On the Use of Solar in Hydrogen Generation and Fuel Cells

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May 23, 2022

Contents

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

[4] Mini Physics *I/V graph of a semiconductor diode*

[5] Winai Changpeng & Yottana Khunatom *The effect of the input load current changed to a 1.2 kW PEMFC performance*

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

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 efficiency of the hydrogen generated, and finally,
- investigate the characteristic response of the solar cell, both under illumination and in the dark,
- to characterise a hydrogen fuel cell's energy conversion.

2 Theory

2.1 Production of electricity through solar energy

- Photovoltaic 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 Photovoltaic 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 photovoltaic 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 categories, 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 extremely 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 efficiency of the process along with a lower waste of energy.
- **Figure 2** shows a PEMFC, In a typical electrolyser cell, the electrolyser is a thin membrane made for example of Nafion. The membrane is only about 0.25 mm thick. The cathode has a porous carbon structure with very defined divided platinum; the anide has mixed ruthenium and iridium oxides as catalyst, again on a porous carbon base. The anode support consists of titanium coated with platinum, and the cathode support is

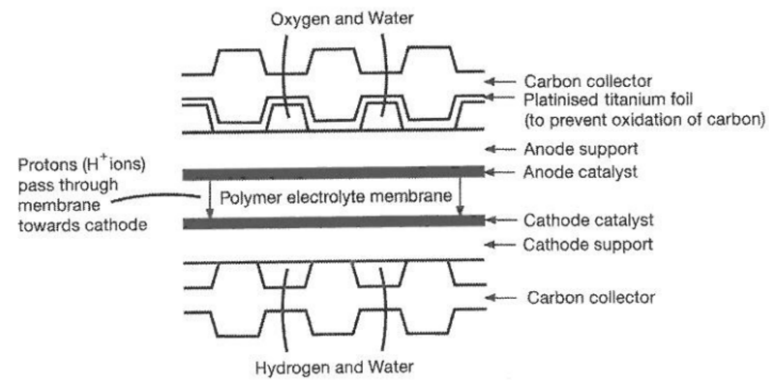

Figure 2: Diagram of a polymer electrolyte membrane water electrolyser assembly [3]

carbon fibre. The carbon collectors carry current, and contain channels so that water can reach all the electrolyte and electrode surface.
Deionised water is used. At the anode, water molecules are oxidised to oxygen and protons, and electrons are released. At the cathode protons are reduced, by gaining electrons to form hydrogen gas. The circuit is completed and the charges are balanced, by protons passing through the membrane from the anode side to the cathode side.
the PEM electrolyser splits pure water into hydrogen and oxygen.

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 oxidised 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]

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

At the cathode: [3]

$$O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O(l) \tag{3}$$

Overall: [3]

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

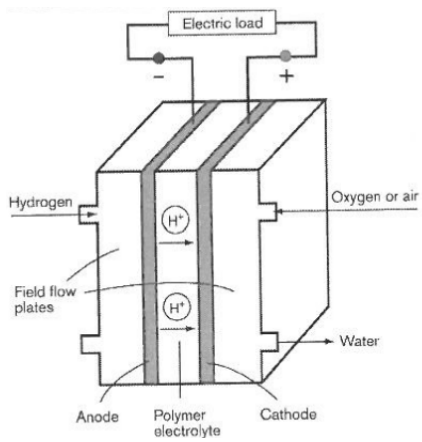

Figure 3: The arrangement in a typical hydrogen fuel cell [3]

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, because of various losses in efficiency, 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.

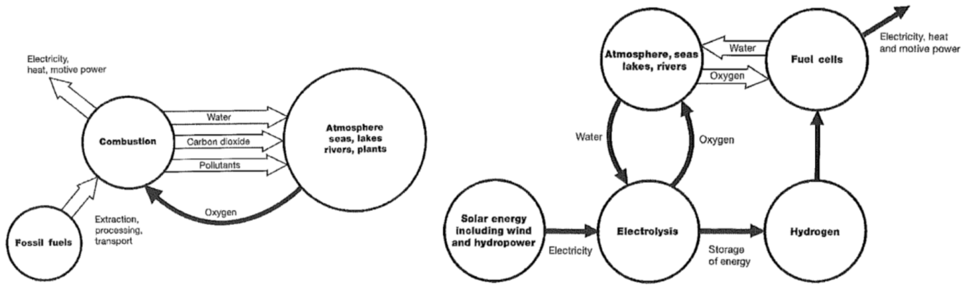

Figure 4: (left) Fossil fuels: main source of energy present, depletion is inevitable. (right) Probable supply of energy in the future through hydrogen: the loop is closed, and the supply can be maintained as long as the sun remains in a steady state. [1]

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 instruments.
- 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.

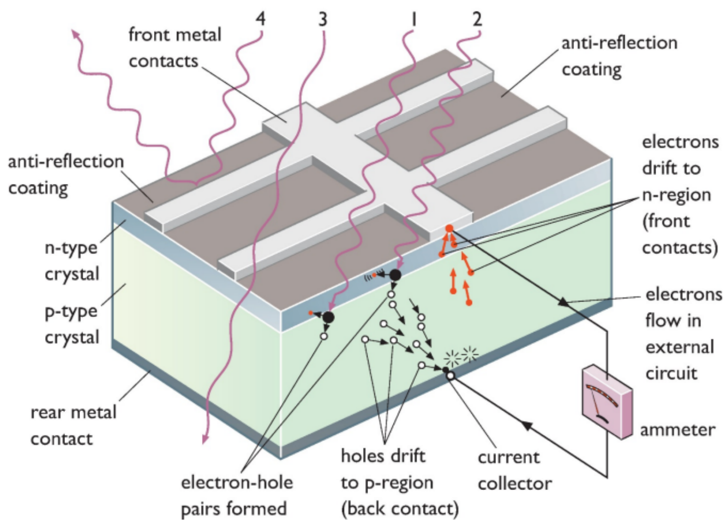

Figure 5: PV solar panel cross section. [2]

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 intensity 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.

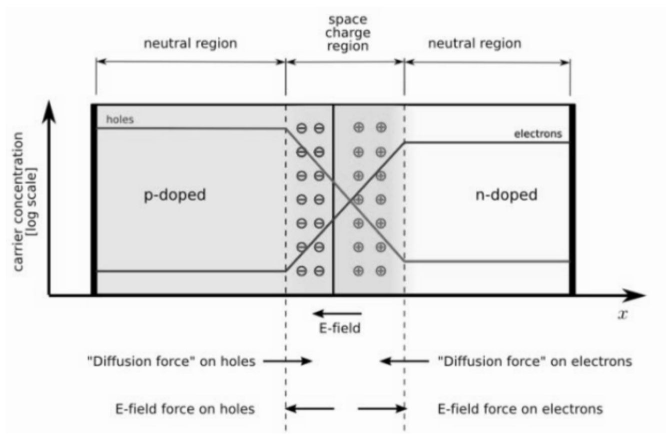

Figure 6: pn junction as used in solar cells. [2]

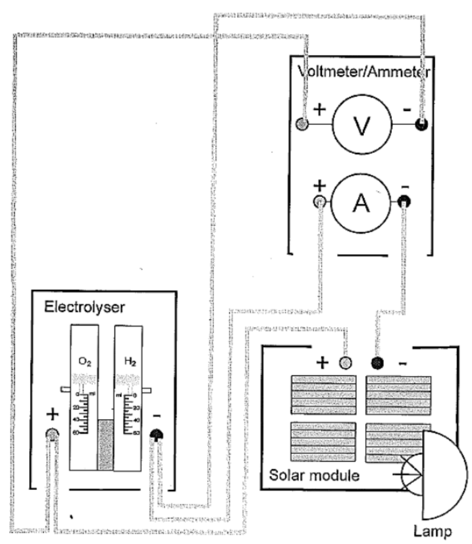

Figure 7: Setup for the electrolysis of water experiment. [1]

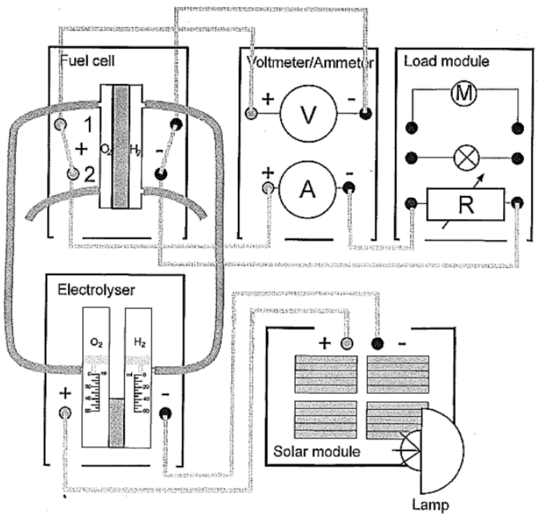

Figure 8: Setup for fuel cell experiment. [1]

3. The gas storage cylinders 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 cylinders. 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 voltage and current at each resistance level. Additionally measure the voltage and current for the lamp and the electric motor.

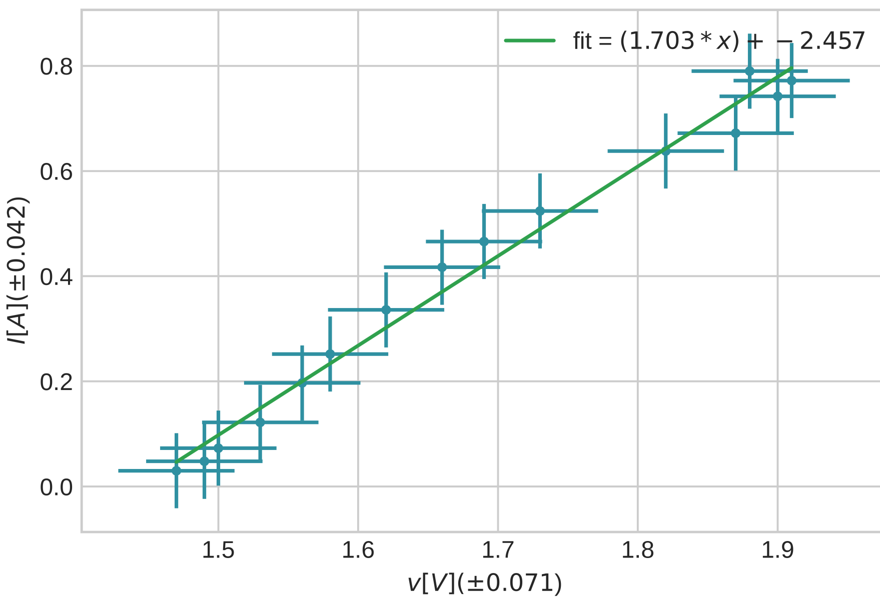

Figure 9: Results from Electrolysis of water → I-V characteristics of electrolyser

5 Results and Analysis

5.1 Investigating the electrolysis of water

Figure 9 shows the I-V response for the electrolyser in the Hydro-Genius^{TM}. The fit is fitted using the scipy python library. The relationship shows a linear relationship between the current and the voltage implying a constant resistance. Here the resistance can be found by calculating 1/gradient since

$$\begin{aligned} V &= IR \\ \frac{V}{I} &= R \\ \frac{I}{V} &= \frac{1}{R} \end{aligned} \tag{5}$$

and therefore, calculating 1/gradient gives a resistance of 0.587 ohms.

Comparing this to **Figure 10**, which shows an I-V response for the solar module without the electrolyser and a load of 2 ohms where using the fit to determine the resistance of the load gives a result of 2.27 ohms, which is closer to the real measured value from the multimeter of 2.25 ohms, shows a discrepancy between the I-V responses. The I-V response of the electrolyser has a minus 2.457 offset. This offset is characteristic of a semi-conductor after voltage V_{th} or the threshold voltage that tends back to 0V, 0A in a curve as shown in **Figure 12**.

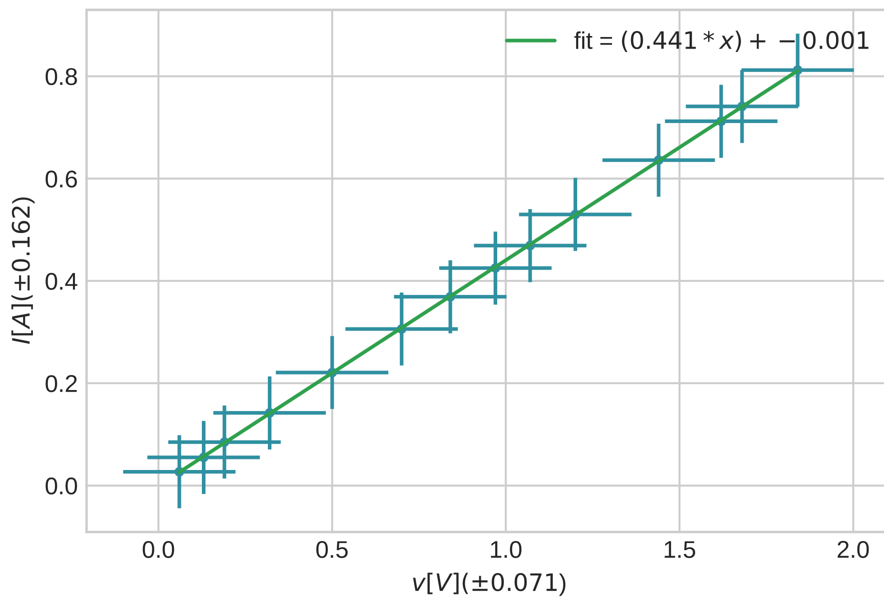

Figure 10: Results from Electrolysis of water → I-V characteristics of 2 ohm resistance load excluding electrolyser

5.2 Current-voltage characteristics of the fuel cell

Figure 11 shows the I-V response of the fuel cell and as expected, since it is the power source of this circuit, it's gradient is negative, showing that higher loads require more voltage but as a cost, lower current. In addition, **Figure 13** shows the same results but with different axis mapping, using this fit shows us that, if only considering the ohmic region of the fuel cells I-V response, it's maximum voltage output is roughly 0.62. However as seen in **Figure 14**, in the Activation region, much higher voltages are possible due to the greater gradient. This allows the fuel cell to output its theoretical maximum of up to 1.23V, the voltage required to electrolyse, or de-electrolyse water.

In addition to the varied resistance load, also seen on **Figure 11** and **Figure 13** are the I-V response for loading the fuel cell with both a lamp (LED) and an electric motor. The motor sits at roughly 0.25V drawing about 12mA and was observed to spin at a moderate speed. However the LED, when its I-V was measured, allowed no current to flow and no light was observed to be emitted. It is likely that one two possibilities explain this.

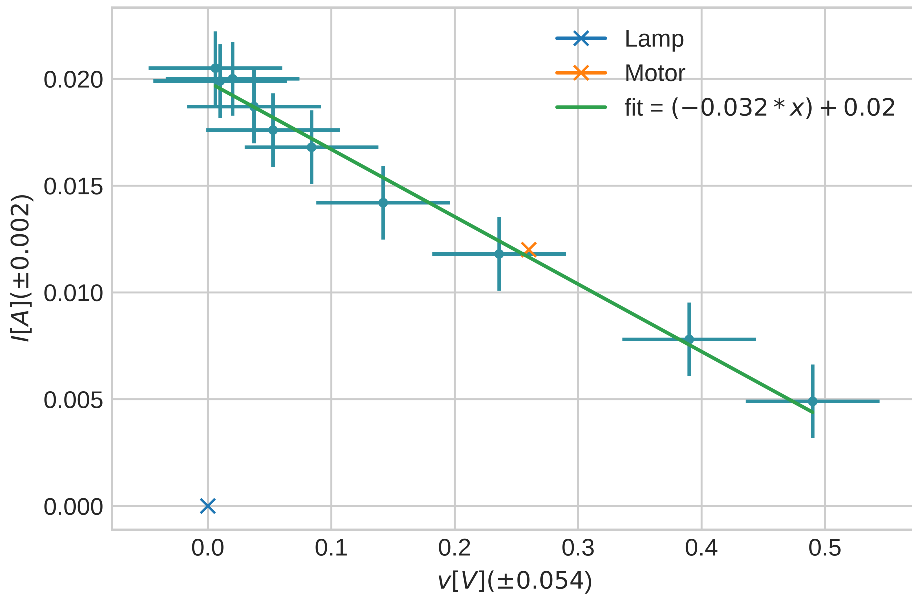

Figure 11: Results from current voltage characteristics of the fuel cell → I-V characteristics of a fuel cell, varying the resistance load with the values 100 | 50 | 20 | 10 | 5 | 3 | 2 | 1 | 0.5 and 0.3Ω

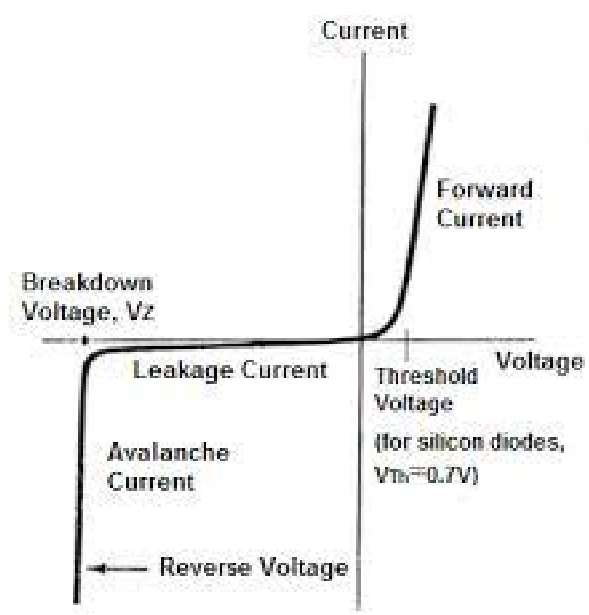

Figure 12: Typical semiconductor I-V response [4]

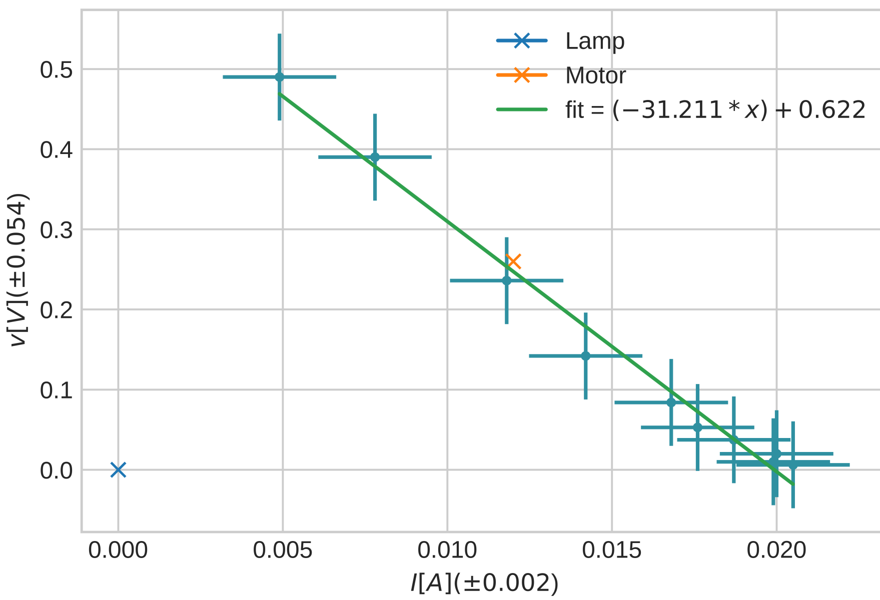

Figure 13: Voltage-Current characteristics of the fuel cell

1. either the LED was broken and allowed no current to flow as the circuit could not be completed,
2. or, as can be seen in **Figure 12**, the voltage could not overcome it's threshold voltage, resulting in no, or negligible forward current hence emitting no visible light.

After using a power supply to test the LED, where in which it did emit visible light. We confirmed it to be option 2.

6 Conclusions

If this extension project, we looked into how water electrolysis using solid electrolyte membranes worked to split water into its constituent parts, and the voltage requirements to do so, how that process can be used to store energy in it's gases and how to generate a current from using the same gases in a fuel cell. Because the voltage needed to split water is a discrete amount, when reversing the process, the output voltage can never be higher than that amount, which in the case of water electrolysis is 1.23V.
We took measurements of these two devices to investigate their I-V characteristics which enabled us to determine their resistances through plotting their respective I-V graphs. This also allowed us to use the y intercept, which is calculated by the fitting algorithm in python, to compare maximum voltage

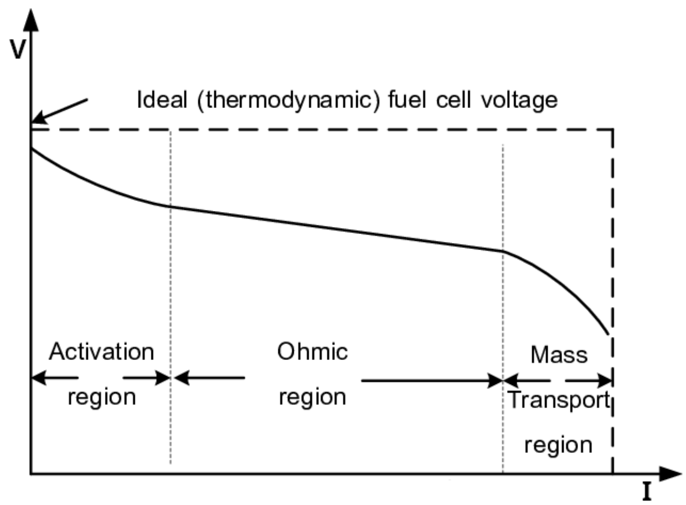

Figure 14: Theoretical I-V curve of a fuel cell [5]

theoretical values and speculate on possible differences between our own data and theoretical predictions.
We managed to successfully determine, during it's ohmic response region, the resistance of the electrolyser, at 2.27 ohms. And suggest reasons as to why our limited range of current and voltage reflected the limited scope of I-V response we received, such as receiving a maximum V from the fuel cell at 0.62V instead of the theoretical 1.23V.

Errors in this project entirely came from resolution or inaccuracies in multimeters. These errors are very low, around a maximum 10% at smaller measured values and as low as 1% for higher values. These and repeated readings were used to calculate SEM ($\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$) since uncertainty is measured with a variance or its square root, which is a standard deviation. This standard error can then be used in the fitting algorithm to obtain more accurate fits since the variance in the data is weighted along a gaussian from it's center.
Our results would have been improved by taking more readings closer to the non-ohmic regions of the I-V responses, this would allow us to model a greater range of I-V characteristics are more accurately determine aspects like maximum voltage and the electrolyser's current offset.