National Renewable Energy Laboratory
Innovation for Our Energy Future

RENEWABLE ELECTROLYSIS INTEGRATED SYSTEM DEVELOPMENT AND TESTING

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Project ID #
PDP_17_Harrison

Overview

Timeline

Project start date: Sept 2003
Project end date: FY 2010

Barriers

G. Cost
H. System efficiency
J. Renewable integration

Budget

- $1300k Industry cost-share (FY06)
- $ 625k DOE (FY06)
- $1000k DOE (FY07)
- $1500k DOE (FY08)
- $200k (FY09)

Partners

- Xcel Energy
- Proton Energy Systems
- Teledyne Energy Systems
- Univ. of North Dakota/EERC
- Univ. of Minnesota
- DOE Wind/Hydro Program

Relevance

Technology Demonstration Objectives

- Test, evaluate and model the renewable electrolysis systems
- Identify opportunities for system cost reduction and optimization as they pertain to electric utilities
- Design and build dedicated power electronics converters to optimize energy transfer from solar and wind sources into hydrogen product.
- Operate system that makes hydrogen from renewable energy sources, document lessons learned and gain operational experience
- Disseminate knowledge and experience to interested industries, companies and the public
- Implement and demonstrate grid support via hydrogen energy storage and hydrogen vehicle fueling
- Determine and implement optimized system operation rules such as stack sequencing, turn-on and turn-off scenarios, and grid support timing

Analysis Objectives

- Develop cost models for renewable electrolysis systems
- Quantify effect of capital reduction and efficiency improvements on hydrogen production from renewable electrolysis

Testing Objectives

- Characterize electrolyzer performance with variable input power
- Test performance of electrolysis systems developed from DOE awarded projects
- Test electrolyzer stack and system response with typical renewable power profiles
- Test and document component and system efficiency ranges

Relevance

TECHNICAL TARGETS

The Wind2H2 project continues to work toward meeting technical targets of the Hydrogen, Fuel Cells & Infrastructure Technologies Program

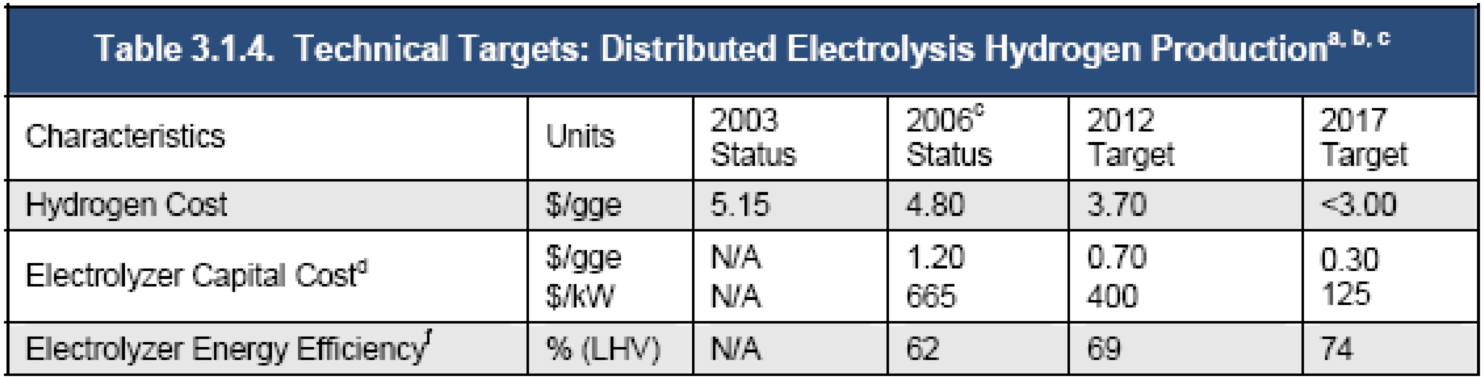


Table 3.1.4. Technical Targets: Distributed Electrolysis Hydrogen Production[a, b, c]

Characteristics	Units	2003 Status	2006[c] Status	2012 Target	2017 Target
Hydrogen Cost	\$/gge	5.15	4.80	3.70	<3.00
Electrolyzer Capital Cost[d]	\$/gge \$/kW	N/A N/A	1.20 665	0.70 400	0.30 125
Electrolyzer Energy Efficiency[f]	% (LHV)	N/A	62	69	74

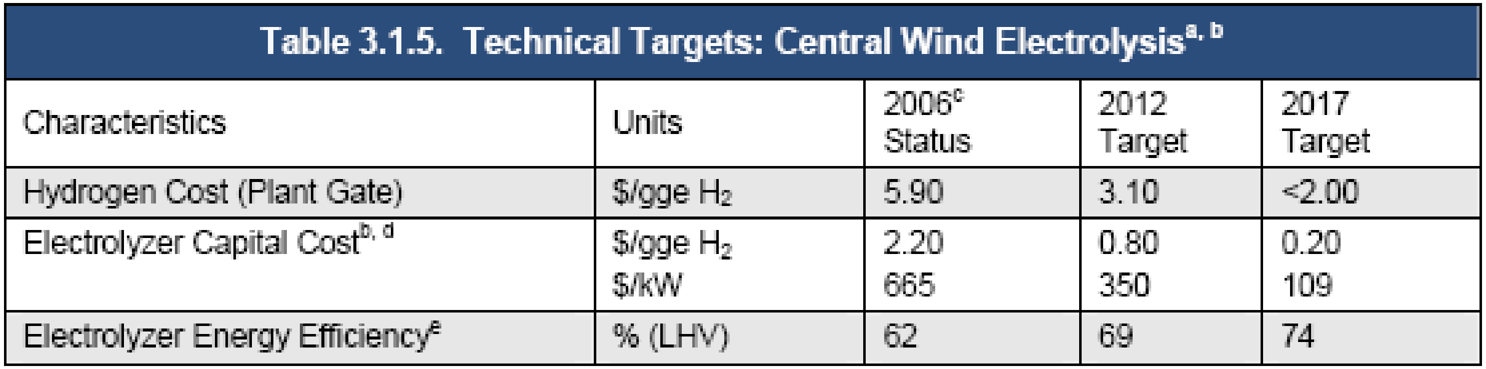


Table 3.1.5. Technical Targets: Central Wind Electrolysis[a, b]

Characteristics	Units	2006[c] Status	2012 Target	2017 Target
Hydrogen Cost (Plant Gate)	\$/gge H_2	5.90	3.10	<2.00
Electrolyzer Capital Cost[b, d]	\$/gge H_2 \$/kW	2.20 665	0.80 350	0.20 109
Electrolyzer Energy Efficiency[e]	% (LHV)	62	69	74

Relevance

BARRIERS ADDRESSED

- *Capital Costs*: R&D is needed to lower capital while improving the efficiency and durability of the system
- *System Efficiency*: In large production facilities even slight increases in efficiency enable significant reductions in hydrogen cost. Efficiency gains can be realized using compression in the cell stack
- *Renewable Electricity Generation Integration*: More efficient integration with renewable electricity generation is needed to reduce costs and improve performance. Development of integrated renewable electrolysis systems is needed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production

Approach

To test, evaluate, model and optimize renewable electrolysis system performance for both dedicated hydrogen production and electricity/hydrogen cogeneration.

Systems Engineering, Modeling, and Analysis

Develop and validate component-level and system-level models and optimization tools.

System Integration and Component Development

Work with industry to develop new advanced hardware and control strategies to couple renewable energy sources and electrolyzer systems.

Characterization, Testing and Protocol Development

Install and maintain equipment; test and characterize performance of system components; and develop standard equipment test procedures.

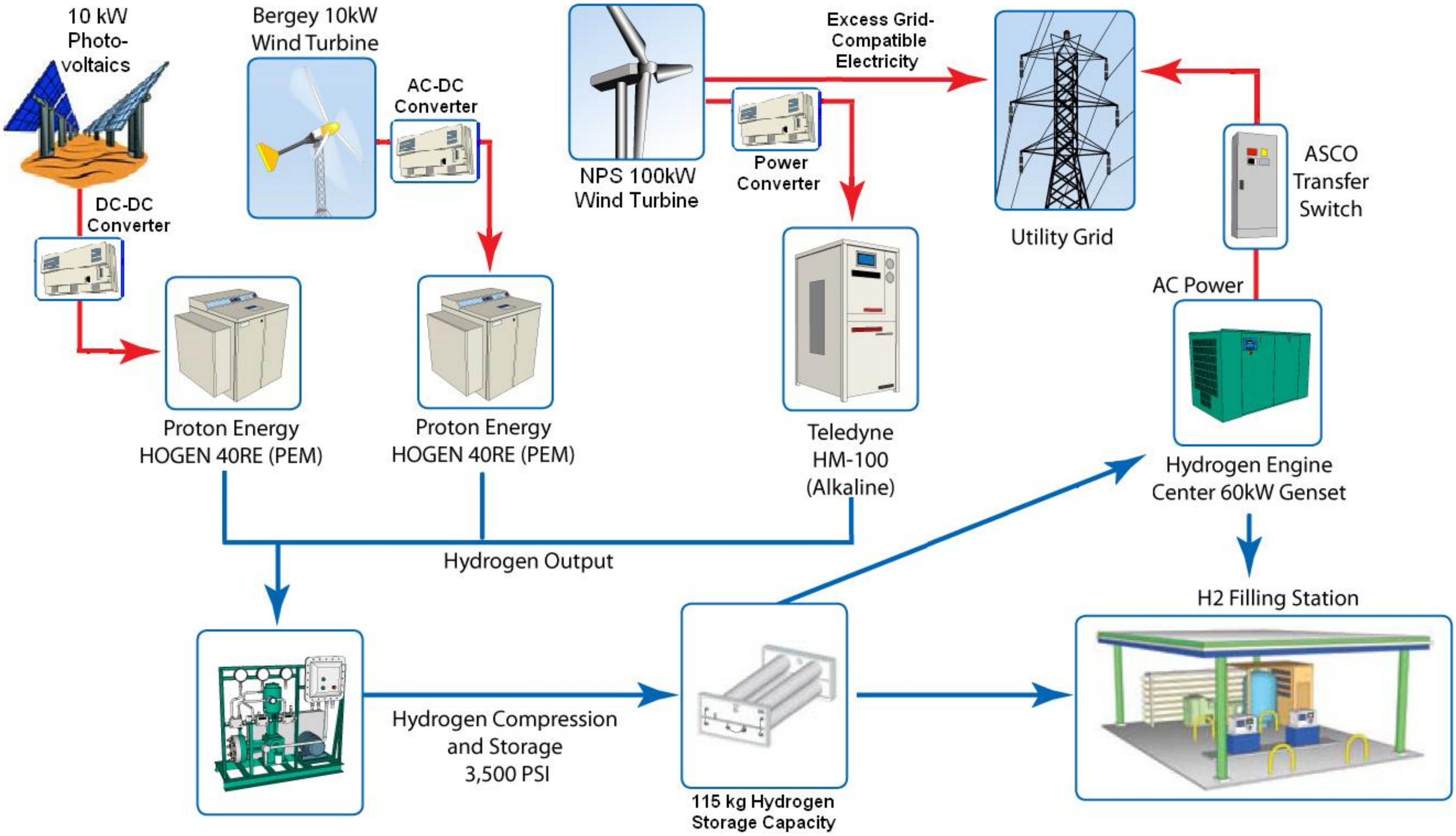
Technical Accomplishments Summary

Wind2H2 Demonstration Project

- **Test results**
  - 10 kW PV electrolysis
  - 10 kW wind electrolysis
  - 100 kW wind electrolysis
  - Electrolyzer system efficiency
  - Compressor efficiency
- **Vehicle fueling systems design and installation**
- **System upgrades**
- **Power electronics system cost reduction modeling results**
- **Electrolyzer capital cost and efficiency modeling**
- **Key findings**
- **Lessons Learned**
- **Publications**
- **Collaborations**

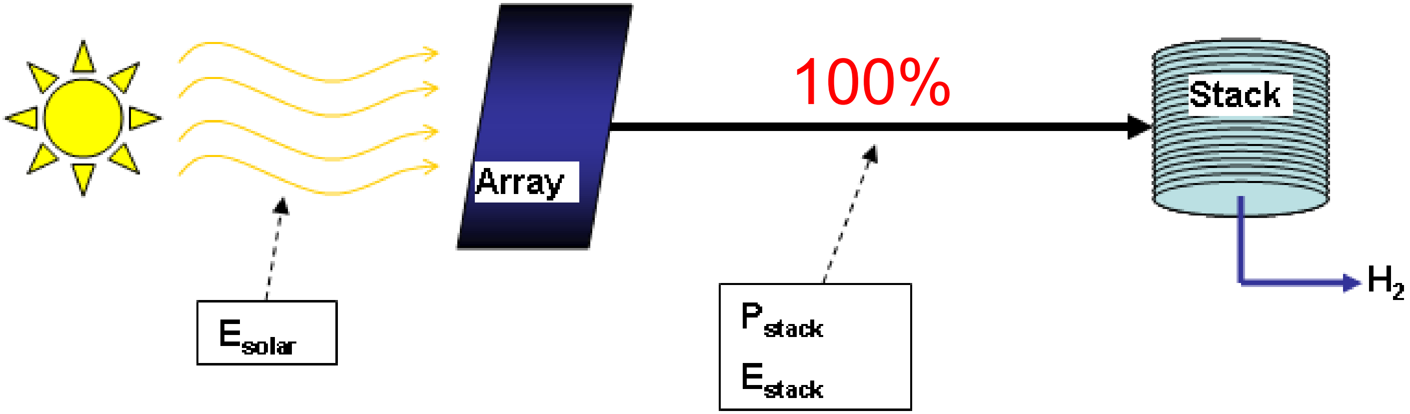
Wind2H2 Demonstration Project

System Overview



Technical Accomplishments

10 kW PV-Powered PEM Electrolysis



Array

100%

Stack

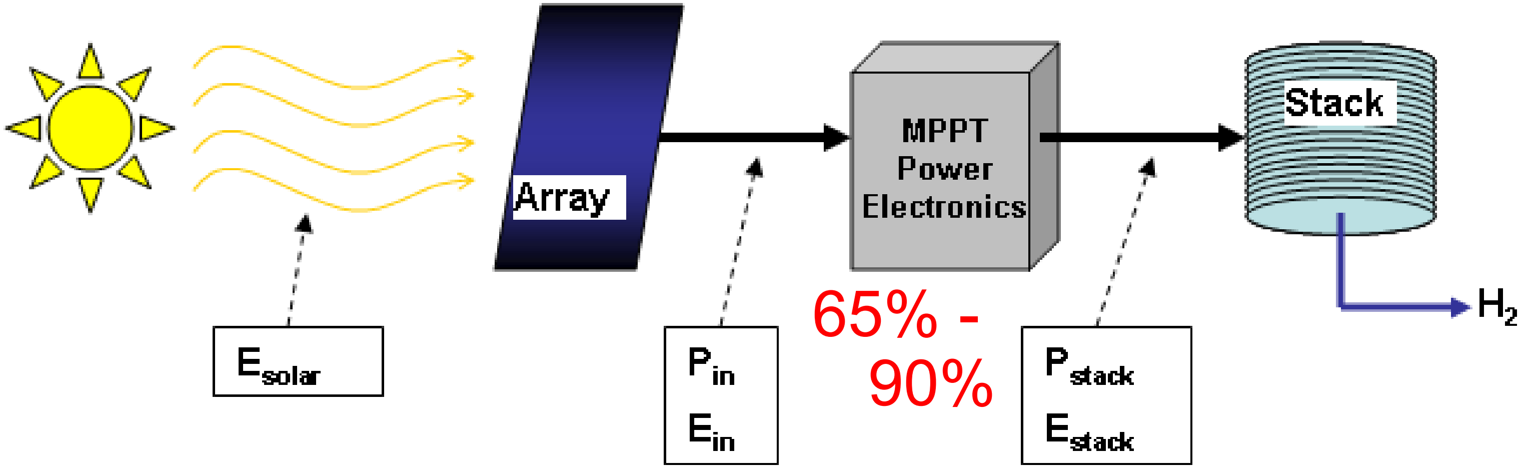
H_2

E_{solar}

P_{stack}

E_{stack}

Direct connect (top, no power conversion losses) versus power converter (bottom, with losses based on input PV array voltage)



Array

MPPT Power Electronics

Stack

H_2

E_{solar}

P_{in}

E_{in}

65% - 90%

P_{stack}

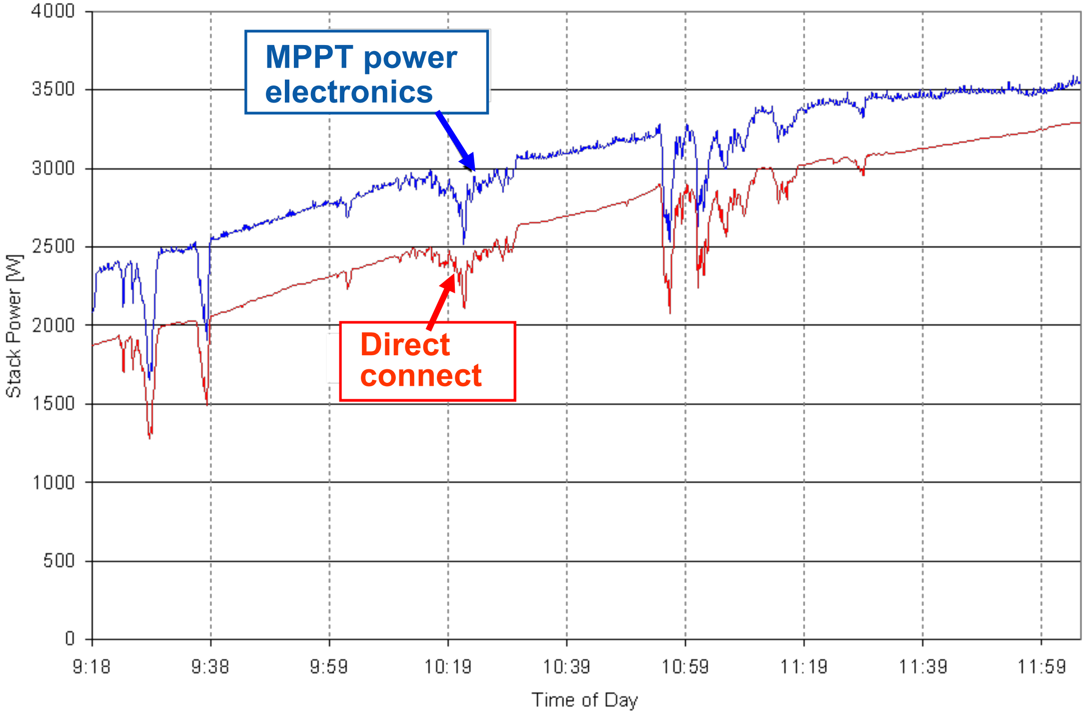
E_{stack}

Technical Accomplishments

10 kW PV-Powered PEM Electrolysis

Capital Costs: Onboard power electronics (AC/DC) are relatively expensive accounting for 15 to 30% of the system cost. This problem is exacerbated when renewable power sources are used, adding a second on-board power electronics module.

Accomplishment: NREL designed, built and tested a power electronics package that captured between 10%–20% more energy that the direct PV-to-stack configuration. The power converter combines functionality, reduces redundant components (i.e., switches, controllers and filter elements) and maximum power point tracking algorithm.



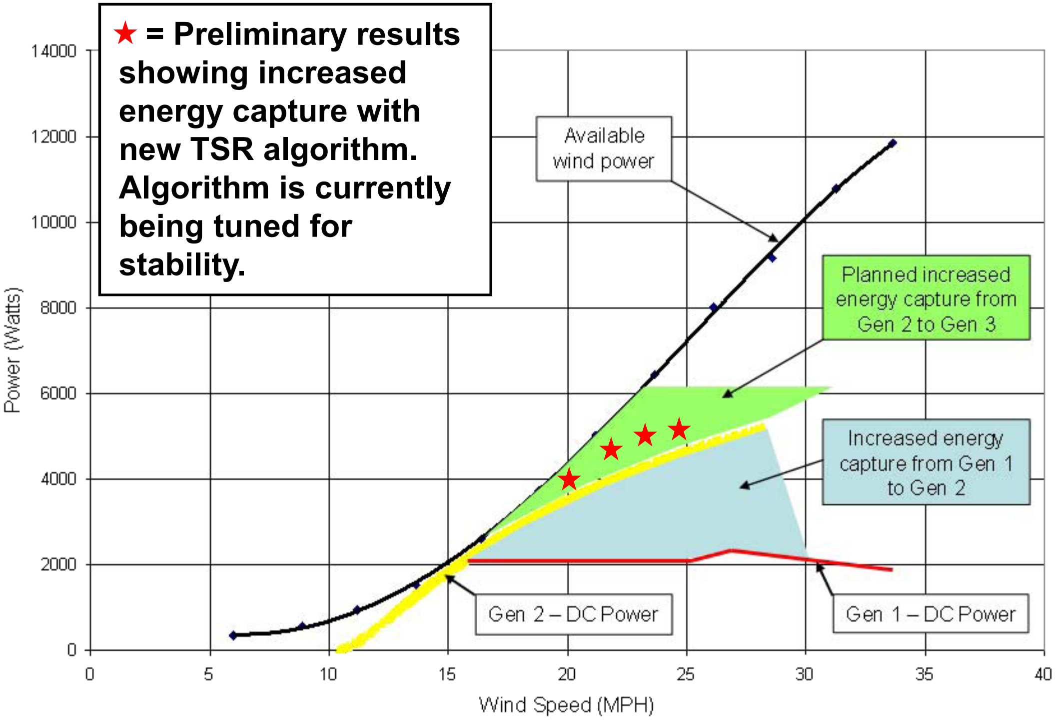
Test data shows improvement in energy output to stack when using MPPT power electronics. Tests were run concurrently from equal 5 kW PV sources with the same solar input.

Technical Accomplishments

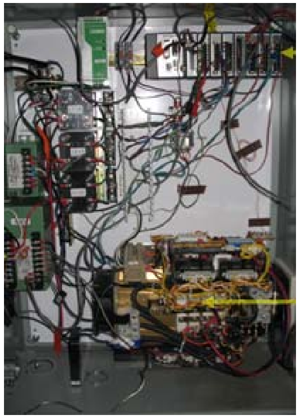
10 kW Wind-Powered PEM Electrolysis

Renewable Electricity Generation Integration: Improve the energy capture from renewable energy sources through controlling renewable source, direct-coupling to stack and unique control algorithms.

Accomplishment: Initial tests with third generation power electronics, wind speed measurement and control algorithm indicate further improved energy capture of wind electricity into hydrogen production.



★ = Preliminary results showing increased energy capture with new TSR algorithm. Algorithm is currently being tuned for stability.



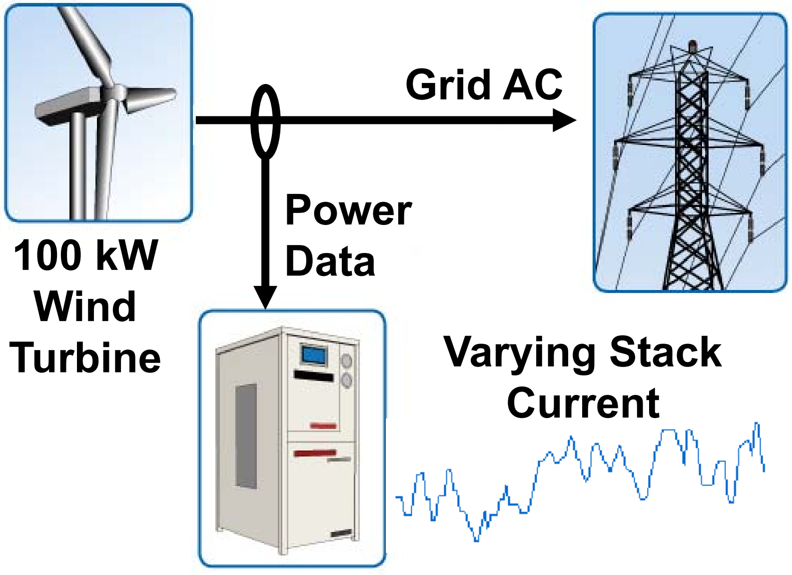
Technical Accomplishments

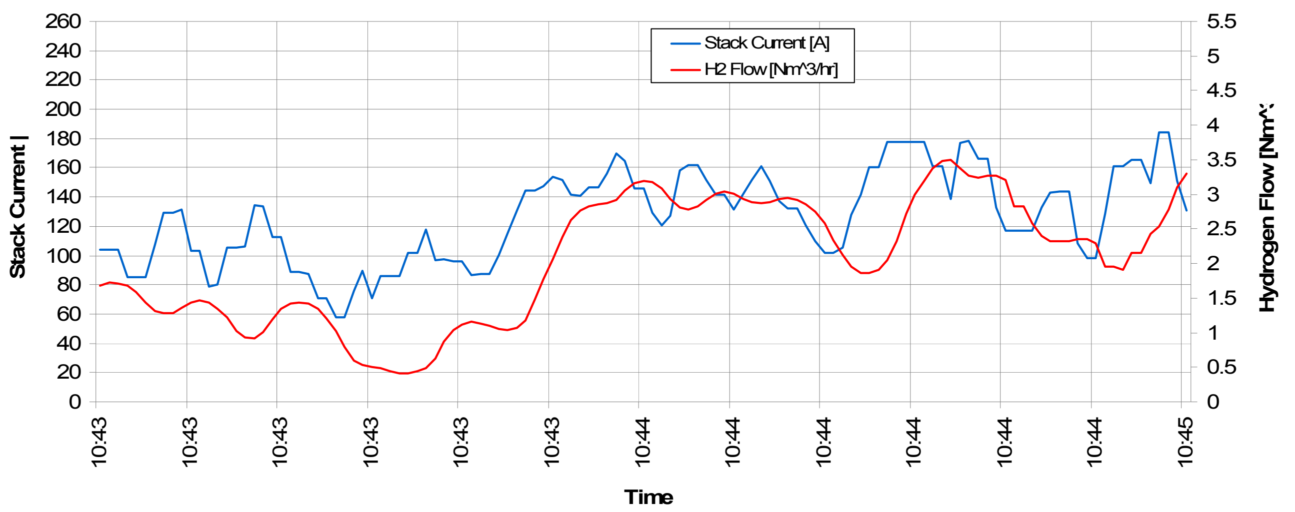
100 kW Wind-Powered Alkaline Electrolysis

Renewable Electricity Generation Integration: Characterize stack and system response of alkaline electrolyzer to varying stack current based on wind turbine power output signal.

Accomplishment: Preliminary data indicates that the electrolyzer system can tolerate brief periods of zero current to the stack.

The graph below illustrates hydrogen product flow lagging behind stack current variations.





Instrumented power signal from 100 kW wind turbine to drive 33 kW alkaline stack current to follow power available from turbine

Technical Accomplishments

Electrolyzer System Efficiency

Equipment Characterization: Characterize performance of electrolyzers operating in the Wind2H2 system. Stack and system efficiency of alkaline (33 kW stack, 40 kW system, 12 kg/day) and PEM-based (6 kW stack, 7 kW system, 2.3 kg/day).

Accomplishment: Monitored and analyzed stack and system performance over full-range of stack currents.

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

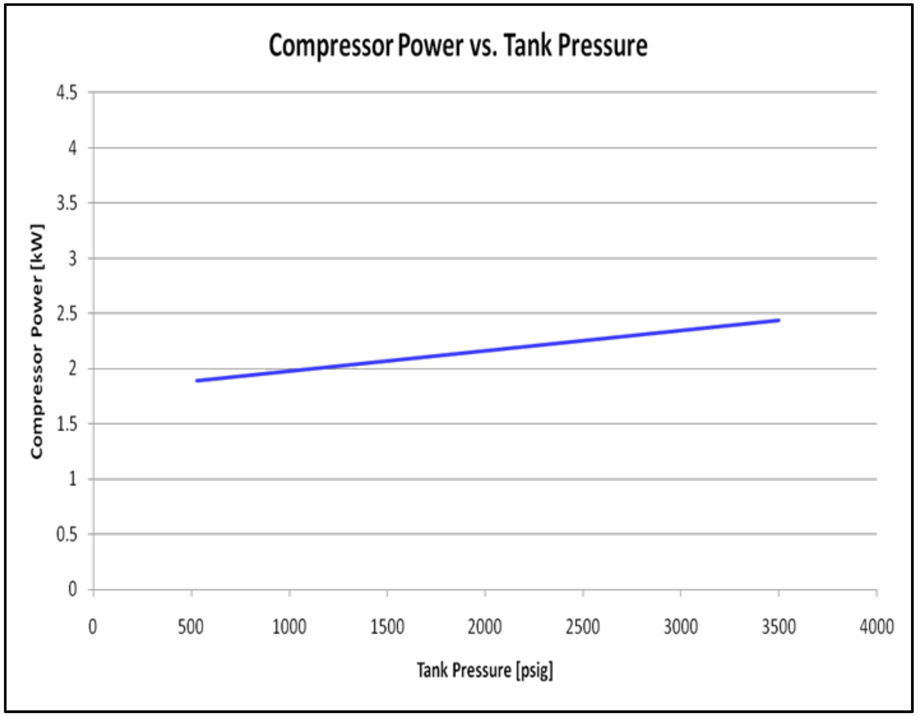
Technical Accomplishments

Compressor Efficiency

Equipment Characterization: Characterize compressor operation and efficiency under varying suction pressure due hydrogen production from renewable electricity sources.

Accomplishment: Determined compressor efficiency of 93% (HHV) and 91% (LHV) over entire pressure range of hydrogen storage tanks.

Next Steps: Continue to evaluate various methods to determine compressor efficiency. Monitor and analyze compressor performance based on suction pressure and hydrogen flow from multiple electrolyzers.



Two-stage diaphragm compressor

$$Efficiency = \frac{\left(H2\ flow\left[\frac{kg}{hr}\right] * HHV\left[\frac{kWh}{kg}\right]\right)}{\left(H2\ flow\left[\frac{kg}{hr}\right] * HHV\left[\frac{kWh}{kg}\right] + Power_{compressor}[kW]\right)}$$

Equipment Installation

Vehicle Fueling Design and Installation

- Design and install a 350 bar filling station
- Data from refueling events will be collected and archived along-side ongoing Technology Validation effort
- Collaboration with NREL Vehicles and Transportation Center for data collection and technology demonstration

New Systems:

- ✓ Outdoor rated diaphragm compressor (6000 psi)
- ✓ 400 bar tank (20 kg)
- ✓ 350 bar non-communication fill dispenser
- ✓ 1.8 kg (~100 mile range) loaner Mercedes-Benz A-Class Fuel Cell (F-Cell) vehicle

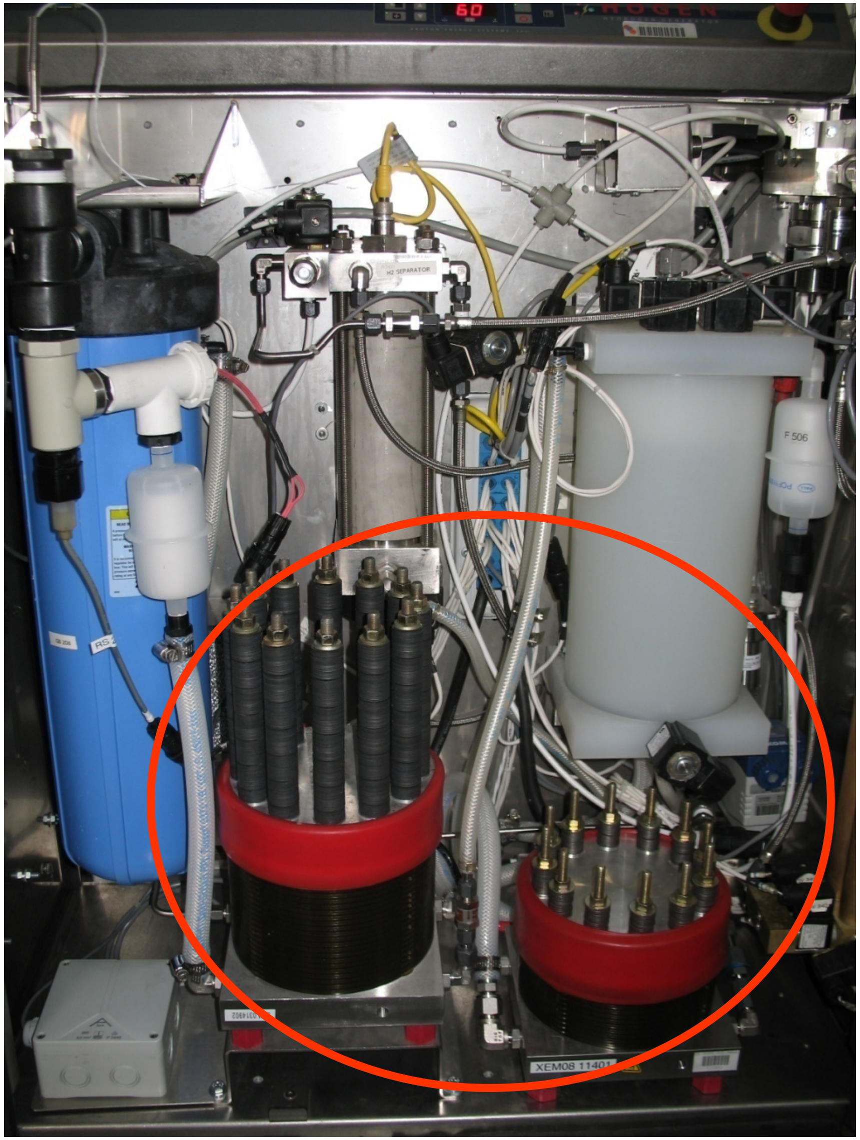
System Upgrades

Renewable-to-Stack Sizing

Goal: Install ½ stack to better match PV and PEM stack operating points

New 1.5x stack sizing will allow next phase of testing between direct connect and MPPT power electronics

Status: Upgrade of DI water pump enabled commissioning and verification of this system in April 2009.



Technical Accomplishments

System Analysis

Capital Component (uninstalled)	**Baseline System**	**Optimized System**
1.5 MW Wind Turbine		
Rotor	$248,000	$248,000
Drive Train	$1,280,000	$1,180,000
including power electronics	*$100,000*	*$0*
Control System	$10,000	$10,000
Tower	$184,000	$184,000
Balance of Station	$262,000	$262,000
2.33 MW Electrolyzer	$1,570,000	$1,350,000
including power electronics	*$220,000*	*$0*
New Power Electronics Interface	$0	$70,000
Resulting Hydrogen Cost ($/kg)	**$6.25**	**$5.83**

Optimization of the power conversion system due to a closer coupling of the wind turbine to the electrolyzer stack can reduce the total cost of hydrogen by 7%.

By better size matching of wind turbine and electrolyzer systems, the efficiency of the DC/DC conversion step of the modified system can be improved from 90% to 93% or more.

Original $100,000 PE package was assessed to include 35% for the rectifier section and 65% for the inverter section.

Rectifier section would still be required in the optimized package to convert wild AC-to-DC.

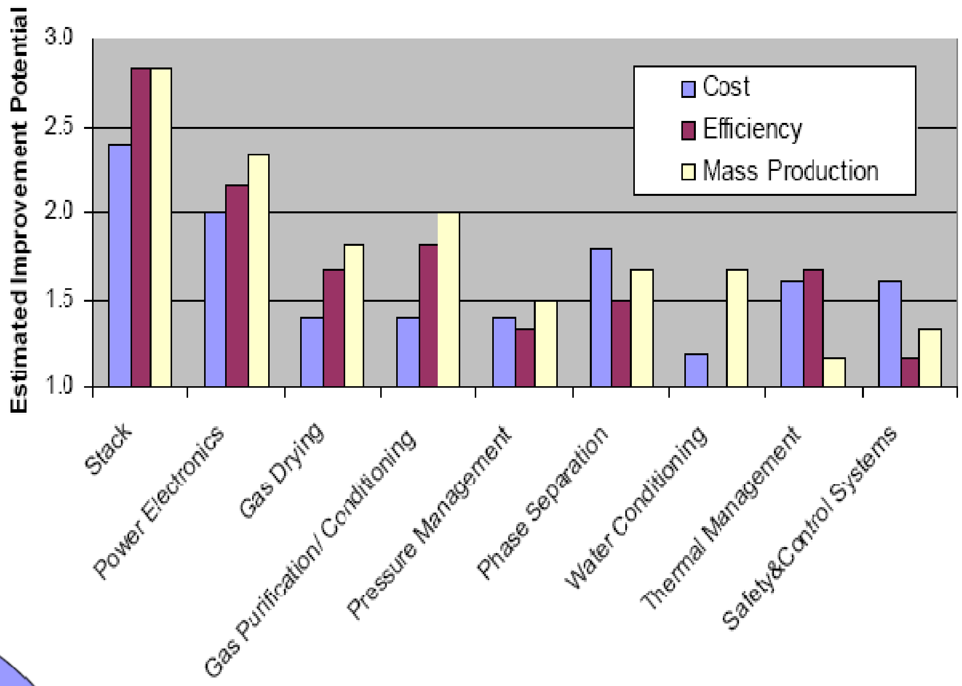
Based on available cost information for DC/DC converter technology, the new DC/DC section was assumed to cost $30/kW. Thus, the DC/DC converter required for the 1.5 MW wind turbine would cost $45,000.

Technical Accomplishments

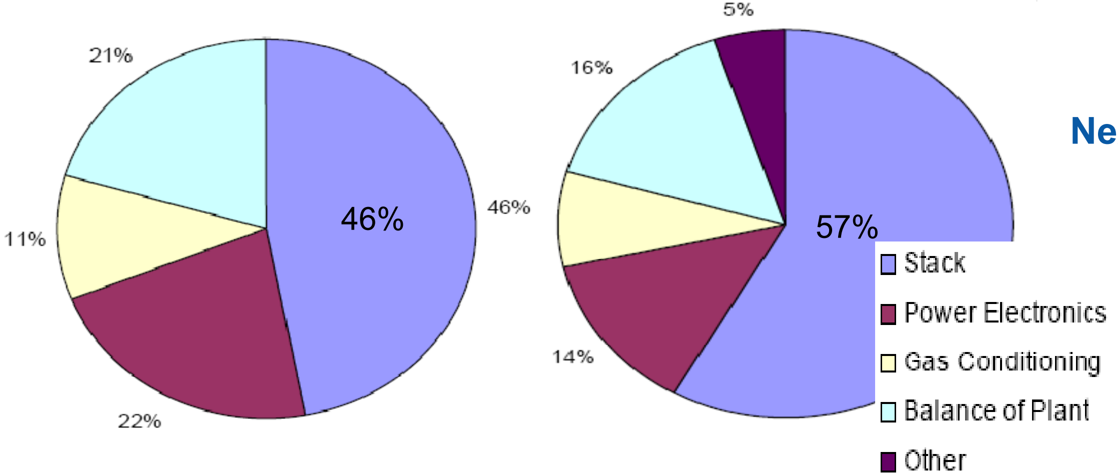
System Analysis

BARRIER ADDRESSED: Evaluate capital cost and efficiency improvements

ACCOMPLISHMENT: Manufacturer survey provided feedback of cost and opportunities for improvement of today's state-of-the-art electrolyzer systems



PEM **Cost breakdown** Alkaline

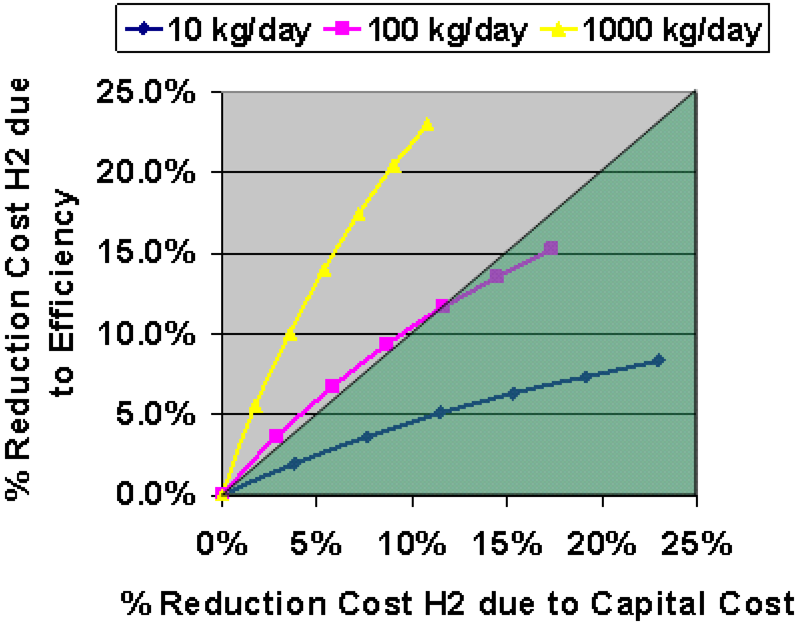


Next Examined:

- *Capital Cost Reduction of Stack and Power Electronics subsystems*
- *Efficiency Improvements*
- *Capital Cost versus Efficiency – incremental improvements for the different size level*

Technical Accomplishments

System Analysis



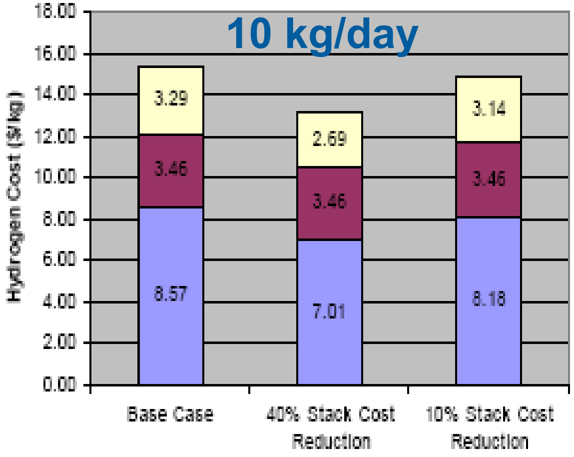
Each point along curve represents 5% improvement to either capital cost or efficiency from base case (5% increments up to 30%)

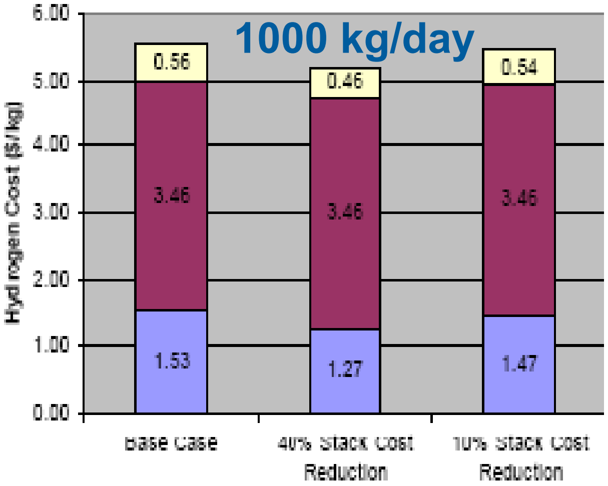
Smaller systems (green zone) represents systems in which capital reduction is better than 5%

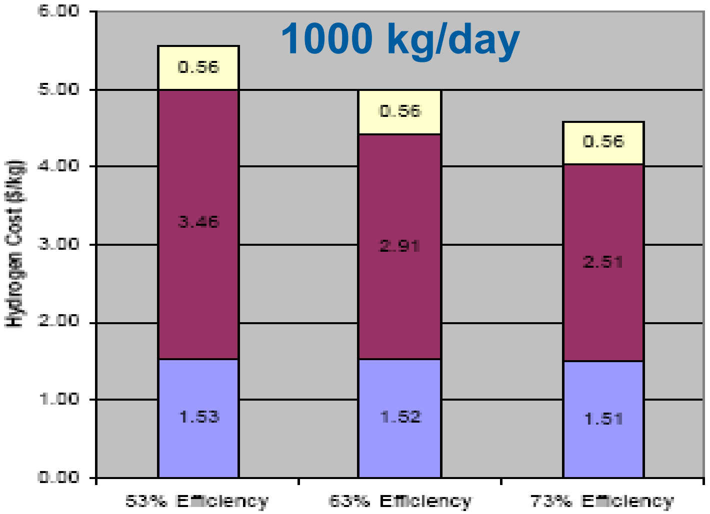
Larger systems (grey zone) efficiency improvement are better

Scaled capital cost

- *10 kg/day ~ $5000/kW*
- *100 kg/day ~ $2000/kW*
- *1000 kg/day ~ $850/kW*







Technical Accomplishments

KEY FINDINGS - Wind2H2 Demonstration Project

System Integration: More research and engineering design related to renewable electrolysis system integration would improve energy transfer and overall system efficiency and would reduce system complexity and capital costs

- Development of optimized power electronics packages in particular is a promising area for system-level improvements

- Development of open architecture communication protocols between different component manufacturers would greatly simplify system integration efforts

Codes and Standards: Development of clear and consistent codes and standards will expedite implementation and reduce the cost of renewable electrolysis projects

Efficiency Measurements: Based on the testing of the Wind2H2 project's small electrolyzer systems, PEM electrolyzers were found to be more efficient than the alkaline electrolyzer, counter to expectations

Energy Transfer Optimization:

- Analysis shows a potential 7% reduction in the cost of hydrogen if the wind turbine inverters are replaced with DC/DC converters that feed directly to the electrolyzer stacks

- For solar PV systems, NREL determined that the use of an optimized power electronics package (called a maximum power point tracking system – MPPT) captured between 10% and 20% more energy than a direct connection to the electrolyzer stack

Technical Accomplishments

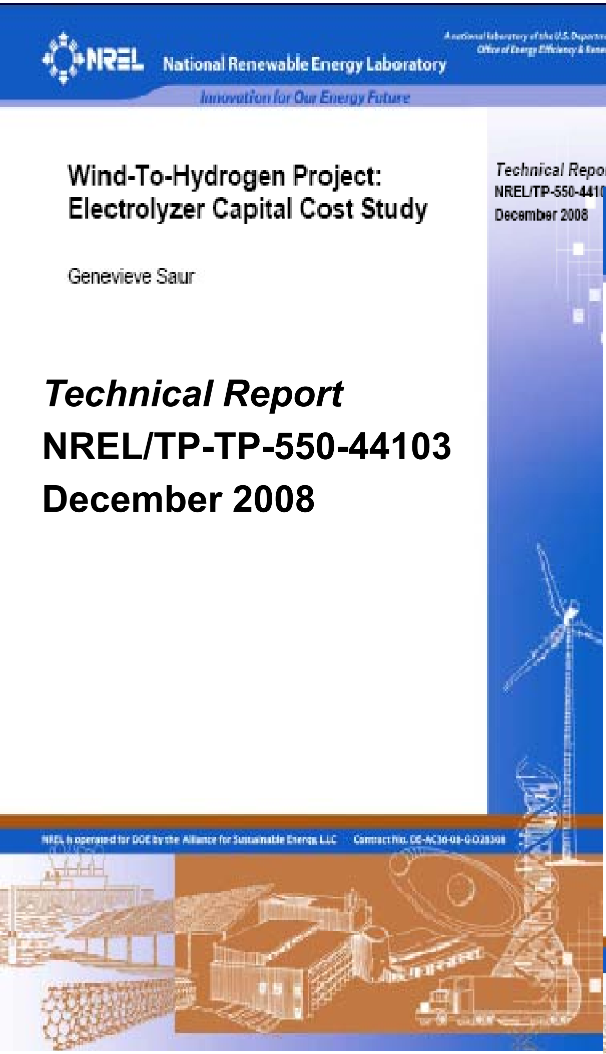
LESSONS LEARNED - Wind2H2 Demonstration Project

The following are implications for electric utilities' component suppliers and hydrogen-based energy storage system integrators.

Hydrogen-based energy storage system component capital costs and efficiencies must continue to improve to become competitive with other electric utility production and storage options. To move toward being a competitive technology, renewable electrolysis systems must address the following:

- **Establish open architecture and communication protocols**
- **Design wind turbines and electrolyzers to be compatible with each other, and to operate in concert as part of an energy production and storage system**
- **Simplify and standardize codes and standards for electrolysis-based hydrogen energy production and storage systems**
- **Optimize energy transfer within the system and eliminate redundant components**
- **Standardize system sizes and match component sizes. Until standardized designs and component sizes are developed, system integrators need to determine appropriate component sizes to meet the needs of electrolysis-based energy storage projects on a case-by-case basis.**

Publications



NREL National Renewable Energy Laboratory

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Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

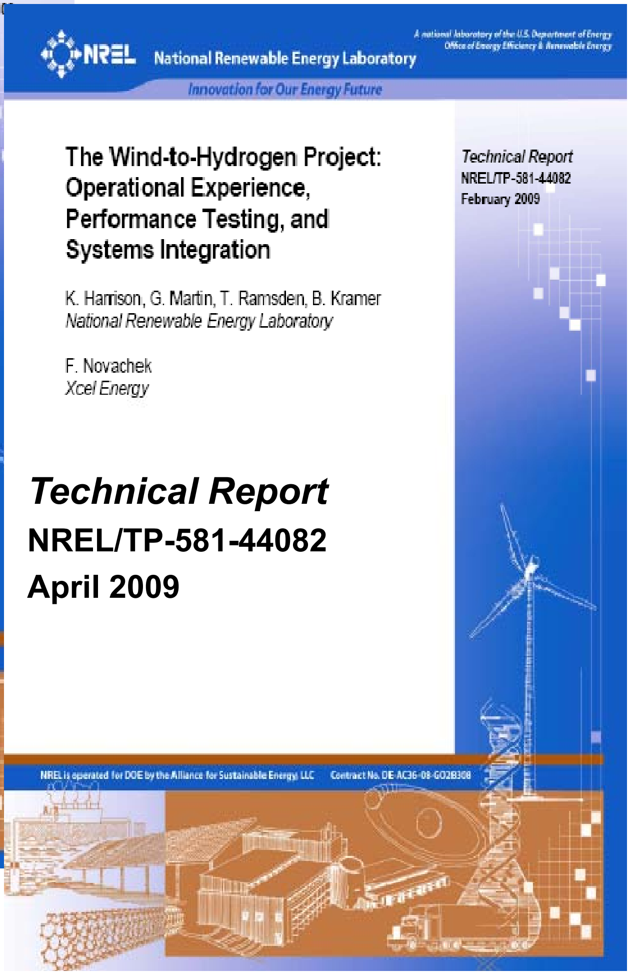
Wind-To-Hydrogen Project:
Electrolyzer Capital Cost Study

Genevieve Saur

Technical Report
NREL/TP-550-441
December 2008

NREL is operated for DOE by the Alliance for Sustainable Energy, LLC Contract No. DE-AC36-08-GO28308

Technical Report
NREL/TP-TP-550-44103
December 2008



NREL National Renewable Energy Laboratory

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Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

The Wind-to-Hydrogen Project:
Operational Experience,
Performance Testing, and
Systems Integration

K. Harrison, G. Martin, T. Ramsden, B. Kramer
National Renewable Energy Laboratory

F. Novachek
Xcel Energy

Technical Report
NREL/TP-581-44082
February 2009

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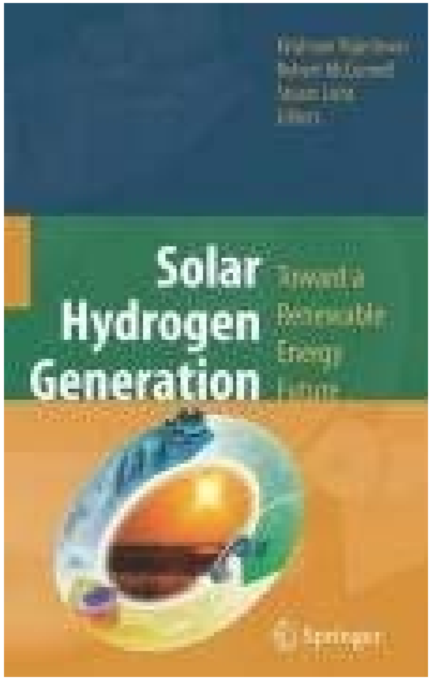
Technical Report
NREL/TP-581-44082
April 2009



Solar
Hydrogen
Generation

Toward a
Renewable
Energy

NREL
Chapter 1 – Co-author
Chapter 3 – NREL authors

Publications

Harrison, K.; Martin, G.: Ramsden, T.; Kramer, B. (2009) The Wind-to-Hydrogen Project: Operational Experience, Performance Testing, and Systems Integration. NREL Technical Report NREL/TP-581-44028.

Saur, G. (2009)The Wind-to-Hydrogen Project: Electrolyzer Capital Cost Study. NREL Technical Report NREL/TP-550-44103.

Rajeshwar, K.; McConnell, R.; Harrison, K.; Licht, S. (2008). Chapter 1: Renewable Energy and the Hydrogen Economy. Rajeshwar, K.; McConnell, R.; Licht, S., eds. Solar Hydrogen Generation: Toward a Renewable Energy Future. New York, NY: Springer pp. 1-18; NREL Report No. CH-581-44203.

Harrison, K.; Levene, J. I. (2008). Chapter 3: Electrolysis of Water. Rajeshwar, K.; McConnell, R.; Licht, S., eds. Solar Hydrogen Generation: Toward a Renewable Energy Future. New York, NY: Springer pp. 41-63; NREL Report No. CH-581-44204.

Harrison, K. W.; Martin, G. D. (2008). Renewable Hydrogen: Integration, Validation, and Demonstration. 13 pp.; NREL Report No. CP-581-43114.

Dale, N. V.; Harrison, K. W.; Han, T.; Mann, M. D.; Salehfar, H.; Dhirde, A. M. (2008). Hydrogen Dew Point Control in Renewable Energy Systems Using Thermoelectric Coolers. Proceedings of the IEEE Power & Energy Society General Meeting, 20-24 July 2008, Pittsburgh, Pennsylvania. Piscataway, NJ: Institute of Electrical and Electronics Engineers (IEEE) 6 pp.; NREL Report No. CP-581-44138. doi:10.1109/PES.2008.4596026

Collaborations

Cooperative Research and Development Agreement

- Xcel Energy – Wind2H2 demonstration project
- Proton Energy Systems (pending) – Advanced electrolyzer sub-system engineering
- FIBA Technologies (pending) – Acoustical emission testing of high pressure (800 bar) hydrogen storage tanks

Informal information sharing

- University of North Dakota/EERC
- Univ. of Minnesota (Morris, MN)
- Ft. Collins Utility (Ft. Collins, CO)

International

- International Energy Agency, Annex 24 “Wind Energy and Hydrogen Integration”
- Risø-DTU (Denmark) – Modeling and experimental verification of enhanced energy storage systems

Proposed Future Work

- Upgrade and configure system for unattended operation
- Model and test methods of electrolyzer stack sequencing for optimal hydrogen generation
- Continue refining PV- and wind-to-stack optimal sizing relationships
- Continue PV-to-PEM stack testing with upgraded system sizing
- Define and design advanced power electronics converter for close coupling 100kW wind turbine to 40kW alkaline electrolyzer
- Implement higher pressure H2 storage (800 bar)
- Test and validate electrolyzer systems from DOE awarded projects

Summary

Relevance: Addressing capital cost, efficiency and renewable energy source integration to reduce the cost per kg of hydrogen

Approach: Demonstrating advanced controls, system-level improvements and integration of renewable energy sources to electrolyzer stack

Technical Accomplishments:

- Designed, demonstrated and tested closely-coupled PV-to-PEM electrolysis system power electronic solutions comparing direct connection option with MPPT electronics option. Realized 10–20% improvement with MPPT power electronics
- Preliminary results for 3rd generation 10 kW wind-to-hydrogen system show further improvement of energy delivery to stack
- Efficiency determination for electrolyzers and compressor
- Implemented 350 bar hydrogen vehicle fueling station
- Released two major technical reports

Technology Transfer & Collaborations: Gathering feedback from and transferring results to industry to enable improved renewable and electrolyzer integration and performance. Active and informal partnerships with industry, academia and domestic/international researchers.

Proposed Future Research: Modeling and testing of methods to sequence electrolyzers for optimal hydrogen production. Perform source, electronics and stack sizing analysis based on test data. Install and use 12,000 psi hydrogen storage system, including acoustic analysis of tank integrity and use for vehicle fueling.

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NREL

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