2013 Hydrogen Program

Annual Merit Review Meeting

PEM Electrolyzer Incorporating an Advanced Low Cost Membrane

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Project ID# PD030

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GINER

Overview

Timeline

- **Project Start:** May 2008
- **Project End:** April 2013
- **Percent Complete:** 100

Budget

- **Total Project Budget: $2.49MM**
  - **DOE Share:** $1.99MM
  - **Contractor Share:** $0.51MM
  - **Funding Received in FY12:** $278K

Barriers

Hydrogen Generation by Water Electrolysis

- **G. Capital Cost**
- **H. System Efficiency**

Technical Targets: Distributed Forecourt Water Electrolysis[1]

Characteristics		Units	2015	2020	Giner Status (2013)
Hydrogen Levelized Cost[2]		$/kg-$H_2$	3.90	<2.30	3.64[3] (5.11)[4]
Electrolyzer Cap. Cost		$/kg-$H_2$	0.50	0.50	1.30 (0.74)[5]
Efficiency	System	%LHV (kWh/kg)	72 (46)	75 (44)	65 (51)
Efficiency	Stack	%LHV (kWh/kg)	76 (44)	77 (43)	74 (45)

[1] 2012 MYRDD Plan. [2]Production Only. [3]Utilizing H2A Ver.2. [4]Utilizing H2A Ver.3 (Electric costs increased to $0.057/kW from 0.039$/kW) . [5] Stack Only

Partners

- **Parker Hannifin Corporation (Industry)**– System Development
- **Virginia Tech University (Academic)**– Membrane Development

Collaborations

- **3M Fuel Cell Components Program**– NSTF Catalyst & Membrane
- **Entegris** – Carbon Cell-Separators
- **TreadStone Technologies** – Metal Cell-Separators
- **Tokuyama** – Low-Cost Membrane
- **Prof. R. Zalosh (WPI)** – Hydrogen Safety Codes

Relevance: Project Objectives

Overall Project Objectives

- Develop and demonstrate advanced low-cost, moderate-pressure PEM water electrolyzer system to meet DOE targets for distributed electrolysis.
  - Develop high efficiency, low-cost membrane
  - Develop long-life cell-separator
  - Develop lower-cost prototype electrolyzer stack & system

Relevance

- Successful development of a low-cost hydrogen generator will enable
  - Integration of renewable energy sources
  - Early adoption of fuel cell vehicles

FY 2012-13 Objectives

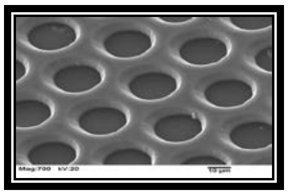
- Deliver/demonstrate prototype electrolyzer system at NREL
- Complete membrane evaluations under aggressive conditions
  - High pressure evaluation
  - High current density evaluation

Low-Cost PEM Electrolyzer Stack

Approach: Overview

Membrane

- Develop High-Strength, High-efficiency membranes



DSM

- DSM-PFSA ionomer incorporated in an engineering plastic support
- Investigate Alternative Low-Cost Membranes
  - □Hydrocarbons ionomers
  - □Bi-Phenyl Sulfone (VT)
  - □PFSA (850EW) membrane (3M)
- **2012-2013**:Evaluate membrane under aggressive conditions

Cell-Separator

- Develop cell-separators with
  - □High electrical conductivity
  - □Resistant to hydrogen embrittlement
  - □Stable in oxidizing environment
  - □Low-Cost

- Evaluate methods of bonding dissimilar metal films
- Evaluate non-metal substrate with conductive coating
- **2012-2013**:Investigate alternative cell-separator materials for future cost reductions

Electrolyzer Stack

- Reduce parts count/cell
- Develop innovative designs to reduce Mat'l costs
- Apply manufacturing methods to reduce costs
- Increase cell active area

- Fabricate 0.5kg-H_2/hr Stack utilizing low-cost components
- **2012-2013:** Broaden product range to include 200 cells/stack

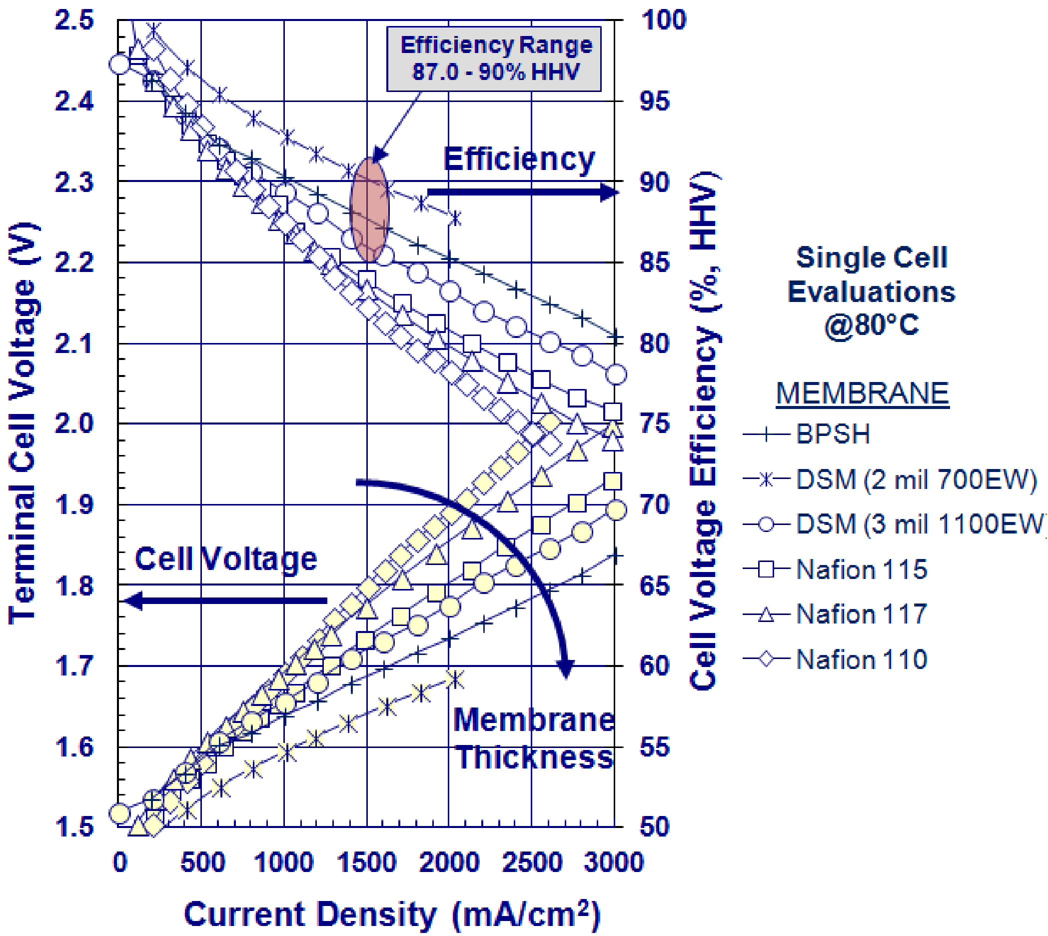
Electrolyzer System

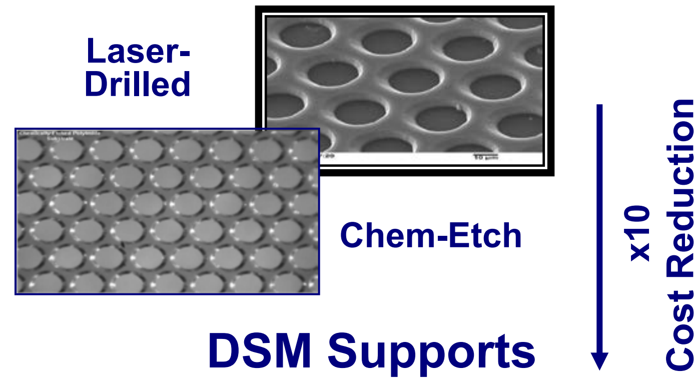
- Reduce BOP capital cost
- Reduce BOP power consumption-through higher efficiency power electronics
- Design high efficiency H_2 dryer
- Improve safety and reliability
- Design for high-volume manufacturing
- Team with large volume commercial manufacturer (**Parker-Hannifin**)

Approach: 2012-13 Milestones

	Go/No Go Decision Points	Progress Notes	%Complete
Membrane	■Scale-up DSM membrane to 290cm² ■Evaluated in short stack @ 80°C and 1500-1700 mA/cm²	■Operated Scaled-up membrane for **5,000+ hrs** ■Reduced membrane costs via innovative supports ■Performance DSM > Nafion® 1135	**100% (June 2011)**
	■DSM evaluation at high pressure, high current density	■Successfully operated DSM at **5,000 psig** ■Successfully operated DSM at **5,000 mA/cm²**, 1,000 hrs	**100% (Mar. 2013)**
Cell Separator	■ Evaluate cell-separators in short stacks @ 80°C for 5,000 hrs	■Completed investigation of new Mat'l for future cost reductions. Includes: nitrided components, low-cost carbon (Entegris), and TreadStone cell-separators ■ Testing Completed – 5,000+ hrs ■Projected cell-separator lifetime: 60,000+ hrs	**100% (Sep. 2012)**
Stack/System Development	■Completed fabrication of prototype electrolyzer system capable of providing 12 kg-H_2/day at 300-400 psi that has the potential of meeting DOE's cost target for distributed H_2 production	■System delivered to NREL and validated ■**Completed DOE's Joule Milestone**	**100% (June 2012)**

Membrane Progress:
Membrane/Catalyst Evaluations

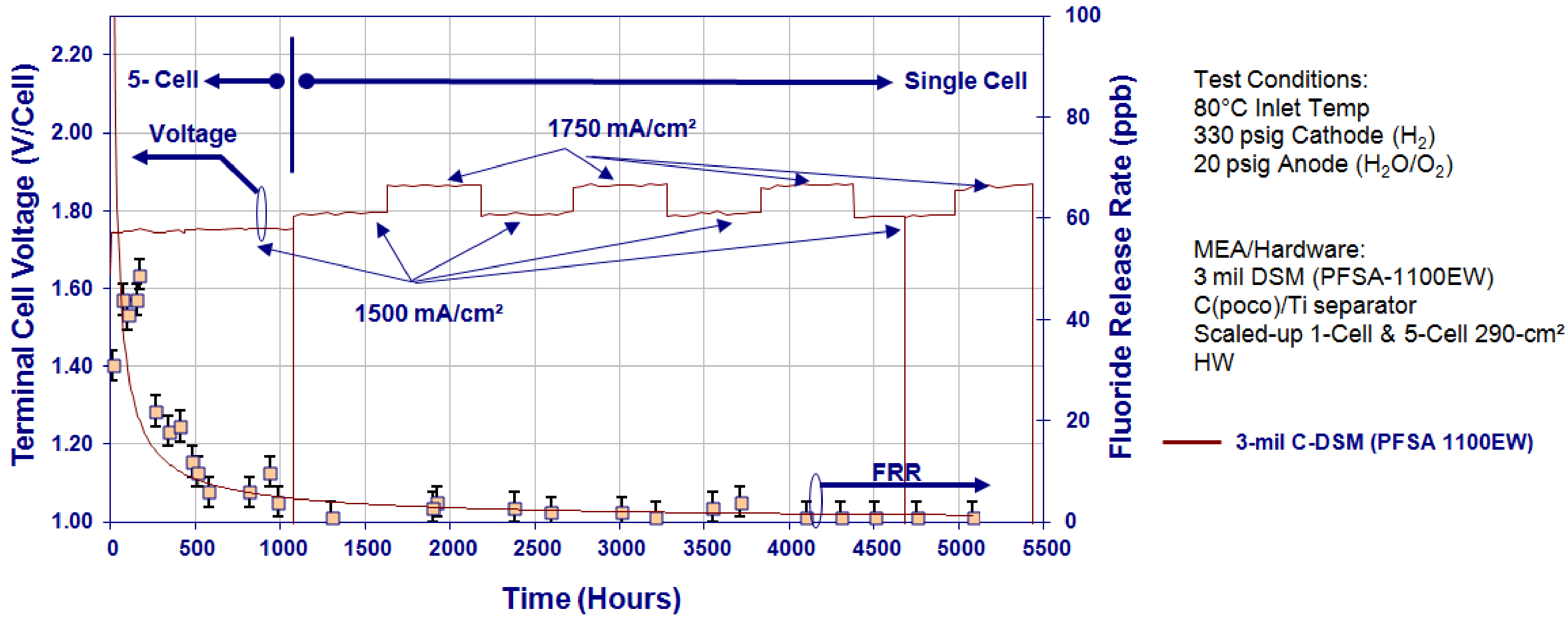




- Developed high efficiency DSM membranes
  - Chem-etched substrates used to lower cost, aid ease of fabrication
- Developed electrode structures with reduced catalyst loadings: 0.7 mg Pt/cm² (Pt/Ir-Anode), 0.4 mg Pt/cm² (Pt/carbon-Cathode)
  - Previously 8 mg Pt/cm²
- Successful testing of 3M NSTF Pt (cathode) and PtIr (anode) catalyst: 3M catalysts are one-order magnitude lower (~0.10 to 0.15 mg Pt/cm² Anode/Cathode)
- Alternative BPSH hydrocarbon membranes exhibited high degradation rates but are effective in reducing cross-over

Nafion is a registered trademark of E.I. du Pont Nemours and Company

Membrane Progress: Durability Testing (5,000 hours)



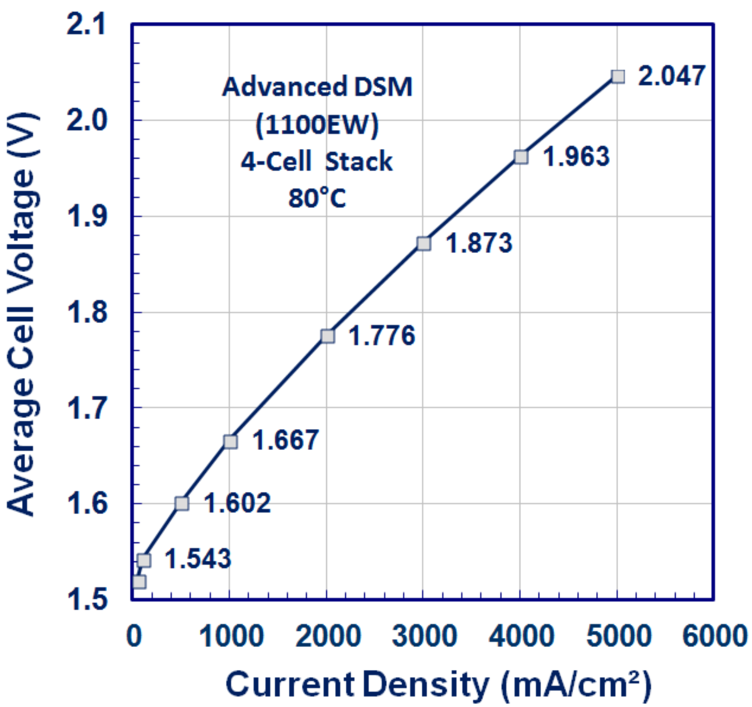
Performance

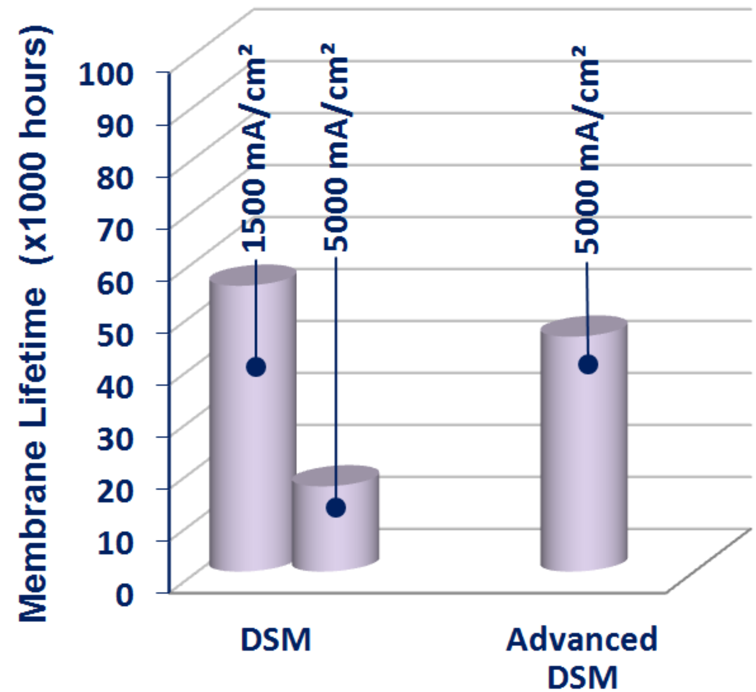
- Completed 1,000 & 5,000 Hour Life-Test Milestones
  - Scaled-up 5-cell (290-cm²)
  - 1.73-1.75V (~88% HHV)
- DSM MEA from 5-cell short stack re-assembled into a single-cell stack, total operating time = 5430 hours
- Scaled-up cells include low-cost components used in final stack assembly

Membrane Degradation (Estimated Lifetime)

- F ion Release Rate: 3.7 μg/hr (<10 ppb)
- DSM -1100EW (Stabilized Ionomer): ~55,000 hours

Membrane Progress: High Current Density Operation (5,000 mA/cm²)





Performance @ 5,000 mA/cm²

- Advanced DSM: Improved membrane stability at high operating current density
- Operated 4-Cell stack at 5,000 mA/cm² for 1,000 hours
  - Average cell voltage: 2.05V (~74% HHV)
- DSM can endure operation at 10,000 mA/cm² (in continuous 24 hour test)

Membrane Degradation (Estimated Lifetime)

- In PFSA membranes, high current density will reduce lifetime
- Advanced DSM with proprietary additive mitigates degradation and improves life at high operating current densities
  - 200,000 hour lifetime expected at 1,500 mA/cm²

Membrane Progress: Mechanical Stability and High pressure Operation (5,000 psig)

Hydrogen at 5,000 psig
(Ambient O_2)
Generated directly in
PEM Electrolyzer

- DSM Utilized in High-Pressure Operation
  - Stack components developed under current program used in the fabrication of high-pressure stacks
  - Utilizes containment rings, eliminates need for stack enclosure (or external support dome)

DSM Membrane

- High-strength
- No x-y dimensional changes upon wet/dry or freeze-thaw cycling
- Customized MEAs provide more support at edge regions and/or at ports under extreme clamping loads
- Demonstrated significant improvement in membrane creep property and mechanical stability

5,000 psi Giner Electrolyzer
Multi-Cell Stack Design
Work conducted under DOE Program DE-SC0001486 (see Poster PD065)

Cell-Separator Progress

Carbon/Titanium

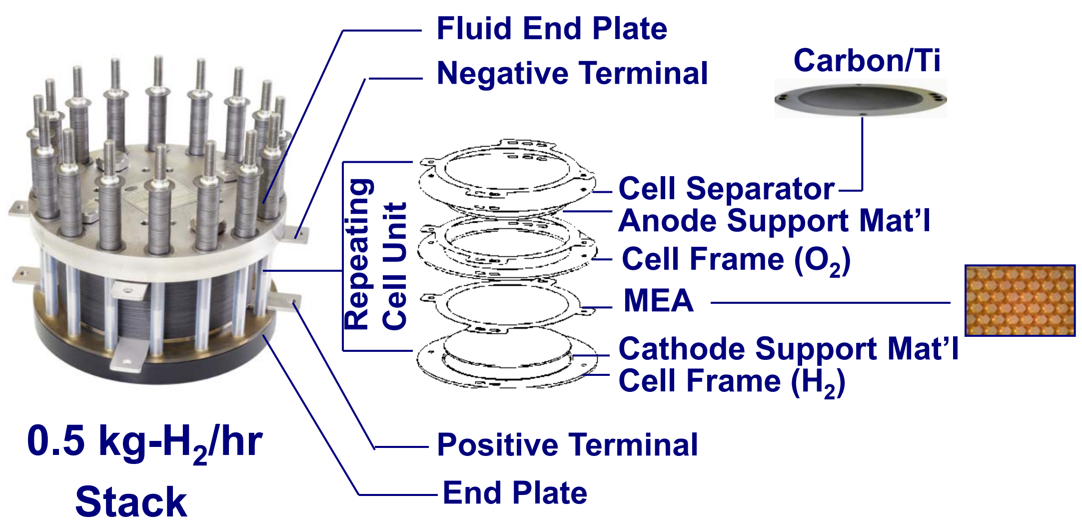
- Carbon/Titanium Cell-Separators Scaled-up to 290-cm²
  - Cell-Separators fabricated with low porosity carbon
    - POCO Pyrolitic Graphite (Surface Sealed)
  - Evaluated in short stack for 5,000+ hours
  - Utilized in final stack build
- Analysis
    - Low hydrogen uptake (low embrittlement)
    - **Lifetime estimate of C/Ti Cell Separators> 60,000 hours**
- Alternative low-cost materials identified
  - Low-Cost Carbon, Nitrided, & TreadStone Cell-Separators
  - Zr/Ti & ZrN/Ti indicate long lifetime, but loss of coating

Cell -Separator	Time (Hours)	H_2 uptake (ppm)
C/Ti (290-cm²)	**5430**	**104**
Zr/Ti(160-cm²)	500	140
ZrN/Ti (160-cm²)	500	31
Dual Layer Ti (160-cm²)	500	1105
Ti (baseline)	0	≈ 60
Ti Failure/Embrittlement: ~8000 ppm		

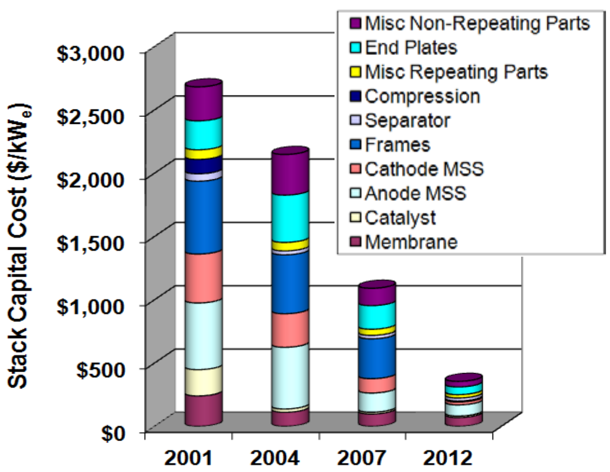
Property	Units	DOE Target FC Bipolar Plates 2017[1]	GES C/Ti Cell-Separator 2012
Cost	$/kW	3	> 10
Electrical Conductivity	S/cm	> 100	>300 (680 Poco)
Flexural Strength	MPa	>25	86.1 (Poco)

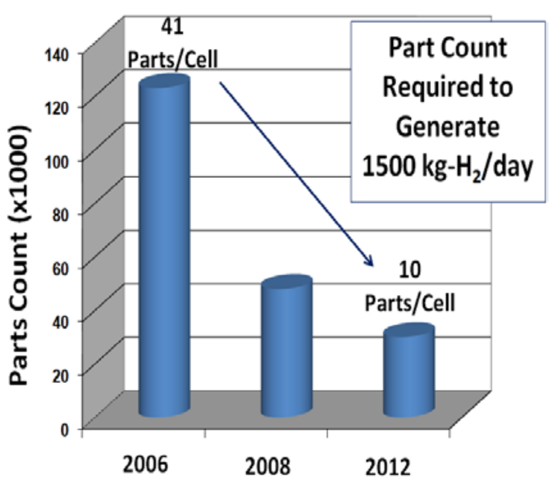
[1]Fuel Cell Technologies Office 2007 MYRD&D

Stack Progress: Advancements & Cost Reductions



The repeating cell unit comprises 90% of electrolyzer stack cost





Stack Improvements

>60% Stack Cost Reduction

- Increased active area (160->290cm²)
- Reduced catalyst loadings 8->1 mg/cm²
- Reduced Part Count from 41 to 10 Parts/Cell-50% labor reduction
- Pressure Pad: Sub-assembly eliminated
- Molded Thermoplastic Cell Frame
- Cell-Separators: Replaced Nb/Ti with Carbon/Ti
- Frame Thickness reduced (by 30%)
  - Reduces Cathode & Anode Support Mat'l
- DSM MEAs fabricated w/chem-etch supports- 90% cost reduction
- Carbon Steel End Plate (previously S.S.) - 66% material cost reduction

- **Stack commercialized**
- **Broadened product range to include large multi-cell stacks(200+ cells/stack)**
- **CE Compliant**

System Progress

- Assembly: 100% Complete
- Completed series of manuals covering construction, safety and performance
  - System Training Manual
  - System Operation Manual
  - Hydrogen Safety & Response Plan
  - Failure Modes and Effects Analysis (FMEA)
- System delivered to NREL for validation

System Specs:

System oversized to accommodate larger stacks.
Dimensions: 7.2′ tall x 6.6′ long x 7.8′ wide.

3 Compartments (H_2, O_2, and Power Supply/Controls)

Production Rate

0.5 kg H_2/hr (-3.4% dryer)

2.0 kg-H_2/hr (w/ larger Stack & Power Supply)

Operating Pressure

H_2 390 psig; O_2 atm

Operating Temperature

80°C

Membrane

DSM-PFSA,

Stack Size

Utilized low-cost stack (290 cm^2/cell, 27 Cells)

Stack Current Density

1500-1900 mA/cm^2

Other

Water Consumption: 5.75 liters/hr

Max. Stack Power Requirement: 24 kW

Heat Rejection: 3.3 kW

Dual-column dryer to reduce maintenance and desiccant replacement

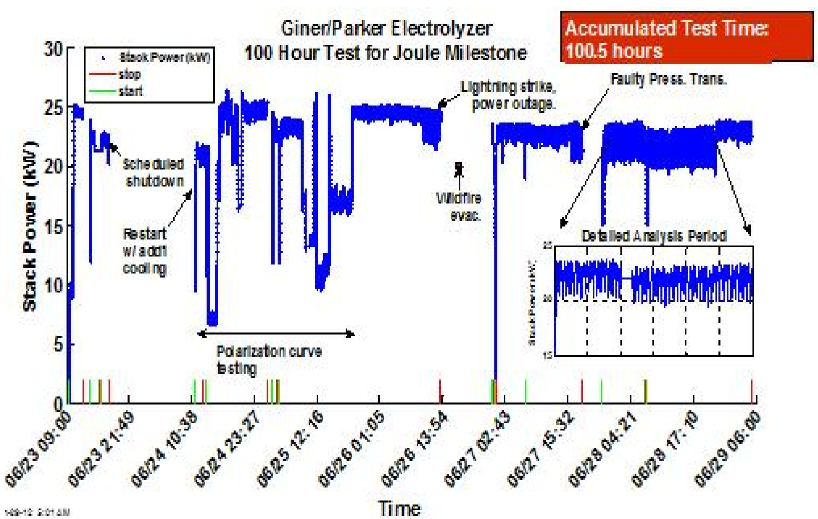
System Enhancements:

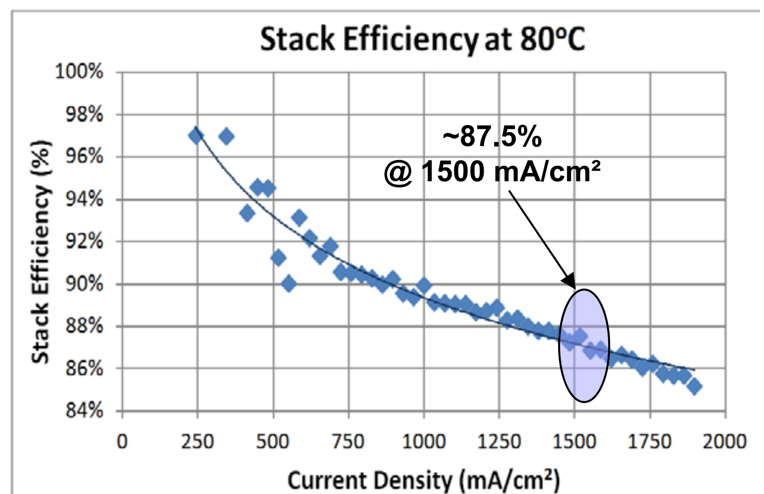
- Eliminated stack enclosure (Dome)
- Added ventilation fan to satisfy safety Hydrogen Refueling System Safety Codes
- Electrical lockouts added to stack compartment

System Progress: Validation

- System Validated at NREL in June 2012
- Nominal operating conditions: 390 psig, 1500 -1900 mA/cm²
  - High stack voltage efficiency: >87% HHV (73.6% LHV) @ 1500 mA/cm²; Energy efficiency;46.6 kWh$_e$/kg-H_2
    - Stack Efficiencies in line with DOE 2012 goals
- Hydrogen drying: 3.4%
- DOE Joule Milestone Completed !

- 3rd party validation of stack by Areva
  - Operating at multiple sites
  - Customer confirms 2,000+ hours at 47 kWh$_e$/kg @ 1,700 mA/cm²





NREL Report: 200 Hour Testing – Giner/Parker Electrolyzer Milestone 3.7.6 (CPS 52066)

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System Progress: Efficiency

Giner/Parker Validation | *NREL DATA

Hydrogen Production & Losses	Units	1500 mA/cm²	1750 mA/cm²	1900 mA/cm²	*NREL DATA 1600* mA/cm²
Stack H2-Production	kg-H_2/hr	0.445	0.519	0.563	0.468
Membrane permeation losses (-0.6%)		-0.003	-0.003	-0.011	-0.005
Phase-Separator (-0.14%)		-0.0006	-0.0007	-0.0011	-0.0007
H_2-Dryer (3 to 4%)		-0.018	-0.021	-0.022	-0.015*
Total H2-Production		**0.424**	**0.494**	**0.529**	**0.43***

Power Consumption		Units	1500 mA/cm²	1750 mA/cm²	1900 mA/cm²	1600* mA/cm²
Electrolyzer Stack		kW	**20.6**	**24.2**	**27.0**	**21.9 ± 3.3***
DC power supply & control **(assuming 94% eff.)**			+1.23	+1.45	+2.3	**+ 4.2**
PLC Rack			0.05	0.05	0.05	0.05
Electrolyzer Water Pump			0.30	0.30	0.30	0.30
Heat exchanger fans A & B			0.05	0.05	0.05	0.05
H2 sensor circuit pump			0.12	0.12	0.12	0.12
Total Energy Consumption (No Dryer)			**22.3**	**26.2**	**29.82**	**26.6 (+0.7)**
H_2-Dryer	Chiller (1.4kW Max)		0.46	0.60	0.82	0.52
	Heaters A & B		0.07	0.07	0.07	0.07
Total Power Consumption (w/Dryer)			**22.9**	**26.8**	**30.71**	**27.9 ±3.8***

Overall Efficiencies	Units	1500 mA/cm²	1750 mA/cm²	1900 mA/cm²	1600* mA/cm²
Electrolyzer Stack (includes permeation)	kWh/kg	**46.6**	**46.9**	**48.9**	**47.3**
System (No Dryer)		**50.5**	**50.8**	**54.1**	**57.5 (+1.6)**
System (w/Dryer)		**54.0**	**54.2**	**58.0**	**64.8***

Operating Range: 1300-1800 mA/cm²

H_2-Dryer Losses: 3.4%

Near Theoretical of 0.44 kg-H_2/hr

Off-the-shelf Power Supply Efficiency was Low (Large Forecourt Rectifiers >95%)

Includes 0.7kW for Safety Ventilation Fans (or +1.6 kWh/kg)

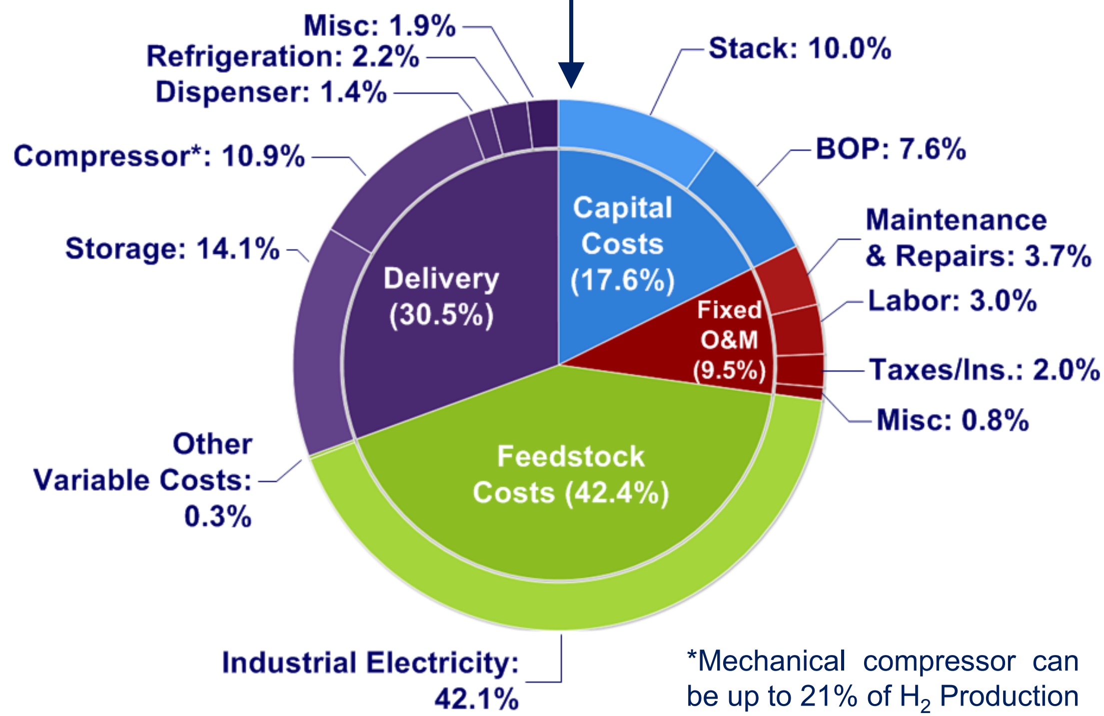
~9 kWh/kg loss due to power supply & safety ventalation

Projected H_2 Cost

H2A Forecourt Model Analysis

H_2 Production Cost Contribution	H2A Ver. 2.1.1 (FY 2012)	H2A Ver. 3.0 (FY 2013)
Capital Costs	$1.06	$1.30
Fixed O&M	$0.59	$0.70
Feedstock Costs @ Efficiency: 50.5 $kWh_e/kg\text{-}H_2$	$1.97 ($0.039/kW)	$3.09 ($0.057/kW)
Other Variable Costs (including utilities)	$0.01	$0.02
***Total Hydrogen Production Cost* ($/kg)**	**3.64**	**5.11**
Delivery (CSD)	$1.80 (300 psig output)	$2.24 (600 psig output)
***Total Hydrogen Production Cost* ($/kg)**	**5.43**	**7.35**

Design Capacity: 1500 kg H2/day. Assumes large scale production costs for 500th unit

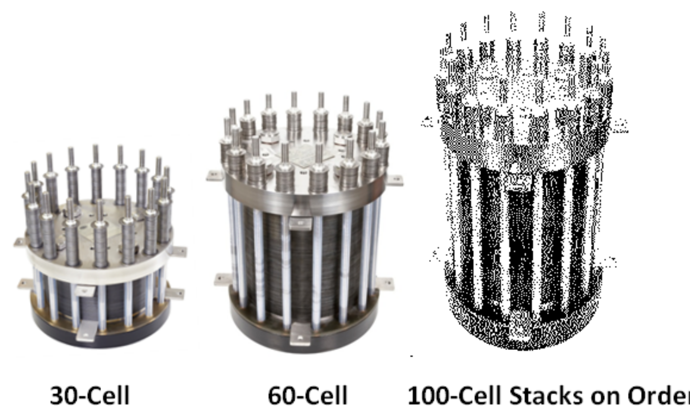


*Mechanical compressor can be up to 21% of H_2 Production Cost (70% of Delivery) depending on maintenance

- Industrial electricity at $0.039/kWh in H2A Ver. 2, $0.057/kWh; H2A Ver. 3 (in addition to higher installation & delivery costs)
  - FY2012: Stack output 333 psig H_2 (compressed to 6,250 psig) FY2013: Stack output 600 psig H_2 (compressed to12,688 psig)
- **Progress inline with achieving *new* 2015 Target of $3.90/kg-$H_2$**

Summary

- **Membrane: Demonstrated Reproducibility, Durability, and Efficiency**
  - Demonstrated high efficiency DSM membranes (single-cell, 5-cell, and 27-cell stacks)
  - Demonstrated 5,000+ hrs lifetime of scaled-up (290 cm²) DSM membrane at 80°C
  - Demonstrated high current density (5,000 mA/cm²) and high pressure (5,000 psig) operation
  - Cell voltage efficiency >87%HHV, 46.6 $kWh_e/kg\text{-}H_2$ @ 1500 mA/cm² meeting 2012 DOE targets
- **Cell Separator & Component Development:**
  - Demonstrated 5,000+ hrs lifetime of scaled-up cell-separators
  - Demonstrated significantly reduced hydrogen embrittlement with carbon/Ti and TreadStone cell-separators
    - Expected cell-separator lifetime range: 60,000+ Hours
- **Scaled-Up Stack:**
  - Significant progress made in stack cost-reduction (cell-components, membrane, & catalyst)
    - 60% reduction in stack cost
  - Stack Commercialized & In production :30, 60, and 100-cell configurations



- **System Development:**
  - Prototype system delivered to NREL
  - DOE Joule Milestone completed
  - Negotiating with multiple OEMs, “Giner-Inside” branded systems

Future Plans & Challenges: FY2013 and Forward

2020 cost targets require further cost reductions and improvements in efficiency

Membrane

- Improve membrane performance
  - Higher operating temperatures, pressures, and current densities required to meet new targets
  - Lower EW ionomers
  - Reduce membrane resistance
  - Improve chemical stability

Stack

- Reduce Stack Costs
  - Labor is 33-50% cost of stack
    - Reduce labor cost through new manufacturing techniques
  - New low-cost materials
  - Reduce part count in cells
    - Unitize cell components (to further reduce parts/cell)
    - Increase stack active-area to 1ft² (or larger) for large energy storage applications

Distributed Forecourt Water Electrolysis[1]	
H_2 Production Cost Contribution	**New DOE Target (2020)**
Capital Costs	$0.50
Fixed O&M	$0.20
Feedstock Costs @ Efficiency: 50.5 kWh_e/kg -H_2	$1.60 (46.9kWh/kg) ($0.037/kW)
Other Variable Costs (including utilities)	<$0.10
Total Hydrogen Production Cost ($/kg)	**2.30**
Delivery (CSD)	$1.70
Total Hydrogen Production Cost ($/kg)	**<4.00**

[1]2012 MYRDD Plan

Future Plans & Challenges…

Stack (Cont…)

- Design for automated assembly
- Improve pressure capabilities of stacks (6,250 and 12,688 psi)
- Demonstrate stacks under aggressive conditions (wind to hydrogen applications)
  - High current density operation

System

- Simplify electrolyzer systems to reduce cost
- Unify BOP components
  - In Regenerative Fuel Cell Systems, combine subsystems

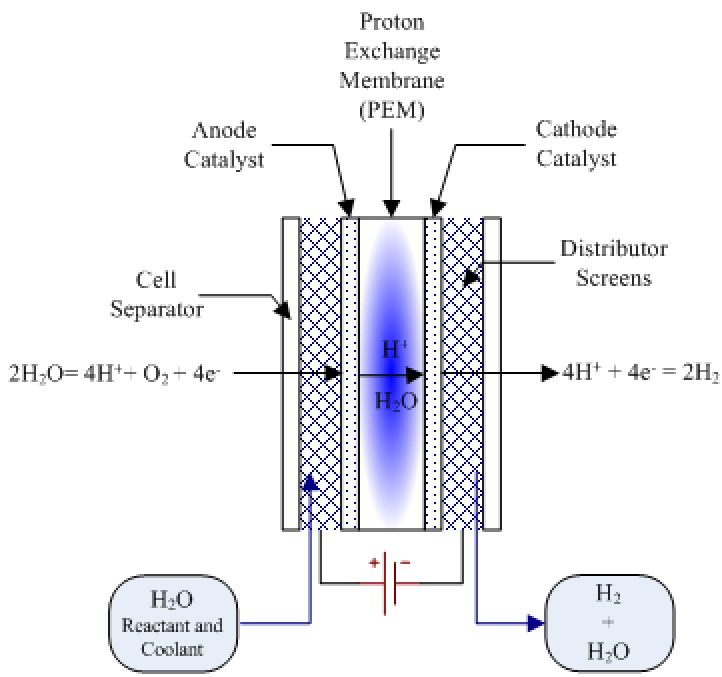
Validation

- Industrial collaborations needed to promote technology
- Testing facilities for validation of large MW scale electrolyzers are needed

AMR
Technical Slides

Technical Slide 1-

Technical principle of the PEM-based water electrolysis



PEM Cell Reactions

$H_2O \rightarrow 2H^+ + 2e^- + \frac{1}{2}O_2$	Anode half-cell reaction
$2H^+ + 2e^- \rightarrow H_2$	Cathode half-cell reaction
$H_2O + 2e^- \rightarrow H_2 + \frac{1}{2}O_2$	Overall reaction

Water permeation through PEM

~$3H_2O/H^+$