# Alternative Energy: Solar Cells, Electrolysers, and Hydrogen Fuel Cells

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Abstract:
Using the H-Tec fuel cell kit, we examine several pieces of technology which pertain to sustainable alternative energy. We first examine the efficiency of two fuel cells in converting light energy into electricity. Second, we examine the efficiency and rate at which two electrolysers convert deionized water into hydrogen and oxygen gas which can serve as means of fuel storage. Third, we examine the efficiency with which a supplied fuel cell recombines the generated Hydrogen and Oxygen gas to produce electric power.

## I. Introduction

With a society dependent on electricity and the major sources of power reliant on the consumption of limited resources, our future may be dependent on the discovery and production of new means of producing and storing energy. A few such alternatives are the use of solar panels to convert light energy into electricity and the use of hydrogen gas to store the energy.

Solar power was first conceived with the discovery photovoltaics in the early 19th Century. However, the mechanism by which it occurs was not explained until Einstein's Photoelectric Effect in 1905. It was found that photons (quanta of light) were capable of energizing electrons in a materiel to successively higher and higher energy states until the point at which the photons acquired enough energy to escape the material entirely. This current can be used to power electric devices.

Electrolysers are necessary in order to store the energy converted by solar cells and other sources of alternative energy to release when the energy sources are no longer present. Prime examples of such situations would be a solar cell at night or a wind turbine in calm.

Electrolysers were first created in 1800. They work by using an electric voltage in separate the slightly negative oxygen molecules from the slightly positive hydrogen atoms. Once separated, the atoms settle into a new stable configuration as diatomic gas. In the specific Polymer Electrolyte Membrane (PEM) Electrolyser which we use, a central, proton-conducting, membrane serves as a layer which facilitates the stripping of excess electrons from oxygen and the addition of electrons to the hydrogen as shown in equations (1) and (2).

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^- \qquad (1)$$

$$4H_2 + 4e^- \rightarrow 2H_2 \qquad (2)$$

The electrons produced by the dissociation of water are passed back into the circuit and those consumed by the hydrogen are from current passed into the

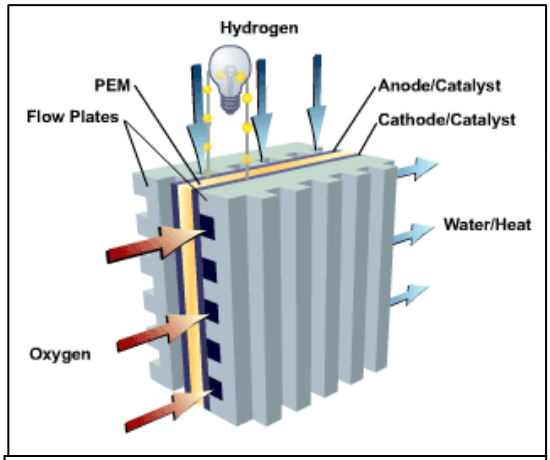


Figure 1: an example of a PEM Fuel Cell

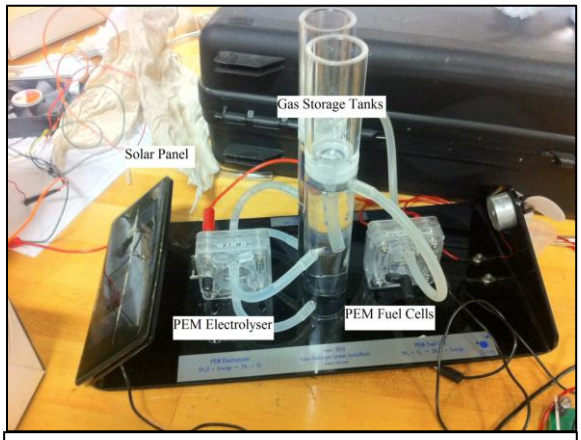


Figure 2: The H-Tec J101 Junior Basic and J102 Junior Sec which includes the Solar Panel, Electrolyser, Storage tanks, and Fuel Cell


Figure 3: The secondary solar panel in the orientation described for testing

electrolyser.

The simplicity of this design means that not only can this mechanism be used as an electrolyser, but can also be run in reverse and the recombination of hydrogen and oxygen can produce a current (Figure 1).

It is the efficiency of the solar panel, the PEM electrolyser, and the PEM fuel cell which we intent to examine and measure.

## II. Methods and Procedure

### Apparatus

Our apparatus for the majority of our trials and experiment were based on the H-Tec J101 Junior Basic and J102 Junior Set combination alternative energy experimental apparatus (Figure 2). This arrangement consisted of a 90cm$^2$ solar panel, a 0-2V Proton Exchange Membrane (PEM) Electrolyser, two 30cm$^3$ gas storage tanks which were each marked to 20cm$^3$ in 1cm$^3$ increments, and a PEM fuel cell.

In addition to the self-contained J101 unit we also used a secondary solar panel and a secondary electrolyser for comparison to those which were included in the J101 unit. The secondary solar panel was also manufactured by H-Tec with a working surface area of 62.4cm$^2$(Figure 3). The secondary electrolyser was, similarly, provided by H-Tec F107 PEMFC kit.

Both Electrolysers throughout the test were powered by a LEADER 718-5D regulated DC power supply. When operated, the limiting current was set to its maximum setting to ensure a full range of voltages. Within the range between 0 and 5 volts, there is an error of ±0.5% or ~0.02V.

All readings were made using the provided H-Tec 2027 Digital Multi-meter

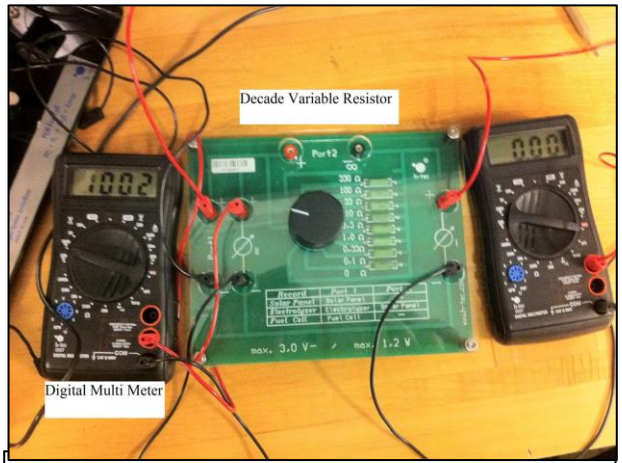


Figure 4: The variable resistor board (center) and the two Digital Multi-meters (Left and Right)

(Figure 4). When recording the voltages, the 2000mV was often used (except where noted). On this setting, the error is also ±0.5% or ~ 5mV for the range of voltages recorded. When used as an ammeter, the 10 A setting was used which has an error of ±2% or approximately 0.1A. The current and voltage measurements were made across a provided H-Tec decade resistor which ranged from 0.1Ω to 330Ω (Figure 4). In addition, readings were taken to account for the additional resistance of the connecting cables and the board of approximately 0.3Ω which is not negligible at the lowest resistances.

Solar Panel Procedure

Two measurements were made regarding the solar panel. First a measurement was made throughout the range of the decade resistor while the panel was exposed only to ambient light. Second, the 65 W halogen bulb was lit ~30cm from the face of the solar panel. In each case, the height and distance of the light was changed such that the light was perpendicular to the surface of the solar panel while maintaining the distance (Figure 2).

The solar panel was connected directly to the decade resistor and the multi-meters in order to measure the current and voltage output of the panel (Figure 5). In order to

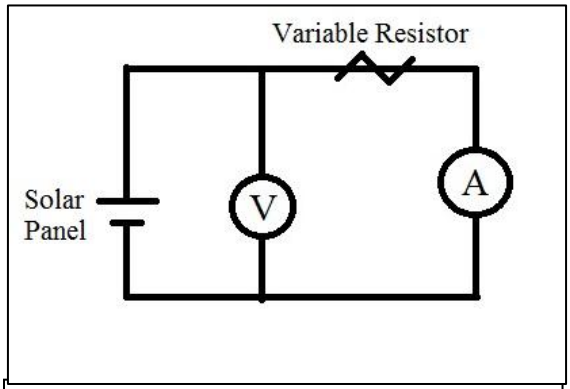


Figure 5: The Circuit Diagram regarding the Solar Panel examination

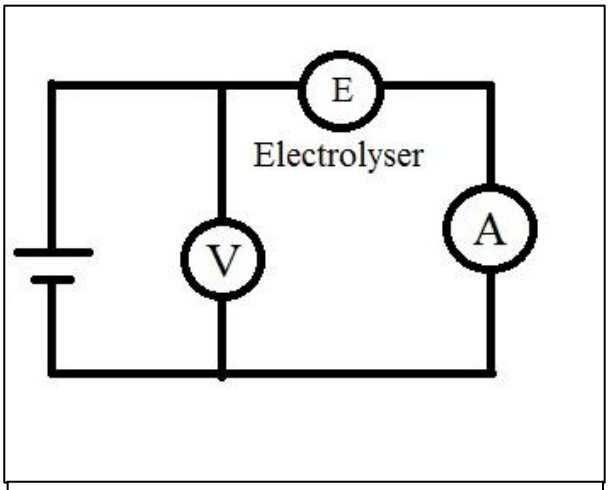


Figure 6: The Circuit Diagram regarding the Electrolyser Trials

accommodate the potential heating caused by direct light exposure, the panel was allowed to remain exposed to the light for a total of 4-5 minutes before any readings were taken.

Electrolyser Procedure

The gas storage tanks were filled with deionized water as per the operating instructions. The rubber tubes connecting the storage tanks to the PEM electrolyser were then squeezed to remove all air bubbles.

A voltage was then applied across the PEM electrolyser using the LEADER 718-5D Voltage supply. Beginning at zero volts, the voltage was increased in 0.10 V increments as measured by the supply. The H-Tec 2027 Digital Multi-meters were then used to record the voltage across and the current passed through the electrolyser in each increment (Figure 6).

This allowed us to measure both the voltage at which electrolysis began to occur and the power which was used in the process as the applied voltage further increased.

Subsequently, those voltages which were sufficient to produce electrolysis were used as a basis from which to begin subsequent measurements of the rate of gas production. The time was then measured using the

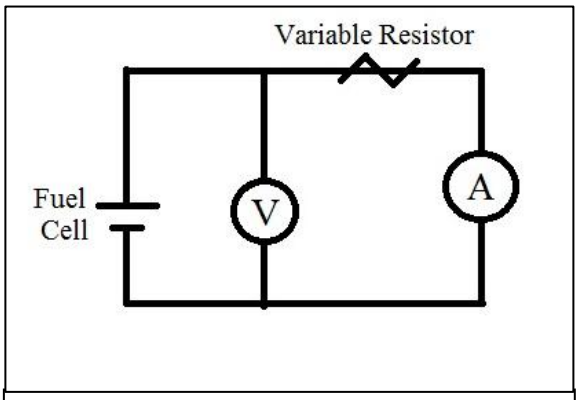


Figure 7: The Circuit Diagram for the Fuel Cell Trials.

provided stopwatch and recorded at 1cm$^3$ increments.

Fuel Cell Procedures

As described above, the electrolyser was used to generate sufficient amounts of both hydrogen and oxygen gas at an applied voltage of 2V. When at least 10 cm$^3$ of Hydrogen and Oxygen gas had been produced, the rubber plugs were removed and the rubber tubes were "purged" of normal air. This "purging" was repeated a second time to ensure that all of the gas remaining in the rubber tubing and the electrolysers was either Oxygen or Hydrogen.

20cm$^3$ was then produced along with at least 11cm$^3$ of oxygen. During gas production, the fuel cell was connected to the decade resistor in the open circuit position. The decade resistor was then changed to one of the selected resistances (Figure 7) and the time was recorded at each interval cm$^3$ of gas consumed.

## III. Results

Solar Panel

In ambient light, the voltage produced by the solar cell is approximately linear with respect to resistance (Figure 8). When the

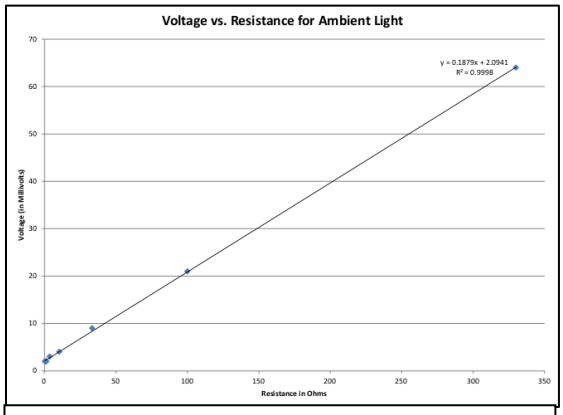


Figure 8: The Voltage produced by the Solar Panel in ambient light

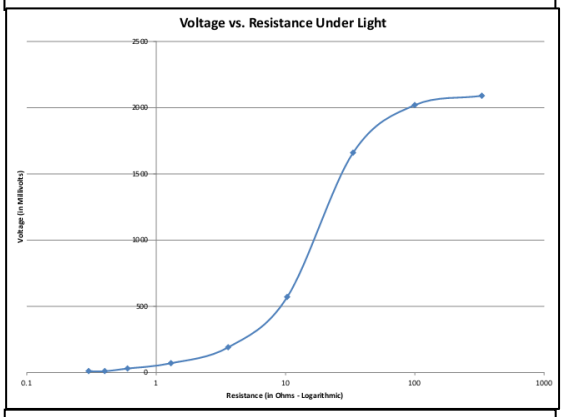


Figure 9: The Logarithmic Voltage produced by the Solar Panel under intense light.

light was applied, the voltage increases linearly to a maximum around 2V and then levels off (Figure 9).

The current is primarily constant throughout the trials, falling quickly to zero at the highest resistance. The power is calculated through the abbreviated Ohm's Law Power formula.

$$P = IV \qquad (3)$$

From this equation, we find that the maximal power across a load occurs at approximately 33 Ω with a value of 0.083 ± 0.001 W (Figure 10).

In comparison with the auxiliary solar cell, the supplied solar panel has a higher voltage and power distribution through most of the resistances. However, under direct

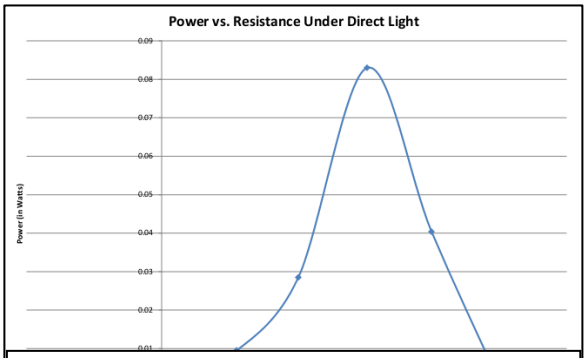


Figure 10: This Graph plots the Power generated by a solar panel against the decade resistance.

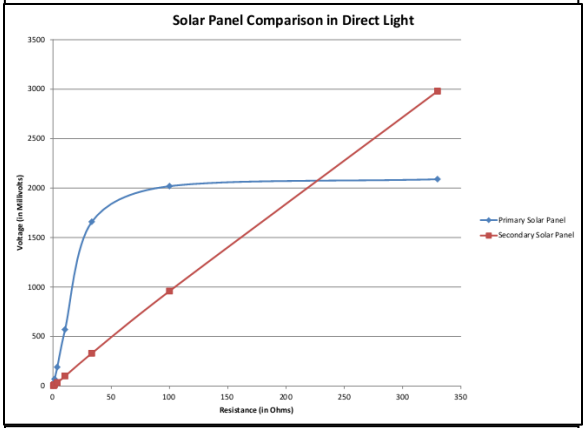


Figure 11: The Comparative Power Curves of the two Solar Panels

light, the secondary panel does not exhibit the 2 Volt limit which is shown by the supplied solar panel (Figure 11).

Electrolyser

We found that the PEM electrolyser required between 1.5 and 1.6 V to begin electrolysis of water.

In recording the rate of Hydrogen production, we found that the 1.5V and 1.6V applied potentials, while hydrolysis did occur, produced hydrogen so slowly that over a 10 minute measuring period, less than $1cm^3$ of Hydrogen gas was produced.

By plotting the time required to produce a fixed volume of gas, we find the inverse production rate of a given resistance (Figure 12). This can then be used to find the efficiency of the electrolyser.

$$Eff = \frac{Vol*H}{V*I*t} = \frac{Rate*H}{P} \qquad (4)$$

Here, "Vol" stands for the Volume of Hydrogen produced, H is the heating value of hydrogen, V is the voltage, t is the time in seconds, and I is the current. By this equation, we find the efficiency of the electrolyser to be between 60±4% at 1.7V and 76±4% at 2V.

We can then calculate the faraday efficiency by dividing the gas produced by the theoretical volume produced.

$$Vol_{Theoretical} = \frac{R*I*T*t}{F*p*z} \qquad (5)$$

$$Eff_{Faraday} = \frac{Vol}{Vol_{Theoretical}} \qquad (6)$$

Here, R is the ideal gas constant, I is the measured current, T is the temperature of 293K, t is the measured time in seconds, F is the Faraday constant, p is the ambient atmospheric pressure, and z is the number of electrons released per molecule. From these equations, we can see a linear relation between the voltage and efficiency in this regime. We can also find that the minimal

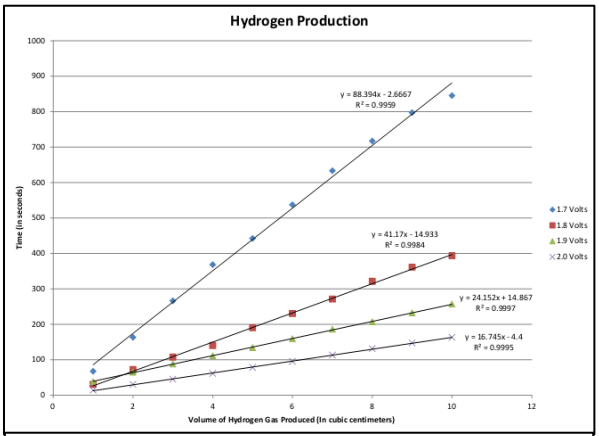


Figure 12: The comparative Hydrogen generation rates based on different voltages.

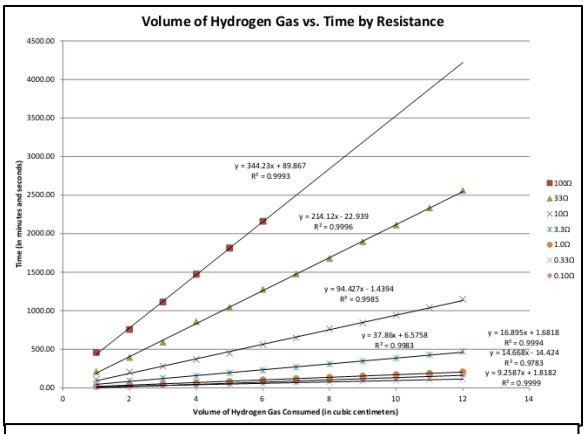


Figure 13: The Hydrogen Consumption Curves with respect to load resistances.

voltage required to produce electrolysis is 1.64V which is in agreement with our previous examinations and literature values.

We can then calculate the Faraday efficiency in terms of our measured time and volume.

$$Eff_{Faraday} = \frac{F*p*z*Vol}{R*I*T*t} \qquad (7)$$

Since each voltage corresponds to a specific current and a measured rate, we can then plot our Faraday efficiency as a function of the applied voltage.

$$Eff_{Faraday} = 7.866E6 * \frac{Rate}{I} \qquad (8)$$

This gives values for the faraday efficiency between 64±4 at 1.7 Volts and 94±6% at 2.0 Volts. This is a relatively high value for the faraday efficiency, however, since it does not account for the energy lost to the resistance of the circuit.

Fuel Cell

The consumption rate of hydrogen gas by the PEM fuel cell was found to be inversely proportional to the resistance such that the consumption rate for the consumption rate for the 330Ω resistor was negligible (Figure 13).

At the highest resistances, a nearly constant potential of .9Volts was generated across the terminals of the fuel cell. This corresponded to a negligible voltage. Similarly, at the lowest resistances, the initial voltage difference and initial current – around .2V and .78A respectively – drop toward zero very quickly

As with the PEM electrolyser, the efficiency of the fuel cell can be calculated by finding the ratio of hydrogen consumed to the power generated across the load resistor.

$$Eff = \frac{V*I*t}{Vol*H} = \frac{P}{H*Rate} \qquad (9)$$

As in equation 7, an analogous expression can be found for the Faraday efficiency of the fuel cell in the same notation.

$$Eff_{Faraday} = \frac{R*I*T*t}{F*p*z*V} \qquad (10)$$

$$Eff_{Faraday} = 1.27E-7 * \frac{I}{Rate} \qquad (11)$$

From these equations, we find the Efficiency for the PEM fuel cell to be between 27±2% and 46±3% with a maximum of 46% between 10Ω and 3.3Ω. Similarly, we find the Faraday Efficiency to be between 43±3% at 100Ω to 96±6% at 1Ω. The currents measured at resistances were unstable and could, therefore, not produce a stable rate with which to estimate the Faraday Efficiency

## IV. Conclusion

The system, as a whole, is a relatively accurate means by which to demonstrate the concepts of hydrogen fuel cell technology. However, with the very limited scope of the variable parameters, a full exploration of the

properties could not be completed adequately.

We examined that with a different, external electrolyser, the rate of gas production further increased, but was incompatible with the other aspects of the system, and thus could not be tested beyond its production rates.

Furthermore, tests of the consumption of hydrogen gas were performed only at atmospheric pressures. However, further examining the fuel cell power properties under pressure could demonstrate methods by which greater efficiency could be created in a hydrogen fuel cell system.

By limiting our variable parameters, however, we also limit our sources of error. The only likely source of error in the fuel cell is the accumulation of water as it runs. When producing gas through electrolysis, the release of bubbles from the tubing was varied and unpredictable, causing slightly greater variation in the timing of higher resistance electrolysis trials.

In the calculations for the Faraday efficiencies, we used an assumed mean value for the current. While this was an acceptable assumption at high resistances, the rate at which the current and voltage dropped in the lower resistance trials may have cause error in our calculations, particularly involving the consumption rates of hydrogen gas by the fuel cell.

In evaluating the efficiency of alternative energy technologies, we have succeeded in fully evaluating this apparatus. By comparing the limits of the efficiency in each portion of the system, the total efficiency is found to range between 16% and 35%. This means that for every 100 Watts of power passed into the electrolyser and thus, stored as hydrogen gas, only between 16 and 35Watts are recovered as usable power by the PEM fuel cell.

Considering that the typical efficiency for fossil fuel power plants is between 30% and 50%, this could be a viable means of storing energy produced by alternative or "green" means, though only if the optimal arrangement of resistances is used.

## V. References


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