Hydrogen Production Using Solar Energy

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Abstract

The objective of this project is to create *clean fuel for transportation* using hydrogen powered by solar energy. Hydrogen has been generated by solar photovoltaic (PV) array and then collected for data analysis to demonstrate efficiency of the hydrogen production in all the steps of the experiment. The hydrogen produced from the electrolysis process was either stored in a metal hydride canister or directly fed into Proton Exchange Membrane (PEM) Fuel Cell to generate electricity. A hydrogen fuel cell remote control car has successfully designed, and demonstrates at least one hour operation per hydrogen charging at room temperature.

Keywords: Solar Energy, Hydrogen Production, Electrolysis, PEM Fuel Cell, Clean Fuel Transportation, Hydrogen Storage, Metal Hydrides, Electrolyzer, Energy Efficiency.

1. Introduction

Looking back in to history, it is clear that renewable energy research has received the greatest quantity of funding during the gas price or availability crises[1]. The main source of energy for 150 years has been fossil fuels, e.g. petroleum. However, the world is running out of this source rapidly and there are detrimental effects of its use e.g. pollution and economic impact[2]. A source without the dangerous by-products (greenhouse gases like CO_2, CO, HC etc.) that is available at all times and renewable is needed: the answer is "*hydrogen*" energy; the purpose of this work is to supply clean energy to a remote control car. The system shows that water electrolysis, powered by solar energy, creates hydrogen[3]. This chemical energy then can be converted into mechanical energy to power a remote control car. The hydrogen can then be stored or transported. In this cycle, hydrogen is an energy carrier, which allows storage and transportation of inexhaustible solar energy[4].

Petroleum has been a great resource and is widely used in many applications, like transportation and stationary generation of electricity. Many of these applications are of huge importance to the world. However, dependency on petroleum is a big problem for society because it is a non-renewable and polluting source. Since petroleum is non-renewable, it will deplete in only a matter of time. So the big question is "*What will the world use for transportation or distribution when petroleum runs out*?"

As mentioned above, petroleum is one of the most significant and important resources for transportation. Nowadays, most means of transportation use petroleum, such as cars, airplanes, motorcycles, and boats[5]. Engineers and scientists have been working hard trying to find other sources of energy that they can use to replace petroleum. The world has many renewable resources such as solar, wind, rain, tides and geothermal heat which are naturally replenished. The technologies associated with these natural energies are solar power, wind power, hydroelectricity, biomass and biofuels for transportation purposes. Natural energy can help alleviate the world's petroleum shortage. There have been a few new developments such as the electric car and the solar powered car. Solar hydrogen fuel cell cars are one of the newest developments in progress today[6].

Hydrogen is a renewable source without hazardous byproducts. More importantly, hydrogen is a source regenerating fuel; it can be produced from water, intermediately stored, and finally used in either internal combustion engines or fuel cells to burn back to water. It is believed that if hydrogen solar cars are successfully developed and deployed; it will represent a huge milestone for renewable energies and the world will be safe from the ever threatening global warming effect[7-9]. It will be energy efficient with the advantage of storing hydrogen reversibly in solid state materials, e.g. metal hydrides, carbon nanotubes, polymers and chemical complexes[10].

2. Experimental Investigations

Two important components of this project are (i) photovoltaics (PV) and (ii) electrolysis. A total of thirteen solar panels (arrays) are utilized for this present study[11]. The first array has 117 modules with each angled at 5 degrees. The second array has 130 modules with each angled at 15 degrees. The third one has 130 modules with each angled at 25 degrees. For this project, solar PV in array #1 was used to get the best performance for the production of hydrogen and oxygen. Additionally, array #1 provided an easy access for connection because it was designed for direct current, utility grid interconnection, capable of delivering a 41.6A max current and 240V max voltage. For this particular project, only one solar PV of array #1 was utilized to produce 23V max voltage and 3A max current.

Electrolyzers on the other hand, are the other main components of this particular design for producing hydrogen. An electrolyzer uses a solid polymer electrolyte to transfer protons and water. When combined with catalysts, a membrane–electrode assembly is formed. Then power is supplied by a source such as solar photovoltaic. The electrolyzer then decomposes water and produces hydrogen and oxygen gases. The system converts water into gaseous hydrogen and oxygen using electrolysis, creating heat with no hazardous by-products as represented by the overall chemical reaction[3] $2H_2O + \textit{Electrical Energy (from Solar PV)} \rightarrow 2H_2 + O_2$.

To obtain hydrogen by this mechanism, six electrolyzers were placed in series as shown in Figure 1. These electrolyzers are capable of utilizing various electrical sources such as solar, hydro, turbine, etc. to produce hydrogen and oxygen. Hydrogen can be used to power fuel cells and oxygen can be released back in to the atmosphere. In this particular experiment, hydrogen was used to power a remote control car.

Figure 1: Hydrogen production set up using solar PV electrolysis

After creating hydrogen from the solar PV, the hydrogen car was designed and built without using conventional batteries. The fabrication of the car began by calculating the potential voltage and current required to power the remote control car. It was determined that the car would power at 6 volts and 2 amps. These calculations helped to determine that a fuel cell which generates at least 12 watts of power was needed. Horizon Fuel Cell Technologies[12] in Singapore had exactly what the design required and was able to ship the hydrogen fuel cell kit at a short notice. The current-voltage (I-V) characteristics of the fuel cell are shown in Figure 2.

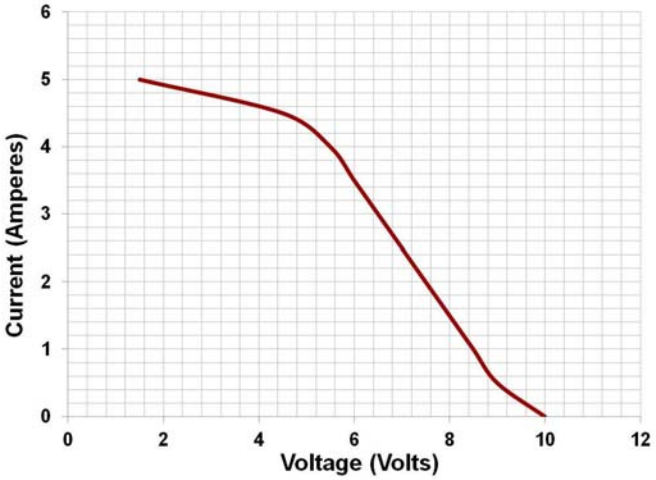

Figure 2: Current-Voltage (I-V) characteristics of the PEM Fuel Cell (Courtesy: Horizon Fuel Cell Technologies)

The second step was to design a fluid system that could transfer hydrogen from a high pressure tank to low pressure (metal hydride) tank. Swagelok[13] coupling devices (Figure 3(a)) made of stainless steel that could withstand high pressure over 5000 psig were used to do this. These devices are also capable of transporting flammable gases such as hydrogen. This particular design could withstand high pressures (pre-tested with 300 psig), but even with high pressure viability, safety was still an important factor when experimenting with such flammable gases.

The third step was to activate the metal hydride tanks (20L standard). Each tank contains 100 grams of a metal hydride (e.g. $LaNi_5$ type) that acts as a sponge for hydrogen sorption after it is activated. To activate this metal hydride, the tanks were connected to the fluid design. Then the low pressure regulator was set to 30 bar (435 psig). After waiting 80 minutes, the pressure was released to about 10 bar (100 psig) and increased the hydrogen pressure back to thirty bars. This process was repeated four times. After activation was complete, the tanks were refueled and reconnected to the fluid system with the low pressure reading set to 30 bars. After 30 minutes of leak testing (see Figure 3(b)), each tank was disconnected.

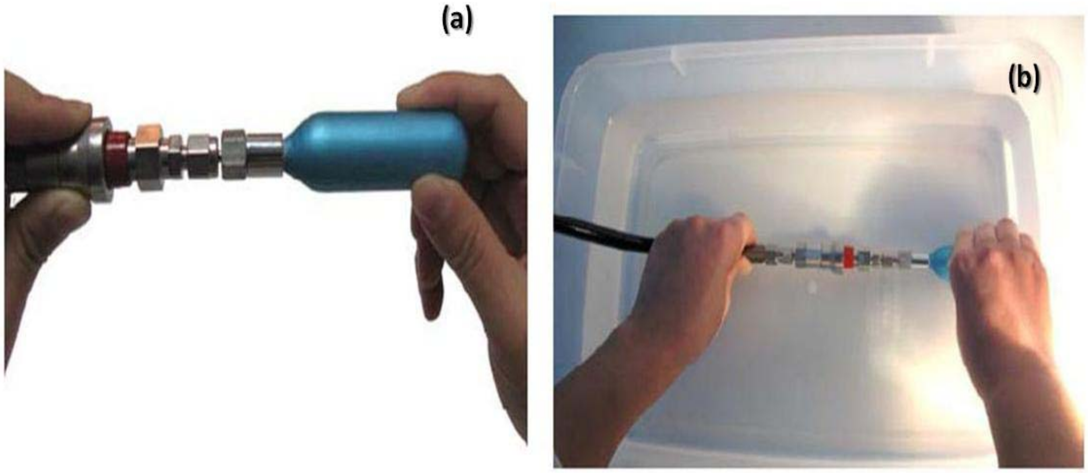

Figure 3: (a) Metal hydride canister connected to high pressure H_2 tank via Swagelok coupling; (b) Metal hydride canister leak testing with high H_2 pressure charging.

Finally the remote control car would be tested by connecting the hydrogen fuel cell to the car. The car was successfully demonstrated and ran just as a battery power remote control car would have (see Figure 4). Also, it was observed that the hydrogen fueled car lasted for about 1 hour while the battery powered car lasted only 30 minutes with six AA batteries (9V).

Because the average voltage output of this fuel cell is 6V, it does not meet the full requirement for this car and causes it to run slower. To run this car adequately, a better fuel cell with output of 9 V should be used or 3 more volts should be added to the fuel cell.

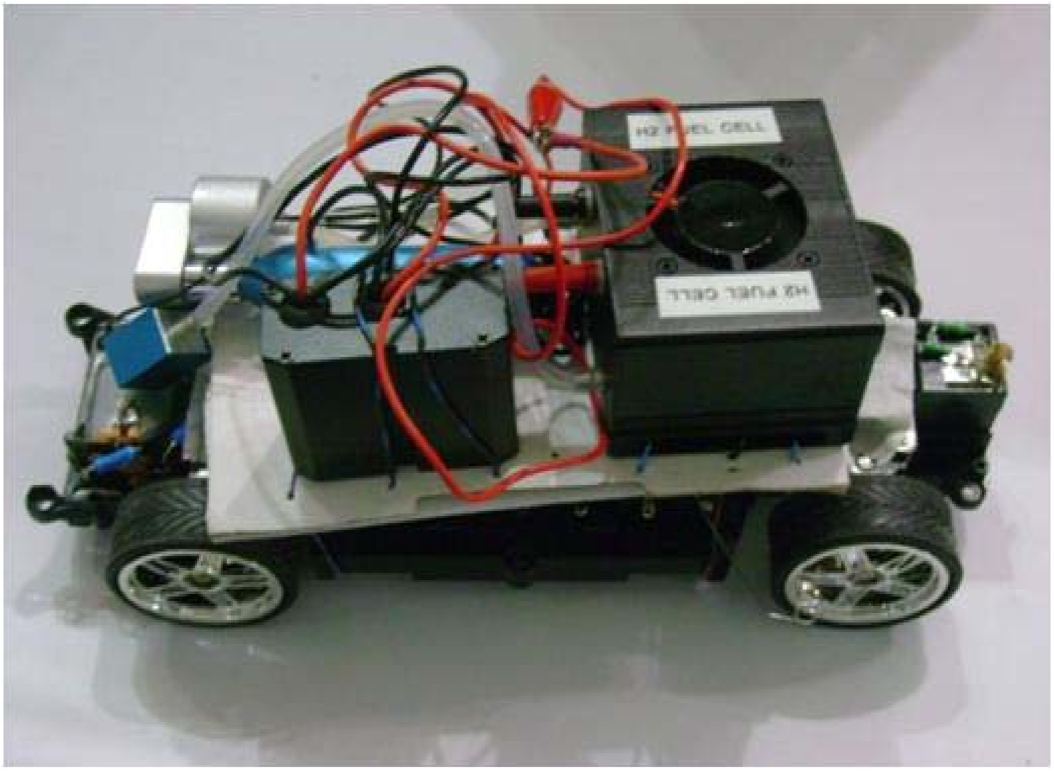

Figure 4: Hydrogen from metal hydride canister-Fuel Cell[14] remote control car

In our experiment, we tried to generate the remaining 3V using modular solar panel. By adding this solar panel to the fuel cell in series, theoretically the problem should be solved and the car should run satisfactorily. However, this did not work in practice. So, we added a 3V battery and the car worked perfectly. The resulting conclusion was that the car needed a continuous power supply to work properly. (There were minor problems with producing an adequate flow rate from the H_2 tanks. To produce a constant flow rate of H_2, the metal hydride tank needed to have more heat (since hydrogen release from metal hydrides associated with endothermic process) but the H_2 was causing the tank to become cooler so an adequate ambient temperature was difficult to achieve.

3. Results and Discussion

Total hydrogen amount and flow rate could be determined by the volumetric water displacement method as shown previously in Figure 1. Hydrogen production flow rate was recorded every 50 ml until 1 L was reached. Six separate trials were done to assure accuracy. The rate of hydrogen production with time is shown in Figure 5. In addition, at each 50ml data point, voltage provided from the solar panels was calculated as well as the current and time. This data was used to illustrate the relationship between the voltage, current and power of the fuel cell and is depicted in Figure 6. Next, efficiency was calculated by determining the amount of hydrogen generated from a gallon of de-ionized (DI) water.

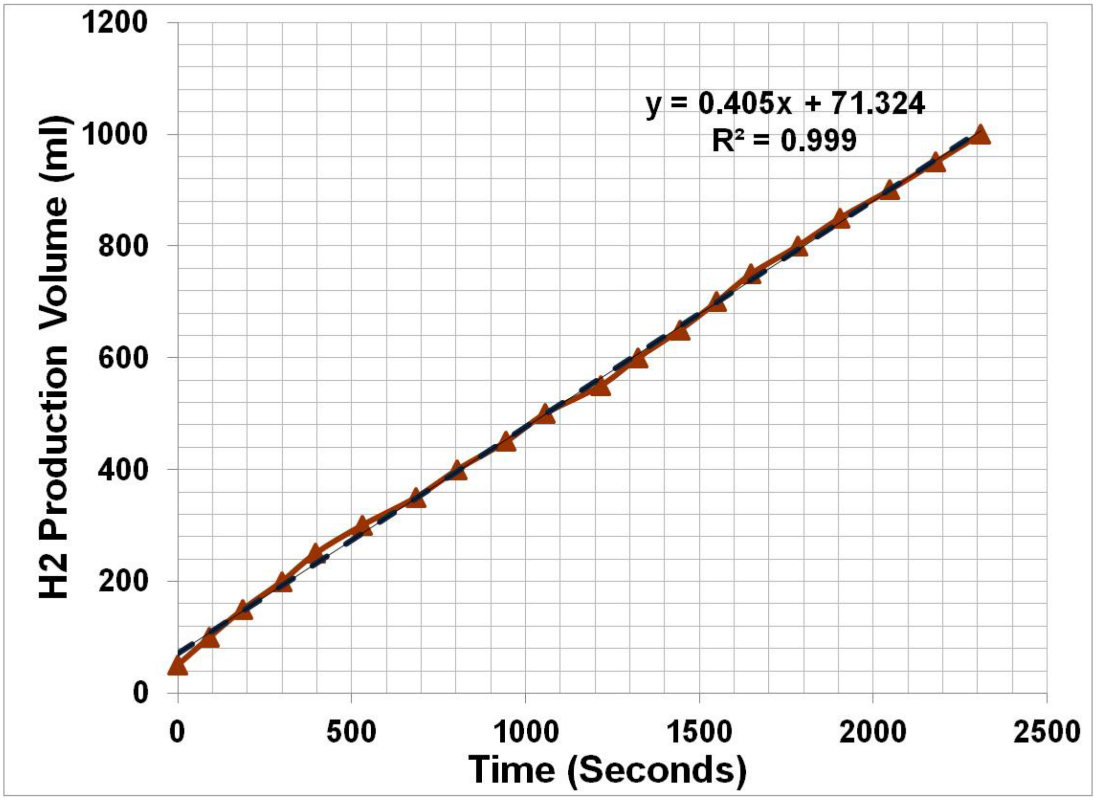

Figure 5: Hydrogen production volume vs. time during the solar-PV driven water electrolysis process

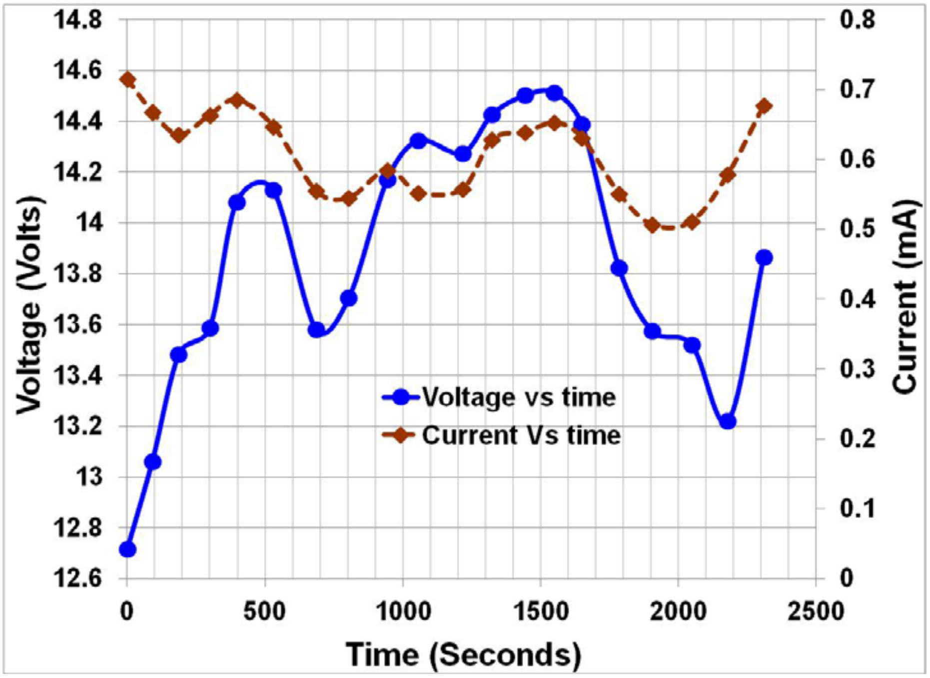

Figure 6: Current and voltage variation with time during fuel cell operation.

The approximate amount of hydrogen produced from one gallon of water (at 1 atmosphere pressure and at 32 degrees Fahrenheit) was 1250 gallons. The volume was 4.7 m^3 or about 3 ft x 3 ft x 15 ft. The wattage needed depends solely on the current flow. 16.5 KW-hours of energy were required to convert 1 gallon of water to hydrogen. If an apparatus used 1000 watts, then the hydrogen could be generated in less than a day. However, the current required is too high to do electrolysis at this rate in a normal household. An industrial line would most likely be needed. Hydrogen could be generated at a slower rate with the wattage on a 10 A or 20 A circuit, since the conversion would still work, but it would take a longer time.

The final and most important calculation was the *Energy Efficiency*. The efficiency was calculated in four different stages based on the data tabulated in Table 1 (see also Appendix 1): Solar PV, Electrolyzers, Fuel Cell, DC motor (see also Figure 7). We have calculated and tabulated the efficiencies and total system efficiency based on the formulas given below. Solar PV driven water electrolysis produced the hydrogen production of about 6000 ml of hydrogen in a total time of 236 minutes (see Appendix 2 for calculation).

Table 1: Observed I-V and calculated average power from the solar to hydrogen production and hydrogen to electricity conversion in Fuel Cells.

TOTAL AVERAGE DATA AFTER 6 TRIALS				
HYDROGEN FLOW RATE (ml)	**AVG VOLTAGE (V)**	**AVG TIME (Sec)**	**AVG CURRENT (A)**	**AVG POWER (W)**
50	12.71666667	0	0.715	9.092416667
100	13.06333333	91.2	0.6675	8.719775
150	13.48416667	187.7	0.635	8.562445833
200	13.58833333	299.7	0.66375	9.01925625
250	14.0825	396.5	0.685	9.6465125
300	14.12916667	529.8	0.6475	9.148635417
350	13.58166667	684.8	0.555	7.537825
400	13.70666667	804.5	0.545	7.470133333
450	14.1725	943.7	0.585	8.2909125
500	14.325	1056.7	0.5525	7.9145625
550	14.275	1216	0.5575	7.9583125
600	14.42833333	1324.3	0.62875	9.071814583
650	14.50333333	1445	0.63875	9.264004167
700	14.51333333	1550.4	0.6525	9.46995
750	14.38833333	1649	0.63125	9.082635417
800	13.825	1783.6	0.55125	7.62103125
850	13.575	1904.3	0.50625	6.87234375
900	13.52083333	2047.9	0.51125	6.912526042
950	13.22	2179.3	0.57875	7.651075
1000	13.86583333	2309.2	0.6775	9.394102083

$$Solar\ PV\ Efficiency\ (PV_{eff}) = 11\%$$

$$Electrolyzer\ Efficience\ (E_{eff}) = \frac{Energy\ Content\ of\ the\ Hydrogen}{Electrical\ Energy\ Consumed\ in\ Electrolyzers} = 82\%$$

$$Fuel\ Cell\ Efficience\ (FC_{eff}) = \frac{Electrical\ Energy\ from\ the\ Fuel\ Cell}{Energy\ Content\ of\ the\ Hydrogen} = 33\%$$

$$DC\ Motor\ Efficience\ (DCM_{eff}) = 78.8\%$$

$$Total\ System\ Efficiency\ (System_{eff}) = S = (PV_{eff})(E_{eff})(FC_{eff})(DCM_{eff}) = 2.35\%$$

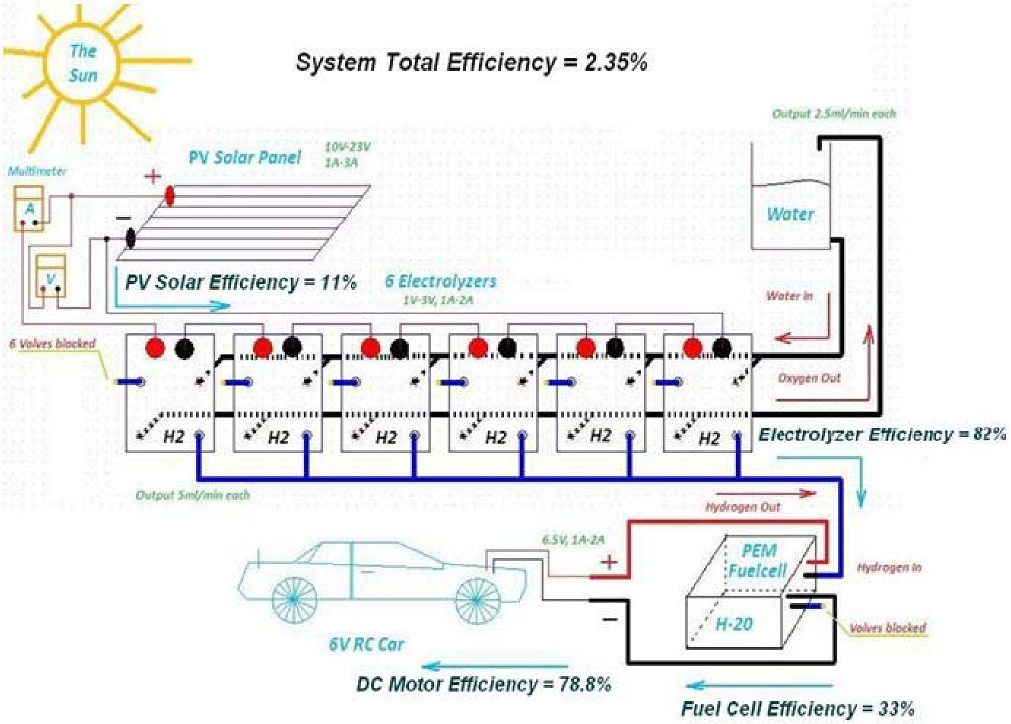

Figure 7: Constructed schematic diagram to calculate the energy efficiencies at every stages such as (a) H_2 production from solar energy, (b) H_2 conversion via fuel cells and (c) DC motor efficiency of utilizing H_2 and O_2 in a remote control car.

Project Safety and Cost:

Project safety was monitored and guidelines adhered to in every step of the design and development. Since working with flammable gas like hydrogen can cause severe damage, the safety vulnerabilities were identified[15]. It is claimed that storing hydrogen in solid state metal hydrides is safer when compared to either high pressure (300-500 bars) gaseous hydrogen storage or low temperature (21K) liquid hydrogen storage[16]. In the current project design, the solar-hydrogen driven fuel cell car, was modified and constructed to house an important component, a metal hydride canister to store and release hydrogen gas.

Hydrogen production and conversion was very costly because of the high cost of components like electrolyzers, a fuel cell, and a hydrogen tank. Hydrogen-Fuel Cell vehicles were at least two to three times more expensive in comparison to the battery operated systems. Hopefully, when hydrogen solar cars are out of the experimental stage and the units are mass produced in industry, the cost will eventually go down. The prices for each material or component purchased for this project are listed in Table 2.

Table 2: Price of each component or materials to design Solar-Hydrogen Fuel Cell car

MATERIALS OR COMPONENTS	PRICE
Hydrogen fuel cell	$650
Hydrogen control car	$20
Electrolyzes	$150
T-connector	$10
¾ tube	$5
Hydrogen tank 10L and 20L	$110
Other accessories	$200
Total Cost	$1,145

4. Conclusions

The design enabled successful production of hydrogen by utilizing solar energy and this hydrogen was successfully used to power a remote control car. The total efficiency of the system was estimated to be 2.35%, which is comparable to the manufacturer's specifications (3.74%). In addition, the basic concept of design and its functionality was evaluated critically through the duration of the project. The efficiency of fuel cell performance has been found to be drop substantially from the initial run due to various factors such (i) power output from the solar photovoltaic cells, (ii) loss of voltage and current between electrolyzers (iii) total effective power output from the fuel cell stack. The recent developments in this research area raised some hopes for *fueling the future with hydrogen*. In conclusion, solar energy is available readily at no cost to produce hydrogen; therefore, it may lead to a future clean alternative fuel (hydrogen) for transportation. In our future work, we will investigate and understand the mechanisms required *to improve the hydrogen fuel cell efficiencies by evaluating the rate limiting factors* in (i) solar PV electrolysis for hydrogen production, (ii) light-weight, high density hydrogen storage and delivery systems.

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Appendix 1:

Energy Efficiency Calculations:

1. PV Efficiency: 11%

2. Electrolyzer Efficiency

Input:

From the data we collected (We took average of P, t, and E): Total Energy = 19231.599 J

Output:

Calculate Mole of H_2 from (1L): $= \frac{1L}{18g} = .056\, moles$

1 mole of H_2 need 282.1 KJ of energy therefore E = .056 x 282100 = 15797.6 J

Efficiency:

Efficiency = $\frac{15797.6}{19231.5} \times 100 = \mathbf{82}\%$

3. Fuel Cell Efficiency:

Input:

Calculate Mole of H_2 from 20L tank: $= \frac{20L}{18g} = 1.11\, moles$

Therefore E = 1.11 x 282100 = 313131 J

Output:

20L of H_2 flow into the fuel cell with the rate of 230 ml/min therefore it will take 86.96 min (5217.6 second) to finish. The fuel cell average Power output is 20 watt therefore
E = pt = 20*5217.6 = 104352 J

Efficiency:

Efficiency = $\frac{104352\, J}{313131\, J} \times 100 = \mathbf{33}\%$

4. Remote Control Car Efficiency: 78.8%

Table 3: Power vs. Minimum Nominal Efficiency[17]

Power (hp)	Minimum Nominal Efficiency
1 – 4	78.8
5 – 9	84.0
10 – 19	85.5
20 – 49	88.5
50 – 99	90.2
100 – 124	91.7
> 125	92.4

System total Efficiency = (11)(82)(33)(78.8) = **2.35 %**

Appendix 2:

Constants used for calculations:

1 gallon = 3785 ml
1000 ml = 1 L
1 ml water weighs 1 gm
1 water molecule yields 1 hydrogen molecule
1 mole of water = 18 g
Electrolysis of 1 mole of water requires 282.1 kJ of energy[18].
1 mole of gas occupies 22.4 L at STP
1 kW-hour = 3600 kJ
1 m^3 = 1000 L

For calculation of amps:

1 mole =6.023 x 10^{23}
2 electrons per hydrogen molecule
1 amp = 1 coulomb/sec
1 coulomb = charge on 6.24 x 10^{18} electrons

Stepwise results from calculation:

1 gallon water
= 3785 ml
= 3785 g water
= 210.3 mole of water
Yields 210.3 mole of hydrogen.
Requires 59,320 kJ of energy.
Requires 16.5 KW-hours of energy.