RESEARCH PAPER

The Solar Hydrogen Home

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ABSTRACT

As oil prices continue to escalate to levels that threaten our economy, alternative energy is starting to play an important role in our society. Hydrogen fuel cells and solar panels are alternatives that promise a non pollutant way of producing energy. A solar cell is a p-n junction, made out of silicon (semiconductor). A p-n junction is the product of two layers of the same semiconductor material that are doped with different materials to leave one free electron in a layer, and a deficit of one electron in the other layer. A photon will move this free electron from one layer to the other, inducing an electrical field at the interface of these two layers, and a current will flow when the circuit is closed. A solar energy arrangement (photovoltaic system) will be used to meet the load of an average household that requires approximately 10,000 kWhr of energy per year. The objective of the current work is to put together a cost effective model house scaled down 1:300 of the energy required for an average residential home to conduct system and energy analysis. The Photovoltaic (PV) size facing south required to meet the load of an average household is 9 kW with efficiency of 75 % that counts for inverter and wiring losses of the system. In this project, two solar panels measured at 15 watts each will simulate the 9 kW PV system. These two solar panels will be used to feed the total consumption of the model house. In New York, the average sun hours per day are 4.3 hours, during which the PV system will produce the total energy needed to run the house for the whole day. The excess portion of solar energy that is not used during the 4.3 hours will be used to electrolyze water and generate hydrogen and oxygen. The hydrogen is stored in tanks to be used after the sun set to produce energy on demand by hydrogen fuel

cells. The current experimental work showed that for 9 kW – PV system, the hydrogen production is one fourth the total amount needed to cover the energy demand for the remaining hours of the day after sun set. This is attributed to the efficiencies of the fuel cell and Electrolyzer at the current state of technology.

INTRODUCTION

Fossil fuels are the main sources that are being used to produce energy today. They are not only being depleted, but also polluting the environment, and affecting our economical stability. Solar hydrogen and fuel cell systems when integrated together represent a new approach that promises clean and friendly energy production.

Our project's objective is to investigate powering residential homes with solar energy and hydrogen fuel cells systems combined using a scaled down model house. This model provided cost effective studies and analysis to estimate systems efficiency, size and capacity necessary to energize an average residential home. It is also very important to establish a reference point by building a small mockup that could eventually help constructing full scale homes, saving money and time.

The current system consists of solar panels that are connected to the household, and to an electrolyser. When the sun is shining, the solar panels produce electricity that is used to produce hydrogen and to provide energy to a residential home. The energy demanded by the household during the period of sunlight will be just a portion of the total energy needed to run the house twenty four hours per day, therefore, the remaining solar energy produced in this process will have to be stored for later demand.

First, solar radiation (photons) hits the solar panels, and produces an electrical reaction in the solar cell itself. The solar cell is a p-n junction made out of silicon (semiconductor), which means that the material is divided into two different regions, the p material region and the n material region. The p material is an impurity that leads to a deficit of mobile electrons in the silicon. The n material is an impurity that leads to extra mobile electrons in the silicon. When joining these two materials together we end up with a neutral region at the interface with an electrical field. When a photon hits this junction and frees an electron, it sees the Electric (E) field and moves toward positive charges. Current flows if there is a complete circuit. This current is utilized to meet the energy demand of a household, and to produce hydrogen.

Secondly, if the solar panels system had been designed to meet 100% demand of energy in the household, then the amount of energy produced by the solar panels will not be completely consumed during the period of sunlight, therefore the remaining energy will be used to produce hydrogen by electrolysis. This hydrogen will be stored in tanks to produce energy using fuel cells as depicted in (figure 1).

Thirdly, by providing energy from the solar panels to the electrolyzer, water can be dissociated into hydrogen (H_2) and oxygen (O_2). One mole of water produces one mole of hydrogen and half mole of oxygen. The hydrogen produced in the process could be stored in tanks and be used after the sun set to supply a fuel cells system and produce energy for the remaining hours of the day (figure 2).

Finally, the hydrogen gas is supply to the fuel cell system. The fuel cell system will produce energy on demand after the sun set. A fuel cell is an electrochemical device that converts chemical energy into electrical energy. Fuel cells consist of a polymer electrolyte membrane (PEM) that is surrounded by electrodes, anode and cathode. The hydrogen is supplied to the anode (negative side) and oxygen or air to the cathode (positive side) (figure 3).

This research project focuses on calculating the amount of hydrogen needed by a regular household 24 hours per day against the amount of hydrogen that could be produced by the conversion of sunlight into electrical energy, and into hydrogen.

MATERIAL AND METHODS

Two solar modules of 15 watts output each was used. The power outputs of these two solar panels, with 0.22 square meters area each, were measured in sunlight to determine their output energy and efficiency. A Dynaload System with various electric loads was used to varying loads and currents on the solar panel from 0 A to 1.5 A. The output of these solar panels was measured three consecutives days every hour from 9:00 AM to 4:00 PM as picture (1) illustrates. After measuring their energy output, it was discovered that they reached a maximum power point of 15 watts at 15 volts and 1.0 amp (Figure 4). The efficiency of these solar panels is based on the fact that 100 % efficiency is defined as 1 KW of solar radiation that 1 sq meter of earth intercepts in 1 Hour. If the solar panel has an area of 0.22 sq meter and 15 watts output, then its efficiency is about 7%.

In the current project, it was assumed that the average household requires more than 10,000 kWhr of energy per year (table 1). This house will use a PV system of 9.08 kW, which will need a roof area of about 1000 sf, and about 700 sf of floor plan area (table 2). The efficiency of this PV system is about 75 %, which accounts for the inverter's efficiency and wiring losses.

The scale for our small scale model house will be calculated based on the numbers from the full scale house. The 9 kW will be simulated by the 300 smaller version of our experiment of 30 watts PV system (picture 2). The dimensions of the real household will be scaled down 100 times in a sample house that is 10 sf of roof area and 7 sf of floor plan area (picture 3). Therefore, the amount of power needed to run this household is about 22,000 watts taking into consideration every appliance and electric light in the house. If the scale factor for energy analysis is 300, then the small model house will be running with about 75 watts of power requirements (figure 5).

In New York, the amount of energy that the earth intercepts per day is 4.3 kWhr, which means that we have power of 1kW of effective sun light during 4.3 hours of the day. During this period of time, it was found that the solar panels will produce sufficient amount of energy required by an average household for the whole day. During these 4.3 hours, the house will consume only a small amount of energy, and the rest will be used to produce hydrogen by electrolysis. The amount of energy that the sample house will be consuming during the time of solar energy production is about 17Whrs, and the amount of energy produced by the sun is about 97Whrs, so the remaining 80Whrs will be used for electrolysis.

The hydrogen flow rate generated by electrolysis used in this project was measured at different levels of voltage and amperage. At 3 volts, 0.7 amps, this electrolyser produces 4.3 mL/min of hydrogen, and as the voltage increased the amperage increased as well, and therefore better hydrogen production rates were obtained. At 6 volts, and 1.6 amps, the hydrogen production rate was 12 mL/min. However, if we keep increasing the voltage even more, the hydrogen production rate would not increase as expected. In fact the voltage was increased to 9 and 12 volts, but the current leveled at 1.6 amps, and the hydrogen production rate remained at 12 mL/min (figure 6). This means that the internal electric resistance inside the electrolyzer was increasing due to the higher flux of gases blanketing the electrode. This could be explained by the amount of hydrogen produced by the hydrogen electrode side of electrolyzer, builds up a wall layer of hydrogen gas against the electrode surface that increase electric resistance and does not allow any electric current increase or further escalation in hydrogen generation. The average hydrogen produced by this reversible fuel cell process was measured to read 10 mL/min at 9.6Whr. In the present work, data from a full scale electrolyzer was used as a reference point for the full scale house energy balance and hydrogen generation at the rate of 1 cubic meter of hydrogen at 5kWhr. In this case the amount of energy produced by the 9.08kW PV system will be around 29kWhr per day, and the amount of energy consumed during the period of solar energy production is about 5kWhr, which gives us a surplus of 24kWhr to be used for hydrogen production.

RESULTS

The amount of energy that could be used to produce hydrogen is about 80Whr per day in the sample/small scale model house. Two electrolyzers or fuel cells will be used in the reversible process to produce hydrogen at a rate of 20mL/min. These two hydrogen electrolyzers, therefore, will produce 0.01 cubic meters per day in 4.3 hours (table 3).

The amount of energy that the sample house will need to run 24 hours period is 97Whrs. 17Whrs will be provided directly form the PV system, and 80Whrs will be required to run the house 19.7 hrs after the sun set. To produce this amount of energy, the hydrogen needed will be calculated from the fact that about 15L/min are needed to produce 1 kW of power. Therefore, the amount of hydrogen required to produce 80Whr is about 0.07 cubic meters (table 4).

In the full scale house, the approximate energy requirement is 29 kWhr per day that can be covered by a 9kW solar PV considering 75% transmission and system losses. The amount of energy consumed by the house during the 4.3 hours that the solar array is effective is about 5kWhr. The remaining 24kWhr will be used to produce hydrogen by electrolysis. The electrolyser that was used in these calculations produces 1 cubic meter of hydrogen while working at a rate of 5kWhr. Therefore, the amount of hydrogen that could be produce in this system is 4.8 cubic meters per day (table 5). Considering that 1kW of power generated by a fuel cell needs 15L/min, thus the house will need 21.09 cubic meters to run during the 19.7 hrs remaining of the day (table 6).

DISCUSSION AND CONCLUSIONS

The energy demand required in a household could be supplied by solar energy; when the sun is shining the photovoltaic array gives free energy from a unique and endless source. In order to provide enough energy to a household, the PV system must be design to generate 100 % of the energy demanded by this household. To calculate this, the amount of effective sun light must be taken into consideration as well as the efficiency of the solar panels, and the overall system's efficiency as well.

The energy provided by the sun must be stored; otherwise we would not be able to capture all this energy and cover the requirements of an average residential home. The current technology offers two ways of storing this energy: storing energy by the use of batteries or by connecting the system to the grid selling the daily surplus of energy to the grid and buying it back when it is needed. These two processes are classified as inefficient and lack cost effectiveness.

The third method is to store the excess solar energy by converting it into hydrogen, which could be stored and used after the sun set to feed a fuel cell arrangement and produce energy on demand to the household. The hydrogen will be produced by the use of an electrolyser that will capture the daily energy surplus from the PV system and convert it into hydrogen. Water will be split into hydrogen and oxygen by electrolysis, the hydrogen generated in this process will be stored and use to feed the fuel cell arrangement.

The amount of hydrogen that could be generated in the sample house by electrolysis came out to be seven times smaller than the amount of hydrogen needed to run this sample. These results are strictly related to the efficiency in the fuel cells arrangement and the electrolyser. The maximum theoretical efficiency in a fuel cell is 83% which is achieved by a fuel cell that has as output 1.23 volts. In this experiment we have worked with efficiency close to 50% working at 0.65 volts output. This fact of course has brought our overall efficiency down in a large scale.

On the other hand, the electrolyser used in this experiment is less than 20% efficient, which also increases the energy losses within the system.

In the full scale house calculations, the amount of hydrogen produced by the combined system was 4.5 times smaller than the amount required by the household (table 7). In these calculations the same efficiency of the fuel cell was used at approximately 50%, however, the efficiency in the electrolyser increased from about 14% to 44%, which has made the hydrogen production to be closer to the hydrogen needed. .

If we could increase the efficiency in the electrolyser and in the fuel cell to its theoretical efficiency of 83%, then the amount of energy produced will be three quarters of the amount needed. Thus if the solar PV is increased by 25% a similar increase in hydrogen will be gained to close the gap in the hydrogen amount needed to capture sufficient solar energy necessary to completely cover the average house hold energy demand . If this occurs then it could be actually possible to use systems like the one described and designed in this project to power residential homes.

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I thank Brookhaven National Laboratory and the Department of Energy of U.S. for giving me the opportunity of becoming a student researcher. I would like to thank to Prof. Devinder Mahajan and his commitment to this program. I would also like to thank Mr. Noel Blackburn and the CCI faculty for working hard to give me the opportunity of participating in this research experience. I thank SUNY Farmingdale for letting me use its IRTT Laboratory and specially Prof. Hazem Tawfik and Dr. Kamel Khatib for their unconditional support toward my project’s success.

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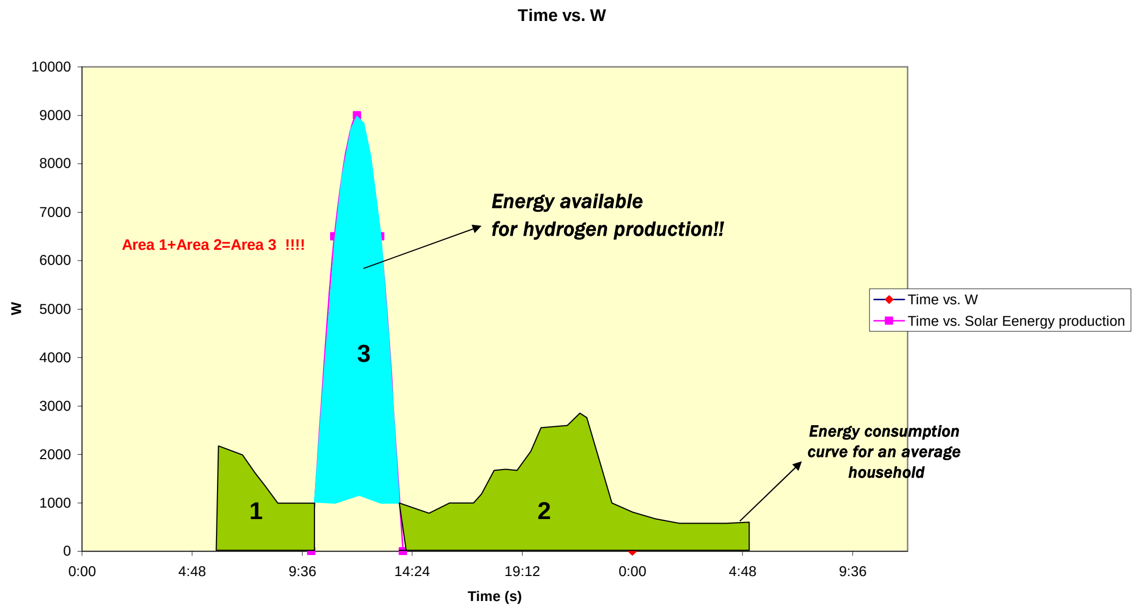


Figure 1: *the green area represents the amount of energy consumed by a regular household in a 24 hours period. The blue area represents the amount of energy that could be produced daily in the PV system designed.*

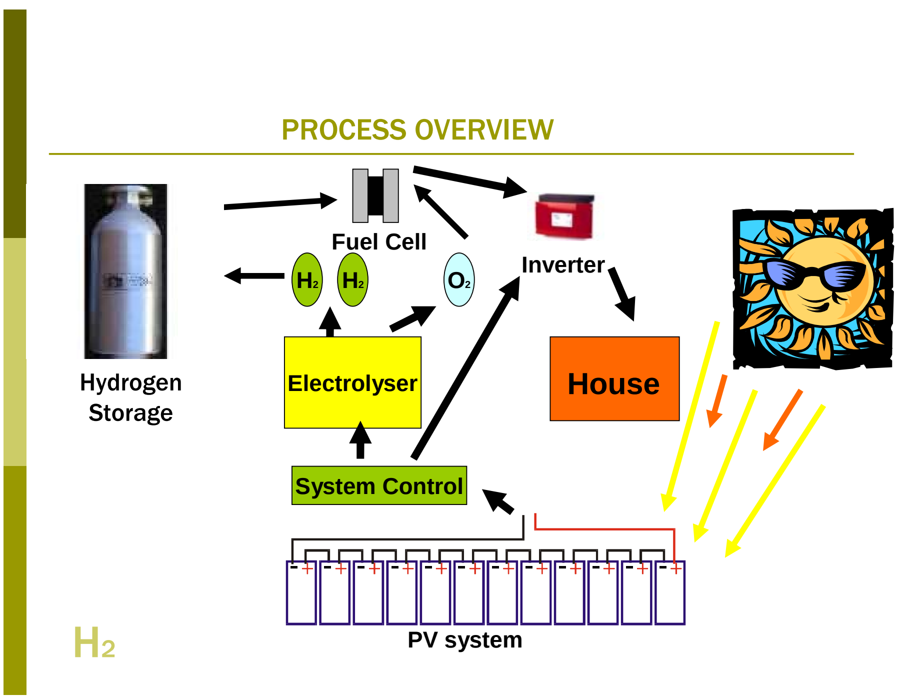


Figure 2: *Photons hit the PV system converting sunlight into electricity which is going to be used as energy source for producing hydrogen and for providing the house with its energy requirements.*

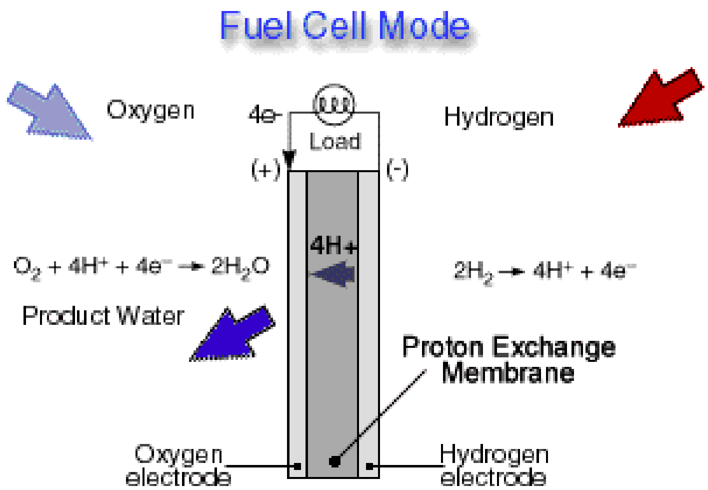
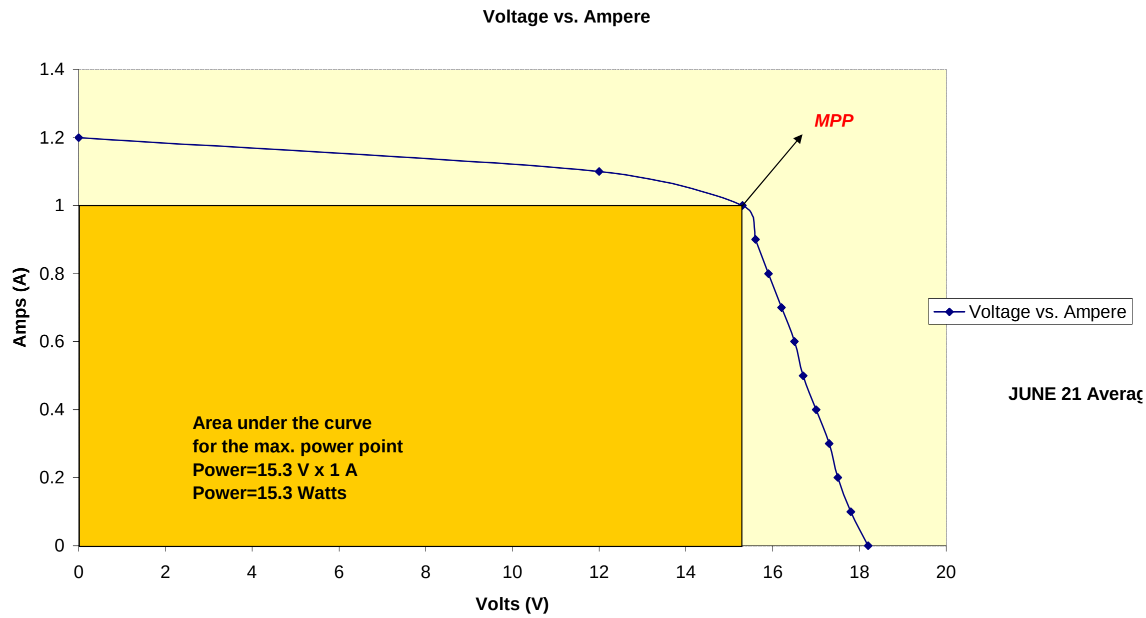


Figure 3: *Hydrogen is supplied to the anode and oxygen to the cathode, producing an electrical current to flow from the hydrogen electrode to the oxygen electrode.*

Picture 1: *The dynoload on the picture was simulating a load that varies from 0 amps to 1.5 amps.*



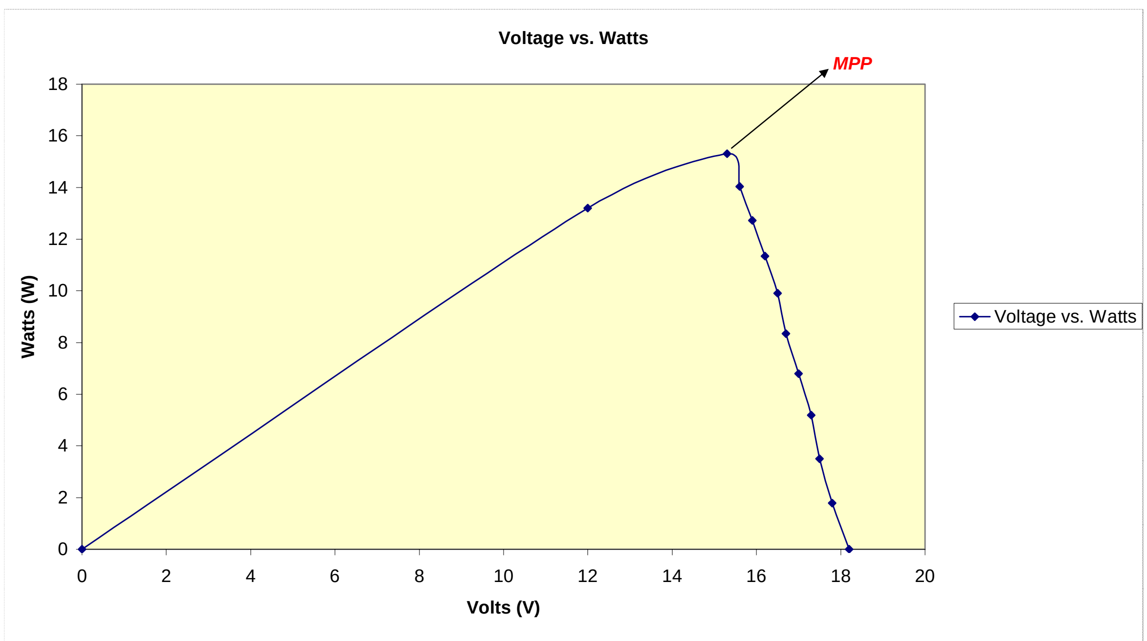


Figure 4: *these graphs represent the average maximum power point obtained throughout 3 days of every hour measurements. The MPP (maximum power point) represents the output of the solar panels. Based on the MPP we will calculate the energy production for this project.*

TOTAL DAILY LOAD					
Device	***Quantity***	***Watts (E*I)***	***hrs/day***	***week***	***WHr/ Day***
Lights	2	22	2	7	88.0
Lights	3	40	2	7	240.0
Lights	4	100	4	7	1600.0
Lights	1	20	0.5	7	10.0
Lights	4	60	4	7	960.0
Lights	3	75	2	7	450.0
TV	1	100	2	7	200.0
Radio	1	100	2	5	142.9
VCR	1	60	2	1	17.1
DVD	1	35	2	1	10.0
Microwave	1	1450	0.5	3	310.7
Toaster	1	800	0.2	7	160.0
Mixer	1	150	0.2	2	8.6
Blender	1	125	0.05	7	6.3
Food procesor	1	450	0.03	7	13.5
Radio Clocks	1	50	1	7	50.0
Water Pump*	1	2000	4	7	8000.0
Refrigerator*	1	600	12	7	7200.0
Oven	1	1200	2	2	685.7
Printer	1	60	0.25	5	10.7
Heater*	1	1000	2	3	857.1
Vent Fan	1	88	0.5	2	12.6
Wash. Mach	1	512	2	1	146.3
Iron	1	1000	0.5	1	71.4
Vacuum	1	600	0.25	2	42.9
Sew. Mach.	1	75	2	3	64.3
Computer	1	250	2	7	500.0
Hair Dryier	1	1000	0.25	3	107.1
Coffee Maker	1	1000	0.25	5	178.6
Central A/C	1	4000	2	5	5714.3
Dehumidifier	1	350	2	7	700.0
Clothes Dryier*	1	5000	1	1	714.3
	Total power	22372			
	Daily Consumption	**29272.4**	**Whr/day**		
	Yearly Consumption	**10684.41**	**Kwhr/year**		

Table 1: *this table represents the daily and yearly consumption of energy in a full scale household.*

PV Module Efficiency %	**PV Capacity Rating, watts (in bold)**							
	100	**250**	**500**	**1,000**	**2,000**	**4,000**	**10,000**	**100,000**
4	30	75	150	300	600	1,200	3,000	30,000
8	15	38	75	150	300	600	1,500	15,000
12	10	25	50	100	200	400	1,000	10,000
16	8	20	40	80	160	320	800	8,000

Table 2: *here we clearly see the amount of area needed per a certain amount of energy output at a known PV system efficiency.*

Picture 2: *Here we see two solar panels of 15 watts output each that adds up to 30 watts total. These panels are located east-west for a better use of the available are of roof.*

Picture 3: *This sample house is about 100 times smaller than a full scale average house of 1000 square foot of roof and 700 square foot of floor plan.*

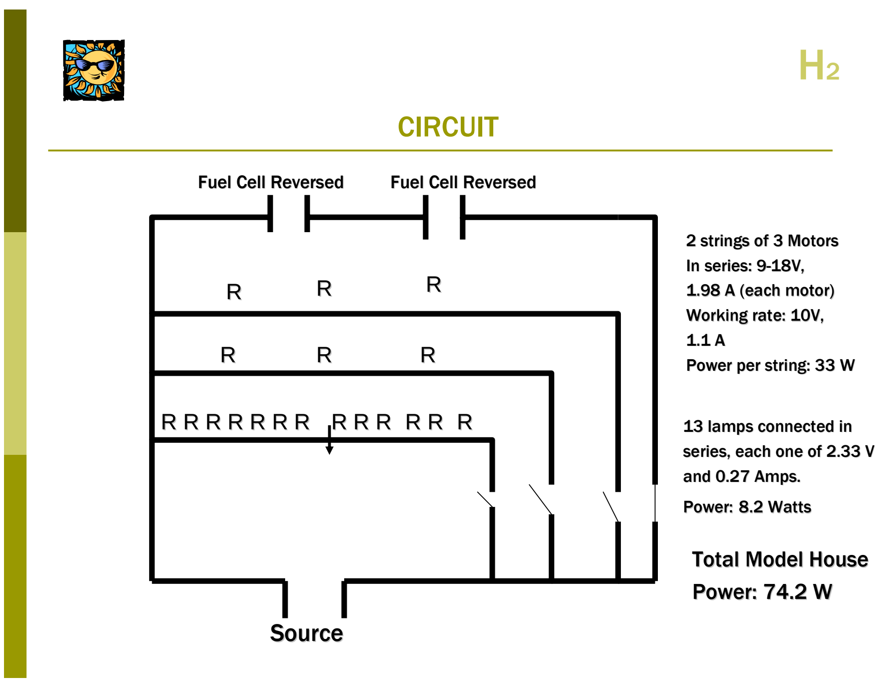


Figure 5*: this is the circuit inside the sample house. The important factor here is to represent the total load requirements of an average household.*

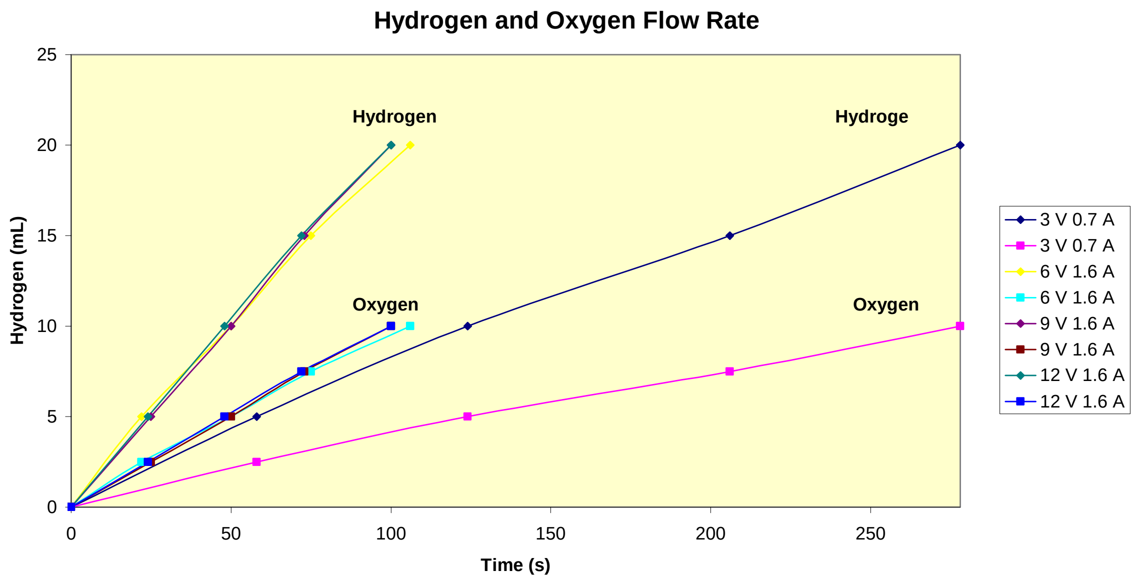


Figure 6: *This graph shows the amount of oxygen and hydrogen produced at different voltages. It clearly shows that the hydrogen production remained the same for 6, 9 and 12 volts. This indicates that the electrolysis depends on the amperage rather than voltage.*

PV PRODUCTION

Energy produced per day	97.6	Whr
Energy spent on 4.3 hours	17.5	Whr
Energy used to produce hydrogen	80.1	Whr
Energy production rate needed from FC per hour	18.63	W
Energy consumption rate per hour	4.07	W

HYDROGEN PRODUCTION BY ELECTROLYSIS

Assumptions	*Electrolyser*			
20	*ml/min*	*@*	*9.6*	*Whr*

Energy used to produce hydrogen	80.1	Whr
Hydrogen produced (per day)	0.010	(m^3-H_2)/day

Table 3: *This is the energy production by the PV system and the amount of hydrogen that could be produced by electrolysis per day.*

ENERGY NEEDED BY FUEL CELLS

Assumptions	*V=650mV*	*T=25C P=1atm*	*80 % of H_2 Cons.*	
Ampers required	I=P/V	28.7	Amps	
$mH_{2, \text{consumed}}$	0.00108	$(g\text{-}H_2)$/hr		
$mH_{2, \text{supplied}}$	0.00135	$(g\text{-}H_2)$/hr		
$mH_{2, \text{supplied (TOTAL)}}$	0.02654	$(g\text{-}H_2)$/day		
Ideal Gas Equation	PV=nRT	R=0.08206	(L atm/mol K)	
Volume supplied	0.016	(m^3-H_2)/hr		
Volume supplied (total)	0.070	(m^3-H_2)/day		
Assumptions	*A=400mA/cm^2*			
Area needed of fuel cells	71.7	cm^2 →	0.007	m^2
Assumption	*Area of cell*	→ *20*	*cm^2/cell*	
Number of cells	3.6	Cells →	4	Cells

Table 4: *the amount of hydrogen needed to run this sample house 24 hours per day is 0.007 cubic meters*

PV PRODUCTION

Energy produced per day	29.3	kWhr

Energy spent in 4.3 hours	5.2	kWhr

Energy used to produce hydrogen	24.0	kWhr

Energy production rate needed from FC per hour	5.6	kW

Energy consumption rate per hour	1.22	kW		
Assumptions	*HOGEN 40*	*Electrolyser*		
1	*m^3/hr*	*@*	*5*	*kWhr*

Energy used to produce hydrogen	24.0	kWhr

Hydrogen produced (per hr)	4.8	(m^3-H_2)/day

Table 5: *with 24 kWrs of energy that is available, we could produce a maximum of 4.8 cubic meters of hydrogen.*

ENERGY NEEDED BY FUEL CELLS				
Assumption	*V=650mV*	*T=25C P=1atm*	*80 % of H_2 cons.*	
Ampers required	I=P/V	8.6	kAmps	
$mH_{2,\ consumed}$	0.323	$(Kg\text{-}H_2)/hr$		
mH_2 Supplied	0.404	$(Kg\text{-}H_2)/hr$		
$mH_{2,\ supplied\ (total)}$	7.961	$(Kg\text{-}H_2)/day$		
Ideal gas Equation	PV=nRT	R=0.08206	(L atm/mol K)	
Volume supplied	4.90	$(m^3\text{-}H_2)/hr$		
Volume supplied (total)	21.09	$(m^3\text{-}H_2)/day$		
Assumptions	*A=400mA/cm^2*			
Area needed of fuel cells	21491.7	cm^2 →	2.15	m^2
Assumption	*Area of cell*	→ *0.25*	*m^2/cell*	
Number of cells	8.6	Cells →	9	Cells

Table 6: *The amount of hydrogen to run an average household is about 21.09 cubic meters.*

PV SYSTEM NEEDED		
Volume NEEDED PER DAY	21.09	m^3-H_2/day
Energy needed per day	105.4	kWhr/day
Energy spent in 4.3 hours	5.2	kWhr/day
Energy produced per day	110.7	kWhr/day
Energy produced per year	40399.5	kWhr/year
PV system required to run the house	34.3	kW

Table 7: *here we can see that the PV system must be 34.3 kW instead of 9.08 kW in order of providing the enough amount of energy to the electrolyser.*