Renewable Energy Based Hydrogen Production
Final Report

Presented To:

Dr. Thomas L. Acker
Associate Professor of Mechanical Engineering
Northern Arizona University

H2 Generation:
Josh Spear; Team Leader
Andrew Boone; Secretary
Ryan Hirschi; Financial Officer
Robert Burke; Team Mediator

Northern Arizona University
College of Engineering and Technology
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General Contents:

Appendix Contents:

H2 Generation Contact Information:

Josh Spear; Team Leader (928) 853-1617, jds33@dana.ucc.nau.edu

Andrew Boone; Secretary (928) 523-3963, adb22@dana.ucc.nau.edu

Ryan Hirschi; Financial Officer (928) 213-0007, rsh6@dana.ucc.nau.edu

Robert Burke; Team Mediator (928) 523-2876, rcb27@dana.ucc.nau.edu

Final Document: Renewable Energy Based Hydrogen Production

1. Summary of the Renewable Energy Based Hydrogen Production Project

1.1. Project Description for the Renewable Energy Based Hydrogen Production Project

The purpose of this project is to design a hydrogen production facility that uses the available water and renewable energy resources located behind the Northern Arizona University College of Engineering & Technology (CET) building in the "Solar Shack" (See Figure 1 below). The following are the requirements stated in a proposal to Dr. Tom Acker, Associate Professor of Mechanical Engineering.

Figure 1.1. : College of Engineering and Technology "Solar Shack"

Design Constraints:

~ Use of existing renewable energy as the energy supply to produce hydrogen gas

~ Hydrogen must be stored in a manner available to fuel a Formula 1 racecar

~ Use available rainwater (utilizing available rooftops) supplemented, if necessary, with CET tap water

The hydrogen production system is split into two separate designs. One design will provide hydrogen for a fuel cell (higher purity), and the other an internal combustion engine (lower purity).

1.2. Deliverables for the Renewable Energy Based Hydrogen Production Project

H2 Generation proposes to provide two main deliverables in the solution to the renewable energy based hydrogen production problem. The first deliverable is the specification of the design layout for the production facility. The second deliverable is a proof of concept demonstration model.

1.3. Design Philosophy of H2 Generation

The design philosophy incorporated by H2 Generation is to break down the large-scale design of the hydrogen generation station into manageable components for individual design and analysis.

1.4. State of the Art Research for the Renewable Energy Based Hydrogen Production System

State of the Art research for this system consisted of three main concepts. These include methods for creating hydrogen, different methods for storing hydrogen, and active hydrogen production facilities.

1.4.1. Research on Hydrogen Generation Methods

The H2 Generation team researched three methods of hydrogen production. The three methods were water electrolysis, chemical hydrogen production, and biomass production. Upon reviewing the results of state of the art research, water electrolysis was selected by Dr. Acker as the method to use. The following is a summary of each generation method.

1.4.1.1. Summary Water Electrolysis Summary

Water electrolysis takes advantage of a phenomenon in which electric current in water causes the splitting of the water molecule into hydrogen gas and oxygen gas. Since this method was the most practical choice from the beginning of this project due to the client's request that water be used to make the hydrogen, most of the research effort was placed into this category. For sources of information on water electrolysis, see "Hydrogen Electrolysis Generation" in Appendix I.

1.4.1.2. Summary of Chemical Hydrogen Production Research

The next method of hydrogen production researched was chemical hydrogen production. This involves producing hydrogen as a product of a chemical reaction. One such reaction takes place between metal and acid. The advantage of this type of generation is that there is a low power requirement to produce the hydrogen.

The disadvantages of this system are that metals are not renewable sources and the acids needed for the reaction are volatile. For sources of information on chemical hydrogen production, see "Chemical Hydrogen Generation" in Appendix I.

1.4.1.3. Summary of Biomass Production Research

The third major method is biomass hydrogen production. Biomass production takes different waste products such as peanut shells and orange peels and biologically breaks them down producing hydrogen or methane. Hydrogen can be extracted from the methane produced. This method does not appeal to the problem statement the H2 Generation team was given because renewable energy and water collected on site are not used. For sources of information on Biomass Hydrogen Production, see "Biomass Generation" in Appendix I.

1.4.2. Research on Hydrogen Storage Methods

Three major methods of hydrogen storage were researched by the H2 Generation team. These methods include compressed gas, liquid hydrogen, and hydride storage. Upon completion of research, Dr. Acker chose the method of compressing the hydrogen. The main justification for this choice was the simplicity of the system, and the fact that the other methods are still developing technologies and would have a substantially higher initial cost. The following paragraphs give a summary of each of these three methods.

1.4.2.1. Summary of Compressed Hydrogen Storage Research

Compressed hydrogen simply uses a compressor to force the hydrogen into a high-pressure container. At the basic level, it involves buying a hydrogen compressor and a storage cylinder. A disadvantage of compressed hydrogen storage is the space required to store cylinders on a vehicle. For sources of information on hydrogen compression, see "Compressed Hydrogen Storage", Appendix I.

1.4.2.2. Summary of Liquid Hydrogen Storage Research

Liquid or cryogenic hydrogen is a second manner of hydrogen storage. This method of storing hydrogen uses cryogenic technology to cool hydrogen until it condenses into a liquid. The advantage of this type of storage is that the energy per unit volume is very close to gasoline and therefore storage containers can be similar in size. The disadvantage of this storage method is that a lot of the energy stored in the hydrogen is used to keep the liquid hydrogen cold enough to stay liquid. There is also a substantial cost involved in purchasing materials for this type of storage. For sources of information on liquid hydrogen storage, see "Liquid Hydrogen Storage", Appendix I.

1.4.2.3. Summary of Hydride Storage Research

The final type of hydrogen storage researched was hydride storage. This method solves hydrogen into metals. The hydrogen can then be extracted through a warming process. An advantage of this type of hydrogen storage is safety. Since the hydrogen is not in a free state, there is no explosion risk. Another advantage is a high energy per unit volume of hydride, similar to liquid hydrogen. The disadvantage of this type of storage is a substantial weight due to metal storage containers and the fact that the technology is currently developing and expensive. For sources of information on hydrides, see "Hydride Storage" Appendix I.

1.4.3. Research on Existing Hydrogen Production Systems

The H2 Generation team researched various existing systems that produce hydrogen via renewable energy. A difference between the system designed by H2 Generation and other systems is that most systems deal with larger quantities of hydrogen. The requirements of our system demand small amounts of hydrogen compared to most of the systems the team researched.

The Schatz Solar Hydrogen project in Oregon, U.S.A. used solar energy to run aerators for large aquariums. During the day there is an excess of solar energy and instead of storing the energy in batteries, it is stored in hydrogen gas instead. During the evening when the sun is not shining, the aerators get power from the energy stored in the hydrogen. A similar system at the Illinois Institute of Technology powers a large freeway sign.

Other existing systems were found in California, U.S.A. and Germany. These systems mostly generate large amounts of hydrogen to fuel a small number of vehicles, but are not dependent solely upon renewable energy to do so. In addition, these sights rarely collect their own water for electrolysis. These exist in limited areas, and their main purpose is to create an infrastructure for hydrogen vehicle use. For sources of information on existing systems, see "Existing Systems" Appendix I.

1.5. Basic Design of the Renewable Energy Based Hydrogen Production Facility

The major theory of the design is to collect and treat water from the "Solar Shack" roof and turn it into compressed hydrogen using electricity collected from solar panels and a wind turbine located on site. The major systems of the design are illustrated in Figure 1.5. below.

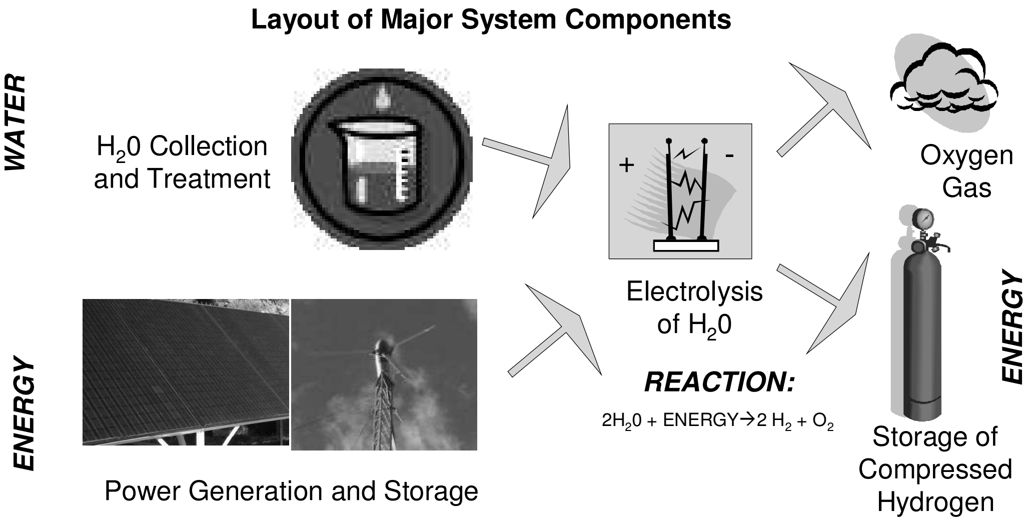


Figure 1.5. : This diagram displays major components of the Renewable Energy Hydrogen System

H2 generation specified two systems for use at the "Solar Shack". Both systems will have water collection and distillation on site. Each proposed system will utilize a large, low-pressure hydrogen storage tank and a safe air-powered hydrogen compressor to pressurize hydrogen for high-pressure storage. The major difference between the two systems is how the hydrogen gas purified.

One system produces higher purity hydrogen (99.9999%) suitable for use in fuel cell technology. This system has safety devices built in and will adapt easily to a control system for safe use. This system also meets OSHA standards without further modification (See Section 4 *Hydrogen Generation and Purification System*).

The second electrolyzer produces lower purity hydrogen (99.5%) for safe use in internal combustion engines. Additional parts are specified for purification, hydrogen leak detection, and automated shut-offs (See Section 4 *Hydrogen Generation and Purification System*).

A projected cost of materials for each unit is displayed in the table below.

System # 1 (Fuel Cells Quality)	System #2 (Combustion Purity)
$26,000	$12,500

Table 1.5. : Projected cost of each hydrogen production facility

1.6. Benefits of the Renewable Energy Based Hydrogen Production Facility

The main benefit of the proposed design is the ability to produce enough compressed hydrogen to fuel a Formula 1 racecar for over 1000 miles per year. This is based on analysis described in section 8 *Computer Simulation of the Renewable Energy Based Hydrogen Production System*. In addition, creating a hydrogen generation facility powered by solar and wind energies has potential for recruiting students to the College of Engineering and Technology at Northern Arizona University interested in studying renewable energy.

Justification for choosing the components in figure 1.5. above comes from the results of H2 Generation's state of the art research discussed in section 1.4. The only way to use available resources including water and renewable energies is to electrolyze water. The most cost effective and simple method to store hydrogen on the proposed Formula 1 racecar is to use high-pressure cylinders.

1.7. Safety Research for Hydrogen Production Plant

Incorporating safety research into the design of the system ensures compliance with current safety standards. Properties of hydrogen relevant to safety are listed are listed below.

- Flammable when volume of hydrogen in air is between 4 and 75 %
- Explosive when volume of hydrogen in air is between 18.2 and 58.9 %
- Flammable when volume of hydrogen in oxygen is between 14.7 and 93.9 %
- Explosive when volume of hydrogen in oxygen is between 15 and 90 %
- Industrial safety standards for purity: 99.5% pure hydrogen
- Research Grade hydrogen: 99.9% pure hydrogen
- Ultra high purity hydrogen: 99.9999% pure hydrogen

(Pyle 1997 page 16, Pyle 1998 page 47)

These numbers describe the nature of hydrogen combustion. They are listed identically in several independent resources (See "Hydrogen Safety" Appendix I). Each of the systems proposed in this report, higher purity and lower purity, take into account the flammable and explosive nature of hydrogen.

There are leak detectors in each of the generation systems that guarantee low levels of hydrogen in storage rooms. The purification process in each of the two systems ensures purity levels between 99.5% and 99.9999% hydrogen. In addition, the specified compression system assures the safe compression of hydrogen.

In addition, OSHA standards for compressed hydrogen storage have been researched and the standards are available at the OSHA website (OSHA 2003). Since the project did not reach the implementation phase, the OSHA standards are not relevant in this report.

1.8. H2 Generation Expenditure Breakdown

Dr. Acker allowed $1000 for the H2 Generation team to complete the design of a full scale Renewable Energy Based Hydrogen Production Facility on paper, and to complete a demonstration of concept model. Table 1.8. below summarizes the actual expenses incurred during the design process.

Design Costs		**Modeling Costs**	
Documentation	$75	Electrolyzer Jr.	$160
Fliers	$15	Engine	$70
Poster Board	$15	Miscellaneous	$30
Total Cost	**$105**	**Total Cost**	**$260**

Table 1.8. : Breakdown Of H2 Generation's Expenses

The table above shows H2 Generation's total spending to be approximately $365. This is less than half of the maximum allowed budget.

2. Renewable Energy, Battery Bank, and Precipitation Expectancy Systems Analysis

2.1. Existing Renewable Energy System

The renewable energy system available to H2 Generation is an existing system located at the "Solar Shack" which is behind NAU's College of Engineering building. This system has four parts (available to H2 Generation) including: 1.5kW Bergey wind turbine, 65.2 square meters of roof-mounted (roof of "Solar Shack") and 16.6 square meters of 45° south-facing PV cells (photovoltaic cells), and a 24 volt 2400 amp-hr 'Surrette S460' battery bank. The system is seen below, the mountains indicate north. (Solar Shack Manuals (1 of 2))

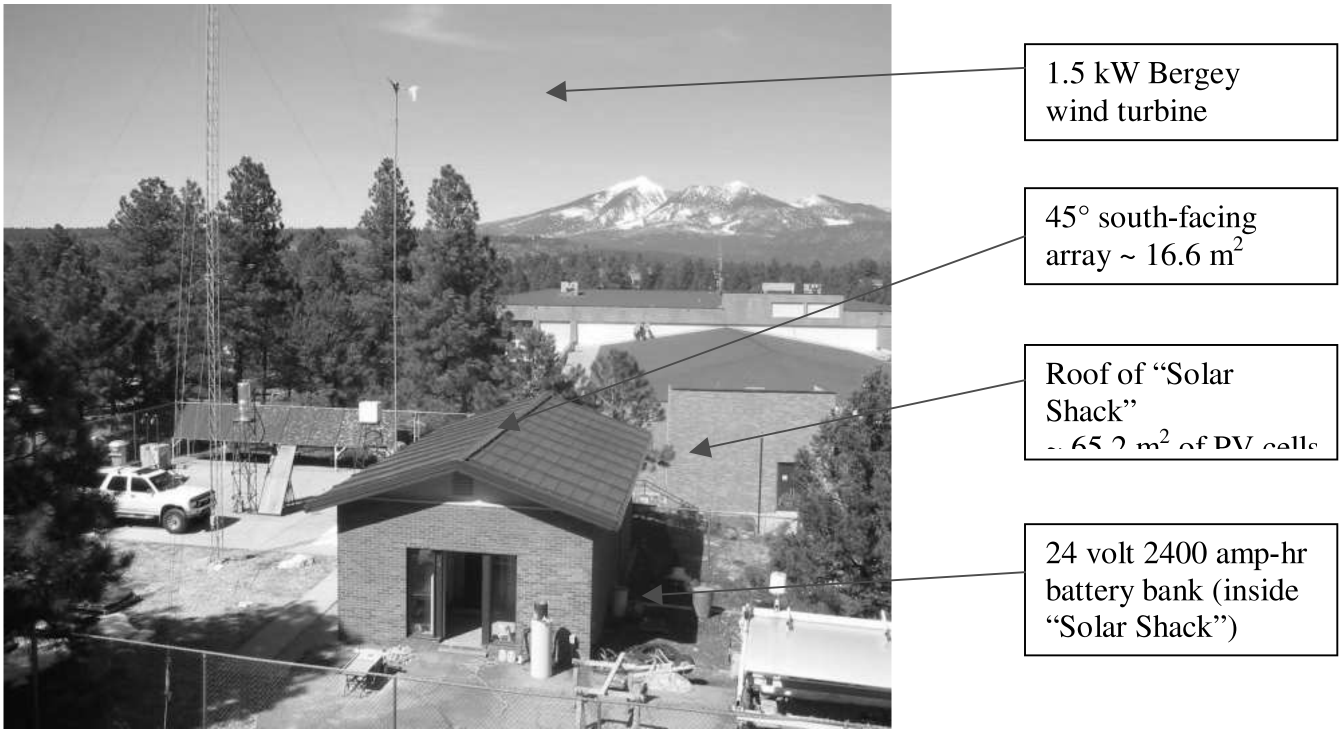


Figure 2.1. : "Solar Shack" behind NAU's College of Engineering building

2.2. The Objective of Analyzing the Renewable Energy System

The objective of analyzing H2 Generation's available renewable energy system is to find if the energy production can power the hydrogen-making equipment. Being that the solution to the problem statement is to have a self-sustaining system; the hydrogen equipment needs to be solely powered by the renewable energy sources.

First, a first-order feasibility analysis needed to be detailed, to ensure that the needed hydrogen production equipment would be supplied with enough energy. Once the decision was made the renewable energy systems produced enough energy to meet hydrogen production requirements, more exact analysis such as interactions between the renewable energy sources, the battery bank, and the hydrogen producing and compressing components was accomplished as seen in section 8. (Appendix A)

2.3. Analyzing the PV Cells, the 1.5kW Bergey wind turbine, and the Battery Bank

The renewable energy system is broken down into each of the four parts: 15° roof-mount PV cells, 45° south-facing PV cells, the 1.5kW Bergey wind turbine, and the battery bank.

2.3.1. Roof-Mounted and 45° South-Facing Photovoltaic Cell Analysis

To analyze the roof-mounted PV cell system, first the area of the PV cells was found to be split into two sides along the roof as seen below in Figure 2.3.1.a. Each side is 15° respectively from the horizontal facing east and west, of which each side has 32.6 square meters totaling to 65.2 square meters. The 45° south-facing array has an area of 16.6 square meters and was verified to face south at a 45° angle as seen below in Figure 2.3.1.b.

Figure 2.3.1.a. : PV cells of the Solar Shack

Figure 2.3.1.b. : PV cells of the 45° south-facing array

2.3.1.1. Finding the Expected Energy from the Sun for both PV cell parts

To find the insolation data for Flagstaff, AZ, 30 years of data is available at a NREL (Nation Renewable Energy Laboratory) website: http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/. This website provides approximate insolation data per month for a particular location and the angle of the array at that location. Insolation is a kWh/m^2 term, which is energy emitted by the sun per unit of area. Since not all of the energy emitted by the sun is collected by the PV cells, an approximate efficiency of 10% (meaning 10% of the sun's energy emitted is collected) is assumed. So knowing the insolation data, the efficiency, and the area, we can find energy (kWh) produced per month and annually, as seen below. (Appendix A, PV Cell Calculations)

PV cell Calculation Table

Month	Roof-mounted PV Cells assumed flat	45 deg. south lat.	KWh/average Day in month	kWh/month	kWh/month with shade
	ave. for 1 day insolation kWh/m^2/day	ave. for 1 day insolation kWh/m^2/day	insolation * area of PV cell * eff. Of PV cells	ave. kWh/day * days/month	kWh/month * 85%
January	3	5	27.86	863.78	734.22
February	4	5.5	35.21	985.96	838.07
March	5	6	42.56	1319.42	1121.51
April	6.5	7	54.00	1620.03	1377.03
May	7.5	7	60.52	1876.09	1594.68
June	8	7	63.78	1913.34	1626.34
July	6.5	6	52.34	1622.51	1379.13
August	6.5	6.5	53.17	1648.27	1401.03
September	5.5	6.5	46.65	1399.56	1189.63
October	4.5	6	39.30	1218.39	1035.63
November	3.5	5.5	31.95	958.62	814.83
December	2.5	4.5	23.77	736.99	626.44

Total PV cell kWh/year:	16162.98	
Total PV cell kWh/year with shade factor:		13738.53

Figure 2.3.1.1. : PV cell calculations spreadsheet with shading factor. (Appendix A, PV cell Calculations)

2.3.1.2. PV Cell Shading Factor

As seen in Figure 2.1, there are many trees around the solar collecting area. Thus, a shading factor of 15% has been implemented for shading from the trees. This means that 15% of the insolation will not be available to the PV cells due to shading in the morning and evening. A total with shading factor for PV cell energy production can be found as seen above in Figure 2.3.1.1. (Appendix A, PV cell Calculations)

2.3.1.3. Clear Day Analysis

The clear day analysis was done using 30 years of clear day data from the Western Regional Climate Center (http://www.wrcc.dri.edu/htmlfiles/westcomp.ovc.html and http://www.wrcc.dri.edu/htmlfiles/westcomp.clr.html). The analysis was done by taking the given number of clear days (in one particular month), the number of cloudy days, and subtracting the total of these two from the total number of days in the month to solve for partial cloudy days. This analysis tells us which how many average days per month we can expect full power, partial power, and minimal power from PV cell system. (Appendix A, PV Cell Calculations)

2.3.2. 1.5kW Bergey Wind Turbine Analysis

The 1.5 kWh Bergey Wind turbine's first order expected energy output was calculated using Betz's equation. This equation:

Energy = (½)(Cp)(ρ)(u^3)(A)

Where Cp is a constant, ρ is the density of air for Flagstaff, AZ (1kg/m^3), u is the average wind speed per month, and A is the swept area of the wind turbine blades. The swept area of a wind turbine is the circle created by rotating wind turbine blades. (Sorensen, pg. 345). The 1.5 kW Bergey wind turbine is seen in the figure below. (Appendix A, Wind Power Calculations)

Figure 2.3.2. : 1.5 kW Bergey wind turbine

2.3.2.1. Average Wind Speed

As stated in section 2.3.2., the power is a function of the average wind speed per month. The Western Regional Climate Center provides month average wind speeds per location. The average wind speeds are listed in Figure 2.3.2.2. (http://www.wrcc.dri.edu/htmlfiles/westwind.final.html)

2.3.2.2. Finding the Expected Energy from the 1.5kW Bergey wind turbine

Finding the expected power using Betz's equation produced a term of energy per time. Through dimensional analysis, kWh per month was found, as see below. (Sorensen, pg. 345). Comparing the calculated annual total energy of 215.62 kWh to the information given by the wind turbine manufacturer which has a range of approximately 200 - 250 kWh/year based on Flagstaff's average annual wind speed. This agrees with the calculated value. (Solar Shack Manuals (1 of 2)), (Appendix A, Wind Power Calculations)

Monthly Breakdown of Energy Produced From Bergey Wind Turbine

Month	Ave. wind Speed (MPH) during Month	Ave. wind Speed (m/s) during Month	ave. joules of energy produced in 1 hr.	kWh/month
		ave. wind spd in mph * 0.44704	using power eq. above * (3600 s / hr)	ave. joules/hr * 24 hr/day * days/month
January	5.90	2.64	82256.77	17.00
February	6.40	2.86	104991.84	19.60
March	6.20	2.77	95453.25	19.73
April	7.10	3.17	143347.69	28.67
May	7.40	3.31	162297.12	33.54
June	7.00	3.13	137375.65	27.48
July	5.40	2.41	63066.24	13.03
August	4.20	1.88	29673.14	6.13
September	4.70	2.10	41582.37	8.32
October	5.20	2.32	56315.21	11.64
November	5.40	2.41	63066.24	12.61
December	6.00	2.68	86510.61	17.88

Total wind kWh/year: 215.62

Figure 2.3.2.2. : Monthly breakdown of energy produced from 1.5 kW Bergey wind turbine (Appendix A, Wind Power Calculations)

2.3.3. Total Energy Capture from Sun and Wind Sources

The total energy production from the PV cells of the Solar Shack roof, the PV cell 45° south-facing array, and the 1.5 kW Bergey wind turbine is seen below in Figure 2.3.3. From this table, the percentage of power from the PV cell systems is 98.5% of the total power. The percentage of wind power is 1.5% of total power. A total charge of 1.99 kWh is needed to charge the batteries (see section 2.4 for batteries, see Appendix A, Option 1: Battery Charging Analysis).
(Appendix A, Total Power Produced by Wind Turbine and PV Cells)

Monthly Energy Produced From Wind and Sun Sources

Month	kWh/month from PV cells	kWh/month from wind turbine	kWh/month total
January	734.22	17.00	751.22
February	838.07	19.60	857.67
March	1121.51	19.73	1141.24
April	1377.03	28.67	1405.70
May	1594.68	33.54	1628.22
June	1626.34	27.48	1653.81
July	1379.13	13.03	1392.17
August	1401.03	6.13	1407.16
September	1189.63	8.32	1197.94
October	1035.63	11.64	1047.27
November	814.83	12.61	827.44
December	626.44	17.88	644.32
Annual	13738.53	215.62	13954.15

Yearly power available to H2 Generation: ***13954.15*** **kWh/year**

Figure 2.3.3. – Monthly energy produced from wind and sun sources (Appendix A, Total Power Produced by Wind Turbine and PV cells)

2.4 Battery Bank and Power

The renewable energy sources, wind and sun, send their energy (charging the battery bank) to a Surrette S460 battery bank through inverters and transformers, respectively. The renewable energies will have the same characteristics for both System Designs I & II. However, the battery banks will respond differently to the electrical draw of each system design. In each case, the battery bank is a 6 volt 460 amp-hr system seen below in Figure 2.4. This means that this battery bank can provide 6 volts at x amps for a time of (460 amp-hrs / # amps) = hrs. For example, if a system has an electrical draw of 6 volts and 20 amps, the time would be (460 amp-hrs / 20 amps) = 23 hours. The battery bank is only going to use the top 80% of the 100% the charge, meaning only 80% of the 460 amp-hrs (368 amp hr) will be used. The battery bank is on a DC (direct current) system. This DC power will be converted into AC (alternating current). Each System Design calls for a different AC conversion. (Appendix A, Option 1: Battery vs. Power Demand Analysis), (Solar Shack Manuals (1 of 2))

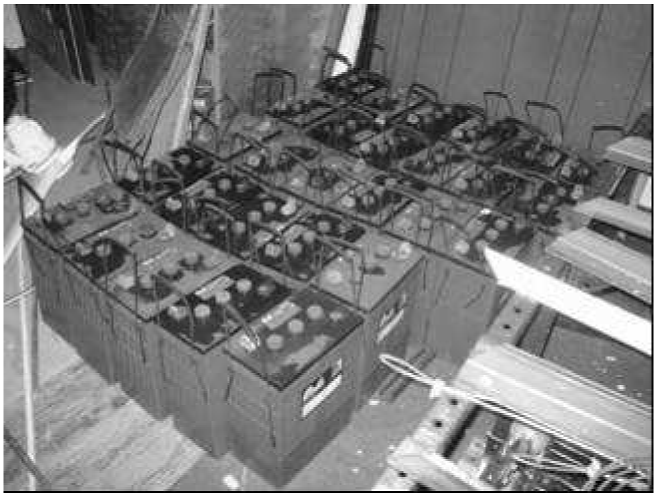


Figure 2.4. :Surrette S460 battery bank, 6 volts, 460 amp hrs

2.4.1. System Design 1 – Battery Bank vs. Power Demand

The power draw from the battery bank to the electrical system producing hydrogen is the electrolyzer, compressor, and a 100-watt miscellaneous allowance. Being that the compressor does not run the same time durations as the electrolyzer, a run time ratio was created to model the compressor running simultaneous with the electrolyzer as seen in Figure 2.4.1.a. System Design I as all electrical demand as 120 volt AC and has approximately 16.5 amp-hr capacity.

Run time Ratio for the Compressor Compared to the Electrolyzer

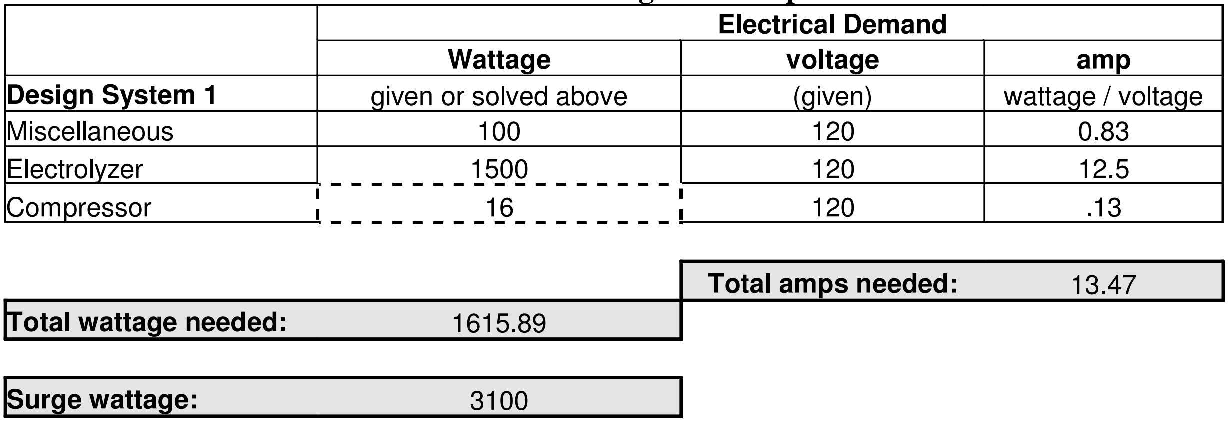
Electrolyzer	Input flow	72	liters / hr
Compressor	Power	1500	watts
	Output flow	4	CFM output
		6796.08	liters / hr

flow (run time) ratio: (in/out)	**0.01**

Figure 2.4.1.a. : Run time ratio for the compressor compared to the electrolyzer. (Appendix A, Option 1: Battery vs. Power Demand Analysis)

Using the run time ratio the compressor's wattage can be converted into wattage as if it were simultaneously with the electrolyzer, meaning their flow rates would be equal. Inputting this wattage into a spreadsheet totaling the data you have data as seen in Figure 2.4.1.b. below. Being that the compressor actually does run for only two units of time per 100 units of time of the electrolyzer, surge wattage was found as seen in Figure 2.4.1.b. (See electrolyzer and compressor sections for further information on these components), (Appendix A, Option 1: Battery vs. Power Demand Analysis)

Total Wattage and Amps



	Electrical Demand		
	Wattage	voltage	amp
Design System 1	given or solved above	(given)	wattage / voltage
Miscellaneous	100	120	0.83
Electrolyzer	1500	120	12.5
Compressor	16	120	.13

Total amps needed: 13.47

Total wattage needed: 1615.89

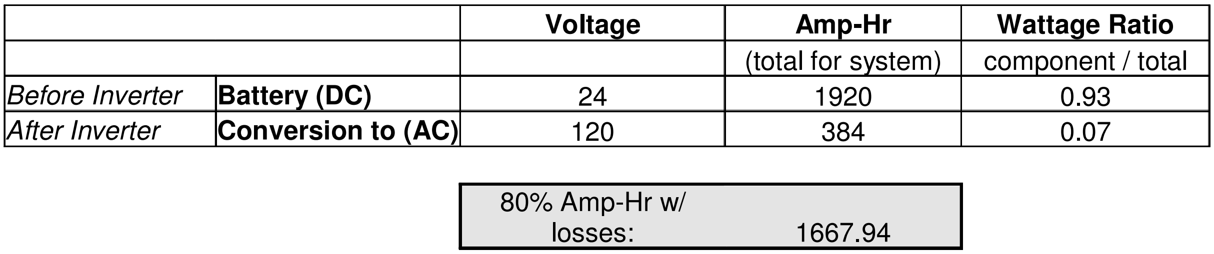
Surge wattage: 3100

Figure 2.4.1.b. :Total wattage and amps; surge wattage (Appendix A, Option 1: Battery vs. Power Demand Analysis)

2.4.2. System Design 2 – Battery Bank vs. Power Demand

The electrolyzers are on a 6 volt DC system. Thus to solve for an amp hr rating using a partial AC conversion is the spreadsheet shown below.

Partial AC Conversion



		Voltage	Amp-Hr	Wattage Ratio
			(total for system)	component / total
Before Inverter	**Battery (DC)**	24	1920	0.93
After Inverter	**Conversion to (AC)**	120	384	0.07

80% Amp-Hr w/ losses: 1667.94

Figure 2.4.2.a. – Partial AC conversion, with electrolyzers using 6 volts, and compressor using 120 volts AC (Appendix A, Option 2: Battery vs. Power Demand Analysis)

The power draw from the battery bank to the electrical system producing hydrogen are the electrolyzers, compressor, and a 100-watt miscellaneous allowance. Being that the compressor does not run at the same time durations as the electrolyzers a run time ratio was created to model as if the compressor did run an equal time as seen below.

Run time Ratio for the Compressor Compared to the Electrolyzer

Electrolyzers (3)	Input flow (for all 3)	68.1	liters / hr
Compressor	Power	1500	watts
	Output flow	4	CFM output
		6796.08	liters / hr

flow (run time) ratio: (in/out)	**0.01**

Figure 2.4.2.b. : Run time ratio for the compressor compared to the electrolyzer. (Appendix A, Option 2: Battery vs. Power Demand Analysis)

Using the run time ratio the compressor's wattage can be converted into wattage as if it were simultaneously running with the electrolyzers, meaning their flow rates would be equal. This wattage is in a spreadsheet totaling the data as seen in Figure 2.4.1.c. below. Being that the compressor actually does run for only 1 unit of time per the electrolyzer running 100 units of time, surge wattage was found to be 3100 watts. (See electrolyzer and compressor sections for further information on these components), (Appendix A, Option 2: Battery vs. Power Demand Analysis).

Total Wattage and Amps

	Electrical Demand		
	Wattage	**voltage**	**amp**
Systems	given or solved above	(given)	wattage / voltage
Miscellaneous	100	120	0.83
Electrolyzers (3)	1500	6	12.5
Compressor	15	120	.13

▼

Total amps needed: 13.46

Total wattage needed: 1615.03

Surge wattage: 3100

Figure 2.4.2.c. :Total wattage and amps; surge wattage (Appendix A, Option 2: Battery vs. Power Demand Analysis)

2.5. Energy Production with Losses

From the renewable energy sources to the hydrogen production equipment, many losses are encountered. Transferring the wind energy from the wind turbine to the hydrogen production equipment introduces losses that can be as high as 50%. Loss introduced transferring solar power is approximately 10% (Solar Shack Manuals (1 of 2)). Total power for each month is broken down as see below. (Appendix Option 1: Battery Charging Analysis)

Monthly Totals of Energy Production with Losses for Solar and Wind

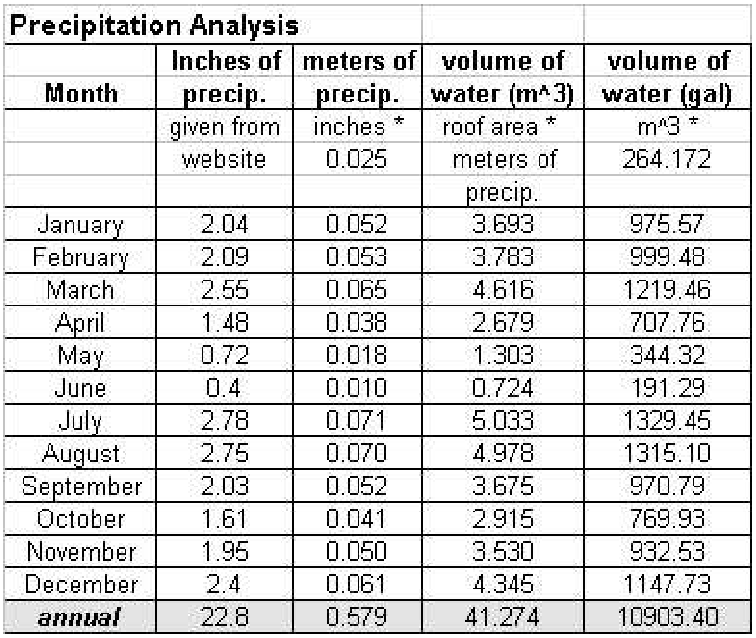
Month	*Wind*		*Solar*		Total energy
	Total energy from wind (from 'Total Power')	Wind energy *with losses* total * losses	Total energy from solar (from 'Total Power')	Solar energy *with losses* total * losses	(with losses) Wind power + Solar power
January	17.00	*8.50*	734.22	*660.79*	669.29
February	19.60	*9.80*	838.07	*754.26*	764.06
March	19.73	*9.86*	1121.51	*1009.36*	1019.22
April	28.67	*14.33*	1377.03	*1239.32*	1253.66
May	33.54	*16.77*	1594.68	*1435.21*	1451.98
June	27.48	*13.74*	1626.34	*1463.71*	1477.44
July	13.03	*6.52*	1379.13	*1241.22*	1247.74
August	6.13	*3.07*	1401.03	*1260.93*	1263.99
September	8.32	*4.16*	1189.63	*1070.66*	1074.82
October	11.64	*5.82*	1035.63	*932.07*	937.89
November	12.61	*6.31*	814.83	*733.34*	739.65
December	17.88	*8.94*	626.44	*563.80*	572.74
Annual	215.62	*107.81*	13738.53	*12364.68*	12472.49

average kWh per day for a year:	

Figure 2.5. : Monthly totals of energy production with losses for solar and wind (Appendix Option 1: Battery Charging Analysis)

2.6. Precipitation Expectancy Analysis

The hydrogen production utilizes hydrogen in water, and thus the amount of water (from rain and snow) expected per month and year needed to be found. The collection system (discussed in section 3) includes a guttering system for capture of water from the roof of the solar shack. First, the total area of the roof was found, this is different than the photovoltaic cell area on the Solar Shack. The total area of the roof of the Solar Shack used in collecting water is 71.3 square meters. Since the roof's eves are pitched, geometry was applied to find the area as if the roof was not pitched (Appendix A, Precipitation Analysis). Next, average monthly precipitation data from University of Utah's Department of Meteorology website (http://www.met.utah.edu/jhorel/html/wx/climate/normrain.html) was used. This data was used with the area calculated for the roof to find a monthly/yearly volume of water expectancy as seen below. (Appendix A, Precipitation Analysis)



Precipitation Analysis				
Month	Inches of precip.	meters of precip.	volume of water (m^3)	volume of water (gal)
	given from website	inches * 0.025	roof area * meters of precip.	m^3 * 264.172
January	2.04	0.052	3.693	975.57
February	2.09	0.053	3.783	999.48
March	2.55	0.065	4.616	1219.46
April	1.48	0.038	2.679	707.76
May	0.72	0.018	1.303	344.32
June	0.4	0.010	0.724	191.29
July	2.78	0.071	5.033	1329.45
August	2.75	0.070	4.978	1315.10
September	2.03	0.052	3.675	970.79
October	1.61	0.041	2.915	769.93
November	1.95	0.050	3.530	932.53
December	2.4	0.061	4.345	1147.73
annual	22.8	0.579	41.274	10903.40

Figure 2.6. – Calculations for monthly/yearly volume of water expectance (Appendix A, Precipitation Analysis)

The total water expected to fall upon the Solar Shack roof per year is 10, 903 gallons. This volume however cannot be all collected. In Appendix B.1.1. it is calculated that 40 gallons of water is needed for electrolysis to produced the amount of required hydrogen. Thus, the incoming precipitation is 287 times more water than needed. (Appendix A, Precipitation Analysis)

3. Water Collection and Storage System

3.1. Summary of Water Collection and Storage System

Our client Dr. Tom Acker has requested that the water used to produce hydrogen be collected from the roof of the "Solar Shack" located behind the College of Engineering and Technology building. In order to meet this requirement H2 Generation will make use of a guttering system to be installed on the roof. H2 Generation's design begins with a system to clean and store collected water.

The parameters involved in this design include the following:

- Amount of water required for electrolysis
- Flowrate of the electrolyzer
- Purity required by the electrolyzer
- Using as little electric power to run the system as possible
- Control system that automates the process

Each of these parameters is detailed in the following sections of this report.

3.1.1. Amount of Water Required for Electrolysis

In order to determine the system's water requirement, an estimation of the racecar predicted fuel consumption is needed. H2 Generation's calculations show for a 35 mpg gasoline efficiency racecar to travel 50 miles per month, 50,800 liters of H2 gas at standard temperature and pressure (STP) is required. (See Appendix B.1.1.)

To determine how much water is required to produce 50,800 Liters of hydrogen gas at STP, H2 Generation took the molecular mass ratio of hydrogen to water, and then used this with a density ratio of water to hydrogen. This calculation showed that for one gallon the team could produce 1300 gallons of hydrogen gas at STP (See Appendix B.1.2.).

By dividing the 50, 800 liters by 1300 liters of hydrogen gas per liter of water it is possible to calculate the amount of water required in order to produce 50,800 liters of H2 gas at STP. The team's calculations show a requirement of approximately 40 gallons (See Appendix B.1.1.) This requirement is easily achieved since calculations for possible yearly collection of rain is over 10,000 gallons (See Appendix A).

3.1.2. Flowrate Required for Electrolyzer

The distiller should produce distilled water faster than the electrolyzer uses it. Having a surplus of distilled water will allow the system to store extra water in case of drought. Since there will be a 55 gallon distilled water reservoir and a 55 gallon rainwater reservoir the system will be able to store a two and three quarter year supply of water.

The flowrate of water into the electrolyzer is determined by working backwards from the output rate of hydrogen from the electrolyte. The ratio of volume of hydrogen gas produced from a volume of water is 1300:1. Taking the maximum electrolyzer output rate of 72 liters/hour and dividing it by 1300 and multiplying it by 8 hours of electrolyzer production/day yields a daily requirement of distilled water. This daily requirement is 0.116 gallons of distilled water per day. (See Appendix B.1.4.)

3.1.3. Purity Required by the Electrolyzer

As research into electrolyzers has shown, there are different levels of purity required by different electrolyzers. Distilled water is the cleanest water required, and the requirement decreases in purity from this level.

There are several methods of water purification including chemical additives, reverse osmosis filters, commercial boiling distillers, and solar distillers. In order for the water purification system to work with any electrolyzer at maximum performance, distilled water is a requirement. This will prevent buildup of alkaline and other impurities that remain when water splits into hydrogen and oxygen during electrolysis.

3.1.4. Control System that Automates the Process

As per client request, the water collection and treatment system should be an automated process with as little user input as possible.

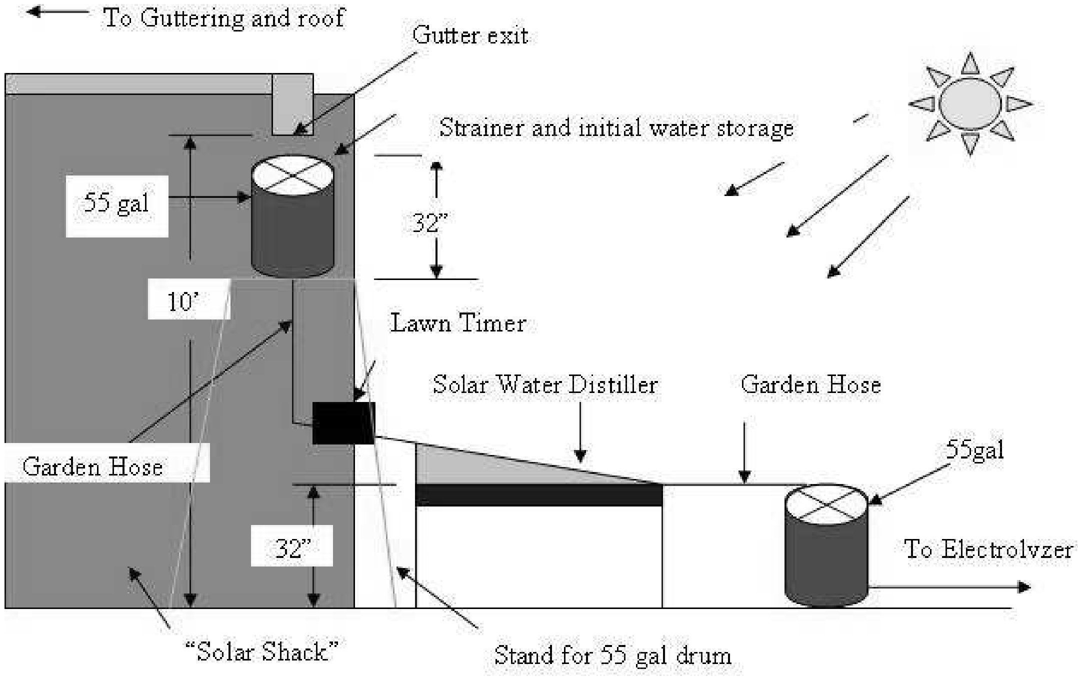
3.1.5. Using As Little Electric Power as Possible to Run the System

As stated earlier in this report, the entire system runs on renewable energy. This is solar and wind energy that is stored in batteries. In order to be successful, H2 Generation's design must make the overall system efficiency a priority. The distillation system should use as little electrical energy as possible.

3.2. The Design of the Water Collection and Treatment System

The design of the water collection and treatment system has taken all of the above parameters into account. The first part of the system is an initial storage container that will use a built in strainer to filter out large impurities from the rainwater entering the system from the guttering. This will be an elevated container to conserve potential energy and be able to feed the water distiller using gravity instead of a pump.

Water will exit through the bottom of this container and flow into a solar water distiller. The purified water then drips into a final distilled water storage container. This is a 55-gallon drum designed for safely storing drinking water. A timer automates the flow of the distilled water system, and supplies a desired amount of rainwater into the distiller each day. Please see Figure 3.2. below, for a schematic of the water collection system.



Detailed Water Collection and Purification System Diagram

Figure 3.2. : Detailed Layout of the Water Collection and Treatment System

For a list of the water collection and treatment system materials, see Table 3.2 below. For comprehensive specifications for each of the components, see Appendix B.2.

General System Components

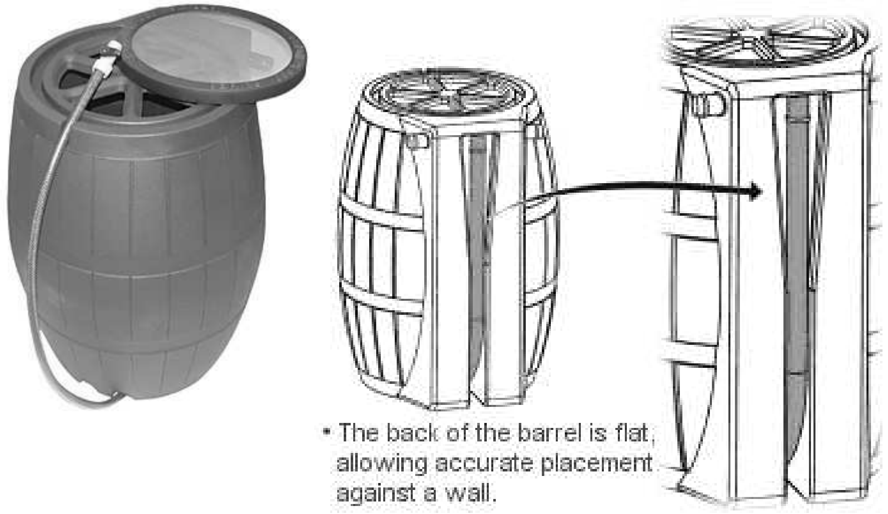
General System Component	Specified System Component
Rainwater storage and coarse filter	"RainCatcher" strainer and 55 gallon drum
Distiller	"Rainmaker" Solar Distiller
Distilled water reservoir	55 gallon water drum
Flow controller into distiller	Gilmore lawn timer
Connection hoses	Standard ¾" garden hose with extra fittings

Table 3.2. : List of general and specified components.

The following outlines will detail each component's specifications and features.

3.2.1. Water Collection System

The "Raincatcher" is a container that holds 55 gallons and has a built in screen designed to catch debris that will accompany rainwater from the roof through the guttering system (See Figure 3.2.1. below). It has a flat back and bottom, which allow for easy resting against the "Solar Shack" wall using a stand.



• The back of the barrel is flat, allowing accurate placement against a wall.

Figure 3.2.1. : The "RainCatcher" rainwater collector and coarse filter (http://www.watersavers.com).

For basic specifications, see Table 3.2.1. below. For a more comprehensive product description, see Appendix B.2.1.

General "RainCatcher" Specifications

Dimensions	32" H x 24" W

Weight	18 lbs
Capacity	55 gallons
Composition	recycled materials

Table 3.2.1. : Specifications for the "RainCatcher" (http://www.watersavers.com).

3.2.2. Water Purification System

The "Rainmaker" solar distiller is a ready-made unit that uses the sun's energy to evaporate water (See Figure 3.2.2. below). This water condenses on the roof of the unit, where it drains into a storage container. This component supplies distilled water without the use of electricity.

Figure 3.2.2. : The "Rainmaker" Solar Water Distiller (http://www.solaqua.com/index.html).

For basic specifications for the "Rainmaker", see Table 3.2.2 below. For a more comprehensive product description, see Appendix B.2.3.

General Specification for the "Rainmaker"

Dimensions	30" W x 48" L
Area	10 sqft
Weight	40 lbs
Maximum Production	2 L/day Winter-6L/day Summer

Table 3.2.2. : List of general specifications for the "Rainmaker" solar distiller (http://www.solaqua.com/index.html).

A disadvantage of the chosen distiller is a maintenance requirement that the unit be flushed with water each day to remain clean. The amount of water required to flush the unit is two times the amount of water requiring distillation. Since rainwater is in excess, this will not be of concern.

3.2.3. Final Storage Unit

The purified water is stored in another 55-gallon storage barrel, keeping the water pure, until it feeds into the electrolyzer using suction applied from the electrolyzer unit (See Figure 3.2.3. below).

Figure 3.2.3. : "55 gallon Storage Barrel" for storage of distilled water (http://www.frontiersurvival.com).

The 55-gallon storage barrel is a generic barrel that is abundantly available. For the purposes of the design, this particular model is specified. The notable specifications are listed in the table below. For more information, please see Appendix B.2.4. or view the website at http://www.frontiersurvival.com.

Specifications for the "55 gallon storage barrel"

Dimensions	35.5" H x 23.5" D
Weight	24.5 lbs
Capacity	57.5 gallons
Openings	2 – ¾" openings on top of unit

Table 3.2.3. : Specifications for the "55 gallon storage barrel" (http://www.frontiersurvival.com)**.**

3.2.4. Control System for Water Collection and Treatment System

The "Gilmore 9100 Lawn Timer" allows regulation of the flow into the solar distiller (See Figure 3.2.4. below). This is an important feature because it automates filling of the solar distiller each morning. An important client requirement is automation.

Figure 3.2.4. : "Gilmour 9100 Lawn Timer" (http://www.gilmour.com/).

The table below summarizes key specifications for the "Gilmour 9100 Lawn Timer". For further information, see Appendix B.2.3.

Specifications for the "Gilmour 9100 Lawn Timer"

Inlet/Outlet Diameters	¾" garden hose compatible
Connections	Swivel nuts to connect to ¾" garden hose
Power Requirements	4 AA alkaline batteries
Programming	Removable electronics, easy programming

Table 3.2.4. : Specifications for "Gilmore 9100 Lawn Timer"(http://www.gilmour.com/).

3.3. Cost of the Water Collection and Treatment System

The major components of the water collection and treatment system come ready to use and require little or no extra assembly. The table below summarizes the cost of these materials. Miscellaneous materials include a stand, garden hose and extra fittings used to connect the various components.

Summary of Material Costs for the Water Collection and Treatment System

The RainCatcher	$119.50
Gilmore 9100	$26.99
The Rainmaker	$398
55 gallon Drum	$29.95
Miscellaneous*	$150.00
Total=	**$725**

Table 3.3. : Cost summary for the water collection and treatment system.

3.4. Maintenance Issues with the Water Collection and Treatment System

The maintenance issues associated with the water collection and treatment system are simple and include the following:

- Cleaning the "Raincatcher" screen
- Cleaning the "Raincatcher" storage container
- Flushing the "Rainmaker" basin

3.4.1. Cleaning the "Raincatcher" Screen

The "Raincatcher" screen strains out debris from the rainwater collected from the "Solar Shack" gutter. After rain, clear any debris caught in the strainer.

3.4.2. Cleaning the "Raincatcher" Storage Container

The "Raincatcher" is open to the environment as this is how water enters the system. Thus, there is opportunity for microbes and algae to get into the container. If there is a long period of storage before the water is used, then there is the possibility that these will cause a problem with water storage.

This unit requires a monthly check to ensure that growth is not occurring. If growth is occurring to a degree that it may inhibit use of the container, then the entire container needs draining and aeration to kill any microorganisms that may be growing in the water.

3.4.3. Flushing the "Rainmaker" Basin

The "Rainmaker" will need daily maintenance, but it will be automatic. Each day when the "Gilmour 9100 Lawn Timer" adds water into the "Rainmaker", it will add three times the water requiring distillation as mentioned in the section on water purification (See 3.2.2. Water Purification System). This will keep the unit clean and remove any deposits that remain in the unit when water evaporates.

There is a substantial waste of water in this method, but the amount of water that is available to us is in such excess (over 10,000 gallons) that it is worthwhile to have a low-cost, easy to maintain, and non-electric water distiller.

In addition, the water flushed through the distiller is collectable and allows use for other purposes. The water that is flushed though the system exits through a nozzle below the level of the distilled water exit. This prevents mixing of the distilled water with water used to flush the system. This also allows for placement of a separate container to catch flushed water.

4. Hydrogen Generation and Purification System

4.1. Summary of the Hydrogen Generation and Purification System

H2 Generation's client, Dr. Tomas Acker, was given preliminary information on possible hydrogen generation methods. His decision was to produce hydrogen using electrolysis methodology. The initial research for electrolyzers was based on the design criteria set by providing enough fuel for the Formula 1 racecar design team to drive 50 miles per month. The design criterion is based on the application being either internal combustion or fuel cell technology. The result of the research and the direction of Dr. Acker, H2 Generation defined a need for two individual electrolysis design layouts.

4.2. Initial Research for Hydrogen Generation and Purification System

Out of the multiple hydrogen generators commercially available, the team chose one based on the production rate. The production rate is significant in the fact that the team determined a fixed amount of hydrogen production per month. For a 50 mile/month, traveling distance of a car with 35 mpg the amount of hydrogen production is 16024 liters/month (See Appendix C.2.). Based on the number of hours per day multiplied by the number of days in a month the team found the minimum flow rate for the fixed amount of hydrogen production had to be greater than 30 L/h. Our selection of hydrogen generators was model number B9400 from Chromtech Inc.

List of researched electrolyzers

Electrolyzer	KW	L / h	Cost
A9090	0.48	5.4	$ 4,135.00
AB9100	0.48	9.6	$ 5,320.00
B9200	0.6	15	$7,560.00
B9400	0.6	30	$9,208.00
B9800	1.5	72	$19,800.00
HM4200	0.5	22.7	$ 3,000.00

Table 4.2. : List of researched electrolyzers

4.3. Further Research into Hydrogen Generation and Purification System

Since the explosion limits of hydrogen are 4.5% to 87% in air, internal combustion engines burn a hydrogen-air mixture containing 10% H_2 and 90% air. Thus, the purity for hydrogen production for use in internal combustion engines is 99.5% pure based solely on safety issues when storing compressed hydrogen.

For hydrogen use in fuel cell technology, the hydrogen purity needed is significantly higher. To achieve high efficiencies using fuel cells, hydrogen purity must be held at 99.999% pure hydrogen (US Car 2003). These two different uses for the hydrogen make a considerable difference in the electrolysis system design.

The information was relayed to our client, Dr. Acker, to determine which type of application of the hydrogen he would like to use. The response of our client was to keep both options viable. The strategy in his decision is to allow the Formula 1 racecar to run on either internal combustion or a hydrogen fuel. The decision of our client led to the design of two independent electrolysis systems.

4.4. Design for Power Availability

The electrical capacity analysis began once the decision was made for two different system solutions based on hydrogen usage. The initial assumption for power was that the renewable energies, located in the “Solar Shack”, would supply enough energy to run the system 24 hours a day. The 30 L/h flowrate would not produce enough hydrogen to meet yearly hydrogen requirement. This is due to downtimes for battery recharge, maintenance, and unexpected off times. In order to produce the required amount of hydrogen in a worst-case situation, the B9800 model with a 72 L/h flowrate was selected.

The cost increase between the two hydrogen generators is substantial due to the change in the purification systems (See Figure 4.4.). The purification system for the B9800 model is made of Palladium, which is extremely expensive but must be used in order to achieve the 99.9999% hydrogen purity at a rate of 72 L/h. An added feature of the upgraded electrolyzer is a constant flow valve for inlet water. Other models required manually filling the water reservoir.

List of Researched Electrolyzers

Electrolyzer	KW	L / h	Cost
A9090	0.48	5.4	$ 4,135.00
AB9100	0.48	9.6	$ 5,320.00
B9200	0.6	15	$7,560.00
B9400	0.6	30	$9,208.00
B9800	1.5	72	$19,800.00
HM4200	0.5	22.7	$ 3,000.00

Table 4.4. : B9800 Electrolyzer Specifications

4.5. Hydrogen Generation and Purification System Design 1: Hydrogen (99.9999% purity)

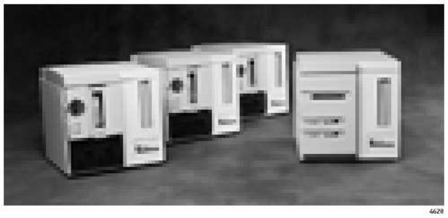


Figure 4.5.a : Packard Hydrogen Generators

The Hydrogen Generation and Purification System Design I layout incorporates a pre-manufactured hydrogen generator. In the research of hydrogen generation, we found a simple system that includes a solid polymer electrolyte (SPE). The function of the SPE is to eliminate the use of caustic solutions that are typically mixed with water in electrolyzer usage. The function of a caustic solution or the SPE is to add resistance to the water so electrons can move more freely when separating the hydrogen and oxygen of the water molecule. The benefit of not needing to mix external solutions to act as an electrolyte reduces the cost and complexity of producing hydrogen. Another benefit of SPE is the electrolyzer life cycle is increased due to the absence of corrosion on the cathode and anode caused by the degradation of materials. The flow diagram for the generator is shown below in figure 4.5.b.

Additional benefits of the Packard Hydrogen Generator include the following:

- Certified Safety: National Fire Protection Agency

- OSHA-1910.103
- Hydrogen produced to: 99.99999%
- Allowable output pressure ranging from 0 to 87 psig
- Hydrogen detection with an automatic shutoff system
- Inline valve for continuous water fill

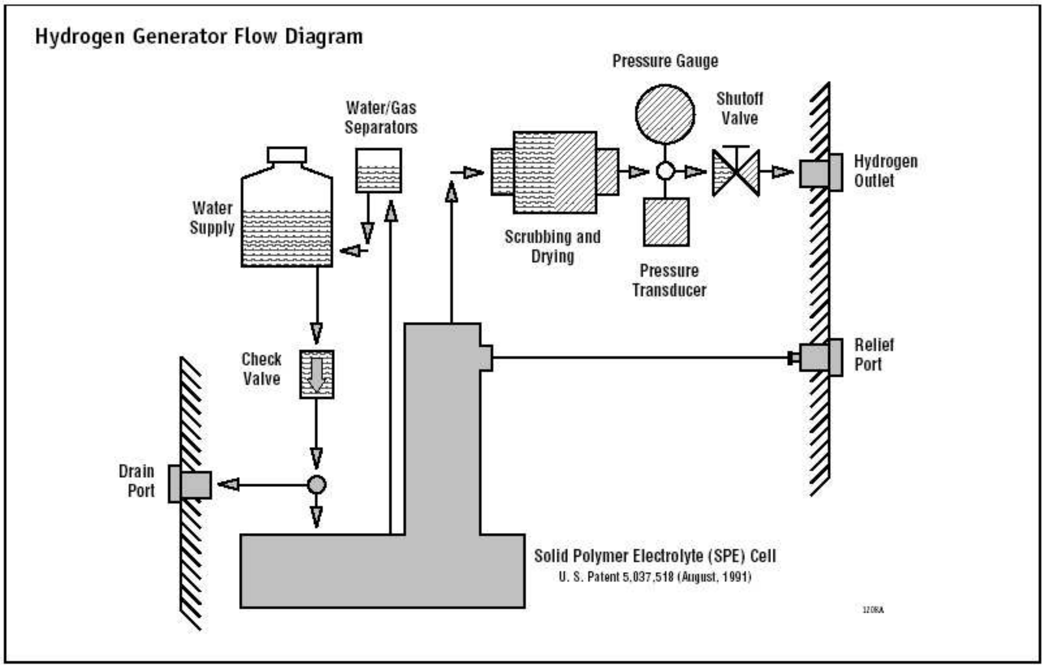


Figure 4.5.b.: Packard Hydrogen Generator Layout

4.5.1. Packard Hydrogen Generator Maintenance

- Deionized Water Reservoir
  - Clean inline attachment for direct water feed
  - Replace deionizer bags every six months or whenever the “change water” light is on.

- Deionizer Replacement
  - Rinse the water tanks and replace the deionizer bags every six months, or when the “CHANGE WATER” message lights up on the front of the generator.

- **Fan Filter**
  - Remove and clean the fan filter located on the back of the unit every two months to prevent dirt buildup and overheating of the unit.

4.6. Hydrogen Generation and Purification System Design II: Hydrogen (99.5% purity)
System design layout II is a specified system with individual components from various manufactures. The three major aspects of this design layout are electrolyzers, a purification train for the hydrogen, and the hydrogen leak detection. The system flow diagram is illustrated below (See Figure 4.6.).

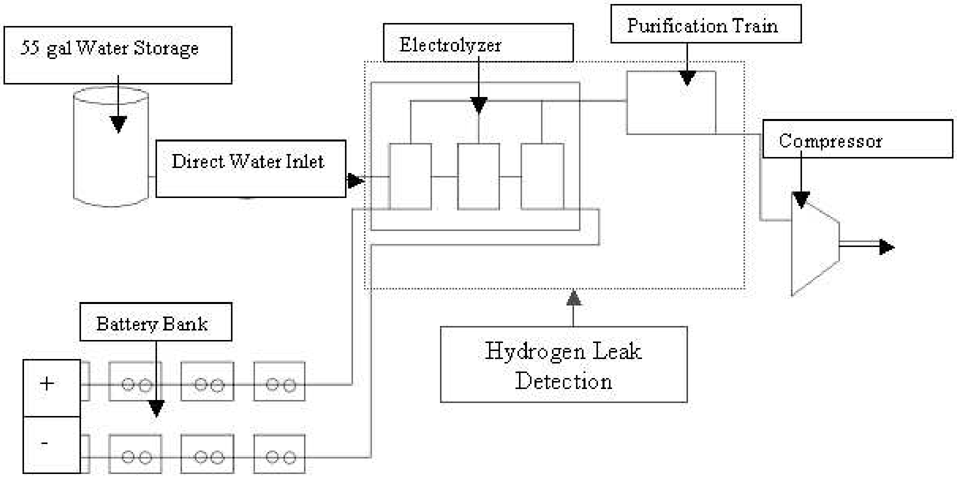


Figure 4.6. : System Design Layout II

4.6.1. Electrolyzer Component for System II

The electrolyzer units are specified from "Thermodine Systems" at $490 each. The production rate of an individual unit is 22.7 L/h. To ensure an equal production of hydrogen as system design I, system II will use three individual electrolyzers running simultaneously. The electrolytes for system II are also a solid polymer to minimize the extra costs of chemicals and the need for a mixing system within the system design. The schematic of a solid polymer electrolyte is shown below in figure 4.6.1. from Greenwinds Inc. (Greenwinds 2003).

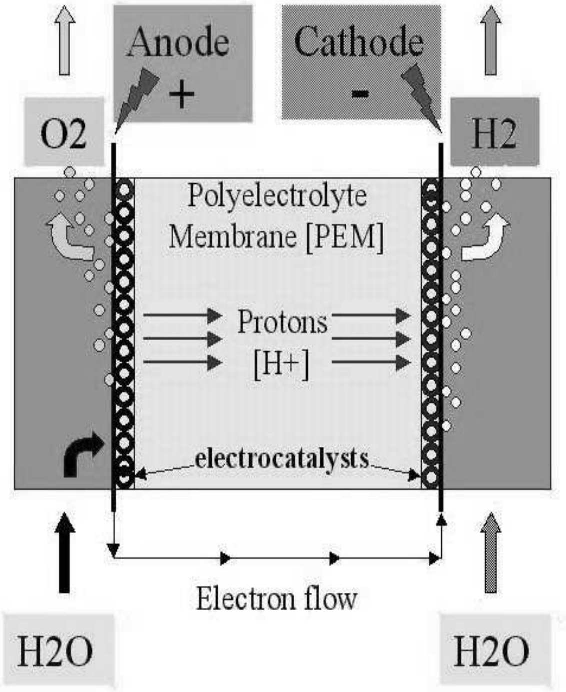


Figure 4.6.1. : Diagram of a Polyelectrolyte Membrane Electrolyzer (PEM)

4.6.2. Purification Train for Hydrogen Generation and Purification System II

The second stage for system design II is the purification of produced hydrogen. This purification system consists of two stainless steel water coalescers, two brass flashback arrestors, one catalytic recombiner [converts H_2 contaminant in O_2, or O_2 contaminant in H_2, back into water], two stainless water purge/drain valves for coalescers, two stainless pressure gauges, and stainless interconnecting fittings. The system was specified from the Hion Solar Company. The layout for the hydrogen purification train is shown below in figure 4.6.2.

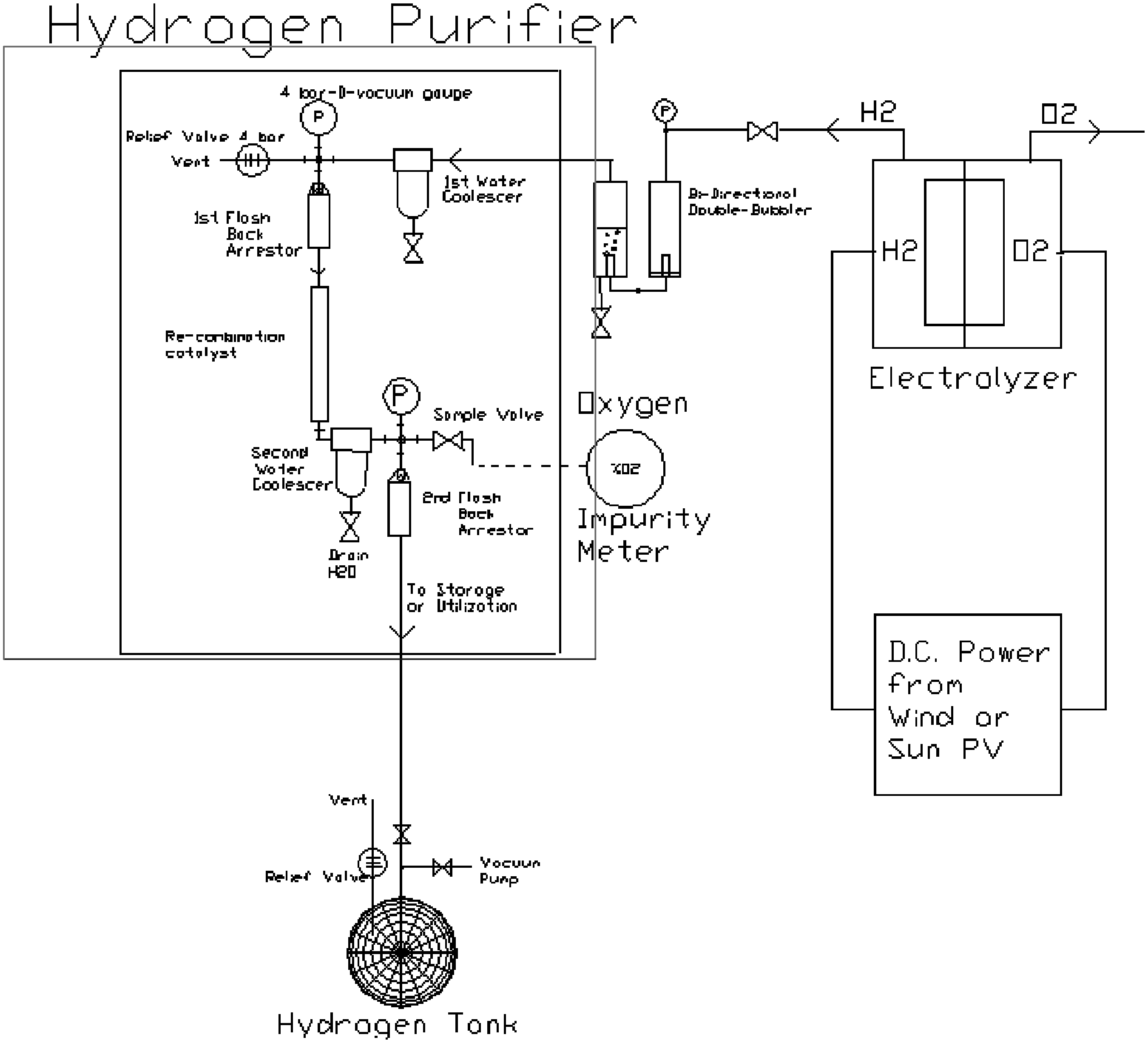


Figure 4.6.2. : Hydrogen Purification Train (Fuel Cell Store 2003)

Purity: 99.9% Hydrogen
Flowrate: 47 L/h at SPT

Delivery Pressure: 0 to 58 psig
Cost: $1750.00 per unit

4.6.3. Hydrogen Sensing Device for the Hydrogen Generation and Purification System

A hydrogen sensor with data acquisition is required for the safety of the system. This feature is needed in case there is any hydrogen leakage. Its main purpose is to shut off hydrogen production until maintenance can isolate and resolve the problem. The figure below shows the selected hydrogen detection device from AFC International Inc.

Figure 4.6.3. : GasSens Economy Gas Detection System (AFC International Inc. 2003)

Major Features of the Hydrogen Sensing Device

- **Analog Output -** An isolated 4-20 mA output is standard. The output will drive loads up to 1,000 ohms for use in recording, data logging or computer input. Analog output is to be used with data acquisition system already in place at the "Solar Shack"
- **Two Alarm Set points -** Alarm set points are factory adjusted to standard values but may be set to any value from 5% to 100% of range. Front panel LED's marked Warning and Alarm indicate the status of each alarm set point. A standard alarm time delay of 2 seconds or a longer delay of 10 seconds may be selected. In addition, alarms may be switch programmed to activate either above or below the set point. Set point for hydrogen detection will be at a minimum of 2.0% of H_2 in air.
- **Remote Reset Input -** Terminals are provided for connection of a remote reset switch so that alarms can be acknowledged form a remote location or through a telemetry system.
- **Pluggable Terminal Blocks -** External electrical connections are made to plug in terminal blocks. Automatic shutoff for hydrogen generation is set by the pluggable terminals
- **Cost: $1,408.00**

(AFC International Inc. 2003)

5. Hydrogen Storage System

5.1. Summary for the Hydrogen Storage System

The hydrogen storage system consists of four major components:

1. compressed gas cylinder
2. gas booster
3. air compressor
4. propane tanks (2)

Hydrogen gas flows and airflows between these four components are shown below in Figure 5.1.

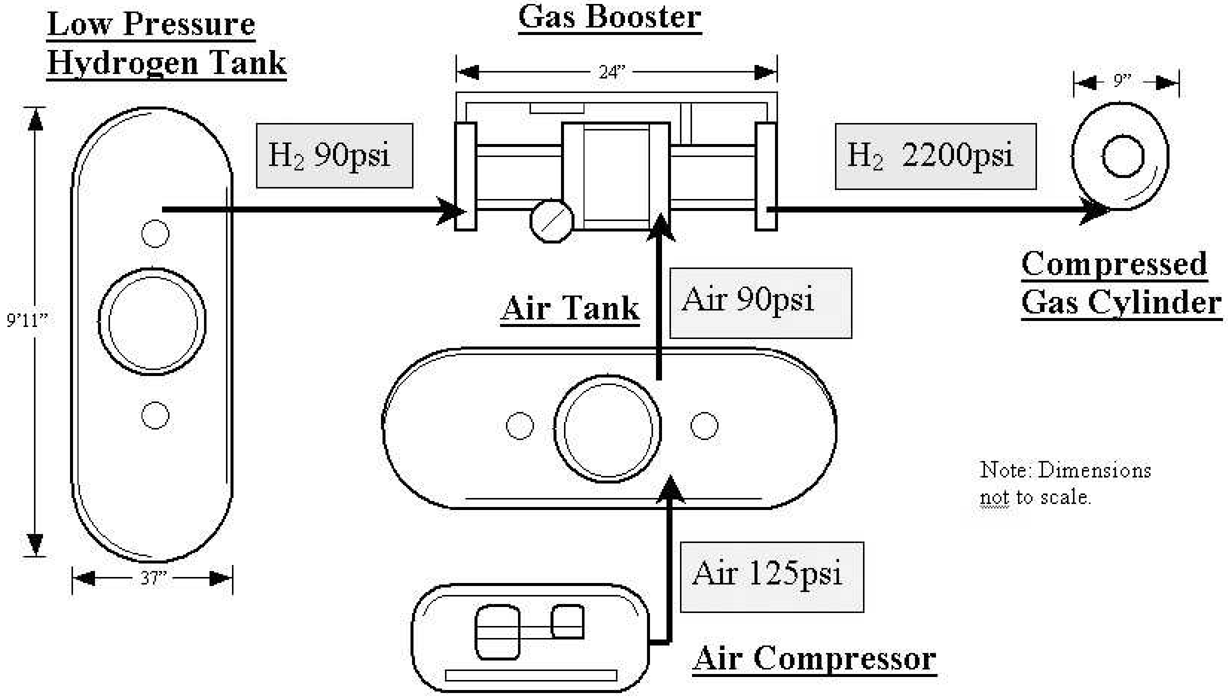


Figure 5.1. : Layout of the Hydrogen Storage System

5.2. Compressed Gas Cylinder for Hydrogen Storage System

The hydrogen gas produced by the electrolyzer will be stored in a compressed gas cylinder. This is the most common and convenient way to store a compressed gas. Compressed gas cylinders of various sizes are shown in Figure 5.2. Any standard compressed gas cylinder can be used to store hydrogen, as long as it follows the Compressed Gas Association's (CGA) standard for hydrogen gas storage, G-5 (CGANet 2003).

There are several standard pressures that compressed gas cylinders are designed to withstand. Compressing hydrogen to a higher pressure into a cylinder will allow more hydrogen gas to be stored, but will cost more.

Figure 5.2. : Compressed Gas Cylinder

(Cyl-Tec 2003)

Therefore, two pressures have been chosen for the design of the hydrogen storage system, resulting in two system designs: 2200psi and 4500psi. Specifications for these two compressed gas cylinders are shown below in Table 5.2.

Manufacturer	Pressure	Capacity (H2 STP)	Weight	Cost
Cyl-Tec, Inc.	2200 psi	2290 gallons	114 lbs	$148
Cyl-Tec, Inc.	4500 psi	4720 gallons	148 lbs	$315

Table 5.2. : Specifications of Compressed Gas Cylinders. (Cyl-Tec 2003)

5.3. Gas Booster for Hydrogen Storage System

A gas booster is a device that increases the pressure of a gas, but runs on compressed air instead of electricity. A gas booster has been chosen because it is the only commercially available option for safe and inexpensive hydrogen gas compression. Max-Pro Technologies is the only manufacturer of small gas boosters than can safely compress hydrogen. A photo of a Max-Pro Gas Booster is shown in Figure 5.3. The Max-Pro DLE5-30 (Cyl-Tec 2003) has been chosen as the booster to provide hydrogen gas at 2200psi, and the Max-Pro DLE15-75 (Cyl-Tec 2003) has been chosen as the booster to provide hydrogen gas at 4500psi. Specifications for these two gas boosters are shown below in Table 5.3.a.

Figure 5.3. : Max-Pro Gas Booster

(Maximator Air Driven 2003)

Specifications of Max-Pro Gas Boosters.

Gas Booster	H2 inlet pressure min.	H2 inlet pressure max.	H2 outlet pressure max.	Weight	Cost
Max-Pro DLE5-30	30 psi	120 psi	4640 psi	50 lbs	$3,500
Max-Pro DLE15-75	100 psi	360 psi	10000 psi	50 lbs	$4,500

Table 5.3.a. : Specifications of Max-Pro Gas Boosters. (Maximator Air Driven 2003)

The flow rate at which a Max-Pro gas booster can provide compressed hydrogen gas depends on three pressures: 1) the inlet hydrogen gas pressure (low pressure), 2) the outlet hydrogen gas pressure (high pressure), and 3) the air inlet pressure used to run the gas booster. Graphs (see Appendix D.1) and charts (Maximator Air Driven page 6) can be used to determine the compressed hydrogen gas flowrate. Max-Pro Technologies has provided the flowrates that result from our choice of electrolyzer (which determines inlet hydrogen gas pressure), compressed gas cylinder (which determines outlet hydrogen gas pressure), and air compressor (which determines the air inlet pressure used to run the gas booster). These flowrates are shown below in Table 5.3.b.

Outlet hydrogen gas flowrates.

H2 inlet pressure	H2 outlet pressure	air inlet pressure	H2 flowrate
90 psi	2200 psi	90 psi	2.0 SCFM
90 psi	4500 psi	90 psi	1.1 SCFM
60 psi	2200 psi	90 psi	1.5 SCFM
60 psi	4500 psi	90 psi	0.7 SCFM

Table 5.3.b. : Outlet hydrogen gas flowrates. (Soltys 2003)

5.4. Air Compressor for Hydrogen Storage System

Figure 5.4. : Coleman Powermate Air Compressor (Air Co 2003)

An air compressor is needed to supply the compressed air necessary to run the gas booster. Both gas boosters specified in Table 5.3.b. above require a minimum of 45 SCFM to operate. Most air compressors capable of producing this flowrate require 15 hp, but there is only about 4.5 hp available from the battery bank that can be used for the air compressor. In order to provide the necessary flowrate while using less electricity, the hydrogen storage system was redesigned to include a second propane tank for storage a large amount of compressed air, as shown in Figure 5.1. This tank will be filled with compressed air to a pressure of 125psi (the maximum output pressure of the air compressor). The compressed air in the tank will then be discharged into the air inlet of the gas booster (regulated at 90psi). This will allow the gas booster to run for about 3 minutes. The air compressor will have to run for about 30 minutes in order to compress this amount of air into the tank.

A Coleman Powermate Contractor Series Everyday Use air compressor has been chosen, which is shown in Figure 5.4. Specifications for this compressor are shown below in Table 5.4.

Specifications of the Coleman Air Compressor

Manufacturer	Model No.	Power Usage	Pressure Max.	Flowrate at 90psi	Cost
Coleman Powermate	CP0200312	2 hp	125 psi	4.0 SCFM	$225

Table 5.4. Specifications of an Air Compressor (Coleman 2003)

5.5. Propane Tank for Hydrogen Storage System

A propane tank will be used as an intermediate storage tank, to store hydrogen gas at the same pressure at which it is outputted from the electrolyzer, for two reasons: 1) because the gas booster and electrolyzer have different flowrates, an intermediate storage tank must be placed between them so that a pressure does not develop at the output of the electrolyzer, and 2) an intermediate storage tank allows for safe long-term storage of

Figure 5.5. : 500-gallon Propane Tank

hydrogen gas. Using a propane tank to store hydrogen is a standard procedure and has been safely done by previous projects (Marshall Mark 2002), (Illinois Institute of Technology 2003).

A 500-gallon propane tank will also be used to store compressed air in order to run the gas booster. This size tank has been chosen so that the gas booster can run for at least a few minutes. According to calculations shown in Appendix D.1, the gas booster would be able to run for about 3 minutes if a 500-gallon tank were used.

A 500-gallon American Welding & Tank propane tank has been chosen, which is shown in Figure 5.6. Specifications for this tank are shown below in Table 5.5.

Specifications of Propane Tank

Manufacturer	Capacity (H2 STP)	Weight	Cost
AWTank	3970 gallon	1000 lbs	$720

Table 5.5. : Specifications of a Propane Tank. (American Welding and Tank 2003)

5.6. Hydrogen Storage System Cost

The cost of the hydrogen storage system is shown below in Table 5.7 for both storage options.

Hydrogen Storage System Cost

Component	H2 at 2200psi	H2 at 4500psi
Compressed Gas Cylinder	$148	$315
Gas Booster	$3,500	$4,500
Air Compressor	$225	$225
Propane Tanks (2)	$1,440	$1,440
Total Cost:	$5,313	$6,480

Table 5.6. : Hydrogen Storage System Cost.

5.7. Hydrogen Storage System Maintenance Issues

All four components in the hydrogen storage system must be maintained in order to function properly. The Gas Booster and Air Compressor will require most of the maintenance because these components have moving parts that must be lubricated occasionally. Instructions for maintenance will be provided from the manufacturer of each component.

5.8. Future Development of the Hydrogen Storage System

Only the four major components described above have been specified. The hydrogen storage system will also require piping, pipe adapters, and valves to connect the components. Flashback arrestors will be required for safety reasons. In addition, it is desired that a Data Acquisition System (DAQ) will be incorporated into the system. This DAQ will record the pressure levels in the propane tank and compressed gas cylinder, and will record the power draw of the air compressor and the length of time that the gas booster and air compressor are running. This data is important to collect because it will give a more accurate estimate of future hydrogen gas production capability.

6. Control of the Renewable Energy Based Hydrogen Production System

6.1. Introduction to Control System

At the start of this project, the H2 Generation team had hoped to specify components that would completely automate the system. However, due to unexpected shifting of available efforts, the control system is at the planning stages. The H2 Generation team did scope out the control logic that needs to be implemented to effectively and safely run the system. Figure 6. below illustrates the logic that needs to be either manually implemented into the system by an operator, or needs to be programmed into a computer that will operate the system automatically.

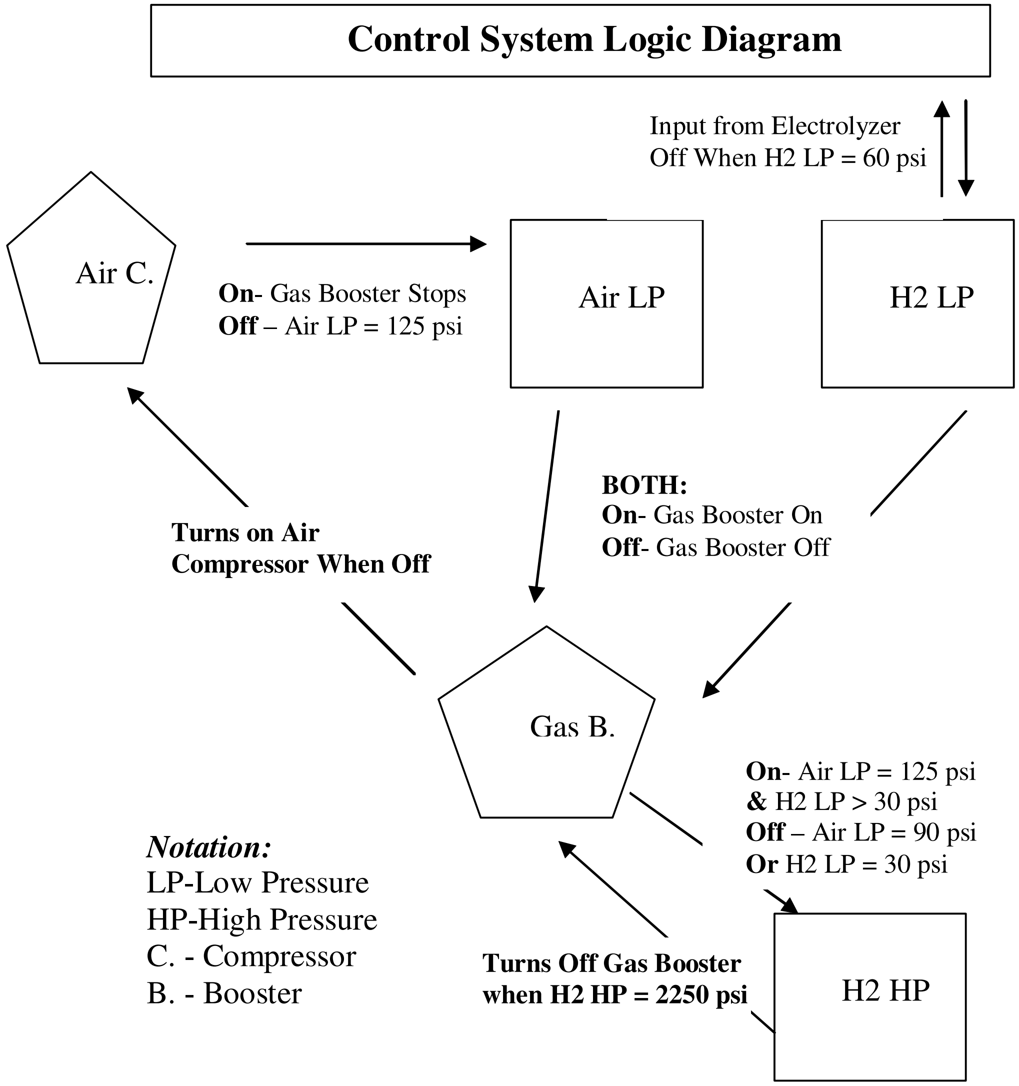


Figure 6. : Control System Logic Diagram

The above diagram describes the basic logic used in the computer simulation program. This next portion of the report will outline each components role in the control process beginning with the high-pressure hydrogen storage container.

6.2. Control of the High-Pressure Storage Cylinder

When the high-pressure container is full, the gas booster (which fills the high-pressure containers) needs to be turned to off. Again, this either can be completed manually by an operator or can be a computer operator.

6.3. Control of the Gas Booster

All of the following requirements **must** be met to turn on the gas booster:

- Air Tank >125 psi
- Hydrogen Low-Pressure > 30 psi
- Hydrogen High-Pressure Cylinder <2250

The compressed air tank needs to be completely full since it is drained to the lower limit of pressure in the process of compressing one gas booster cycle.

The hydrogen container must have above 30 psi because hydrogen is regulated into the gas booster at 30 psi. The level placed here is up to the user, and will depend on the strategy used. In the computer program, the electrolyzer was keeping up with the demand of hydrogen and thus the pressure level in the low-pressure hydrogen container never got below 30 psi. In order to keep a few gas booster cycles of reserve in case of the loss of ability to produce hydrogen for any reason 45 psi may be a good value to use.

In addition, the high-pressure hydrogen storage cylinder must be below 2250 psi in order to compress more hydrogen into it.

The gas booster will turn off when **any** of the following occurs:

- Air Tank < 90 psi
- Hydrogen Low-Pressure Storage < 30 psi
- Hydrogen High-Pressure Cylinder > 2250 psi

If any of these occurs the gas booster needs to be turned off.

When the gas booster ends its cycle, it will trigger the air compressor to refill the low-pressure air tank.

6.4. Control of the Air Compressor

The air compressor will need **all** the following to be true in order to turn on:

- Battery Banks > 30% full
- Air Tank < 125 psi

There must be energy to run the compressor and thus the batteries need to have a desired level of above 30% capacity. The air tank must also be below 125 psi because this is the rated output of the air compressor.

The air compressor will turn off when **any** of the following occurs:

- Battery Banks < 30% full
- Air Tank > 125 psi

If either of these becomes true, the air compressor will need to be turned to off.

6.5. Control of the Electrolyzer

The electrolyzer will run most of the time there is hydrogen and energy available. For the electrolyzer to turn on the following must **all** be true:

- Battery Banks > 30% full
- Hydrogen Low-Pressure Storage < 60 – 90 psi (depending on Electrolyzer 1 or 2)

There must be power available in the batteries to run the electrolyzer, and the pressure in the low-pressure container must not be above the output pressure of the electrolyzer.

If any of the following occurs, the electrolyzer will need to be turned to off:

- Battery Banks < 30% full
- Hydrogen Low-Pressure Container >60 – 90 psi (depending on Electrolyzer 1 or 2)

If the battery banks become low, or the low-pressure hydrogen tank pressure becomes higher than the electrolyzer output pressure the electrolyzer must be turned off.

7. Thermodynamic Analysis of the Renewable Energy Based Hydrogen Production System

7.1. Thermal Analysis for Hydrogen Generation and Storage

The thermodynamic analysis for the system is based on energy balances between initial states and final states of each component. The system layout includes the electrolyzer (hydrogen generator), the low-pressure hydrogen storage tank, the pressurized air tank, and the air compressor. Each component had its own governing equations and assumptions about how it worked.

7.2. Air Storage Tank Blow down: Data collected from TEST Website

http://thermal.sdsu.edu/testcenter/features/features.html

Variables:

- To = 25 C
- State 1: P = 125 psi, T = 25 C
  State 2: P = 90 psi

Assume:

- Pollytropic process n=1.3 (based on tank blow down data), adiabatic, neglect KE and PE
- Mass = m1-m2 = 4.525 kg

Polly Tropic Process: T2= T1 *(P2/P1) ^ (n-1)/n

Variables:

- Fixes T2 @
- T2 = 281.2 K
- ΔS for ideal gas: =cp*ln(T2/T1)-R*ln(P2/P1)
- ΔS = .01398 KJ/Kg
- ΔS*m = .0632595 KJ
- Ed = To*ΔS
    - **Ed = 18.85 KJ**

7.3. H2 Storage Tank Blow down: Data collected from the TEST website

http://thermal.sdsu.edu/testcenter/features/features.html

Variable:

- To = 25 C
- State 1: P = 60 psi, T = 25 C
  State 2: P = 30 psi

Assume:

- Polly tropic process n=1.3, adiabatic, neglect KE and PE
- Mass = m1-m2 = .26378 kg

Polly Tropic Process:

- T2= T1 *(P2/P1) ^ (n-1)/n
- Fixes T2 @
- T2 = 253.9 K
- ΔS for ideal gas: =cp*ln(T2/T1)-R*ln(P2/P1)
- ΔS = 1.956 KJ/Kg
- ΔS*m = .5161 KJ

- Ed = To*ΔS
  - **Ed = 153.8 KJ**

7.4. Compressor Efficiency

Work consumed by compressor 1.5 kW

Isentropic Efficiency: η = (h2s – h1) / (h2-1)

Assumptions: Adiabatic, Neglect KE and PE, SSSF,

First Law:

- Wc = m*(Δh)
- State 1: air @ Standard Temperature and Pressure
- State2: P2 = 125 psi
- Using first law:
- h2 = 1.5kW / m - h1

Flow rate = 4 CFM @ STP

4CFM = .1133 m^3/min * 1min/60s = .00188 m^3/kg

Density of air = 1.23 kg/m^3

Mass = 2.3124 E-3 kg

- h2 = 970.8 kJ/kg
- η = (h2s – h1) / (h2-1)
- **η = 37.53 %**
- Ed = To*ΔS: To = 25C
- ΔS = 2.275 kJ/kg K – 1.696kJ/kg K
  - **Ed = 172.6 KJ**

7.5. Electrolyzer Calculations

Assume: Steady state steady flow

State 1: Water at standard temperature and pressure
State 2: Hydrogen at 90psi

For this analysis, we compared the energy going into the system to the out put energy stored as hydrogen. The thermal efficiency is defined as the desired state divided by what it costs to provide the desired state, i.e. what you want over what you pay.

Want: Hydrogen at 90 psi:

- 1 kg of hydrogen = 119,600 kJ, The Lower heating value of the hydrogen fuel.
- Mass = 13.5E-6 kg/s *(3600s/1h) = 48.62E-3 kg/h

- Electrolyzer runs at 600 Watts/cell with 3 cells = 1800 watts = 1.8 kW
- 1.8 kJ/s * (3600s/1h) = 6480 kJ/h

- How many hours for 1 kg of H2:
- 1kg / 48.62E-3 kg/h = 20.567 hours

Pay:

- Electrolyzer: 6480 kJ/h * 20.6 h = 133,274 kJ

- η =Want / Pay = 119600 kJ / 133,274 kJ
- η = .897

7.6. Thermodynamic Conclusions

The thermodynamic analysis has demonstrated that the least efficient process in the overall hydrogen generation system is the hydrogen compression process. All of the components could have higher efficiencies in the future as technology develops, but the hydrogen compression process could easily be improved by eliminating the need to compress air to run a gas booster.

8. Computer Simulation of the Renewable Energy Based Hydrogen Production System

8.1. What the Simulation Entails

What the simulation entails is an Excel program that models the productivity of H2 Generation's hydrogen production facility as if it were installed and running in the year 2000. Refer to Appendix G for additional information on the simulation.

8.2. The Variables of the Simulation

The simulation's use is to find the amount of hydrogen that would have been produced in the year 2000 if the system had been installed and running. Since hydrogen production is directly correlated to how much renewable energy is collected, then to know how much hydrogen would have been produced in the year 2000, the incoming renewable energy must be known. The third incoming variable is water collection, which as listed in Appendix B.1. This is approximately 40 gallons per year to meet our client requirements. In section 2.6. it was found that over 10,000 gallons of water per year are going to fall on the "Solar

Shack" roof. The water collection was ignored for the simulation, due to abundance. Thus, the two main variables in the simulation are the renewable energy inflow and the hydrogen produced.

8.3. The Assumptions of the Simulation

The variable of inflow renewable energy is from photovoltaic cells (solar) and the 1.5kW Bergey wind turbine. The needed solar information was locally collected in 15 minute increments for everyday in the year 2000 (RERC 2003) in the form of energy density, power per area. Recalling the renewable energy calculations (See Appendix A), solar accounts for approximately 98.5% of renewable energy inflow, and thus the simulation ignores energy incoming from the wind turbine (approximate energy in from wind turbine is 1.5%).

The renewable energy calculations also had a "shading factor", to avoid this shading factor the simulation only has energy incoming from the hours of 9:00 AM to 4:00 PM. The reason H2 Generation chose to avoid shading for the simulation is due to do the surrounding trees and the random variable of tree height in a given year. By not calculating energy inflow during times of possible shading the possible photovoltaic cell string shut-down is not a concern (RERC 2003).

8.4. How the Simulation Works

First, the energy inflow from renewable sources is calculated from the energy density (RERC 2003). Next, the components of electrolysis (and the hydrogen tank), and air compression (and the air tank) are analyzed for their respective energy draw. The energy draw is controlled by a logical structure that controls when each of the energy-drawing components needs to be on or off.

Recalling the system layout, the renewable energies charge a battery bank. The logical structure tests the production system to make sure that all components are over their lower limits: the battery bank (20% lower limit), the hydrogen tank (limit of five hours to refill), and the air tank (limit of a half hour to refill).

The upper limit is as follows: the battery bank is full, the hydrogen and air tanks are full. If the logical structure finds that the battery bank, hydrogen tank, and air tank are above their lower limit, then the logic "cycles". When a cycle is completed, hydrogen and air are used from their respective tanks and the hydrogen is compressed. After a cycle, a "time to refill" is added to each of the tanks. This "time to refill" means that a particular component needs to run a certain time until it reaches its upper limit, then the logic structure can turn the energy supply off to that component. Once all components are ready for another cycle, the logic structure tests each of the components for the requirements (above lower limit) and cycles again. This process takes place numerous times each day for all 366 days of the year 2000. Refer to Appendix G for a full explanation of the simulation process.

8.5. The Results

The simulation found a conservative value of 84,033 gallons of hydrogen at STP would be produced if the system were installed and running in the year 2000. This exceeds our client requirement by a factor of 1.75. The renewable energy collected to create this hydrogen was found to be 9,378 kWh.

9. Demonstration of Concept Model Summary

9.1. Purpose of Demonstration of Concept Model

Through client interactions, H2 Generation determined a need for a demonstration of concept model for use in promotion of the project. This model can be used in demonstrations of the project. In addition, there is the possibility for study of the energy flow though the model for use as an educational tool.

9.2. Components of the Demonstration of Concept Model

The model consists of all the major portions of the "System Component Layout" illustrated in Figure 1.5. There are battery banks, storing electrical energy. Figure 9.2. below is a photograph of the model.

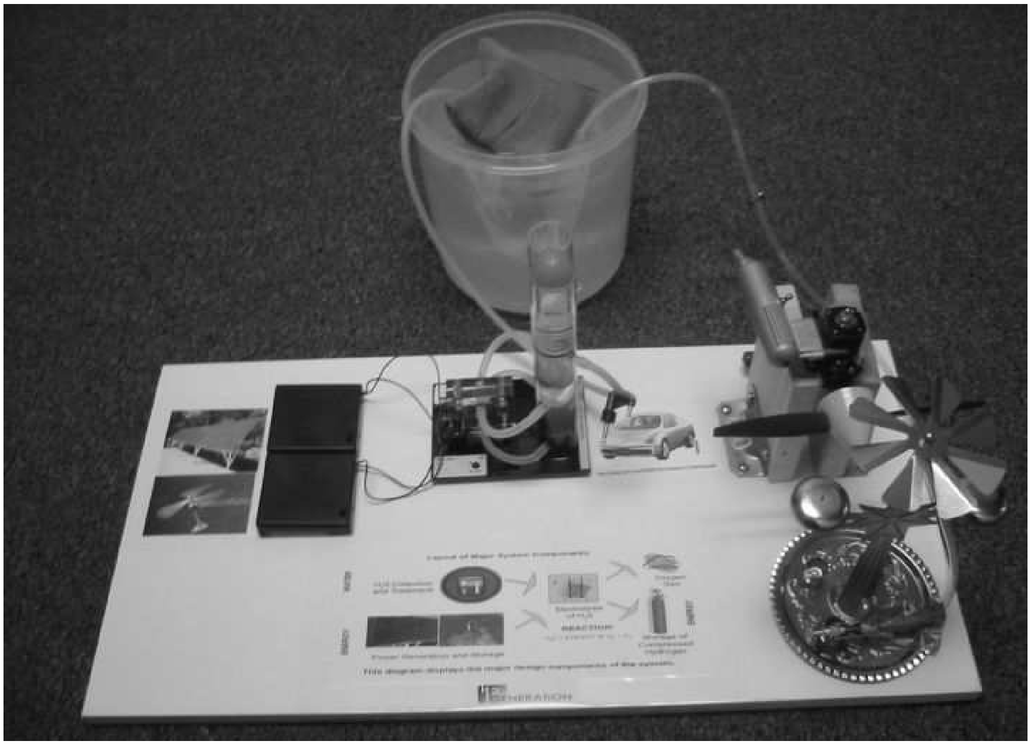


Figure 9.2. : Photograph of Demonstration of Concept Model

A small electrolyzer generates hydrogen using small fuel cell. There is a hydrogen container made out of Tupperware containers. The last portion of the model is a portion that demonstrates hydrogen's capability to do work. Initially a small radio aircraft engine was going to be used, but the team was unable to convert the air-fuel mixing system over to a gaseous fuel. As consolation to this initial idea, a small fan turned by natural convection from candle flames was used. Hydrogen is burned using a nozzle and the heat from the nearly invisible flame spins the fan.

9.3. Cost of the Demonstration of Concept Model

The cost of the model totaled to less than half of the allowance of $1000 for the design and modeling process. The cost is broken down in Table 9.3. below.

Breakdown of the Model Cost

Electrolyzer	$160
Engine	$70
Miscellaneous Costs	$30
Total Cost	**$260**

Table 9.3. : Model Cost Breakdown

10. Projected Cost of the Renewable Energy Based Hydrogen Production Project

Each of the major systems that make up the comprehensive renewable energy based hydrogen production project has been detailed in prior sections. This section tabulates the entire system costs into the two different electrolysis purities (See Tables 10. below).

System I Design Projected Cost (99.999% purity)

Water Collection and Treatment	$725
Electrolyzer	$19,802
Hydrogen Storage	$5,405
Total:	$25,932

Table 10.a. : Materials cost of System I.

System II Design Projected Cost (99.5% purity)

Water Collection and Treatment	$725
Electrolyzer	$6,378
Hydrogen Storage	$5405
Total:	$12,455

Table 10.b. : Materials cost of System II.

11. Recommendations & Conclusions for the Hydrogen Production Facility Project

11.1. Recommendations for the Hydrogen Production Facility

H2 Generation has the following recommendations:

- Collect onsite solar radiation and wind speed data for more exact analysis. H2 Generation's computer simulation is based on local data, but not exact data collected at the Solar Shack. This could provide a more accurate simulation of the system's behavior.

- The hydrogen compression method is an inefficient process. Between the time of the design and building of the system, further technology may become available. It is recommended to stay abreast of current technologies in hydrogen compression.

- Since the hydrogen compression process has been found to be under-developed for the scale of this project, a future Capstone Design Project may be to find a more efficient method of compression.

11.2. H2 Generation Hydrogen Production Project Conclusions

H2 Generation has designed a Renewable Energy Based Hydrogen Production Facility to be located at the "Solar Shack" behind the College of Engineering and Technology Building.

The major results of H2 Generation's work are a full-scale system design, cost estimate, and estimate of the actual hydrogen production capabilities. To meet requirements, two different systems have been designed: a system for fueling a fuel cell costs $26,000, and a system for internal combustion use costs $12,500. Based on the simulation that proves feasibility each proposed system will supply at least 1.75 times the hydrogen required to fuel a Formula 1 racecar for 600 miles a year.

Each system includes renewable energy and precipitation collection, battery and water storage, water treatment, hydrogen production through electrolysis, and compressed hydrogen storage.

11.3. H2 Generation Deliverables Summary

The completed deliverables agreed upon in the project proposal include the following: a specified full-scale design incorporating requirements, maintenance requirements for each component, a thermodynamic analysis, a simulation proving feasibility, a demonstration of concept model, and a website.

The deliverables not completed include the following: data acquisition and control system for the full-scale design, life cycle analysis of each component, and environmental impact analysis on each component.

11.4. Closing Remarks

H2 Generation advocates the full-scale construction of our designed Renewable Energy Based Hydrogen Production Facility. The construction of this facility will demonstrate the feasibility of a renewable energy based hydrogen-refueling station.

In addition, the project will pave the way for future projects focused on preserving and improving the health of our planet. In his 2003 state of the union address, President George W. Bush has indicated that hydrogen is the fuel of the future:

"A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car, producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."

Appendix A. Renewable Energy, Battery Bank, and Precipitation Analysis

Appendix B. Water Collection and Storage System

B.1 Calculations Required for the Water Collection and Treatment System

B.1.1. Water Required*

Assumptions:

1. 35 mpg vehicle
2. 50 miles required/month

50 miles/month * 12 months = **600 miles**

600 miles * 1gal./35 miles = 17.14 gal. Gasoline

17.4 gal. Gasoline * 8890 gal. H_2 gas/ 3 gal. Gasoline = 50,800 gallons H_2 gas

50,800 gallons H_2 gas * 1 gal. water/ 1300 gallons H_2 gas ~ = **<u>40 gallons water/Year</u>**

*Energy content information obtained from:
Bartok, William Sarofim, Adel. *Fossil Fuel Combustion.*
New York: Wiley, 1991.

B.1.2. Gallons of Water → Gallons of H_2 gas @ STP*

- Take ratio of molecular weights of H_2 and H_2O.

1 part H_2 / 9 parts H_2O ~ = .11

- Find weight of H_2 in one gallon of water. Convert to m^3.

.11 * **<u>1 unit H_20</u>** = .11 units H_2

- Multiply by the mass density of H_2O and divide by mass density of H2

.11 units H2 *(999 kg/m^3) / (0.084 kg/m^3) ~ = **<u>1300 units H2 gas</u>**

*Densities and conversions obtained from:
Munson, Young, Shapiro. *Fundamentals of Fluid Mechanics.*
New York: Wiley, 1990.

B.1.3. Confirmation of Gallons of Water → Gallons of H_2 gas @ STP*

From David Seo, UCB, Berkeley:
Using Molar Equivalency:
1 gallon H_20 = 1243.5 gallons H_2 Gas @ STP

This is very close to the calculation in B.1.2. The difference is due to an estimation of the desity of water and of hydrogen at STP. (See PHYS LINK 2003, Works Cited).

B.1.4. Matching Flowrate of Electrolyzer

72 L H2 / hour * (1 L H2)/(1300 L H2O) * 8 hours run/ day = **<u>0.44 L H2O / day</u>**

Appendix C. Hydrogen Generation and Purification System

Appendix D. Hydrogen Storage System

D.1 Calculations for the Hydrogen Storage System

Volume (at STP) and Mass of air in Air Tank:

At maximum pressure (125psi):

$$v_i = \frac{p_f v_f}{p_i} = \frac{(125psi)(500gal.)}{(11.5psi)} = 5434.8gal. \times \frac{.0037855m^3}{1gal.} = 20.57m^3$$

$$m = \frac{pV}{RT} = \frac{(11.5psi \times \frac{6894.8Pa}{1psi})(20.57m^3)}{(287kJ/kgK)(300K)} = 18.95kg$$

At minimum pressure (90psi): $$v_i = \frac{p_f v_f}{p_i} = \frac{(90psi)(500gal.)}{(11.5psi)} = 3913.0gal. \times \frac{.0037855m^3}{1gal.} = 14.81m^3$$

$$m = \frac{pV}{RT} = \frac{(11.5psi \times \frac{6894.8Pa}{1psi})(14.81m^3)}{(287kJ/kgK)(280K)} = 14.61kg$$

Mass and Volume (at STP) of air going into the Gas Booster in one cycle:

$$m = 18.95kg - 14.61kg = 4.33kg$$

$$V = \frac{mRT}{p} = \frac{(4.33kg)(287J/kgK)(300K)}{(11.5 \times \frac{6894.8Pa}{1psi})} = 4.70m^3 \times \frac{35.31ft^3}{1m^3} = 166.0ft^3$$

Time the Gas Booster would run in one cycle:

$$166.0 ft^3 \times \frac{1 \min.}{50 ft^3} = 3.3 \min.$$

Time for the air compressor to fill back up:

$$166.0 ft^3 \times \frac{1 \min.}{4 ft^3} = 41.5 \min.$$

Volume of hydrogen gas (at STP) that would be compressed in one cycle:

$$3.32 \min \times \frac{2.0 ft^3}{\min.} = 6.64 ft^3$$

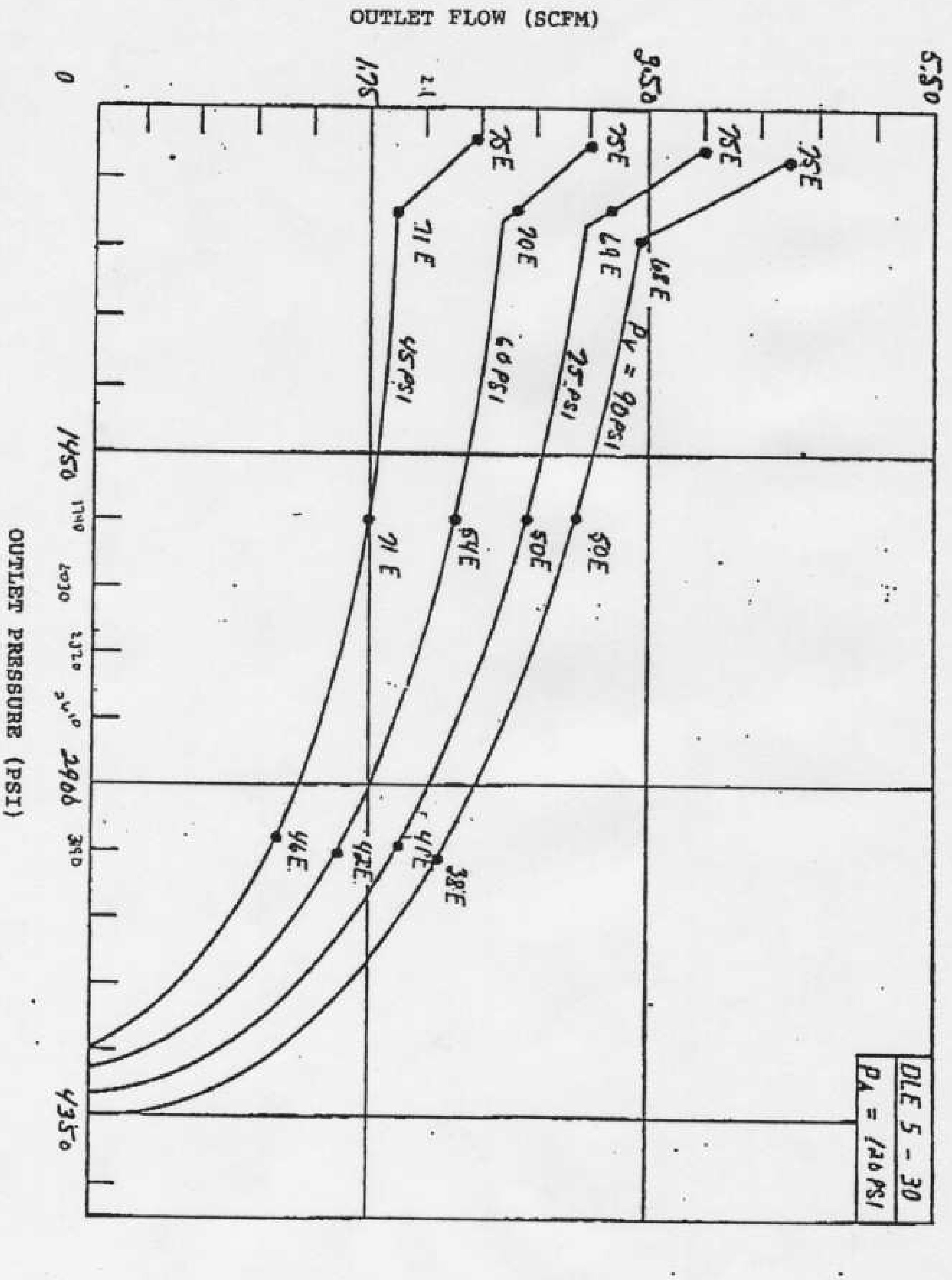
Time to compress a month's supply of hydrogen gas:

$$4000 gal. \times \frac{.1337 ft^3}{1 gal.} = \frac{534.8 ft^3}{6.64 ft^3} \times (41.5 \min.) = 3342.5 \min. \times \frac{1 hr.}{60 \min.} = 55.7 hr.$$

Electricity used by air compressor to compress a month's supply of hydrogen gas:

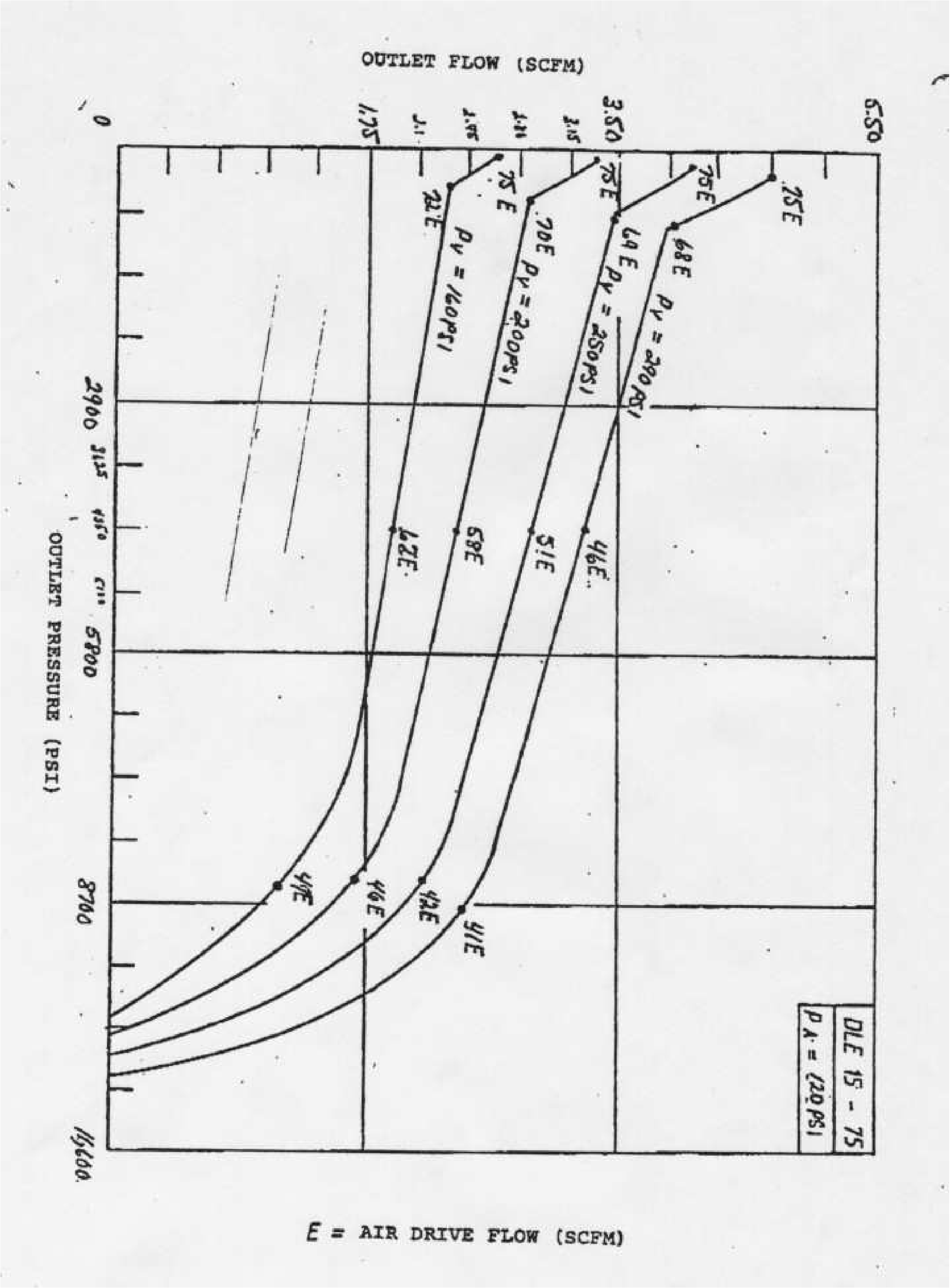
$$2 hp \times \frac{.7457 kW}{1 hp} \times 55.7 hr. = 83.1 kWh$$

D.2. Hydrogen gas output flow rates for the Max-Pro DLE5-30 Gas Booster [7]



E = AIR DRIVE FLOW (SCFM)

D.3. Hydrogen gas output flow rates for the Max-Pro DLE15-75 Gas Booster [7]



E. Miscellaneous Cost Analysis

Miscellaneous Cost Analysis

Water Collection and Storage System

Shelving Installation: Water Filtration

Materials	Cost	
Shelves	$100.00	
Hardwear	$50.00	
Installation	$40.00	$20/h @ 2 hours
Total:	$190.00	

Electrolizer Modifications: System Design II Welded Fittings

Welder	$152.00	$38/h @ 4 hours
Electrician	$76.00	$38/h @ 2 hours
Total:	$228.00	

Hydrogen Storage System: Welded Fittings for Leak Protection

Welder	$114.00	$38/h @ 3 hours
Total:	$114.00	

Costs Estimated Based on NAU wages for welding, electrical, and general maintenance.

F. Demonstration of Concept Model Manual

F.1. Purpose of Demonstration of Concept Model

Through client interactions, H2 Generation determined a need for a demonstration of concept model for use in promotion of the project. This model can be used in demonstrations of the project. In addition, there is the possibility for study of the energy flow though the model for use as an educational tool.

F.2. Components of the Demonstration of Concept Model

The model consists of all the major portions of the "System Component Layout" illustrated in Figure 1.5. There are battery banks, storing electrical energy. Figure F.2. below is a photograph of the model.

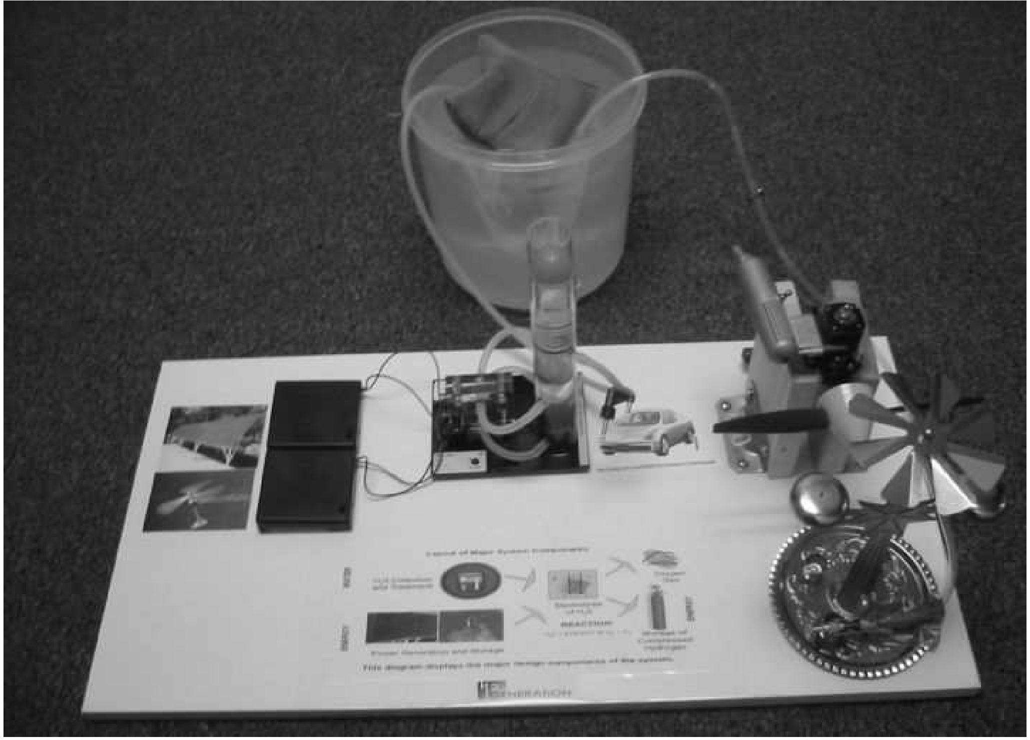


Figure F.2. : Photograph of Demonstration of Concept Model

A small electrolyzer generates hydrogen using a small fuel cell. There is a hydrogen container made out of Tupperware containers. The last portion of the model is a portion that demonstrates hydrogen's capability to do work. Initially a small radio aircraft engine was going to be used, but the team was unable to convert the air-fuel mixing system over to a gaseous fuel. It is encouraged by H2 Generation that a future user works on the engine conversion.

As consolation to this initial idea, a small fan turned by natural convection from candle flames was used. Hydrogen is burned using a nozzle and the heat from the nearly invisible flame spins the fan.

F.3. Cost of the Demonstration of Concept Model

The cost of the model totaled to less than half of the allowance of $1000 for the design and modeling process. The cost is broken down in Table F.3. below.

Electrolyzer	$160
Engine	$70
Miscellaneous Costs	$30
Total Cost	**$260**

Table F.3. : Model Cost Breakdown

F.4. Operation of the Demonstration of Concept Model

The operation of the demonstration of concept model is comprised of a few main part including: Batteries, Electrolyzer, Tupperware Storage, and the Convection Fan. In addition to the operating instruction written here, there is an owner's manual for the electrolyzer and the engine supplied with the model itself.

F.4.1. Battery Operation

The batteries required to run the electrolyzer are 8 AA batteries. Two separate battery packs place 4 AA batteries in parallel. The electrolyzer will run with only one of the packs turned on, but the hydrogen flowrate will be slower.

The batteries will run the electrolyzer for about ten minutes before getting hot and becoming ineffective. When this occurs, the electrolyzer should be turned off or batteries should be replaced.

F.4.2. Electrolyzer Operation

The electrolyzer requires 1.5 volts to operate properly. If more than 1.5 volts is connected to the electrolyzer, it will burn electrical components. The electrical power to the electrolyzer needs to connected to the proper terminals. This means the positive battery terminal needs to connected up to the positive (Oxygen) side of the electrolyzer. The negative battery terminal needs to be connected to the negative (Hydrogen) side of the electrolyzer.

The water supplied to the model needs to be only distilled water or deionized water. Other water will cause the unit to corrode.

F.4.3. Tupperware Storage Operation

In order to store hydrogen safely in the container there cannot be any oxygen or air in the container. To empty the container of air, the water level in the larger outer container needs to be higher than the smaller inner container and all air must be bled out of the nozzle-ended hose. Once all of the air is bled from the system it is ready to be filled.

To fill up the Tupperware storage container the hydrogen side of the electrolyzer water tower must be plugged. For the purposes of presentation, a rubber “bouncy ball” was used. Once the tower is plugged, the electrolyzer should be turned on and the clamp hooked to the hose feeding into the Tupperware container should be open.

The hose feeding the nozzle must be clamped to prevent the escape of hydrogen.

F.4.4. Operation of the Convection Fan

To operate the convection fan, two steps need to occur. The clamp blocking flow into the nozzle needs to be opened and the hydrogen escaping the nozzle must be lit on fire using a lighter.

To stop the flame the clamp on the nozzle-ended hose must be clamped. This should be done before the hydrogen tank is completely empty of hydrogen to avoid sucking water through the nozzle.

F.5. Trouble Shooting Demonstration of Concept Model

Electrolyzer does not flow:

Possible Problems:

- Batteries dead
- Use of non-purified water deteriorated fuel cell
- Too much voltage damaged electronics

Hydrogen will not flow into Tupperware:

Possible Problems:

- Hose feeding Tupperware Clamped
- Electrolyzer water tower is not plugged and pressure is not built up

Hydrogen will not flow out of Tupperware:

Possible Problems:

- Tank Empty
- Hose feeding nozzle is clamped
- Not enough water in larger outer Tupperware tank to force hydrogen out

Hydrogen will not light on fire:

Possible Problems:

- Oxygen in tank due to switching electrodes or switching hoses to water towers.

- No hydrogen exiting tank

Tupperware Tank Exploded:

Possible Problems:

- Hydrogen-air mixture in the tank, did not evacuate air fully

Appendix G. How to Understand and Function the Simulation

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