Senior Capstone Design
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Waste to Watts: Biogas Engine

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[Retrofit an engine to run on biogas for the cogeneration of electricity and heat]

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Final Report

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1. Project Definition

1.1 Problem Statement

The world's population is expected to grow in coming years, the vast majority of which will occur in developing countries. Rapid population growth in these regions will only add to the estimated two billion plus people in the world that still lack access to basic sanitation and electricity. Every year, food and water tainted with fecal matter cause up to 2.5 billion cases of diarrhea among children, resulting in 1.5 million child deaths.[i] These conditions are an issue largely for people living in developing countries where fecal matter and water for use are in close contact. Unfortunately, the predominant method for water sanitation is burning biomass, which causes significant carbon emissions and fatal respiratory problems.

While access to electricity is something taken for granted in the U.S., electrification rates in developing countries is significantly lower. The WHO and International Energy Agency (IEA) estimate that 1.5 billion people around the world currently live without electricity, the majority of which are in rural areas of developing countries. Telecommunications companies have recently made cell phones and cell phone service more accessible in these areas, yet there are few-to-no reliable electricity sources for charging. Off-grid power generation is important in rural areas as they are well beyond the established power grid and usually in poorer areas where infrastructure expansion is unlikely.

1.2 Solution

Our project aims to provide those far away from the grid with electricity while simultaneously addressing the growing demands for hot water and sanitation. Human waste can be sequestered and harvested for both energy generation and waste disposal. Funded by the Bill and Melinda Gates Foundation, Dr. Marc Deshusses's lab at Duke University is researching the best technologies to process fecal sludge into energy dense biogas. As Deshusses explains in his

Grand Challenges Exploration program grant below:

> "**Fecal sludge energy recovery**: Fecal sludge tends to be a serious community liability despite the resource value available for energy recovery. The majority of evacuated fecal sludge is either dumped locally in nearby streets or drains or taken to dumping sites where little if any treatment takes place. The indiscriminate dumping of a truckload of fecal sludge is the public health equivalent of 5,000 incidences of open defecation. Fecal sludge, however, is a concentrate of organic material with high energetic value. Energy can be derived through digestion, extraction, or combustion, simultaneously reducing the volume of sludge that must be disposed. Unfortunately, relatively few facilities are designed to recover the energy value from sludge and many existing facilities have fallen into disrepair."[ii] Dr. Marc Deshusses, Duke University, *Effective Sewage Sanitation with Low* CO_2 *Footprint*

When fecal sludge is processed in an anaerobic digester, biogas is produced. Biogas is typically composed of 60% methane and 40% carbon dioxide, which is easily combustible. Figure 1 shows the entire energy harvesting process, starting with raw biomass and ending with electrical energy and heat. This project focuses on the physical energy generation process, which is shown below by the engine illustration and the red cycle. Retrofitting an existing gasoline generator to run on biogas is the most efficient way to transform human waste into electricity. The high temperature of the engine's exhaust heat will also be harnessed in a cogeneration process to heat water for daily activities such as showering.

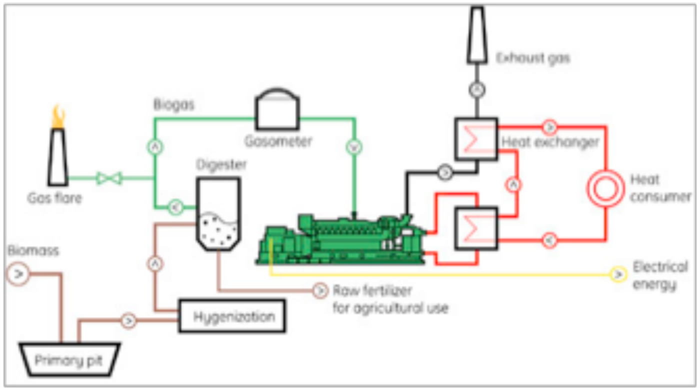

Figure 1: Overall biomass cogeneration cycle

1.3 Goals

Three major goals were identified based on the problem and solution: biogas combustion, electricity generation and heat recapture. The primary goal was to produce a combustible mixture of air and fuel. This required combining biogas and air at appropriate pressures, velocities, and mole ratios for maximum fuel combustion upon ignition. Without correct proportions, the unit would not run correctly or generate electricity and neither of the other goals could be accomplished.

The secondary goal was to generate a minimum amount of electricity for a significant period of time in order to address the electricity demand of a village in the developing world. The target goal was to generate an output to be able to charge four cell phones at a time for approximately an hour. This would require 5.475 kWh annually.

The final goal was to have the system be used for cogeneration. Water can be heated by recapturing heat energy lost in the system as exhaust heat. This requires a heat exchanger system to turn the exhaust heat back into usable energy for heating water. The ultimate threshold was to heat water to an acceptable shower temperature. The amount of water that can be heated is a function of the heat transfer capabilities of the heat exchanger, as well as the runtime of the engine itself. The heat exchanger should be able to heat water to approximately 42 degrees Celsius.

While designing to reach these goals, the key factor was to make the engine accessible to developing areas. This involved keeping costs low, using materials easily found, and making the design simple in order to keep maintenance as low as possible. This led to developing an engine with the specific need of powering cell phones in mind as opposed to meeting the total electricity demand of an area.

1.4 Critical to Quality

The team further refined its goals by breaking them into “critical-to-quality” (CTQ) values, which set numerical targets for quality and functionality. Comparing the CTQ values to the final output of the engine allows a quantifiable means to determine the project’s success. The final CTQs and target values evolved with the design and performance of the biogas engine.

The initial CTQs were determined from experimental data gathered by running the generator unit on gasoline. During this test, 0.5 L of gasoline was consumed while running a 1.875 kW hair dryer. The engine ran for 20.5 minutes, generated a voltage of 119.3 V, and induced a current of 13.04 A. The voltage output was very close to the rated voltage output of 120 V. This was a good indication that the engine was operating correctly. By multiplying current and voltage, a power output of 1.56 kW was calculated. By multiplying power and time, an energy output of 1,912 kJ was calculated. The energy densities of gasoline and biogas were used to determine that, to produce the same amount of energy, the volume of biogas at atmospheric conditions must be 840 times greater than that of gasoline. Relating this volume ratio to our initial run of the engine on gasoline, this would mean that 420 L of biogas is required to produce 1,912.4 kJ of energy. This relationship was used to calculate the optimal and target volume of biogas for a chosen runtime and power output, shown in Table 1.

Table 1: Initial CTQs

CTQ	Optimal	Targeted
Fuel Consumed	157 gallons (unpressurized)	118 gallons (unpressurized)
Tank Pressure (assume 20 gallon tank)	115 psi	86 psi
Run Time	45 minutes	45 minutes
Electricity Generation	1 kW	0.75 kW
Water Heating	42 °C	35 °C

After running numerous tests using biogas, detailed below in the Final Experimentation, Results and Analysis section, it became clear that the CTQs had to be adjusted. By using the gasoline-to-biogas volume and energy relation, the CTQ calculations used the efficiency of the engine running on gasoline, 12%. In reality, the engine running on biogas had a much lower efficiency and therefore could not perform to meet our initial CTQs. Tests results obtained from running the engine on biogas were used to calculate the final accomplished and in-the-field CTQs, shown in Table 2.

Table 2: Final CTQs

CTQ	Accomplished	In the Field
Biogas Volume	3.24 ft^3	21.2 ft^3
Run Time	2.5 minutes	76 minutes
Power Output	64 W	15 W
Electrical Energy Output	9.54 kJ	68.3 kJ
Efficiency	0.3%	0.3 %
Exhaust Heat	160 °C	160+°C

The runtime accomplished with a 64 W load was only 2.5 minutes because a longer runtime would require more biogas, which requires a much longer test preparation time. The in-the-field runtime was calculated by using the expected daily biogas produced by a family of 10 and the desired power output of 15 W, the load from about 4 cell phones. It is also important to note that the final in-the-field CTQs assume the same efficiency as that achieved with a 64 W load.

2. Design Evolution

Biogas engines are normally designed and implemented for large-scale applications. However, smaller community- or household-sized biogas engines for cogeneration are not readily available. The following design choices reflect the development of a small-scale biogas engine to be used for cogeneration in developing areas.

2.1 Generator Selection

At the onset of the project it was important to choose the correct engine in order to improve the chances of successfully running it on biogas. The three main options were a diesel engine, a two-stroke gasoline engine, and a four-stroke gasoline engine. Retrofitting a diesel engine was eliminated first because combustion in a diesel engine is done by compression alone, with a higher compression ratio than what is typically found in a gasoline engine. This compression would not be sufficient to combust biogas. Two-stroke gasoline engines need additional fluid for lubrication. Four-stroke gasoline engines have spark plugs, which ignite the gas in order to make it combust. Additionally they are self-lubricating allowing for a gaseous substance to be used without friction problems. For these reasons, a four-stroke gasoline engine was selected and an appropriate generator unit was purchased.

Our group selected a generator with a large energy output in order to both easily meet the minimum design requirement of charging four cell phones while also having substantial quantities of spare energy for other purposes. We designed to have additional energy from the generator in case the system required other loads, such as a self powered compressor or a large battery in addition to the cell phones for the hypothetical villager's future and more convenient use. Specifically a 212cc, 4000 Watts max/3200 Watts rated portable generator from Harbor Freight was purchased for the project. This generator has a horizontal single cylinder engine, designed for a 10 consecutive hours of use at 50% capacity. The generator met all of the criteria of an ideal generator for the project; a four-stroke gasoline powered, inexpensive generator with way more than sufficient energy output to charge four cell phones.

2.2 Gas Pressurization

For the engine to run, biogas must be pressurized to ensure fuel flow into the cylinder. Over the course of the project, multiple pressurization techniques were designed and tested.

The first attempt at pressurization was to fill the biogas bag in Dr. Marc Deshusses's lab and squeeze it directly into the engine's air filter. While crude, using manpower was effective in making the engine run for a short period of time. The method continued with the final designed carburetor, but with biogas being squeezed into the gas intake. Manually squeezing the gas was ideal for initial testing because it was quick, relatively easy to setup, and proven sufficient to start the engine. If the engine would not start with the strength of the team pushing on the bag, it was a good indicator that the problem was not fuel intake related. This was valuable information during the design phase.

There were several setbacks to the “brute force” method of pressurization that led to deciding on a different system. First, pushing on the bags is inconvenient. It was mildly strenuous for any team members to get the engine to run for five minutes with on the 190cm bags by squeezing. As resistance to flow increased towards the end of our short trials due to the crumpling of the deflated bag, it often took two group members to apply the force needed to maintain the correct pressure. The manual squeezing method was also unsteady. Unsure how much pressure squeezing the bags was providing, the user was forced to adjust their applied force by listening to how well the engine was running. Changes in applied pressure that resulted in too much or too little fuel movement caused the engine to stop or to exude non-combusted methane. This constant adjustment does not achieve the best possible engine performance results.

In the scaled up application of the engine there will be larger quantity of biogas and a longer runtime. It is inefficient to store large volumes of biogas in multiple small bags for individual, manual pressurization over the course of an hour. The first pressurization system design used a modified bike pump. A hole was drilled in the pump cylinder as a biogas inlet, and a check valve was used to ensure proper gas flow direction. As the piston was raised, biogas would be sucked into the pump cylinder. When pushed down, the gas would only have one possible flow direction – through the already existing exit tube. This tube was connected to a pressure tank, which was attached to the carburetor via a pressure regulator and tube. This allows the user to more accurately control the flow of biogas from the pressure tank into the engine.

Unfortunately, the curved face of the cylindrical bike pump made it very difficult to attach a check valve without any leakage. Furthermore, the resistance of the biogas flowing through the check valve was much greater than that of air flowing around the piston. As a result, this system was unable to transfer biogas from the atmospheric bag to the pressure tank. Even with further modifications to make the bike pump system work, it would share some of the same problems as the manual squeezing method. Pumping over twenty-one cubic feet of biogas into a tank would be time and energy intensive. The bike pump method, like the squeezing method, proved too labor intensive and inefficient for the goals and application of the biogas engine.

The final design for biogas pressurization harnesses the force of gravity and requires very little manpower. Bricks, cinder blocks or other heavy materials placed on a moveable lid push down on the bags, thereby pressurizing the biogas inside at a constant rate. The setup is straightforward and can be seen in Figure 6 in the Product Architecture section. The biogas bags are confined within a large plastic drum that prevents them from expanding horizontally, forcing the gas straight down. Holes in the bottom of the drum allow tubes to extend from inside each bag to a single outlet tube. The design includes a t-connection to connect multiple bags to a single outlet. The outlet tube is connected directly to the carburetor. As the bags deflated about the height of one weight, additional weight can be placed on the lid to offset the increasing resistance from the biogas bags. With this setup the user is able to provide a steady intake of fuel to the engine with minimal effort.

This method is ideal because it is comprised of materials well suited to the region it is designed for. Plastic tubing and the large drum are inexpensive and sturdy, properties that are a must for developing areas. The weights would most likely be free of cost since sizable rocks can easily be used. Since none of the materials are particularly valuable, it is also unlikely that they will be stolen, another key design concern in these regions. This brickage method combines both functionality and cost-effectiveness to create the ideal pressurization mechanism for this engine and it’s location.

2.3 Carburetor Design

In order to ensure that the proper mix of air and biogas for complete combustion enter the engine, the carburetor had to be substantially modified. Carburetors are used to create a combustible mixture of air and fuel. It does so by the Venturi effect, which describes the pressure drop created by restricting flow area. Based on the Bernoulli equation, the increase in flow velocity due to the restricted area lowers the pressure in that space. At the narrowest point in the carburetor Venturi tube, gasoline is drawn up into the flow due to the lower pressure.

Prior to entering the Venturi tube, the gasoline is held in the float chamber. The float chamber regulates the amount of gasoline by moving a buoyant piece up and down depending on the amount of fluid in the chamber. When there is excess fluid in the float chamber, the inlet into the float chamber from the gasoline tank is blocked off to prevent additional overflow, as seen in Figure 2. Once sufficient gasoline leaves the float chamber, the inlet opens again. This float chamber is extremely important for a liquid fuel source, but is irrelevant for a gas. As such, the float chamber was deemed superfluous to requirements, and a newly designed carburetor more appropriate for mixing biogas and air was merited.

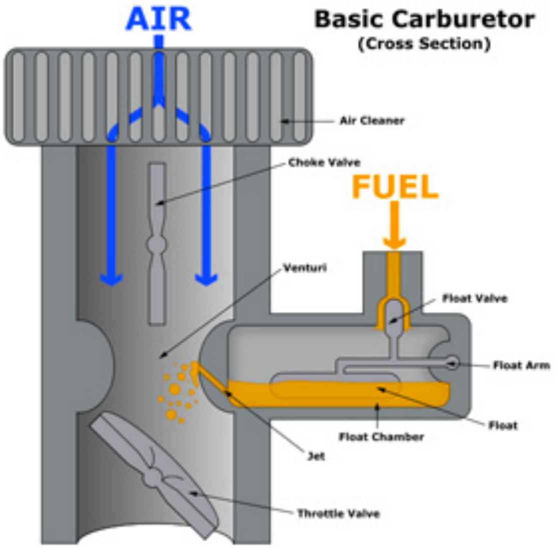

Figure 2[iii] : Basic Configuration of Float Chamber

It was determined that the existing carburetor on the generator was not ideal for a gaseous substance. The first design choice for the new carburetor was to remove the float chamber. As previously stated, the float chamber was not useful for gas as only a liquid could move the buoyant float piece. Instead, the float chamber created extra resistance by adding to the flow path of the biogas. The carburetor design was originally simplified to contain a t-shaped cavity sized to appropriately mix the air and biogas.

In order to determine the original sizes for the air and fuel intakes, an air to fuel ratio was calculated. It is important to know that there is approximately 21% oxygen in air and that the biogas produced is about 60% methane. The molar masses of oxygen and methane are 28.97 g/mol and 27.2 g/mol respectively. Calculations to get the mass ratio can be seen below.

$$\left[\frac{1\text{ mol air}}{0.21\text{ mol }O_2}\right]\times 2O_2 + CH_4 \times \left[\frac{1\text{ mol biogas}}{0.6\text{ mol }CH_4}\right]$$

$$9.5424\text{ mol air} + 1.667\text{ mol biogas}$$

$$\text{Use molar mass to find:}$$

$$275.9\text{ g air} + 45.33\text{ g biogas}$$

This yields a minimum air to fuel ratio of 6.086:1. Ultimately, it is best to have a ratio much larger than this to ensure all of the fuel is being combusted and that there is excess air. It is advantageous to have biogas as the limiting reagent because it is more expensive than readily abundant air. It is sensible to guarantee that there is enough air present to combust the gas since it is a valuable commodity in the developing world and should not be wasted.

A simpler carburetor designed to accommodate biogas was machined from a block of aluminum. The fuel inlet was drilled and threaded to fit a 3/8” barbed fitting. From there, we drilled a channel 0.08” in diameter to allow the biogas to reach the chamber where mixing would occur. Lastly, the air inlet was bored to allow a choke to be screwed into the front. A 1/2” NPT butterfly valve was used as a choke.

The throttle valve was taken from the original carburetor. A hole was drilled allowing for the post to sit through the center of the carburetor and fit a butterfly valve. The throttle was designed to attach to the existing springs in order to rotate open and closed based on engine running speeds. Transferring this design over into the new carburetor helps the engine self-regulate the gas intake into the engine, restricting airflow if the engine is running too hard.

The carburetor was attached to the engine in the same place as the original carburetor: using long bolts attached to the horizontal cylinder. The air filter that had preceded the original carburetor was removed entirely.

SolidWorks Flow Works analysis was done to better assess fluid flow inside the carburetor. Figures 3 and 4 show the velocity and pressure distributions of flow. These do not take the pressure from the cycling of engine's pistons into account. Rather these diagrams indicate flow at a certain point in the cycle. The long entry length, and a lack of proper airflow caused problems getting the engine to fully run.

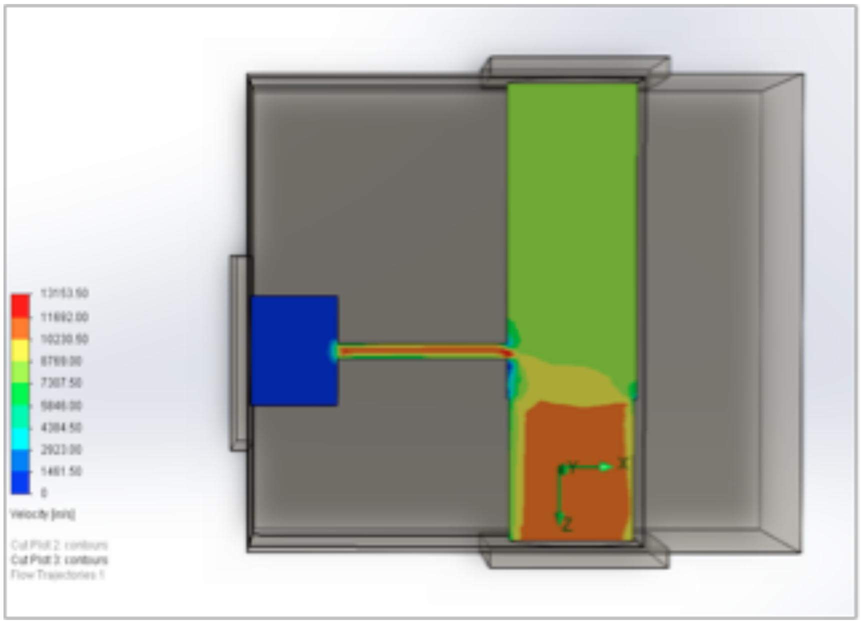

Figure 3: Velocity distribution inside the carburetor

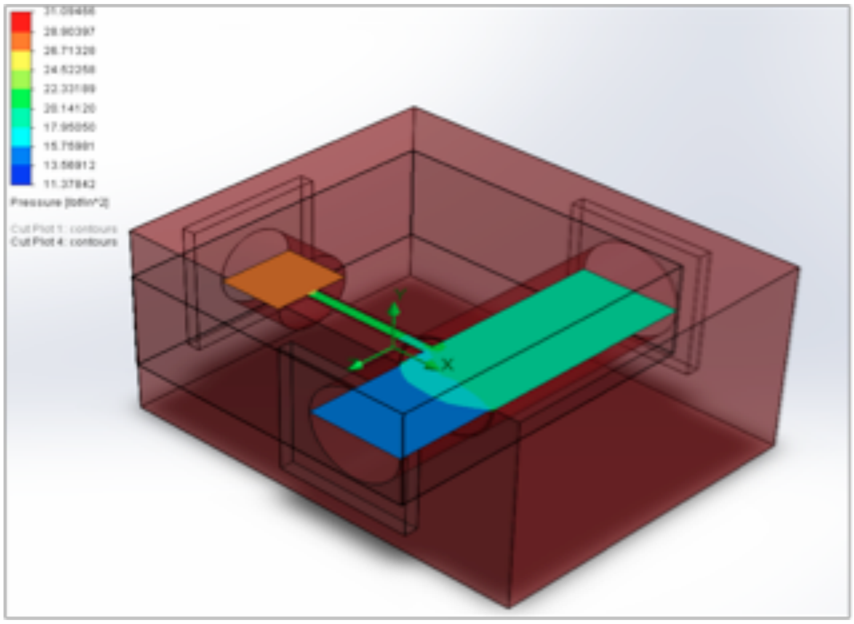

Figure 4: Pressure distribution inside the carburetor

Initial tests indicated that the engine was not getting enough air, so the choke was removed and the inlet diameter was increased to 1”. Various tests were run to increase the amount of air entering the engine. Various methods included directing a bike pump, a fan and tank of compressed air into the air inlet at different times.

It was later discovered that it was not the volume of additional air that made the difference, but rather the velocity of the air. In order to increase the velocity of incoming air, a sliding cover was made to create a Venturi effect. After testing different settings it was found that the ideal setting to start the engine was to have 50% of the air inlet covered. Once the engine started, the ideal setting was to cover ~90-95% of the inlet. A piece of pliable aluminum was used to cover the bottom of the inlet. A second piece of aluminum was cut to rotate around a screw and cover an additional 40-45%.

By using this method to increase the air velocity, the generator was able to run while “cold” for the first time. Running “cold” means that the generator is first being turned on and started. After a generator has been running for a significant period of time, even if turned off for a bit, it is considered to be running “warm” and is easier to restart.

Lastly it was found that the throttle was not made to allow full range of motion of the butterfly valve. The valve was removed and the springs were not attached to the cap while running tests. Images and SolidWorks models of the carburetor can be found in the Product Architecture section of this report.

2.4 Heat Exchanger

After comparing multiple designs, the team settled on a configuration for the heat exchanger that would have an excellent heat exchanging capacity, simple setup and maintenance, and use locally available materials. Three types of designs were proposed to achieve cogeneration; wrapping the muffler with copper tubing, having the exhaust gas pass through a plate heat exchanger, and finally attaching a long tube to the output of the exhaust and passing it through water.

Wrapping the muffler with a copper tube was an appealing design because it did not require tinkering with the current structure of the exhaust or impede the exiting gas. Slowing down the flow of exhaust gas was a concern given that stagnating the outgoing air had the potential to generate a pressure in the opposite direction of the flow, referred to as backpressure. Backpressure is problematic because the buildup of pressure causes exhaust to re-enter the engine and interfere with combustion. Thus any addition to the engine that could hinder combustion, and therefore the injection of biogas into the carburetor, was avoided.

There were two major drawbacks to wrapping the muffler with copper tubing. Firstly it was discovered that closely wrapping the muffler with copper tubing would be difficult. Copper tubing itself is not incredibly malleable, and wrapping an ellipsoid muffler accurately was important given that close contact is essential for high heat exchanger efficiencies. Combined with the evidence suggesting a poor heat exchanging efficiency by running the flow of hot exhaust gas perpendicular to the water caused the team to consider another method for cogeneration.

The next design considered was a water trickling system through a plate heat exchanger. This design was preferred to wrapping the muffler because the air enters the heat exchanger and runs parallel to the water, as opposed to perpendicularly. This change led to higher predicted heat exchanging capabilities. Although this design was an improvement over the wrap-around configuration, plate heat exchangers are not commonly found, can be expensive, and require a precise setup to match the size of the exhaust tube to that of the heat exchanger entrance. Lastly this design left many opportunities for leaks and melted parts given the required number, joints, connections, and valves. While this design had a higher ceiling for success than the previous one due to its improved method of heat transfer, the group continued to modify the recommended design in order to simplify the setup and lower the cost.

The final preferred design involved attaching a copper tube to the exit of the exhaust. The initial concerns over backpressure were quelled with a small test involving a PVC pipe about 4.5 feet long. The extension of the exhaust caused no noticeable change in the running or performance of the motor. Removing the muffler did increase the noise coming from the generator but reduced the ability for creating problematic a backpressure. The team settled on an extension of the exhaust via a long copper tube coiled into and out of a bucket of water. While an added expenditure, given the large amounts of energy exiting the generator the team feels the extension is worthwhile in order to best capture the remaining energy wasted in the exhaust gas and achieve cogeneration. The advantages of the exhaust extension are its heat exchanging potential and room for impreciseness compared to an ellipsoid wrapped in copper. The final tube extension design has not been tested due to time constraints. However, the measured heat output from previous tests coupled with the simplicity of the design makes the team confident that this design will be the most effective. The heat exchanger design is the best suited option for low-cost use in the developing world.

3. Product Architecture

3.1 Schematic

Figure 5 shows an overview of how the gas pressurization system, engine, electrical output and heat exchanger link together.

Figure 5: Overview of system architecture

Each biogas bag has a protruding tube, which can be linked with other bags via a barbed tee tube fitting. Our system comprises of two bags placed in a large plastic drum with small holes drilled in the base. The two tubes are reduced to one by a tee fitting before being attached to the carburetor. Weights are then added to a wooden movable lid to pressurize the gas. Figure 6 below show the plastic drums, tubing, and weights used to pressurize the biogas. Figure 7 shows the carburetor connection and SolidWorks model.

Figure 6: Plastic drum with two biogas bags, tee tube fitting, and pressurization

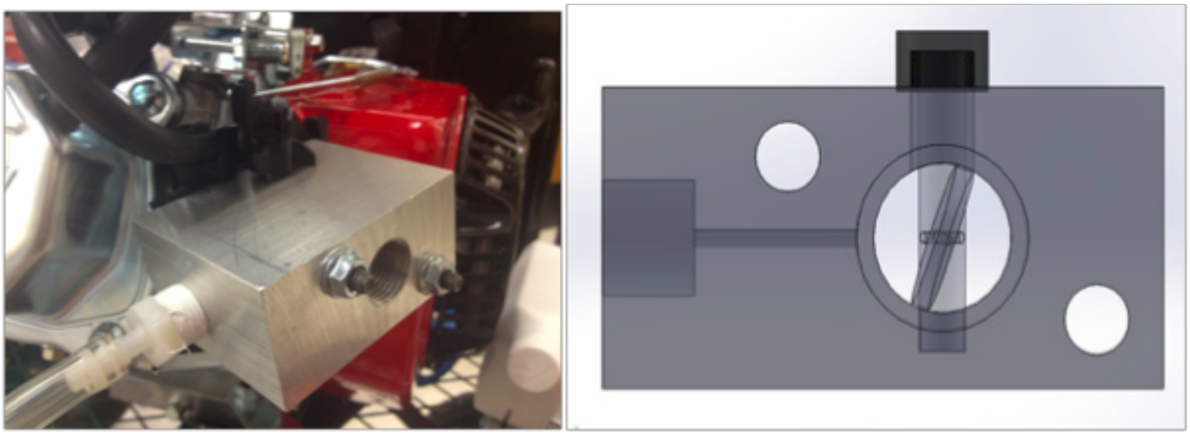

Figure 7: Fuel-to-carburetor connection and carburetor SolidWorks model

Since the engine is already linked to a generator, there is a voltage supply as soon as the engine starts running. Therefore, when enough power is being generated, a cell phone can be directly plugged in without any further modifications.

The heat exchanger can attach to the engine's exhaust pipe where the muffler has been removed. Figure 8 shows the engine both with and without the muffler.

Figure 8: The engine both with and without the muffler

3.2 Parts List & Budget

As shown in Table 3 below, the total cost of the prototype is approximately $430. It is important to note that this does not include the cost for the proposed heat exchanger, since no materials were actually purchased. Since most of the necessary materials were easily found in both Dr. Marc Deshusses's lab and the Fabrication Lab, the only component of the final prototype that was purchased was the Harbor Freight generator.

Table 3: Complete Parts List and Budget

Material	Quantity	Ceiling Cost	Notes
Pressurization System			
Plastic Drum	1	$50	Most likely a usable drum already in the area
Brickage Weight	N/A	$0	Can easily innovate depending on location (rocks, cinder blocks, etc.)
Plastic Tubing	3 ft	$7.50	
Barbed Tee Tube Fitting	1	$0.30	
Biogas Bag	2	$0.08	Will need to be replaced

			occasionally, but reusable
Cable Ties	10	$0.02	Will need to be replaced when bags are replaced
Generator Unit			
4000 Watts max/3200 Watts rated portable generator (Harbor Freight)	1	$339.99	Engine could be donated or cost could be subsidized
Aluminum block (for carburetor)	12.5”x3”x1.5” block	$30.00/ft	
Total		$427.89	

Depending on the deployment plan, the cost of the generator and machined carburetor could be fully subsidized, partially subsidized, or purchased locally. If fully subsidized, the actual cost to the community or household would be much less. Ignoring the cost of the heat exchanger, there would be a cost of only $57.90 for a two-bag setup. Since plastic drums are very commonly found in these areas, the cost could be as low as $7.90.

4. Experimentation, Results and Analysis

4.1 Final Tests

Final testing involved pressurizing the gas with brickage, sending the gas into the new carburetor with a sliding cover, and applying two different loads. For the first test, 4.56 cubic feet of biogas between two bags was used to power a 7.2 W fan. While two cinder blocks were used for initial pressurization, two more were applied over the course of the test to overcome the additional resistance from the bags folding on top on themselves. The engine ran and powered the fan for 4.2 minutes, yielding a final electrical energy output of 1.84 kJ. Overall, this test had an efficiency of 0.04%.

In order to try to improve the efficiency, a higher load was applied to the generator. A Dremel tool, with a power output of 64 W, was applied. For this test, 3.24 cubic feet of biogas was used.

Variation in biogas amount was mostly due to the fact that bags needed to be cut and remade after some tests and it was difficult to get them exact. This volume ran the system for 2.5 minutes with a final electrical energy output of 9.54 kJ. Here the efficiency increased almost tenfold to 0.3%. Additionally, the exhaust temperature was measured after 2.5 minutes and was found to be 160° C. Table 4 summarizing the results can be seen below.

Table 4: Summary of Test Results

Information	Fan	Dremel Tool
Biogas Volume	4.56 ft^3	3.24 ft^3
Run Time	4.2 minutes	2.5 minutes
Power Output	7.2 W	64 W
Electrical Energy Output	1.84 kJ	9.54 kJ
Efficiency	0.04%	0.3%

4.2 Analysis

In an ideal case, the generator would continue to have an efficiency of at least 0.3%. In order to understand what the test results would mean in the field, they must be scaled for the appropriate amount of fuel and load. The expected daily biogas output for a family of ten is about 21.2 cubic feet. Assuming constant efficiency, powering four cell phones totaling at 15 W, would yield 76 minutes of run time and 68.3 kJ of electrical energy output. The run time can be increased with improved efficiency, allowing for the ability to charge more cell phones.

The most notable result from these two tests is the varying efficiency. The expected load from four cell phones is in between that of the fan and the Dremel tool, at about 15 W. Thus, it is likely the efficiency would be somewhere between 0.04% and 0.3%. A load of 15 W was not tested but it is advised to test the engine at that load going forward. More data would help clarify these variations. Figure 9 shows a plot of the two test results with different fits. The first fit is linear and the second is exponential.

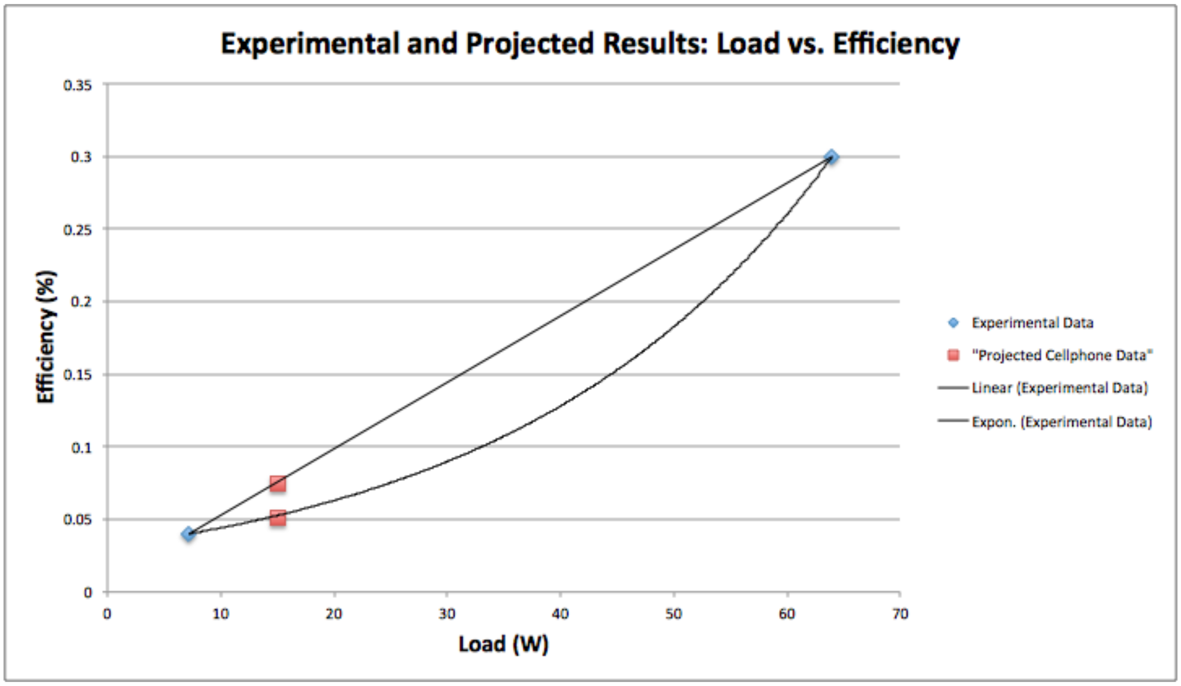

Figure 9: Load vs. Efficiency Plot

Based on these fits, the efficiency would either be 0.051% or 0.075%. As previously stated, this is the key parameter to improve moving forward.

5. Triple Bottom Line Analysis

5.1 People

Currently rural areas in Sub-Saharan Africa have an electrification rate of around 14.2% compared to 59.9% in urban areas.[iv] People in rural regions of the developing world, well beyond the reach of the necessary infrastructure for electricity, that will have to rely on off-the-grid electricity provisions to fulfill their electricity demand. The biogas engine is projected to be able to provide around 5 kWh of electricity per year. While this is much less than the estimated minimum-rural electricity demand is 250 kWh per year, these calculations rely our current calculated efficiency of the engine, which can be greatly improved. Additionally this demand is somewhat out of context with the problem at hand. This engine was intended to charge cell phones as opposed to trying to meet the entire electricity demand of an area.

The WHO further estimates that two billion people lack the access to proper sanitation as mentioned above. These unsanitary conditions create an environment where high rates of diarrheal illnesses associated with exposure to infected water and unsanitary conditions cause one and a half million child deaths every year.[v] The ability to heat water with the cogeneration aspect of our engine improves sanitary conditions by allowing users to heat water for safe drinking and but also by encouraging the collection of fecal matter in a central location to create biogas to power the engine. With the capacity to heat water the biogas engine will allow people to sufficiently heat water for cooking, cleaning or consumption giving easier access to more sanitary water than is currently available under present conditions.

5.2 Planet

Access to a biogas engine lessens the need to burn biomass for heating purposes. Burning biomass creates carbon emissions and leads to problems with indoor air pollution. Table 5 shows, given the average heating value and carbon content of biomass, using the biogas engine instead of biomass to heat water for a shower will offset at most 18.73 kg of carbon emissions per shower.

Table 5: Environmental Impact of Burning Biomass To Generate Heat

Heating Value of Biomass	19 MJ/kg
Carbon Content	50%
Oxygen Content	44%
Comparable Biomass to Heat Water	37.45 kg
Carbon Emissions Produced	18.73 kg

Given laboratory constraints the engine was not tested with a methane-CO2 combination but a methane-nitrogen mixture. Although this had no impact on the output and efficiency of the engine, the team was unable to calculate the emissions of the biogas engine. With the cogeneration capacity of the engine, any emissions for heating water also apply to electricity generation. Technically if looking strictly at electricity generation, the biogas engine creates additional emissions will be created given that in no electricity generation currently takes place. While this is true, we do not feel this is a valid complaint given the impact of electricity provision in regions currently without and the lack of other off-grid alternatives.

5.3 Profit

Access to electricity infrastructure has not slowed down the demand for cell phones in the developing world. Currently data suggests that in developing countries such as Uganda, 97% of people have access to cell phones and service but only 5% of people have access to electricity and the ability to charge the cell phone.[vi] A 2011 Harvard School of Engineering and Applied Science Study showed that people in Uganda were willing to pay between the equivalent of \$0.50-\$1.00 to charge their cell phone.[vii] Table 6 shows that given the average cost of electricity and the average Nokia cell phone battery found in these regions, the price to charge a cell phone in these developing countries is around a 1000% markup from what it costs to charge a cell phone in the U.S. based on average electricity prices.

Table 6: Cost of Charging Cell Phone is U.S. at Current Electricity Prices

Average Cost of Electricity in the U.S.	\$0.12/kWh
Average Nokia Cell Phone Battery	1050 mAh, 3.7V
kWh Needed to Charge Phone	0.003885 kWh
\$ Equivalent Per Charge	\$0.0004662

This arbitrage between prices per charge in the U.S. and developing world demonstrates the demand in developing countries for this service. Even at only a fraction of the markup, demand for charging capacity still far exceeds the cost of providing the service.

6. Future Works

6.1 Biogas Pressurization

While the final pressurization system is more efficient and effective than the initial designs, additional changes could allow for even smoother operation. Following permanent installation of the biogas engine system, it is recommended that a pulley system be added to more easily apply and remove weights. The ideal design would consist of a rope attached to a circular lid, which acts as the base for the weights. The pulley system would allow the operator to add weight in a smooth, controlled fashion, minimizing inefficiency in the system. It would also allow for easy removal of the weights from the bottom of the drum once the bag has fully deflated.

6.2 Carburetor Design

The final carburetor underwent a number of changes in an attempt to create the ideal mixture of air and biogas. For the best results, it was necessary to restrict the air intake in two different amounts. Changing the exposed area of the air intake to 50% closed while starting the engine and then to 95% closed during normal runtime yielded the best engine performance. A thin strip of aluminum was first attached to the carburetor face to permanently cover 50% of the opening. A circular, rotating piece was then attached with a screw so that the opening could be restricted to 95% closed when running.

This specific solution is not ideal for two reasons. Firstly, it is imprecise because the user has to estimate the correct placement of the cover. Secondly, placing the cover on the outside with only one point of attachment to the carburetor allows air to slip in around the perimeter of the cover where it was not completely flush. Since the engine runs best when air flows through a small opening at a high velocity, air leaking in through the sides prevents optimal performance.

In order to fix this problem, it is recommended that a slit be cut into the top of the carburetor as close to the air intake face as possible. A T-shaped thin piece of metal will be sized to fit into this slit snuggly while still being able to move up and down. In order to ensure that the air intake is restricted to the correct amount, one side of the flange (the top of the T-shape) will be hinged.

To start the engine, the hinged flange will be at a 90° angle, propping the sliding cover up at 50% closed. Once the engine is fully running, the flange will be fully extended to 180° so that the cover drops to its final resting position, covering 95% of the opening.

6.3 Heat Exchanger

Due to time constraints, the group was unable to physically attach a heat exchanger to the engine's exhaust pipe. However, having proved the engine's capability to produce exhaust temperatures of 160°C after only 3 minutes of burning biogas, adding a heat exchanger to heat water is highly recommended. As previously stated, access to hot water has the potential to improve sanitation and save many lives in certain developing areas. To continue using cheap and locally available materials, a simple heat exchanger design is ideal. A copper tube could be easily attached to the exhaust pipe of our engine. This tube will be coiled and placed in a pot of water so that the tube's exit stays above the surface. Curling the end of the pipe maximizes the exposed surface area, thereby transferring more heat into the water. The high conductivity of copper will also increase the transfer of energy from the exhaust to the water. Implementing this heat exchanger allows the engine to meet its cogeneration goals and provide a much needed resource to the developing world.

7. Conclusion

This paper outlines the design and development process of a cogeneration biogas engine for electricity generation and water heating in developing countries. The key components of this design include a gas pressurization system, carburetor modifications, and a proposed heat exchanger.

Multiple pressurization methods were designed and tested, with brickage being the most reliable, steady, and low-cost. The engine was able to start easily even when cold, and the brickage design allows for the connection of more or less biogas bags, as needed. Finally, it does not require any electricity input and can be constructed with locally available and inexpensive materials.

To ensure optimal flow for a gaseous fuel, as opposed to liquid gasoline, a new carburetor was fabricated and retrofitted to the engine. The biggest improvements made to the carburetor were the removal of the float chamber and the restriction of flow at the face of the air inlet. This obstruction caused the velocity of air in the carburetor to increase, greatly improving the engine's performance.

Finally, the high experimental exhaust heat temperatures reached after a short runtime proved the ability for cogeneration to produce hot water. Though the generator does not currently have an attached heat exchanger, a simple design utilizing readily available materials has been proposed and detailed above.

The goals of this project were met by producing an engine generator unit that reliably runs on biogas, generates a steady supply of electricity, and creates exhaust hot enough to heat water. This unit is low maintenance and, excluding the generator, uses all cheap and locally available materials. Providing rural households and communities with electricity to charge cell phones and hot water to take a shower is a major step towards development.

8. References

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[i] BMGF, 2011 http://www.gatesfoundation.org/What-We-Do/Global-Development/Water-Sanitation-and-Hygiene

[ii] http://www.grandchallenges.org/Explorations/Topics/WaterSanitation/Pages/Round7.aspx

[iii] http://hdabob.com/the-vehicle/fuel-injection/carburetor/

[iv] WEO, 2011 http://www.worldenergyoutlook.org/resources/energydevelopment/accesstoelectricity/

[v] BMGF, 2011 http://www.gatesfoundation.org/What-We-Do/Global-Development/Water-Sanitation-and-Hygiene

[vi] http://www.westga.edu/~bquest/2012/divide2012.pdf

[vii] http://www.westga.edu/~bquest/2012/divide2012.pdf