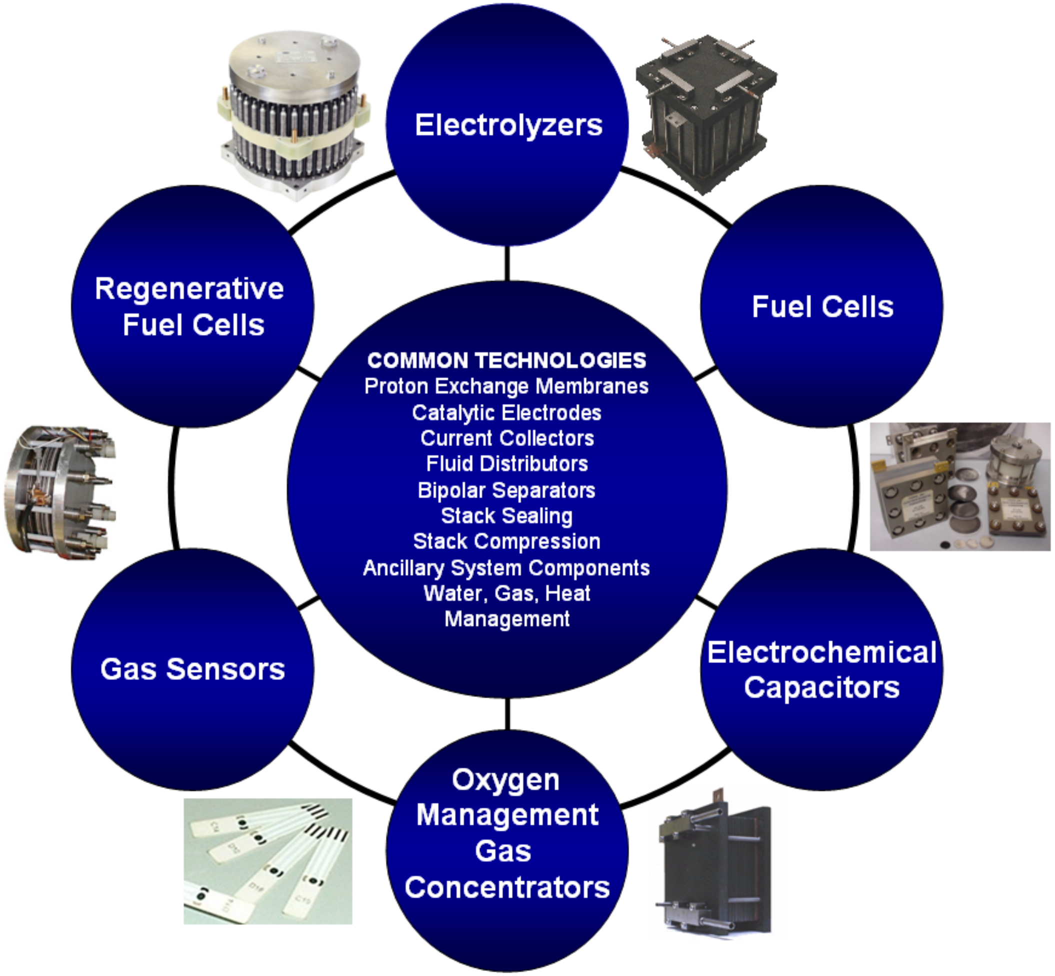
Giner, Inc./GES Newton , Ma.

Monjid Hamdan
Senior Program Manager
May 23, 2011

- Giner, Inc.: Founded in 1973
- Giner Electrochemical Systems, LLC (GES): Founded in 2000 with a 30% Ownership by General Motors
    - Specializing in development of PEM based electrochemical technology, devices, and systems



Synergy of Giner, Inc./GES Technologies

PEM Electrolyzer Stack Technology

Over 7500 units in the field

- Over last 15 years there has been rapid development of high-efficiency PEM-based water electrolyzer stacks for both military and commercial applications
- PEM Electrolyzer can generate hydrogen at high or low, balanced or differential pressure
- PEM Stacks have shown high durability and reliability with over 7500 Giner stacks in field use today
- Electrolyzers are also used for oxygen generation. PEM electrolyzer stacks are in use on the SeaWolf and Trident submarines
- Improvements in membrane technology are leading to higher efficiencies
  - Efficiencies demonstrated ~ 43.5 kWh/kg H_2

Navy Stacks

Compact High-Pressure Design

55-kW Electrolyzer

Current Density (2000 A/ft^2)

1000 psi H_2/Ambient O_2

No High-Pressure Water Feed Pump or Containment Vessel

Laboratory Stacks

0.05 ft^2/Cell

1-2 cells/Stack

0.3 to 0.6 lpm H_2

Ambient –120 psi H_2

Ambient O2

3000 psi H_2

High Pressure Stacks

0.17 ft^2/Cell

140SCFH H_2 (0.34kg/hr)

2000 A/ft^2

Ambient O_2

500 psi H_2

PEM Electrolyzer Markets

Government – Early

- US Navy
  - Life Support Oxygen Generators
- Aerospace / Space Electrolyzers
  - Radar Platforms; DARPA and MDA
  - Space Exploration; NASA
- RFC Electrolyzers
  - Moderate rate 0.3 - 2 kg/hr DOD Backup Power

Distributed Hydrogen - Today

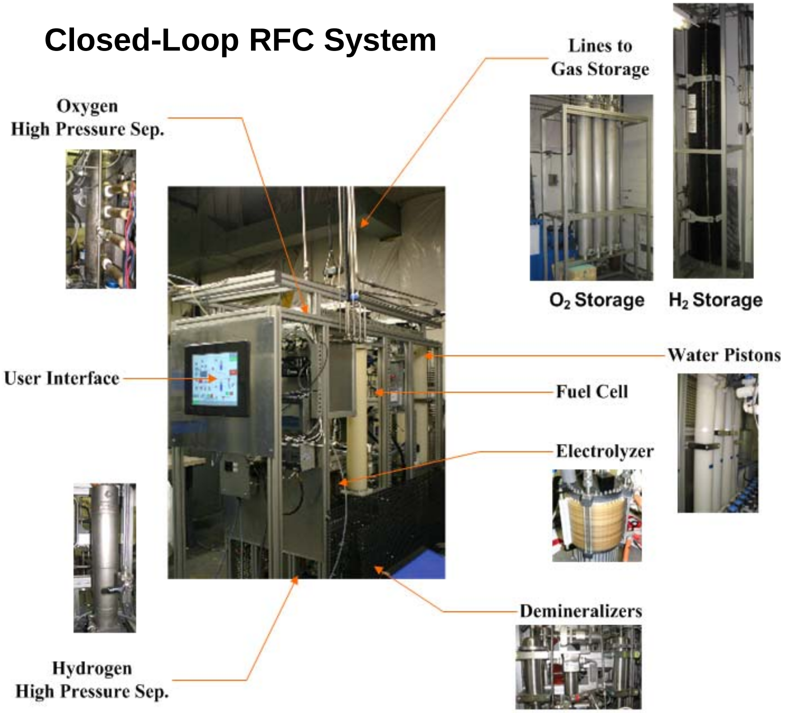
- Analytical Hydrogen
  - Analytical labs : 1 - 3 g/hr (low rate)
- Industrial Hydrogen
  - "High purity" manufacturing processes: 0.1 - 5 kg/hr (Moderate rate)

Commercial – Near Term Future

- Grid Stabilization
- " On-Site" H_2 Generators for car refueling
  - 12 - 20 kg/hr (large rate)
- " Renewable" power storage
  - > 200 kg/hr (industrial rate)
  - > 100,000 kg/day (Centralized Stations)

Prototype ⟶ Market

Closed-Loop RFC System



On-board Vehicle Electrolyzer System (S-10)

6 kW Electrolyzer
40 SCFH-H_2 (~0.1 kg-H_2/hr)
1500 ASF
1250 psi H_2/Ambient O_2
Volume ~ 6 ft^3

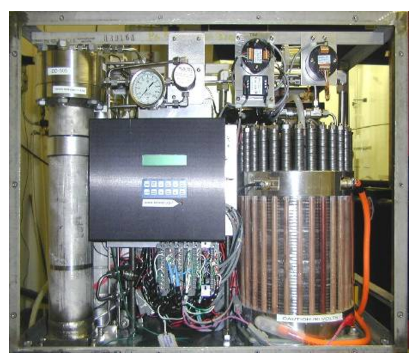
Electrolyzer Niche Applications

Unmanned Vehicle Applications

12 Cells - 0.17 ft² Cells/Stack
6-kW Electrolyzer
40 SCFH-H_2 (~0.1 kg-H_2/hr)
High Current Density (1300-1500 A/ft²)
1000 psi H_2/Ambient O_2
No High-Pressure Water Feed Pump or Containment Vessel
Volume 12.5ft^3

On-Site H_2 Generators

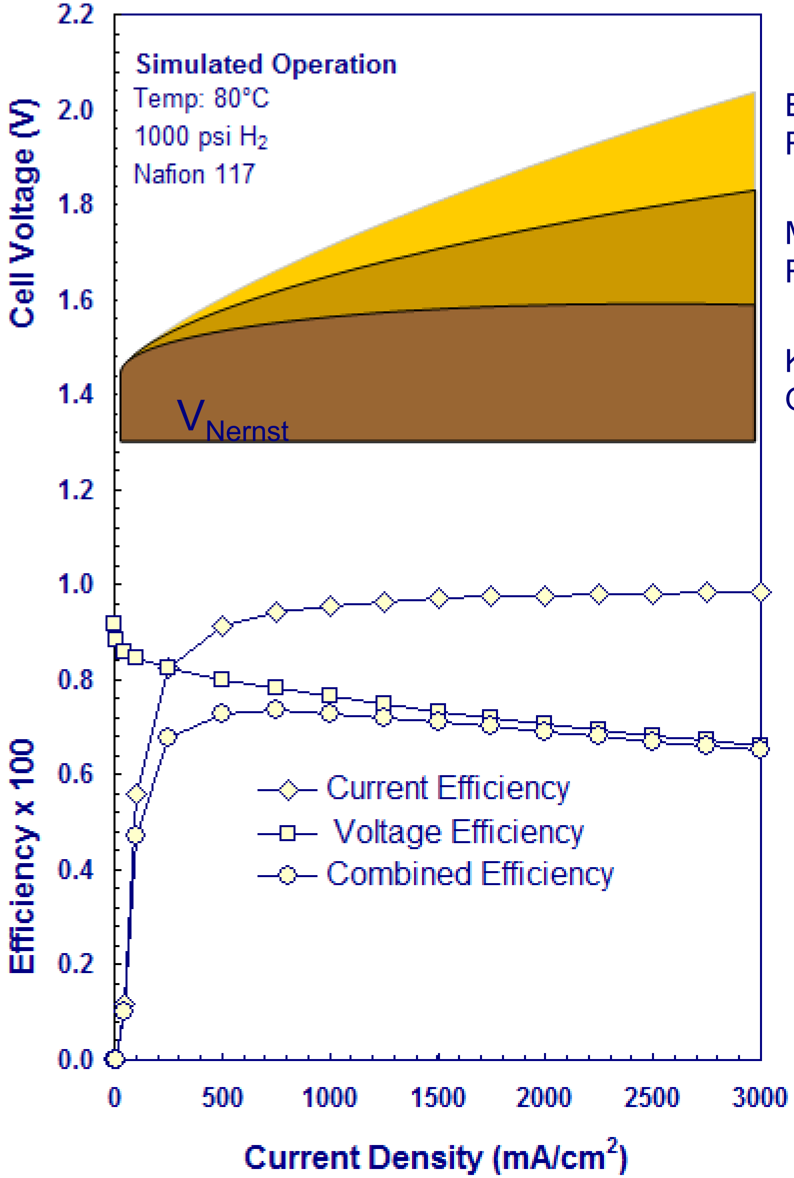
20 kW Electrolyzer
0.35 kg H_2/hr
1500 ASF
1250 psi H_2/Ambient O_2
Volume ~ 16 ft^3



Advantages of PEM Electrolyzer

- PEM electrolyzers operate at high current density
  - Offsets higher cost/area of PEM electrolyzer
- At given current density PEM electrolyzers have higher stack efficiencies than alkaline systems
- PEM differential pressure technology produces H_2 at moderate to high pressure with O_2 production at atmospheric pressure
  - Eliminates handling of high-pressure O_2, reducing system cost & complexity, and improving safety
- Cost is benefited by advances in PEM fuel cell technology

Optimizing Performance of PEM Electrolyzers



Electrical Resistance → Component resistivity

Membrane Resistance → Membrane thickness, Ion Exchange Capacity

Kinetic Overpotential → Similar to fuel cells, majority of efficiency losses are due to slow oxygen kinetics and membrane resistance

$$V_{CELL} = V_{NERNST} + \beta \ln \frac{i}{i_o} + i \sum R$$

$$V_{NERNST} = V_{THN} + \frac{RT}{2F} \ln \frac{[O_2]^{0.5}[H_2]}{H_2O}, \quad V_{THN} = 1.48V\,(HHV)$$

$$\sum R = R_{dif} + R_{bipolar} + R_{electrolyte} + R_{contact}$$

The thermoneutral potential of 1.48 V represents the total amount of energy (HHV) required to disassociate water. The Nernst potential (V_{NERNST}) adds an additional term to account for the electrochemical compression energy required to pressurize the gases in the stack. The terminal cell Voltage (V_{CELL}) must also account for activation potential & iR losses.

GES

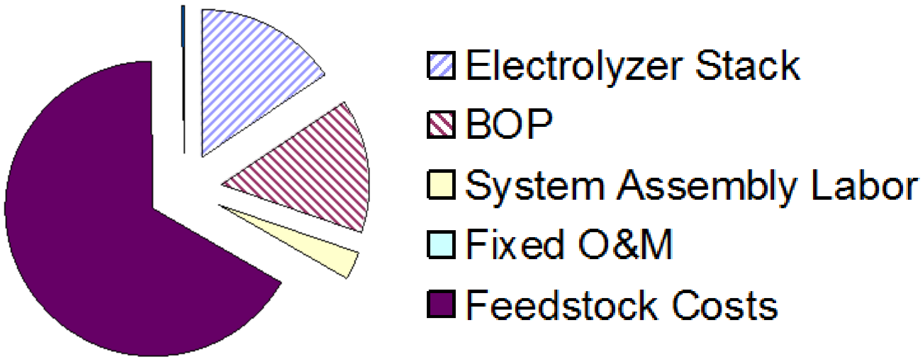
DOE Program

PEM Electrolyzer Incorporating an Advanced Low Cost Membrane

***Challenges**: Improve efficiencies and reduce capital costs of PEM-electrolyzer stacks & systems*

***Strategy:** PEM electrolysis costs can be dramatically lowered by increasing membrane efficiencies, lowering part counts, increasing component durability, and thru implementation of new manufacturing processes*

***Analysis:** Scaled to high volume production- Forecourt* **1500 kg H_2/day, 500 units**



Electricity/Feedstock is the key cost component in hydrogen generation

DOE Targets: Distributed Water Electrolysis

Characteristics/units	2006	2012	2017-2020
Hydrogen Cost ($/kg-$H_2$)	4.80	3.70	2.00 - 4.00
Electrolyzer Cap. Cost ($/kg-$H_2$)	1.20	0.70	0.30
Electrolyzer Efficiency %LHV (%HHV)	62 (73)	69 (82)	74 (87)

Program 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
- Fabricate scaled-up stack components (membrane, cell-separators)
- Assembly electrolyzer stack/system & evaluate efficiency
- Deliver and Demonstrate prototype electrolyzer system at NREL

Low-Cost Electrolyzer Stack developed in DOE program

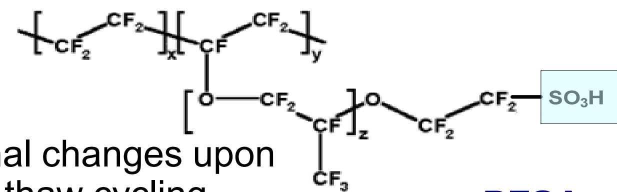
High Efficiency Membrane Development

Supported Membranes

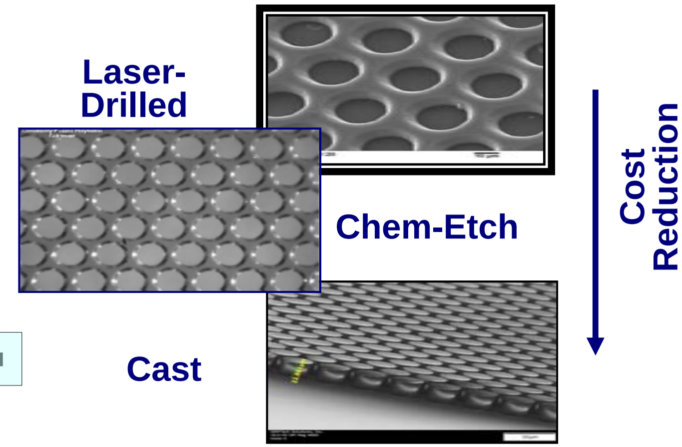
Dimensionally Stable Membrane (DSM™)

Perfluorosulfonic acid (PFSA) ionomer incorporated in an engineering plastic support

- High-strength
- High-efficiency
- No x-y dimensional changes upon wet/dry or freeze-thaw cycling
- Superior to PTFE based supports



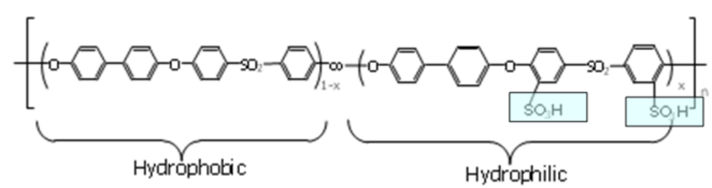
PFSA



DSM Supports

Alternative Membranes

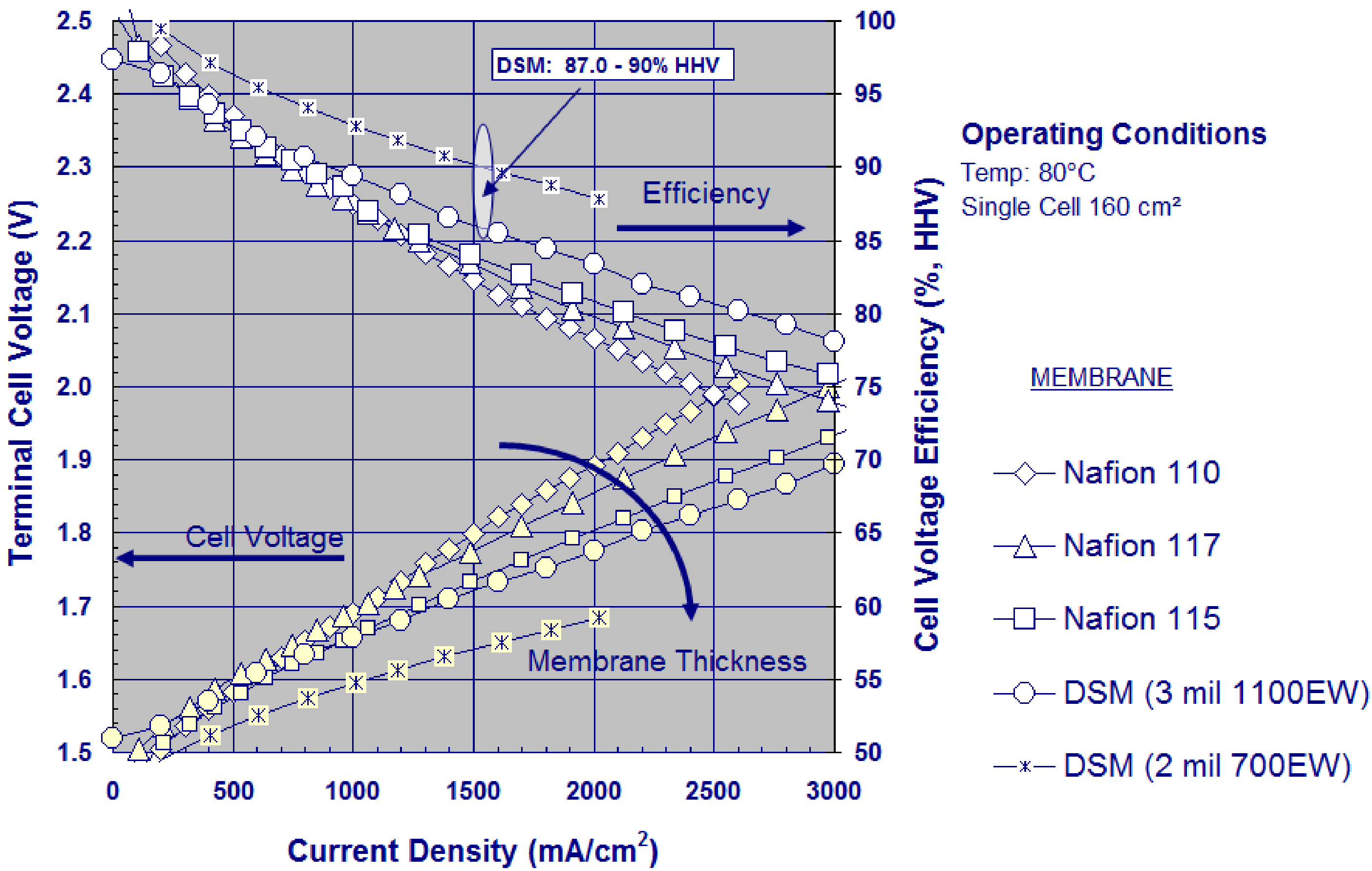
- Hydrocarbon Membranes
  - Bi-Phenyl Sulfone Membrane (BPSH)
  - Hydrocarbon/Phosphonate Membrane
  - Inexpensive starting materials
    - Trade-off between conductivity and mechanical properties
- PFSA (700 EW & 850EW) membranes



BPSH

Approach is to optimize membrane ionomer EW and thickness, scale-up fabrication methods and techniques, and improve costs

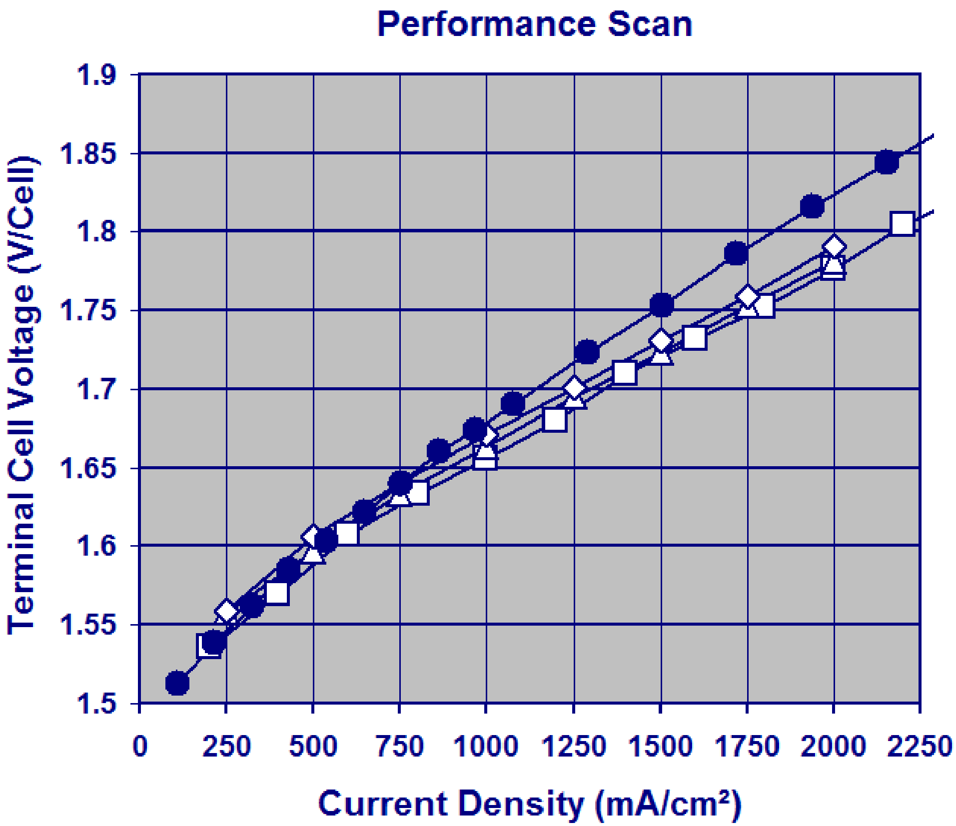
Optimizing Performance of PEM Electrolyzers



- **Performance Milestone** (Mar-2009/Mar-2010)
  - Chemically-Etched (C-) DSM > Nafion® 1135
- **C-DSM (1100EW) selected for use in electrolyzer build**
  - Lower cost, ease of fabrication

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

Performance: Scaled-up DSM & Stack Hardware



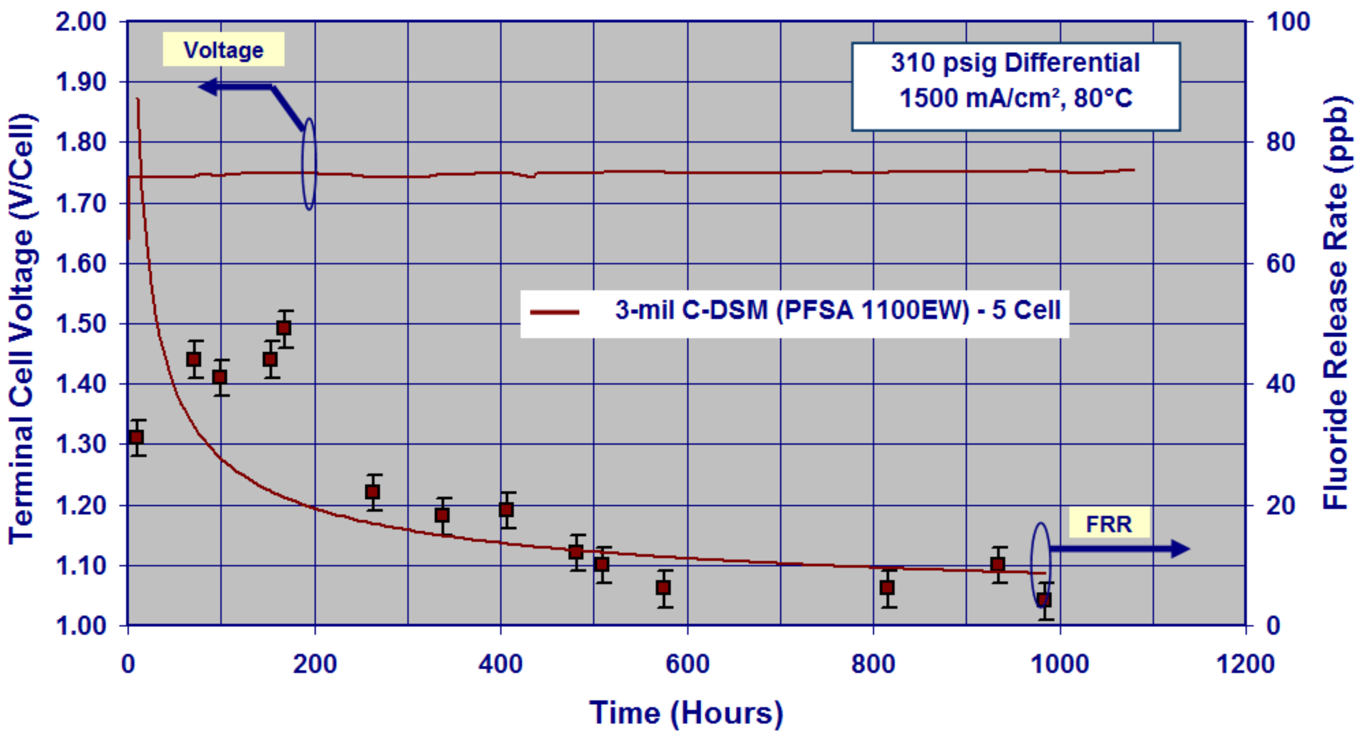
Test Conditions:
80°C
320-330 psig Cathode (H_2)
20 psig Anode (H_2O/O_2)

MEA/Hardware:
DSM thickness (3 mil)
C(poco)/Ti seperator used in scaled-up 290-cm² HW

HW	#Cells	MEA
160-cm²	1	C-DSM
290-cm²	1	C-DSM
290-cm²	5	C-DSM
160-cm²	1	Nafion 1135

- **Milestone (Dec-2010): 5-cell Scaled-up Short-Stack**
  - Performance comparable to 160-cm² HW w/DSM > Nafion 1135®
  - Electrolyzer Stack utilizes scaled-up 290-cm² cell components (DSM, carbon/titanium, cell-separators)

Membrane Progress: Life Testing



Durability Performance

- Completed 1000 Hour Life Test Milestones
  - 1-cell (160-cm²) & 5-cell (290-cm²)
  - 5-cell includes scaled-up components
  - 1.73-1.75V (~88% HHV)
- DSM MEA from 5-cell short stack re-assembled into a single-cell stack, total operating time = 4100+ hours

Membrane Degradation (Estimated Lifetime)

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

Catalyst Demonstration

Successful testing of 3M catalyst, Pt loadings of 3M anode & cathode catalyst are one-order magnitude lower than currently in use (~0.10 to 0.15mg Pt/cm²)!

High Durability Cell-Separator

- **Requirements**
  - Gas-impermeable (separates H_2 and O_2 compartments)
  - High electrical conductivity and high surface conductivity
  - Resistant to hydrogen embrittlement
  - Stable in oxidizing environment
  - Low-Cost
- **Legacy Design**
  - Multi-Layer piece consisting of Zr on hydrogen side and Nb on oxygen side
- **Single or Dual-Layer Ti separators**
  - Ti subject to hydrogen embrittlement
  - Lifetime limited to <5000 hours, depending on pressure and operating conditions
- **Approach**
  - Develop a new low-cost dual-layer structure
    - Evaluate methods of bonding dissimilar metal films
    - Evaluate non-metal substrate with conductive coating

Titanium Cell-Separator with Carbon coating

Cell-Separator Progress

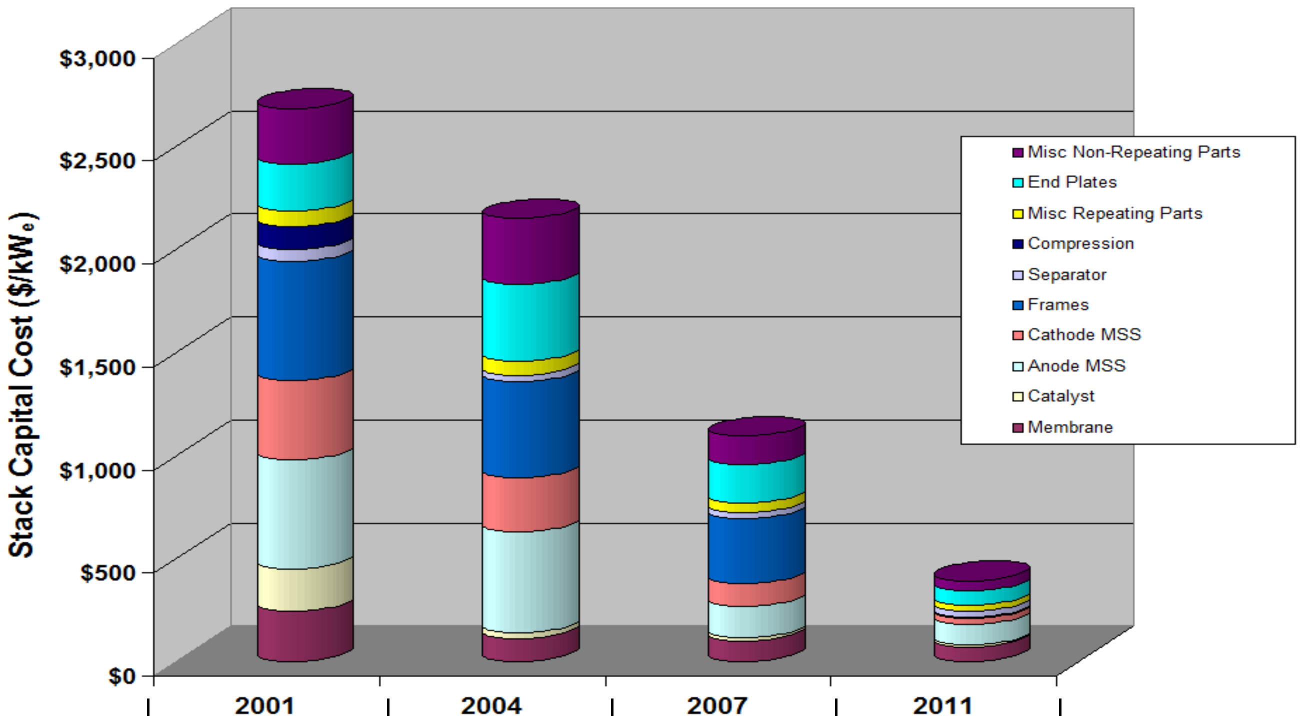
Carbon/Titanium

- Carbon/Titanium Cell-Separators Scaled-up to 290-cm² (Milestone Oct-2010)
  - Evaluated in 5-cell short stack for 1000-hours
  - Single cell-separator testing ongoing (4100+ hours)
  - Cell-Separators fabricated with low porosity carbon
    - POCO Pyrolitic Graphite (Surface Sealed)
    - Low hydrogen uptake (embrittlement)
    - **Life-time estimate > 60,000 hours**
- Analysis
  - C/Ti: No carbon delaminating or loss in thickness
  - Zr/Ti & ZrN/Ti (PVD coatings)
    - Delamination
- New low-cost carbon materials identified

Cell -Separator	Time (Hours)	H_2 uptake (ppm)
C/Ti (290-cm²)	**1000**	**105**
C/Ti (160-cm²)	500	64
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		

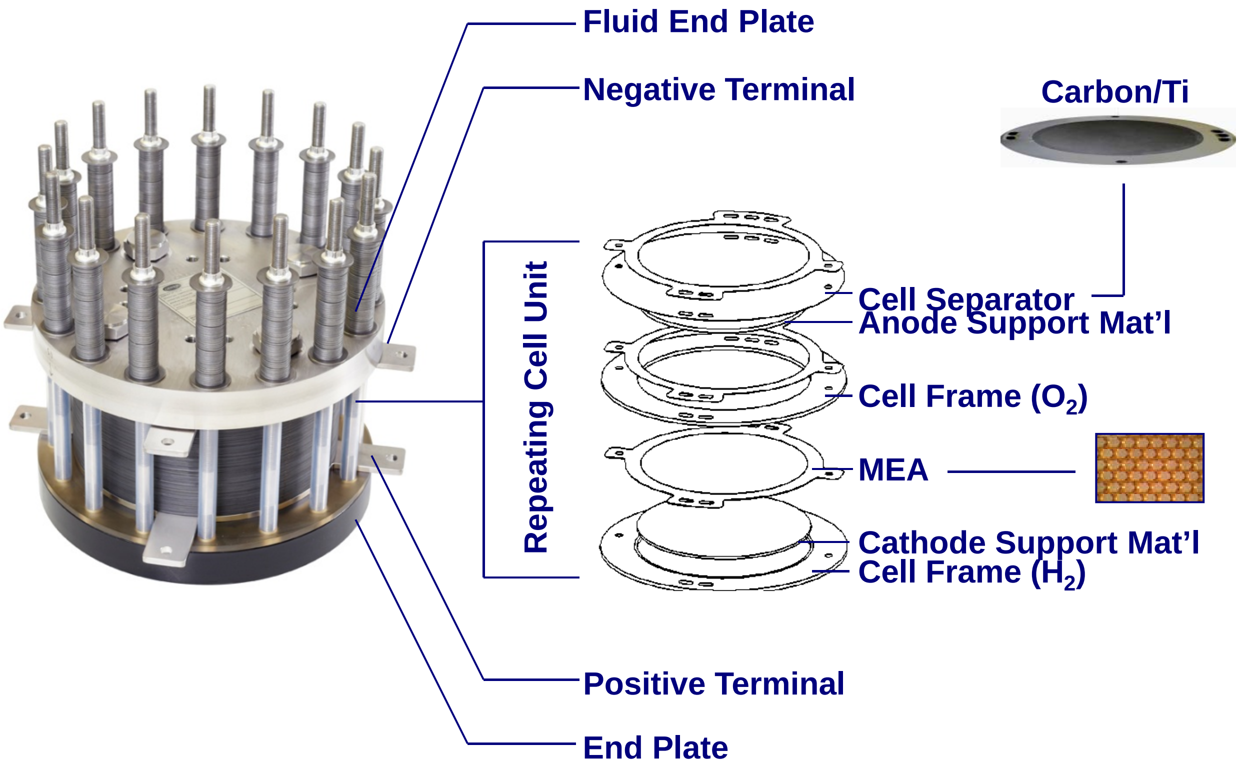
Property	Units	DOE Target FC Bipolar Plates 2015	GES C/Ti Cell-Separator 2011
Cost	$/kW	3	> 10
Weight	kg/kW	<0.4	0.08
Electrical Conductivity	S/cm	> 100	>300 (680 Poco)
Flexural Strength	MPa	>25	86.1 (Poco)
Contact Resistance to GDL (MEA interface)	mΩ. cm²	< 20 @ 150 N/cm²	17 @ 350 N/cm²

Stack Progress: Cost Reduction, Efficiency



	Early	2001	2004	2007	2011	Future
Efficiency (%,HHV):	70	70	78	83	88	>88
Specific Energy (kWh/kg-H_2):	56	56	51	47	45	<45
Membrane Thickness (mils):	10	10	7	5	3 (DSM™)	<3
Temperature (°C):	50	50	55	80	80	80
Power Density (kW/kg):	<0.001	0.76	0.80	0.90	1.0	2.4

Stack Progress:
Advancements & Cost Reductions



The repeating cell unit comprises 90% of electrolyzer stack cost

(2007-2010)

- Increased active area (290cm²)
- Reduced catalyst loadings
- Reduced Part Count 41 to 16
- Pressure Pad: Sub-assembly eliminated
- Molded Thermoplastic Cell Frame
- Cell-Separators: Replaced Nb/Zr with Carbon/Ti

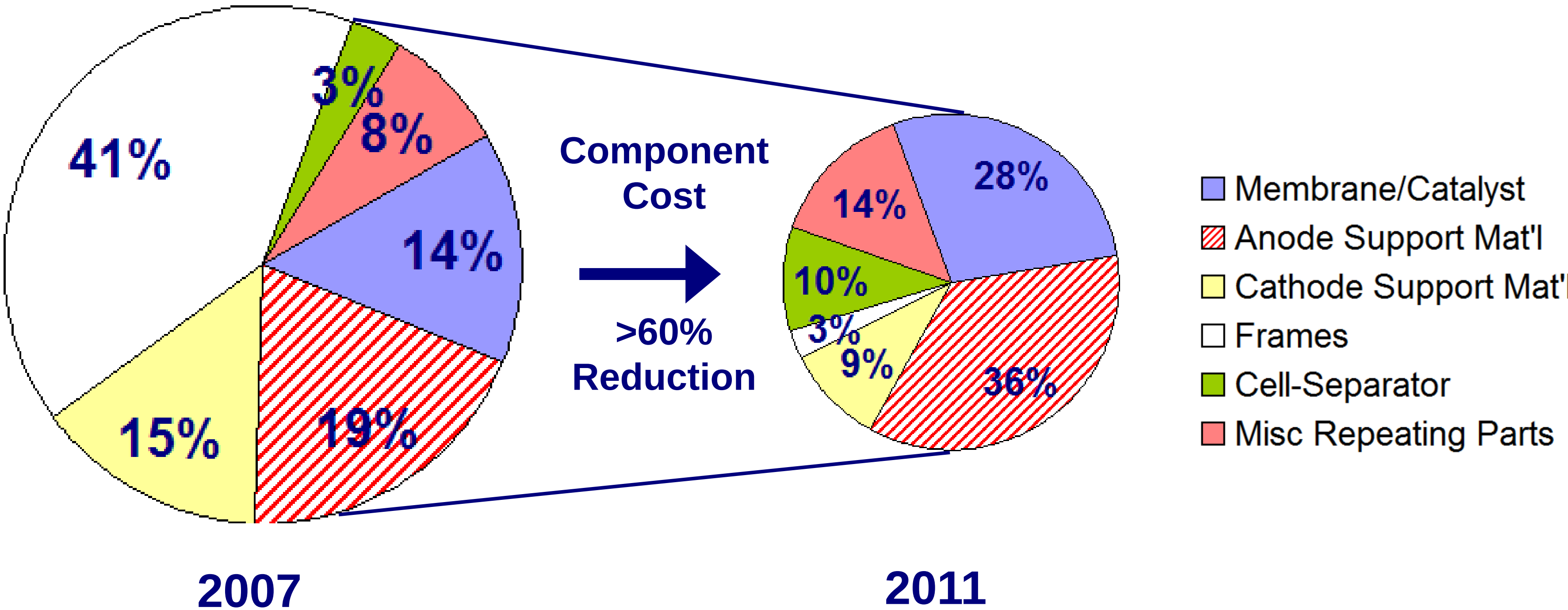
(2010-2011)

- Frame Thickness reduced (by 30%)
  - Reduces Cathode & Anode Support Mat'l
- Reduced Part Count from 16 to 10 Parts/Cell-50% labor reduction
- Nb and Zr mat'l in Anode & Cathode supports eliminated- up to 98% material cost reduction
- DSM MEAs fabricated w/chem-etch supports- 90% cost reduction
- Carbon Steel End Plate (previously S.S.) - 66% material cost reduction

(Future)

- Frame thickness reduced by 90%
- Carbon Steel Fluid End Plate
- Poco in carbon/Ti cell-separators replaced w/low-cost carbon (Entegris).
- Further catalyst reductions (3M)
- Increase Cell-Size
- Low-Cost Ionomers (Tokuyama)

Stack Progress: Repeating Cell Cost



- During DOE funding periods there has been significant cost reductions via new manufacturing techniques
- Anode Support Material & MEAs (membrane & catalyst) now dominate cost of the electrolyzer stack

System Progress

Teamed with large volume commercial manufacturer
(domnick hunter group of **Parker-Hannifin**)

Controller & Power Supply

- Power Supply Efficiency: 94%
- 30kW, 600A, 50V
- Stack Requirement: 23.8kW

System Dimensions

7.20′ H x 6.6′ L x 7.84′ W

Electrolyzer Stack & Dome (O_2 Compartment)

H_2 –Dryer (H_2 Compartment)

- Dryer Efficiency: 96-97%
- Dual desiccant bed
- H_2 cooling prior to dryer

- Stack Efficiency: 88%
- Output: 0.5 kg-H_2/hr(-3% dryer),2.0 kg-H2/hr (w/larger Stack & PS)
- Stack Voltage: 47 V (27 Cells @1.75 V/cell,1741mA/cm²)
- Dome can accommodate >90-cell stack
- Operating Pressure: H_2 350 psig; O_2 atm
- Water Consumption: 5.75 liters/hr
- Cooling Requirement: 3.3 kW

System Progress: Safety

- Failure Modes and Effects Analysis (FMEA) -Analysis indicates highest degree of safety is to enclose stack
- GES designed a Dome to enclose stack
  - Satisfies Codes Pertinent to Hydrogen Refueling Systems
  - Dome design modified for lower cost
  - Pressurized dome: reinforces stack during high pressure operation (future study)
  - Reviewed National & International Codes & Standards

FMEA

PROB-ABILITY	SEVERITY Catastrophic I	Critical II	Marginal III	Negligible IV
Frequent				
Probable				
Occasional				
Remote			1	
Improbable	7	12	1	
Incredible	12	2		

Colour indicates class:- Class A | Class B | Class C | Class D

Risk Class	Initial Status
A	5
B	3
C	24
D	3

Risk Class	Current Status
A	0
B	0
C	32
D	3

- System design improvements and the use of a Dome eliminate the highest severity cases related to hydrogen ignition (Class A), & electrocution (Class B)

Don't Forget about the SAFETY Codes!

Electrolyzer systems must follow specific codes to become commercially viable

System Components

IEC 60079-10-1:
Explosive Atmospheres,
Classification of Areas

ISO 4126-1,-2:
Safety Devices for Protection Against Excessive Pressure: Valves & Rupture Disks

CSA America HGV 4.7-2009:
Automatic Valves for use in Gaseous Hydrogen Fueling Stations

SAE J2600:
Compressed Hydrogen Fueling Receptacles

Electrolyzer Systems

ISO/DIS 22734-2:
Hydrogen Generators Using Water Electrolysis Process

Eventual UL and CSA
Versions of **ISO/DIS 22734-2**

Vehicle Refueling

CSA America HGV 4.1-2009:
Hydrogen Dispensing Systems

NFPA 52-2010, Chapter 9:
GH2 Compression, Gas Processing, Storage, and Dispensing Systems

International Fire Code Section 2209:
Hydrogen Motor Fuel Dispensing and Generation Facilities

SAE TIR J2601:
Compressed Hydrogen Fueling Protocol

Codes Pertinent to Hydrogen Generators

Projected H_2 Cost

Specific Item Cost Calculation **Hydrogen Production Cost Contribution**	
H2A Model Version (Yr) Forecourt Model	Rev. 2.1.1 (FY2010)
Capital Costs	$0.60
Fixed O&M	<$0.39
Feedstock Costs $1.54 min. @ 39.4 $kWh_e/kg\text{-}H_2$ (~100% Eff.)	$1.86 **(DSM)**
Byproduct Credits	$0.00
Other Variable Costs (including utilities)	$0.01
***Total Hydrogen Production Cost* ($/kg)** (Delivery not included)	**2.86**
Delivery (Compression, Storage, Disp.)	1.80
Total Hydrogen Production Cost ($/kg)	**4.66**

Miles travelled kg-H_2/gallon of gasoline	60/30
Total Cost in gallons of gasoline equivalent ($)	**2.33**

- Design capacity: 1500 kg H_2/day
- Assume large scale production- costs for 500th unit
- Assume multiple stacks/unit
  - Low-cost materials and component manufacturing
- 333 psig operation. H_2 compressed to 6250 psig
- Operating Capacity Factor: 70%
- Industrial electricity at $0.039/kWhr

Cost of Electrolysis is Becoming Competitive

Summary

- **Demonstrated membrane reproducibility and durability**
  - Demonstrated DSM membrane performance better than that of Nafion 1135 at 80°C
  - Demonstrate DSM membrane lifetime at 80°C for 1000 hours
    - Single-cell ($160cm^2$), 5-Cell ($290cm^2$)
    - Single-cell ($290cm^2$) life test ongoing – 4100+ hours
- **Cell Separator Development:**
  - Demonstrated performance comparable to dual-layer Ti separator in 160-cm^2 & 290-cm^2 electrolyzer
  - Demonstrated significantly reduced hydrogen embrittlement with carbon/Ti separators
    - Expected cell-separator lifetime in the range > 60,000 hours
- **Scaled-Up Stack Design**
  - Significant progress made in stack cost-reduction (cell-components, membrane, & catalyst)
    - New manufacturing techniques used to reduce labor cost
    - Commercialized stack (orders have been delivered)
  - Further reductions in membrane (material/labor) costs are required
- **System Development:**
  - High efficient H_2-dryer demonstrated

Challenges

Market

Is this technology feasible for cost effective storage of renewable electricity?

- *Dependent on scale*
- *Systems need to be demonstrated*
- *Industrial collaborations needed to promote technology*
  - PEM electrolyzers have been purchased for grid stabilization, industrial and analytical H2 production, and military use. Vehicle refueling market needs to be established.

Technical

What are the materials and systems barriers to developing this technology?

- *New low Pt loaded Catalyst loadings have been reduced by 100x in only the last 5 years but need to be life tested*
- *Reduced cell-frame thickness that reduce material requirements*
- *Low-cost carbon for cell-separators/nitrided cell-separators*
- *Low-cost membranes*
- *Adapt low-cost stack designs for high pressure applications*

What are the manufacturing issues that need to be addressed to be cost effective?

- *Reduce labor cost thru new manufacturing techniques*
- *Reduce part count in cells*

System efficiency is still key for cost competitiveness!