RENEWABLE ELECTROLYSIS INTEGRATED SYSTEM DEVELOPMENT AND TESTING

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Overview

Timeline

Project start date: Sept 2003
Project end date: Oct 2011*

Barriers

G. Cost
H. System efficiency
J. Renewable integration

Funding

$ 200k (FY09)
$ 300k (FY10)
$ 450k (FY11)

Partners

- Xcel Energy
- Giner Electrochemical Systems
- Avalence
- Proton Energy Systems
- Univ. of North Dakota/EERC
- DOE Wind/Hydro Program

* Project continuation and direction determined annually by DOE

Relevance – Main Objectives

Demonstration

- Identify opportunities for system cost reduction and optimization as they pertain to electric utilities
- Characterize, evaluate, and model the integrated renewable energy systems
- Characterize electrolyzer performance with variable stack power
- Design, build, and test shared power electronics and direct-coupled renewable-to-stack configurations

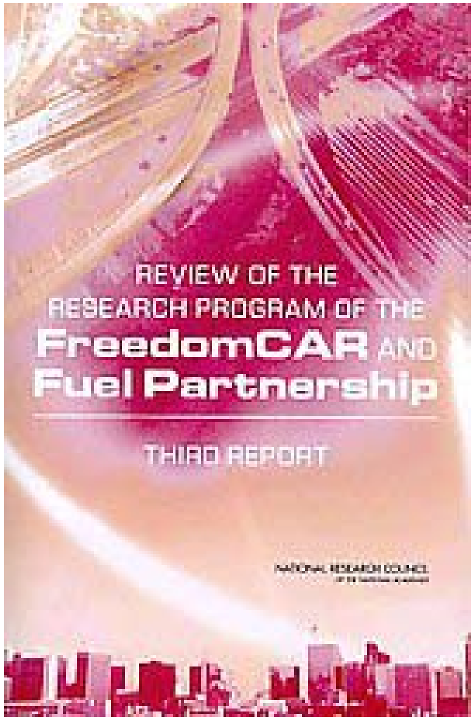
Analysis

- Develop cost models for renewable electrolysis systems
- Quantify capital cost and efficiency improvements for wind- and solar-based electrolysis scenarios

Testing

- Perform characterization and performance testing on electrolysis systems developed from DOE awarded projects
- Test electrolyzer stack and system response with typical renewable power profiles

FreedomCAR and Fuel Partnership



REVIEW OF THE RESEARCH PROGRAM OF THE FreedomCAR AND Fuel Partnership

THIRD REPORT

NATIONAL RESEARCH COUNCIL

Wind- and Solar-Driven Electrolysis

The DOE continues to study at NREL opportunities to couple wind and solar energy with electrolysis, and it has several projects to improve the efficiency of electrolyzers. The program has recently demonstrated about 70 to 71 percent efficiency at the stack level. Higher-pressure electrolyzers could be a thrust for the future and could reduce the compression energy for storage and vehicle refueling.

The hydrogen storage can be used to offset at least in part the intermittent and variable nature of the wind and solar resource. **This approach can be employed with three different energy pathways: wind to grid; wind to electrolysis unit to hydrogen; and hydrogen to fuel cell to grid.** These outputs can be varied if there is not enough demand for hydrogen for vehicle fueling.

Some of the challenges with a wind- and solar-driven electrolysis approach include efficient power electronics for dc-to-dc and ac-to-dc conversion, and controllers and communications protocols to match the source to the electrolyzer. Additional valuable data and experience can be gained by continuing the operation and upgrades of the facility at NREL.

Recommendation 4-11. Work on close coupling of wind and solar energy with electrolysis should be continued with stable funding. Further improvements in electrolyzers, including higher stack pressure, and in power electronics will benefit this application.

Relevance – Barriers Addressed

Capital Costs: R&D is needed to lower capital and improve 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.

Integrated Renewable Electrolysis Systems: These need to be developed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production.

Approach

Test, evaluate, model, and optimize the renewable electrolysis system performance for dedicated hydrogen production and electricity/hydrogen cogeneration

Systems Engineering, Modeling, and Analysis*

Develop concept platforms, develop and validate component and system models, system assessment, and optimization tools.

System Integration and Component Development

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

Characterization Testing and Protocol Development

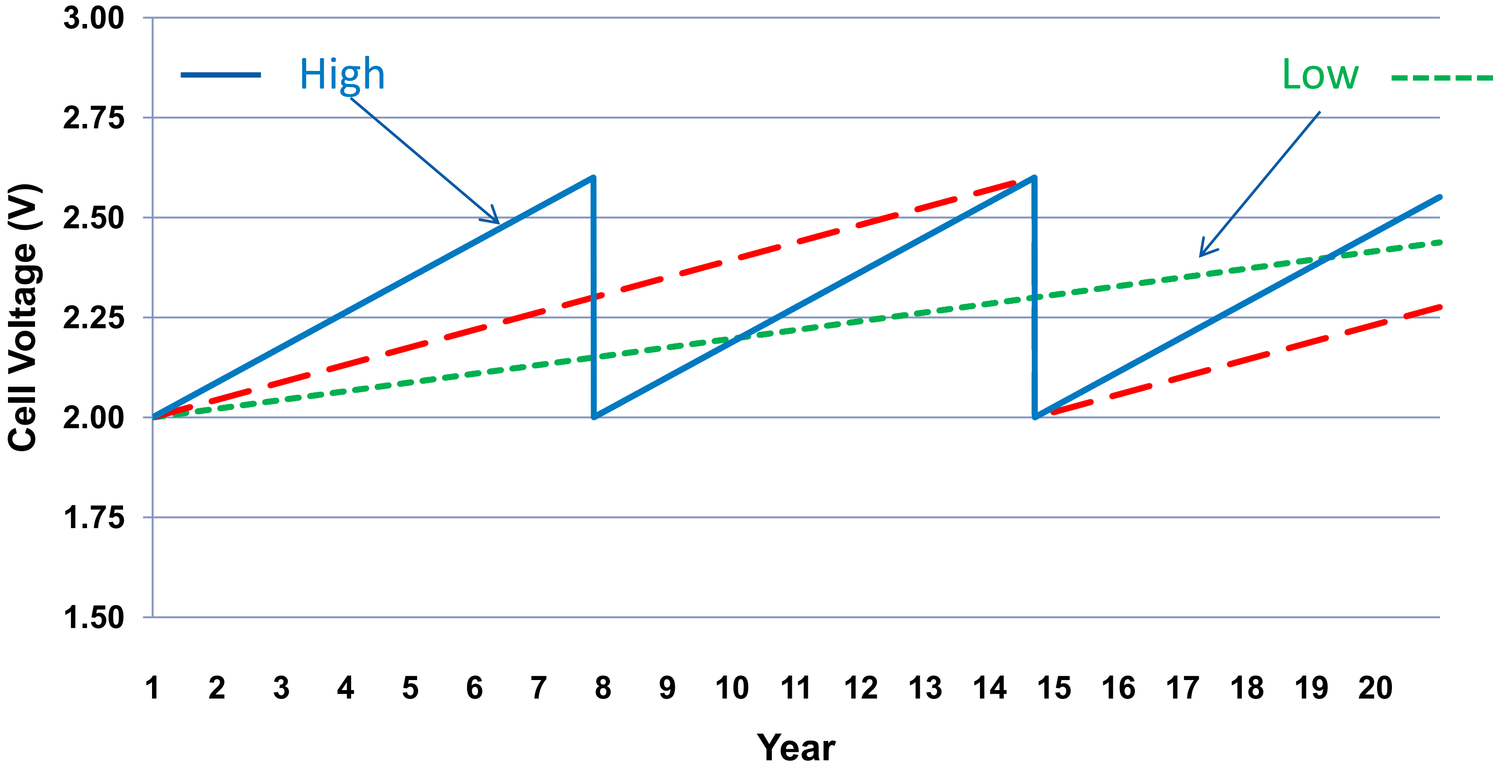
Install equipment, characterize performance, and develop standardized test procedures.

*** Analysis work presented as poster (PD085) by Genevieve Saur**

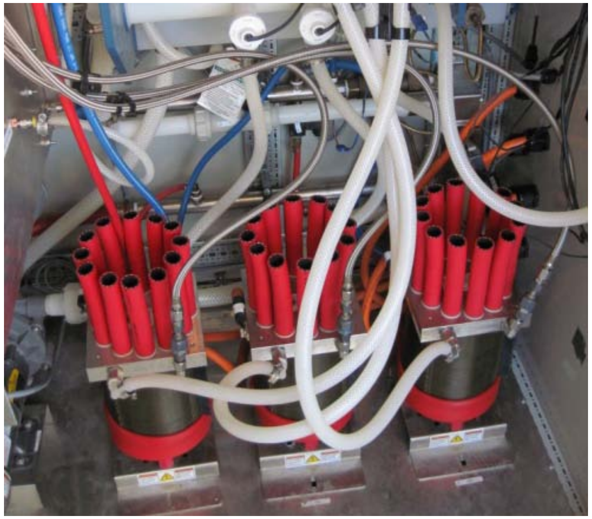
Stack Performance – Varying Current

Purpose

- Low 2.5, mid 5 and high 10 μV/cell/hr decay rate
- Means the difference between 0, 1, and 2 stack replacements in 20 years
- Lower decay rate reduces power supply and cooling system overhead



Stack Performance – Varying Current

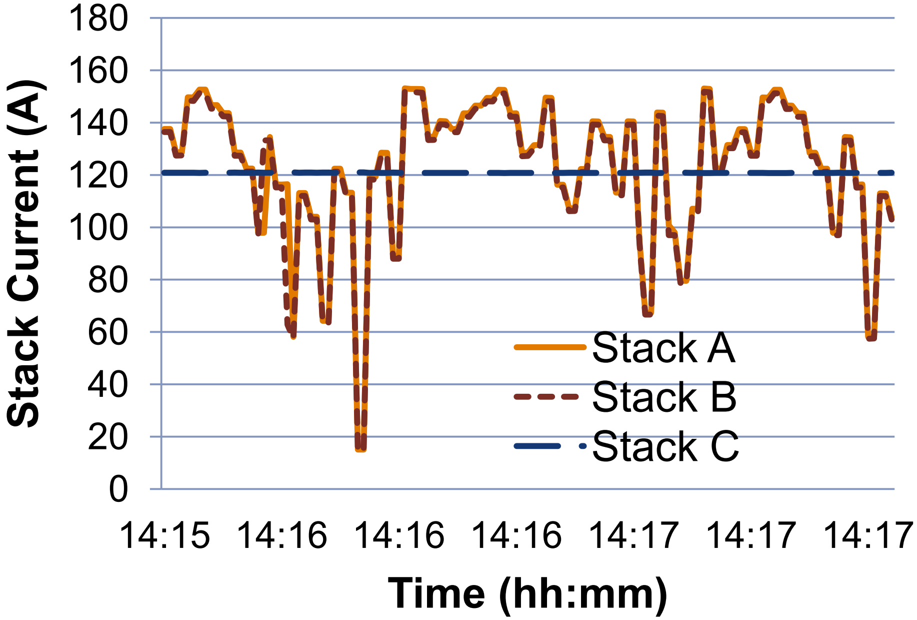


Monitoring all 3 stacks

- Input water temperature
- Output water temperature
- Stack current
- Stack voltage

Controlling Stack Currents

- Two stacks operating on varying wind energy profile (Stacks A, B)
- Third stack operating at constant current (Stack C, Steady-state operation)
- All three have same average stack current (121 A)

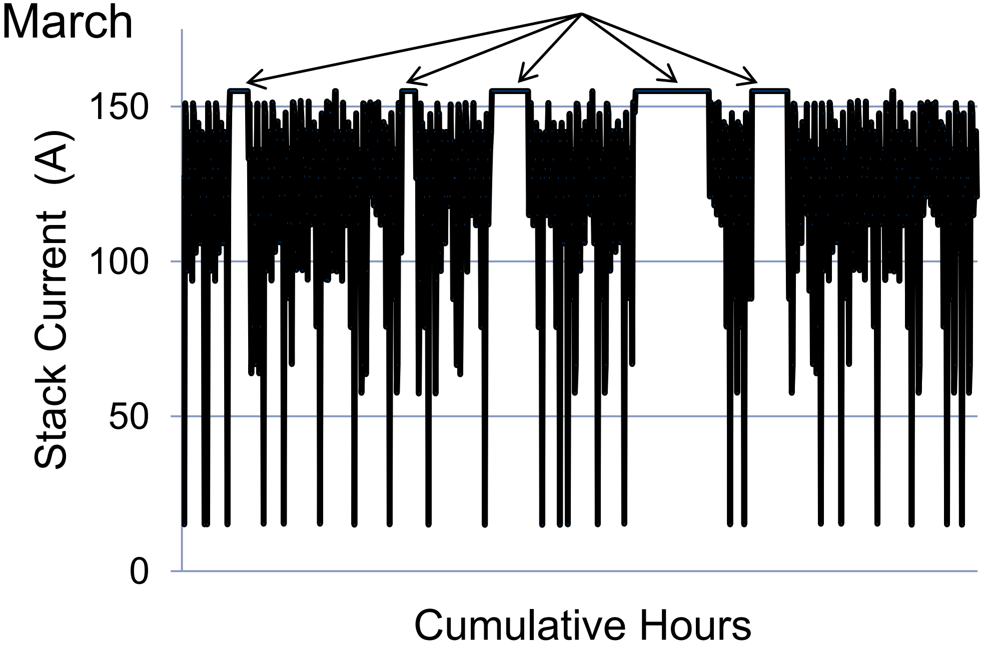


Stack Performance – Varying Current

Approach

- Analyze steady-state (SS) periods
- Followed by long periods of varying (Var) wind profile stack currents
- About 2000 hrs combined at end of March

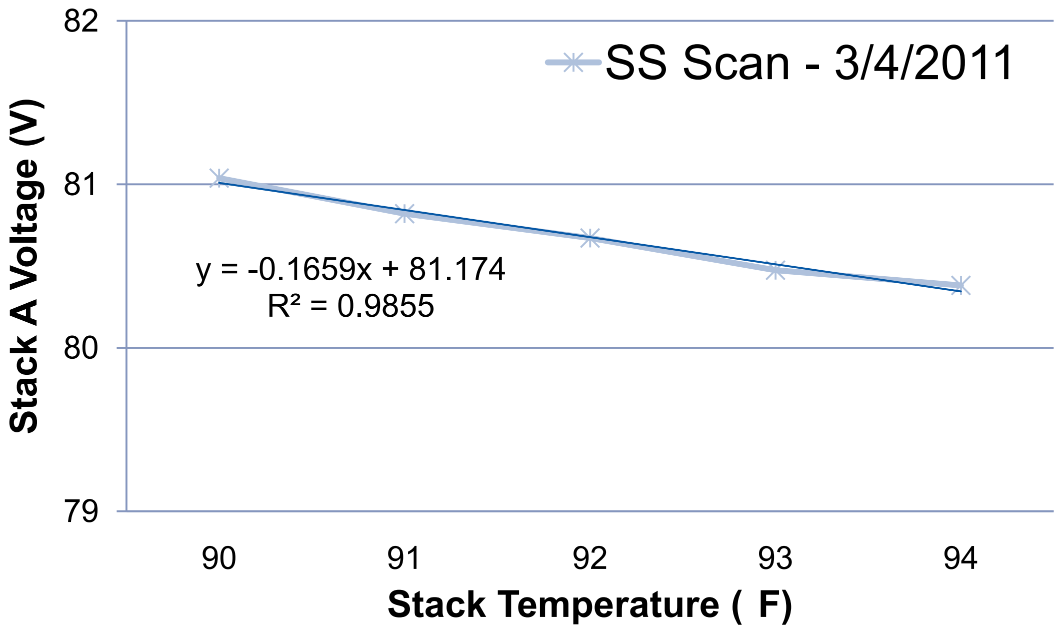
Start Date	End Date	Var Hours	SS Hours	Cumulative Hours
11/10	11/10		0.17	0.2
11/11	11/21	163.2		163.3
12/2	12/2		2.0	165.3
12/2	12/6	84.2		249.5
12/6	12/7		18.7	268.2
12/7	12/14	119.9		388.1
1/6	1/7		21.8	409.9
1/7	1/24	358.1		768.0
1/24	1/25		15.8	783.8
1/25	1/31	153.9		937.7
2/8	2/9		44.7	982.5
2/9	2/21	289		1271.5
2/23	**2/28**		**108.2**	**1379.6**
2/28	2/28	10.6		1390.2
3/1	3/2	41.7		1431.9
3/2	**3/4**		**38.3**	**1470.1**
3/4	3/29	492.1		1940.6



Steady-State Stack Current Periods

Stack Performance – Methodology

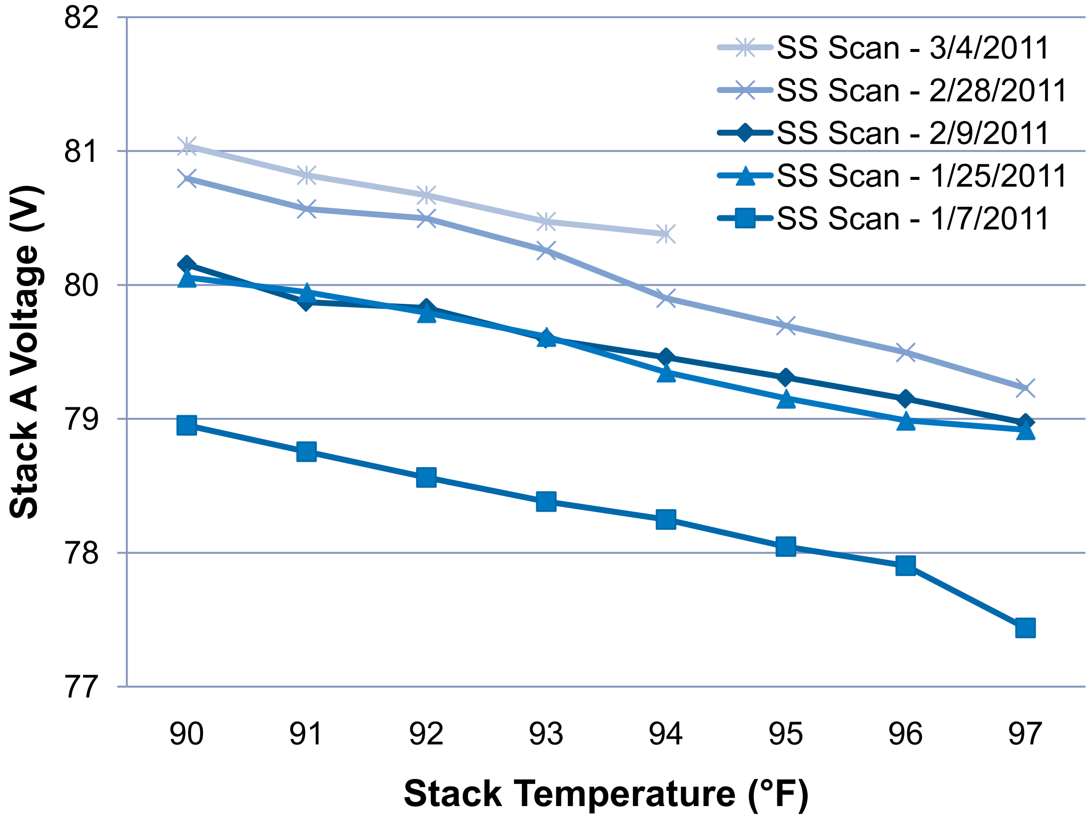
Temp Bin (F)	Stack A Index (min)	Stack A Temp (F)	Stack A Voltage (V)	Stack B Index (min)	Stack B Temp (F)	Stack B Voltage (V)	Stack C Index (min)	Stack C Temp (F)	Stack C Voltage (V)
88				1	88.80	79.54			
89	2	89.91	81.15	**49**	**89.48**	**79.39**	**34**	**89.67**	**79.59**
90	**46**	**90.60**	**81.04**	**305**	**90.74**	**79.11**	**86**	**90.67**	**79.36**
91	**120**	**91.73**	**80.82**	**994**	**91.51**	**78.96**	**852**	**91.58**	**79.21**
92	**904**	**92.59**	**80.67**	**774**	**92.40**	**78.76**	**982**	**92.47**	**79.00**
93	**961**	**93.45**	**80.47**	**173**	**93.37**	**78.77**	**322**	**93.34**	**78.92**
94	**258**	**94.27**	**80.38**				**20**	**94.11**	**78.84**
95	4	95.08	80.31						
96	1	96.18	78.88						



Steady-State

- All three stacks operated at full stack current (~150A)
- 1 minute sample rate
- < 5 minutes at temperature data eliminated
- Data further filtered based on stack current
- Stack input and output temperatures are averaged
- Narrow operating temperature
- Cold weather operation (to date)
- Linear fit – cell membrane resistance f(T)
- Data extrapolated to 40°C (104 F)

Stack A – Results (preliminary)

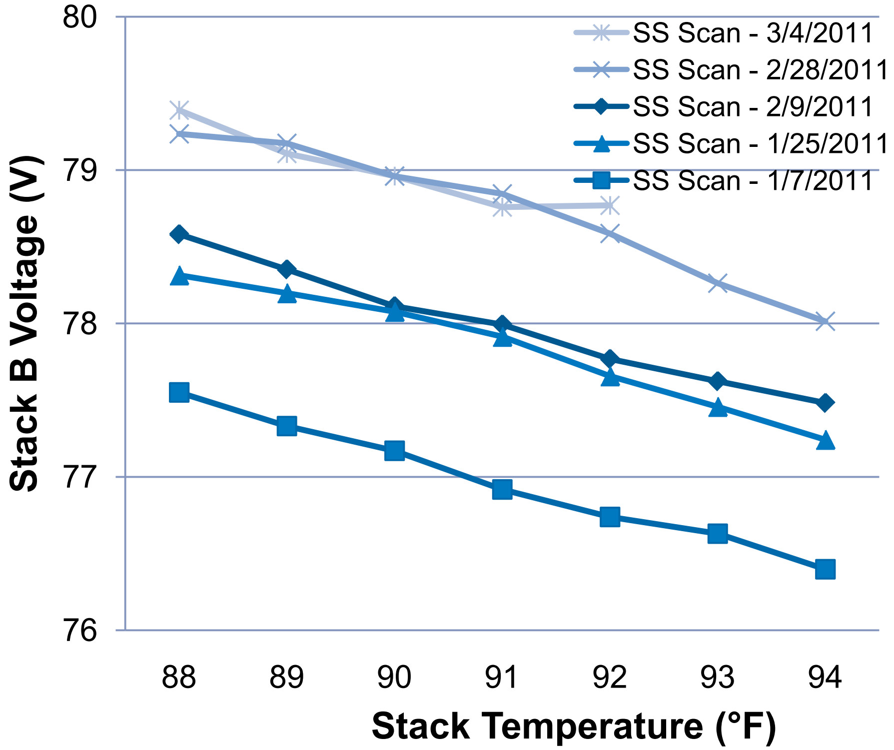


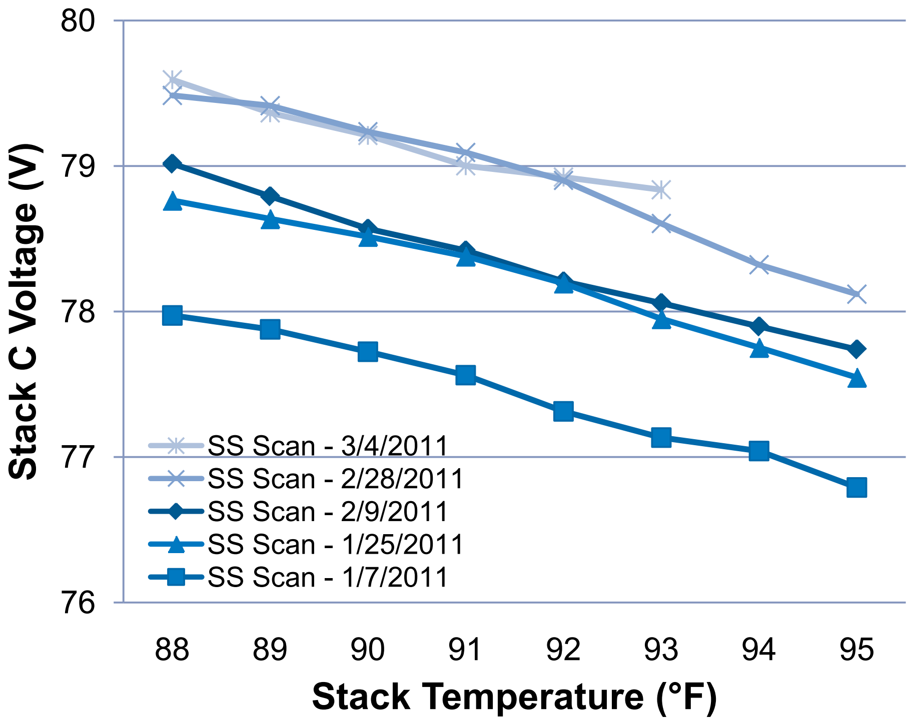
SS Scan	Linear Fit	R^2	Stack V (104°F)
1/7/2011	y = -0.1968x + 79.172	0.973	58.70
1/25/2011	y = -0.1778x + 80.278	0.9867	61.79
2/9/2011	y = -0.1616x + 80.27	0.9907	63.46
2/28/2011	**y = -0.227x + 81.077**	**0.9877**	**57.47**
3/4/2011	y = -0.1659x + 81.174	0.9855	63.92

Data for all SS Scans

- Steady state scans nested between 100 – 500 hours of varying stack current
- **2/28 SS data** – Longest SS period (108.2 hrs) produced steeper slope than shorter SS periods
- Results suggest anode catalyst oxidation state may have role in transient voltage behavior

Stack B & C – Results (preliminary)





SS Scan	**Linear Fit**	**R^2**	**Stack V (104°F)**
1/7/2011	y = -0.1891x + 77.718	0.9939	58.05
1/25/2011	y = -0.1829x + 78.569	0.9826	59.55
2/9/2011	y = -0.1823x + 78.717	0.9909	59.76
2/28/2011	**y = -0.2096x + 79.564**	**0.9658**	**57.77**
3/4/2011	y = -0.1592x + 79.475	0.914	63.57

SS Scan	**Linear Fit**	**R^2**	**Stack V (104°F)**
1/7/2011	y = -0.1724x + 78.202	0.99	60.27
1/25/2011	y = -0.1764x + 79.01	0.9851	60.66
2/9/2011	y = -0.1804x + 79.149	0.9951	60.39
2/28/2011	**y = -0.2037x + 79.813**	**0.9745**	**58.63**
3/4/2011	y = -0.1516x + 79.686	0.9668	63.92

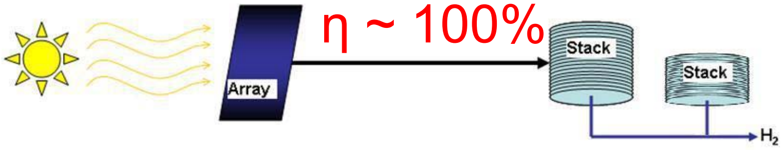
Direct Coupling v. Power Converter

Types of Losses in Power Converter

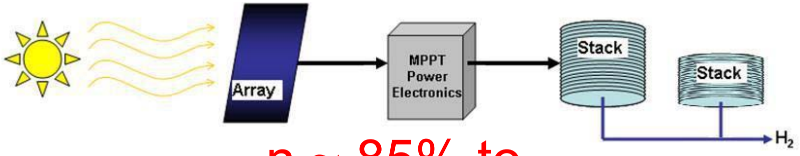
Conduction
- Transistor On Resistance and Voltage
- Diode On Resistance and Voltage

Switching
- Transistor Turn Off
- Diode Reverse Recovery

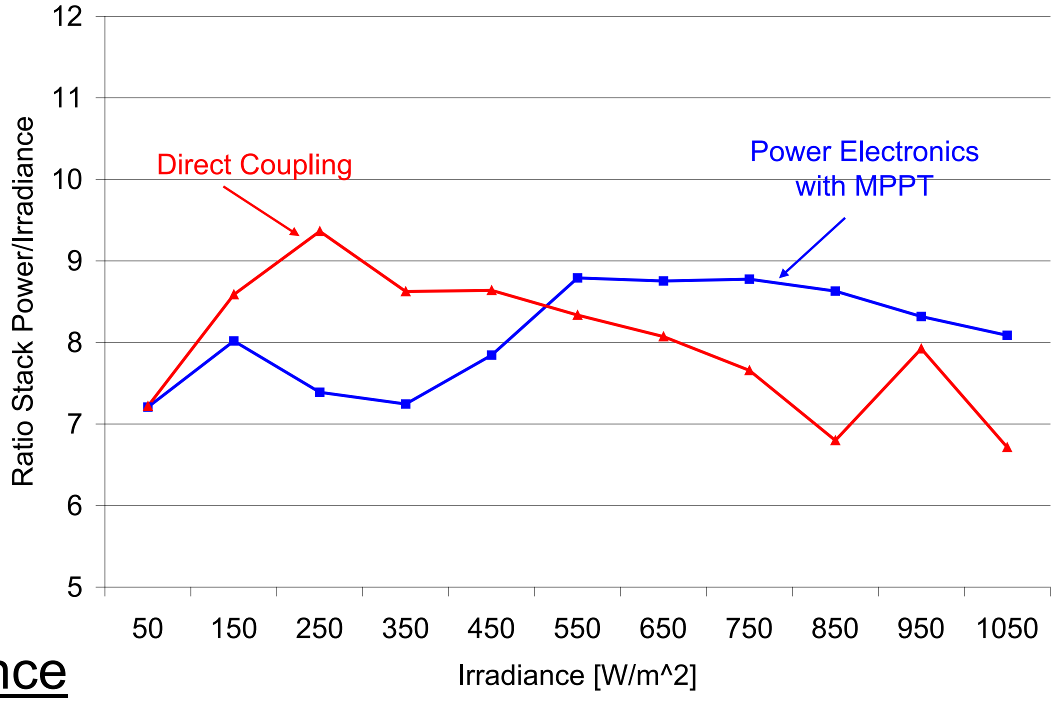
Magnetic
- Inductor



η ~ 100%



η ~ 85% to 92%



Power Converter Performance

- Suffered at low irradiance due in-part to switching/diode losses representing larger percentage of available power

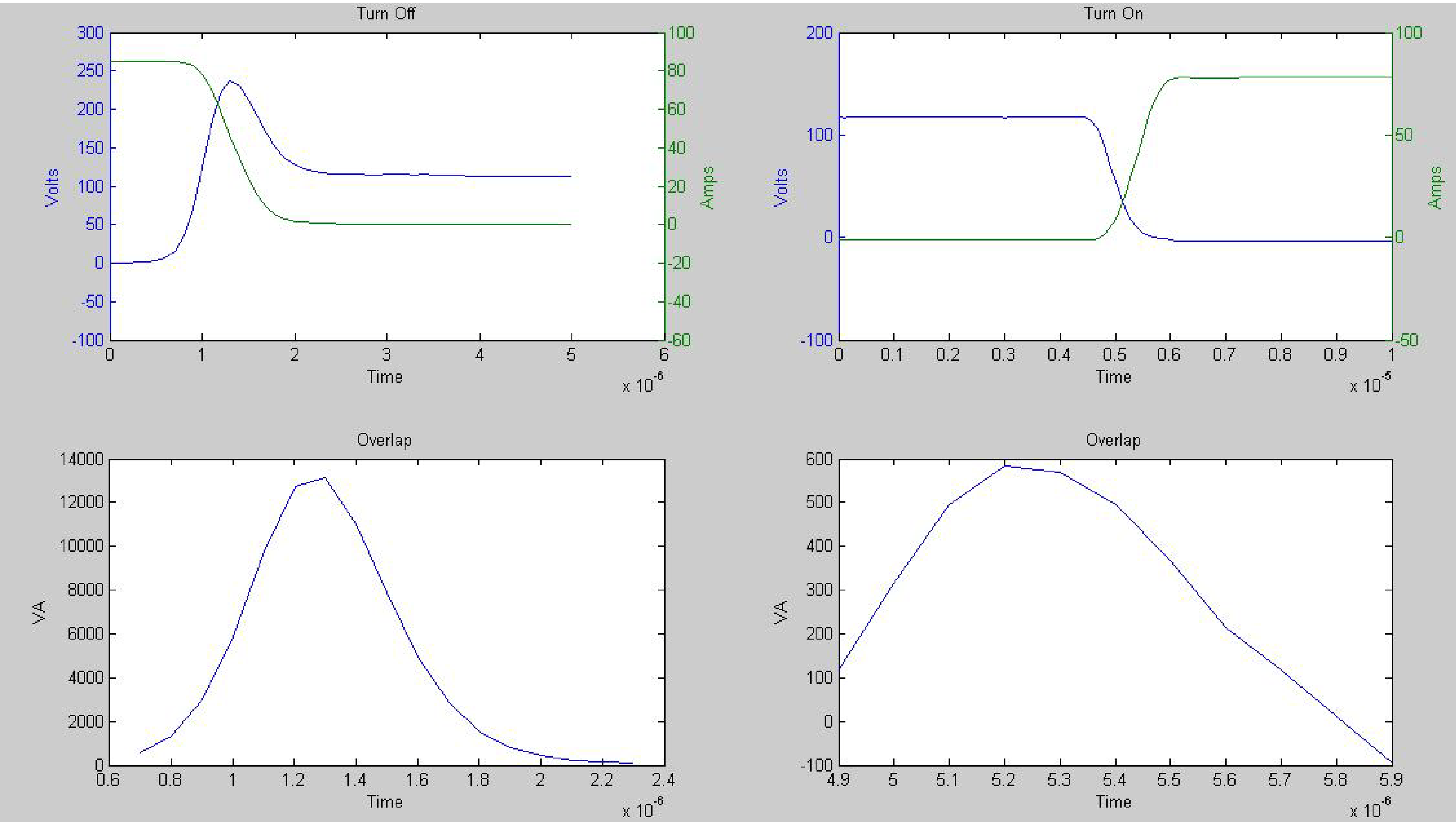
Direct Coupling v. Power Converter

Power Converter Loss Mechanisms

- t_r – diode reverse recovery time
- V_{in} – relatively constant over wide irradiance
- Switching losses relatively constant

Opportunities

- Faster diode → Reduce diode recovery
- Reduce inductor → Reduce I^2R losses
- MOSFET → Reduce switching losses



DOE Awarded System Testing

NREL Infrastructure Improvements

- Test facility adjacent to Wind-to-Hydrogen Production building
- 480/208V, 3p, 75 kVA transformer
- Water, cooling, and hydrogen services

Giner Electrochemical Systems

Expected delivery in May/June 2011

- **Improved stack performance**

Used by Permission, M. Hamdan, March 2011

Avalence, LLC

Expected delivery in late 2011

- **High stack pressure operation**

350 bar Vehicle Fueling System

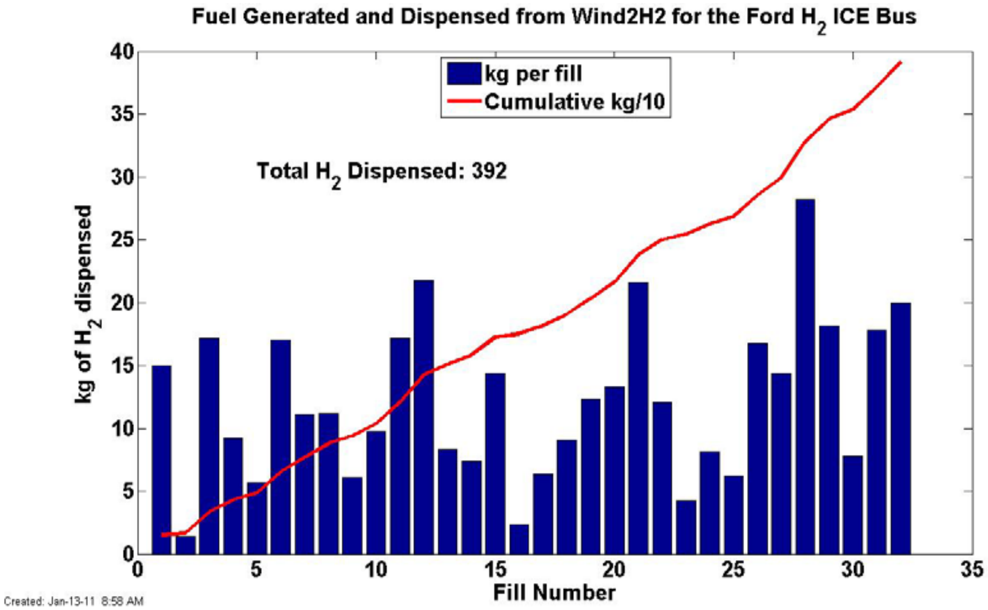
Installed 6 additional 6000 psi storage tanks

- Online October 2010
- 250 kg total at 3500 psi and 6000 psi

Gas Management Panel

- Enabling cascade filling (3 banks, 135 kg)

Ford H2 ICE (30 kg)



Experimental Results & Operational Lessons Learned

Implications for Electric Utilities, Component Suppliers, and Hydrogen-Based Energy Storage Systems Integrators

NREL is expanding its work with the electrolyzer industry, utilities and system developers

- AREVA/Helion
- Greensburg, KS
- West Wind Works
- RE2H2 Energy Development

AREVA's integrated FC emergency gen-set

Collaborations

Cooperative Research and Development Agreement

- Xcel Energy – Wind2H2 demonstration project
- Proton Energy Systems (pending) – Advanced electrolyzer sub-system engineering, energy storage and All Renewable Electrolyzer

Information sharing

- Hydrogen Utility Group
- Electrolyzer manufacturers
- University of North Dakota
- Energy & Environmental Research Center (Grand Forks, North Dakota)
- Ft. Collins Utility (Ft. Collins, Colorado)

International

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

Future Work

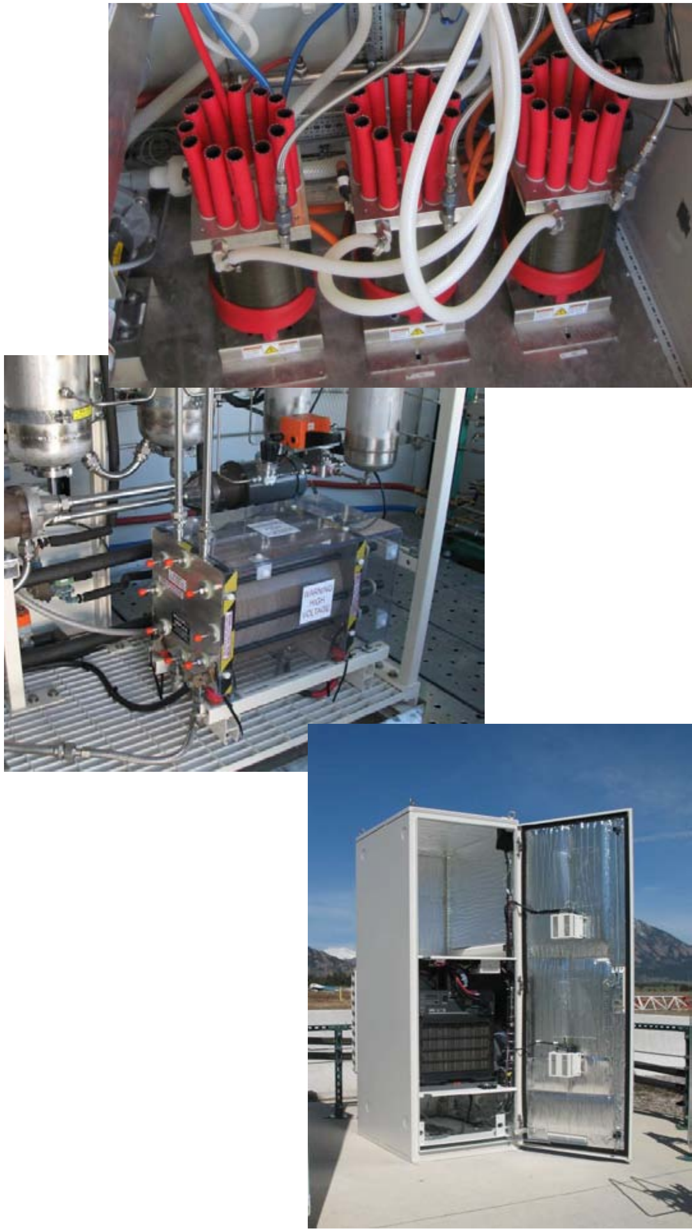
Multiple Stack Configuration

- Three stacks equaling 15kW, ~110Vdc
- Electrical isolation challenges
- Electrically floating stack ground operation
- Bi-polar operation for use with utility-scale wind turbines

Wind Close-Coupling v. Power Converter

- Using results from multiple stack configuration testing
- Passive rectifier v. Active rectifier
- Reduced capital cost and improved efficiency with wind energy systems

Future Work



PEM Variable Stack Current Testing

- Improve understanding of stack transient voltage
- Steady-state periods preceded by few hours shutdown/off and longer durations (~100+ hrs)

Alkaline Variable Stack Testing

- New stack installed and commissioned 2Q FY11
- Trouble keeping balance-of-plant running for long duration

Integrated Renewable Energy System

- Dynamic response of 5 kW fuel cell with PV and wind
- Long-duration operation
- Improved integration with renewable energy systems

Summary

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

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

Technical Accomplishments:

- 13 kg/day PEM electrolyzer running 24/7 with stack monitoring
- Continued comparison testing of direct-coupling PV array with MPPT power converter.
  - Exploring loss mechanisms and opportunities for improvement
- Operating 2 (of 3) stacks with wind profile for stack decay comparison. ~2000 hrs
  - Comparison of voltage decay rates of steady-state and variable stack current operation
  - Improving understanding of short-term voltage transients
- Completed installation, commission and cascade fueling of H2ICE shuttle

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:

- Multiple stack testing
- Wind turbine to multiple stacks coupling R&D
- Alkaline stack operating on wind profile
- Integrated renewable energy system investigating FC, PV and battery dynamic response

Supplemental Slides

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