DOE Hydrogen and Fuel Cells Program Record	
Record #: 6002	**Date:** September 28, 2006
Title: Electrolysis Analysis to Support Technical Targets	
Originator: Roxanne Garland	
Approved by: Sunita Satyapal	**Date:** December 16, 2008

Item #1:
Distributed Water Electrolysis – Technical Targets.

Table 3.1.4 and Table 3.1.4A in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan.

Reference:
This Record provides further information vis-à-vis the assumptions and corresponding references used in Table 3.1.4 "Technical Targets: Distributed Water Electrolysis Hydrogen Production" and Table 3.1.4A "Distributed Electrolysis H2A Example Cost Contributions" in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. All assumptions are standard H2A assumptions from the following forecourt electrolysis cases unless otherwise noted below.

For 2006 standard H2A case, see Record 6002g H2A Standard Forecourt Electrolyser Current Case; for 2012 standard H2A case, see Record 6002h H2A Standard Forecourt Electrolyser Advanced Case; and for 2017 standard H2A case see Record 6002i H2A Standard Forecourt Electrolyser Longer-Term Case.

This link http://www.hydrogen.energy.gov/h2a_analysis.html#assumptions provides a list of standard H2A assumptions.

The specific H2A analyses used as input in determining the technical targets in Tables 3.1.4 and 3.1.4A in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan are Record 6002d, H2A MYPP Current Forecourt Electrolysis Case (2006); Record 6002e, H2A MYPP Advanced H2A Case Forecourt Electrolysis Case (2012); and Record 6002f H2A MYPP Longer-Term Forecourt Electrolysis Case (2017).

Data/Assumptions/Calculations:

The following provides additional information to the footnotes listed in Tables 3.1.4 and 3.1.4A in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

d. Electrolyzer capital costs (uninstalled) are assumed to be $665/kW in 2006 and $400/kW in 2012. These costs include the electrolyzer balance of plant (i.e., power electronics, dryer, KOH pump if necessary, etc.). The 2017 electrolyzer capital costs are assumed to be $125/kW uninstalled.
g. Assumption for forecourt compressor power requirement from Hysys® simulation http://www.aspentech.com/hysys/.

i. Dispenser costs based on 3 dispensers, each at $22,400.

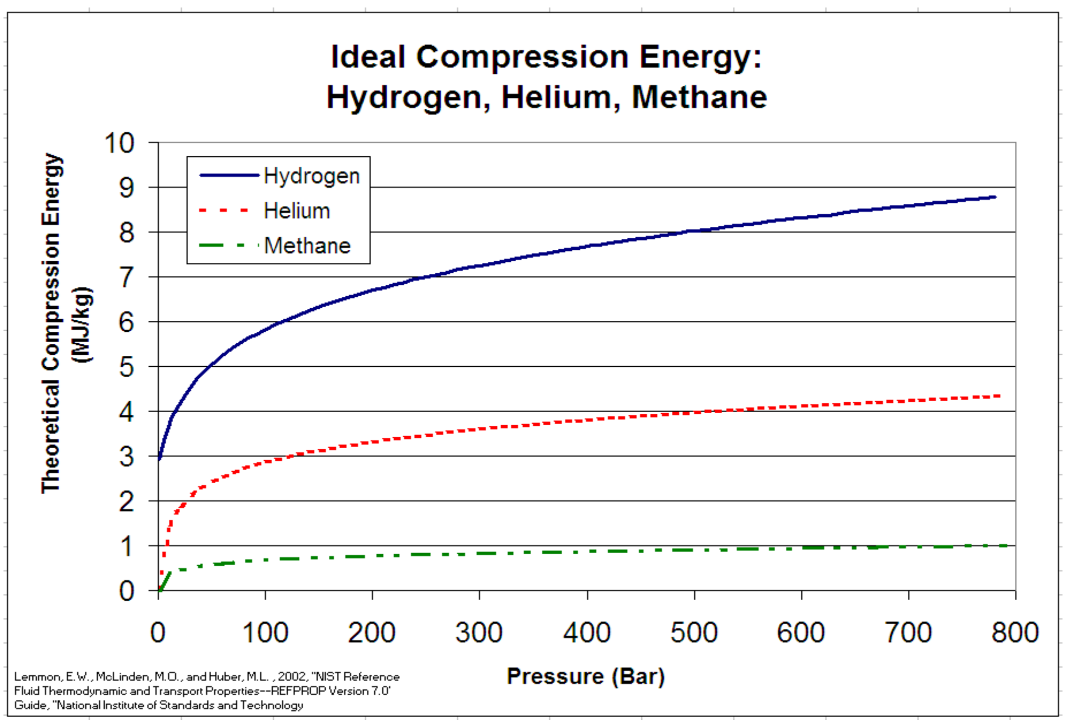
The following are deviations from the standard H2A model assumptions.

Assumption:
Footnote d – Electrolyzer capital costs assume high volume annual production of 1,000 units for all purposes and markets. 2017 electrolyzer capital costs are assumed to be $125/kW uninstalled.

Reference:
See "The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs," by the National Research Council and National Academy of Engineering[1] for $125/kW capital cost for the electrolyzer.

Assumption:
Footnote h – In 2017, hydrogen is produced from the electrolyzer at 1000 psi, and the electricity cost contribution is lowered by $0.09/kg as a result of a stage reduction due to the electrolyzer producing hydrogen at 1000 psi. (From estimate resulting from a run of the H2A Delivery Components Model [www.hydrogen.energy.gov/systems_analysis.html] that shows if hydrogen is produced in the electrolyzer at 1000psi it reduces the number of stages in the compressor by one.)

Reference:
Electrolyzer manufacturers have recently begun to search for the optimum pressure at which to operate their electrolyzers – balancing high pressure issues with energy savings. There are energy savings if the inlet pressure to a hydrogen compressor can be above roughly 50 bars (49 atm or 725psi); however, any additional potential issues with high pressure operation of electrolyzers would need to be addressed. The chart below shows the compression energy needed for various final pressures.[2]



Note that there is a very steep slope to this curve until about 50 bar. This, along with discussions with electrolyzer manufacturers, led us to select 1000 psi (69 bar) as the target outlet pressure for an onsite electrolysis unit. This pressure selection is based on the point the slope beings to flatten and the manufacturers' consensus of reasonable pressure.

The cost reduction results from a run of the H2A components model that shows if hydrogen is produced in the electrolyzer at 1000psi it reduces the number of stages in the compressor by one, and reduces the cost by $0.09/kg of hydrogen. The following figure shows an extract of the two H2A components model cases. The cells of interest are highlighted in bright yellow.

Extract of the Two H2A Components Model Cases

Forecourt Compressor

NOTE: This page will not design or select a compressor for the user. It is designed to be used when a compressor has been selected, and the user is interested in the hydrogen delivery cost of the compressor. Calculations assume isentropic compression. Interstage cooling is assumed between the stages of all multistage compressors. This tab is for compressors smaller than 1500 kg/day. For larger compressors the user should use the H2 Compressor tab.

Calculation Outputs (Be sure ALL data is entered before checking)

	~440 psi inlet pressure	~1000 psi inlet pressure	Price difference
Forecourt Compressor Portion of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$0.580	$0.492	$0.09
Capital Cost Contribution to the Forecourt Compressor Share of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$0.141	$0.141	
Energy/Fuel Cost Contribution to the Forecourt Compressor Share of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$0.296	$0.208	
Other Cost Contribution to the Forecourt Compressor Share of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$0.142	$0.142	
Mass Efficiency (H2 out/H2 in)	99.5%	99.5%	
System Energy Use (MJ/kg of H2 out)	13.060	9.177	
System Energy Efficiency, LHV (%, H2 out/(H2 in + Energy/Fuel Use))	89.8%	92.5%	
Real After-Tax Discount Rate (%)	10.0%	10.0%	

THERE ARE NO ERRORS PRESENT ON THIS SHEET

Forecourt Compressor Design Inputs

Design Input	Value		Comments
Average Hydrogen Flow Out (kg/day)	1,050	1,050	
Peak Hydrogen Flow Out (kg/day)	1,500	1,500	
Capacity Factor (%)	70%	70%	
Inlet Pressure (atm), no vacuum pressures allowed	30	68	30 atm = pressure out of electrolyzer (~440 psi)

Compressor Calculations

Item	Value	Value
Gas Constant (kJ/K.kg-mol)	8.3144	8.3144
Mean Compressibility Factor	1.14186	1.15490
Pressure Ratio	2.5	2.5
Number of Stages	3.0	2.0
Net Hydrogen Delivered (kg/year)	383,250	383,250
Design Compressor Flow to Each Compressor (kg/day)	754	754
Theoretical Power Requirement (kW)	37	26

Color Code Key

- **= Calculated Cells (do not change formulas)**
- **= Input Required**
- **= Optional Input**
- **= Information Cells**
- **= Cells of interest**

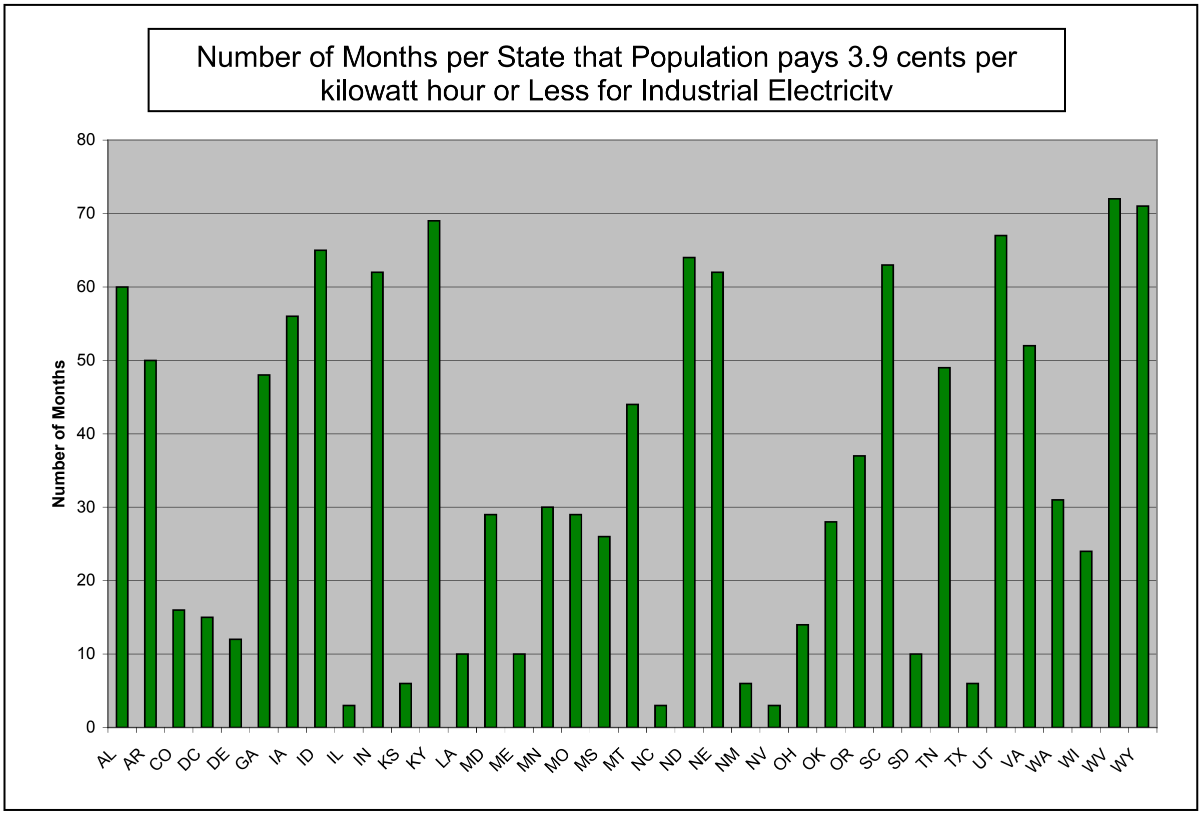
Assumption:
Footnote I – Electricity costs are $0.039/kWh. Electricity costs are based on the lowest average industrial grid electricity price that 25% of the US paid from 2000-2005 according to historical EIA data.

Reference:
In order for electrolysis to be cost competitive for hydrogen production, areas with low industrial priced electricity must be used. An analysis was completed to determine the lowest industrial electricity rates at least 25% of the US paid for electricity from 2000-2005, according to historical EIA data. The raw data for electricity "Average retail price industrial ¢/kWh" broken out by state, month, and year was obtained from http://www.eia.doe.gov/cneaf/electricity/page/sales_revenue.xls[3]. The raw data for population was extracted from 2000 census data obtained from http://www.census.gov/popest/counties/files/CO-EST2003-alldata.csv[4].

The electricity price data was combined with the population data by adding a column that detailed the 2000 population of each state. This population value along with the state's average industrial electricity rate formed the basis for the analysis. The data was sorted from lowest average industrial electricity rate paid to highest. Next, the population data was summed, from lowest electricity price to highest, and the result divided by the total population in the US in the years 2000-2005. An assumption was made that the population state by state from the year 2000 could be applied to all the years from 2000-2005. Finally, it was determined at what point 25% of the US population was included in the data set, and then the "Average Retail Price Industrial (¢kWh)" value was averaged for the entire dataset, giving us the lowest average industrial electricity price paid by at least 25% of the US population from 2000-2005. A subset of the dataset can be seen below.

Year	**Month**	**State**	**Average Retail Price Industrial (¢/KwH)**	**State Population in 2000**	**Population Sum**	**Average Electricity Price**	**% of U.S. Population from 2000-2005 served by electricity rate**
2005	**2**	**DC**	1.93	783,600	783,600	1.93	0%
2000	**5**	**WA**	2.52	5,894,121	6,677,721	2.22	0%
2000	**4**	**ID**	2.6	12,419,293	19,097,014	2.35	0%
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2001	**1**	**AR**	4.36	5,130,632	5,048,603,139	3.9	25%

The following figure displays how the average rate calculated was dispersed through the US over time and geographically.



Assumption:
Footnotes j, k and m –

j. Compressor costs are based on $4580/(kg/hr) in 2006, $4000/(kg/hr) in 2012, and $3000/(kg/hr) in 2017 for 1500kg H_2/day size compressor which are consistent with the status and cost targets of Section 3.2 – Delivery of the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan.

k. Storage costs are based on $820/kg at 6250psi in 2006, $500/kg at 6250psi in 2012 and $300/kg H_2 at 10,000 psi in 2017 which are consistent with the status and cost targets of Section 3.2 – Delivery of the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. Storage capacity for 1000 kg of hydrogen at the forecourt is included. It is assumed that the hydrogen on-board storage pressure is 5000 psi for 2006 and 2012 and is 10,000 psi for 2017.

m. "Start Up Time" assumption changed from 1 yr. to 0.5 yrs., "Percent Variable Costs During Start-up" changed from 100% to 50%, and "Fixed Costs During Start-up" changed from 100% to 75% based on the recommendations from the 2006

Independent Assessment of the Status of Distributed Natural Gas Reforming (www.eere.energy.gov/hydrogenandfuelcells.)"

Reference:
A communication was received from the FreedomCAR and Fuel Partnership Delivery team on July 12, 2006 that stated the following parameters needed to be changed so that the forecourt electrolysis target and the steam methane reforming target are consistent with the recommendations from the 2006 Independent Assessment of the Status of Distributed Natural Gas Reforming.

1. Change the Start Up Time from 1 yr. to 0.5 yrs.
2. Change the % Variable costs during start-up from 100% to 50%.
3. Change the Fixed Costs during start-up from 100% to 75%.
4. Change the compressor purchased capital for the Advanced Case to $4,000/(kg/hr).
5. Change the compressor purchased capital for the Longer-term Case to $3,000/(kg/hr).
6. Change the storage purchased capital for the Advanced Case to $500/kg of H2.

Item #2:
Central Wind Electrolysis – Technical Targets.

Table 3.1.5 and Table 3.1.5A in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan.

Reference:
This Record provides further information vis-à-vis the assumptions and corresponding references used in Table 3.1.5 "Technical Targets: Central Wind Water Electrolysis" and Table 3.1.5A "Central Wind Electrolysis H2A Example Cost Contributions" in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. All assumptions are standard H2A assumptions from the following wind electrolysis cases unless otherwise noted below.

For 2006 standard H2A case, see Record 6002j H2A Standard Central Wind with Electricity Co-Product Current Case; for 2012 standard H2A case, see Record 6002k H2A Standard Central Wind with Electricity Co-Product Advanced Case; and for 2017 standard H2A case see Record 6002l H2A Standard Central Wind with Electricity Co-Product Longer-Term Case.

This link http://www.hydrogen.energy.gov/h2a_analysis.html#assumptions provides a list of standard H2A assumptions.

The specific H2A analyses used as input in determining the technical targets in Tables 3.1.5 and 3.1.5A in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan are Record 6002a H2A MYPP Current Wind Electrolysis with Co-Product Electricity Case (2006); Record 6002b H2A MYPP Advanced Central Wind (2012); and Record 6002c H2A MYPP Longer-Term Central Wind (2017).

Data/Assumptions/Calculations:
The following provides additional information to the footnotes listed in Tables 3.1.5 and 3.1.5A in the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

d. These costs include the electrolyzer balance of plant (i.e., power electronics, dryer, KOH pump if necessary, etc.).
f. Current wind turbine cost comes from WindPACT report "WindPACT Turbine Rotor Design Study" by Malcom and Hansen, http://www.nrel.gov/docs/fy02osti/32495.pdf.
g. The standard H2A assumption for system production tax credit is only applied to the electricity sold to the grid (or third party).
h. All by-product electricity is sold for 3 cents/kWh; generation is based on optimization as outlined in WindPOWER report, "An Economic Analysis of Hydrogen Production from Wind" by J. Levene.

The following are deviations from the standard H2A model assumptions.

Assumption:
Footnote d – Electrolyzer capital costs assume high volume annual production of 1,000 units for all purposes and markets. Electrolyzer capital costs (uninstalled) are assumed to be $665/kW uninstalled in 2006, $350/kW in 2012 and $109/kW in 2017.

Reference:
2012 electrolyzer capital costs (uninstalled) are assumed to be $350/kW assuming a 12.5% savings on a standard H2A assumption for an advanced electrolyzer cost of $400/kW. See "Modeling the Market Potential of Hydrogen from Wind and Competing Sources," by W. Short, N. Blair, and D. Heimiller[5] for 12.5% reduction of electrolyzer cost for combined wind/electrolyzer electronic controls.

2017 electrolyzer capital costs are assumed to be $109/kW uninstalled assuming a 12.5% savings on a $125/kW system. See "The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs," by the National Research Council and National Academy of Engineering[1] for $125/kW capital cost for the electrolyzer, and "Modeling the Market Potential of Hydrogen from Wind and Competing Sources," by W. Short, N. Blair, and D. Heimiller[5] for 12.5% reduction of electrolyzer cost for combined wind/electrolyzer electronic controls.

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[1] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs, Committee on Alternatives and Strategies for Future Hydrogen Production and Use*, National Research Council and National Academy of Engineering, 2004. pp. 182. Available: http://www.nap.edu/openbook.php?isbn=0309091632
[2] E.W. Lemmon, M.O. McLinden, and M.L. Huber, "NIST Reference Fluid Thermodynamic and Transport Properties—REFPROP Version7.0 Guide," National Institute of Standards and Technology, 2002.
[3] Available: http://www.eia.doe.gov/cneaf/electricity/page/sales_revenue.xls
[4] Available: http://www.census.gov/popest/counties/files/CO-EST2003-alldata.csv
[5] W. Short, N. Blair, and D. Heimiller, "Modeling the Market Potential of Hydrogen from Wind and Competing Sources," May 2005. p. 6. Available: http://www.nrel.gov/docs/fy05osti/38138.pdf