ABSTRACT

The Use of Biogas from Anaerobic Digestion in a Fuel Cell with an Application in Developing Countries

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The focus of this project is to provide clean energy to third world countries where there is a need for electricity generation or energy infrastructure. The concept presented is to use table scraps/manure from farms to produce methane gas using anaerobic digestion. An anaerobic digester contains an oxygen free environment that allows microorganisms to break down the organic material to produce biogas (methane). Once the biogas is produced it can be used for different applications to aid the developing world. One technology this paper will explore is a fuel cell, more specifically the solid oxide fuel cell (SOFC), that has the potential of operating on biogas. When methane gas (biogas) and oxygen (air) combine in the fuel cell, it produces electricity along with water and carbon dioxide. Even though the SOFC produces carbon dioxide, studies shows that the level of carbon dioxide produced using a fuel cell is much less than the typical method of producing electricity by burning biomass. For this experiment, the analysis of the anaerobic digesters, made from materials found in the developing world, will be accomplished to determine if they produce sufficient quantities of methane gas to make the use of a solid oxide fuel cell feasible. A hydrogen fuel cell was studied to understand the basic function of the fuel cell.

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THE USE OF BIOGAS FROM ANAEROBIC DIGESTION IN A FUEL CELL WITH AN APPLICATION IN DEVELOPING COUNTRIES

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CHAPTER ONE

Introduction

1.1 Sources of Energy & Greenhouse gases

As the technological complexity of society advances, the demand for energy, especially electricity, worldwide becomes greater. It has been projected that demand will rise 53% by the year 2034 [1]. Currently, the major energy source in developed countries is fossil fuels such as oil and coal. Developing countries use significantly lower amounts of oil and coal, due to a lower standard of living. Even with the technological growth evident today, about 20% of the world does not have access to electricity, which includes over 1.1 billion people as reported by The World Bank [2]. If the goal of developing countries is to increase their standard of living similar to that of a developed country using fossil fuels as the energy source, this will put in jeopardy the current energy supply generated by fossil fuels. To meet the increased energy demand, a new energy source could be used.

The most common energy sources are traditional power plants which burn oil and coal as fuel. These power plants are a leading cause of greenhouse gasses in the environment, resulting in pollution that has contributed to global warming and healthcare issues. According to the U.S Energy Information Administration, in 2008 the United States created 19% of the global carbon dioxide emissions from fossil fuel combustion [3]. Although there have been efforts in the United States to lower greenhouse gases, in 2012 the United States produced 2,039 million metric tons of carbon dioxide. These efforts to decrease greenhouse gasses include using solar and wind to help generate power and reduce the carbon footprint traditional power generation systems leave behind. Unfortunately, these renewable sources are limited by the amount of sunshine and climate change wind patterns. Also, hydroelectric power plants can be up to 90% efficient and can provide a source of energy and clean water for the nearby region. The downside to hydroelectric power is its interference with the freshwater ecosystems and the obstruction of naturally flowing water. Figure 1 shows a wind and solar farm in Costa Rica.

Figure 1: Wind and Solar farms in Costa Rica (M.Godoy)

A main reason for the move to renewable energy is sustainability. Sustainability is where humans and nature coexist in productive harmony ensuring the resources for current and future generations. It allows a community to grow and prosper without the need for imported energy resources from other countries. The development of sustainable energy resources must also consider clean air, fresh water, and fertile soil necessary for the survival of humankind. One renewable energy source that has been overlooked is methane gas.

Methane gas is readily available in the atmosphere and is the 2^{nd} most prevalent greenhouse gas reported by the United States Environmental Protection Agency [4]. The sources of methane include landfills, coal mines, enteric fermentation, waste and manure, along with natural gas and petroleum systems [5]. This valuable source of energy is prevalent in the atmosphere and can be produced almost anywhere through anaerobic digestion. Even though methane does contribute to the greenhouse gases, it can be consumed as an energy source in a fuel cell or other applications. Once consumed, the amount of pollution released into the atmosphere becomes minimal. Methane gas could provide a sustainable solution to the energy supply crisis, reduce greenhouse gasses released, and finally provide sustainable energy to areas with no established energy source.

The Kyoto Protocol, an extension of the 1992 United Nation Framework Convention on Climate Change, requires participating members to reduce greenhouse gas emissions. Many countries around the world are researching the potential in biomass energy and have set up programs to try to reduce greenhouse gas production. Research, primarily on biomass, has been performed by New Energy and Industrial Technology of Japan, Huazhong University of Science and Technology in China, and Wenisch & Rousseaux in Denmark, described by Jinnan [6]. The research focuses on technologies that can extract energy from biomass, how to evaluate the utilization of the biomass, and the benefit to households of producing biomass. Aside from the research into biomass utilization, Jinnan mentions studies on the policy of biomass performed in Europe by Thornley and Cooper. The lack of appropriate legislation, economical elements, and pricing without consideration of environmental impact are analyzed. The EU "have set forward a goal of supplying 20% of the European energy demands from renewable energy systems by year 2020" [7]. Peru plans to increase the amount of energy produced with renewable sources 33% by 2030[8]. The USA has set up a climate action plan which includes a strategy to reduce methane emissions. There is a demand for renewable energy however, governments have set aside subsides for this type of development. The focus is not only about providing energy to the world, but also preserving the natural resources the world provides.

CHAPTER TWO

Background and Literature Survey

2.1 Methane Gas and Applied Technology

2.1.1 Overview

The renewable resource described in this paper is methane gas, specifically generated from biogas. Biogas consists primarily of methane gas and carbon dioxide with other trace gasses that are not valuable for this application and are seen as impurities. Different types of organic substances produce a variety of methane to biogas ratios when decomposed in the absence of oxygen [9]. Biogas is currently used in applications like combustion, heating, gas turbines and co-generation plants. One simple way of producing biogas is through anaerobic digestion. Anaerobic digester size can range from big, commercial systems producing distributed energy up to 50MW to small, local systems useful for on-site energy producing only a few kW [10]. This project will focus on a small, simple systems due to the ease of implementation in a developing world that has no or minimal energy infrastructures. Beginning with the process, "the most significant outcome of anaerobic digestion processes is that they generate energy in the form of biogas—namely, methane and hydrogen."[11] The process requires waste to be put into an oxygen free environment for 30-60 days. This process consists of three phases: hydrolysis and fermentation, acidogenesis and dehydration, and methane fermentation. The first phase, hydrolysis, is where proteins, fats, and carbohydrates are broken down to their simple organic compounds such as amino acids, fatty acids, and sugars, through bacterial action with water. Acidogenesis and fermentation is the second step. This phase consists of metabolizing the products from hydrolysis. Here, the short chain fatty acids and alcohol are broken down further to volatile fatty acid, acetic acid, hydrogen and carbon dioxide. Lastly, in the methane fermentation phase, methanogenic microorganisms convert the previous products to methane and carbon dioxide, producing biogas. The process can be seen in Fig. 2. In order for the phases of the anaerobic process to occur, different variables, such as pH, temperature, hydraulic retention time (HTR), carbon to nitrogen ratio, must be monitored in order for the production and quality of biogas to be useful as an energy source. Optimizing these variables can further improve the anaerobic process [12].

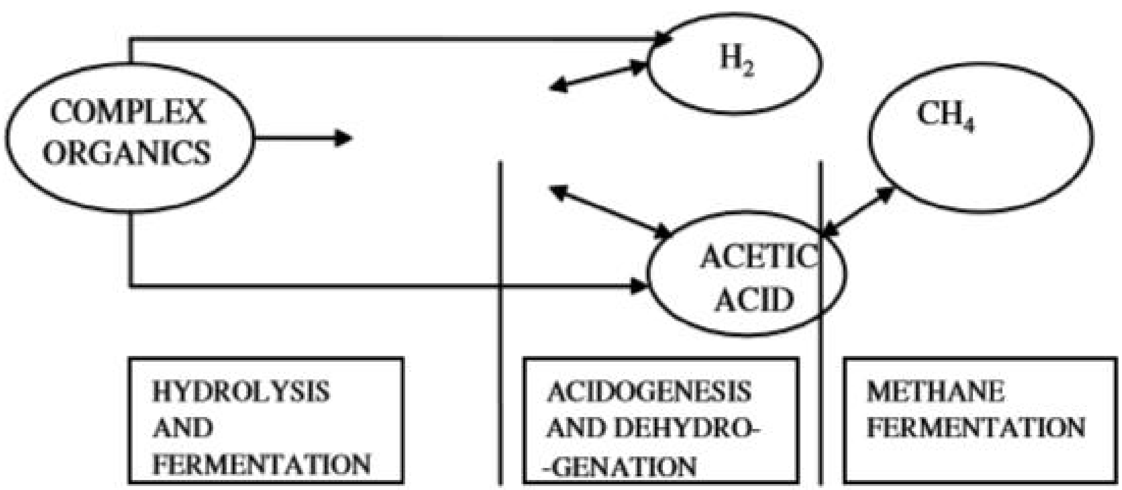


Figure 2: Diagram of the anaerobic digestion process [12]

2.1.2 Advantages

Utilizing biogas is a way of repurposing manure and waste into useful energy (methane gas) that would have previously been released to the environment. In comparison to oil and natural gas, which takes carbon storage from underground reserves exposing trapped greenhouse gasses to the environment, the use of biogas allows for a zero net methane production in the atmosphere. Manure and waste, when left to decompose on their own, produce biogas slowly and uncontrolled. Most rural areas around the world use manure and compost as a natural fertilizer, making it a multi-purpose resource. After methane gas is extracted from bio-waste, the remaining waste can still be used as a fertilizer. The raw material is essentially “free” or rather inexpensive and renewable in contrast to oil and natural gas. Also, when looking at the amount of greenhouse gas emissions from biogas and fossil fuels, fossil fuels produce significantly more compared to biogas.

A life cycle analysis of biomass energy was performed in the city of Jilin Province, China. The city’s commercial basis depends consists mostly on agriculture and contains an abundant resource of biomass [6]. Currently there is an energy shortage in Jilin. The Jilin analysis covers many different sources of biomass including straw and agricultural residues, firewood and forestry residues, livestock manure, and municipal waste. With each source of biomass, the amount of the reserve is quantified and given a standard energy equivalent based on a coal standard. The energy equivalent is then compared with a conversion coefficient. The life cycle analysis takes into account the environmental impact of the emitting pollutants in a complete process of each energy system. The process includes agricultural production, transportation and plant operation. The resulting projected biomass energy for the province is 21.26 million tons of coal equivalent, 36.9% coming from livestock manure and municipal waste. If the biomass energy were used it could make up 1/4th of the total energy consumption. Further, when comparing the environmental impact of using biomass power generation versus coal combustion, the analysis showed the ratio of environmental damage for coal combustion to biomass power generation is 25:1, with coal having a significantly greater environmental impact.

Figure 3: A picture of deforestation

http://www.umt.edu/ethics/debating%20science%20program/odc/climatechange/climatealternatives/reduceddeforestation.php

It is also important to note that the use of biogas from manure does not interfere with the food supply or industry. Other forms of biomass can be used as argobiofuel and have better energy production quality than biogas, but they cut into the food, natural forest, and fresh water supply. When there is competition with farmland, agricultural crops increase in price making food and energy crops more expensive [13]. For developing countries where there is a high percentage of malnutrition, this can be especially devastating. In some places, the primary forest gets destroyed in order to use the land for energy crops, which can be seen in Fig. 3. In Southeast Asia, particularly in Indonesia and Malaysia, oil palm plantations take priority over the rain forest causing deforestation and permanently damaging the ecosystem. Deforestation contributes to the increase of greenhouse gasses in our atmosphere in the following ways. Cutting down and burning trees is the most popular way to clear a forest. As the amount of leaves decreases, less photosynthesis occurs, taking less carbon dioxide from the atmosphere, to assimilate the greenhouse gas into the plant. The removal of the forest also poses potentially devastating threats to biodiversity and the living conditions of indigenous people. Forests are home to many endangered animals. Taking away the forest reduces the ability for these animals to survive, harming the natural ecosystem of forests. The issue of deforestation should not just be limited by technology and economic concerns but should also expand to ecological, societal and socioeconomic issues.

2.1.3 Application

http://www.houstonchronicle.com/business/article/Despite-recycling-gains-there-s-still-plenty-of-6584778.php

Figure 4: A picture of a landfill in Houston TX

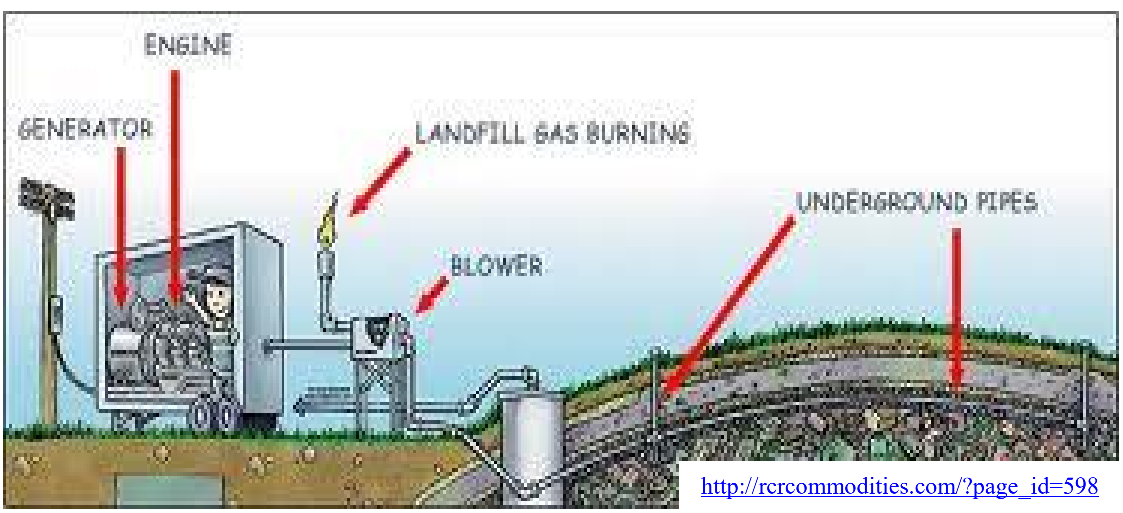
In order to look into the application of methane gas and the various way one can extract energy from the resource, landfills should be considered first. The repurposing of landfills and the use of municipal solid waste as an energy source is similar to the ideas presented later in this paper. For developed and developing countries, there is a current system of waste disposal that includes a local garbage pick-up, taking waste from the community and depositing it into landfills. Fig. 4 shows a picture of a landfill. These systems of disposing waste vary with different countries depending on the amount of waste produced, collection processes, land availability, and environmental regulations [14]. Landfills are a simple and economical way of disposing of waste. They also provide methane gas naturally from the decomposition of biomass. Many landfills do not require the separation of waste, therefore, the methane gas becomes contaminated with impurities. Since landfills are left exposed to the elements, there are environmental concerns dealing with water contamination, greenhouse gas emission, and odor. Currently, landfills are seen as a contributor to the environmental degradation, but with advances in technology, landfills could be a source of renewable energy in the near future.

As stated earlier, there has been a push for sustainability in many different countries, especially for well developed countries where a trash recovery system is already in place and where recycling is part of the governing legislation. “Recycling of waste materials is important not only to minimize the use of non-renewable resources, but also to reduce the amount of waste added to landfills.”[11] European Union countries heavily tax landfills, making recycling a more reasonable option. Although the efforts to increase the reduction, reuse, and recycling of solid waste has been significant, it is still not enough. A growth of more than 100 million tons of municipal solid waste has been accumulated from 1980 to 2005 and is projected to increase by 150 million tons in 2015, to reach a total of 300 million tons [15].

The amount of environmental damage can vary depending on the substances contained in landfills. One problem is contamination of both ground and surface water. Leachate takes contaminates from the landfills and carries into the water supply [14]. The materials located in the landfills can determine the severity of the contamination.

Contaminates range from dissolved gases, heavy metals and xenobiotic compounds. A solution to prevent water pollution is the use of landfill covers with low permeability layers. Unfortunately, with aging and seasonal changes, the lining often cracks releasing the toxic material into the ground. A better outcome can be achieved with the revegetation of the land. A cap is constructed of vegetation with the purpose of preventing the escape of gases, reinforcing the barrier, and increasing the water storage.

With revegetation, landfills can be used to generate biomass. Many experiments have been conducted to determine the ideal energy crop for landfills. The energy crop for a landfill site should have high yield, low input for maintenance and harvesting, and low nutrient demand [14]. Landfills could be a perfect space for energy crop farming because it is not decreasing the farmland used for local food crops. A concern for farming on landfills is the crops may be grown in contaminated soil. This is not a problem for energy crops as they should not be held to same stands as food crops.



http://rcrcommodities.com/?page_id=598

Figure 5: A diagram of a landfill gas collection system

Another challenge noticed in multiple landfills is the production of greenhouse gasses. The most dominant gas produced from a landfill is methane gas, produced through microbial methanogenic process, a similar process to anaerobic digestion. Landfills produce approximately 5% of the total greenhouse gases produced globally [14]. A possibility to lower the amount of landfill gas escaping in to the atmosphere is to capture the gas and use it to produce energy, as seen in Fig. 5. A benefit of repurposing the gas is the reduction of odor and emission. A systems of wells and blowers/vacuums can be installed to the move the gas to a central point which can be extracted, processed and treated. The amount of energy produced by landfill gas is dependent on its quality. The purity of the gas directly drives the method used for producing energy and can result in improvements to the energy output. Once landfill gas is extracted, a purification process can be used to obtain non-contaminated gas, but this process increases the overall costs of the gas. The separation and correct preprocessing treatment can greatly increase the usefulness and production of landfill gas.

Redefining landfills from the final solution of waste to a "temporary storage place awaiting further treatment" [15] can further help the development of landfill gas to help reduce the environmental impact. A new type of landfill can be produced by using the concepts of Enhanced Waste Management and Enhanced Landfill Mining [14]. These landfills require more recycling of the materials and optimal storage of garbage in order to reduce the amount to heterogeneity of garbage. The goal is to encourage a closed loop system where there is minimal release of greenhouse gases. A two-step process is to be incorporated into landfills: first convert the waste into a secondary energy carrier, then use the carrier to produce energy with the appropriate technology. The energy producing technology would be placed onsite or close to the site to reduce transportation cost and emissions. Some of these new landfills can be considered zero net energy power plants, producing enough energy to run its facilities. But the ultimate goal is an energy plant where energy can be supplied to the community.

2.1.4 Advances

There are many different technologies that deal with the conversion of waste to energy, or energy carriers. The oldest and most common method used to reduce the volume and to deal with hazardous material is incineration. The incineration process is the complete oxidation of combustible materials contained in waste made up of three overlapping steps: drying and degassing, pyrolysis and gasification, and oxidation. The system produces carbon dioxide, water, oxygen gas, nitrogen gas and other contaminates depending of the starting material. If incineration is the only processing done to the waste the release of the gases can be harmful to the environment. Incineration can also be combined with an energy recovery, emission control and disposal method of waste, reducing the environmental impact. Modern incinerators provide pollution control and reusability of the solid ash produced in the process. To improve efficiency and pollution control of incineration, the feedstock for the system should be as homogenous as possible. Incinerated gas can then be used for energy production. For example, in 2005, Denmark and Sweden produced 4.8% of electricity and 13.7% of domestic heat with incineration [15].

Two processes more controlled than incineration are pyrolysis and gasification. Both pyrolysis and gasification differ from incineration as they may be used for recovering the chemical value of the waste rather than its energetic value. Pyrolysis is the thermal degradation of waste using the complete absence or limited amount of oxidation occurring at a temperature of 400-900°C. Three products are produced from pyrolysis: pyrolysis gas, pyrolysis liquid, and solid coke. Depending on the conditions of the processing, namely heating rate and processing time, the percentages of the products can vary. Four main steps are considered in pyrolysis: 1) preparation and grinding, 2) drying, 3) pyrolysis, and 4) secondary treatment of product. Since pyrolysis requires the pretreatment of the waste, there is an increased overall cost to the technology. The usefulness of the products produced through pyrolysis is directly related to the amount of contamination of the original substance. It is also recommended that the starting material be stored properly before pyrolysis, also contributing to the increase of cost.

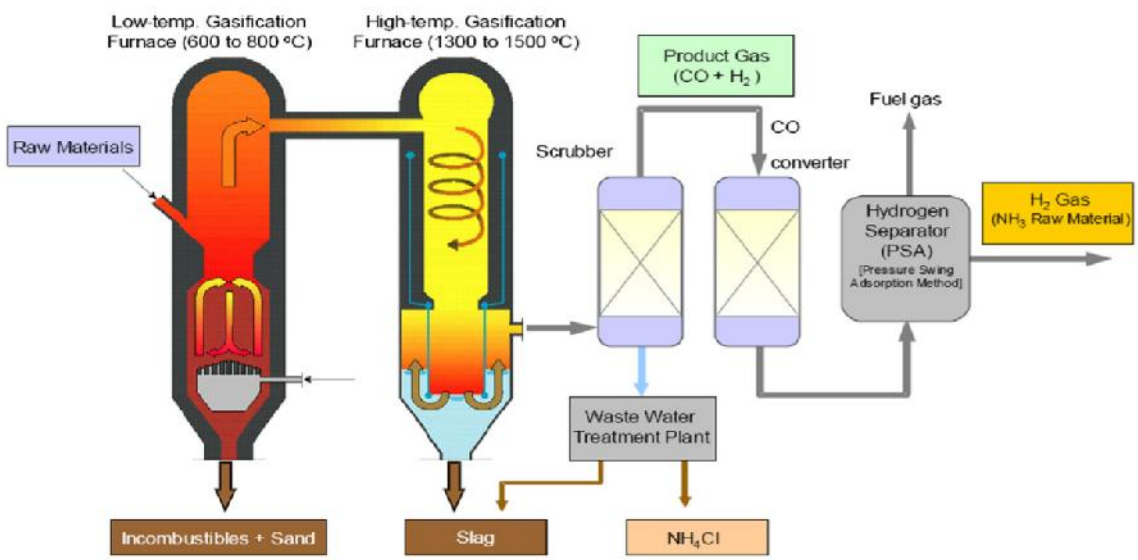


Figure 6: A diagram of a two-stage gasification process [15]

Gasification is the partial oxidation of organic substances at a high temperature, ranging from 500-1800°C, to produce a synthesis gas or syngas. Figure 6 shows a diagram of a two-stage gasification process. Syngas is consistent of a mixture of carbon monoxide, carbon dioxide, hydrogen gas, water, methane gas, and other higher hydrocarbons (ethane and propane). Depending on the gasification agent and feedstock, traces of contaminates can be contained in the gas. Common gasification agents are air, oxygen, steam, carbon dioxide or a mixture of the gases. Just like pyrolysis, pretreatment of the waste is required and garbage sorting is recommended to boost performance of the syngas. One of the benefits includes the capture of inorganic resides within slag produced during the pretreatment process. Also, gasification allows for the smaller volume when compared to incineration, which can lead to smaller manufacturing components. The smaller volume of the syngas reduces the waste water flow for the cleaning of the gas. Lastly, gasification favors the formation of carbon monoxide rather than carbon dioxide which can be used for industrial purposes.

In order to produce electricity, the products from pyrolysis and gasification needed to be used by an additional technology. The pyrolysis gas and syngas could be used in an internal combustion or gas turbine engine to produce energy. In addition, syngas can be used for the production of methanol, dimethyl ether (DME), and Fischer-Tropsch diesel [13]. Pyrolysis liquid can be upgraded by chemical means to improve its miscibility with gasoline or diesel. Finally, the solid coke from pyrolysis can be used to make char which consists of elemental carbon, hydrogen and various inorganic species. The fly ash recovered from gasification can be used in the production of concrete. The inorganic material contained in the slag can be reprocessed to extract metals like aluminum, copper, and iron. The combination of the three processes, incineration, pyrolysis, and gasification, can yield greater product quality of the waste.

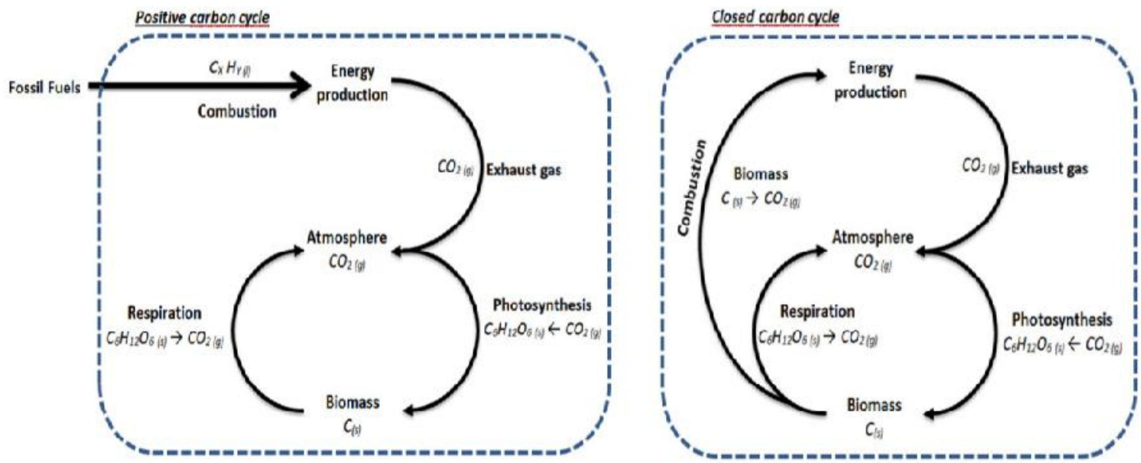


Figure 7: A diagram of a positive carbon cycle and closed carbon cycle [8]

Transformation of the agricultural waste to energy is the central concept for the project. The concept is to incorporate a closed loop system, limiting the amount of greenhouse gases released into the atmosphere while producing energy, as seen in Fig. 7. Dealing with agricultural waste may be considered less complicated because it does not require as much pretreatment when compared with the heterogeneous collection of municipal solid waste located in landfill. The similarities lie in the two-step system of producing energy carrier from the biomass and using the carrier to produce energy.

Biomass is an organic material that can be used for the production of energy. The sources of biomass for energy production should be influenced by natural availability, food dependency, and different economic uses for the resource. All the technologies mentioned that transform municipal solid waste to an energy carrier can be used for biomass. Since, the starting material is directly related to the product outcome of a particular technology, a high calorie substance gives better performance.

One source of biomass that has a high energy content is corn stover and corn cob with a heating value of 18.06 and 19.14 MJ/kg [1]. Approximately 5.8% of the US energy comes from biomass energy. An experiment was performed by the Department of Mechanical and Industrial Engineering at Northeastern University in Boston transforming biomass to energy. The experiment analyzed corn biomass and grass samples for the production of energy using pyrolysis. Pyrolysis has been proven to produce higher quality products for the purposes of producing energy. The corn biomass was a Dried Distillers Grains with Solubles or DDGS, a byproduct of an ethanol manufacturing process. DDGS is usually used as a low-cost, high protein feed for cattle. The grass samples came from *Viaspace Inc*., known as King Grass. The grass is a fast growing crop that can reach 13ft in 190 day after harvesting. It can be continuously harvested in 120 day period. Both of the grains, corn biomass and grass samples, are rich in energy storage.

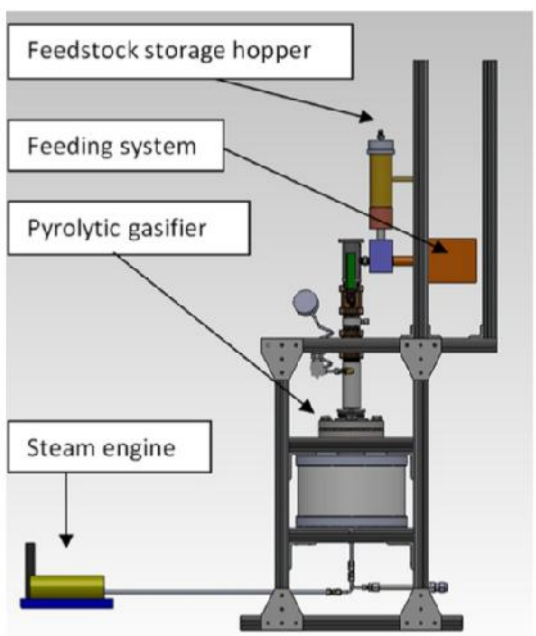


Figure 8. The laboratory-scale pyrolytic gasification apparatus [1]

The Northeastern University experiment consisted of a lab scale pyrolytic gasifier for the thermal decomposition of granulated or pelletized feedstock which can be seen in

Fig. 8. The main system parts included a feeding system, a furnace or heating chamber, and miniature steam generator and steam engine set up. The feeding system is equipped with a reservoir containing a hopper where the feedstock is stored, an electric motor and an auger-driven feeding box. The generator and steam engine is a model D18 from the company Wilesco. With the mass flow rate of 1 g/min of the pelletized solid feedstock, the pyrolytic gasifier ran a mini-steam engine at 1800 rpm for 20 min to light a miniature light bulb. The experiment showed that it was possible to produce electricity from biomass using a pyrolysis gasifier and a steam engine. An economic analysis showed that a large scale system would provide a viable option for the production of electricity. The resulting graph of the economic analysis is shown in Fig. 9, showing that at feed rates of 2700kg/h or higher are profitable.

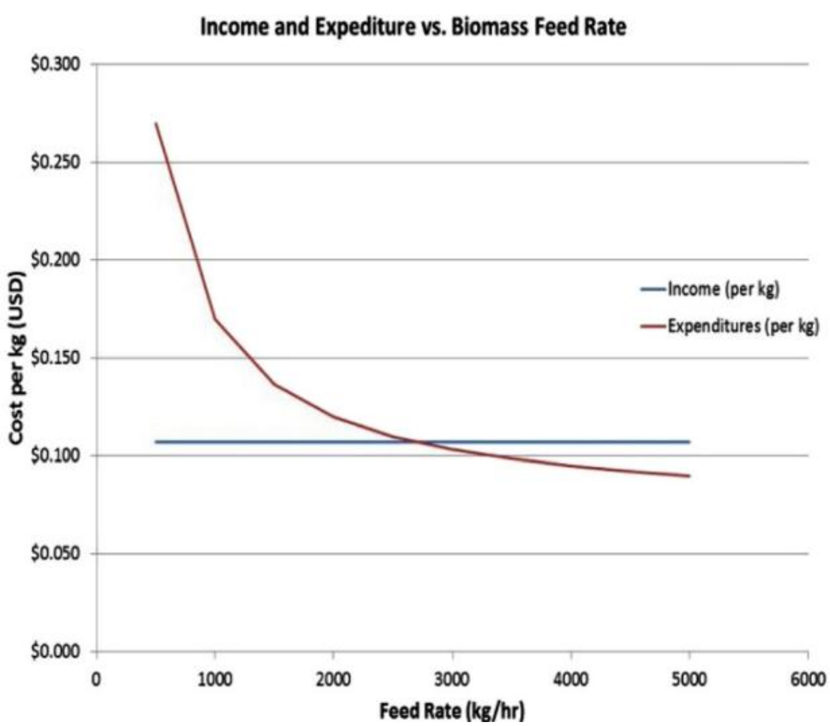


Figure 9. The biomass generation profitability as a function of feed rate and income and expenditure [1]

Some issues not mentioned in the report are the effects of using the corn biomass and grass samples to produce energy. For example, since DDGS is used as cattle fodder, does producing energy with DDGS interfere with the cattle feed supply and prices? Also, the use of farmland for King Grass could interfere with food production or require deforestation. In order to make sure a system is environmentally friendly, these issues should be addressed.

The study mentioned above is more suitable for developed countries with food security. Pyrolysis can also be used in a developing country like Peru. Peru is a megadiverse country with increasing energy demand and a high volume of waste and has looked into the use of pyrolysis for the production of biofuel. Peru provides 24% of its land for agriculture with 70% of the land preserved as a national forest, home to 1700 different birds and other animal species. As stated earlier, Peru wants to increase their renewable energy production from 27% of total energy produced to 33% in the year 2030. The Pontificia Universidad Catolica de Peru has built a small flash pyrolysis facility to test the viability of the technology. The use of flash pyrolysis requires a moderate temperature system with a shorter period of exposure time. These conditions are ideal for liquid production. The interest in liquid fuel comes from its transportability and the ease of storage due to the energy to bulk density relationship. The construction of the small flash pyrolysis facility consisted only of materials found in Peru. Coffee grounds were used as the raw material for the system. Coffee is a main export of Peru and coffee produces waste that ends up in landfills. Sometimes coffee grounds are used as fertilizer and deodorizer, but are usually thrown out, leaving no further use of raw material. The repurposing of coffee grounds can increase the renewable energy the country wants while avoiding use of agricultural crops needed for food production.

Unlike landfills, where there is not a secondary use for waste, certain biomass can provide food for the communities. When comparing different biomasses for energy production, like manure and straw, there is an obvious difference in calorie output between the two. Although one could get more energy from straw, there should never be a situation where the food supply is to suffer. Also, the need for farmland to produce biomass energy crops could cut into the production of other essential food crops. Therefore, it might be more appealing to use a lower quality resource to produce energy such as manure, even if it requires a greater volume of the resource.

Anaerobic digestion is a natural event which is the decomposing organic waste. From an engineering perspective, there is a simplicity to this process. The real work comes in the collection, processing, distributing, and applying the decomposing organic waste for energy production. Some northern areas in the European Union have strict laws regulating animal waste. These laws require farmers to collection the slurry from the animals in large storage tanks that have a 6-9 month capacity. The reason for this law is pollution prevention of nutrients leaching into the ground water. Areas with no restriction also store their manure, but the storage period is usually shorter.

An implemented storage system of animal manure allows for large scale collection, co-digestions, and redistribution to take place. Denmark is a pioneering country of integrated systems [7]. In 2010, 20 centralized and more than 35 farm scale biogas plants existed [11]. The centralized system require the transportation of storage tanks from the local farms to large scale biogas plant. The manure is pre-sanitized, mixed, and co-digested for a period of 12-25 day. The digested biomass is then taken back to the farms to be used as a fertilizer. The government also regulates the amount of fertilizer taken back to the farms to prevent over-fertilizing. The remaining fertilizer is sold by the processing plant to other crop farms. The biogas is used for combined heat and power generation or as vehicle fuel. The benefits of the an integrated system are renewable energy, waste recycling, lower emission of greenhouse gases, pathogen reduction through sanitation, improvement of fertilizer, reduced odor, and economic profit to farmers. With large scale systems, quality control of the product and the health and safety of the communities are concerns for government. Proper legislation ensures appropriate processing of biomass for the application of anaerobic digestion.

The biogas extracted can then be used raw or upgraded to increase the energy output. At minimum the cleaning of hydrogen sulfide, a compromising compound in energy production, needs to be incorporated into the post-treatment of biogas. After post treatment the biogas can be used in heat and/or steam production, combined heat and power plants, vehicle fuel, chemical production, upgraded and injected in natural gas grids or fuel for fuel cells. Peru has produced 114.9 GWh of electricity "from January 2012 to September 2012, nearly twice the production in the same period in the 2011" from biogas [8]. A government funded system like the one described above is ideal where manure storage is mandatory, but legislation of agricultural manure is commonly not required by most countries. Therefore, low-cost anaerobic digesters are the easiest to implement.

As stated in the introduction, many variables must be monitored in the anaerobic process. Many experiments have been conducted on how to get the best gas production through anaerobic digestion. A review of the anaerobic process show the use of additives, recycling of slurry, and operational parameters can help gas production [12]. Biological and chemical additives can increase gas production by increasing microbial activity. Plant additives can help contain maintain pH, inhibit or promote acetogenesis and methanogensis. Microbial strain additives of bacterial and fungi can stimulate the activity of enzymes. Inorganic additives like metal cations, adsorbents, and salts can improve gas production. Recirculation of digested slurry allows for the addition of microbial population, thus, increasing production. The ideal temperature range for mesophilic anaerobic digestion is 30°C-40°C and for thermophilic, 50-60°C. It is also important for the temperature to remain constant using insulation. The best pH for a digester should be contained in the range of 6.8-7.2. Volatile fatty acids and acetic acids can affect the pH, therefore, a concentration of 2000mg/l or lower is ideal. The carbon to nitrogen (C:N) ratio of 20-30:1 allows for the correct amount of utilization by mircroorganisms. Hydraulic retention rate (HRT) of 30-50 days for tropical countries have best results, while colder countries can require up to 100 days. These are just some of ways to improve anaerobic digestion, but these can also increase the cost of anaerobic digestion.

An experiment was performed examining if the different types of feed a cow eats affects methane production [16]. The experiment was conducted in Denmark where 40% of the manure came from cattle. The dairy cattle were given different feeds, which ranged from fat rich diets, a standard diet and a low fat diet. The results showed that fat rich diets had a higher production of methane. The experiment also showed that a high storage temp of 35°C produced the most methane gas. High rich diets can cost a farmer more to maintain their cattle, but should be considered if biogas is being used for energy production.

Another experiment was performed regarding the separation of liquid and solid manure at psychrophilic temperatures [17]. Mesophilic temperatures can provide better production of methane gas but comes at a cost. In order to accommodate the cost, anaerobic digesters can use the biogas produced for heating the system. During the winter season, biogas is needed in various locations on the farm for heating, so using biogas for anaerobic digestion takes away the heating potential for the farm. Therefore, an experiment was done to see how the separation of liquid and manure effects methane production at the lower temperatures of 24°C and 14°C. The results showed a 70% decrease of methane production from 24°C compared to 14°C. Also, the unseparated batch of manure at 24°C proved to have better yields due to the availability of more volatile solid.

2.1.5 Disadvantage

The biggest concern for biogas is that it is a greenhouse gas, and if left untreated, contributes to the amount of pollutants in the atmosphere. Depending on the starting material, the amount of methane that can be extracted from biomass varies in quality. When methane is used to for energy production, some methods require purification, which can increase the cost of the system. Other methods can be used increase biogas production of anaerobic digestion, such as the uses of additives, temperature and pH control, but increases the overall cost of the system. Many countries do not have governing policies regulating biomass, leading to a mixture of garbage. Especially with livestock manure, it might be difficult to collect the waste if animals are able to roam about freely. With an increase in population, food production should also increase for survival, resulting in the need for farmland to produce food crops not energy crops. Without proper planning, animal farms could contribute to the greenhouse gases in the atmosphere if they increase in size. It can be prevented if anaerobic digestion was considered for all farms. When biogas is used for heating purposes, it is usually burned which can reintroduce the greenhouse gases into the atmosphere. A better way to utilize biogas is with fuel cell technology. Fuel cells have a high efficiencies and lowers the amount of emissions produced.

2.2 Fuel Cell

2.2.1 OVERVIEW

The easiest way of thinking of a fuel cell is to envision a battery. The basic components of a fuel cell are the same: cathode, anode, and electrode. Unlike batteries where the chemicals are stored inside the cell, fuel cells use gas that flows through the device to generate electricity. Similarly protons move from the anode to the cathode traveling through the electrode, causing a chemical reaction. When leads are attached to the end of the materials, electricity can be collected from the fuel cell. The principles of the reaction are like an exergonic chemical reaction where high chemical energy reactants combine to form lower chemical products and energy is released. Traditionally, combustion style reactions convert the chemical energy into heat, but the electrochemical reaction which occurs in a fuel cell directly converts the chemical energy into electricity. There are many different types of fuel cells, the most common are alkaline fuel cells (AFC), phosphoric acid fuel cell (PAFC), proton exchange membrane fuel cell (PEMFC), molten carbonate fuel cell (MCFC), and the solid oxide fuel cell (SOFC). Most fuel cells are able to run on hydrogen gas, which takes the hydrogen gas and air (oxygen) and converts it to water producing electricity in the process. Some fuel cells cannot use biogas as a source of energy because it contains impurities and is a low quality methane source. This would ruin the fuel cells. Finally, fuel cell technology is not new, but like methane gas, is underused.

2.2.2 Proton Exchange Membrane Fuel Cell (PEM Fuel Cell)

The PEM Fuel Cell is the most common fuel cell that uses hydrogen and oxygen to produce electricity. The process can be simplified as the reverse of water electrolysis. For electrolysis, a voltage is required for water to create hydrogen and oxygen. Reversing the process, hydrogen and oxygen combine in a combustion reaction which releases energy. A PEM fuel cell allows the two gasses to react on separate ends of the fuel cell only allowing the transfer of the hydrogen atoms. The process eliminates combustion and captures the energy released from the reaction of hydrogen atoms and oxygen gas. To understand the process of a fuel cell, an analysis of water electrolysis is described in this section. The electrolysis of water is an oxidation- reduction reaction, where one element is reduced, or gains electrons and the other is oxidized, or loses electrons. The reaction is also non-spontaneous, meaning an external energy source is required for the reaction to occur. Fig. 10 shows an experimental set up for the electrolysis of water, with a battery applying the external source of energy.

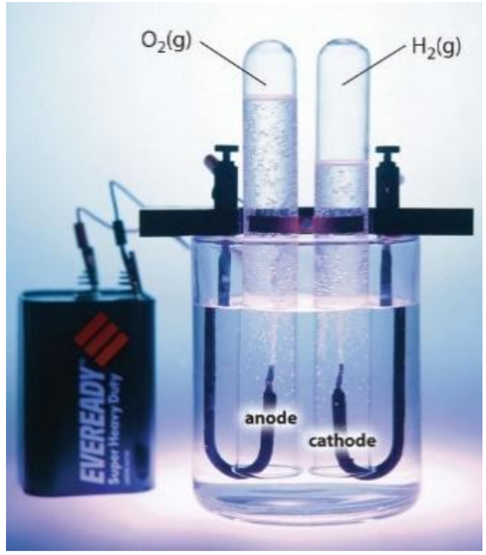


Figure 10: A picture of the electrolysis of water

To analyze the chemical reaction, an equation for the electrolysis of water is assessed. Eq. (1) shows the complete balanced equation for the electrolysis of water. In an oxidation-reduction reaction, the elements are reacted on different ends of the electrode. The loss of electrons occurs on positive electrode, or the anode, and the gain of electrons occurs at the negative end of the electrode, or the cathode. In order to see how each element is behaving half-reactions can be written. Half reactions use the oxidation number for each elements. Eq. (2) shows the corresponding oxidation numbers. In water, H_2O, the oxygen part corresponds to group 6A on the periodic table and has an oxidation of -2. The hydrogen is part needs to give the water molecule a neutral oxidation value, therefore it has an oxidation of +1. Hydrogen gas and oxygen gas have an oxidation number of 0 because they are neutral gases. Since hydrogen is going from an oxidation number of +1 to 0, the element is reducing and gaining elections. Oxygen's oxidation number is going from -2 to 0, so the element is oxidizing and losing electrons. Half reaction equations can be written to see what is happening to each element. For the reduction of hydrogen, two electrons are gained by water, producing hydrogen gas and two hydroxide ions. For the oxidation of oxygen, water loses 4 electrons, by hydrogen atoms leaving water and oxygen atoms combining with each other to produce oxygen gas. Finally a complete net ionic equation can be written, combining the two equations. For this to be done, Eq. (3) should be multiplied by two, shown in Eq. (4) so the number of electrons can balance. The hydrogen and hydroxide ions can combine to produce water, and the electrons cancel out, leaving the original equation. This is a non-spontaneous reaction, meaning it does not happen naturally, needing the addition of an electrical current. It is important to note, there is a 1:2 mole ratio for oxygen gas to hydrogen gas, meaning twice as many hydrogen atoms are produced in the electrolysis process.

Complete Balanced Equation:	$2H_2O \rightarrow 2H_2 + O_2$	(1)
Oxidation numbers:	$2H_2^{+1}O^{-2} \rightarrow 2H_2^0 + O_2^0$	(2)

Half- reaction equations:

Reduction of Hydrogen:	$2H_2O + 2e^{-1} \rightarrow H_2 + 2OH^-$	(3)
Eq. (3) multiplied by two:	$4H_2O + 4e^{-1} \rightarrow 2H_2 + 4OH^-$	(4)
Oxidation of Oxygen:	$2H_2O \rightarrow O_2 + 4H^+ + 4e^{-1}$	(5)
Complete net ionic equation	$6H_2O+4e^{-1} \rightarrow 2H_2+4OH^-+O_2+4H^+ + 4e^{-1}$	(6)

The reverse process can be captured in a PEM fuel cell. The basic fuel cell contains a membrane and electrode assembly (MEA), flow field plates, current collectors, stainless steel endplates and heating or cooling plates. The hydrogen gas and oxygen gas react at separate ends of the MEA. The electrolyte separates the two reactions and only allows protons to flow through. The reactant gases flow through the flow plates parallel to the MEA, allowing the gases to diffuse and react. Water is produced and moved to the flow field by the excess gas flow. The electric potential can be captured by the current collectors. The reactions of a PEM fuel cells are as shown in Eq. (7-9).

Anode:	$2H_2 \rightarrow 4H^+ + 4e^-$	(7)
Cathode:	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	(8)
Overall:	$2H_2 + O_2 \rightarrow 2H_2O + \Delta E$	(9)

The reason this type of fuel cell is so popular is because the only byproduct of the device is water when operating with hydrogen and oxygen gas. However, this fuel cell has the ability to run on hydrogen captured in biogas. According to an experiment in Germany, "Biogas production and utilization with polymer electrolyte membrane (PEM) fuel cells provides a clean and reliable option for decentralized energy supply" [18]. The only issue with using a PEM fuel cell with biogas is the need for reforming. Reforming extracts hydrogen from biogas. The process of using biogas and fuel cells will be discussed further in the integrated system section.

2.2.3 Solid Oxide Fuel Cell

The Solid Oxide Fuel Cell (SOFC) converts chemical energy with high efficiency directly into electrical energy with low emissions. Sulfur and nitrogen oxides, hydrocarbon pollutants, and carbon dioxide emissions are lowered by using a SOFC. Using a SOFC has a significant environmental advantage over conventional power generation [19]. This device, just like the anaerobic digester, can range from large commercial devices with many stacks of cells put together in a block to smaller cell stacks that can be as small as a pen. The larger devices are more focused on centralized distribution of power onto the grid while the smaller stacks can be put in cars and individual houses or in developing countries.

A SOFC has a solid ceramic inorganic oxide as the electrolyte, usually yttria-stabilized zirconia, requiring an operation temperature of 750-1000°C. They run off of a mixture of hydrogen gas and carbon dioxide, by internally reforming hydrocarbon fuel inside the fuel cell. Internal reforming breaks down the hydrocarbon fuel into simple molecules such as carbon monoxide and hydrogen. The final products of the fuel cell are water and carbon dioxide. SOFC differ from the PEM fuel cell because the membrane allow the exchange of oxygen ions rather than hydrogen protons as seen in Fig. 11. The following equations, Eq. (10-13) show the electrode reactions.

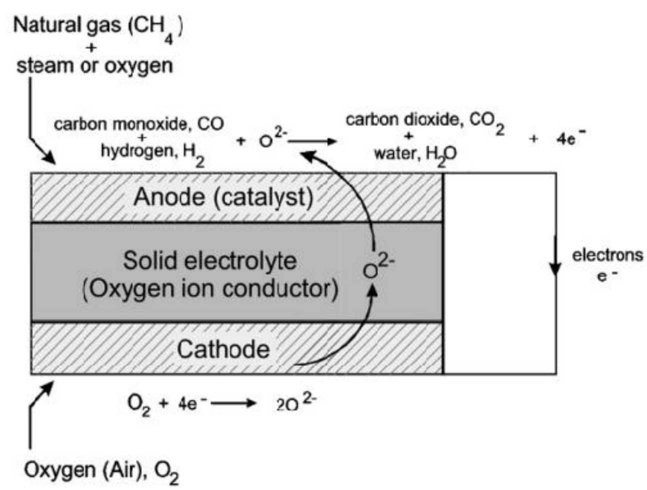


Figure 11: A diagram of the Solid Oxide Fuel Cell [19]

Anode:	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	(10)
	$CO + O^{2-} \rightarrow CO_2 + 2e^-$	(11)
Cathode:	$O_2 + 4e^- \rightarrow 2O^{2-}$	(12)
Overall:	$H_2 + CO + O_2 \rightarrow H_2O + CO_2 + \Delta E$	(13)

Over the years, there have been many attempts to lower the temperature which the solid oxide fuel cells operates in order to increase the application of the fuel cell and to make the cell last longer. By using different materials for the cell elements, Yoshikawa, T., developed a SOFC operating at a temperatures between 850-650°C [20]. The cell showed no degradation of cell performance over the 200h period at 750°C and a 0.7V load. Lower temperature can decrease the overall cost of the fuel cell and increase the safety of operating the system.

The most popular of the SOFC is a planer design, because of the ease of production. A planer design has the contents of the fuel cell in thin sheets that are stacked together. However, there is an efficiency loss due to the lack of contact in flow plates. Also a high fuel utilization can lead to an internal temperature gradient causing ceramic cracking. Microtubular fuel cells are a way to increase the efficiency to the fuel cell by controlling the fuel rate and temperature of the stack. This design can extend the life and efficiency of the SOFC [21].

2.3 Integrated System

The combination of biogas with fuel cell technology is basic concept presented in this paper. Experiments have been done tying the two technologies together. According to Schmersahl, R., a system which produces biogas with an anaerobic digester, refines the gas through a steam reformer, then produced electricity with a PEM fuel cell is described [18]. The study results confirm the feasibility of the technology for renewable energy production. The experiment used cattle manure and straw as the raw material with a hydraulic retention rate of three months at mesophilic temperatures. The gas was collected in 16 m^3 balloon gas holders. The steam reformer and PEM fuel cell were connected as one unit. The hydrogen content was between 53-56% of the biomass. A maximum power output of >600 W was achieved. The system would be suitable for a combined heat and power production. The down side to this system was the requirement of fuel reforming which increases the cost of the overall system.

Another experiment showing the possibility of using biogas with a fuel cell is shown by Staniforth, J. [22]. This experiment illustrated the possibility of running the SOFC on biogas, at low levels of methane, where conventional heat engines would not work. This system offers a valuable and environmentally friendly use for poor-quality biogas that is currently wasted by detrimental venting to the atmosphere, which increase greenhouse gas emissions. The system uses small tubular SOFC operating at 850°C. The maximum power occurred at 45% methane, with maximum production of hydrogen gas and carbon monoxide through internal reforming. The experiment showed that ammonia could be utilized to produce energy. The products of the device were nitrogen gas and water with no other pollutants.

An experiment was conducted determining the best treatment for bioenergy when comparing combustion and fuel cell application using and exergy and emission standards [23]. The experiment used partially premixed flames for the combustion analysis and a tubular anode supported solid oxide fuel cell. The conclusion of this experiment showed that fuel cells using biogas produced more energy and the byproducts of this process were less harmful to the environment when compared to the combustion process. The modeling of the experiment used flame reactor modeling OPPDIFF of Chemkin software for the combustion process and a numerical model of MatLab using a Cantera interface for the SOFC process. The results showed that a SOFC can have higher exergetic emission when compared to partially premixed flames and have lower pollution outputs. The conclusion is that a SOFC proves to be a better technology when compared to combustion.

There are current designs of using biogas in direct operation with a fuel cell. One example is of a SOFC working with waste water and exhaust carbon recycling from algae growth [24]. The system consists of a SOFC fed by biogas from anaerobic digestion. The biogas is drained, cleaned, and reformed to hydrogen using steam and then sent into the stack. The water and carbon dioxide will be collected and used for algae growth in photobioreactor producing a closed carbon cycle. Another example comes from California, with an implemented pilot project that uses anaerobic digestion to make biogas in order to run it a 2 mega-watt fuel cell from a landfill [25]. This shows that it is possible to run a fuel cell using biogas produced in an anaerobic digester and implement it into modern society.

CHAPTER THREE

Anaerobic digester/ Fuel Cell Experiment

3.1 Overview

Figure 12: Completed anaerobic digesters

For this experiment, anaerobic digesters were made from materials available in developing countries. Fig. 12 shows the anaerobic digesters constructed for this experiment. The amount of biogas will be analyzed in order to determine the amount of methane that can be produced. The quantity of methane then determines how much power can be produced with a fuel cell. This power that can theoretically be produced from a fuel cell would be the power available to developing countries.

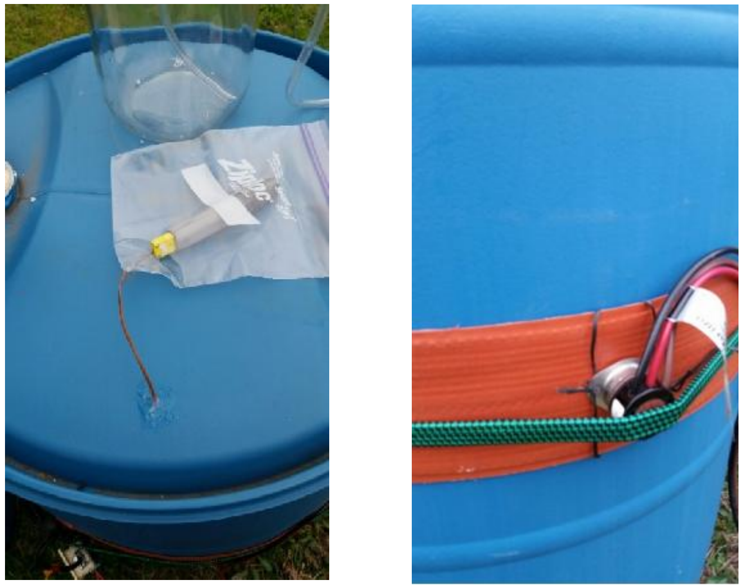
The overall experiment consists of four different steps. The first step is the biomass collection process requires animals to be keep in a closed environment in order to easily gather manure. The second step would be the methane production where the collected biomass is put in an oxygen free environment. Once methane is produced, it is to be extracted into the third step of gas collection. Finally, the gas can be further processed by the use of a fuel cell.

3.2 Step 1: Biomass Collection

An efficient way to collect biomass without having to collect manure with a large amount of manual labor is needed. On a trip to Costa Rica by the author, a pig pen was observed. The structure consisted of concreate floors equipped with a watering system and a small outlet at the back of the structure for manure collection. The caretaker would come in regularly to clean the floor by spraying water and sweeping the waste into a corner where the outlet was located. The waste traveled outside the outlet into a bucket. The five gallon bucket contained a metal grate where the collection of non-digested solids could be separated from the manure. Water could then be added to the manure in the bucket to make the slurry which went into their anaerobic digester.

The design was constructed of materials found in Costa Rica, which would be similar to a system built in a developing country. If this were to be constructed in a developing country, available resources would be considered in the design for animal pens. The floor material would need to be easily washable and equipped with a water supply. The walls would need to be strong enough to enclose the animals, preventing their escape. A roof would need to be placed sheltering the animals from the sun. Enough space should be allocated for the animal's comfort. There should be an outlet where the manure could be collected and funneled into a storage container or anaerobic digester. Places that already accumulate and store the biogas in government required containers would have an easier time implementing a fuel cell integrated system.

3.3 Step 2: Anaerobic Digestion



(a) Thermocouple (b) Heating system

Figure 13: Anaerobic Digestion system

The Anaerobic digesters were built based on of materials easily found in developing countries. In building the anaerobic digesters, 55 barrel drums were donated from Mars Company in Waco, TX. The rest of the materials were purchased from Home Depot, Omega, Uline, and Amazon. The digesters are equipped with an inlet PVC pipe with a cover, located at the top of barrel. The manure slurry is transferred into the pipe via a funnel. At the bottom of the barrel an outlet pipe is located, sealed with an UNISEAL flexible tank adapter. The outlet pipe is equipped with a sealing valve to allow the manure to be removed when the anaerobic digestion process is over. There is a thermocouple sensor at the top of the barrel for temperature measurement which can be seen in Fig. 13 (a). One digester is equipped with a heater and sensor that monitor the power input of the device as seen in Fig. 13 (b). Lastly, there is a gas outlet tube made of PVC plastic tubing that leads to the gas recovery step.

3.4 Step 3: Gas Collection

(a) Gas collection system (b) Portable gas detector

Figure 14: Gas Collection system

The gas collection system is a glass jar with a lid from Omega. The top of the glass jar has two pipes, one inlet and one outlet. The inlet tube reaches the bottom of the jar. The jar is to be filled half way with water, this way one can monitor when gas is being produced. The outlet tube contains a valve for sealing and measuring the tube. A handheld gas sensor was purchased to measure the quality of the gas produced. The gas detector is a GX-2012 model from RKI instruments. The device detects the percent volume of methane, oxygen, carbon monoxide, and hydrogen sulfur. Therefore, given the volume of the container, one can determine how much biogas is produced and what percentage is methane gas. Since the device is portable, it can be used on all three gas collectors.

3.3 Step 4: Energy Production Using a Fuel Cell

3.3.1 PEM Fuel Cell

Figure 15: The experimental PEM fuel cell

The RU-2101 Proton Exchange Membrane Fuel Cell was used for this experiment. The PEM Fuel Cell is located at the Baylor Research and Innovation Center in Waco TX. The specific setup for this fuel cell takes hydrogen gas and compressed air and converts it into electricity with the water being the only by-product. The MEA of the RU-2101 is an ionically conductive polymer membrane (Nafion®) with a catalytic electrode on both sides. The Nafion® Teflon contains sulfonated side chains allowing the conduction of protons H^+. The catalytic electrodes are composed of a porous gas diffusion layer (GDL), Nafion® and platinum catalyst on a carbon support providing electronic conductivity. The fuel cell stack contains three MEAs configured in series. The reactant gases are fed to all stacks starting in order of arrangement. The first cell receives the gas first, the effluent from cell one is fed to cell two, and the effluent from cell two is fed to cell 3. The gas inlet connects to the front of the stack and gas outlets connect to the back of the stack. The top of the stack has one heater, four voltage and five temperature leads connecting to the left side panel of the RU-2101. There are two humidifying bottles for hydrogen and air that are bubbled to humidify the gas streams. The bottles are equipped with Kapton heaters on the outer surface. There are also two beakers filled with deionized water, to visually confirm the exhaust gas flow [26].

CHAPTER FOUR

Results

4.1 Modeling of the Barrel System

The amount of manure of livestock can be quantified by the amount of livestock by the following eq. (14):

$$D = \sum_{i=1}^{n} Qd_i \times M_i$$

Eq. (14)

where D, is the physical amount of manure, Qd_i is the number of livestock, and M_i is the manure yield of livestock "i" within the whole breeding cycle. The Breeding cycle and manure yield of different livestock and poultry are showing in the Table 1.

Table 1: Breeding cycles and manure yields of different livestock and poultry [6]

Livestock	Hogs	Herds hogs	Cattle	Cows	Sheep	Horse	Jennets	Poultry
Breeding cycle (day)	300	365	365	365	365	365	365	55
Manure yields (kg)	1050	1460	8200	21900	632	5237	3092	4.5

From the amount of manure, one can convert 60% to biogas through anaerobic digestion. If one collects 1/3 of the total manure, these coefficients can be added to the physical amount of manure equation to get B, the amount of biogas produced by manure as seen in eq. (15).

$$B= \sum_{i=1}^{n} Qd_i \times M_i \times .60 \times \frac{1}{3}$$

Eq. (15)

According to the USDA 2012 Ag Census, the average herd size of cattle is 40 heads. If this is applied to eq. (14), 328,000 kg. of manure is produced for every heard of cattle each year. If one can conservatively collect one third of the total biomass, 109,300 kg of manure is left for the anaerobic digestion process. The anaerobic digestion process last 30-50 days, so the process can be repeated every 2 months for tropical regions. This leaves about 18,200 kg that should be used in a digester anaerobically every 2 months. One anaerobic digester can hold up to 208 kg of liquid, which would require 88 anaerobic digesters for one herd of cattle. The amount of biogas produced can be found using eq. (15), which is 65,600 kg. of biogas for one herd of cattle in one year.

The cost of one anaerobic digestion system with a heater is about $330 – Appendix A.2. If 88 anaerobic digesters are needed for one herd of cattle, this puts the cost to $29,040. Although if the anaerobic digesters are used in tropical area with warmer temperatures, a heater would not be necessary, dropping the price to $133. The total cost for 88 anaerobic digesters would be $11,704. The addition of a heater adds a great cost to the anaerobic digester, so this application would be more economical in more temperate regions. Instead of using a heater, the digesters can be buried underground for insulation.

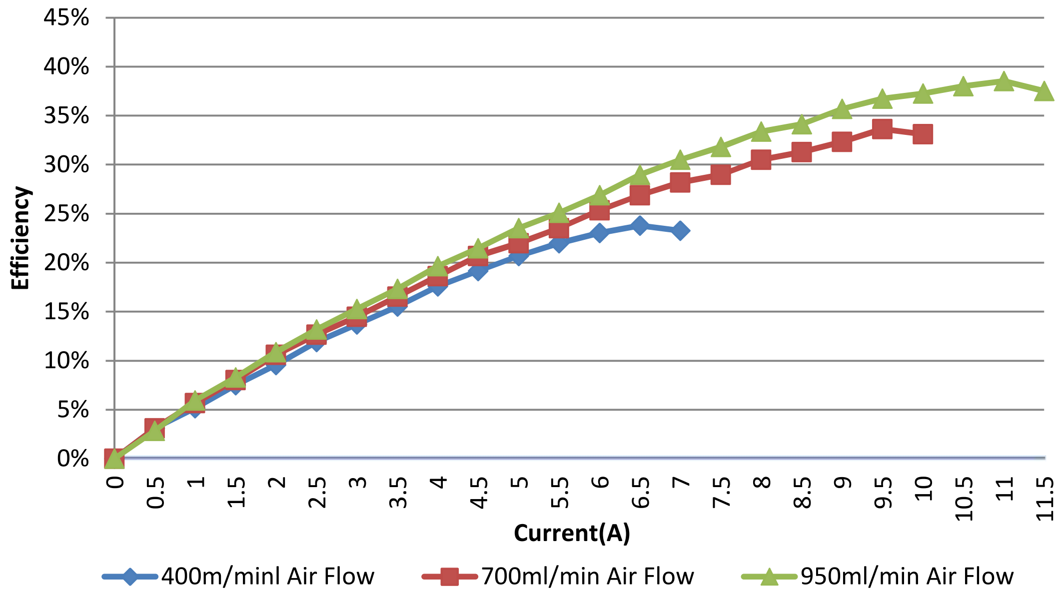


Figure 16: A graph of PEM fuel cell stack efficiency with 200ml/min H_2 flow

Figure 16 shows the data for the PEM fuel cell experiments performed at the BRIC at a constant flow rate of 200 ml/min of H_2. The best flow rate proved to be 950 ml/min of air flow. The efficiency at increased current had a higher efficiency than lower flow rates. The efficiency of the fuel cell can be calculated using the energy released when hydrogen and oxygen combust, which is 11.6 J/ml, and the flow rate of hydrogen gas. The amount of theoretical power can be calculated by Eq. (16) assuming 100% of the hydrogen is consumed. For a hydrogen flow rate of 200 ml/min the theoretical max power is 38.7 W. The efficiency is then calculated using the Eq. (17).

$$\text{Theoretical power} = \text{Flow rate}\ \frac{\text{ml}}{\text{min}} \times 11.6\ \frac{\text{J}}{\text{ml}} \times \frac{1\text{min}}{60\text{s}} \tag{16}$$

$$\text{efficiency (\%)} = \frac{\text{Actual Power}}{\text{Theoretical power}} \times 100 \tag{17}$$

The minimum flow rate of air can be calculated from the complete balanced equation for a PEM fuel cell which can be seen in Eq. (1). There is a 2:1 stoichiometric ratio of hydrogen to oxygen, based off the coefficients of the equation. Since this experiment used air, consisting of 21% oxygen and 79% nitrogen by volume, the flow rate of air would have to be about 4.76 times greater than that of oxygen. The minimum flow rate of air for stoichiometric purposes is 476 ml/min at a hydrogen flow rate of 200 ml/min. A 950 ml/min flow rate of air exceeds the minimum requirement for flow rate and has the greatest efficiency at an increased current.

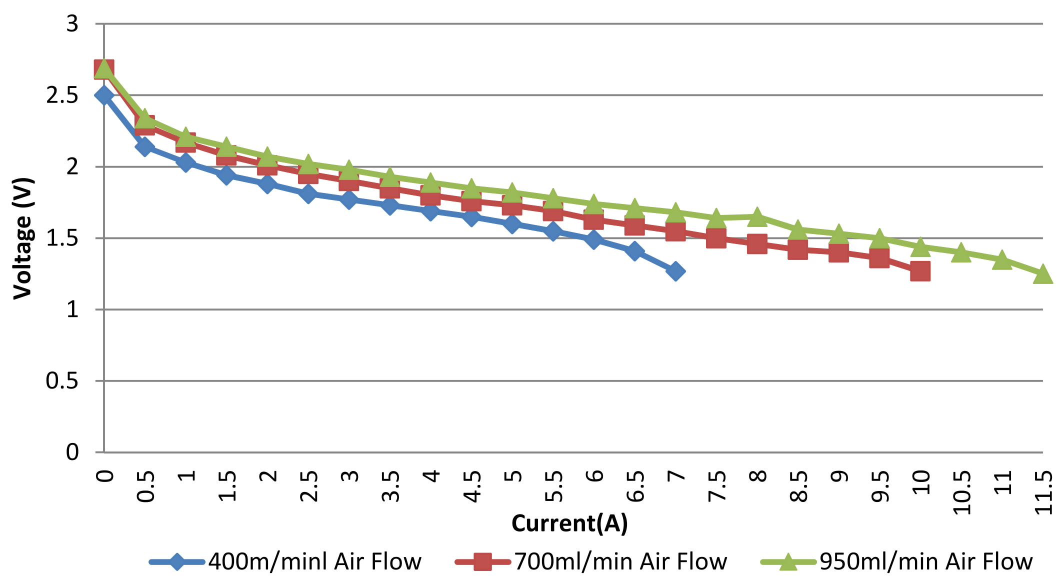


Figure 17: A graph of PEM fuel cell stack voltage at 200 ml/min H_2 flow

The graph of stack voltage at a constant flow rate of 200 ml/min of hydrogen gas can be seen in Fig. 17. The graph shows a stack voltage drop as current increases for all the various air flow rates. The voltage drops can be caused by four different factors, activation losses, fuel crossover and internal currents, ohmic loses, and mass transport or concentration losses. The activation loss is affected by the type of catalyst. Using a catalyst with a lower activation resistance and increasing the surface area can reduce the amount of loss in this region. The loss from gas crossover and internal currents can be reduced by increasing the thickness of the membrane. Ohmic loses come from ionic resistance of the membrane, contact resistance of electrodes and current collectors. Using materials with lower resistances can improve the loss. Mass transport or concentration losses can be explained by the gas not being transported fast enough to keep up with the reaction. Increasing the flow rate can lower the loss the region. Fig. 18 shows how the different factors affect cell potential.

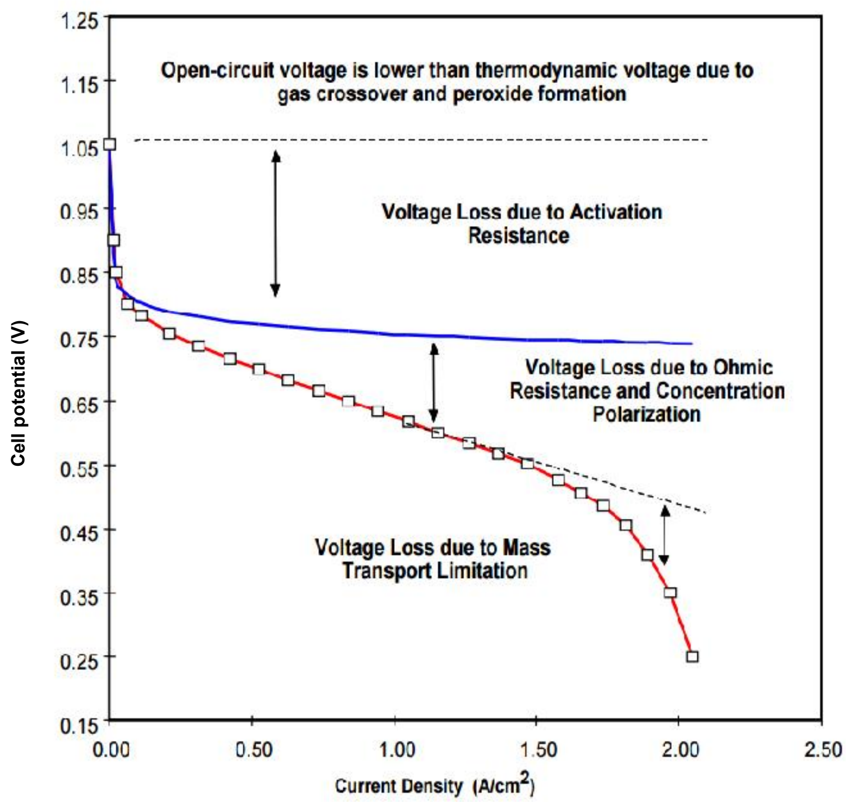


Figure 18: A polarization curve of a H_2/O_2 PEM fuel cell [26]

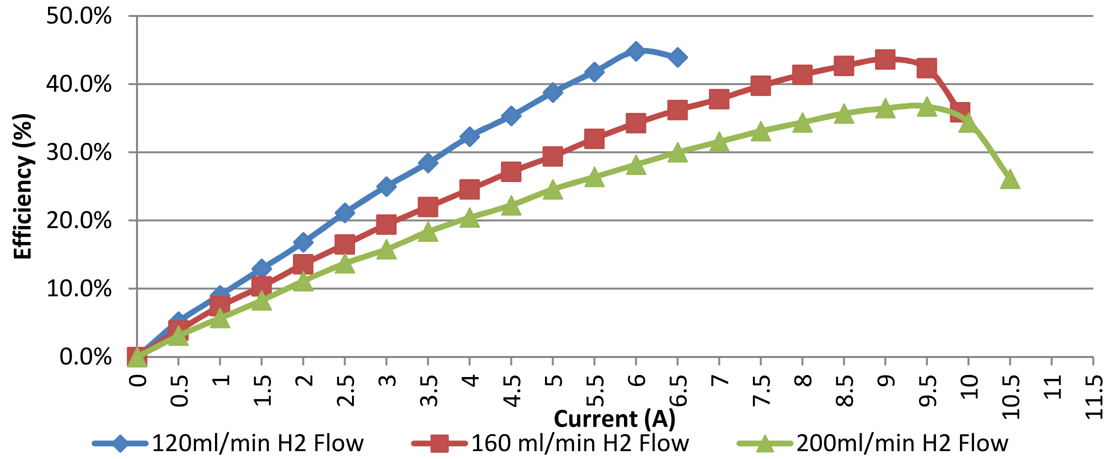


Figure 19: A graph of PEM fuel cell efficiency at 600 ml/min air flow

With a constant air flow rate of 600 ml/min, 120 ml/min of H_2 showed to have the best efficiency. This can be seen in Fig. 19. Since efficiency is based off of the hydrogen flow rate, the theoretical power had to be calculated for each flow rate. The theoretical max power for the hydrogen flow rates of 120ml/min and 160 ml/min are 23.2 W and 30.9 W respectively. The values for max power and efficiency were calculated using Eq. (16) and (17). For all flow rates of hydrogen there is a drop after peak efficiency is reached. This means if high current is necessary for particular application, a higher flow rate of air should be used.

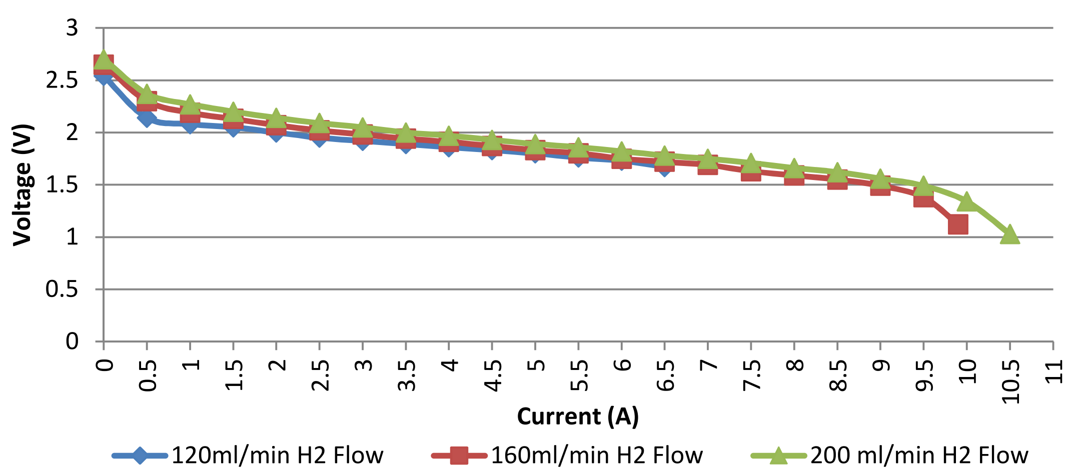


Figure 20: A graphs of PEM fuel cell stack voltage at 600 ml/min air flow

The stack voltage for a constant air flow of 600 ml/min can be seen in Fig. 20. The same voltage drop observed at a constant hydrogen flow of 200 ml/min can be seen. The stack voltage for all hydrogen flow rates with a constant air flow rate of 600 ml/min stays above 2 V until the current reaches 4 A. The drop of voltage can also be explained by the various factors mentioned in Fig. 18.

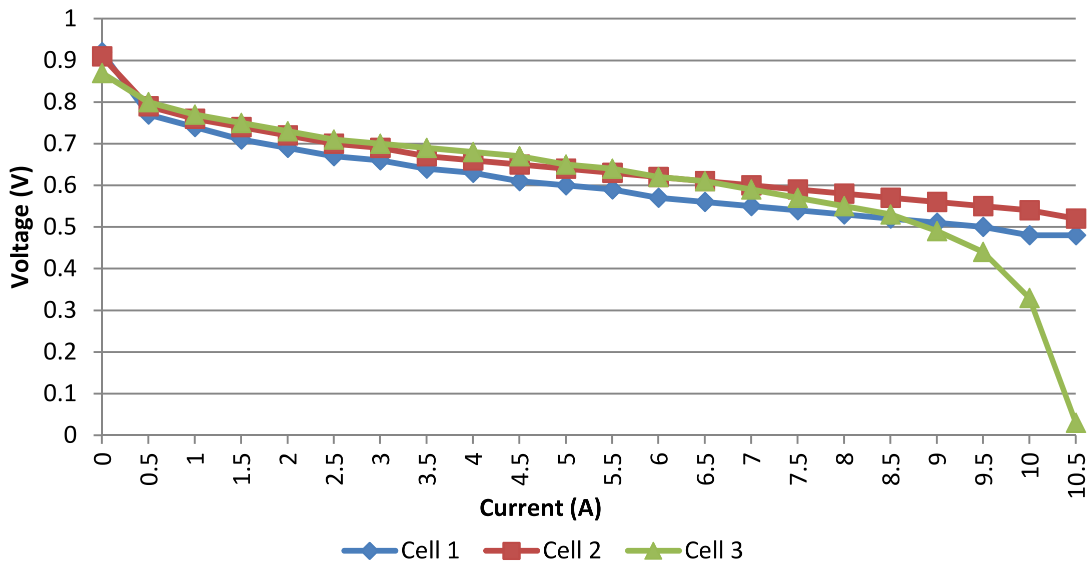


Figure 21: A graph of PEM fuel cell voltage at 600 ml/min air flow and 200 ml/min H_2 flow

The variation of the cell voltage at zero current is near zero, as seen in Fig. 21. As the current increases so does the separation of the cell voltages. The third cell starts to dramatically drop after the current reaches 9 A. This can be explained by the rise of current density which out the increase of hydrogen flow rate. More hydrogen is used up at the first two cells, leaving the third cell without enough hydrogen to produce a voltage.

When this is applied to the biogas produced every two months. The biogas would have to be reformed in order to be used in a PEM fuel cell. If the biogas was reformed using a steam reformer from, Schmersahl, R [18], about 50% of the biogas can be transformed in hydrogen gas. This leaves 32,800 kg of H_2, meaning it would be possible to run the PEM fuel cell for 164,000 min with a constant power output of 14.7W to have the greatest efficiency. This system would be able to run for 113 days, or provide 40.18 kWh.

4.3 SOFC Analytical Data

If the fuel cell from Staniforth, J was used in this experiment [22], the maximum power output for one small tubular solid oxide fuel cell at a flow rate of 6 ml/min of 50% methane gas would be 240mW for one cell. Now if 50 of the cells were stacked together, a power output of 12 W could be obtained. Using the biogas produced from the anaerobic digesters, 39,360 kg of pure methane gas can be obtained. If the system only needs 50% at a time, the amount of gas used in the SOFC would be 78,730 kg. To run a 50 cell stack the flow rate would need to increase to 300 ml/min. The SOFC would be able to run for 262,433 min. at a power of 12W for maximum efficiency. This system would be able to run for approximately 180 days or provide 52.48 kWh.

CHAPTER FIVE

Conclusion and Recommendations

Due to the lack of funds for this project, an actual SOFC was not able to be purchased. It was also not possible due to unforeseen circumstances to gather enough slurry to test the anaerobic digesters. Therefore, the results were theoretically determined. It is important to note that the type of application discussed in this paper would only be suitable in areas with high agricultural availability and/ or an abundant organic waste reserve. It serves the purpose of making underdeveloped areas self-sustaining without the need of importing resources to increase the standard of life. Further, the idea is to preserve the environment while still being able to enjoy the higher quality of life achieved in developed areas. It is important to note that consideration of food and water supply must always be considered when dealing with any renewable energy resource.

As of right now the efficiencies for both the anaerobic digester methane production and the SOFC could produce a current stream of 12W for 180 days. This might not seem like much, but a system like this requires no import of fuel and is environmentally friendly. The best solution to reduce the use of fossil fuels is to combine other renewable resource to aid in the energy production. As research and development continues, in the near future it is possible to see an anaerobic digestion and fuel cell system that could be self-sufficient for the developing world, to provide household electricity.

Municipal solid waste can also be applied to this application, although the handling of this in the United States becomes difficult because of the laws and regulation due to pathogens related. So the experimentation of it is limited. Although, if there were a push for recycling of organic material, anaerobic digestion could be seen as an option for urban communities.

In applying a small scale system for local biogas usage, the idea for a larger system should always be kept in mind. For example, if the farm gets bigger, how to add more digesters and incorporate them into the fuel cell system should be easily implemented. Also, the anaerobic digester should be flexible in becoming a storage tanks so it could be possible to have an integrated system similar to Denmark's where biogas is integrated into a grid power system. There will always be room for development as anaerobic digestion and fuel cell technology advance, therefore the need for future analysis of the system is to be considered.

APPENDIX

Bill of Materials for Anaerobic Digester

Bill of Materials

	Store:	Item:	Description:	Part #:	Quantiy:	Cost:	Total:
1	Home Depot	Copper coil	1/4in X10ft	647788	3	$ 9.98	$ 29.94
2	Home Depot	PVC socket ball valve	1 1/2in	20003581034	3	$ 6.63	$ 19.89
3	Home Depot	PVC pipe	1 1/2 in	136263	1	$ 5.13	$ 5.13
4	Home Depot	bucket	5 gallon	131227	3	$ 2.85	$ 8.55
5	Home Depot	bucket lid	5 gallon lid	529776	3	$ 1.68	$ 5.04
6	Home Depot	PVC pipe	4in	491550	3	$ 7.33	$ 21.99
7	Home Depot	PVC pipe cap	4in	811459	3	$ 7.71	$ 23.13
8	Home Depot	Funnel		863196	1	$ 1.77	$ 1.77
9	Home Depot	Clear PVC tubing	5/16in X20ft	714422	1	$ 3.86	$ 3.86
10	Uline	Glass Jar w/ lid	1g clear jar	S-127580	3	$ 3.30	$ 9.90
11	Omega	Standard Drum Heater		SHDH 1200-120	1	$ 197.00	$ 197.00
12	Amazon	Tank Seal	Uniseal 1 1/4in flexible tank seal	U123	3	$ 4.80	$ 14.40
TOTAL:						$ 252.04	$ 340.60
13	Amazon	Water Barrel	55gallon drum	B006KAAUSQ	3	$ 77.15	$ 231.45
TOTAL:						$ 329.19	$ 572.05

REFERENCES

[1] Davies, A., Soheilian, R., Zhuo, C., and Levendis, Y. A., 2013, "Pyrolytic Conversion of Biomass Residues to Gaseous Fuels for Electricity Generation," J. Energy Resour. Technol., **136**(2), pp. 021101–021101.

[2] The World Bank, 2016, "Energy Overview," from http://www.worldbank.org/en/topic/energy/overview#1 accessed on September 2016

[3] U.S. Energy Infromation Administration, 2016, "International Energy Statistics," from http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8 accessed on September 2016

[4] US Environmental Protection Agency, 2016, "Overview of Greenhouse Gases," from https://www.epa.gov/ghgemissions/overview-greenhouse-gases accessed on September 2016

[5] Wuebbles, D. J., and Hayhoe, K., 2002, "Atmospheric methane and global change," Earth-Science Reviews, **57**(3–4), pp. 177–210.

[6] Junnian Song, Wei Yang, Helmut Yabar, and Yoshiro Higano, 2013, "Quantitative Estimation of Biomass Energy and Evaluation of Biomass Utilization - A Case Study of Jilin Province, China," Journal of Sustainable Development, **6**(6), pp. 137–154.

[7] Holm-Nielsen, J. B., Al Seadi, T., and Oleskowicz-Popiel, P., 2009, "The future of anaerobic digestion and biogas utilization," Bioresource Technology, **100**(22), pp. 5478–5484.

[8] Klug, M., Gamboa, N., and Lorber, K., 2013, "Sustainable Development and Renewable Energy from Biomass in Peru - Overview of the Current Situation and Research With a Bench Scale Pyrolysis Reactor to Use Organic Waste for Energy Production," Journal of Sustainable Development, **6**(8), pp. 130–139.

[9] Lin, Y., Zhan, Z., Liu, J., and Barnett, S. A., 2005, "Direct operation of solid oxide fuel cells with methane fuel," Solid State Ionics, **176**(23–24), pp. 1827–1835.

[10] 1995, "World renewable energy congress 1994 final reports," Renewable Energy, **6**(3), pp. 181–189.

[11] Demirel, B., Scherer, P., Yenigun, O., and Onay, T. T., 2010, “Production of Methane and Hydrogen from Biomass through Conventional and High-Rate Anaerobic Digestion Processes,” Critical Reviews in Environmental Science and Technology, **40**(2), pp. 116–146.

[12] Yadvika, Santosh, Sreekrishnan, T. R., Kohli, S., and Rana, V., 2004, “Enhancement of biogas production from solid substrates using different techniques—a review,” Bioresource Technology, **95**(1), pp. 1–10.

[13] Kullander, S., 2009, “Energy from biomass,” Eur. Phys. J. Spec. Top., **176**(1), pp. 115–125.

[14] Bolan, N. S., Thangarajan, R., Seshadri, B., Jena, U., Das, K. C., Wang, H., and Naidu, R., 2013, “Landfills as a biorefinery to produce biomass and capture biogas,” Bioresource Technology, **135**, pp. 578–587.

[15] Bosmans, A., Vanderreydt, I., Geysen, D., and Helsen, L., 2013, “The crucial role of Waste-to-Energy technologies in enhanced landfill mining: a technology review,” Journal of Cleaner Production, **55**, pp. 10–23.

[16] Møller, H. B., Sarker, S., Hellwin, A. L. F., and Weisbjerg, M. R., 2012, “Quantification of methane production and emission from anaerobic digestion of cattle manure derived from different feeding,” ResearchGate.

[17] Witarsa, F., and Lansing, S., 2015, “Quantifying methane production from psychrophilic anaerobic digestion of separated and unseparated dairy manure,” Ecological Engineering, **78**, pp. 95–100.

[18] Schmersahl, R., Mumme, J., and Scholz, V., 2007, “Farm-Based Biogas Production, Processing, and Use in Polymer Electrolyte Membrane (PEM) Fuel Cells,” Ind. Eng. Chem. Res., **46**(26), pp. 8946–8950.

[19] Ormerod, R. M., 2003, “Solid oxide fuel cells,” Chem. Soc. Rev., **32**(1), pp. 17–28.

[20] Yoshikawa, T., Yamahara, K., Shinde, N., Murata, K., Hirano, A., Takeda, Y., and Yamamoto, O., 2010, “Intermediate Temperature Solid Oxide Fuel Cells With Bi2O3–Eu2O3 Infiltrated La0.8Sr0.2MnO3 Cathodes,” J. Fuel Cell Sci. Technol, **7**(6), pp. 061004–061004.

[21] Tsai, T.-I., Du, S., Fisher, P., Kendall, K., and Steinberger-Wilckens, R., 2013, “Control system design for micro-tubular solid oxide fuel cells,” Int. J. Low-Carbon Tech., p. ctt006.

[22] Staniforth, J., and Ormerod, R. M., 2003, “Running solid oxide fuel cells on biogas,” Ionics, **9**(5-6), pp. 336–341.

[23] Quesito, F., Santarelli, M., Leone, P., and Aggarwal, S. K., 2013, “Biogas Combustion in Premixed Flames or Electrochemical Oxidation in SOFC: Exergy and Emission Comparison,” J. Energy Resour. Technol., **135**(2), pp. 021201–021201.

[24] Gandiglio, M., Lanzini, A., Santarelli, M., and Leone, P., 2014, “Design and Balance-of-Plant of a Demonstration Plant With a Solid Oxide Fuel Cell Fed by Biogas From Waste-Water and Exhaust Carbon Recycling for Algae Growth,” J. Fuel Cell Sci. Technol, **11**(3), pp. 031003–031003.

[25] Wichert, B., Wittrup, L., and Robel, R., 1994, “Biogas, compost and fuel cells,” BioCycle, **35**(8), p. 34.

[26] Knobbe, M. W., and Nguyen, T. V., 2004, “RU-2101 Proton Exchange Membrane Fuel Cell Experiment.”