An Experimental Set-up for Electricity Generation from Water Using Hydrogen Fuel Cell

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Abstract
In this research, electricity is successfully generated at the Faculty of Engineering, Department of Electrical & Computer Engineering (ECE) laboratory from water using a hydrogen fuel cell as an alternative to the popular hydroelectric technology; which possess limitations ranging from seasonality to construction time. This was achieved by building a Proton Exchange Membrane Fuel cell (PEMFC), more popularly known as the PEM fuel cell and using it to generate electricity from water. On first trial, an input voltage and current of 3.4V & 1.54A respectively were applied to the system of 1.37liters of water and 411g of NaOH. No system output was recorded. A second trial was then carried out with the fuel reduced to a quarter of the original amount, this recorded an increase in hydrogen production rate as well as a peak voltage in addition to current of 11 volts and 5.3 amps respectively. However, no activity was observed in the fuel cell or bubbler. Trial 2 revealed that the hydrogen was not reaching the Membrane Electrode Assembly (MEA) inside the assembly, the solution was to increase the gas port from $^{9}/_{64}$'' to $^{1}/_{5}$''. The gas port, input voltage and current were increased for a 3rd trial. After several component troubleshooting & testing, the system was set up and within a period of 1 – 2 minutes the fuel cell gave a rising output starting at 0.01 volts and peaking at 0.7 volts driving a small motor at 0.3V. These results showcase the flexibility of fuel cells to extract energy from water to invigorate low power electronic devices as well as the portability of the technology compared to hydroelectric technology.

Keywords: Renewable Energy, Fuel cell, Electrolyzer, Proton Exchange Membrane (PEM), Sodium Hydroxide (NaOH), Membrane Electrode Assembly (MEA)

Introduction

The Renewable energy sector has made significant progress in an attempt to tackle the issue of global warming (World Bank, 2018). Traditional fossil fuels are a natural and unsustainable energy storage medium with limited reserves and notorious pollution problems, therefore demanding a better choice to store and utilize the green and renewable energies in the future. Energy and environmental problems require a clean and efficient way of using the fuels (Sazali et al., 2020). The world is currently experiencing a severe energy crisis as a result of the unsustainable rate at which energy demand is growing (Sarma et al., 2021). The recent usage of renewable energy sources in response to rising energy demand and issues brought on by the use of fossil fuels. Renewable energy sources considerably lessen environmental crises and are clean and readily available (Wang et al., 2021). The most common way of producing electricity from water is hydroelectric technology, one of the oldest renewable energy sources. However, the use of water as a fuel has been restricted due to limitations such as seasonality, location, initial cost, and construction time, the use of water as a fuel has been limited (Rajput, 2015; Sundmacher, 2010).

The fuel cell, on the other hand, is a sustainable energy technology that can convert water to electricity without the limitations of hydroelectric technology. A fuel cell is a type of stationary energy conversion device that converts a fuel's chemical energy into direct current (DC) electrical energy(Hashem Nehrir & Wang, 2015). With the help of power electronic converters, fuel cells can be used for a variety of applications, such as stationary power for buildings, cogeneration, and power generation for stand-alone systems (such as standalone micro-grids) and grid-connected ones. Fuel cells can also be used for electric transportation as the primary and/or auxiliary power source. (Hashem Nehrir & Wang, 2015).

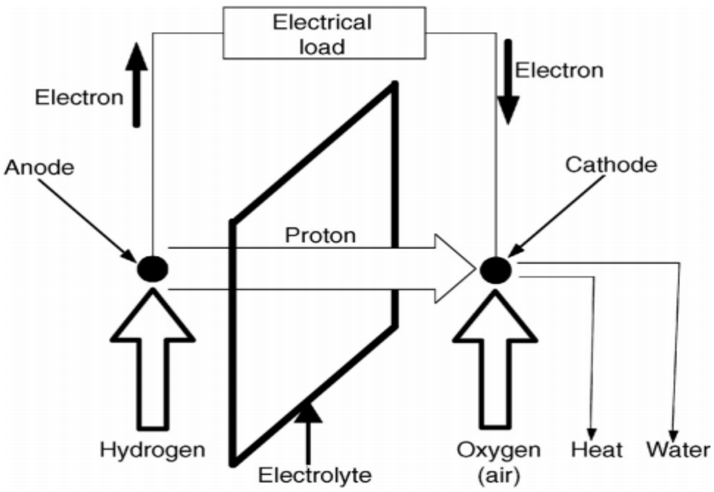

Figure 1: Working Principle of a Hydrogen Fuel Cell(Hashem Nehrir & Wang, 2015)

Figure 1 shows the fundamental hydrogen fuel cell's operational idea. At the anode, electrochemical reactions split hydrogen atoms (the fuel) into hydrogen ions and electrons. From the anode to the cathode, hydrogen protons can go through the membrane/electrolyte, but electrons cannot. The cathode is where electrons go via an external electrical circuit (load) to recombine with hydrogen protons and oxygen atoms to create water and heat (Hashem Nehrir & Wang, 2015). The following are the chemical reactions at the anode and cathode respectively(Felseghi et al., 2019):

$$2H_2 = 4H^+ + 4e^- \quad (1)$$

$$0_2 + 4H^+ + 4e^- = 2H_2O + heat \quad (2)$$

A hydrogen fuel cell must be part of a system made up of the fuel, fuel processor, fuel cell, power conditioner in order to function (Kunze-Liebhäuser et al., 2019).

According to the characteristics of their electrolyte, which also defines their working temperature, fuel type, and a variety of uses, fuel cells are categorized. The electrolyte can be an ion-conducting solid ceramic or polymeric membrane, an acid, base, or salt (Edwards et al., 2008).The six types of fuel cells that are most frequently used on the market today are the polymer electrolyte membrane/proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), direct methanol fuel cell (DMFC), solid oxide fuel cell (SOFC), and molten carbonate fuel cell. (Hashem Nehrir & Wang, 2015).

While fuel cells fall short of hydroelectric technology in terms of efficiency (by 40–60% compared to 90%), they make up for this in terms of portability, noiseless operation, absence of seasonal dependence, cost, required space, and diversity (Hashem Nehrir & Wang, 2015; Rajput, 2015; Interior et al., 2005)

Literature Review

In (Lucia, 2014) PEMFC (proton exchange membrane or polymer electrolyte membrane fuel cell) uses platinum-catalyzed electrodes and an acidic, water-based polymer membrane as the electrolyte. It uses carbon monoxide-free natural gas as well as pure hydrogen. It operates at a temperature of less than 100°C. (Kirubakaran et al., 2009) provides a thorough analysis of various fuel cell technologies, including their operating principles, benefits, drawbacks, and suitability for use in residential/grid-connected systems, transportation, businesses, industries, and other settings.

The goal of (Edwards et al., 2008) is to succinctly summarize the current situation, significant technological and scientific problems, and projection of hydrogen and fuel cells within a long-term vision of sustainable energy. The paper (Felseghi et al., 2019) examines the particular qualities of hydrogen energy and suggests using it as a clean energy source to power stationary applications. The purpose of the review was to identify opportunities for increasing the share of hydrogen energy in stationary applications, as well as to provide an overview of the sustainability components and potential of using hydrogen as an alternative energy source for stationary applications. By evaluating control strategies in the literature for fuel economy, (Hames et al., 2018) presents the best hydrogen fuel cell vehicle layouts and control strategies for safe, affordable, and high efficiency. (Hassan et al., 2019) demonstrated the potential for producing bioelectricity from sugarcane molasses utilizing microbial fuel cell technology employing a bacterial strain that was isolated from the molasses. Table 1 compares fuel cells to other renewable energy sources among the various literatures analyzed (Rajput, 2015; Hashem, et al 2015).

Table 1: Comparisons between Fuel Cell and other Renewable Energy Sources

Parameters	**Fuel Cell**	**Solar**	**Wind**	**Geothermal**	**Hydroelectric**	**Nuclear**
Efficiency	40-60%	15-20%	30 - 50%	12-21%	90%	33 -45%
Portability	Highly portable	Portable	Not portable	Not Portable	Not portable	Not portable
Noise	Noiseless	Noiseless	Noise is present	Noise is present	Noise is present	Noise is present
Seasonal	No	Yes	Yes	No	Yes	No
Input Fuel	Hydrogen	Sunlight	Wind	Steam	Water	Nuclear materials
Surface Space Requirement	Low	High	High	Low	High	High
Versatility	High	Medium	Low	Low	Low	Low

Methodology

Fuel Cell System

The system's components were carefully chosen. It consists of water, which served as the primary fuel. However, NaOH (sodium hydroxide) was added to make the water more conductive (Hurley, 2002). For efficient gas production, the concentration of the Sodium Hydroxide solution should be between 23% to 30%. The fuel processor used is an alkaline electrolyser which is a gadget that uses electrolysis to split down water into oxygen and hydrogen (Smolinka, 2009).

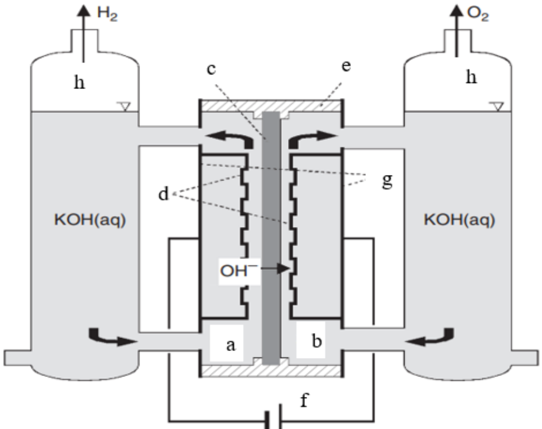

Figure 2: Schematic Diagram of an Alkaline Electrolyser(Smolinka, 2009).

(a) Anode Compartment, (b) Cathode Compartment, (c) Diaphragm/Separator, (d) Electrodes, (e) Cell Frame/Casing,

The schematic diagram of an alkaline electrolyser, which was chosen because it is inexpensive, is shown in Figure 2 above, and table 2 below lists the components that were utilized to make the device. Proton exchange membrane (PEM) fuel cells are the fuel cell of choice since they convert hydrogen into electrical energy. There is no need for a power conditioner or storage device because the load that needs to be powered is a modest DC load. The aforementioned decision was primarily influenced by three variables: cost, availability, and renewable potential.

Table 2: Materials used for the Electrolyzer.

Part	Material
Anode/Cathode Compartment	1 Litre Polyethylene Terephthalate (PET) Bottle
Separator	Absent
Casing	1.5 Litre PET Bottle
Electrodes	Stainless Steel
Dc Power	Laboratory Dc Rectifier Circuit
End Plates	Stainless Steel
Miscellaneous parts include steel and plastic washers nuts and bolts, copper hose, and plastic tube	

PEM fuel cells are the most recently researched fuel cell, making them a great option for this research because the majority of their material is one of the most widely used on the market.

Table 3: Materials used in the fuel cell

Fuel Cell Part	Material
End Plate	Polyvinyl (PVC) Sheet
Bipolar/Graphite Plates	Graphite
Gasket	Silicone Rubber
Membrane Electrode Assemble (MEA)	Was purchased
Miscellaneous Parts Include Stainless Steel, Steel Nuts Bolts& Washers, Shrink Tubing, and Mylar Sheet	

Table 4: Table showing Measurement of electrolyser component

Material	Measurement/Quantity
Stainless steel	10 pieces in total each being 6"(inch) long, 2" wide, with 4 hole $^{39}/_{100}$" in diameter
Polyvinyl Chloride (PVC) Hose	$1^{1}/_{2}$ " inside diameter tube and 2" outside diameter pipe
Copper Tube	$1^{1}/_{2}$ " inside diameter and 2" outside diameter
Polyethylene Terephthalate Bottle	A single three-liter bottle and two 1 litre bottle will be needed
Power supply	A DC voltage source of 13V
Screws and Nuts	socket head nuts $3^{1}/_{2}$" in length, hex nuts with $3^{1}/_{2}$" in inner diameter and washers having $^{3}/_{16}$" in inner diameter

Measurements of fuel cell components

The measurements of each fuel cell component, including the sizes of the holes for the gas port and fasteners, were included in a schematic design for a fuel cell taken from the literature review (in order for nuts to pass through and bind the cell). A 0.20-inch thick, 12 by 12-inch thin gauge silicone rubber sheet was bought, cut using a cutting knife to the dimensions shown below, and the hole was drilled with a bench drill using the template below:

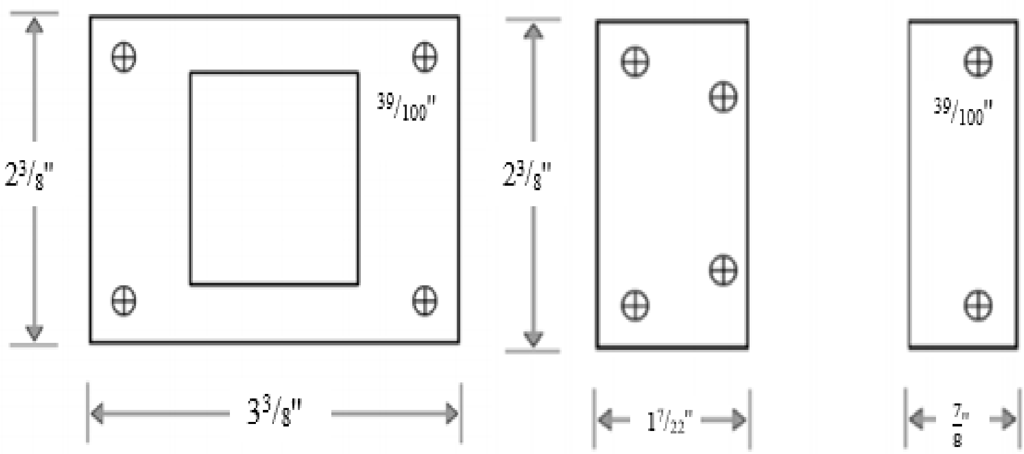

Figure 3: Measurement of Silicone Rubber (Hurley, 2002)

Using the below-listed parameters, the graphite was bought, the hole was drilled, and the dimensions were cut:

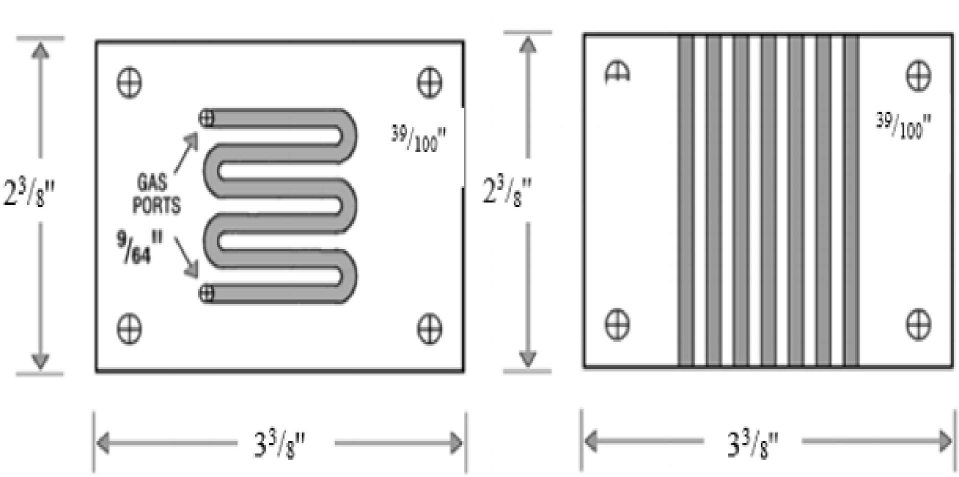

Figure 4: Measurement of Graphite Used (Hurley, 2002)

The 3/8-inch-thick Polyvinyl Chloride (PVC) sheet was obtained, cut (with a hack saw) to the following dimensions, and the holes were drilled to correspond to the picture below:

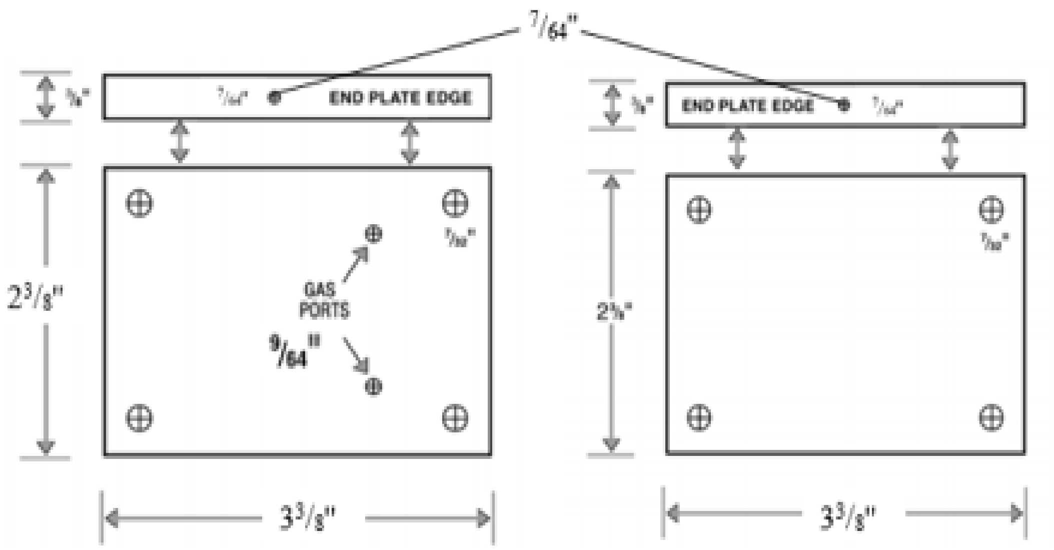

Figure 5: Polyvinyl Chloride (PVC) Sheet (Hurley, 2002)

Using figure 6 below, a steel sheet measuring 24 inches wide by 7 inches long and 0.010 inches thick was obtained. A bench press was used to get the appropriate dimension, and a bench drill was used to get the desired hole size.

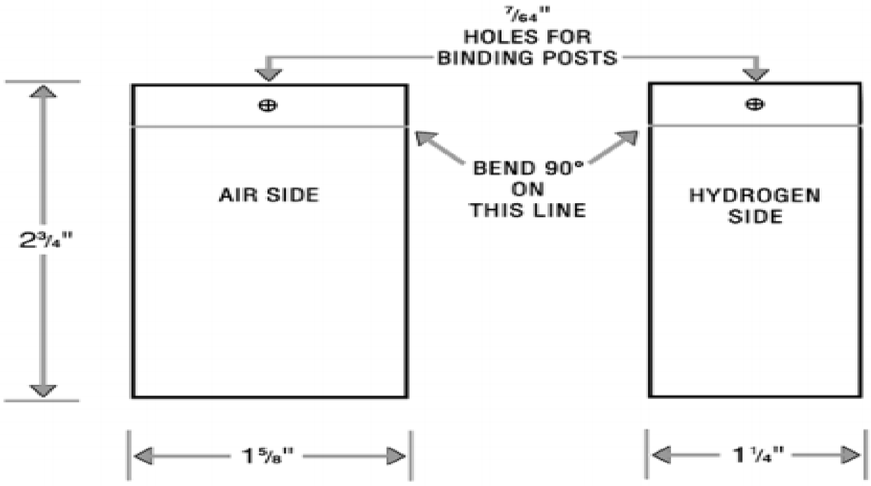

Figure 6 : Steel electrodes (Hurley, 2002)

Table 5: Table showing measurement of fuel components

Material	**Measurement/Quantity**
Membrane Electrode Assembly (MEA)	4.33" × 4.33"
Screws	Sockets head, $1^1/_2$" in length
Nuts	Hex, $1^1/_2$" in inner diameter
Washers	$^3/_{16}$" in inner diameter
Shrinking tube	should be able to be reduced to $^1/_8$"
Copper tube	$^1/_5$" inner diameter
Mylar sheet	This material is to follow the specifications of silicon rubber
The screws, nuts, & washer materials should be at least four in quantity. The shrinking and copper tube should be at least 30cm in length	

Tools used

The table below lists the tools used to streamline materials to the measurement desired.

Table 6: List of tools used for the project

Tool	**Materials used on**
Hacksaw	PVC sheet, PET bottle, Graphite.
Cutter	Silicone rubber, PET bottle, copper and PVC tubes.
Glue gun	PVC bottle, copper and PVC tubes
Shearing machine	Stainless steel.
Drilling machine	Graphite, PVC sheet, Stainless steel, silicone rubber, mylar sheet.
Soldering iron	PET bottle
Files	PVC sheet, Graphite
Spanners	Nuts & bolts

Laboratory Set-up

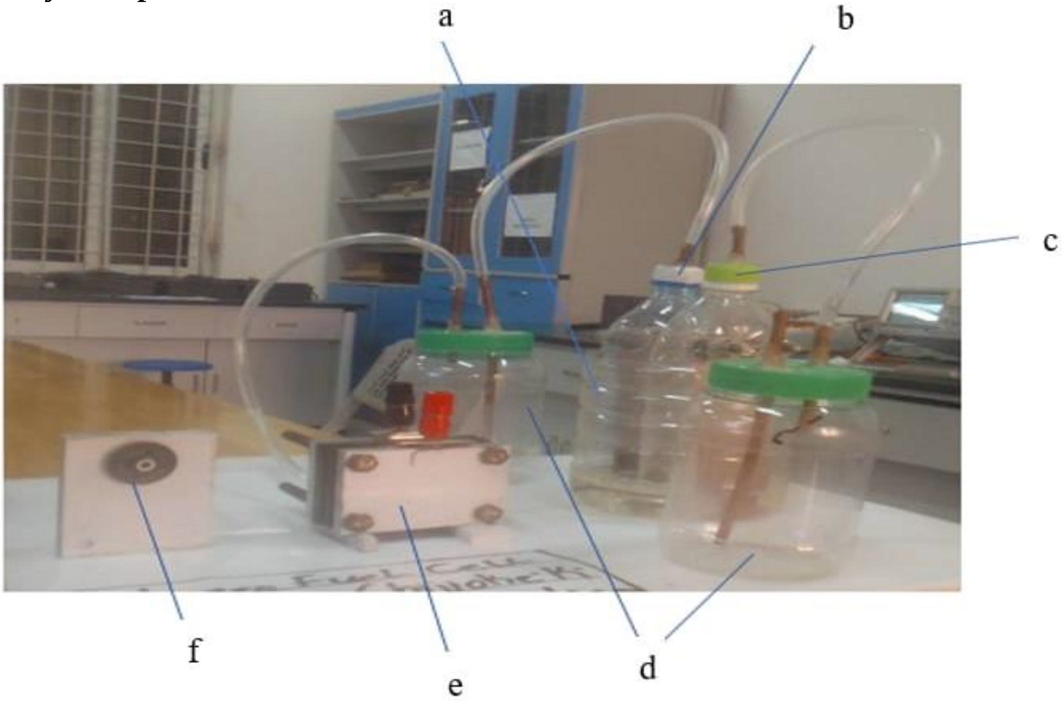

Figure 7: Image of Constructed Hydrogen Fuel Cell System

(a) base/casing of electrolyzer (b) anode compartment of electrolyzer (c) cathode compartment of electrolyzer (d)bubblers of electrolyzer (e) coupled fuel cell (f) DC motor

The built-in fuel cell system is depicted in figure 7 above. The experiment was run three times before it was successful.

<u>Trial One</u>

Figure 7 depicts the assembly of an electrolyzer comprised of ten (10) stainless steel plates, pet bottles, steel, plastic bolts, nuts, and washers. Then, using copper tubing and PVC pipe, this was connected to a fuel cell made of stainless steel, Polyvinyl Chloride (PVC) sheet, graphite, binding post, Mylar sheet, and Membrane Electrode Assembly (MEA). A 1.5-liter container contained 1.37 liters of distilled water. At 3:00 p.m., 411 grams of sodium hydroxide (NaOH) were weighed out and added to the water in the storage tanks to create a 30 percent NaOH solution. Heat started to be produced by the reaction, and as it continued to increase in temperature, the PET container eventually split and leaked. The electrolyzer's base was quickly filled with the solution.

The fuel cell's gas port was connected to the bubbler by the cathode compartment, and the electrodes were inserted into the base of the electrolyzer and connected to the Department's Laboratory DC supply. The electrolyzer's anode section's flame arrestor was allowed to discharge its output into the atmosphere. After then, the DC supply was turned on.

<u>Trail Two</u>

Then, in an effort to address the overload problem, the number of plates on each portion of the electrolyzer was decreased to one. The DC supply was then connected in an open circuit with these compartments, and readings as high as 39 volts were noted. The system was next tested after being set up identically to the prior trial and using a fresh NaOH solution. The DC's overload indicator was still functioning, though, and readings of 3.4 to 4 volts and 1.4 to 1.6

Amps were taken. A continuity test was performed on the fuel cell after replacing the DC supply. The gas port was extended from 9/64" to 1/5" since it was determined that hydrogen was not getting to the Membrane Electrode Assembly (MEA).

Trial Three

Although the gas port was enlarged as required, the fuel cell failed to generate energy. At this stage, the input voltage and current ranged between 9.4 and 11 volts and 4.67 and 5.3 amps. The electrolyzer's old base had to be replaced because it was damaged. The fuel processor was then filled with pure water, and a voltage as high as 39 volts was recorded, but the rate of hydrogen synthesis was zero. After then, the NaOH solution's concentration was lowered while the pace at which hydrogen was produced also increased. However, no output voltage or current were seen.

The fuel cell underwent a continuity test, and the results were unfavorable. Additionally tested, the Membrane Electrode Assembly (MEA) burned out as a result. After some troubleshooting, it was determined that the fuel cell's gasket, which prevented continuity between the graphite plate and metal electrode, needed to be removed. The spare Membrane Electrode Assembly (MEA) was then used. The fuel cell was then put together, the system was configured, the bench power supply was turned on, and after 1–2 minutes, output from the fuel cell running a little motor at 0.3V was measured.

Results and Discussion

The first trial's highest input voltage and current were just 3.4 volts and 1.54 Amps, respectively, whereas a total of 13 volts was anticipated. Small amounts of hydrogen production were indicated by bubbles in the electrolyser, but the load, a DC motor connected to the fuel cell, showed no signs of movement. A voltmeter was then connected to the binding post of the fuel cell, but no reading was seen. Table 7 below provides a summary of the first experiment.

Table 7: Summary of Trail One

Parameter	**Value**
System Input voltage	3.4 volts
System Input Current	1.54 Amps
Total number of plates	10
Amount of water	1.37 liters
Amount of NaOH(concentration)	411 grams (30%)
Temperature of solution	Not recorded
System Output voltage	Nil
System Output current	Nil

While the solution in the anode area remained unaltered, the solution by the cathode compartment started to turn pink. The electrolyzer base displayed evidence of heat distortion, the laboratory overload indicator was on, and the steel plates had both brown and black coloration where they were in contact with the fuel.

In experiment two, the fuel was cut in half from the initial amount, which resulted in an increase in the rate at which hydrogen was produced as well as a peak voltage and current of 11 volts and 5.3 amps, respectively. However, neither the fuel cell nor the bubbler showed any signs of action. In table 8 below, a summary of trial two is presented.

Table 8: Summary of Trial two.

Parameter	**Value**		
Open circuit voltage (with plates)	39 volts	Not measured	Not measured
System Input voltage	3.4 – 4 volts	6.2 volts	11.2 volts
System Input Current	1.4 – 1.6 Amps	2.35	5.3 Amps
Total number of plates	2	2	2
Amount of water	1 liter	1 liter	250ml
Amount of NaOH(concentration)	300 grams (30%)	300 grams (30%)	Not measured (30%)
Temperature of solution	Not recorded	Not recorded	Not recorded
System Output voltage	Nil	Nil	Nil
System Output current	Nil	Nil	Nil
Continuity Test	Not conducted	Not conducted	Passed

The electrolyzer's cathode compartment was then directly linked to the fuel cell, but no difference was noticed. The membrane electrode assembly (MEA) was then removed from the fuel cell and tested. This was accomplished by covering the cathode part with the Membrane Electrode Assembly (MEA), which allowed voltages between 0.1 and 0.2 volts to be recorded. This test showed that the hydrogen was not getting to the Membrane Electrode Assembly (MEA) inside the assembly. The gas port was increased from 9/64" to 1/5" as a result of this. The input voltage and current ranged from trial three onwards, from (9.4 to 11) V and 4.67 to 5.3 Amps, respectively.

Several minutes after the fuel cell was turned on, a tiny motor was driven at 0.3 volts by a growing output that began at 0.01 volts and peaked at 0.7 volts. 53.24mA was the peak current that was recorded. A summary of Trial Three can be seen in the table below.

Table 9: Summary of Trial three.

Parameter	**Value**			
System Input voltage	9.4-11 volts	39 volts	11.5 volts	11.5 volts
System Input Current	4.67-5.3 Amps	Not recorded	5.01 Amps	5.01 Amps
Total number of plates	2	2	2	2
Amount of water	<250 ml	750ml	>250ml	>250ml
Amount of NaOH (concentration)	Not measured (30%)	Not added	Not measured	Not recorded
Temperature of solution	Not recorded	Not recorded	Not recorded	Not recorded
System Output voltage	Nil	Nil	Nil	0.7 volts(peak)
System Output current	Nil	Nil	Nil	53.24mA(peak)
Continuity Test	Not conducted	Not conducted	Failed	Not Conducted

Conclusion

This study proposes an experimental configuration for hydrogen fuel cell-based electricity generation. A hydrogen fuel cell and electrolyzer were built in the lab to do this. In order to develop a design for the fuel cell and electrolyzer's construction, a comparative literature review was investigated. Along with this, a market analysis of the building materials was conducted, the necessary components were bought, and the fuel cell was built as specified utilizing the available tools. The objectives of building a fuel cell and electrolyzer have been accomplished, according to the results. Throughout this work, other benefits of fuel cell technology have also been illustrated, including portability, a minimal surface demand, independence from the seasons, noiseless operation, and versatility.

Fuel cell technology is not a recent development, and like all technologies, it has drawbacks and advantages. If implemented properly, our economy may transition from one based on fossil fuels to one based on water, or more commonly, hydrogen.

Recommendation

The following suggestions are suggested in order to prevent some of the issues encountered:

1. Nickel sheet should be used in place of stainless steel as it is more readily available, than pure steel, and easier to machine to the desired product.
2. Single plates should be used for the compartments in each electrolyzer. Stacking up plates as done in the first trial will give way to the faraday cage effect, which makes the stacked plated give the same output as a single plate.
3. A DC source (Battery or solar panel) should be used instead of a Laboratory rectifier source. Although the electrolyzer bubbler and the fuel cell gasket had to be bypassed in order to accomplish the goal, every material used suited its purpose, especially in the fuel cell. The system will need to be optimized to create more electricity, and it will need to be made sure that every component utilized during the designing process is also used throughout the construction phase.

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