# II.E.4 Renewable Electrolysis Integrated System Development and Testing

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

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## Objectives

- Explore system-level integration and optimization opportunities for renewable-energy-based electrolysis production facilities.
- Work closely with the electrolyzer 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.
- Quantify 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 photovoltaic (PV) arrays to the electrolyzer stacks.
- Model, simulate, and optimize the renewable electrolysis system performance for dedicated hydrogen production for energy storage and electricity/hydrogen cogeneration.
- Evaluate the potential of using hydrogen as an energy storage mechanism to help integrate variable output renewable energy.
- 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.

## 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 (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 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 will help reduce the capital cost and improve the efficiency to 68% (lower heating value, LHV) or 81% (higher heating value, HHV) of hydrogen production from 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.

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

- Published major technical report on testing and findings of Wind-to-Hydrogen (Wind2H2) system operation.
- Developed and tested a 3rd generation power electronics package to integrate a variable-speed wind turbine to polymer electrolyte membrane (PEM) electrolyzer stack; measurements showed

improved energy power transfer of about 17% over previous power electronics configurations.

- Performed analysis showing a 7% cost reduction in the cost of electrolytic hydrogen based on systems integration improvements of power electronics developed as part of the Wind2H2 project.
- Performed a wide array of comparison testing between the custom built direct current (DC)/DC power converter with maximum power point tracking (MPPT) and PV array directly connected to an electrolyzer stack.
  - For solar PV systems, NREL found that optimized MPPT power electronics delivered 10% to 20% more PV electricity to the electrolyzer stack compared to a direct connection.
- Published technical report on electrolyzer capital cost and efficiency improvement opportunities based on a worldwide survey of electrolyzer manufacturers.

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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. Xcel Energy and the U.S. Department of Energy's (DOE) NREL have collaborated to design, install, and operate the Wind2H2 project, which demonstrates how to make hydrogen with renewable energy without producing greenhouse gases or other harmful by-products. The Wind2H2 project is helping researchers 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 system-level 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 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. 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 by the turbine to DC, which must then be converted back to AC for connection to the electric grid. By designing and incorporating dedicated power electronics packages that allow wind turbines to be more closely coupled to electrolyzer stacks, energy transfer within the system can be improved and costs lowered.

## 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:

- Exploring system-level integration and optimization opportunities for renewable-energy-based electrolysis production 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.
- Developing and optimizing advanced controls, subsystems, and power electronics to reduce electrolyzer capital cost and improve system efficiency.

## Results

### Experimental Findings

**Efficiency Measurements**: Electrolyzer system efficiency varies based on stack current and was measured for both the PEM and alkaline electrolyzer technologies (Table 1). The Wind2H2 Project found PEM electrolyzers more efficient than alkaline electrolyzers, contrary to expectations. At full stack current, the PEM electrolyzer had a system efficiency of 48% LHV (57% HHV). At the rated stack current, the alkaline system efficiency was found to be 35% LHV (41% HHV). Worth noting, the

measured hydrogen flow from the alkaline electrolyzer was 20% lower than the manufacturer's specifications. If the full hydrogen flow was measured, the alkaline system efficiency would have reached 50% (HHV).

**TABLE 1.** Electrolyzer System and Stack Efficiency

| Efficiency | PEM Elecrolyzer | | Alkaline Electrolyzer | |
|---|---|---|---|---|
| | LHV | HHV | LHV | HHV |
| **Stack Efficiency** | | | | |
| Low Current | 80% (5 A) | 95% (5 A) | 78% (30 A) | 92% (30 A) |
| Rated Current | 63% (135 A) | 75% (135 A) | 59% (220 A) | 70% (220 A) |
| **System Efficiency** | | | | |
| Low Current | 0% (15 A) | 0% (15 A) | 0% (35 A) | 0% (35 A) |
| Rated Current | 49% (135 A) | 57% (135 A) | 35% (220 A) | 41% (220 A) |

LHV – lower heating value; A – amps

**Energy Transfer Optimization**: NREL engineers have been investigating how to maximize renewable energy use and optimize energy transfer within the Wind2H2 system by designing and incorporating dedicated power electronics packages between the renewable electricity source and hydrogen-producing stacks of commercially available electrolyzer systems. Testing of these dedicated power electronics packages has shown improved energy transfer compared to non-optimized systems.

**Wind Energy Optimization**: NREL improved the energy transfer within wind-turbine-based renewable energy system and tested an AC/DC power electronics converter between a 10 kW wind turbine and 6 kW PEM electrolyzer stack. The test results of Figure 1 show about a 17% improvement over the Gen2 (yellow line) to the latest data (★) of the Gen3 design.

**Solar (PV) Energy Optimization**: NREL investigated energy transfer from a renewable energy solar PV array, comparing a direct-connect from the PV array to the electrolyzer stack with a connection through an MPPT power electronics package designed at NREL. Measurements showed that in all cases, the system employing MPPT electronics captured 10% to 20% more energy than the direct-connect configuration (Figure 2).

## Analysis

Based on the system-level optimization investigations conducted with the Wind2H2 system, NREL engineers estimated that optimizing power electronics in large-scale wind-based renewable electrolysis systems could reduce the cost of wind-to-hydrogen production from $6.25/kg to $5.83/kg. This 7% reduction in cost per kg of hydrogen is based on a capital cost improvement by eliminating the inverter from the wind turbine and the AC/DC power electronics in the electrolyzer and replacing them with a DC/DC converter between a wind turbine and electrolyzer stack. System-level integration of renewable energy sources and electrolyzer stacks can improve energy transfer within the system, increasing system efficiency and lowering overall cost of production.

This cost reduction analysis is based on the findings of an electrolyzer capital cost reduction investigation conducted by NREL. From a worldwide survey of electrolyzer manufacturers, NREL found that power electronics subsystems account for 14% to 22% of total electrolyzer system cost, and improvements in power electronics subsystems hold the second highest potential for lowering the cost of hydrogen produced via electrolysis, next to improvements in the electrolyzer stacks themselves. This research indicates that along with continued research into improving stack cost and performance, research and development efforts on power electronics subsystems can yield significant gains in overall electrolyzer system performance and cost.

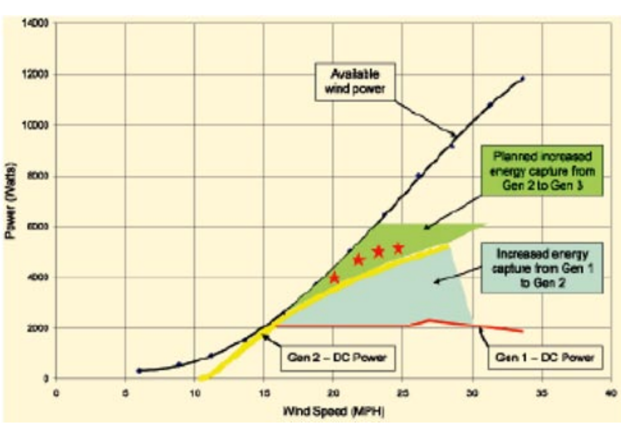


**FIGURE 1.** Energy Transfer Improvements from 3rd Generation of the Wind Turbine Power Electronics Converter

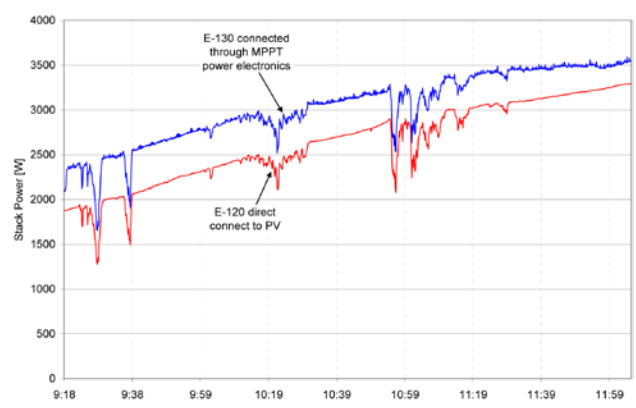


**FIGURE 2.** Energy Transfer Improvements for MPPT Power Electronics over Direct Connect for 5 kW PV Array to PEM Electrolyzer Systems

## 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 hydrogen. 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 algorithms developed at NREL showed significant improvements in energy transfer within the system. Based on this work, NREL estimated that system-level optimization of power electronics subsystems alone could reduce the cost of wind-based hydrogen production by 7%.

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.

Additionally, NREL will complete the following:

- Modeling and analyzing cost and performance of future, large-scale renewable electrolysis systems based on lessons learned from Wind2H2 experimentation.
- Testing and charactering the 3$^{rd}$ generation 10 kW wind turbine to electrolyzer stack power electronics.
- Testing and charactering upgraded PEM electrolyzer (1.5 stack) configuration with direct and MPPT power electronics.
- Measuring 33 kW alkaline electrolyzer performance when provided a stack current proportional to the power signal from a 100 kW wind turbine.
- Verifying automated operation of the Wind2H2 system and conducting subsequent longer duration system testing and characterization.
- Testing and validating electrolyzer systems from DOE-sponsored projects.

## FY 2009 Publications/Presentations

**1.** 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.

**2.** Saur, G. (2008). Wind-To-Hydrogen Project: Electrolyzer Capital Cost Study. 48 pp.; NREL Report No. TP-550-44103.

**3.** Harrison, K.; Martin, G.; Ramsden, T.; Saur, G. Renewable Electrolysis Integrated System Development and Testing – 2009 Hydrogen Merit Review Poster; NREL Report No. PO-560-45678.

**4.** Steward, D.M. "Scenario Development and Analysis of Hydrogen as a Large-Scale Energy Storage Medium." Presented at the Generation Conference: Fossil Fuels and Renewables, Englewood, CO. June 10, 2009.

**5.** Harrison, K.W. "Wind to Hydrogen Demonstration Project." Presented at the National Hydrogen Association 2009 Conference, Columbia, SC. April 1, 2009.

## 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.