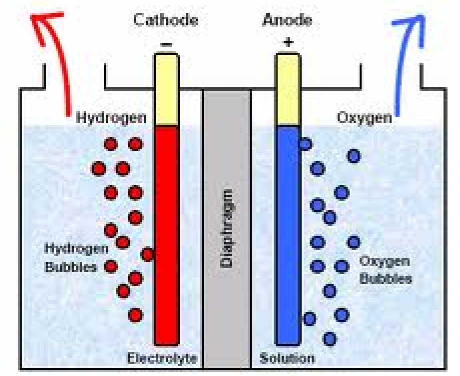
HYDROGEN ELECTROLYZERS

What: A hydrogen electrolyzer is an electrochemical device used to split water into it elements. The operation of an electrolyzer in its simplest form is shown below. A DC electric current is applied to a conductive aqueous solution which results in the evolution of hydrogen at the cathode and oxygen at the anode.



Standard Electrolysis

TYPES OF ELECTROLYZERS:

PEM. A PEM (Polymer Electrolyte membrane) electrolyzer can be considered as a PEM fuel cell run in reverse. The PEM electrolyzer has virtually all of the attributes of the PEM fuel cell. As the membrane is a proton conductor, the PEM electrolyzer runs in an acid solution.

Electrodes need the Pt catalyst
Membranes are expensive
Good start-stop capabilities

Alkaline electrolyzer: The other major electrolyzer technology uses an alkaline electrolyte, a potassium hydroxide solution. Owing to the high pH of the electrolyte, the electrodes in these systems use a nickel electro-catalyst.

Overall Process:

H_2O liquid -→ $H_2 + ½ O_2$

Hydrogen Energetics: Basic Numbers

	Higher Heating Value		Lower Heating Value	
Hydrogen Qty	**Qty**	**Units**	**Qty**	**Units**
1 kg	134,200	BTU	113,400	BTU
1 kg	39.3	kWhr	33.2	kWhr
1 kg	141,600	kJ	119,600	kJ
1 kg	33,800	kCal	28,560	kCal

It is useful to think of hydrogen by the kilogram rather than by a gas volume; the former is state independent and equal to 0.997 gge[1] while with gas volumes, one must always know the conditions which are not standardized.

Electrolysis energetics: Including the energy needed for the process, the electrolysis reaction becomes:

H_2O (liquid) + 237.2 kJ/mol (electricity) + 48.6 kJ/mol (heat) -→ H_2 + ½ O_2

The energy terms represent the minimum required energy to deconstruct 1 mol (18 g) of water. In real operation, considerably more energy is needed per unit water converted owing to such items as system resistances, electrode kinetics and reactant transport. The Ohmic heat generated in the electrolyte results from the passage of electricity through the resistance of the cell, $=i^2R$.

PROCESS EFFICIENCIES[2]:

Electrical efficiency[3] (HHV) =HHV of H_2 made/electricity used

The Hydrogenics PEM Electrolyzer

Production rate = 1Nm3[4]/hr = 0.08988 kg which required 4.9 kWh

Electrical efficiency = ((0.8988 kg x 39.3 kWh/kg)/4.9 kWh) x 100% = **72%**

The PEM electrolyzer uses 54.6 kWh (193.6 MJ) electricity per kg hydrogen made and would take over 11 hours for a kg make.

The Hydrogenics alkaline electrolyzer

The largest system yields 60 Nm3/hr = 5.39 kg/hr x 57.9 kWh/kg (208.3 MJ/kg)

Efficiency = 39.3 kWh/kg (141.6 MJ/kg)/57.9 kWh/kg (208.3 MJ/kg) x 100% = **67.9%**

[1] Gge = gallon of gasoline equivalent. So, a kg of hydrogen has about the same energy content as a gallon of gasoline.
[2] There are 2 approaches to calculating the efficiencies of hydrogen fuel cells and their reverse process, water electrolysis. In the US the HHV for hydrogen is usually used as the water typically ends up as liquid in the fuel cell system and starts as liquid water in electrolysis. The European convention is to use the LHV for hydrogen which is smaller. Use of the LHV value will give a higher calculated efficiency (division by a smaller number).
[3] Calculation of the electrical efficiency will use operating data from Hydrogenics, a major electrolyzer manufacturer.
[4] 1 Nm3 = 1 normal meter cubed H2 per hour, 1 m3 at 0 C and 1 atm pressure.

The PEM electrolyzer is slightly more electrically efficient compared to the alkaline electrolyzer. However, the output from the alkaline electrolyzer is a factor of 60 times greater per unit time.

What about pressure?

There are 2 (quasi) standards for the hydrogen gas pressures used for operation of fuel cell vehicles, 35 MPa (5,000 psi) and 70 MPa (10,000 psi). The hydrogen gas produced by the electrolyzers is evolved at much lower pressures, e.g., 115 psi for the PEM electrolyzer. Thus, the hydrogen must be compressed for use in the desired application. Compression of hydrogen to these pressures requires input of considerable energy[5].

Energy required to get to 35 MPa (5,000 psi) = 13 MJ/kg (multi-stage mechanical compression)
Energy required to get to 70 MPa (10,000 psi) = 16 MJ/kg (multi-stage mechanical compression)

Energy required to get to 35 MPa by isothermal compression (direct high pressure electrolysis) = 6.5 MJ/kg

Thus, the overall efficiency of the alkaline electrolyzer for 70 MPa hydrogen becomes:

[141.6 MJ/ (208.3 MJ + 16 MJ/kg)] x 100 % = **63%**

ELECTROLYZER SUPPLIERS

There appear to be a large number of water electrolyzer supplies. A 2004 NREL report[6] listed about 8 different suppliers. A more recent report[7] showed a table, below, of the suppliers included in their study. There was very little overlap in the 2 lists. Further, this second report mentioned GE as a supplier but did not include their equipment in the study. GE has been active in this area. These electrolyzers are on a scale appropriate for distributed generation for servicing hydrogen fueled vehicles.

Supplier	Location	Technology	Production Capacity (kg/day)	H_2 Product Pressure (psi)
Avalance	United States	Unipolar Alkaline	Up to 10	Up to 6,500
Giner	United States	Bipolar PEM	Up to 8	Up to 1,250
H2 Technologies	Norway	Bipolar Alkaline	Up to 1,000	Atmospheric
Hydrogenics	United States	Bipolar PEM	Up to 127	Up to 363
IHT	Switzerland	Bipolar Alkaline	Up to 1,500	Up to 464
Proton	United States	Bipolar PEM	Up to 13	Up to 435

[5] Ulf Bossel, The Physics of the Hydrogen Economy, European Fuel Cell News, (2003), 10, (2)
[6] NREL 36734 2004
[7] NREL 2009, listed in Appendix A.

Electrolyzers of all sizes are in operation around the world. A more comprehensive list is given in Appendix B. It has been very difficult to get any hard costing data for water electrolyzers designed for hydrogen fueling stations. There has been a 10+ year project at NREL devoted to wind to hydrogen electrolyzers; some of the more applicable recent reports are in Appendix A.

Not listed in the NREL report was some work performed by GE for the DOE. Not sure why NREL ignored this work, it appears to be very right on to the target. The following figures come from the final presentation of the work to the DOE[8]. They do give one a sense of the projects goals and the progress towards made by the GE team.

The project was to explore the economic and technical feasibilities for developing a pressurized low-cost water electrolyzer for hydrogen make. The 2012 DOE targets for the systems are shown in the figure below.

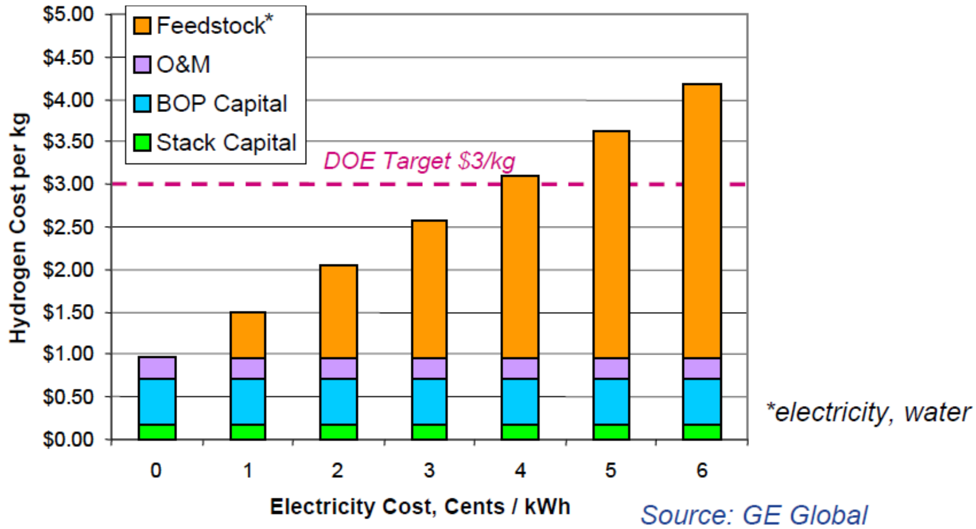
	Units	DOE 2012 Target
Cell Efficiency	%	69% (1.8V)
System Cost	\$/kg H2	\$0.70 (\$400/kW)
Electricity Cost	\$/kg H2	\$2.00
O&M Cost	\$/kg H2	\$0.60

GE came up with a novel design for the electrolyzer, alkaline electrolyte, which made extensive use of GE engineering plastics. The production stack cost was estimated to be about \$100/kW at 50 kWh/kg H2. The Hydrogenics electrolyzers, above, came in around 55 kWh/kg H2.

Projected CapEx, 5 kg/hr stack :	Per kg/hr	Per Nm^3/hr
Prototype	\$16,000	\$1,426
Production	\$5,000	\$446

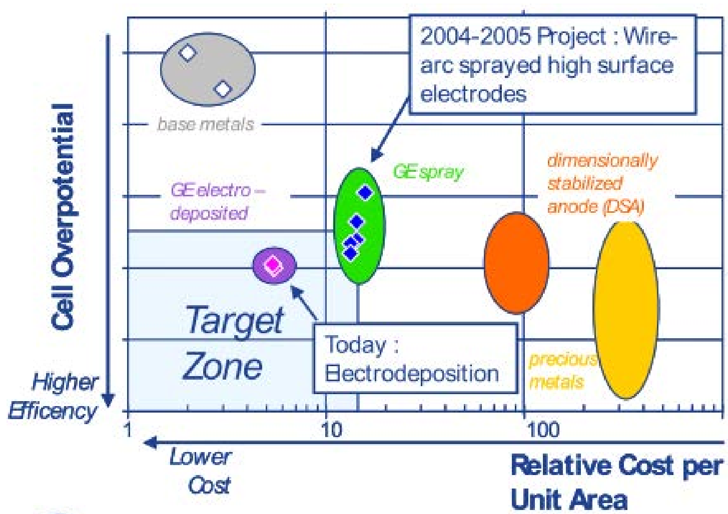
The sensitivity to electricity costs is shown in the following graph; the system feedstock consists of water (purified) and electricity.

[8] *www.hydrogen.energy.gov/pdfs/review07/pdp_16_**bourgeois**.pdf*



Source: GE Global Research, NREL H2A Model

The GE system contained plastic electrodes in a bipolar configuration. Platinum metal catalysts were still required however no indication of the loading was made.



There doesn't appear to have been any commercialization of this technology. The wind to hydrogen work is now located at NREL. The goal of $3/kg hydrogen has not been reached. It has been raised to $4-6/kg hydrogen in response to gasoline running around $4/gal. One kg of hydrogen is equivalent to 0.997 gallon of gasoline. As hydrogen fuel cell vehicles get more than twice the mileage of their gasoline counterparts these costs are reasonable. Consider that the Toyota Highlander fuel cell vehicle has a range of 431 miles at an average of 68.3 miles/kg of hydrogen. The fuel tank holds about 4 kg of hydrogen at 70 MPa (10,000 psi).

The electrolyzers are not competitive with natural gas reforming unless the electricity is almost free. This situation may soon obtain in some areas owing to large potential generating capacities by installed wind generators in areas where the ISO doesn't want the wind energy; this is happening.

APPENDIX A: REFERENCES:

Harrison 2010: K. W. Harrison, R. Remick, G . D. Martin and A. Hoskin, Hydrogen Production: Fundamentals and Case Study Summaries, conference paper, NREL/550-43702, January 2010

NREL 2009: Independent Review, Current (2009) State-of-the- Art Hydrogen Production Cost Estimate Using Water Electrolysis, NREL/BK-6A1-46676, September 2009

Saur 2011: G. Saur & T. Ramsden, Wind Electrolysis: Hydrogen Cost Optimization, NREL/TP-5600-50408, May 2011

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Ogden 2011: J. Ogden & L. Anderson, Sustainable Transportation Energy Pathways, A Research Summary for Decision Makers, ITS UC Davis, Davis, CA 2011

Ball 2009: M. Ball & M. Wietschel, eds., The Hydrogen Economy, Cambridge University Press, New York, NY, 2009 (ISBN 978-0-521-17854-9)

O'Hayre 2009: R. O'hayre, S-W Cha, W. Collella, & F. B. Prinz, Fuel Cell Fundamentals, 2nd edition, John Wiley & Sons, New York, NY, 2009

Davis 2011: S. C. Davis, S. W. Diegel & R. G. Boundy, Transportation Energy Data Book, 30th edition, ORNL-6986, cta.ornl.gov/data, June 2011

Company	Website
AccaGen	http://www.accagen.com/
Available Energy	http://www.availableenergy.com
Avalence	http://avalence.com/default.asp
Electric Hydrogen (Eh!)	http://www.electrichydrogen.com/
ELT Elektrolyse Technik	http://www.elektrolyse.de/vkp/index.php
Gesellschaft für Hochleistungsele	http://www.ghw-mbh.de/english/01_home/index.html
Giner	http://www.ginerinc.com/
Hamilton Sundstrand	http://www.hamiltonsundstrand.com
Hydrogen Technology Ltd.	http://www.hydrogentechnology.com.au/
Hydrogenics	http://www.hydrogenics.com/onsite/products.asp
Idroenergy	http://www.idroenergy.it
Industrie Haute Technologie	http://iht.ch
Infinity Fuel	http://www.infinityfuel.com/
ITM	http://www.itm-power.com/
Linde	www.linde.com/hydrogen
Lynntech	http://www.lynntech.com/
Nitidor Clever	http://nitidor.com/index.asp
Peak Scientific	http://www.peakscientific.com/
PIEL (ILT Tech.)	http://www.piel.it/
Proton Energy Systems	http://protonenergy.com/
Schmidlin-DBS	http://www.schmidlin-dbs.com/
Siam Water Flame	http://www.waterflame.co.th/
StatoilHydro Hydrogen Technologies	http://www.electrolysers.com/
Teledyne Energy Systems	http://www.teledynees.com
Treadwell	http://www.treadwellcorp.com/
UTC Power	http://www.utcpower.com