Hydrogen Fueling Station Cost Reduction Study

Survey Results and Analysis of the cost and efficiency of various in-operation Hydrogen Fueling Stations.

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by

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I. Executive Summary

Hydrogen's promising future as an energy carrier continues to gain more acceptance. Its versatility for use in fuel cells and internal combustion engines makes it one of the most viable sustainable energy alternatives available. Hydrogen professionals, supporting the continued progression of hydrogen acceptance, require the most up to date information and data on which to build a hydrogen economy and communicate with others in the adoption curve. Experienced based information, such as those gathered by Engineering Procurement and Construction (EPC), will help further the understanding of hydrogen transportation applications and provide real-world, baseline data to further hydrogen development.

Based on extensive surveys, interviews and data gathering, from hydrogen fueling station installations, EPC has gained valuable knowledge regarding hydrogen, compression efficiency, performance, storage, and capital investment. This study presents the information associated with hydrogen compression from a small available sample of the 60 U.S. hydrogen refueling stations surveyed.

EPC found that compressor efficiency, on an all-inclusive energy basis, is about 45% versus the 50-80% manufacturer design specification literature. The average cost of work for compression was found to be \$1.38/kg H_2, similar to NREL's previous findings of an 11% (15) compression cost [\$1.34/kg H_2] (18). This cost is imbedded in the total energy cost to generate hydrogen. The actual required equipment cost for compression and storage, as taken from a detailed Humboldt State University study, is 39% of the total equipment cost, and 14% of the station's total cost. Depending on the availability of the compression equipment and production rate of the station, this can easily add over \$2.00 per kg additional cost to the value of the delivered fuel. When looking at total cost of the station equipment, O&M costs, and required input electricity the general trend is that the more hydrogen produced annually, the greater the costs. For the stations able to monitor and report costs of production, the total annual energy costs range from \$100,000 to \$400,000, depending on the quantity of hydrogen produced. An important finding of the analysis is that increasing production from ~4,000 - 5,000 kg H_2/year production nearly doubles the capital cost from \$150,000 to \$270,000. Yet, to more than double the production from 5000 kg to 14,000 kg H_2/year, the total associated costs is only increased by \$120,000 in addition to the \$270,000.

In order to meet DoE requirements as an affordable and competitive fuel source, hydrogen fuel costs must decrease. Hydrogen compression is a large portion of both energy and capital costs, and merits consideration for research and optimization to achieve higher efficiencies. Further instrumentation on existing and future stations (a hardware cost of <\$10,500) is recommended. This will provide data to optimize future station designs and allow comparison of future compression technologies. It is likely that the incremental cost of compression will decline as stations continue to increase in size.

II. Overview

This section discusses the process of data collection, downselection, and all attached files. Site location compilation using a multitude of published internet sources began the list of possible sites as data points for the study. After a thorough list generation, numerous calls and emails narrowed down existing sites. The questionnaire was sent out to responding sites, and those with enough data for analysis are included in the Excel™ spreadsheet as data points. These points comprise the data used in the report.

Attached Excel™ files:

1. "Preliminary data from sites" = more detailed information of sites that may not have been included in the analysis due to the lack of detailed data

2. "Site data compilation" = list overview of sites analyzed including things such as model + manufacturer of the equipment

3. "Station Information" = detailed list of all stations [compiled from multiple websites and adjusted per the current existence of the station]

4. "System Total Calculations" = efficiency and cost calculations for report

5. "Capital contribution to Fuel costs"

III. Introduction

Critical to the adoption of hydrogen use in vehicles is the cost to produce hydrogen. Integral in this production, is the capital equipment, including compressors and high pressure storage tanks used in the gas production process. In order to accurately calculate the cost of a kilogram of hydrogen, these capital costs need to be part of the price which is usually compared to the price of a gallon of gasoline. Although it is difficult to compare heavily subsidized gasoline costs with hydrogen, that is the comparison that will continue to be made, irrespective of the non-calculated health, pollution and carbon costs that are inherent in carbon fuel use. This study provides baseline hydrogen fueling station capital cost information which impacts the present and future equivalent (kilogram) cost per gallon.

A. Purpose

The goal of this study is to determine the specific role compressors play in hydrogen fueling stations costs and benchmark actual costs associated with current compression systems. Once benchmarked, future alternative compressor technologies can be evaluated. By having this data as a basis of comparison, determinations can be made as to the efficiencies and possible cost savings that may be realized through the installation of the Linde Group's cryogenic liquid hydrogen system concept. Utilizing liquid hydrogen instead of high pressure gas eliminates the need for high gas compression and compressors, as well as high pressure storage tanks. While this liquid method still requires cryogenic tanks, these tanks are significantly less expensive than conventional high pressure ASME tanks thus further reducing the initial capital cost for a fueling station using this technology.

In this study, total purchase price, including tank costs, operational costs, and energy efficiency are considered. By defining the efficiency and cost of current and future methods of compression, we hope to determine optimal systems that can guide future research and will decrease the cost of compression, enhancing the viability of hydrogen as a fuel source or energy carrier.

B. Background

Compression of hydrogen gas is required as it comes out of either an electrolyzer or reformer (~20-400 psig) to storage tanks that will dispense to vehicles at either 5,000 or 10,000 psig standard (1). At most fueling stations built in the US, hydrogen is compressed and stored above the desired dispensing pressure to allow cascade filling from the storage tanks without further compression. An alternate technology being evaluated under this grant is a more on-demand system; an example shown in Figure 1 of Linde's theoretical cryogenic design.

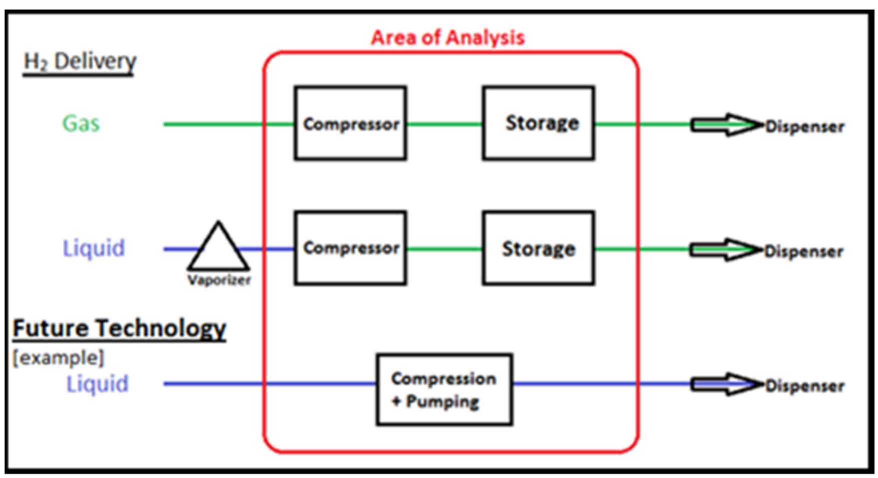


Figure 1: Compressor analysis scope for various methods of Hydrogen compression.

Liquid hydrogen may be a lower cost fueling methodology; it tends to be easier to maintain low temperature than extremely high pressure. The isothermal compressor efficiency for Carnot (ideal) work can be calculated by the equation:

$$\eta = [\text{cost to change } H_2 \text{ at } P_1 \text{ to } P_2] / [\text{cost of } E_{compressor} + \text{cost of } E_{intercoolers}]$$

Where E is the electrical costs associated with either the compressors or required chillers, and P refers to the pressure change over each stage of the compressor. An example can be taken where hydrogen gas at 300K can be compressed optimally in two stages, 200-2000 psig and 2000 - 6000 psig. Ideal work (cost to change H_2 to pressure) is ~4.24 and ~1.5 kWh/kg. The optimal work associated with liquefying hydrogen can be calculated by the equation (4):

$$\eta = v\,(P_2 - P_1)/\,(h_{2a} - h_1)$$

Where v is the volume of the liquid and h is the enthalpy at state 1 and the isentropic state 2.

An example of liquid hydrogen compression at 20 K from gaseous hydrogen at 300 K requires 3.3 kWh/kg (2) power input (represents $h_{2a} - h_1$). This is nearly half the work of existing systems working with gas; however note this is an optimal value.

Some of the alternatives evaluated to date include the following:

- NREL analyzed a prototype cryogenic compression system at Santa Clara Valley as part of the hydrogen bus fleet funding from the DoE. The goal of that prototype design was to theoretically reduce venting of the hydrogen. They experienced significant problems with vapor leaks and remote shut downs from Air Products, as was expected with a newer technology (3). Further research is needed to determine the effectiveness of this idea.
- Other research is being done by vehicle manufacturers to promote hydrogen fuel technology by modifying the compression or production system. GM has experimented with various manufacturers and systems regarding hydrogen compression and production (4). Honda is currently utilizing a test fuel station that has a 4 stage piston air-cooled compressor attached after a reformer system (5 kW Plug Power GenSys) that compresses from atmospheric to 5,000 psi. Their new approach from this is a personal at-home refueler that runs on 48 solar panels and directly feeds hydrogen (with a high differential pressure electrolyzer) into a parked fuel cell vehicle. With a national average of 4.2-4.5 sun hours per day (5), Honda claims it can generate enough hydrogen with a 6kW solar panel for the FCX clarity to go 10,000 miles/yr (6). Table 1 shows the power and system requirements given 100,000 miles per year of driving (7).

Table 1: Honda's home solar-powered refueling system.

9198	total annual power gen	=	55.188	kW available/kg
166.7	kg required / yr			

for 1 day there is:	25.2	available power
	0.019026	kg/hr reqd

As this is solar power, all of the cost would be consumed in the initial purchase price and any O&M issues during operation. This direction is inspired by the statement in the 2010 news release by Honda: "The previous [system] required both an electrolyzer and a separate compressor unit to create high pressure hydrogen. The compressor was the largest and most expensive component and reduced system efficiency" (8). By creating a new high differential pressure electrolyzer, Honda engineers were able to eliminate the compressor entirely.

With all of these ideas to combat the difficulty of hydrogen compression and storage driving up the cost ($/kg) of hydrogen for fueling stations, it is necessary to establish a baseline of how fueling stations are operating currently. This analysis of compressor system efficiency and cost offers insight into how new technologies compare and what areas might be researched in the future due to a high impact on costs.

C. Methodology

There are approximately 60 hydrogen fueling stations in the US in operation or recently disassembled, both private and public (9) (10). It is surmised that a majority of these hydrogen stations have be financed, to some degree, by the DoE. To see a complete list, including addresses, type of hydrogen generation, and date opened; please see the attached Excel Database “Preliminary data from sites “.

The process used for analysis began with data collection. Questionnaires were filled out by various station operators, owners, and researchers of some of the fueling stations listed above. It was surprising how many fueling stations were done by Air Products [34 in operation in the U.S. alone, as seen in Appendix A] (11) and that their systems are a complete black box. Even though there are federal dollars involved in at least some of these stations, no pressures, temperatures, or anything of intermediate stages was provided by Air Products in response to our requests. Even the compressors themselves are considered proprietary. Outside the Air Products installations there are a few systems that had enough information to calculate efficiencies that could be analyzed. The results are provided on page 11, in the Results and Analysis section.

The analysis that was done involves two distinct parts: efficiency and cost. These are detailed below with results shown in later sections.

1. Efficiency Calculation Overview

Figure 2 is a free body diagram that shows the measurable states of interest in order to calculate compressor efficiency.

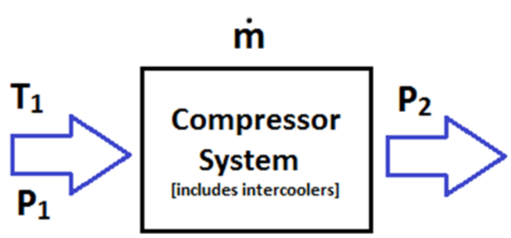


Figure 2: Compressor Flow Diagram

The standard equations for compressor efficiency (12):

$$P = W_{dot} = m_{dot} c_p \Delta T$$

$$\Delta T = \frac{T_1}{\eta_{isentropic}} * ((\frac{P_2}{P_1})^{\frac{\gamma-1}{\gamma}} - 1) * m_{dot}$$

Where P is power, W_{dot} is work per unit time, m_{dot} is the mass flow in kg of H_2, c_p is the specific heat of hydrogen, ΔT is the temperature change of the gas from the inlet and outlet. The second equation is used to calculate isentropic efficiency by relating the change in temperature to the initial temperature, pressures of the inlet and outlet, mass flow of hydrogen, and is c_p/c_v, (c_v being specific volume of hydrogen). However, these equations assume the system is adiabatic (13) (meaning there is no heat loss but there is temperature loss from the system) which is not realistic.

Isothermal compressor efficiency (meaning the temperature remains constant – as in heat flow generated from gas compression is removed from a coolant system for the most part) is far more accurate. (14) The following equations are to calculate compressor efficiency (η_c) using ideal vs actual work.

$$\eta_c = \frac{W_{ideal}}{W_{actual}}$$

$$W_{ideal} = m_{dot} R T_1 ln(\frac{P_2}{P_1})$$

$$W_{actual} = m_{dot}(e_{compression} + e_{cooling}) + m_{dot} Q_{lost}$$

Where R is the Ideal Gas Constant (8.314472 J/mol K), m_{dot} is the flowrate of hydrogen into the compressor, $P_{1,2}$ is the pressure from one stage to the other – and the compilation of stages (1 to 2, 2 to 3, 3 to 4, etc) is summed for the ideal work. Q_{lost} is the energy in btu's lost within the cooling system calculated by Q = mcΔT. In this case the mass flow, specific heat, and temperature difference values come from the cooling system fluid.

This method of efficiency analysis is more realistic than the given efficiencies from compressor company datasheets because the energy costs of cooling and lost heat are also factored in and added to the simple electric cost required to compress the gas.

The cost of work to produce 1 kg Hydrogen is calculated by the following equation:

Cost of actual work [$/kg H_2 Produced] = W_{actual} [kWh] *cost of electricity [$/kWh]

2. Cost Calculation Overview

1) First Cost [$] = Cost of compressors (include all step-up compressors + intercoolers) [$] + Cost of any additional chillers required [$] + Cost of tanks and GMP [$]

2) Annual Cost [$/yr] = (electricity required for compression + electricity required for cooling)[kWh] *(hours in operation per year) [hr/yr] *(cost of electricity [$/kW]) + Cost of Preventative Maintenance + Cost of Repair

3) Cost of Preventative Maintenance [$/yr - averaged annually] = Cost of Spare Parts[2] [$] + (Man Hours[2] [hrs])* (Mechanic Salary [$/hr])

4) Cost of Repairs [$/yr - averaged annually] = Cost of Spare Parts[2] [$] + (Man Hours[2] [hrs])* (Mechanic Salary [$/hr])

5) Total Cost over X yrs[3] [$] = First cost[$] + (Annual Cost[$/yr])*(X years[yr])

IV. Results and Analysis

A. Compressor/Station Data

The seven stations that were able to offer data with the required level of detail to calculate efficiency and cost are reported in Table 2 including specific compressor operation data. The primary compressor type for hydrogen at the needed flow rates are multi-stage diaphragm compressors.

Table 2: Compressor data for each station

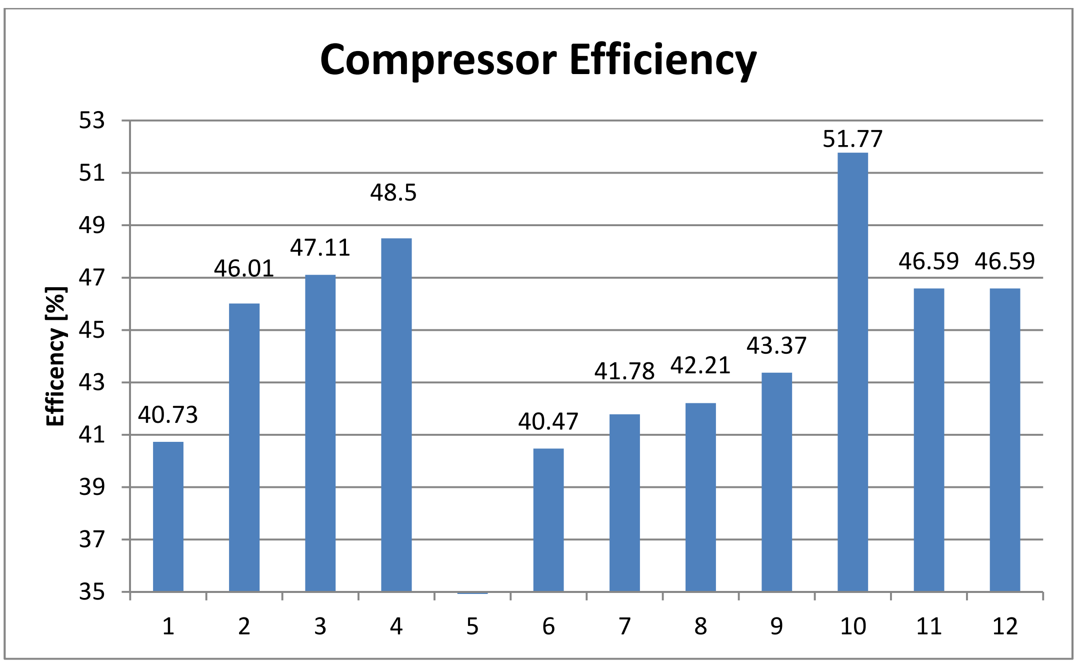
Station	**# on Figure3**	**Compressor Data**				
		Type	**Model #**	**Mass Flow [kg H2/hr]**	**Pin [psig]**	**Pout [psig]**
NREL W2H2	1	2 stg Triple Diaphragm	PPI 2L-072H044H	0.5	14.7	3500
	2	1 stg Diaphragm	PPI 2053M	2.3	2000	6000
CaFCP	3	6 Cylinder, 5 Stg Reciprocating [cryogenic gas w/vaporizer]	Henderson International B65 H S/N 312	6	25	6200
Humboldt State University	4	1 stg, Triple Diaphragm	PDC 3-6000	0.12	200	2000
University of Montana	5	single stg reciprocating	from electrolyzer	4	-0.3	145
	6	3 stg	PDC -3- 7000	4	145	6000
Sunline Thousand Palms	7	5 stg Diaphragm	PDC 5-650-3500	9.0624	70	3000
	8	4 stg Diaphragm	PDC 4 - Duplex	7.9296	1800	6000
Chula Vista	9	Rotary Vane	Compair 5409H	1.175	200	2000
	10	Rotary Vane	Compair 5409H	1.175	2000	6000

CSU LA	11	4 stg Diaphragm	PDC 4-1000-6500	2.5	130	1100
	12	Single Stage intensifier	Hydro-Pac c12-60-105000	30	5070	10153

Triple diaphragm compressors are the most predominant in hydrogen fueling stations, however, a variety of compressors are used based on flow rates and desired pressures. A duplex compressor has two identical heads on either side of the crank case and can apply to 2 and 4 stage compressors.

B. Compressor Efficiency & Performance

The isothermal compressor efficiency of the twelve compressors above is shown in Figure 3. The table below the plot acts as a legend for the 1 or 2 compressors associated with each station, and can be associated with Table 2 by the identification numbers in the second column.



# on Figure 2:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Station:	NREL W2H2		CaFCP	Humboldt State University	University of Montana		Sunline Thousand Palms		Chula Vista	CSU LA		
Compressor:	1	2	1	1	1	2	1	2	1&2	1	2	3

Figure 3: Compressor efficiency analysis.

It is to be noted that the compressors at CSU LA (10) are a theoretical value from datasheets and design rather than actual operating data. In this case, the listed efficiency for these three (10, 11, 12) CSU LA compressors would likely be higher than in operation due to inherent inefficiencies that occur in systems versus a stand-alone compressor. The average efficiency is 45%, compared to the 50-80% given by compressor datasheets due to the addition of cooling and heat loss costs. The diaphragm systems are 44.3%. The Humboldt State compressor has the highest efficiency due to the low flow rate (.12 kg/hr) of the system. This system is used for primarily for research. Lower efficiencies are directly correlated to increasing flow rate. This is critical because the idea of a hydrogen vehicle future involves significant hydrogen production, so future stations (and compressors) will be required to produce even higher flow rates.

NREL has published data that compressor power input comprises +11% of the total cost of energy input to a single kg of hydrogen (15). However this was done on an LHV basis (energy of the hydrogen out of the process LHV divided by the energy input to compress the hydrogen), comparing the energy used for compression ($E_{compressor}$) vs. the LHV hydrogen ($E_{Hydrogen}$). The LHV is the lower heating value, or heat generated in combustion; like a chemical potential for fuels. The reason to use this performance efficiency (ϕ) is to compare various fuels, not systems. The inherent problem faced with using this efficiency for the above analysis is that the energy in the pressurized hydrogen is neglected. Because some of the systems store hydrogen (P_{out}) at extremely high pressures compared to other systems, those systems should be considered inherently less efficient if the measure of their output is just including the energy of combustion. NREL focuses on electrolyzer performance integrating with 57% HHV (49% LHV) PEM @ full stack current and renewable power generation system integration (16). The baseline cost to produce 1 kg of hydrogen is $6.25. Using the complete efficiency analysis outlined in the Methodology section 1, the compressor performance for the NREL findings is **0.294%,** similar to the stations shown in Table 3 below.

Table 3: Compressor performance (LHV) by station.

Station	Compressor Performance		
	$E_{compressor}$	$E_{Hydrogen}$	ϕ Compressor Performance
	kWh/kg	kWh/kg	-
NREL W2H2	9.751	33.200 LHV H2 in kWh	0.294
CaFCP	6.160	39.000 HHV H_2 in kWh	0.158
	this needs to be HHV by $ liquid -> gas		
Humboldt State University	12.500 averaged from their data, is per kg	33.200 LHV H_2 in kWh	0.370 averaged from their data
University of Montana	7.14	33.200	0.215
Sunline Thousand Palms	4.911	33.200	0.148
Chula Vista	6.786	33.200	0.204
CSU LA	15.805	33.200	0.476
	this is theoretical from datasheet [not running]		

LHV H2	**33.2 kWh/kg**	**A measure of the fuel heat input of combustion (how much energy can be made by this fuel); calculated by a sum of enthalpies of the components of combustion. (19)**
HHV H2	39 kWh/kg	LHV + energy it takes to vaporize water (frequently used in change of phase)

The reason CaFCP uses HHV, which is the higher heating value, and not LHV (18) is because they begin with liquid hydrogen which is subsequently vaporized, so the latent heat of vaporization should be included in the energy contained within the fluid. From this figure, the very low flow compressor from Humboldt State appears to be optimal, however what is not considered is the pressures to which the hydrogen is compressed, as they vary for each station. This is the primary reason why this performance value is less expressive of each compressor than the efficiency shown in Figure 3 and Table 5.

C. H2 Production Costs

The cost of work in $/kg H_2 of the analyzed systems relates to the work required (in kWh) to compress 1 kg H_2 to the $ cost for that electricity. This is shown in Table 4. It is to be noted that the standard CaFCP price of electricity is used for most of the stations, however the CaFCP station was not directly included as the data associated with their cryogenic system is proprietary.

Table 4: Cost of the compression of 1 kg hydrogen

Station	Cost of Work	
	Cost of E $/kWh	Cost of Work $/kg H2
NREL W2H2	0.07	$1.37
	may be reduced by cost of wind energy, average CO industrial rate (6-2001), supplied by NREL	
CaFCP	0.19937	$1.23
	used CaFCP	
Humboldt State University	0.12	$1.50
	.12$/kWh from standard Ca values	
University Montana	0.1396	$1.00
	used ratio between E costs in Ca and Mo (70%) applied to CaFCP number	
Sunline Thousand Palms	0.19937	$1.71
	used CaFCP	
Chula Vista	0.19937	$1.35
	used CaFCP	
CSU LA	0.19937	$1.26
	used CaFCP	

The average cost of work for these stations is $1.35 per kg H_2. NREL ran studies involving SunLine Transit with a fleet of busses in California. The hydrogen fueling station provided ~4,729 kg of hydrogen at an average cost of $12.15 per kg including parts and labor, amortization of the equipment, and natural gas and utilities (monthly costs ranged from a low of $6.50/kg to a high of $158/kg) (17). With their stated 11% efficiency, the cost of work is approximately $1.34 per kg H_2. This value is similar to others in the study, and the fraction of the cost of energy devoted to compression for some of the sites are shown below (utilizing published and actual data for total cost to produce hydrogen, including electrolyzer/reformer):

Station	% Compression Cost in Total Production Cost
NREL	10.921
Sunline Thousand Palms	12.15
Chula Vista	13.531

Table 5 below outlines the annual costs associated with hydrogen compression. Values for repair costs are discussed in the 'Station O&M and Total Costs' Section.

Station	Annual Cost [$/yr]								
	kWh compression	kWh cooling	hr/yr in operation	$ electricity [$/kWh]	$ PM	$ Repairs	kg H2 Produced/yr	$/kg H2 Produced	Annual Cost [$/yr]
	This shows the cost each year for the operation and maintenance of the compressor system, normalized by kg H2 produced annually.								
NREL W2H2	13.5	5.97	4000	$0.07	$3,300	$0	2000	0.683	$4,666
notes:	Supplied by NREL	Supplied by NREL	Supplied by NREL	avg CO industrail rate (6-2001), supplied by NREL			estimated hrs/yr*kg/hr	from efficiency calcs	
Humboldt State	12.6	0	43.8	$0.20	$1,500	$2,700	119.6	1.5	$4,379
notes:			.12 kg x 365					from efficiency calcs	
U of Montana	15.752	0.998	1460	$0.20	-	-	5840	0.209	$1,221
notes:		estimated 4 hrs/day			NA	NA		from efficiency calcs	
Sunline Thousand Palms	33.57	0.8	1460	$0.20	$4,000	-	7154	0.245	$5,753
notes:		4 hrs/day given by Contact				NA	not always full capacity operation		
Chula Vista	18.383		1460	$0.20	-	-	1715.5	1.353	$2,321
notes:			Given by Contact		NA	NA	estimated hrs/yr*kg/hr	from efficiency calcs	
CSU LA	76.04	4.991	9000	$0.20	-	-	14400	1.260	$18,150
notes:		60 kg/day projected; estimated 9000			NA	NA	estimated hrs/yr*kg/hr	from efficiency calcs	

Table 5: Annual Cost of Hydrogen Production by station.

Obviously the annual cost to operate a system that produces more hydrogen is significantly larger than for example Humboldt State, used for 1 car and primarily research. However, from the efficiency calculations, the cost to produce 1 kg of hydrogen appears to be optimal for an intermediate hydrogen production (~6000 kg). Please note there are a variety of factors that are involved in this annual cost, for example the length of time the station is in operation, so definitive conclusions should not be drawn from this section alone.

First cost, or initial equipment cost, is a strong dictator controlled by the budget that restricts hydrogen production amount. Table 6 below is a cost spread for compressors, tanks, and required cooling systems for each station. These values come either as direct quotes for the project or similar quotes, outlined in Appendix C.

Station	First Cost [$]					
	$ Compressors		$ Chiller Sys	$ Tanks/GMP	First Cost of Compressors + Chillers ONLY	Total First Cost
	This shows initial cost required prior to any operation of the plant.					
NREL W2H2	$55,845	$27,000	$4,251	$165,598	$87,096	$252,694
notes:	compr 1, exact [EPC datashts]	approx from ppi quote 11-14-07	exact [EPC datashts], note = oversized for electrolyzer also	file: FIBA quote NRel 7-07-09		three zone auto cascade system = +10,000 (included here)
Humbolt State U	$46,600	-	-	$45,100	$46,600	$91,700
notes:	from humboldt state andrea alestone					
University of Montana	$30,000	$31,000	-	$84,000	$61,000	$145,000
notes:		revamped existing				
Sunline Thousand Palms	$72,000	$87,000	$1,000	$100,000	$160,000	$260,000
notes:	estimated from PDC-3-1250-6500 quote	estimated from PDC-4-1500-12000	Air Products TAE/TWA 051, estimated cost from NREL ratio	estimated from tank quote compilation		
Chula Vista	$23,841	$23,841	$1,000	$75,000	$48,682	$123,682
notes:	used from compairs	used from compairs	minor cost,	estimated from		
CSU LA	$72,000	$87,000	$1,000	$180,000	$160,000	$340,000
notes:	estimated from PDC-3-1250-6500 quote	estimated from PDC-4-1500-12000	minor cost, modeled from NREL	estimated from tank quote compilation		
		they did buy 3 but 1 not used				

Table 6: Initial costs associated with the compression/storage system by station.

D. Humboldt State Cost Breakdown

Humboldt State has done a significant amount of record-keeping in order to effectively analyze the hydrogen fueling station. The following figures describe the cost breakdowns of the equipment and overall costs which is typical of a lower flow system. (Data was provided via Humboldt State personnel.)

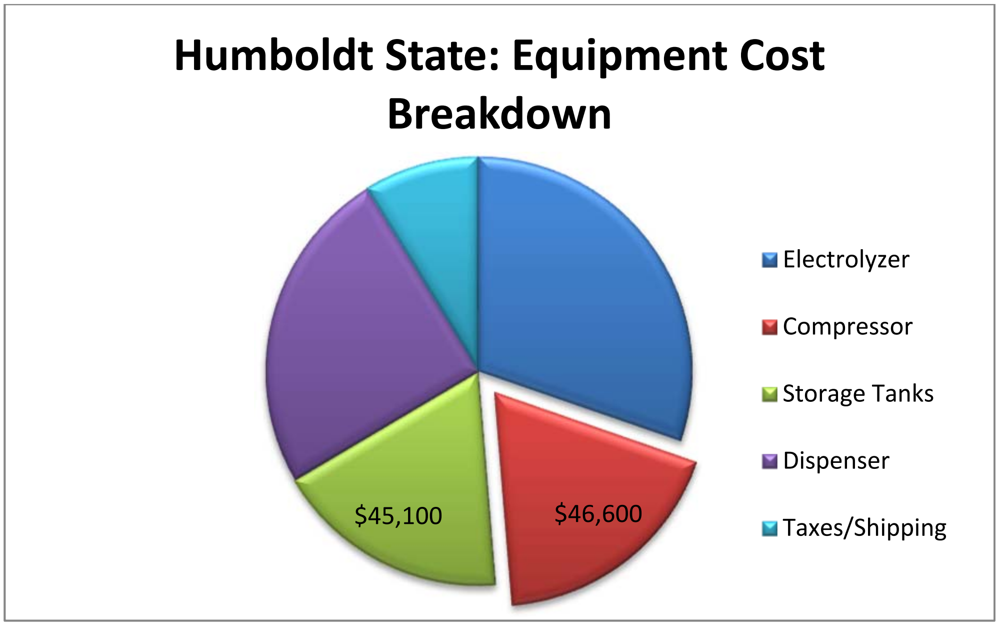


Figure 4: Equipment Costs for Humboldt State Fueling Station

The total cost for all equipment was $235,000. As shown, the electrolyzer is the largest fraction; however compression and storage combined make up the largest piece (39%). The total project cost was $678,000, with installation and equipment as the largest portions. The compressor and storage tanks make up 14% of this total cost, about 7% for storage and 7% for the compressors.

E. Station O&M and Total Costs

The operation and maintenance costs of a system tend to heavily rely on the simplicity of the equipment. Preventative maintenance encompasses gauge checks, general inspections, periodic lubrication and other steps that attempt to prevent problems from occurring. Repairs are self explanatory. Table 7 shows this data if it was provided by the station contact. Note downtime was not considered in this calculation as the stations are frequently not in operation. This is another area that would benefit from better record keeping.

Table 7: O&M costs by site

Station	Cost of Preventative Maintenance [$/yr]				Cost of Repairs [$/yr]			
	$ Spare Parts	# Man Hrs	$/hr Worker Wage	$ PM	$ Spare Parts	# Man Hrs	$/hr Worker Wage	$ Repairs
	This shows a cost aspect of the complexity of the compressor system by $ paid to maintain its operation in				This shows the cost aspect of the reliability of the compressor system by $ paid to repair it.			
NREL W2H2	$2,500	16	$50	$3,300	0	0	$50	$0
notes:	from NREL contact				to date	given by NREL		
Humbolt State U	$0	30	$50	$1,500	-	-	-	$2,700
notes:	ist and op checks + oil change every 3000 hrs [little downtime]			estimated	multitude of repairs reqd but simple setup = quick fixes			estimated
U of Montana	-	-	-	-				
notes:	NA	NA	NA	NA	multiple pressure switches fail, check valves fail, ss diaphragms (5 day lead time)			
Sunline Thousand Palms	3000	20	50	$4,000	1500	20	$50	$2,500
notes:			estimate				estimate	
Chula Vista	-	-	-	$4,000	-	-	-	-
notes:	Contact only knows "extremly costly + req daily maintenance"; estimated				NA	NA	NA	NA
CSU LA	-	-	-	-	-	-	-	-
notes:	NA	NA	NA	NA	NA	NA	NA	NA

Chula Vista uses very old equipment and requires daily maintenance, so the generalized cost of preventative maintenance may be low compared to actual. Humboldt state reported frequent issues specifically with their diaphragm compressor leaking. These O&M values factor into the total cost and annual cost of each station, shown below in Table 8.

Table 8: Total cost spreadsheet by station.

Station	Total Cost [$]				
	# yrs in operation	First Cost	Annual Cost	Total Cost [$]	Amount of H2 Produced total [kg]
	This shows total cost of the chiller system throughout its lifetime				
NREL W2H2	5	$252,694	$4,666	$279,324.00	10000
notes:	20 expected				
Humboldt State	2	$91,700	$4,379	$104,659	239.2
notes:	July 08-Aug 10				
University of Montana	1	$146,000	$1,221	$147,221	5840
notes:	projected				
Sunline Thousand Palms	5	$260,000	$5,753	$266,500	35770
notes:	06 to present				
Chula Vista	8	$131,629	$6,321	$150,197.57	13724
notes:	Jun 03 to present				
CSU LA	1	$340,000	$18,150	$358,150	14400
notes:	projected				

Chula Vista, as discussed earlier, has the oldest equipment that was procured secondhand, and thus (do not get the correlation between old and largest annual cost) has the largest annual cost for its hydrogen production range. The station at CSU LA is much higher (although not yet considered commercial) capacity and thus requires more input energy. To better compare these stations, annual hydrogen production potential versus cost is plotted in Figure 5 below.

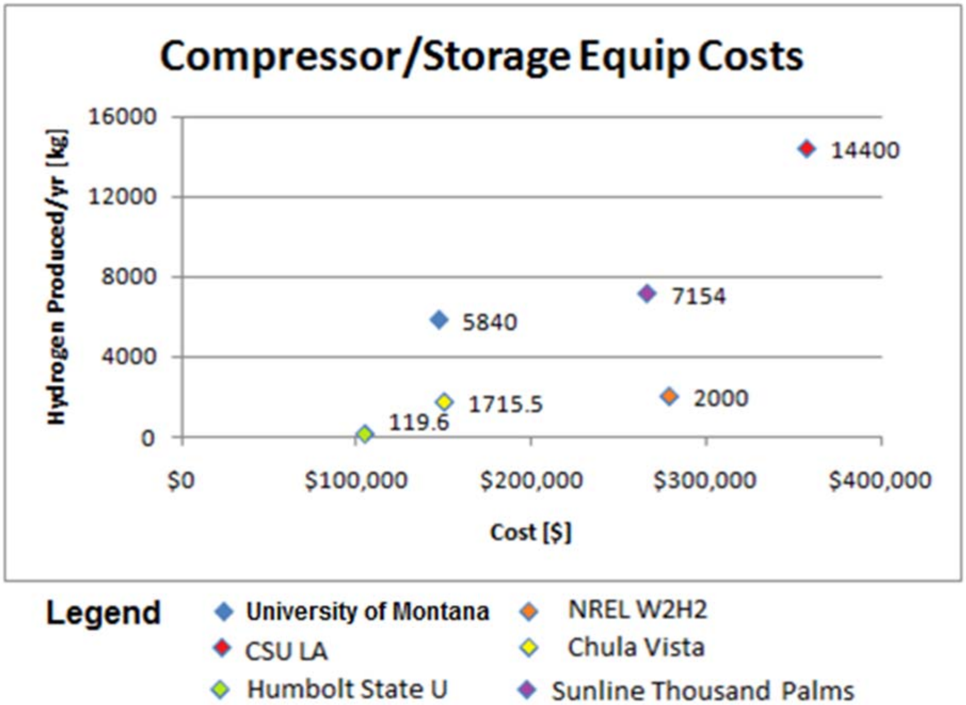


Figure 5: Annual Hydrogen Production vs. Total Costs (for compressors and storage equipment)

From this data, there is no linear or exponential fit, which is expected with such a small amount of data for something with inherently varying characteristics such as individual prices, quality of equipment, etc. For example Chula Vista is old and made with used parts, and probably worked far better years ago (so increase production or decrease cost, shifting the point on the plot). More data would be required to make accurate predictions. It is also to be noted that the amount of hydrogen produced annually is also influenced by public or private demand. In other words, many of the stations are not operating to full capacity. However, increased production increases operating, not capital cost. A generalized cost figure is shown below to help visualize how capital cost, efficiency, and storage are related.

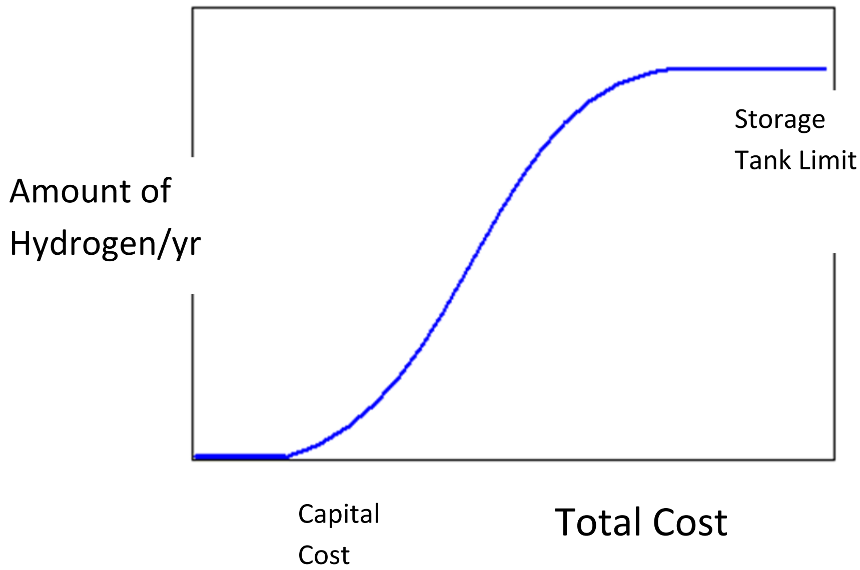


Figure 6: Total Costs relating efficiency to first cost (generalization)

The shape of the curve is strongly related to compressor efficiency and flow rates [i.e. what type of compressor(s) used]. The total cost is comprised of the equipment cost (only paid once) and the annual cost to operate the equipment. The final limitation is related to the amount of storage available as well as flow rates that year (operation statistic).

An obvious conclusion is as hydrogen production increases, the total cost (first costs + operation costs) increases. However, the important note is the magnitude of this increase. For instance, the mean cost for 4,000 kg/yr H_2 is $150,000. At 5,000 kg/yr H_2 this cost jumps to $270,000. At 14,000 kg/yr H_2, the total cost is $390,000. So from 4-5 thousand kg produced one would pay almost double the total cost (annual + first costs), but from 5-14 thousand kg the cost increase is only $120,000, for an increase in production of +200%. In other words, for a large increase in production up to +12,000 kg H_2 annually, the cost increase is less than smaller increases from 4,000 to 5,000 kg H_2. This is explained by the first and total cost comparison (Table 6 and Table 8). While operating costs increase rather linearly, the number and cost of the compressors is fairly constant. As a first cost, CSU LA has the same compressor and chiller initial costs as Sunline; however the larger capacity of H_2 produced requires significantly more expensive tanks. If this were a cryogenic process, this high tank cost would be greatly decreased with heavily insulated instead of high pressure tanks.

V. Conclusions

Based on the work completed the following conclusions were made:

1. There is a critical on-going need to collect data from hydrogen fueling station installations.
2. It was found that compressor efficiency, compared on an all-inclusive energy basis, are performing at ~45% efficiency (not on an LHV basis such as those found in manufacturers literature). This is significantly different from the 50-80% reported in the design specs of an individual compressor.
3. Lower flow and discharge pressures tend to have a higher efficiency than higher flow rates of +4 kg H_2/hr and high discharge pressures or compression ratios. The average cost of energy required for compression was found to be $1.38/kg H_2, very similar to NREL's previous findings of an 11% (15) compression cost [$1.34/kg H_2] (18). This cost is reflective of the energy cost to generate hydrogen.
4. The actual required equipment cost for compression and storage, as taken from a Humboldt State University study, is 39% of the total equipment cost, and 14% of the stations total cost.
5. It is likely that the incremental cost will decline as stations continue to increase in size.
6. When looking at total cost of the station equipment, O&M costs, and required operation energy, the research showed:
   a. the more hydrogen produced annually, the greater the costs.
   b. the costs range from $100,000 to $400,000 is dependent on hydrogen production.
   c. The importation aspect of the analysis is that from ~4,000 -5,000 kg H_2/year production, the cost of the system is doubled.
   d. To more than double the production to 14,000 kg H_2/year, the cost is only increased by $120,000.
7. The compression and storage systems are a significant portion of the operational and capital costs.
8. Many of the stations do not measure, collect or compare the critical capital and operational costs of a hydrogen station installation.

VI. Recommendations

1. The data would support that trial installations using the cryogenic liquid hydrogen method be positively considered.
2. All installations using any federal dollars should be required to collect and make available data regarding the production, storage and use of hydrogen. Repeatable O&M data is especially lacking at all current installations. It is recommended to require instrumentation to monitor and further explore the optimal operation and efficiency in order to decrease the cost of hydrogen compression and storage. Such instrumentation would require the station be fitted with current and potential transformers ($1,500) to measure energy usage, and pressure transmitters to be able to calculate the efficiency of the compressors. Such additions would typically be ~$6,500 with but could provide important information to the industry. Along with collaboration for accurate data to advance the hydrogen fueling station technology, such data could also indicate the cost of problems where repair is required, and can also be used to optimize the system.
3. A virtual national data bank be established to assimilate real-time data from all hydrogen fueling stations on a daily basis.
4. Continued research regarding compression storage and cryogenics hydrogen production methods should be conducted.

VII. Bibliography

1. **Department of Energy.** Hydrogen Dispensing. *U.S. DoE Hydrogen Proram: Permitting Hydrogen Facilities.* [Online] http://www.hydrogen.energy.gov/permitting/stations_dispensing.cfm.

2. *An Economic Analysis of Three Hydrogen Liqufication Systems.* **M.T. Syed, S.A. Sherif, T.N. Veziroglus, J.W. Sheffield.** 7, pp. 565-576, Great Britan : International Association for Hydrogen Energy, 1998, Vol. 23.

3. **Kevin Chandler, Leslie Eudy.** *Santa Clara Valley Transportation Authority and San Mateo County Transit District - Fuel Cell Transit Buses: Evaluation Results.* s.l. : NREL/TP = 560-40615, November 2006.

4. **O'Connell, Daniel.** *GM H2 Demonstration Global Representative.* November 3, 2010.

5. Solar Electric (PV). *Environmental Solar Systems.* [Online] Environmental Solar Systems. http://sunmatesolarpanels.com/content/view/25/28/.

6. **Yamashita, Ikuya.** *Honda R&D Americas, Inc.* Torrance, Ca, December 8, 2010.

7. **Honda R&D.** Honda Fuel Cell Vehicle. *Honda.* [Online] Honda. http://world.honda.com/FuelCell/.

8. *Honda Begins Operation of New Solar Hydrogen Station: Los Angeles-based Station to Re-fuel Honda Fuel Cell Electric Vehicle.* **Honda R&D.** s.l. : Honda Corporate, January 27, 2010, Vols. http://world.honda.com/news/2010/c100127New-Solar-Hydrogen-Station/index.html.

9. **National Hydrogen Association.** Hydrogen Fueling Station Database. *National Hydrogen Association.* [Online] NHA, Technology Transition Corporation. http://www.hydrogenassociation.org/general/fuelingSearch.asp.

10. **U.S. DoE.** Operational Hydrogen Fueling Stations. *Hydrogen Analysis Resource Center.* [Online] April 2009. http://hydrogen.pnl.gov.

11. **Air Products.** Stationary Hydrogen Fueling Experience—Through 2007. *Air Products.* [Online] through 2007. http://www.airproducts.com/products/merchantgases/hydrogenenergyfuelcells/projects.htm.

12. **K. Ueno, R.E. Bye, K.S. Hunter.** *Compressor Efficiency Definitions.* s.l. : Vairex, May 12, 2003.

13. **J. Larmine, A. Dicks.** *Fuel Cell Systems Explained.* s.l. : Ed 2. Wiley, 2003.

14. *Compressor Efficiency Definitions.* **Ueno, K., Bye, R.E., Hunter, K.S.** May 12, 2003, VAIREX Corporation.

15. **National Renwable Energy Lab.** *On-Site Hydrogen Compression Efficiency and Energy Use.* 3-11-2010. NREL CDP61.

16. **K.W. Harrison, G.D. Martin, T.G. Ramsden, W.E. Kramer, F.J. Novachek.** *The Windo-to-Hydrogen project: Operational Experience, Performance Testing, and Systemts Integration.* s.l. : NREL Technical Report TP-550-44082, March 2009. Contract No. DE-AC36-08-GO28308.

17. **Leslie Eudy, Kevin Chandler.** *SunLine Transit Agency Fuel Cell Transit Bus: Fifth Evaluation Report.* s.l. : NREL/ TP-560-46346-1, August 2009.

18. *Bruce Lin thesis: Rules of Thumb.* **Lin, Bruce.** s.l. : http://hypertextbook.com/facts/2005/MichelleFung.shtml, September 13, 1999.

19. **Nave, R.** Specific Heat of Gases. *HyperPhysics - Thermodynamics.* [Online] http://hyperphysics.phy-astr.gsu.edu/hbase/kinetic/shegas.html#c5.

20. **Peter Lehman, Greg Chapman.** *Hydrogen Compressor Summary of Operation: July 2008 through August 2010.* Schatz Energy Research Center : Humboldt State University, 2010.

VIII. Appendix

A. Air Products Systems in the U.S.

Air Products: Stationary Hydrogen Fueling Experience—Through 2007 (11)

Year describes the date the station began operation.

Agency / Affiliate	Year	Description
Proton, White Plains, NY	2007	Series 200 fueling station supplied by a PEM electrolysis unit to support fuel cell vehicles.
BP, Jamestown, FL	2007	Series 200 fueling station supplied by a PEM electrolysis unit.
Proton, UNLV	2007	Series 100 fueling station supplied by a PEM electrolysis unit.
University of CA, Irvine	2007	Series 200 fueling station, supplied by liquid hydrogen with both 350 Bar and 700 Bar dispensing to support fuel cell vehicles.
BP, Detroit	2006	Series 200 hydrogen fueling station to support fuel cell vehicles.
Proton – Evermont	2006	Series 200 Hydrogen fueling station supplied by a PEM electrolysis unit to support hydrogen internal combustion engine vehicles.
Penn State University	2005	Series 300 hydrogen and HCNG fueling station supplied via an advanced natural gas reformer with liquid hydrogen back-up.
Honda, Torrance CA	2006	HF-150 self contained, transportable fueling station to support hydrogen fuel cell vehicles.
General Hydrogen, Nashville, TN	2006	HF-150 self contained, transportable fueling station to support hydrogen fuel cell forklifts and AGV's.
South Coast Air Quality Management, City of Burbank, CA	2006	Series 200 hydrogen fueling station and a PEM electrolyzer to support fueling of hydrogen, internal combustion engine vehicles.
South Coast Air Quality Management, City of Santa Monica, CA	2006	Series 200 hydrogen fueling station and a PEM electrolyzer to support fueling of hydrogen, internal combustion engine vehicles.
South Coast Air Quality Management, City of Ontario, CA	2006	HF-150 self contained, transportable fueling station to support hydrogen, internal combustion engine vehicles.
South Coast Air Quality Management, City of Santa Anna, CA	2006	HF-150 self contained, transportable fueling station to support hydrogen, internal combustion engine vehicles.
Camp Pendleton, San Diego, CA	2006	HF-60 self contained, transportable fueling station to support fuel cell vehicles.
BP, Orlando, FL	2005	HF-150 self contained, transportable fueling station.
Ford Arizona Proving Grounds, Yucca, AZ	2005	Series 100 hydrogen fueling station supplied by gaseous hydrogen.
BP, Sacramento, CA	2005	HF-150 self contained, transportable fueling station.

BP, San Francisco, CA	2005	HF-150 self contained, transportable fueling station.
Honda – Albany, NY	2004	HF-150 self contained, transportable fueling station to support fuel cell vehicles.
Honda – San Francisco	2004	HF-60 self contained, transportable fueling station to support fuel cell vehicles.
Angel's Nest – Taos, NM	2004	Series 100 hydrogen fueling station supplied by a PEM electrolyzer. Completely renewable power source (wind/solar) in a utility-independent, self-sufficient community.
Proton Energy Systems / University of Nevada, Las Vegas	2004	Series 100 hydrogen fueling station supplied by a PEM electrolyzer. A portion of the power is provided by solar cells. .
Shell Hydrogen, Washington D.C.	2004	Series 200 hydrogen fueling station with 350 and 700 bar gaseous dispensing and LHY dispensing supplied via an underground liquid hydrogen storage tank.
GM, Ft. Belvoir, VA	2004	Series 100 hydrogen fueling station supplied by gaseous hydrogen.
EPA National Vehicle Fuel Emission Laboratory, Ann Arbor, MI	2003	Series 200 hydrogen fueling station with 350 bar gaseous dispenser.
Ford Motor Company, Romeo, MI Proving Grounds	2003	Series 100 hydrogen fueling station
University of California, Irvine and South Coast Air Quality Management District	2003	Series 100 hydrogen fueling station supplied by gaseous hydrogen.
University of California, Davis	2003	Series 100 hydrogen fueling station and HCNG fueling station so support ICE buses and fuel cell vehicles, supplied from a liquid hydrogen source.
University of California, Davis / Toyota	2003	Series 100A hydrogen fueling station for fuel cell vehicles.
Valley Transit Authority, San Jose, California	2003	Liquid hydrogen pumping system for 350 bar fueling of fuel cell buses
Honda / City of Los Angeles, CA	2003	HF-150 mobile fueler, self contained, transportable fueling station.
University of California, Irvine and South Coast Air Quality Management District	2003	HF-150 mobile fueler, self contained, transportable fueling station.
California Fuel Cell Partnership, Sacramento, California	2003	HF-150 mobile fueler, self contained, transportable fueling station.
DOE / City of Las Vegas	2002	On-site hydrogen reformer based on natural gas with liquid hydrogen backup, Internal Combustion Engine (ICE), hydrogen and hydrogen/natural gas blend dispensing for light duty vehicles and buses
BMW, Oxnard, California	2001	Liquid hydrogen supply system for supporting hydrogen ICE vehicles.

B. Personal Citations for the Site data:

These contacts are the primary source for compressor and general station data. Assume this is the citation for information in tables if not otherwise specified.

1. Larry Shroyer Chula Vista 10/20/2010 station operator
2. William Loper Sunline 11/10/2010 SunFuel group @ Sunline Transit
3. DR. David Blekhman CSU LA 10/12/2010 Associate Professor; Power Energy and Transportation
Dept of Technology CSU LA
4. Dr. Kevin Harrison NREL W2H2 10/10/2010 station operator
5. Andrea Alstone Humboldt State 12/10/2010 graduate student working on the station
6. John Cornish EPC significant hydrogen fueling station design experience

C. Compressor + Tank Quote Compilation

PDC:

1. PDC-4-1500-12000
$87,000
Mateen Afzal PDC Sales (1-21-08)
2. PDC-3-1250-6500
$72,000 Standard
Mateen Afzal PDC Sales (10-29-08)

PPI:

Note current prices are as follows:

Basic Model 4X080 is $50,000 USD.

Basic Model 4LX-100-068 is $85,000 USD.

Tim Ratkowski (1-28-11)