On the Use of Solar in Hydrogen Generation and Fuel Cells

Elliott Ashby

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References

[1] Department of Physics: University of Southampton *Solar Cells extension - Hydrogen Electrolyser and Fuel Cell instructions*

[2] Department of Physics: University of Southampton *Production: Solar Energy*

[3] Averil Macdonoald & Martyn Berry *Energy through Hydrogen*, heliocentris

1 Introduction

This project will investigate and document the properties and characteristics of energy generation and conversion using the Hydro-Genius^{TM}Professional module (**Figure 1**), which contains a solar cell, a water splitting cell in order to generate hydrogen and a hydrogen fuel cell. This project aims to provide it's author with an understanding of the fundamentals in the solar hydrogen technology space in addition to explaining why solar hydrogen is a suitable form of sustainable energy for the future. As seen in **Figure 4**.

1.1 Aim

The projects aims are listed below:

- succeeding that, using the solar energy generated to record the characteristic response and efficency of the hydrogen generated, and finally,
- investigate the characteristic response of the solar cell, both under illumination and in the dark,
- to characterize a hydrogen fuel cell's energy conversion.

Figure 1: Hydro-Genius^{TM}[1]

2 Theory

2.1 Production of electricity through solar energy

- Photovotaic panels convert some frequencies of electromagnetic radiation into and electric current.
- These PV panels (see **Figure 5**) create higher-grade electrical energy compared to thermal solar panels

The Photovotaic Effect

- Crystalline semi-conductors are composed of atoms and electrons bound in a lattice.
- If an electron in the lattice gains enough energy, it is radicalized from the lattice and can move, creating a current.
- In photovotaic materials this process can be performed through electrons absorbing electromagnetic radiation.
- The crystalline lattice can be 'doped' using other elements to change how it interacts with these free electrons that fall into two catagories, wither positive (p) or negative (n) carriers.

- For silicon (group IV):
  - P-type: Boron (group III)
  - N-type: Phosphorus (group V)
- These p and n type semiconductors can be placed next to one another to create pn junctions (see **Figure 6**).
- By creating a pn junction, carriers at the interface recombine forming the labeled 'Space Charge Region' also known as the 'depletion layer'.
- The width of the depletion layer can additionally be controlled by applying an external voltage. This is called the diode-effect.
- The IV-curve of the pn-junction (diode) is called the Shockley equation

$$I_D = I_S(e^{\frac{qV_D}{nkT}} - 1) \tag{1}$$

  where I_D and V_D are the diode and voltage respectively, q is the charge on the electron, n is the ideality factor: n=1 fro indirect semiconductors or n=2 for direct semiconductors, k is Boltzmann's constant, T is temperature in kelvin, $\frac{kT}{q}$ is also known as V_{th}, the thermal voltage.
- Under illumination the solar cell follows the Shockley equation but vertically shifted by the photocurrent.

2.2 Water electrolysis using solid electrolyte membranes

In order to electrolyse water, electrodes must be separated by a membrane preventing gases from mixing and creating and explosive combination of hydrogen and oxygen, but still requires ions to pass through it. In order to keep electrical resistance low, the electrodes and solid electrolyte membrane are in extremeley close contact.

- The theoretical voltage required for splitting water into its constituent components is 1.23V. However, in practice, there is waste energy and therefore the usual voltage has to be higher then 1.23V. Good electrode and catalyst design can bring the voltage required down to 1.7 - 1.9V and the closer the operating voltage is to the theoretical minimum voltage, the greater the efficency of the process along with a lower waste of energy.
- **Figure 2** shows an alkaline electrolyser. At it's anode, hydroxide ions give up their extra electrons and are oxidised to oxygen and water. At the cathode, water is instead reduced to hydrogen and hydrogen ions. This completes the circuit since hydroxide ions passing through the membrane from the cathode pass through to the anode side.

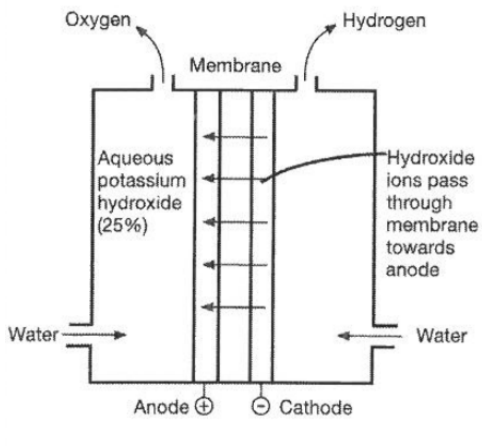

Figure 2: Schematic diagram of an alkaline electrolyser [3]

At the anode: [3]

$$4OH^-(aq) \rightarrow O_2(g) + 2H_2O(l) + 4e^- \tag{2}$$

At the cathode: [3]

$$4H_2O(l) + 4e^- \rightarrow 2H_2(g) + 4OH^-(aq) \tag{3}$$

Overall: [3]

$$2H_2O(l) \rightarrow 2H_2(g) + O_2(g) \tag{4}$$

2.3 Fuel cells

A basic hydrogen fuel cell (see **Figure 3**) consists of two porous carbon cloth electrodes bonded to a polymer electrolyte membrane. Outside the electrodes are flow field plates. These contain channels to ensure that the gases are in contact with the whole surface of the electrodes. They also serve to remove the water which is produced.

Oxidation occurs at the anode and reduction at the cathode. The fuel, hydrogen, is oxydised at the anode and releases electrons. These electrons flow from the anode around the circuit to the cathode. Hydrogen ions flow through the polymer electrolyte membrane to the cathode to balance the charges. [3]

The reactions are hence:

At the anode: [3]

$$2H_2(g) \rightarrow 4H^+ + 4e^- \tag{5}$$

At the cathode: [3]

$$O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(l) \tag{6}$$

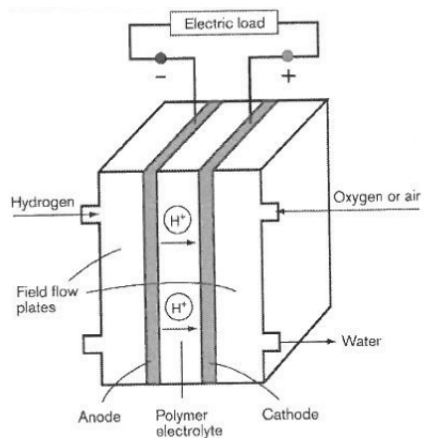

Figure 3: The arrangement in a typical hydrogen fuel cell [3]

Overall: [3]

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(l) \tag{7}$$

A hydrogen fuel cell has a maximum theoretical output voltage of 1.23V since the potential is the same as the decomposition of water. However in practice, becuase of various losses in efficency, such as back reaction, internal resistance and bad diffusion of gases, typically a good voltage will be between 0.6 and 0.9V.
Higher voltages can be easily obatained by connected fuel cells in series in what are called 'stacks'.

3 Apparatus

The Hydro-Genius^{TM}module which contains:

- Electrolyser
- Fuel Cells
- Load (resistance) module
- Ammeter
- Voltmeter
- Solar module

In addition, leads (to connect the apparatus into the circuits required), tubes (for directed water transportation), a fan (for cooling the solar cell), a lamp (100-150 Watt), and distilled water (tap water contains higher proportions of minerals and impurities), are required to carry out the experiments.

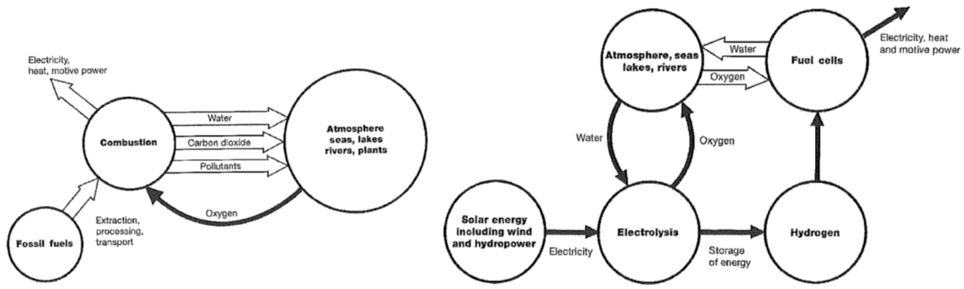

Figure 4: (left) Fossil fuels: main source of energy present, depletion is inevitable. (right) Probable supply of energy in the future through hydrogen: the loop is closed, and the supply can be maintained as long as the sun remains in a steady state. [1]

3.1 Apparatus Notes

In order to maintain good operation of the module and it's components the following notes should be observed:

- Only distilled water should be used, as other liquids may cause corrosion and damage to the intruments.
- The solar module should stay below $60°C$ otherwise damage may be caused to the solar cells or melt the plastic parts.
- Any voltage $>$ 3.5 Volts connected to the modules could cause damage to the instruments and as such no external power supplies with voltage output $>$ 3.5 Volts should be connected.

3.2 Safety

The experiments will produce both oxygen (O_2) and hydrogen (H_2), which will be contained within the module and should pose no risk under normal circumstances and in small amounts. Most notably, ignition sources should be kept at distance to prevent ignition of either the oxygen or the hydrogen when using the electrolyser.
The solar module will become hot when absorbing radiation from the lamp. In the instances when the solar cells are hot, refrain from touching them. A temperature sensor can be used to monitor the temperature of the unit. Make sure the temperature does not exceed $60°C$ By keeping the lamp a good distance from the solar module.

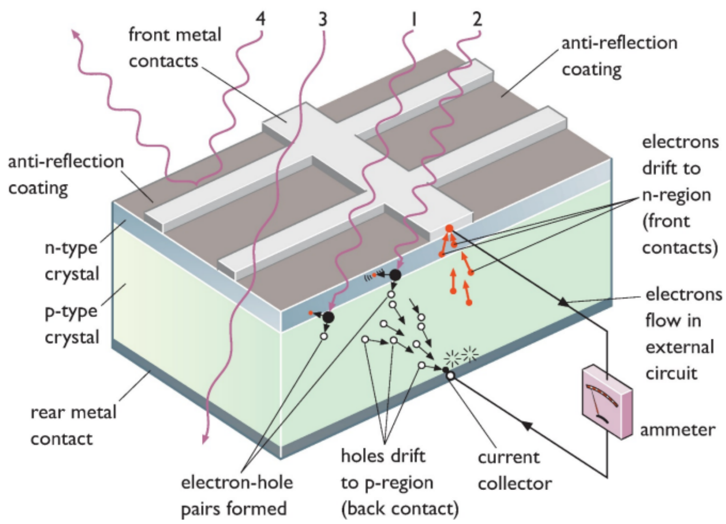

Figure 5: PV solar panel cross section. [2]

4 Methods

4.1 Investigating the electrolysis of water

1. Set up the apparatus like in **Figure 7**, making sure the correct terminals are connected.

2. Vary the light intesity to adjust the current generated by the solar cell. This can be done most easily rotating the solar module at different angles to the lamp. Set different values of current, approximately 30mA to 800mA and record the voltage across the electrolyser.

4.2 Fuel cell

4.2.1 Current-voltage characteristics of the fuel cell

This experiment will use the energy stored in the hydrogen to power a hydrogen fuel cell which works through reverse electrolysis, combining the oxygen and hydrogen to produce electricity and water.

1. The fuel cell, in order to produce electricity and water, needs a supply of hydrogen and oxygen from the electrolyser (see **Figure 8**). Make sure the tubes are correctly connected.

2. Rotate load resistor to the 'OPEN' position.

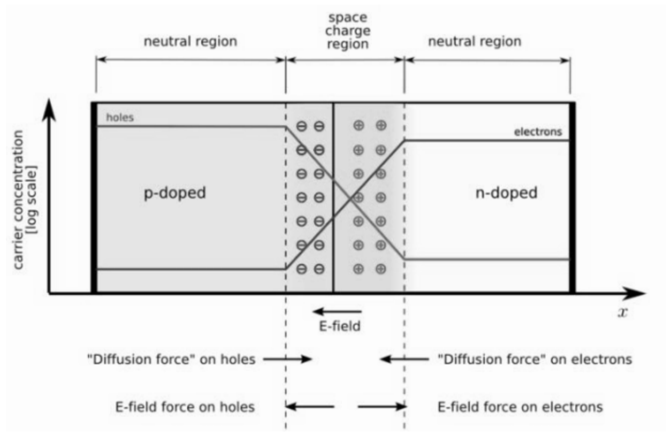

Figure 6: pn junction as used in solar cells. [2]

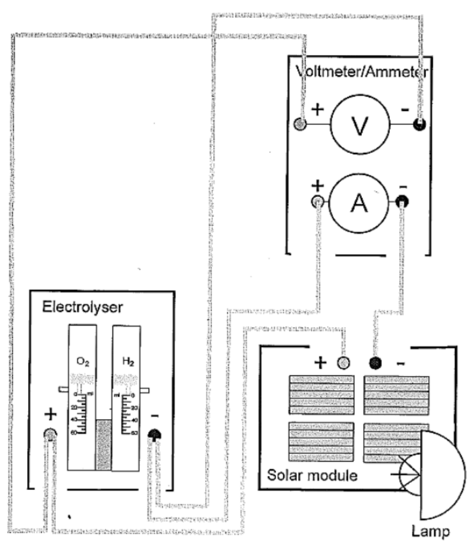

Figure 7: Setup for the electrolysis of water experiment. [1]

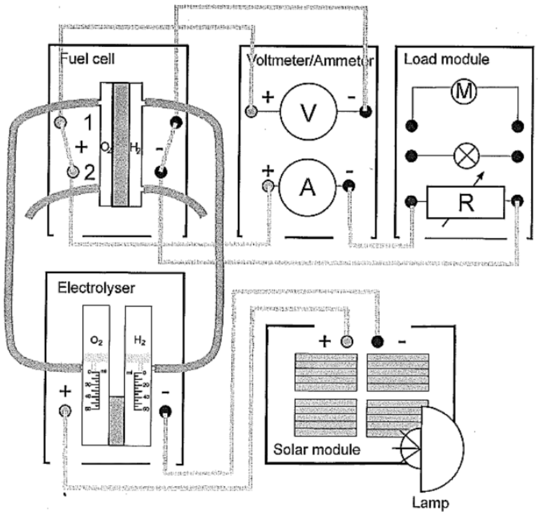

Figure 8: Setup for fuel cell experiment. [1]

3. The gas storage cyclinders should be filled to the 0ml mark. Using the solar module, set a constant current to the electrolyser of between 200 and 300 mA.

4. Purge the system for 5 minutes with the produced gases. Then rotate the load resistor to 3 ohms for 3 minutes. The ammeter should show a current being produced. Purge the system again with the load resistor at the 'OPEN' position.

5. Stop the power supply briefly and use the tube clips to close the two shorter tubes on the lower half of the fuel cell.

6. Reconnect the power supply to the electrolyser and store the gases in the gas storage cyclinders. Interrupt the power supply when the hydrogen side of the electrolyser reaches the 10ml mark.

7. Record the characteristic curve of the fuel cell by varying the measurement resistance. Start at the 'OPEN' position, then measure the volatage and current at each resistance level. Additionally measure the volatage and current for the lamp and the electric motor.

5 Results and Analysis

6 Conclusions