Clean Gen

Portable Charging and Power for Developing Countries

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Powering a brighter tomorrow

Capstone Group M1

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1. Abstract

Clean Gen is an energy generation and storage system devised to provide energy to those with limited or no access to reliable electricity. The system combines battery and fuel cell technologies to efficiently store and deliver energy generated by a solar panel. It is designed to meet the energy needs of those currently underserved by energy providers in developing countries. The system is financially accessible to the lower economic brackets of developing countries because it is shared among a group of users, who together contribute payments to cover the system cost. Clean Gen is an affordable, efficient option for those living without electricity in developing parts of the world.

2. Introduction

To understand the aim of Clean Gen, it is necessary to investigate the background of the project, the primary motivations, and an overview of the proposed system.

2.1 Background

Renewable energy has become an important issue both environmentally and economically across the globe. There is a strong need to consider the future of the environment and to find clean energy that is affordable for all. Solar energy is a readily available renewable resource that can provide power to people around the world, but only when the sun is shining. Solar energy is widely available during the day, but energy usage typically is the highest at night, when more people are in their homes.

Solar energy can provide power to those who do not have access to the grid, such as populations in developing nations. In order to provide this energy to people who do not have access to electricity, it must be stored so that these people can have access to power for 24 hours a day. Many systems available are typically too expensive for these individuals.

The idea for Clean Gen derived from a Tanzanian solar energy company called Sikubora. In Tanzania, 75% of the population does not have access to energy. The energy that is available is provided by TANESCO, a government-owned utility; however, TANESCO cannot meet the energy needs of Tanzanians and as such, those connected to the grid endure regular power outages. Sikubora, along with other solar providers, installs solar systems for people who do not have access to the grid or experience frequent blackouts. Their systems are installed into homes so that families can have electricity for their phones, TVs, radios, and lighting. These systems can be costly, so Sikubora must offer loan options to reach customers in need of energy. Even with the cost of a system reduced to low monthly payments spread out over three years, energy is still inaccessible to a wide economic bracket. Thus, a substantial percentage of the citizens there cannot afford a solar home system and are left unserved. This is the case in many developing parts of the world where solar energy is a viable resource.

2.2 Project Overview

Clean Gen is an innovative, efficient technology that will serve those still without access to energy. The proposed system implements a solar panel to collect energy from the sun which is subsequently stored in a hybrid fuel cell and battery system. The solar panel generates electricity, which simultaneously charges a battery and powers an electrolyzer. The electrolyzer is supplied water and splits it into oxygen and hydrogen, which can then be used in the fuel cell. Water enters the electrolyzer and pure H_2 will be either passed to the fuel cell or stored for later. The fuel cell and battery system work in tandem, with a switch connection to the output controlled by an Arduino microcontroller. Depending on hydrogen availability, the appropriate power source, fuel cell or battery, will be connected to an inverter to power common household appliances like mobile phones and LED lights. The system is placed on a cart to enable mobility and facilitate sharing between households.

Clean Gen is an environmentally sustainable alternative to current systems that rely only on batteries. By using a fuel cell, negative environmental impact can be minimized, yet a high level of efficiency can still be maintained in the system. The battery used is more efficient and will last longer than currently used batteries in many solar home systems. Clean Gen is an ideal combination of environmental consciousness and practical efficiency. The inputs to the system are solar energy and water, which are largely available resources in many parts of the world.

2.3 Motivation

There is a strong benefit to providing electricity to underserved communities in Tanzania and in other developing nations. Electricity has been the foundation for developing many of the aspects that are ubiquitous today, such as the internet and mobile phones, technologies that have increased the quality of life of many people around the world. Electricity allows students lighting to study at night and aids medical professionals in treating disease, for example. Although electricity is a fundamental aspect of life, for a country where the gross domestic product per capita is approximately $865/year, it can be hard for a family to finance the purchase of a solar home system costing approximately $850, even with the help of a payment plan or loan.

Sikubora explained some challenges with current systems offered. There are many customers who cannot afford their systems, and they are experiencing a few technical problems with their systems. The way energy is currently stored for a solar panel is inefficient and expensive, and it could be more environmentally friendly. After learning about Sikubora's challenges, Team M1 formed two primary focus points for Clean Gen in order to best solve such problems with present solar energy systems in Tanzania. The first consideration evaluated for the system was its cost. Unlike some of the current systems today, Clean Gen will be comprised of lower cost materials that still provide an acceptable level of performance to meet these needs of these individuals in developing countries. By providing a system that is cheaper, a much larger percentage of the population can have access to some form of electricity.

The second consideration for the project was to make the system mobile. Shared economies around the globe have made access to different goods and services much more affordable to each individual that uses them. The same can be done in relation to energy. If a system is mobile, then it can be shared. Several families within a village or other small community can pool together money so that all can have electricity. A single family might not be able to afford one system, but several families as a whole can.

In this capstone project, traditional energy generation and storage elements are combined with novel elements to develop a system tailored to the needs of developing countries. This is realized via appropriate tradeoffs between costs, power efficiencies, and overall energy density. Due to the natural resources in Tanzania and a campaign for hydrogen fuel that is spreading from South Africa, fuel cells have a bright and economical future in this region. In addition, by increasing the efficiency of a pre-existing system, this project lays a foundation that will guide the integration of greater developments in technology.

The goal of the project is to provide energy to residents in developing countries that have either intermittent power access or none at all. The design aims to address current issues with pre-existing solutions. Many of these solutions are prohibitively expensive, especially for those that cannot afford access to a power grid. Additionally, many energy generation solutions do not produce a substantial amount of energy or if they do, it is at a higher financial or environmental cost. The Clean Gen solution aims to generate cleaner energy than the current solutions that exist. The proposed system largely address these problems, as well as capitalizes on an untapped niche within developing marketplaces.

2.4 Optimization of Factors

After completing a needs assessment, multiple factors were considered to optimize the proposed system.

2.4.1 Cost Effective

The most important factor in the design of this system is cost. The reduction of costs will allow residents of northern Tanzania as well as around the world to gain access to electricity.

To lower the cost of the product, Clean Gen will be a mobile system. By creating a mobile system to be shared amongst residents of small communities, the cost can be shared as well. One family may not be able to afford a system that is approximately $1000, but several families sharing this cost is more feasible. By leveraging a shared economic model for the Clean Gen system, it will be affordable and able to meet the demands of a niche group largely considered unreachable.

Although Sikubora is already using cost effective components in their system, there are some parts whose price can be further reduced. For instance, the battery Sikubora currently uses is expensive and utilizes antiquated technology causing it to have a short shelf life. Clean Gen implements a newer battery technology that will be cheaper per amp-hour as well as hold a charge longer. As a result, Sikubora can keep a larger stock of batteries to meet the requirements of their customers and purchase in bulk to receive a volume discount.

Additionally, Clean Gen uses many local materials to build the system such as graphite. Although certain components must be imported because they are not available in Tanzania, they are competitively priced within each respective market, further reducing the cost of the system.

2.4.2 Energy Efficient

Another factor to be considered in this solution was how energy efficient it would be. Clean Gen uses a solar panel and battery with similar power requirements as the battery Sikubora currently uses. However, as mentioned above, Sikubora currently uses an older battery technology consisting of a GEL based lead acid battery. These batteries have a smaller amount of cycles, as well as discharge faster. The proposed solution will utilize an AGM battery, which can hold a charge longer as well as provides more charge cycles.

2.4.3 Environmentally Friendly

Another goal of this solution is to be more environmentally friendly. To accomplish this, a fuel cell will be implemented into the system. A fuel cell is less harmful for the environment, because it's only byproduct is pure water. Additionally, the system design utilizes a solar panel, so that all of the energy in the system is generated by renewable energy. No fossil fuels or other environmentally detrimental sources are used in the system.

Another element towards making the system environmentally friendly is the fact that it will use primarily locally sourced materials reducing the need for parts to be imported.

3. Use cases

There are several possible use cases for our system. Team M1 in collaboration with the founder of Sikubora envisioned a few usage cases most widely applicable in Northern Tanzania.

The first usage case focuses on renters. In northern Tanzania, both in urban areas and far from them, there are apartment clusters on one property belonging to a single landlord. Many residents in these communities are renting for a few years at a time, but not long term. Whether connected to the unreliable power grid or far enough out of town that they do not have access at all, these people seek quality energy. Unfortunately, Sikubora is currently unable to expand their product offerings to the renting population due to property and credit concerns. However, with a shared “microgrid” style solar energy storage system, users could pay to gain access as part of their monthly rent. This kind of setup is simpler to implement with the landlord and more economically attainable for residents. Furthermore, a central communal area on the property would serve as a base station for the system, to be accessed easily by all renters.

The second usage case is a collection of small business owners with adjacent shops. In Tanzanian towns, as well as in residential areas far from town, there are rows of simple, one-room shops with low power requirements. These shop owners could pool funding to obtain an affordable, shared system to meet their needs.

The final usage case is common in rural Tanzania, where numerous tribespeople and others inhabit areas far from the power grid. A substantial portion of this population is currently underserved due to economic reasons or lack of resources. Sikubora cannot tend to the needs of these rural Tanzanians because the line of credit is often too weak to offer a loan for an expensive system. However, if a group of families living as neighbors (such as the Maasai tribe "boma" style) could each contribute to monthly loan payments, they could together afford a shared energy system to meet their needs. These families would likely move the system between each home to distribute stored energy, in contrast to the centralized location that the gated communities might have.

In any of the usage cases, the shared system can accommodate a general load. For four homes or businesses, each building can have a 3W security light and two 2W indoor lights, and the system will additionally support a few phone chargers. The system could either be used by one user at a time or by all users simultaneously. In the former case, the system would be shared between different residences in time slots. In the latter case, the system would work best with a group of residences that are in close physical proximity. At the inverter in the system, a power strip with branching extension cords would bring power to each individual home simultaneously.

The system will charge during the day in the presence of sunlight and then be used primarily at night. Most people are out of their homes during the day, and for those who are home or working in a small business, daylight is sufficient until evening. At night, users would then have lighting in their homes and could charge their mobile devices.

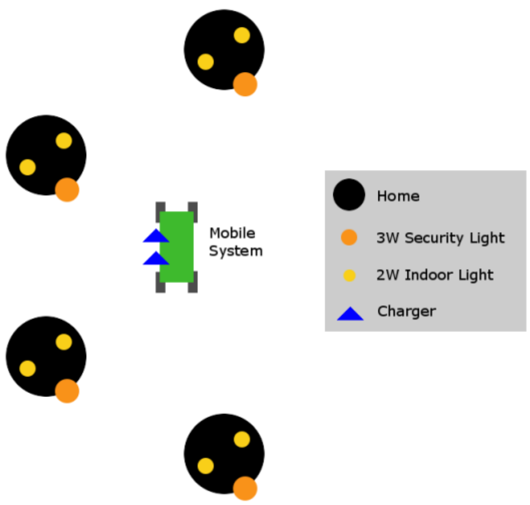


Figure 1. System Usage Example

4. Related Works

There are several similar products that exist on the market but do not meet the needs of Sikubora's customers. Some examples of similar devices are solar kits which lack a battery or other energy storage medium. This means that this charging system could only be used during the day when there is sunlight, which is a major issue. If the system is only usable during the day, users will be deprived of electricity at night.

Another example of a system that exists is one that is a portable solar panel with a very small 7.8 Ah battery, the 30-Watt Venture Solar Recharging Kit. This system's battery lacks the power to charge a smartphone more than 2 times, and the system only stores energy via a battery and does not utilize local or renewable materials (e.g. fuel cell), which is more detrimental to the environment. Additionally, the system has no AC port which means only DC devices can be used.

What makes Clean Gen different is that it has a 50 Ah battery which is a substantial amount of charge that could power multiple devices, as well as an AC port that can power non-USB devices such as laptops, lights, radio, fan, etc.

A slightly similar service is being implemented in the US that is called the Sunshot Initiative. This program allows for shared access to solar energy; however, it does not implement mobile systems nor is it economically feasible to implement at this time in a location like Tanzania.

5. System Design

5.1 Electrolyzer

The main components of the electrolyzer are the electrolyte, electrodes, and membrane. Electrolysis is a chemical process which uses DC current to induce non-spontaneous reactions; for hydrogen production, the polar H_2O molecule is separated into H_2 and O_2 ions according the following equations:

Anode: $2H_2O(l) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$

Cathode: $4H^+(aq) + 4e^- \rightarrow 2H_2$

Overall: $2H_2O \rightarrow 2H_2 + O_2$

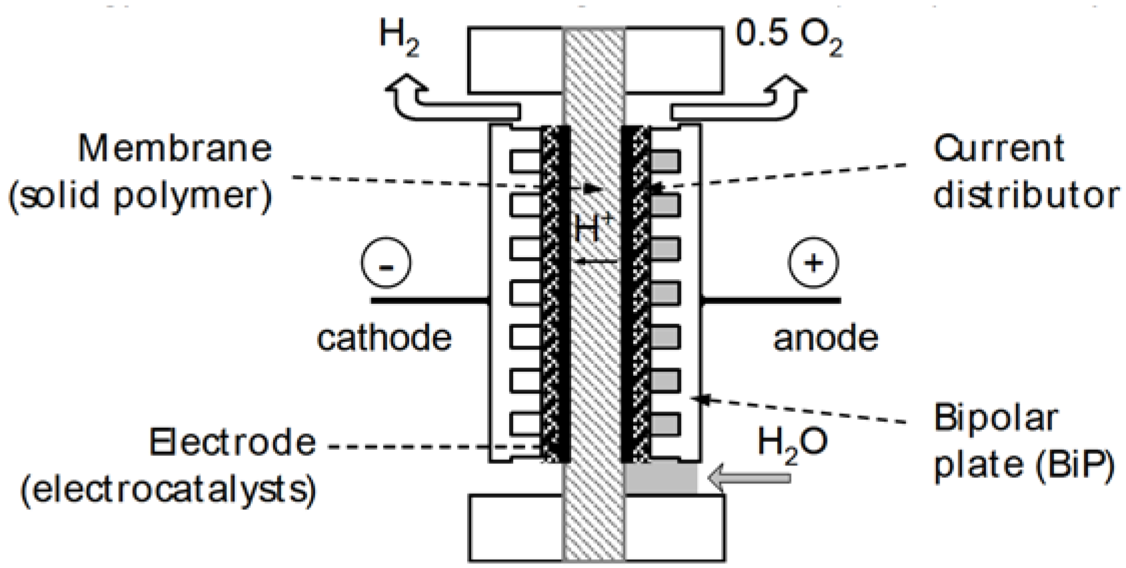


Figure 2. PEM Electrolysis

The solar panel/fuel cell system utilizes a Proton Exchange Membrane (PEM) electrolyzer. We were able to purchase a PEM electrolyzer which would provide the system with a higher hydrogen output than would be possible with a constructed Alkaline Electrolyzer. In addition to being more efficient than the alkaline electrolyzer, the PEM was cheaper to purchase/implement into our system.

5.1.1 Proof of Concept

To determine the feasibility of the electrolyzer design, it was necessary determine if enough hydrogen could be produced to feed the fuel cell. The rate of hydrogen production, the amount of water needed as an input, as well as the estimated theoretic conversion rate from water to hydrogen were also needed.

For electrolysis of water to occur at standard conditions, there is a theoretical minimum of 237.13kJ to dissipate the one mole of water (Gibbs free energy). Additional energy is needed to overcome the entropy change during the reaction. Thus, electrolysis only occurs above 285kJ per mole, unless additional external energy is added.

$$1 \text{ Mole } H_2O \rightarrow 1H_2 + \frac{1}{2}O_2 \text{ occurs at 285kJ}$$

The Electrolyer we implemented produces 7 mL of pure hydrogen per minute.

Time to produce 22.4L of H_2 = 22.4 L/0.007 L= 3200 Minutes
3200 Minutes = *53 Hours to produce 1 mole of Hydrogen*

The fuel cell's estimated consumption of hydrogen is 180 cm^3 of hydrogen per minute, so the electrolyzer will be producing hydrogen at a rate slower than the fuel cell consumes hydrogen.

Enough hydrogen would need to be stored to feed the fuel cell during periods when access to the sun is limited or unavailable, thus it would be necessary to store roughly 3 hours worth of hydrogen for the fuel cell's consumption.

$$3 \text{ hours} * (60 \text{ Minutes/Hour}) * (180 \text{ cm}^3\text{/minute}) * (1\text{L}/1000\text{cm}^3)$$
$$=32.4 \text{ liters at 1 atm.}$$

Thus the electrolyzer will need to produce 32.4 liters for 3 Hours of the Fuel cell operating.

Next, the amount of water needed for electrolysis will have to be estimated. 1 mole of water has an atomic weight of 18.01g/mole.

1 mole of water = 18.01g/mole = 0.01801 liters of H_2O.

This can be used to estimate the quantity of hydrogen that can be produced:

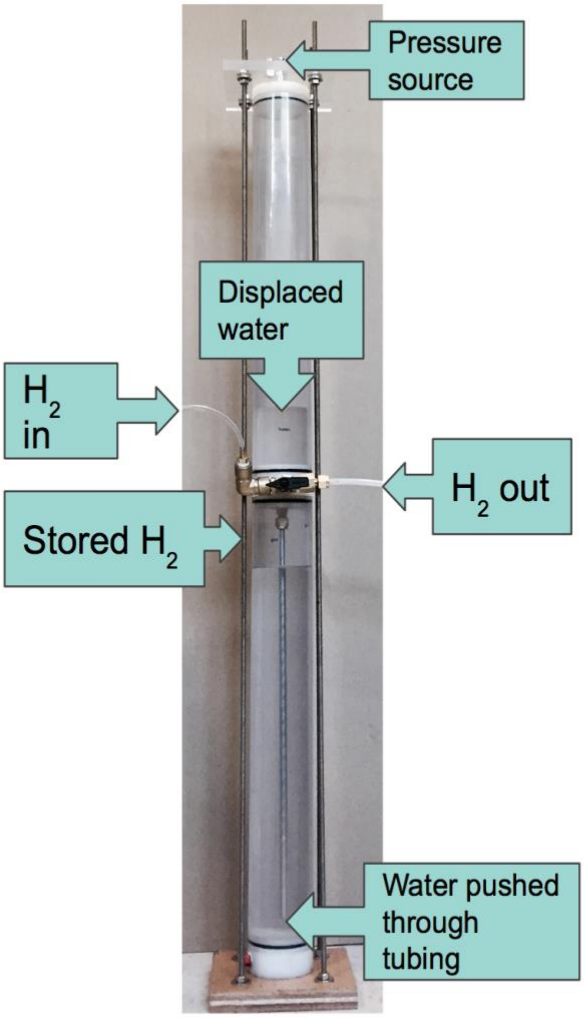
> 1 liter of Water * (mole/0.01801liters) * (22.4 Hydrogen/ mole Hydrogen) = 1240 liters of Hydrogen

Thus a small amount of water can be used to produced a large amount of hydrogen.

5.1.2 PEM Electrolyzer

Distilled water, which is the main input to the system, lacks ions and other impurities and is therefore unable to conduct current. The electrolyzer requires an input voltage of 1.8-3V and an input current of 0.7A-1A to produce the optimal 7mL per minute. As the electrolyzer runs low on distilled water, the current being drawn slowly reduces. Monitoring the current level is a good indicator the the current rate of production. Silicon tubing is used to deliver the Hydrogen produced to the storage system.

5.2 Hydrogen Storage



The water column stores the hydrogen created by the electrolyzer until it is ready to be consumed by the fuel cell. It operates by Hydrogen displacing water stored in the column.

The bottom of the column is completely filled with water. Hydrogen is fed into the storage system from the electrolyzer through the middle of the column. By storing the generated hydrogen in an area previously completely filled with water, this ensures that we are keeping the hydrogen as pure as possible. The importance of this is in preserving the fuel cell, which can become corroded by inputs that are not pure hydrogen. The hydrogen displaces the stored water through the stainless-steel tubing in the column. The pressure applied by the hydrogen holds the displaced water in place.

When hydrogen is being consumed, the stored hydrogen flows out of the storage system through the hydrogen outlet tubing. The displaced water stored above the hydrogen flows back into the lower portion of the column.

The flow out of the electrolyzer is 44 mL per minute, which is lower than the 180mL per minute needed to get 12W from the fuel cell. The output flow rate can be increased by adding a pressure system to the pressure source input of the column.

A water sensor is included in the design to monitor the hydrogen level. When the hydrogen reserves drop below a predetermined level, the control system switches from drawing power from the fuel cell to the battery.

5.3 Water Supply

Distilled water is needed as an input for the electrolyzer. Standard filter cartridges are rated for ~380,000 L, which gives us an effectively unlimited lifetime. Since water is a byproduct of fuel cells, either a pump can be installed to return the water to storage or it can be done manually. For the most energy-efficient model, a gravity filter can be installed, with water being supplied at the top of the system.

5.4 Fuel Cell

5.4.1 Fuel Cell Components

A hydrogen air PEM fuel cell will be used in the design of the system to draw power from in addition to the battery. The fuel cell will contribute 12W. The fuel cell consists of a membrane electrode assembly (MEA), gas diffusion layers (GDL), two bipolar plates, two current collectors and two end compression plates ("Types of Fuel Cells | Department of Energy", 2017). The MEA is where the chemical reaction takes place. The membrane serves as a barrier between the anode and cathode to prevent unwanted chemical reactions and also contains the catalyst for initiating the reaction (Merle, Wessling & Nijmeijer, 2011). The GDL serves as a passage for the reactant and also provides heat and water removal from the membrane to optimize the catalyst's performance. The bipolar plates are used contain the chemical reactions and contain flow channels which act as current collectors for the electrons to pass through, directing them to either the anode or cathode.

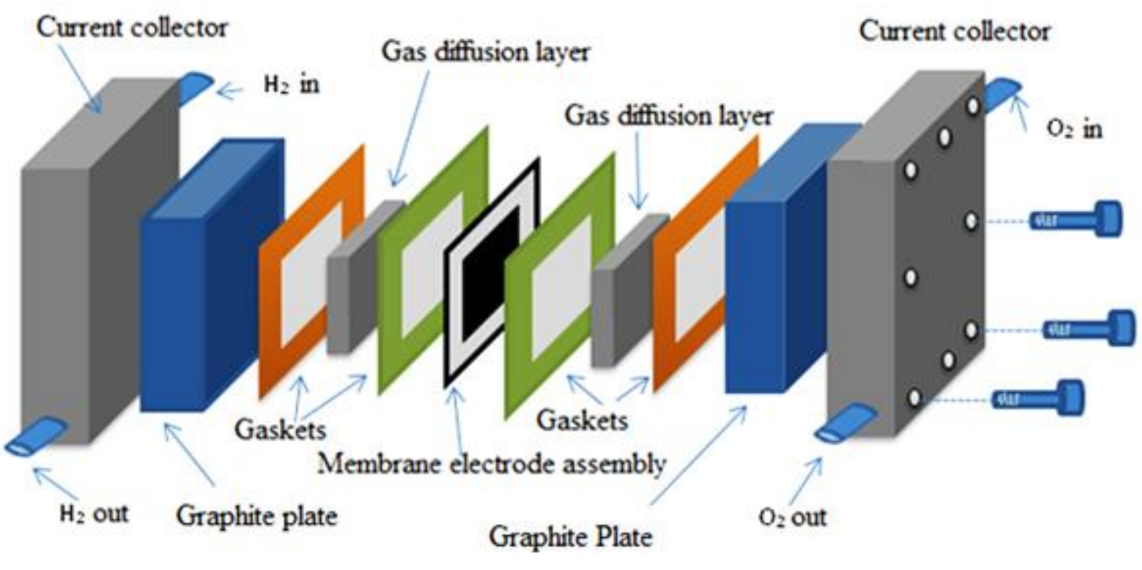


Figure 5. Assembled Fuel Cell Components

5.4.2 Fuel Cell Chemical Reaction

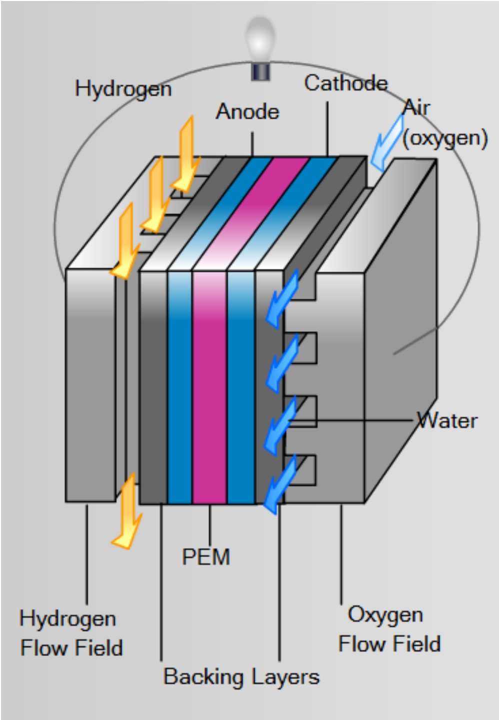


Figure 6. PEM Fuel Cell Flow Process

Air and hydrogen are passed through the bipolar plates and the gas is diffused by the GDL on either side of the membrane. At the anode, hydrogen is oxidized by the platinum catalyst on the electrodes which causes the di-hydrogen and hydroxide ions to split into H_2O and electrons. The released electrons flow through an external circuit creating charge and thus electricity, and return to the cathode where the electrons combine with oxygen and H_2O to form hydroxide ions. This process is called oxygen reduction. The net reaction of the system consumes oxygen and hydrogen producing two water molecules. Electricity and heat are formed as byproducts of the reaction.

$$\begin{array}{ll} \text{Anode reaction} & 2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \\ \text{Cathode reaction} & O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \\ \text{Overall cell reaction} & 2H_2 + O_2 \rightarrow 2H_2O \\ & +\text{electrical energy} + \text{heat} \end{array}$$

Figure 7. Fuel Cell Reaction

5.4.3 Membrane Electrode Assembly (MEA)

Our original fuel cell design would contain an MEA with integrated gas diffusion layers. The membrane type is an anion exchange membrane (AEM) made of nafion with a platinum catalyst. An AEM is a semipermeable membrane designed to conduct anions while being impermeable to gases such as oxygen or hydrogen.

Figure 8. Pre-Assembled MEA

MEA Properties	
MEA Type	Hydrogen Air Fuel Cell
Membrane Type	Nafion PFSA NR-212
Membrane Thickness	50.8 micrometers (2 mil)
Anode Loading	0.5 mg/cm²
Anode Catalyst	60wt% Pt on Vulcan (Carbon)
Cathode Loading	0.5 mg/cm²
Cathode Catalyst	60wt% Pt on Vulcan (Carbon)
Gas Diffusion Layer	Carbon Cloth with MPL - W1S1005
Gas Diffusion Layer Type	Woven Carbon Fiber Cloth
Gas Diffusion Layer Thickness	.410 mm (410 microns)

Table 2. MEA Properties

5.4.3 Fuel Cell Stack Construction

The power output of a given fuel cell stack will depend on its size, and the desired wattage output is 12W. Increasing the number of cells in a stack increases the voltage, while increasing the surface area of the cells increases the current. The number of cells in the stack is determined by the desired output wattage and the operating voltage. The cell area is designed to operate at a required current and when multiplied by total stack voltage will give the maximum power requirement for the cell stack. To maximize output wattage, the cells will be connected in parallel in the cell stack.

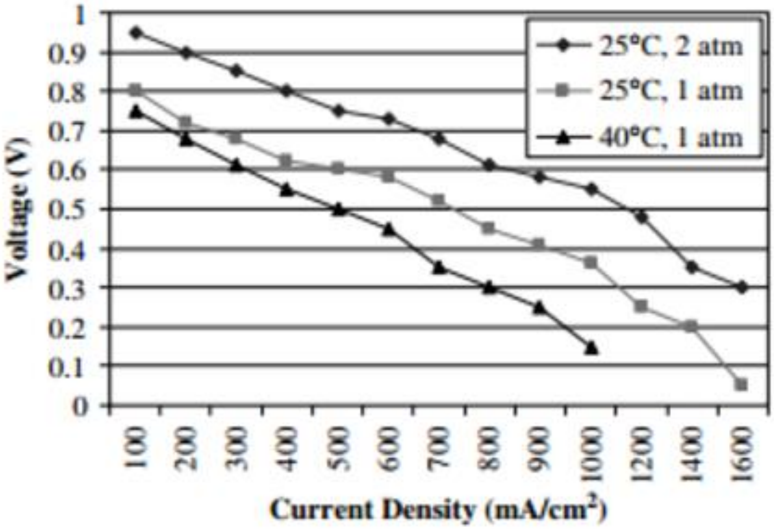


Figure 9. Polarization Curve for PEM Fuel Cells

The table above details the standard polarization code for alkaline fuel cells using KOH as an electrolyte (MacDonald, Sen, Grimes, Tewari & Sambhy, n.d.). To determine the number of fuel cells to use in the fuel cell stack, the total active area of the electrolyte membrane and the current density from the graph above are used. From the graph, 800mA/cm^3 can produce approximately 0.6V. To produce 24W, the fuel cell stack will be comprised of 4 cells with a load of 6-10A and voltage of 2.4 volts.

For 25 degrees C at 2 atm:

Membrane 7.1cm x 7.1cm

50.41 cm^2 = total active area

50.41 cm^2 (800mA) = 40.32 A

40.32 A (0.6V) = 24 W

P = IV

24 W = 6 A (V)

V = 4 V

2.4V / 0.6 V = 7 cells

The cost to build a fuel cell stack of this size with the given components listed above would be approximately $800. The cost breakdown for a 7 cell stack is as follows:

Component	**Price**
Pre-assembled MEA	$90 * 6 = 540
Graphite End Plate	$37.50 * 2 = 75

Current Collector	$75 * 2 = 150
Rubber Gaskets	$4 * 6 = 24
	= $789

Table 3. Building Fuel Cell Cost

It was determined this price was too high given our capstone budget and other parts in the system design. In addition, a fuel cell must be run under specific temperature conditions with a specific flow rate of oxygen. Although 7 cells can produce 24W, it is dependent on the efficiency of the actual stack construction. Also it would need to run at 6A which would cause the cell stack to overheat. To combat this problem, we'd add a fan to the design but this would again be an additional cost. The fuel cell stack depicted below has 13 cells and provides a maximum wattage of 35W. Under normal operating conditions, the fuel cell will output a sustained 12W which is more efficient than one we could build given our budget constraints. As a result, it became apparent that it was more cost effective to purchase a pre-assembled fuel cell stack.

Figure 10. PEM Fuel Cell

In the design implementation, due to pressurization issues with the hydrogen storage, we were unable to get the desired 12W output. The storage container was not pressurized enough so the hydrogen flow rate from the storage to the fuel cell was not high enough. As seen in the table below, the fuel cell needs a flow rate of 180 mL/min. However, our operating flow rate was 44 mL/min resulting in an output of only 3W.

Type of fuel cell	PEM
Number of cells	13
Rated Power	12W
Performance	7.8V @ 1.5A
Purging valve voltage	6V
Blower voltage	5V
Reactants	Hydrogen and Air
External temperature	5 to 30ºC
Max stack temperature	55ºC
H2 Pressure	0.45-0.55bar
Hydrogen purity	≧99.995% dry H2
Humidification	self-humidified
Cooling	Air (integrated cooling fan)
Weight (with fan & casing)	275 grams(±30 grams)
Dimension	7.5cmX4.7cmX7.0cm
Flow rate at max output*	0.18 L/min
Start up time	≦30S at ambient temperature
Efficiency of stack	40% @ at full power

Table 4. PEM Fuel Cell Specs

5.5 Control System

A control system is necessary to properly switch between using the battery or the fuel cell as the primary power source to the load. Our hybrid system is designed to alternate the power source to the load based on how much hydrogen for the fuel cell is available at the time. The control system is responsible for switching between the two following possible modes of operation:

(1) There is not enough enough hydrogen available for the fuel cell, so the battery will be used as the power source. When enough hydrogen has been produced, the system will then switch back to the fuel cell.

(2) There is enough hydrogen available for the fuel cell and so the fuel cell will be used as the primary power source. If the fuel cell has run out of available hydrogen, the system will switch over to the battery as the power source.

To determine how much hydrogen is available, a non-contact water level sensor is mounted to the external wall of the water column. The sensor conveys data to the Arduino Microcontroller, reporting as a digital signal whether or not water is present beyond the barrier. As hydrogen is being generated and replenished, the water level in the water column is lowered, as water is pushed to its higher water storage area. If there is no water detected, then an ample amount of hydrogen is available and the Arduino can act upon this signal. The Arduino controls a pair of relays that connect the output of the fuel cell and the battery to the input for the load. These relays are either in an open or closed state based on input from the Arduino. If there is not enough hydrogen available as determined by the water level sensor, then the Arduino will open the switch fuel cell, disconnecting it from the load, and close the switch for the battery, connecting it to the load as the power source. If there is enough hydrogen, the Arduino will open the relay for the battery and close the relay for the fuel cell, thus powering the load with the fuel cell. The Arduino requires a 5 V power connection and is powered by the battery via a 12 V to 2 V DC to DC converter which is subsequently connected to a 2 V to 5 V USB DC to DC converter to achieve the necessary port conversion.

5.6 Solar Panel

For the Clean Gen system, in an effort to save costs, a solar panel used by a previous capstone group was to be used. This solar panel proved to be incompatible with our system however so we decided to buy a solar panel + charge controller bundle. This solar panel is approximately 0.5 m^2 and provides 50 W which will be charging the battery. The solar panel will be connected to a charge controller to regulate the amount of current from it to the battery.

All solar panels decrease in efficiency over time, with most panels reaching 80% efficiency within 20 to 25 years. Thus, the team has accounted for any performance degradation.

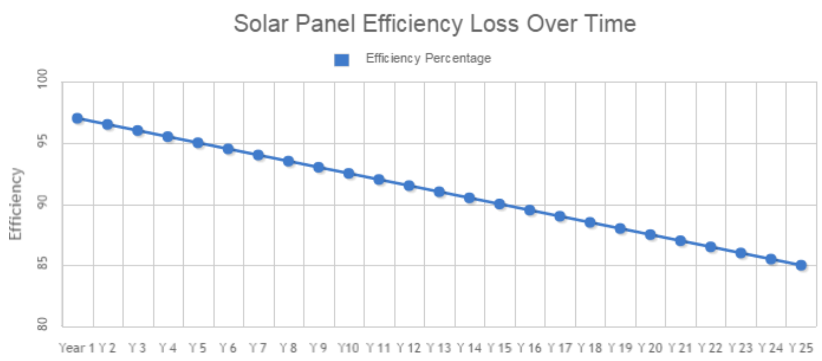


Figure 11: Chart of solar panel efficiency over time

5.7 Charge Controller

The system will require a charge controller to regulate the amount of current that will be sent to the fuel cell as well as the battery in our system. Clean Gen utilized a Renogy 10A Charge Controller Solar Panel Battery Intelligent Regulator with USB Port Display (12V/24V). This charge controller was selected because it was competitively priced when included in a bundle with the solar panel and has some additional features which are quite useful. This controller can support 12V or 24V outputs, which means there is a larger voltage tolerance and the output voltage load (in this case the 12V battery and fuel cell), could be increased. Additionally, a 24 V battery could be used if desired. The charge controller also supports charge currents up to 10A, as well as more advanced charge management and electrical protection. Additionally, this charger includes a built in LCD to monitor performance. Another convenient feature is this charge controller includes a 5V USB port, so one can charge their mobile device before any energy loss occurs in the energy storage process.

5.8 Inverter

The system is primarily powering devices that will rely on USB power or DC, such as mobile device chargers and LED lights. However, the system should be able to use other devices such as radios or a television, especially in the more affluent gated communities. These devices will require a common AC port so an inverter is needed.

The proposed design used a 300W Modified Sine Wave Auto Power Inverter 12V DC to 120V AC. This inverter was chosen because it was competitively priced.. Additionally, there are two extra USB ports allowing additional mobile device to be charged without additional loss from an AC to USB charging block. Some other benefits are that this inverter supports up to 300W, which means the system could be expanded to take in more energy (e.g. adding additional solar panels), without the need to upgrade the inverter.

One thing to note is that inverters are designed to operate at only one output AC voltage. For testing purposes, the inverter purchased operates at only 120V/60 Hz and contains only North American outlets, not universal outlets. The inverter that would be used in Tanzania would contain a universal outlet, due to the variance in plugs in Tanzania and the region as a whole. The inverter would also operate at 220V/50 Hz, which is the AC voltage and frequency in Tanzania. Additionally, countries that use a nominal voltage of 220, 230, and 240V have devices which are compatible with each other, assuming the same electrical frequency and plug type is used. Most modern electronics can tolerate minor voltage swings such as the difference in voltage between 220 and 240V.

5.9 Battery

One of the big challenges that Sikubora faces with its existing systems is that the batteries do not hold charge effectively and lose a lot of charge during shelf life. The Sikubora system uses GEL batteries, an older battery technology that is prone to losing charge during storage. This project will use a newer battery technology, AGM, which is still cost effective and will not suffer from these same problems. The battery will be 12V, because many electrical systems (including the components for this project), are designed to either draw charge or store energy to a 12V battery, i.e. the inverter and the charge controller.

The battery that was actually used for our prototype however was a 12 V AGM 35 Ah battery, and not a higher capacity one as originally intended. The specifications for the battery used might be a bit different, however the overall motivation behind this new battery is the same. By implementing an AGM battery that is designed for deep cycle applications, the lifetime of the battery as used in the scenarios described above will be much longer.

5.10 Cart

The system will need to be kept on some sort of platform in order to ensure its mobility. A cart will be assembled using large rubber casters and several pieces of wood. Large casters are essential for this project due to the lack of paved roads in many parts of northern

Tanzania. The actual cart used for the prototype was one already available from the capstone lab:

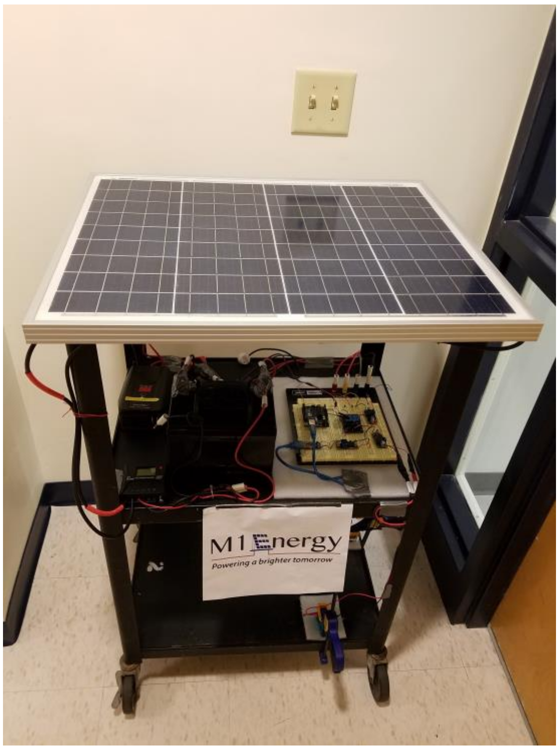


Figure 12: Final Assembly without Water Column

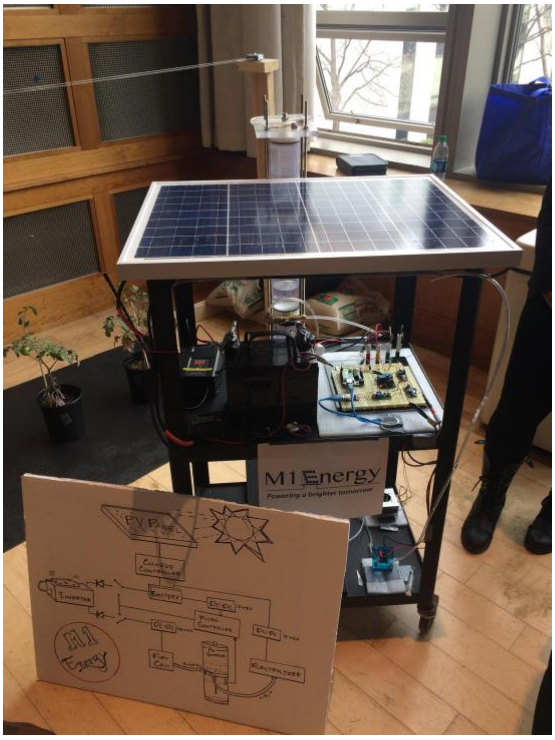


Figure 13: Final Assembly on Capstone Day

6. System implementation

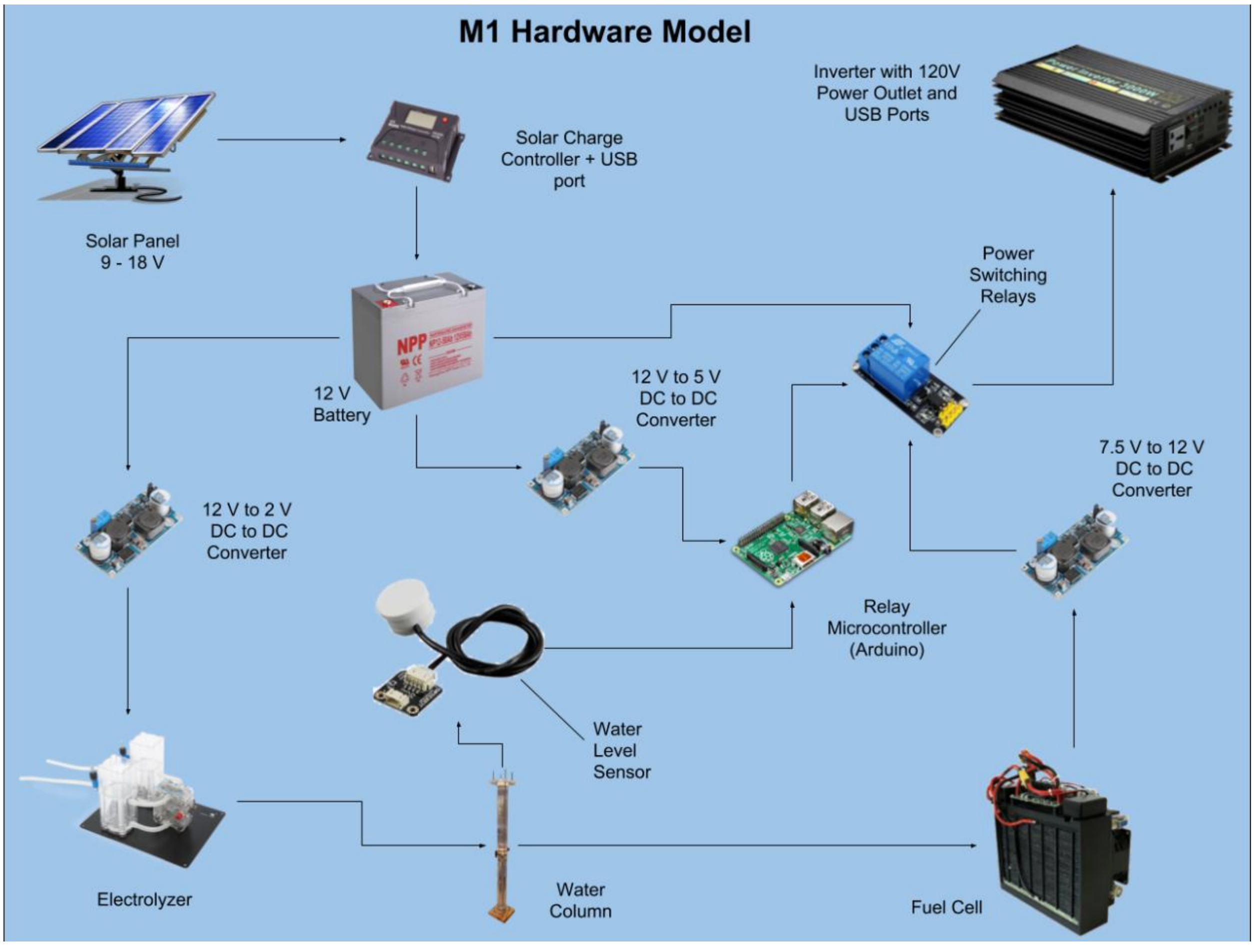


Figure 14. System diagram

7. Further Considerations

There are many next steps to carry the project to completion. One factor to be considered is the management of user sharing. It may be necessary to include software that appropriately divides charging time slots so that users all get an equal amount of energy. A safety-related factor is that while this system can work in many parts of the world, this system cannot operate in extremely hot temperatures. The battery is not designed to safely operate above 55ºC, and the fuel cell will likely generate high amounts of heat due to the large current passing through it. As a result, the system may require additional cooling.

Another consideration is to change the electrolyzer to a larger one. Our current electrolyzer produces 7mL of hydrogen per minute versus the fuel cell which consumes 180mL of Hydrogen to operate at an optimal 12W. Additionally, a pressure system would need to be introduced to improve the output rate of flow of hydrogen from the storage system. The current rate is 44mL per minute, versus the required 180mL that is needed to provide a 12W output.

9. Cost Analysis

There is a capstone budget of $1000. One of the goals of this project was to be as cost effective as possible, and as such maintaining a budget of $1000 was reasonably doable. The team tried to be as resourceful as possible and also make use of any products that were already available from the capstone lab or other professors. The cost breakdown of our product after completion is shown below:

Equipment	Cost
Inverter	$25
Electrolyzer	$55
DC Step Down Converters	$11
DC Step Up Converters	$10
Fuel Cell	$409
Relays	$8
Diodes	$1
Brass Fittings	$13
Solar Panel + Charge Controller	$126
DC to DC Up Converters	$14
LED Lamp	$8
USB DC to DC Converters	$7
Microcontroller	$20
Water Sensor	$22
Total	**$729**

We actually ended up coming in under budget. Our initial financial projections from capstone 1 were $842, we ended up spending a total of $729. However, this was only the cost of our prototype. For a mass production implementation, we expect a cost breakdown as follows:

Equipment	Cost
Inverter	$10
Electrolyzer	$40
Battery	$100

DC Step Down Converters	$2
DC Step Up Converters	$2
Fuel Cell	$200
Relays	$3
Diodes	$0
Solar Panel + Charge Controller	$85
LED Lamp	$3
Water Sensor	$5
Cart	$10
Water Column	$5
PCB	$5
Air Pump	$15
Microcontroller	$15
Miscellaneous Parts	$15
Total	**$515**

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11. References

1. Barrett, S. (2013). HySA Infrastructure: producing and using hydrogen for energy in South Africa. *Fuel Cells Bulletin, 2013*(6), 12-17. doi:10.1016/s1464-2859(13)70239-6
2. DiMarzio, C. (2017, May). Personal interview.
3. Hollister, J. (2017, June 16). Personal interview over video call.
4. Kabza, D. A. (n.d.). Um was es bei dieser Seite geht. Retrieved June 23, 2017, from http://www.pemfc.de/#zweipunktsechs
5. Lehman, B. (2017, June 15). Personal interview.
6. MacDonald, M., Sen, A., Grimes, P., Tewari, A., & Sambhy, V. *Design and Test of a Carbon-Tolerant Alkaline Fuel Cell*. Penn State University. Retrieved from https://arxiv.org/ftp/physics/papers/0504/0504130.pdf
7. Merle, G., Wessling, M., & Nijmeijer, K. (2011). Anion exchange membranes for alkaline fuel cells: A review. *Journal Of Membrane Science*, *377*(1-2), 1-35. http://dx.doi.org/10.1016/j.memsci.2011.04.043
8. Mukerjee, S. (2017, June 9). Personal interview.
9. "Tanzania GDP per capita." *TradingEconomics*. N.p., n.d. Web. <https://tradingeconomics.com/tanzania/gdp-per-capita>
10. *Types of Fuel Cells | Department of Energy*. (2017). *Energy.gov*. Retrieved 23 June 2017, from https://energy.gov/eere/fuelcells/types-fuel-cells
11. Active Control of a Hybrid Fuel Cell-Battery System. A. Nasiri, V. S. Rimmalapudi, and A. Emadi. Illinois Institute of Technology
12. *Hydrogen Air MEA - 5 Layer*. (2017). *Fuelcellstore.com*. Retrieved 23 June 2017, from http://www.fuelcellstore.com/hydrogen-air-mea
13. Spiegel, C. (2007). *Designing and Building Fuel Cells*.
14. Intelligent Controller Based on Raspberry Pi. Feidias Ioannidis. University of Manchester.
15. *Www2.ignatius.edu*. Retrieved 18 June 2017, from http://www2.ignatius.edu/faculty/decarlo/EarthToMoon/pages/AlkalineFuelCell.htm
16. Papadimitriou, C., & Vovos, N. (2017). *Integration of a hybrid fuel cell-battery system to a distribution grid - ScienceDirect*. *Sciencedirect.com*. Retrieved 16 June 2017, from http://www.sciencedirect.com/science/article/pii/S0378779611000290
17. Students of Dimarzio, C. (2009). Capstone Final Report - Solar Hydrogen.
18. Satterlund, T. (2017, June 19). Personal interview over video call.
19. Community and Shared Solar. (n.d.). Retrieved June 23, 2017, from https://energy.gov/eere/sunshot/community-and-shared-solar
20. Santos, Diogo M. F., César A. C. Sequeira, and José L. Figueiredo. "Hydrogen production by alkaline water electrolysis." Química Nova. SBQ, n.d. Web. 23 June 2017.
21. Yuvaraj, A.L., and D. Santhanaraj. "A systematic study on electrolytic production of hydrogen gas by using graphite as electrode." Materials Research. Materials Research, n.d. Web. 23 June 2017.
22. Symes, Daniel, Bushra Al-Duri, Waldemar Bujalski, and Aman Dhir. "Cost-effective design of the alkaline electrolyser for enhanced electrochemical performance and reduced electrode degradation." International Journal of Low-Carbon Technologies. Oxford University Press, 27 May 2013. Web. 23 June 2017.

23. Kandah, Munther. "Enhancement of Water Electrolyzer Efficiency - ResearchGate." Journal of Energy Technologies and Policy, n.d. Web. 23 June 2017.

Appendix: Control System Code

Below is the simple Arduino code used to control the system.

```
#define RELAY_B 7 //connection to battery
#define RELAY_FC 8 //connection to fuel cell
#define WATER_SENSOR 5

int liquid_level = -1, temp, n = 1;
void setup() {
  Serial.begin(9600);
  pinMode(RELAY_B, OUTPUT);
  pinMode(RELAY_FC, OUTPUT);
  pinMode(WATER_SENSOR, INPUT);

  Serial.print("Opening both relays to start");
  digitalWrite(RELAY_FC, HIGH);
  digitalWrite(RELAY_B, HIGH);
  delay(1000);
}

//use NO terminals of relay (connected to inverter?) w COM at batt
or fc
//low water level means we have plenty of H! use fuel cell; high
water level means H has depleted
void loop() {
  temp = digitalRead(WATER_SENSOR);
  if (n % 5 == 0) {
    Serial.print("\nliquid_level = ");
    Serial.print(temp, DEC);
  }
  //Serial.print("\nliquid reading = ");
  //Serial.print(temp, DEC);
  if (liquid_level == -1) {
    //first pass
    liquid_level = temp;
    Serial.print("\nOpening initial relay");
    if (liquid_level) {
      Serial.print("\nHigh water level--connecting to battery");
      digitalWrite(RELAY_B, LOW); //close (connect) switch to
battery
    } else {
      Serial.print("\nLow water level--connecting to fuel cell");
      digitalWrite(RELAY_FC, LOW); //close (connect) switch to fuel
cell
```

```
    }
    delay(1000);
  } else if (liquid_level != temp) {
    //change in water level detected... print more info
    Serial.print("\n^^ change in liquid level!");
    liquid_level = temp;
    if (liquid_level) {
      Serial.print("\nHigh water level--switching to battery");
      digitalWrite(RELAY_FC, HIGH); //open (disconnect) switch to
fuel cell
      delay(1000); //give relay ample time
      digitalWrite(RELAY_B, LOW); //close (connect) switch to
battery
    } else {
      Serial.print("\nLow water level--switching to fuel cell");
      digitalWrite(RELAY_B, HIGH); //open (disconnect) switch to
battery
      delay(1000); //give relay ample time
      digitalWrite(RELAY_FC, LOW); //close (connect) switch to fuel
cell
    }
    delay(1000);
  } else {
    delay(1000); //no change, wait 1s before checking again
  }
  n++;
}
```