed for a mid-sized energy storage system consisting of a 300-

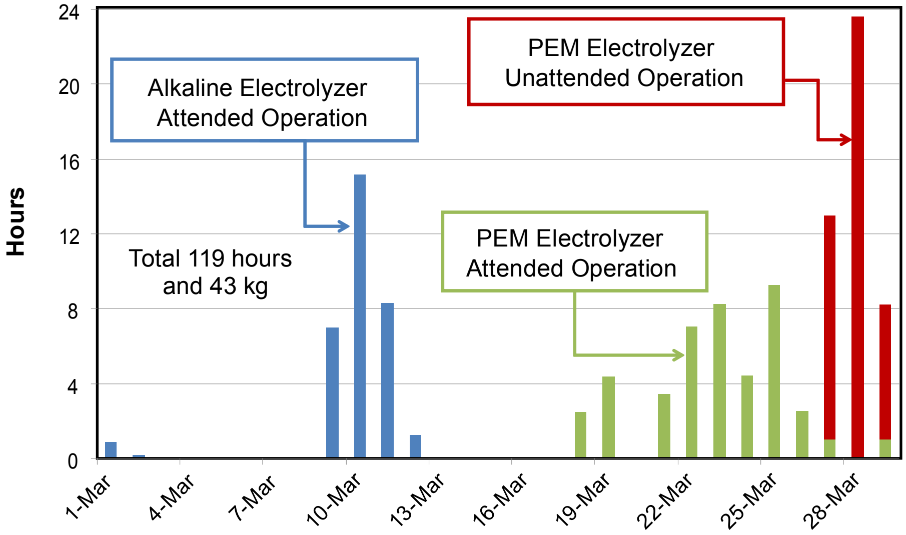

FIGURE 2. Run Times and Operational Modes of Operation for the Month of March 2010

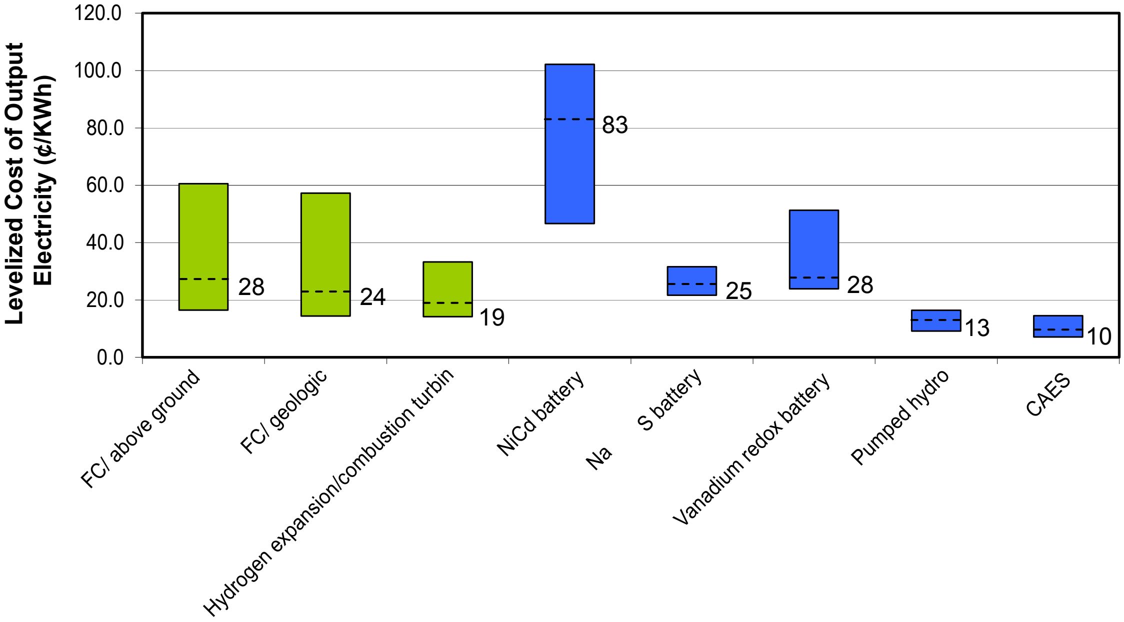

FIGURE 3. Hydrogen-Based Energy Storage Analysis and Companion Energy Storage Benchmarking Study

MWh nominal storage capacity that is charged during off-peak hours (18 hours per day on weekdays and all day on weekends) and discharged at a rate of 50 MW for 6 peak hours on weekdays. The full report can be found at http://www.nrel.gov/docs/fy10osti/46719.pdf.

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 of hydrogen production. 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. Testing and characterization of power electronics packages and control algorithms developed at NREL showed significant improvements in energy transfer within the system.

The experimental results from the direct-coupling versus power converter testing between the PV array and combined PEM electrolyzer stacks provide a valuable starting point for higher voltage testing. These results establish gains in the energy transfer between renewable resources and the hydrogen-producing electrolyzer stacks as a function of the sun's irradiance.

Long-duration testing of the Wind2H2 system will continue. The new H-series PEM electrolyzer was instrumented with stack voltage and current sensors. This enables long duration testing of two (of three) PEM stacks under a wind-based stack current profile while the third stack operates at constant current. Stack voltage monitoring over long duration provides decay rates to confirm industry reports of constant current operation and enables comparison of multiple stacks receiving current based on varying wind profile. The alkaline stack will be replaced and operated under the same wind profile. Stack decay rates will be compared between the varying and constant current stacks.

NREL will test and evaluate the 5 kW fuel cell system that has been integrated into the Wind2H2 system. Hydrogen produced during long-duration system testing will be used to provide fuel for the 5 kW fuel cell. Such testing will demonstrate the use of a fuel cell in an integrated, hydrogen-based energy storage system. As part of this evaluation, NREL will characterize the performance of the fuel cell in terms of turn-down rate, turn-on time, and system efficiency at power levels below the maximum power output to better understand the real-world aspects of using fuel cells in hydrogen-based energy storage systems.

NREL will also continue to model and analyze the potential of hydrogen-based energy storage systems, including analysis of dual-use energy storage systems. These systems use hydrogen for energy storage and fuel for vehicles. The analysis with include the impact of carbon taxes and carbon policies on hydrogen-based energy storage and compressed air energy storage.

NREL will continue to work to transfer technology and foster collaborative relationships with industry. This work will enhance the existing active and informal partnerships with industry, academia, and domestic/international researchers.

FY 2010 Publications/Presentations

1. Steward, D.M.; Ramsden, T.; Harrison, K. (2010). Hydrogen for Energy Storage Analysis Overview (Presentation). 19 pp.; NREL Report No. PR-560-48360.

2. Harrison, K.W.; Remick, R.; Hoskin, A.; Martin, G.D. (2010). Hydrogen Production: Fundamentals and Case Study Summaries; Preprint. 21 pp.; NREL Report No. CP-550-47302.

3. Ramsden, T.; Harrison, K.; Steward, D. (2009). NREL Wind to Hydrogen Project: Renewable Hydrogen Production for Energy Storage & Transportation (Presentation). 26 pp.; NREL Report No. PR-560-47432.

4. Harrison, K.W.; Martin, G.D.; Ramsden, T.G.; Kramer, W.E.; Novachek, F.J. (2009). Wind-To-Hydrogen Project: Operational Experience, Performance Testing, and Systems Integration. 95 pp.; NREL Report No. TP-550-44082.

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.