#### **Innovation for Our Energy Future**

## Renewable Electrolysis Integrated System Development and Testing

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This presentation does not contain any proprietary or confidential information.

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#### **Overview**

#### **Timeline**

Project Start Date: 9/2003 Project End Date: Ongoing

#### **Budget**

**Total Project Funding:** 

FY05 - **\$400K** 

FY06 - **\$625K** DOE

- \$1.3M Industry cost share

FY07 - **\$1M** DOE

#### **Production Barriers**

- G. Cost
- H. System efficiency
- J. Renewable integration

#### **Partners**

- Xcel Energy
- Distributed Energy Systems
- Teledyne Energy Systems
- Hydrogen Engine Center
- Univ. of North Dakota
- Univ. of Minnesota
- Basin Electric
- Ft. Collins Utilities
- DOE Wind/Hydro Program

### **Project Objectives**

This project examines the issues with using renewable energy to produce hydrogen by electrolyzing water.

- Characterize electrolyzer performance under variable input power conditions and develop standard testing procedure.
- Design, build and test shared power electronics packages and controllers to reduce cost and optimize system performance.
- Identify opportunities for system cost reduction through breakthroughs and incremental improvements in component integration focused on commercialization and manufacturability.
- Test, evaluate, model and optimize the renewable electrolysis system performance for both dedicated hydrogen production and electricity/hydrogen cogeneration.

### Renewable Electrolysis

#### **Verify DOE goals of:**

#### **Distributed electrolysis**

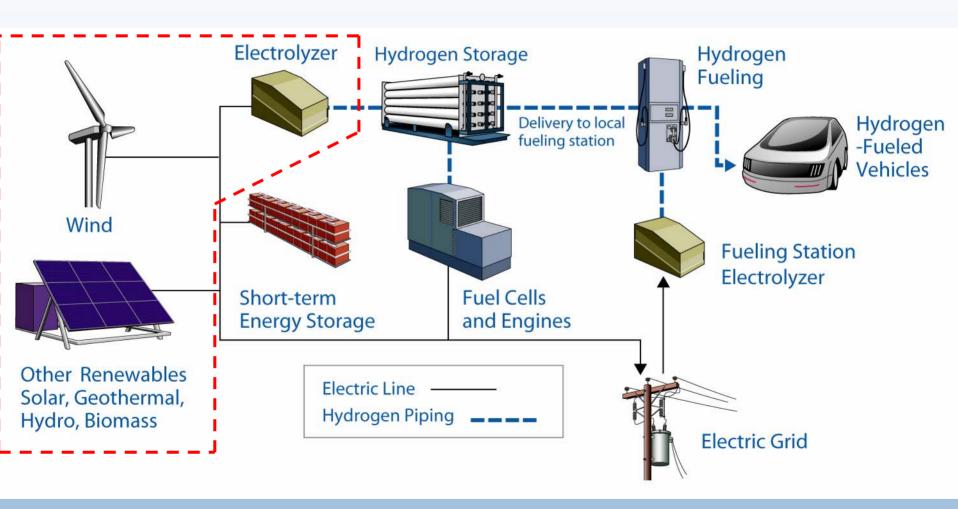
- By 2012, reduce the cost of distributed production of hydrogen from distributed electrolysis to \$3.70/gge of H2 (delivered) at the pump.
- By 2017, reduce the cost of distributed production of hydrogen from distributed electrolysis to <\$3.00/gge of H2 (delivered) at the pump.

#### **Central Electrolysis**

- By 2012, reduce the cost of central production of hydrogen from wind electrolysis to \$3.10/gge of H2 at plant gate (\$4.80/gge delivered),
- By 2017, reduce the cost of central production of hydrogen from wind electrolysis to <\$2.00/gge of H2 at plant gate (<\$3.00/gge delivered).



## **Project Background**Importance and Need – Project Focus



### **Project Tasks**

#### 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**

Equipment installation, performance characterization, and standard test procedure development



### **Technical Accomplishments**

#### Systems Engineering, Modeling, and Analysis

Summary report of electrolytic hydrogen production

Developed model and simulation of 10 kW WT and 6 kW PEM electrolyzer stack

#### **System Integration and Component Development**

Developed and tested second generation power electronics interface between 10 kW WT and electrolyzer

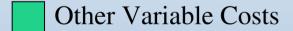
#### **Characterization Testing and Protocol Development**

Stack and system level analysis of performance



### **Electrolysis Analysis**

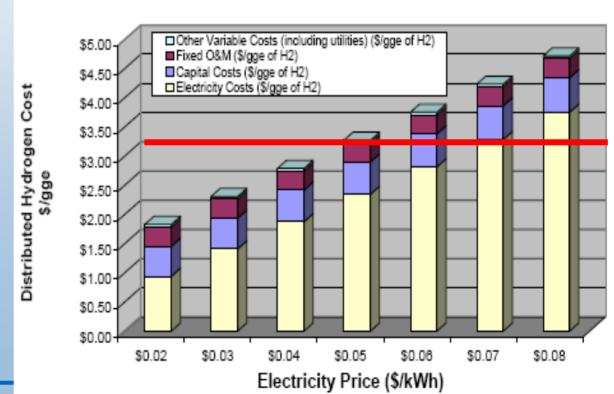
- Updated "Summary of Electrolytic Hydrogen Production" report.
- Current cost of hydrogen via electrolysis



Fixed O&M

Capital Costs

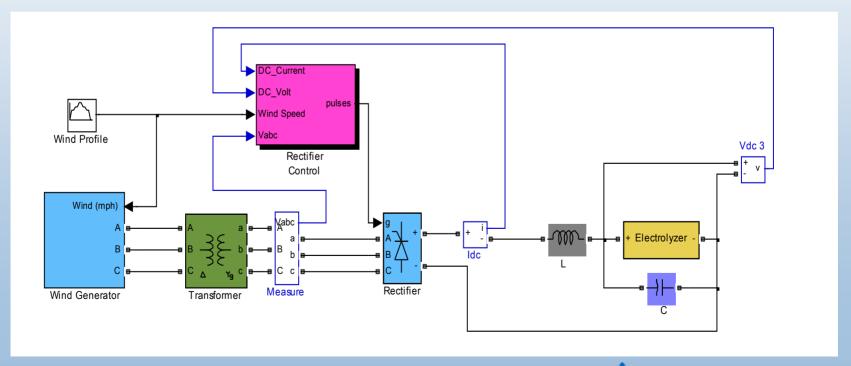
Electricity Costs



### **FY07 Technical Accomplishments**

Systems Engineering, Modeling, and Analysis

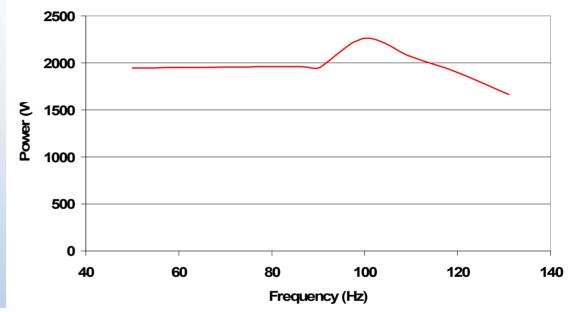
- Simulated wind turbine to stack system with Simulink
- Compared model and PE to explore gate-firing discrepancies and enhance control algorithm.

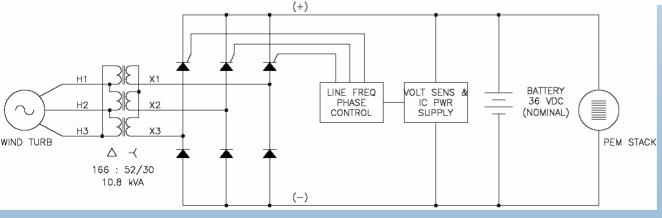


### FY07 Gen1 PE Test Results

#### **System Integration and Component Development**

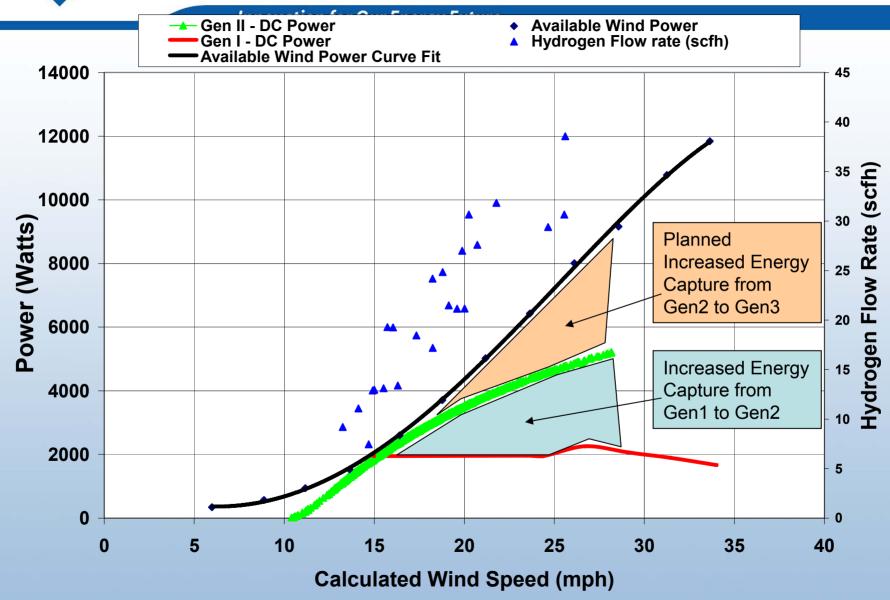
- Gen1 PE for 10kW WT
- Battery interaction at lower frequency and state-of-charge
- Big opportunity for optimization







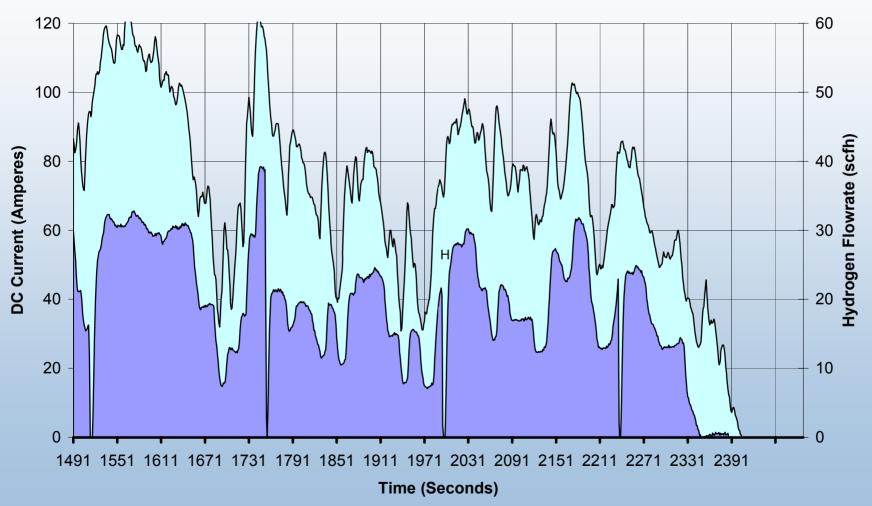
### NREL National Renewable Energy Laboratory



### FY07 Gen2 PE Interim Test Results

#### **System Integration and Component Development**





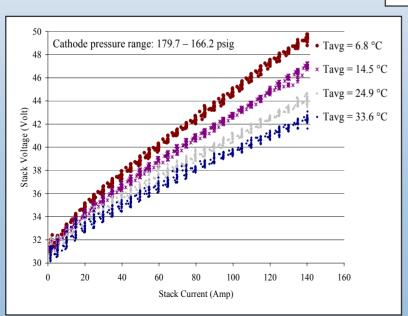
Hydrogen Production and Current as a function of Time

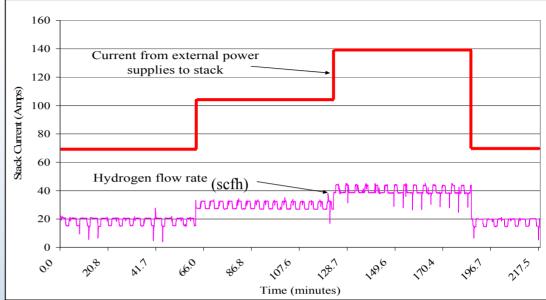
NREL National Renewable Energy Laboratory

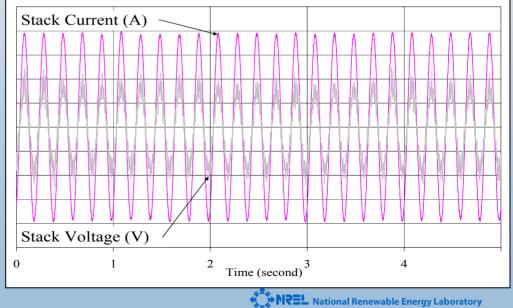
### **FY07 Technical Accomplishments**

#### Characterization

- Stack level perspective
- Current control
- Step and frequency response
- Polarization curves f(T)



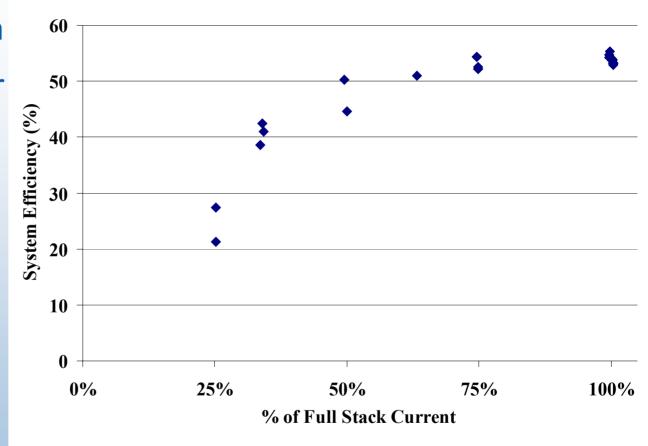




### **FY07 Technical Accomplishments**

#### Characterization

- Single electrolyzer system-level perspective
- Efficiency suffers at low current
- Working with industry to improve opportunity for RE electrolysis



### **Xcel-NREL Wind2H2 Collaboration**



#### **Benefits of the Collaboration:**

- Examine benefit to utility by shifting wind production in time
- Research optimal wind/hydrogen through systems engineering
- Characterize and control wind turbine and H2-producing stack
- Evaluate synergies from co-production of electricity and hydrogen
- Compare alkaline and PEM electrolyzer technologies
- Realize efficiency gains though a unique integrated PE

# Xcel-NREL Wind2H2 Collaboration Component Integration

 Electrolyzers of both PEM and alkaline technologies.





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 Ability to accommodate the varying energy input from wind and PV

### **Xcel-NREL Wind2H2 Collaboration**

### **Direct Coupling**

 Variable speed wind turbines directlycoupled to the hydrogen-producing stacks of commercially available electrolyzers.



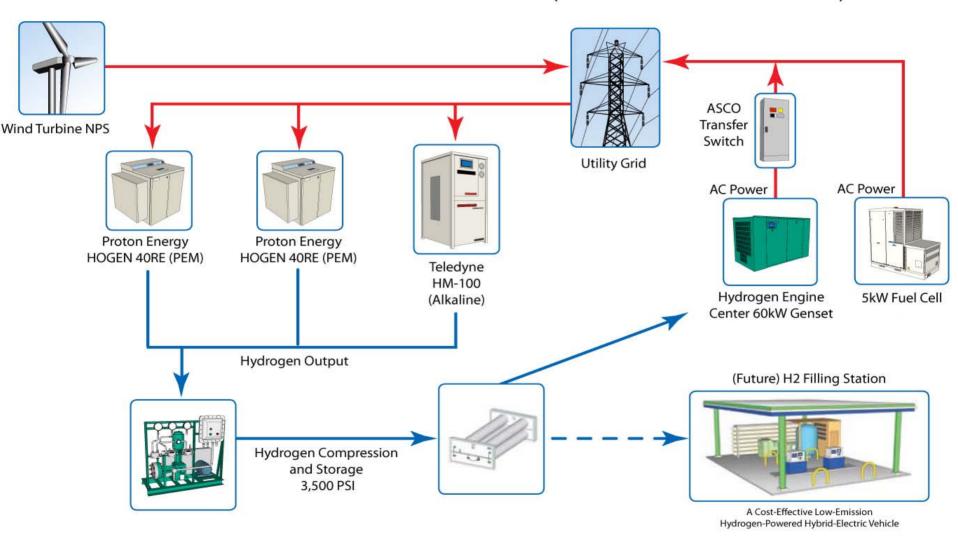


DC varying with wind speed



### **FY07 Testing**

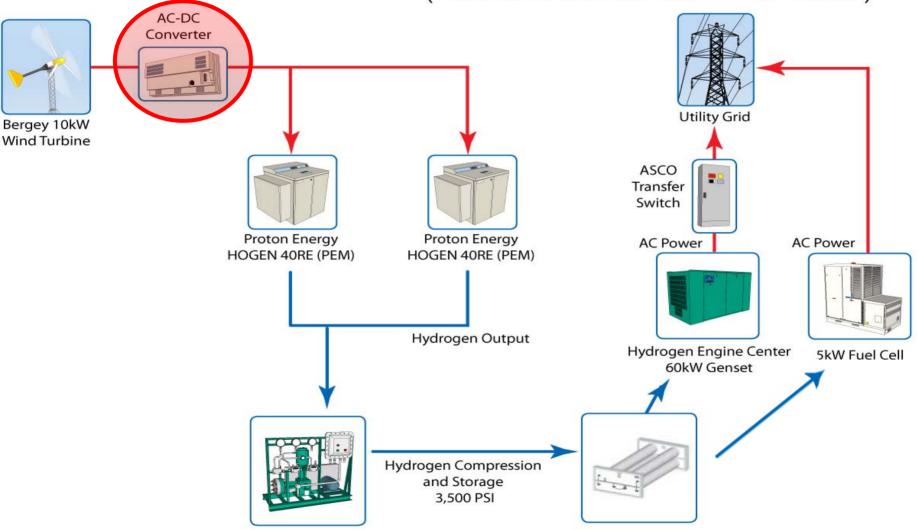
### Wind2H2 Testing Configuration I (AC Grid Connected Baseline)





### FY07 Testing

### Wind2H2 Testing Configuration III ("Wild AC to DC from 10kW Wind Turbine)





### **Xcel-NREL Wind2H2 Collaboration**

Dick Kelly (Xcel) and Dan Arvizu (NREL) shake hands after pushing button to light H2 sign and dedicate system in December 2006

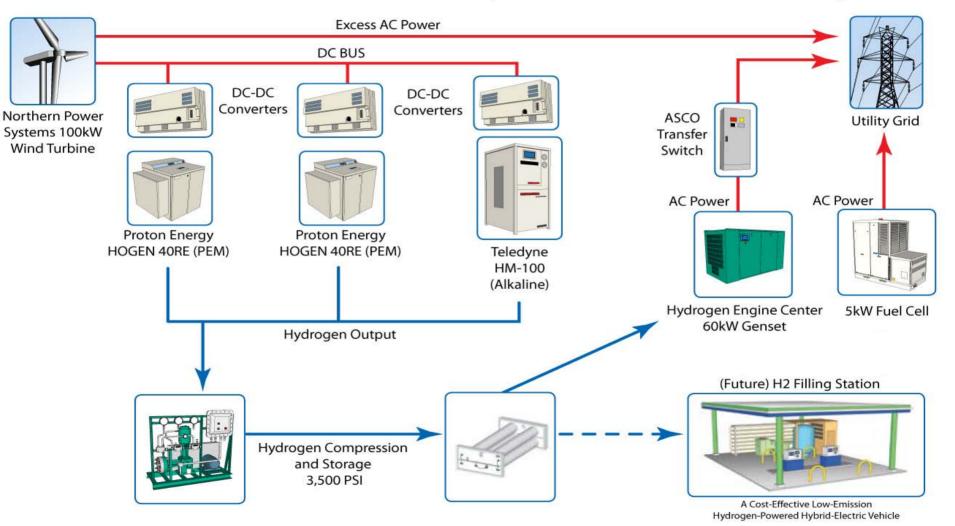






### **Future Work FY08 Testing**

### Wind2H2 Testing Configuration II (DC/DC from 100kW Wind Turbine)





#### Added Value from Collaboration

- Timetables originally parallel
- Inter-project collaboration, data sharing and H2 safety
- Welcome additional partners to the informal renewable electrolysis collaborative

Coordinated "Wind Storage"

AC/DC and DC/DC Interface

· Re-deployable

Basin Electric
Univ. of N. Dakota

Hydrogen Utility
Group (HUG)

NREL and

**Xcel Energy** 

Fort Collins
Utilities &
Colorado OEMC

- Larger Scale "Wind Storage"
- Vehicle Applications
  - Larger Scale "Wind Storage"
  - Anhydrous Ammonia Production
  - Vehicle & Hybrid Applications

- High-Pressure Electrolysis
- Vehicle Fueling Station & FC
- Hydrogen/Natural Gas Mixing

University of Minnesota

National Renewable Energy Laboratory

### **Path Forward**

- FY07 Operation of Wind2H2 Project in Grid and small WT
  - Test high-pressure PEM electrolyzer
- FY08 Design, built and test of PE for 100kW WT to stacks
  - Complete standard test protocol development for renewable-electrolyzer performance and operation
  - Model/simulation of renewable-electrolyzer performance
- FY09 Test and validation support for DOE Electrolysis-based
   Hydrogen Production projects
- R&D MW-scale wind to electrolysis components and systems

### **Summary Slide**

- Economic analysis shows that renewable electrolysis can meet DOE hydrogen cost targets
- Integrate components and engineer systems to increase efficiency and reduce cost of renewable electrolysis
- Multi-partner collaborative effort to evaluate renewable electrolysis and share safety and operational experience. (industry, universities, utilities, government)
- Work with HUG to examine how utilities can effectively produce and use hydrogen



### **Additional Slides**

 The following slides are included as supplemental information.

### **Project Timeline**

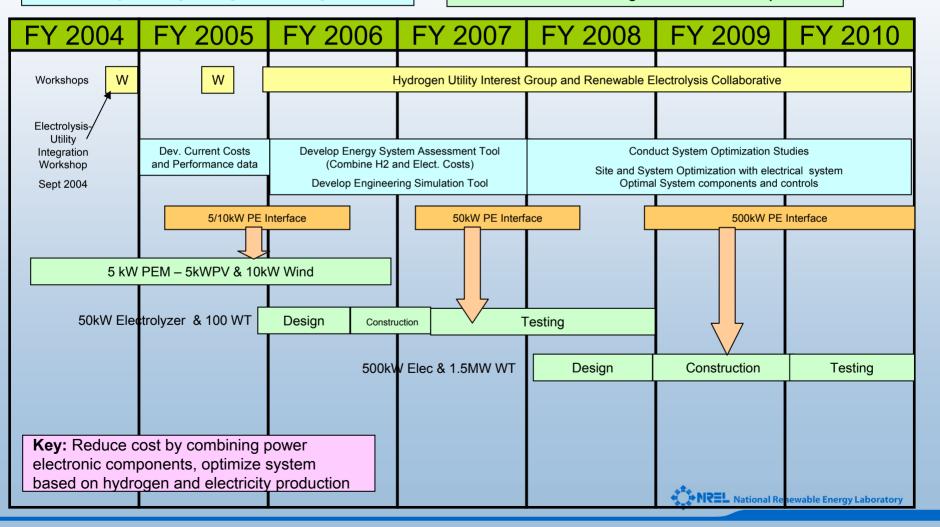
Renewable Electrolysis - Integrated Systems Development and Testing

Coordination, Planning and Stakeholder Development

System Engineering and Modeling

System Engineering and Modeling

Characterization Testing and Protocol Development



### **Distributed Electrolysis Targets**

Table 3.1.4 Technical Targets: Distributed Electrolysis Hydrogen Production a,b,c					
Characteristics	Units	2003	2006°	2012	2017
		Status	Status	Target	Target
Hydrogen Cost	\$/gge	5.15	4.80	3.70	<3.00
Electrolyzer Capital Cost <sup>d</sup>	\$/gge	N/A	1.20	0.70	0.30
	\$/kW	N/A	665	400	125
Electrolyzer Energy Efficiency <sup>f</sup>	%	N/A	62	69	74
	(LHV)				

Table 3.1.4A Distributed Electrolysis H2A Example Cost Contributions <sup>a,b,c</sup>					
Characteristics		Units	2006° Status	2012	2017
Electrolysis Unit	Cost Contributiond	\$/gge H2	1.20	0.70	0.30
	Capacity Factor <sup>e</sup>	%	70	70	70
	Energy Efficiency <sup>f</sup>	% (LHV)	62	69	74
Compression, Storage, Safety and Dispensing <sup>g,h,i,k</sup>	Cost Contribution	\$/gge H2	0.60	0.40	0.30
	Energy Efficiency	% (LHV)	93.8	93.7	95.0
O&M	Cost Contribution	\$/gge H2	0.80	0.60	0.40
Electricity	Cost Contribution	\$/gge H2	2.20	2.00	1.80
Total <sup>m</sup>	Energy Efficiency	% (LHV)	60.0	66.2	71.0
	Cost	\$/gge H2	4.80	3.70	<3.00

### **Central Wind Electrolysis Targets**

Table 3.1.5 Technical Targets: Central Wind Electrolysis <sup>a,b</sup>					
Characteristics	Units	2006° Status	2012 Target	2017 Target	
Hydrogen Cost (Plant Gate)	\$/gge H2	5.90	3.10	<2.00	
Electrolyzer Capital Cost <sup>b,d</sup>	\$/gge H2 \$/kW	2.20 665	0.80 350	0.20 109	
Electrolyzer Energy Efficiency <sup>e</sup>	% (LHV)	62	69	74	

Table 3.1.5A Central Wind Electrolysis H2A Example Cost Contributions <sup>a,b</sup>					
Characteristics		Units	2006° Status	2012	2017
Wind Farm <sup>f</sup>	Cost Contribution	\$/gge H2	2.50	2.10	3.00
	Capacity Factor	%	41	50	54
Electrolysis Unit	Cost Contribution <sup>d</sup>	\$/gge H2	2.20	0.80	0.20
	Capacity Factor	%	44	58	77
	Energy Efficiency <sup>e</sup>	% (LHV)	62	69	74
O&M	Cost Contribution	\$/ggeH2	1.50	0.80	0.80
By-product Electricity	Cost Contribution <sup>9</sup>	\$/gge H2	-0.30	-0.60	-2.00
	Percentage of electricity produced sold as by-		40	0.7	50
	product <sup>h</sup>	%	10	27	59
Total	Cost	\$/gge H2	5.90	3.10	<2.00

### **Technical Barriers**

- **Electrolysis**: Capital cost reductions and efficiency improvements are required along with the design of utility-scale electrolyzers capable of grid integration and compatible with low-cost, near-zero emission electricity sources.
- Capital Cost. The capital costs of electrolysis systems are prohibitive to widespread adoption of electrolysis technology for hydrogen production. R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital while improving the efficiency and durability of the system.
- System Efficiency. New membrane, electrode, and system designs are needed to improve system efficiency and durability. Development is needed for low-cost cell stack optimization addressing efficiency, compression, and durability.

### **Hydrogen Utility Group (HUG)**

This Project has also worked with HUG

Dedicated group committed to exploring the unique perspective utilities bring to the hydrogenelectric future

Utilities: DTE Energy, Sacramento Municipal Utility District, Nebraska Public Power District, Connexus

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Energy, BC Hydro, KEPRI Nuclear Power Laboratory, Arizona Public Service Company, Entergy, Xcel Energy, Southern California Edison, Fort Collins Utilities, New York Power Authority, Southern Company, and Sempra Energy.

Supporting Organizations: DOE, NREL, EPRI, NHA

