Overview of U.S. Department of Energy Efforts on Hydrogen Production from Water Electrolysis

ElectroHyPEM Workshop

December 11, 2014

Taormina, Italy

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U.S. Department of Energy

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Los Alamos National Laboratory
• U.S. DOE Hydrogen and Fuel Cell Program
• Hydrogen Production SubProgram
• Electrolysis Workshop
• H2A Production Model
• Electrolysis Accomplishments/Types
• Renewable Electrolysis
DOE Program Overview

The Program is an integrated effort, structured to address all the key challenges and obstacles facing widespread commercialization.

More than 200 projects currently funded at companies, national labs, and universities/institutes.

Basic & Applied Research and Technology Development

Hydrogen Fuel R&D
- Production
- Delivery
- Storage

Fuel Cell R&D

Technology Validation

Market Transformation

Systems Integration & Analysis

Manufacturing R&D

Safety Codes & Standards

Education

WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS
- Transportation
- Stationary Power
- Auxiliary Power
- Backup Power
- Portable Power

The DOE Hydrogen and Fuel Cells Program Plan Released Sept 2011
Update to the Hydrogen Posture Plan (2006)
Includes Four DOE Offices
EERE, FE, NE and Science
DOE Activities Span from R&D to Deployment

DOE’s RDD&D activities are enabling commercialization of fuel cells

Research & Development

- **50% reduction since 2006**
- **80% electrolyzer cost reduction since 2002**

Fuel Cell System Cost*

![Graph showing fuel cell system cost reduction over years](image)

Status Today ($55/kWh)

Goal $30/kWh)

*At 500,000-unit production

Demonstration

- **>180 FCEVs**
- **25 stations**
- **3.6 million miles traveled**
- **World’s first tri-gen station**
  (250 kW on biogas, 100 kg/d H₂ produced)

Deployment

- **Government Early Adoption**
  (DoD, FAA, California, etc.)
- **Tax Credits: 1603, 48C**
- **~1,600 fuel cells deployed**
- **DOE Recovery Act & Market Transformation Deployments**

![Map showing FC units deployment in states](image)
Hydrogen Production & FCEVs

- Fueling infrastructure is needed in the immediate near-term
- Traditional sources (NG) meet near-term H₂ demand, but large-scale production from renewable sources will be needed in long-term

<table>
<thead>
<tr>
<th>Number of Fuel Cell Cars Served</th>
<th>Hydrogen Demand (metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily ¹</td>
<td>Yearly</td>
</tr>
<tr>
<td>1 million</td>
<td>~780</td>
</tr>
<tr>
<td>250 million</td>
<td>~137,000</td>
</tr>
</tbody>
</table>

¹Based on “Transitions to Alternate Transportation Technology - A Focus on Hydrogen” NRC 2008

Major merchant suppliers
- Air Products and Chemicals
- Airgas, Inc.
- Air Liquide
- BOC India Limited
- Linde AG
- Praxair Inc.
- Taiyo Nippon Sanso Corp.

Global Hydrogen Production, by Technology, 2009
- ~95% of U.S. H₂ production comes from SMR
- 48% Steam Reforming of Methane
- 18% Partial Oxidation of Oil
- 30% Gasification of Coal
- 4% Electrolysis of Water

- ~9M Mt (US)

U.S. Hydrogen Production Market 2009 - 2016 (million metric tons)
- Merchant
- Captive

12/11/2014
H₂USA Public-Private Partnership to address H₂ Infrastructure Challenges

3X increase in partners and growing since 2013

H₂ USA

U.S. DEPARTMENT OF ENERGY

California Fuel Cell Partnership

The Power of Dreams

HONDA

The Power of Dreams

HYUNDAI

Mercedes-Benz

NISSAN

TOYOTA

ARGONNE NATIONAL LABORATORY

EDTA

HNEI

HYDROGENICS

Intelligent Energy

ITM POWER

KOBELCO

Linde

Massachusetts Hydrogen Coalition

NED

NREL

NUVERA

PacifiC NorthwesT NATIONAL LABORATORY

PDC

Plug Power

PROTON

Sandia National Laboratories

SRNL

SCRA

CHRYSLER

Global Automakers

NESCAUM

Fuel Cell & Hydrogen Energy Association

American Gas Association

AIR LIQUIDE

arc: HYDROGEN

Argonne National Laboratory

Electric Drive Transportation Association

H2UPutin.com

NACS

National Renewable Energy Laboratory

Nevada Energy Studies Associates
H2 Refuel H-Prize

Promoting H₂ fueling system development in the community
Visit http://hydrogenprize.org/

$1 million competition for on-site home and community-scale H₂ fueling systems.

1st Year
Teams form and submit designs

2nd Year
Selection of finalists and testing

Late 2016
Technical & cost analysis to select winner

Award
$1M
Contest is now open at www.hydrogencontest.org

**What**
- Contest to develop innovative hydrogen fueling station business and financing models

**Who**
- Undergraduate and graduate students worldwide

**When**
- Early Registration by Dec 8, 2014
- Jan 16, 2015 - Deadline to register and to submit abstracts
Objective: Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of $4/kg $H_2$ by 2020

Technology Readiness of DOE Funded Production Pathways

- Natural Gas Reforming
- Biomass Gasification
- Coal Gasification With CCS
- High-temperature Electrolysis
- Photo-biological
- PEC
- STCH

Today - 2015
- Natural Gas Reforming
- Electrolysis (Grid)

2015-2020
- Bio-derived liquids
- Fermentation

2020-2030
- Solar pathways - longer term

Estimated Plant Capacity (kg/day)
- Up to 1,500
- 50,000
- 100,000
- ≥ 500,000

P&D Subprogram R&D efforts successfully concluded

FE, NE: R&D efforts in DOE Offices of Fossil and Nuclear Energy, respectively
Critical Challenges in H$_2$ Production

Broad challenge to maintain broad R&D portfolio of near- to longer-term pathways

Bio-Derived Liquids Reforming
- High capital costs
- High operation and maintenance costs
- Design for manufacturing
- Feedstock availability, quality, and cost

Coal and Biomass Gasification
- High capital costs
- System efficiency
- Feedstock cost and purity
- Carbon capture and storage

Water Electrolysis
- Low system efficiency and high capital costs
- Integration with renewable energy sources
- Design for manufacturing
- Electricity costs

Solar Thermochemical
- Cost-effective reactor and system
- Effective and durable reaction and construction materials

Photo-electrochemical
- Efficient and durable photocatalyst materials
- Innovative integrated devices

Biological
- Sustainable H$_2$ production from microorganisms (O$_2$ tolerance)
- Optimal microorganism functionality (maximize yields and rates)

Meeting H$_2$ production cost threshold for all near- and longer-term pathways requires improvements in materials efficiency and durability, and reductions in overall capital costs

For some pathways, feedstock cost is a key driver
Hydrogen Production Strategies

H₂ from natural gas is available now while H₂ from renewables is a longer-term focus.

Current Technology
- Natural Gas (D/C)
- Electrolysis (D)

Near to Mid-Term:
- Electrolysis – Wind- and Solar-Powered (D/C)
- Bio-derived Liquids (D/C)
- Fermentation (D/C)

Long-Term (not shown):
Central Renewable H₂
- Solar-based water splitting
- Photolytic Bio-hydrogen

D- Distributed  C- Central
Techno-economic analyses and stakeholder input inform programmatic decisions

Workshops:
- BioHydrogen
- Delivery
- Electrolysis
- Infrastructure

U.S. DRIVE Tech Team Roadmaps

Analysis & Studies

Collaboration & Coordination

RD&D Portfolio Priorities, Metrics, Targets

Stakeholder Input

Pathway Working Groups

Table 3.1.7 Technical Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
<th>Ultimate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Driven High-Temperature Thermochemical Hydrogen Cost</td>
<td>$/kg</td>
<td>NA</td>
<td>14.60</td>
<td>3.70</td>
<td>2.00</td>
</tr>
<tr>
<td>Chemical Tower Capital Cost (installed cost)</td>
<td>$/TPD H2</td>
<td>NA</td>
<td>4.1MB</td>
<td>2.3MM</td>
<td>1.18MM</td>
</tr>
<tr>
<td>Annual Reaction Material Cost per TPD H2</td>
<td>$/TPD H2</td>
<td>NA</td>
<td>1.6MM</td>
<td>91K</td>
<td>11K</td>
</tr>
<tr>
<td>Solar to Hydrogen (STH); Energy Conversion Rate</td>
<td>%</td>
<td>NA</td>
<td>10</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>1-Sun Hydrogen Production Rate</td>
<td>kg/hr per m²</td>
<td>NA</td>
<td>8.1E-7</td>
<td>1.6E-6</td>
<td>2.1E-6</td>
</tr>
</tbody>
</table>
### Technical Target Tables for Water Electrolysis Hydrogen Production

**From DOE FCTO 2012 Multi-Year Research, Development, & Demonstration (MYRD&D) Plan:** [http://www1.eere.energy.gov/hydrogenandfuelcells/mypp](http://www1.eere.energy.gov/hydrogenandfuelcells/mypp)

#### Forecourt/Distributed Targets

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Levelized Cost <em>(Production Only)</em></td>
<td>$/kg</td>
<td>4.20</td>
<td>3.90</td>
<td>2.30</td>
</tr>
<tr>
<td>Electrolyzer System Capital Cost</td>
<td>$/kg, $/kW</td>
<td>0.70</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>System Energy Efficiency <em>(LHV)</em></td>
<td>%</td>
<td>67</td>
<td>72</td>
<td>75</td>
</tr>
<tr>
<td>kWh/kg</td>
<td>50</td>
<td>46</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Stack Energy Efficiency <em>(LHV)</em></td>
<td>%</td>
<td>74</td>
<td>76</td>
<td>77</td>
</tr>
<tr>
<td>kWh/kg</td>
<td>45</td>
<td>44</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>Electricity Price</td>
<td>$/kWh</td>
<td>From AEO 2009</td>
<td>From AEO 2009</td>
<td>0.037</td>
</tr>
</tbody>
</table>

#### Central Targets – Renewable Electricity

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015 Target</th>
<th>2020 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen Levelized Cost <em>(Plant Gate)</em></td>
<td>$/kg H₂</td>
<td>4.10</td>
<td>3.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Total Capital Investment</td>
<td>$M</td>
<td>68</td>
<td>51</td>
<td>40</td>
</tr>
</tbody>
</table>
| System Energy Efficiency *
  | kWh/kg H₂     | 50           | 46          | 44.7        |
| Stack Energy Efficiency *
  | kWh/kg H₂     | 45           | 44          | 43          |
| Electricity Price                                    | $/kWh          | From AEO 09 | $0.049      | $0.031      |

#### Table 3.1.4.A Distributed Electrolysis H2A Example Cost Contributions

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis System Cost Contribution</td>
<td>$/kg H₂</td>
<td>0.70</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Production Equipment Availability</td>
<td>%</td>
<td>98</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Electricity Cost Contribution</td>
<td>$/kg H₂</td>
<td>3.00</td>
<td>3.10</td>
<td>1.60</td>
</tr>
<tr>
<td>Production Fixed O&amp;M Cost Contribution</td>
<td>$/kg H₂</td>
<td>0.30</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Production Other Variable Costs</td>
<td>$/kg H₂</td>
<td>0.10</td>
<td>0.10</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Hydrogen Production Cost Contribution</td>
<td>$/kg H₂</td>
<td>4.10</td>
<td>3.90</td>
<td>2.30</td>
</tr>
<tr>
<td>Compression, Storage, and Dispensing</td>
<td>$/kg H₂</td>
<td>2.50</td>
<td>1.70</td>
<td>1.70</td>
</tr>
<tr>
<td>Total Hydrogen Levelized Cost (Dispensed)</td>
<td>$/kg H₂</td>
<td>6.60</td>
<td>5.60</td>
<td>4.00</td>
</tr>
</tbody>
</table>

#### Table 3.1.5.A Central Water Electrolysis H2A Example Cost Contributions

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>2011 Status</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Cost Contribution</td>
<td>$/kg</td>
<td>0.60</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>Feedstock Cost Contribution</td>
<td>$/kg</td>
<td>3.20</td>
<td>2.30</td>
<td>1.40</td>
</tr>
<tr>
<td>Fixed O&amp;M Cost Contribution</td>
<td>$/kg</td>
<td>0.20</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Other Variable Cost Contribution</td>
<td>$/kg</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Total Hydrogen Levelized Cost (Plant Gate)</td>
<td>$/kg H₂</td>
<td>4.10</td>
<td>3.20</td>
<td>2.00</td>
</tr>
</tbody>
</table>
2014 Electrolytic H₂ Production Workshop

Held February 27-28, 2014 in Golden, CO

Objective: To identify research, development and demonstration (RD&D) needs to enable DOE cost goals for hydrogen production to be met by the electrolysis of water

4 Expert Panels and Breakout Sessions
  • Technical challenges & RD&D needs – Commercial Technologies
  • Technical challenges & RD&D needs – Pre-commercial Technologies
  • Manufacturing and scale-up challenges
  • Additional market/revenue opportunities

Workshop report published:

### Commercial Technologies (e.g., PEM, Alkaline)

**Challenges**
- Improved stack performance
- High-pressure stack/system components
- Increase stack size
- Market issues (manufacturing investment vs. market size)
- Grid integration

**RD&D Needs**
- Improved catalysts & membranes
- Better anode support media
- Studies of high P electrolysis vs. compression
- Demonstrate large-scale viability (MEA, power conversion, etc.)
- Low-cost hardware
- MW-scale demonstration

### Pre-commercial Technologies (Solid Oxide, Alkaline Membrane, Reversible)

**Challenges**
- Material & systems durability
- Scale-up: large format cells
- Efficiency at high current density (cell performance)
- Production volume
- BOP/pressurized operation

**RD&D Needs: Near Term**
- Materials durability: mechanisms, accelerated tests
- Scale-up: multi-kW pilot plant (advance TRL)
- Efficiency at high current density
- New, more active catalyst materials (AEM)
- Lower temperature SOEC materials

**RD&D Needs: Long Term**
- Long-term integrated system testing

### Stakeholder Input:

Electrolytic H₂ Production Workshop Results
H2A Production Model

Uses a standard discounted cash flow rate of return analysis methodology to determine the hydrogen selling cost required for a desired internal rate of return.

- Developed and maintained by NREL
- Provides transparent reporting of process design assumptions and a consistent cost analysis methodology for the production of hydrogen at central and distributed (forecourt/filling-station) facilities
- Establishes a standard format for reporting the production cost of H₂, allowing for a comparison across a broad range of H₂ production technologies
- Assists in prioritizing R&D efforts and tracking progress of R&D programs
- H2A case studies are publicly available at: http://www.hydrogen.energy.gov/h2a_prod_studies.html
  - Example case studies: Natural gas, biomass gasification, photoelectrochemical, PEM electrolysis
Strategic Analysis and NREL recently completed industry-vetted case studies of hydrogen production costs via PEM electrolysis.

Four PEM Electrolysis cases developed in H2A v3

<table>
<thead>
<tr>
<th>Case</th>
<th>Technology Year</th>
<th>Production of H₂ (kg/day)</th>
<th>Plant Life (years)</th>
<th>H₂ Outlet Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Forecourt</td>
<td>2013</td>
<td>1,500</td>
<td>20</td>
<td>450</td>
</tr>
<tr>
<td>Future Forecourt</td>
<td>2025</td>
<td>1,500</td>
<td>20</td>
<td>1000</td>
</tr>
<tr>
<td>Current Central</td>
<td>2013</td>
<td>50,000</td>
<td>40</td>
<td>450</td>
</tr>
<tr>
<td>Future Central</td>
<td>2025</td>
<td>50,000</td>
<td>40</td>
<td>1000</td>
</tr>
</tbody>
</table>

- Current case: Demonstrated state-of-the-art technology manufactured at production volume
- Future case: Advanced electrolyzer system that will be technology-ready in 2025 manufactured at production volume

Methodology:
Representative PEM electrolyzer systems based on input from several key industry collaborators with commercial experience were evaluated using the process:
- Solicited relevant detailed information from the companies
- Synthesized data, amalgamated into base parameters for cases
- Base parameters & sensitivity limits vetted by the companies
- Four H2A v3 Cases Populated and models run to project H₂ cost
- Baseline costs and cost ranges established for the 4 PEM cases
Cost projections range from ~$4-5/kg H\textsubscript{2}. Largest cost driver is electricity feedstock cost. Improvements in efficiency, capital cost, & durability will have smaller impact on H\textsubscript{2} production cost.

<table>
<thead>
<tr>
<th></th>
<th>Low Range ($/kg H\textsubscript{2})</th>
<th>Baseline Cost ($/kg H\textsubscript{2})</th>
<th>High Range ($/kg H\textsubscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forecourt</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Case</td>
<td>$4.80</td>
<td>$5.10</td>
<td>$5.50</td>
</tr>
<tr>
<td>Future Case</td>
<td>$4.10</td>
<td>$4.20</td>
<td>$4.40</td>
</tr>
<tr>
<td><strong>Central</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Case</td>
<td>$4.80</td>
<td>$5.10</td>
<td>$5.40</td>
</tr>
<tr>
<td>Future Case</td>
<td>$4.10</td>
<td>$4.20</td>
<td>$4.30</td>
</tr>
</tbody>
</table>

**Sensitivity Analysis**

Current, Forecourt

**H\textsubscript{2} Production Cost Breakdown**

- **Electricity** 78%
- Other Costs 2%
- Fixed O&M 5%

**H\textsubscript{2} Production Cost Only ($/kg H\textsubscript{2})**

- @ 6.12¢/kWh (avg.)
- @ 6.88¢/kWh (avg.)
- @ 6.22¢/kWh (avg.)
- @ 6.89¢/kWh (avg.)

**Stack Capital Costs**

- Indirect Capital Costs and Replacement Costs
- Decommissioning Costs
- Fixed O&M

**BOP Capital Costs**

- Feedstock Costs (including stack and BOP efficiencies)
- Other Variable Costs (including utilities)
Recent Capital Cost Reduction Accomplishments

Key Accomplishments:

• > 80% reduction in electrolyzer stack cost through design optimization and manufacturing innovations since 2001 to less than $400/kW; > 60% reduction since 2007

• > 75% reduction in stack part count since 2006 with 50% reduction in manufacturing labor.

• Achieved > 40% reduction in cell stack cost for a large active area (> 500 cm²) electrolysis cell design compared to 2011 baseline primarily due to bipolar plate innovations.

Innovations continue with 3 active SBIR Phase II projects and 3 Phase I electrolyzer membrane projects

Source: Giner, Inc.; 2013 Annual Merit Review
http://www.hydrogen.energy.gov/annual_progress13.html

18%  60%  10%  1%  11%  MEA
Flow fields and separators
Gas diffusion layers
Balance of cell
Balance of stack
18%
17%
11%
2%
10%
42%
MEA
Flow fields and separators
Gas diffusion layers
Balance of cell
Balance of stack

2011 Baseline (~$1.00/kg H₂ Stack Cost)

Source: Proton Energy Systems

Current Status (~$0.60/kg H₂ Stack Cost)
By adapting two different electrocatalysis approaches originally investigated for lowering PGM loading in PEM fuel cell cathodes, demonstrated equivalent electrolysis MEA performance with ≥10x lower PGM electrode loading than baseline cells

Proton OnSite: Brookhaven National Lab Core-Shell Catalyst

Proton OnSite successfully transferred the manufacture of BNL-developed core shell catalyst technology to its facilities and achieved equivalent cathode performance at 1/10th of the cathode PGM loading of commercial electrolysis cells.

Giner: 3M Nano-Structured Thin Film (NSTF) Catalyst

Giner’s testing of 3M NSTF anode technology under electrolysis conditions demonstrated comparable performance at 1/16th of the anode PGM loading of Giner’s standard anode.

![Graph showing potential vs. current density for cathode GDE and baseline MEA.]

![Graph showing voltage vs. current density for Giner standard anode and 3M NSTF anode.]

12/11/2014
AEM technology (and the alkaline environment) offers potential for > 80% electrolyzer cell-stack material cost savings through:

- Use of stainless steel or nickel instead of titanium for the bipolar plates
- Use of non-PGM catalyst materials

**Low TRL Status**

**Recent Progress**

- Low-PGM pyrochlore-based OER catalysts with better performance than IrO$_2$ baseline (Proton/IIT)
- Membrane stability improving
High Temperature Electrolysis

High temperature electrolysis offers the potential for significantly higher stack (and potentially system) level efficiency

- High current densities possible at high stack electrical efficiency
- Heat often less expensive than electricity
- Opportunity to integrate with high grade heat from nuclear reactor

Detailed solid oxide electrolysis (SOEC) H2A case study being developed by SA/NREL with input from INL:
- Aimed at obtaining a better understanding of potential system level efficiency advantages offered by HT electrolysis and its impact on H₂ production cost

\[
\text{H}_2\text{O} = \text{H}_2(g) + 0.5\text{O}_2(g)
\]

From J O’Brien, et.al, INL Report: INL/EXT-09-16140

<table>
<thead>
<tr>
<th>ASR (Ω.cm²)</th>
<th>SOEC</th>
<th>SOFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% humidity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen/air operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>0.169</td>
<td>0.190</td>
</tr>
<tr>
<td>750</td>
<td>0.223</td>
<td>0.224</td>
</tr>
<tr>
<td>700</td>
<td>0.345</td>
<td>0.290</td>
</tr>
</tbody>
</table>

Versa Power Systems RSOFC Pol Curves

\[
\Delta H^°_{R} \text{ Total Energy Demand} \\
\Delta G^°_{R} \text{ Electrical Energy Demand}
\]

\[
TAS^°_R, \text{ Heat Demand}
\]

\[
\text{Energy Demand per unit mass of steam}
\]

\[
\text{50% humidity}
\]

\[
\text{Hydrogen/air operation}
\]

\[
\text{Electrolyser Mode}
\]

\[
\text{H}_2\text{O} \rightarrow \text{H}_2 + 0.5\text{O}_2
\]

\[
\text{Fuel Cell Mode}
\]

\[
\text{H}_2 + 0.5\text{O}_2 \rightarrow \text{H}_2\text{O}
\]

12/11/2014
Integration of electrolyzers with photovoltaics

- Optimizing efficiency for a PV to electrolysis system: Comparing PV direct connect versus DC-DC power electronics
- By switching between direct coupling and power converters can improve overall energy capture of a PV-to-H₂ system by 10% (average) across the full range of sun irradiance.

Impact of renewable energy profile on electrolyzer operation

- Researching the long term effects of operating an electrolyzer stack with a wind-simulated, highly variable, profile.
- Preliminary data suggests for a 10,000 hr duration there is no significant difference in electrolyzer decay rate between constant and variable powered operation.
Exploring how electrolyzers can provide grid support

- Renewable energy sources tend to be highly variable and can lead to grid instability
- NREL testing has shown that electrolyzers should be able to provide grid ancillary services, including voltage and frequency regulation, to assist with balancing the grid

Electrolyzer response follows PJM regulation signal test closely

Electrolyzers demonstrated ability to quickly mitigate frequency disturbance
Large Active Area Electrolyzer Stack Test Bed

Located at NREL’s Energy System Integration Laboratory

- Fills need to ramp up to “MW-scale” electrolyzer stack/BOP/system development and testing
- AC-DC power supplies capable of 2,000 ADC and 250 VDC (500 kW)
- Looking at interactions between distributed generation and loads
- System efficiency improvements via optimizing balance of plant for variable stack power (e.g. variable flow drying technique)
- First testing recently completed
  - ~500 kW of PEM electrolysis using 3 Giner stacks with currents of up to 900 A
Thank You

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