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Tubular polyethylene biogas digesters

– Development and testing of a biogas technology in Malawi to reduce deforestation and support climate change mitigation and adaptation

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Cover: Installed biogas system at a rural household in Malawi, 2014. Photo: Viktor Larsson

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Abstract

The aim of the study was to install a biogas system consisting of three tubular polyethylene biogas digesters at a rural household in Malawi and to evaluate the constructed biogas system with regards to relevant system parameters. The purpose was to evaluate if the technology is a possible solution to reduce deforestation and support Malawi in climate change mitigation and adaptation.

The study was carried out in the southern part of Malawi in cooperation with the University of Malawi. Locally available materials were used to construct and install the system. Three different feed materials, cow, goat and a mix of cow and goat manure, were used in order to determine which one was best suited to utilise as a digester substrate. After the installation, measurements of temperature, pH, biogas production, biogas composition and system functionality were made.

The results of the study show that a biogas system with tubular polyethylene biogas digesters can be successfully installed at a rural household and that the most suitable feed material is a mix of cow and goat manure. The study and the conducted testing also makes up basic research to further establishing that tubular polyethylene biogas digesters can be used as a part of the solution to reduce deforestation and support climate change mitigation and adaptation in Malawi.

Keywords: renewable energy, small scale biogas production, construction, Minor Field Study, Malawi

Sammanfattning

I Malawi använder 96 % av befolkningen träkol eller ved som energikälla för matlagning. Detta innebär en stor påfrestning på skogarna och medför även utsläpp av koldioxid till atmosfären. En förändring måste till för att minska användningen av träkol och ved och den måste utformas för att tillåta den malawiska befolkningen att upprätthålla och utveckla sitt uppehälle. Ett sätt att skapa denna förändring är att tillhandahålla en alternativ energikälla för matlagning.

Målet med studien var att installera ett biogassystem bestående av tre cylindriska rötkammare av polyeten vid ett hushåll på landsbygden i Malawi samt att utvärdera det installerade systemet med avseende på relevanta processparametrar. Syftet var att utvärdera ifall tekniken är en möjlig lösning för att minska avskogning och för att stödja Malawi i arbetet att minska klimatpåverkan.

Studien utfördes i södra Malawi under 8 veckor och i ett nära samarbete med universitet "Chancellor College" i Zomba. Ett krav som sattes upp var att lokalt tillgängligt konstruktionsmaterial skulle användas för att bygga systemet, vilket var nödvändigt om lösningen skulle kunna implementeras i större skala i framtiden. Tre olika rötmaterial användes; kogödsel, getgödsel och en 50/50 blandning av ko- och getgödsel. Detta gjordes för att testa vilket rötmaterial som var mest lämpligt att använda i rötprocessen. Efter att installationen av systemet var klar utfördes regelbundna mätningar av temperatur, pH, biogasproduktion, biogassammansättning samt en utvärdering av systemets funktionalitet överlag.

Resultaten från studien visar att ett biogassystem med cylindriska rötkammare av polyeten kan installeras vid ett hushåll på landsbygden och att det mest lämpliga rötmaterialet är en 50/50 blandning av ko- och getgödsel. Studien utgör också basforskning för att vidare fastställa om cylindriska rötkammare av polyeten kan användas som en del i lösningen för att minska avskogningen och klimatförändringen i Malawi.

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1 Introduction

The world's forests are essential resources for humans and vital parts of the planet's environment. They provide people with food, building material, fuel and many other services needed in order to sustain a livelihood. The forests are also an absolute necessity for stabilising the world's climate but their usefulness for humans have made them a diminishing resource which negatively affects the people who are using them but also the climate. Deforestation and forest degradation has by van der Werf et al. (2009) been estimated to contribute to 12 % of the global carbon dioxide (CO_2) emissions during 2008, making it the second largest anthropogenic source of CO_2 to the atmosphere. According to The Food and Agriculture Organization of the United Nations and their Global Forest Resource Assessment (2010) the total forest area in Malawi has decreased by 17 % since the year 1990 and shown an annual decline rate of almost 1 % between the years 2005 and 2010. The extensive use of the forests in Malawi is comprehensible from the point of view that firewood and charcoal are widely used as cooking fuels by the Malawian people and are an essential part of their livelihood. According to the 2008 Population and Housing Census carried out by the Government of Malawi (2008), 96 % of the population used charcoal or firewood as an energy source for cooking. It is clear that the biomass provided by the forests are of great importance to Malawi and especially to the Malawian people. However, the extensive use of biomass as an energy source for cooking negatively affects the climate and continued overuse might cause a chronic deforestation which in turn will remove the forests as a service provider for the Malawian people. Bandyopadhyay et al. (2011) suggest that a scarcity of biomass in Malawi is associated with a lower household welfare and that 80 % of the rural poor households would benefit from an increase in biomass. A change is needed in order to stabilize the usage and still allow the Malawian people to sustain and further develop their livelihood. One way of doing this is to provide an alternative energy source for cooking which, if implemented at a large scale, would help decrease the deforestation in Malawi.

Biogas is one possible energy source for cooking could be used as an alternative to firewood and charcoal. It has in Malawi's Climate Technology Transfer and Needs Assessment by the Environmental Affairs Department (2003) been pointed out as one of the technologies which would contribute to a reduction of greenhouse gas emissions and which would fit very well in the agriculture-based economy of Malawi. Additional advantages with biogas include nutrient recycling, improved animal health and reduction of direct methane emissions from waste (Chagunda et al. 2009). Biogas would also help to reduce the household pollution associated with using solid fuels for cooking and thereby reducing connected health issues for the users (Smith 2006). In the assessment by the Environmental Affairs Department (2003) it is identified that Malawi has sufficient raw materials to support a biogas programme but that barriers to dissemination of the technology existed. The barriers included aspects such as lack of appropriate technical skill, lack of public awareness, lack of specification standards and high initial investment cost. One of the major barriers for adoption of the biogas technology was the high initial investment cost. Under the consideration that according to The World Bank (2014) 52.4 % of the population was living below the national poverty line in 2004, the investment cost as a barrier becomes evident. This can be assumed to relate to the circumstance that the two promoted biogas digester types were The Fixed Dome and Floating Drum (Gunya 2013). Both of these designs have a long lifespan and need little maintenance but require large amounts of material and high labour requirements, hence giving rise to high initial investment costs (Gunya 2013). There are nevertheless low cost alternative biogas digester designs that can be used.

At the Chancellor College in Zomba, Malawi a project called "Low Cost Biogas Digester: A magic pill to cure chronic deforestation and enhance climate change mitigation and adaptation in Malawi", is concentrating on research concerning tubular polyethylene biogas digesters (TPBD). A TPBD is a low cost biogas digester that is simple and inexpensive to construct but has an efficiency equal to traditional designs such as the Fixed Dome. Instead of concrete and brick masonry as a main digestion vessel material, the TPBD is constructed of thick tubular polyethylene material. The method has been used successfully in Kenya, Rwanda, Tanzania and Zimbabwe. So far the research carried out in the scope of the project has been encouraging and the TPBD has been determined to perform well under Malawian local material and environmental conditions.[1] There is however a need for further research in order to confirm that the TPBD is a functional alternative to solid cooking fuels and one that can lead to reduced deforestation and climate change mitigation and adaptation in Malawi.

2 Aim

The aim of this study is to install a biogas system consisting of three tubular polyethylene biogas digesters in a rural area household in Malawi and to evaluate the system with regards to relevant system parameters and functionality. In order to fulfill the aim of the study the following objectives were established:

- To construct and install a fully functioning tubular polyethylene biogas digester system at a rural household by using locally available and affordable materials
- To evaluate the performance of the system with regards to temperature, pH, gas production and gas composition.

3 Previous Research

A previous study was made last year at Chancellor College in Zomba, where the local construction feasibility and performance of tubular polyethylene biogas digester technology was tested. The feed materials being used were locally available pig manure, animal stomach contents and kitchen food wastes. Each feed material was fed into two different digesters and hence in total six digesters were installed.

It was verified that the digesters were able to perform relatively well at a local mean temperature of as low as $18°C$. The gas production started initially in the digesters containing pig manure,

[1] Personal correspondence with Ephron Gausi, author to a previous study about TPBDs at The University of Malawi.

where gas was being produced from the second day. The two digesters containing goat stomach wastes started to produce gas after 3-4 days and the ones containing kitchen food wastes required two weeks before gas was being produced. No reliable gas production data was however obtained from the kitchen food wastes digesters due to plant failure attributed to low pH levels. The overall collected data of the produced gas are represented in table 1.

Table 1: Overall collected data of the system.

Feed material	Start of gas prod. [days]	Produced gas [l/day]	Gas quality [% CH_4]	pH-level of slurry [pH]	Temperature of slurry [$°C$]
Pig manure	1	32.55	56.95	6.9-7.7	23.9 ± 1.3
Goat stomach w.	3-4	38.95	67.30	6.9-7.7	22.8 ± 1.3
Kitchen food	14	—	—	—	23.4 ± 0.5

Concerning the burning characteristics of the produced gas it was concluded that the produced biogas was easy to ignite and burned with a characteristic blue flame.

Testing of covering the digesters with a greenhouse to raise the temperature was also made. The results showed that the gas production from the digesters operated in greenhouses was slightly higher (36.45 l/day) than those without greenhouses (35.07 l/day). However, T-test results showed that the difference was not statistically significant.

4 Theory

The following section brings up a theoretical background for key components of the study and explains the theory behind the processes involved in biogas production.

4.1 Microorganisms

The biogas production process involves a complex system of microbiological processes which have to be considered when initiating a biogas system (Jarvis and Schnürer 2009). It is a combination of different microorganisms that produce the biogas and these have to coexist for the process to continue. According to Weiland (2010) the microorganisms are involved in the four steps which are crucial to the biogas production. More information about these steps is found in section 4.2.

The microorganisms need the right substrate composition to be able to grow and work properly, it is their food. The substrate includes energy source, electron acceptors, building stones for new cells, vitamins and metals (Jarvis and Schnürer 2009). The microorganism need both macro- and micronutrients to survive. The macronutriens are carbon, phosphor and sulphur and the micronutriens are trace elements like iron, nickel and cobalt etc (Weiland 2010). When the microorganisms use the substrate they not only build new cells, but they also leave behind waste residues that can not be used by the same microorganism again. The waste can be used by another microorganism as a substrate, which means that the microorganisms live of each other. Some waste products are not only substrates for other microorganisms but also the wanted product in a biogas production system, like methane.

Jarvis and Schnürer (2009) explains that by adding substrate the microorganisms will be able to perform their metabolism. The more varied the composition of the organic material, the more components are available for the microorganisms, which helps their growth. In addition to the composition of the substrate, the environment surrounding the microorganisms is of equal importance. Some environmental factors that could have an impact on the microorganisms are temperature, pH, oxygen and salt concentration. Different microorganisms have different demands on the enviroment which implies that biogas production requires an environment that is suitable for many different microorganisms. An effect of this is that the environment in the biogas digester is not perfect for all microorganisms but good enough for them all to coexist.

4.2 Anaerobic Digestion

According to Labatut and Gooch (2012) anaerobic digestion systems are extremely sensitive to environmental changes. Correct design and control of the system are important to maximize production and prevent system failure. Nizami (2012) describes the anaerobic digestion as a four step microbiological process. These steps are as follows: hydrolysis, acidogenesis, acetogenesis and methanogenesis, as seen in figure 1.

Anaerobic digestion takes place in many natural environments, such as cow's stomach and swamps (Nizami 2012). The process is a biological methanogenesis that degenerates carbonaceous matter and one of the rest products is methane (Chynoweth et al. 2001). Klass (1984) explains that since the complex organic substrates can not be metabolized by the methanogens, many other microorganisms are needed in the mixture. According to Serna (2009) the first step is hydrolysis in which bacteria decompose organic substrate into liquefied monomers and polymers, and carbons and fats are decomposed into amino acids. In the next step, the acidogenic bacteria decomposes the products from the hydrolysis into even smaller products, such as acids, ketones alcohols, hydrogen and carbon dioxide. The third state is the acetogenesis where the rest of the acidogenesis products are transformed into hydrogen, carbon dioxide and acetic acid. This is done by acetogenic bacteria. The last state, the methanogenesis the microorganisms convert hydrogen, carbondioxide, and acetic acid into methane, water, and carbon dioxide. The microorganisms responsible for this transformation are called methanogens and are strict anaerobes.

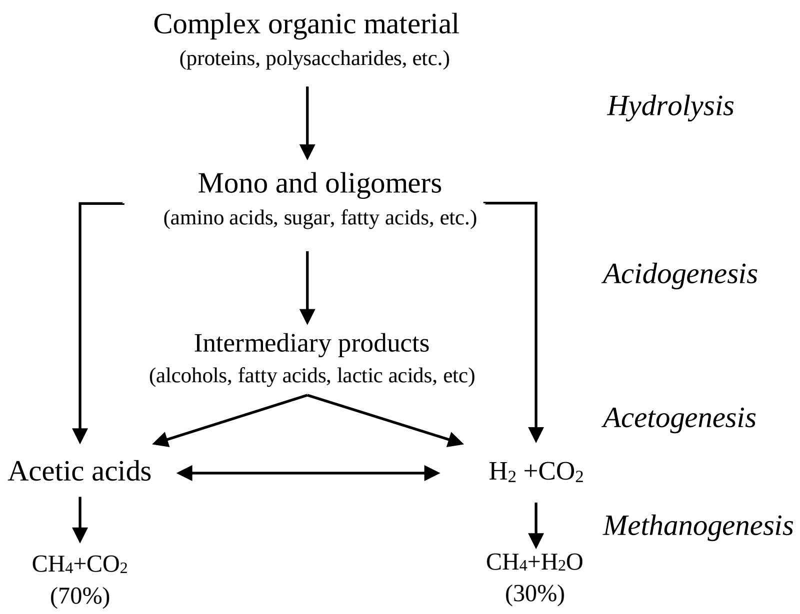

Figure 1: Degradation of organic material into methane.(Serna 2009).

4.3 Biogas Composition

The composition of the biogas is dependent on the feed material used in the digestion process and the type of digestion process that is used. The main components of biogas are methane (CH_4) and carbon dioxide (CO_2) which together constitutes the largest part of the biogas. The amount of CH_4 in the biogas can vary between 45 and 70 % depending on the feed material used and is typically in the range of around 65 % for animal manure (Carlsson and Uldal 2009). The type of digestion process used, also influences the amount of CH_4 and CO_2 in the biogas composition. Table 2 shows typical biogas compositions for three different digestion processes.

Table 2: Biogas composition for three different digestion processes (Jönsson et al. 2003).

Component	Biogas plant	Sewage plant	Landfill
CH_4 (%)	60 - 70	55 - 65	45 - 55
CO_2 (%)	30 - 40	balance	30 - 40
N (%)	< 1	< 1	5 - 15
H_2S (ppm)	10 - 2000	10 - 40	50 - 300

As can be seen in table 2, a biogas plant has the highest CH_4 content, which is not very surprising as it is optimised to produced biogas; both in terms of feed material composition and process efficiency. From table 2 one can also see that both nitrogen (N) and hydrogen sulphide (H_2S) are present in biogas. These substances are trace compounds that occur in often small concentrations and are related to the feed material. H_2S can be problematic when biogas is to be used for applications such as combustion engines and natural gas supplements because the possibility of corrosion effects (Jönsson et al. 2003). When used for these applications the biogas has to be cleaned to be used efficiently and safely (Jönsson et al. 2003). However, when using biogas as a cooking fuel in a urban household environment in Africa the trace compounds would have little effect on the overall performance of the process. Although, a cheap and efficient way of getting rid of the CO_2 in the produced biogas from a tubular polyethylene biogas digester would be desirable because of the increase of the heating value.

4.4 Dr. Einhorn's Fermentation Saccharometer

One fast and easy way to establish the composition of biogas, i.e. how much of the gas that is carbon dioxide, is to use a Dr. Einhorn's fermentation saccharometer. The saccharometer is a bent, graded glass pipe, which is filled with a solution of sodium hydroxide ($NaOH$) with a concentration of 7 M. In this solution, a known amount of a biogas sample is injected, and the carbon dioxide immediately dissolves in the solution while the methane forms a gas bubble at the top of the pipe. By determining the volume of the gas bubble, the amount of methane in the biogas can be established (Jarvis and Schnürer 2009). However, as noted above in section 4.3 the obtained amount of methane is not 100 % accurate because of trace compounds in the biogas but it does provide a result sufficient for biogas applications in a rural household environment.

4.5 Spectrophotometric analysis

To be able to analyse the gas composition even further a spectrophotometer can be used. Figure 3 to 4 are spectrums for the most important substances in the gas provided by The National Institute of Standards and Technology (2009c), The National Institute of Standards and Technology (2009a), and The National Institute of Standards and Technology (2009b). The gases chosen for analysis are methane, carbon dioxide and hydrogen sulfide.

According to Toxic Substances and Registry (2006) hydrogen sulphide can cause severe health problems in doses greater than 500 ppm, and in small doses it can cause irritation to eyes, nose or throat. Hydrogen sulfide can be produced by bacteria that break down organic matter and can also have a negative impact on the gas quality and repress the microorganisms in the process (Jarvis and Schnürer 2009). Because of this it is of interest to see if there is any production of hydrogen sulphide when producing biogas. In figure 4 the IR spectrum for hydrogen sulphide is shown which can be used to compare with an IR spectrum of a biogas test sample to see if there are any traces of the substance.

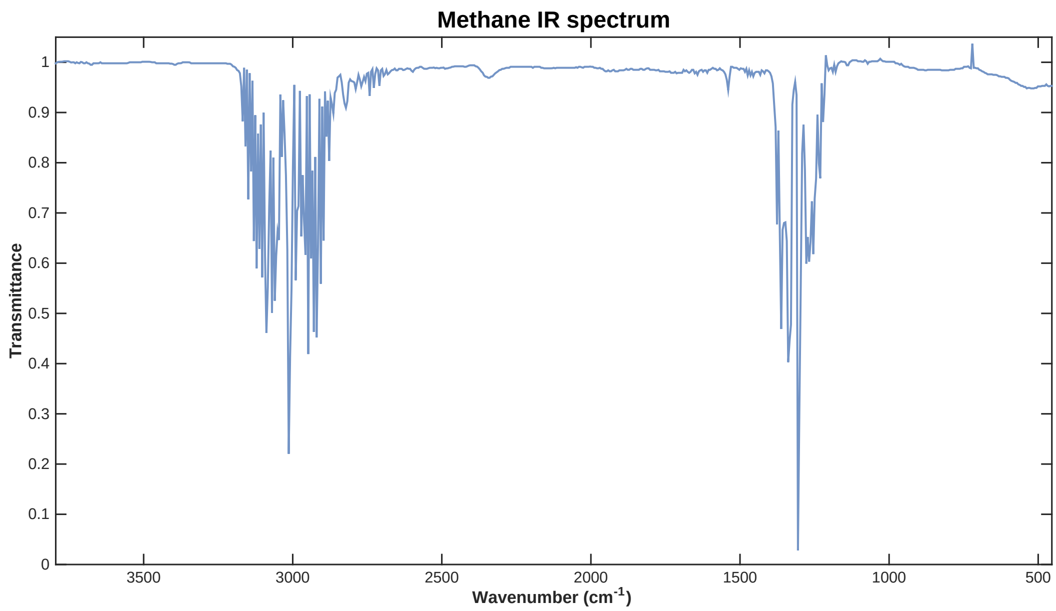

Figure 2: Reference IR spectrum for methane(The National Institute of Standards and Technology 2009c).

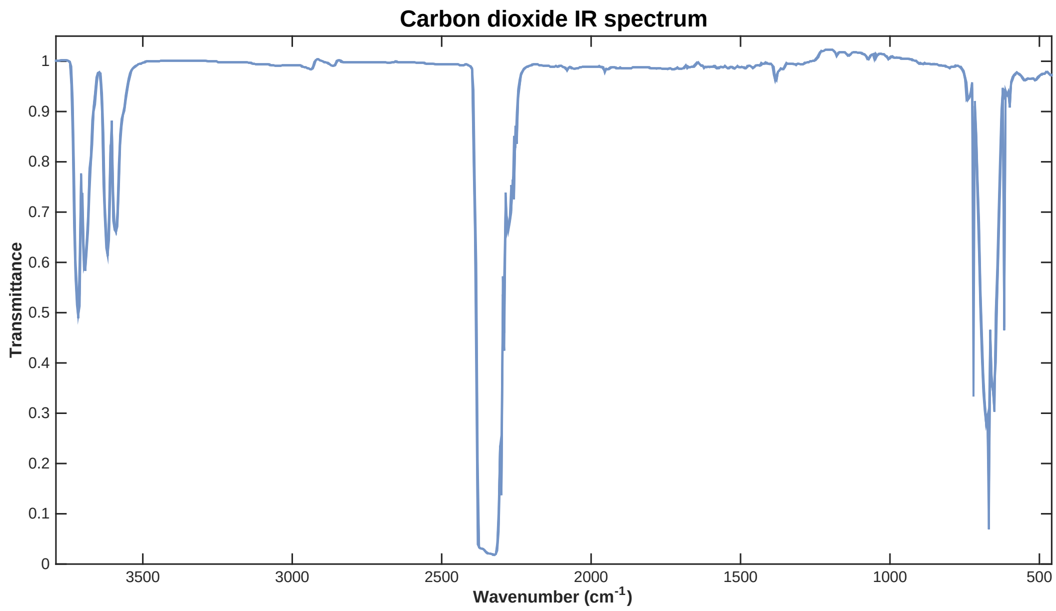

Figure 3: Reference IR spectrum for carbon dioxide(The National Institute of Standards and Technology 2009a).

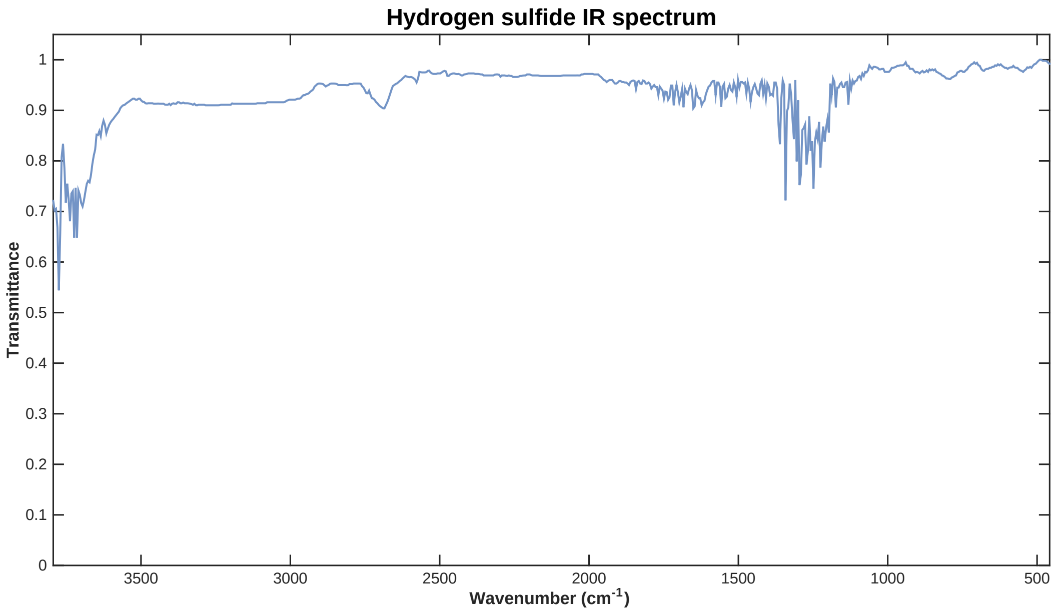

Figure 4: Reference IR spectrum for hydrogen sulphide (The National Institute of Standards and Technology 2009b).

As can be see from the figures above there are clear peaks at some distinct values. One problem is that the peaks from hydrogen sulphide are in the same area as one peak from the methane spectrum and one peak from the carbon dioxide spectrum, which makes it hard to detect.

4.6 Temperature

There are a few different types of microorganisms that produce the biogas. These different types of microorganisms are operative, and thrives the best, in different ranges of temperature. The microorganisms are divided into different groups, depending on in which temperature range they operate; psychrophilic, mesophilic, thermophilic and hyperthermophilic. The temperatures in which the microorganisms operate are strongly connected to the environment from which the organisms originate. The mesophilic microorganisms, for example the human intestinal bacteria, thrives best at roughly 37 °C. The growth of mesophilic microorganisms can however start at as low a temperatures as 10 °C, but the higher the temperature, the better the microorganisms thrive. Although, the microorganisms die a couple of degrees above the optimal temperature (Jarvis and Schnürer 2009). The temperature ranges for the different types of microorganisms are shown in figure 5.

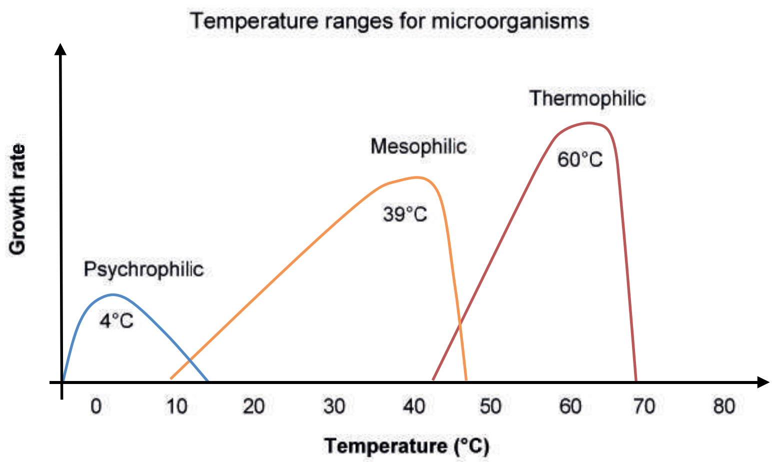

Figure 5: Temperature range for different types of microorganisms (Jarvis and Schnürer 2009).

4.7 pH

Generally, the optimal biogas process is run on a neutral pH level between 7.0 and 7.5 (Jarvis and Schnürer 2009). In order to reach this level during operation the pH level of the feed material should be somewhat higher because a decrease in the pH-level can be expected during the start-up process (Abbasi et al. 2011). The decrease in the pH level in the beginning of the process can be explained by the formation of organic acids in the acidogenesis and acetogenesis stages of the anaerobic digestion (Abbasi et al. 2011). When the process has been running for some time the ammonia concentration increases and with it the pH level which in turn stabilizes the pH (Abbasi et al. 2011). Even though the ideal pH level for a biogas process is in the range of 7.0 - 7.5 there are methane producing bacteria that can be productive at both lower and higher levels (Jarvis and Schnürer 2009). As with temperature, the pH level that yields the highest production rate is often one close to the pH level that causes the methane producing bacteria to die (Jarvis and Schnürer 2009). Hence, when it comes to running a high performance and economically dependent biogas process, measures to push the process to its pH limit can be motivated. However, when running a biogas process aimed at producing biogas as an energy source for cooking in low-income countries, a pH level able to cope with pH changes is preferable because it is less likely to be unsuccessful.

4.8 Feed Material

There are a wide variety of feed materials that can be used for biogas production and they effect the digestion process in various ways. Slaughterhouse waste, farm crops, food waste, and animal manure are some examples of materials which can be used as feed materials and there is also a possibility of combining feed materials in order to create a more balanced biogas process (Carlsson and Uldal 2009). Depending on what feed material that is used, a number of parameters have to be evaluated to secure an efficient and sound biogas process. Among the parameters are temperature, desired hydraulic retention time, organic load rate and, possible toxic compounds in the feed material

(Jarvis and Schnürer 2009). However, the most important parameter when choosing feed material for a biogas process in a rural household setting would be availability. One would not have the option of choosing between many different feed materials but would have to use materials which are generated and available in a close proximity to the planned biogas installation. The feed material should also be chosen so that its use does not imply removing an important resource for the household in question. Animal manure is a feed material that is often available and generated in a close proximity to a rural household which makes it a suitable option for biogas production. Even though animal manure is also used as a fertilizer for crops it is a fit choice because the digestion process improves the nutrition composition of the manure and by that providing a better fertilizer for the household.

At the household in Malawi the available types of animal manure was primarily goat and cow manure. The theoretical biogas yield from the two materials are around 300 $m^3/dry\ t$ for cattle manure and 100 $m^3/dry\ t$ for goat manure (Batzias et al. 2005). The obvious choice would be using cow manure as it in theory has a higher biogas yield but there are other factors that have to be taken into account, such as possibility of material shortage for the household. In case there is a shortage of either cow manure or goat manure a biogas process operated on a mix of the two is better adapted to handle only using one of the material as a substitute. This is because the microorganisms are adapted to digesting both cow and goat manure (Jarvis and Schnürer 2009). One problem associated with goat manure is the form in which it is generated since the often hard consistency requires a pretreatment or a couple of days of soaking in water prior to being used as a feed material in the digester. Otherwise the risk of undigested material and decreased efficacy can increase and by that decrease the amount of produced biogas (Jarvis and Schnürer 2009). The feed material has to be fluent in order to work in a biogas process, especially when used in a continuous biogas process, which means water has to be added. The manure to water ratio is important because the water molecules are necessary to support the hydrolysis reaction and acetogenesis stage (Putri et al. 2012). Although, it is important not to add to much water as it can result in a flush out of microorganisms and undigested materials from the digestion process (Jarvis and Schnürer 2009). A manure to water ratio of 1:3 has been show to produce the highest yield of biogas and hence the one used in the study at hand (Putri et al. 2012).

4.9 Hydraulic Retention Time

The hydraulic retention time (HRT) is the amount of time the organic material spend in the digester from insertion to exit (Abbasi et al. 2011). For a normal biogas process the HRT is between 10 to 25 days but it can also be longer depending on the feed material and the temperature (Jarvis and Schnürer 2009). A material which is easy for the microorganisms to degrade and/or a biogas process operating at a high temperature would allow for a lower HRT (Jarvis and Schnürer 2009). A long HRT can be required for biogas processes operating at temperatures below 30°C, especially for a more complex material such as animal manure. Likely a HRT of at least 50 days would be required.[2]

[2] Personal correspondence with Prof. Anna Schnürer, Swedish University of Agricultural Sciences.

4.10 Trenches

Martí-Herrero and Capriano (2012) emphasises that the dimensions of a trench are often not optimized with respect to maximise the volume of the plastic tube when implementing small scale biogas digesters. The consequence of this is a smaller final liquid volume in the tube digester which in turn causes a loss in hydraulic retention time. The decreased hydraulic retention time could result in a lower biogas production than calculated in theory.

Martí-Herrero and Capriano (2012) have in their article developed a method for the optimum way to design a biogas digester trench. Since the trench for the tubular digester sets the limit of the liquid volume in the tube, the ideal optimum would be a trench with a circular cross-section. This would allow the plastic tube to keep its original form and to retain maximum volume. However, a circular shaped trench is very challenging to dig and instead one would have to dig a polygonal shaped cross-section. The most typical and easiest way to dig a trench is by digging a trapezoidal shape. The trapezoidal shape is the shape that Martí-Herrero and Capriano (2012) have been optimizing for a circular plastic tube.

The total volume of a plastic tube in a trench is the sum of the trapezoidal cross-section and the cross-section of the biogas bell multiplied by the length of the plastic tube. Figure 6 shows the parameters of the trench and biogas bell cross-sections, which Martí-Herrero and Capriano (2012) were optimizing.

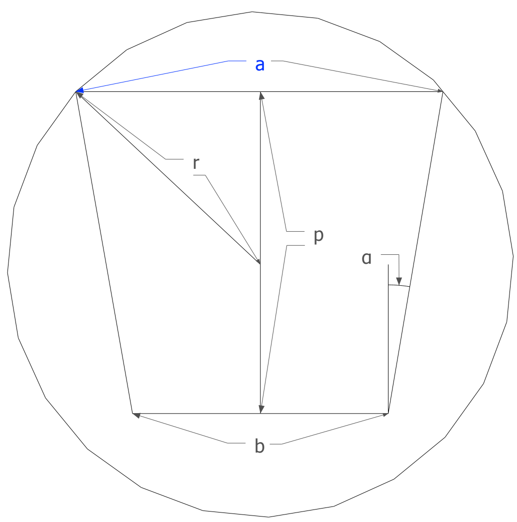

Figure 6: Cross section of the trapezoidal trench and the biogas bell. Modified image from Martí-Herrero and Capriano (2012). r is the radius of the plastic tube, p is the height of the trench, a is the top width of the trench, b is the bottom width of the trench and α is the angle of the walls.

In table 3 some typical trench dimensions are shown with optimum angels and sizes from Martí-Herrero and Capriano (2012).

Table 3: Optimum dimensions of trenches for typical tubular low cost biogas digester for different circumferences of plastic (Martí-Herrero and Capriano 2012). Here CS_{bell} is the cross section of the bell filled with produced gas and CS_{trench} is the cross section of the trapezoidal trench.

C(m)	r(m)	a(m)	b(m)	p(m)	CS_{trench} (m^2)	CS_{bell} (m^2)	α(°)
2	0.32	0.39	0.52	0.49	0.223	0.0538	7.5
2.5	0.40	0.49	0.65	0.61	0.348	0.0841	7.5
3	0.48	0.58	0.78	0.73	0.496	0.1211	7.5
3.5	0.56	0.68	0.91	0.86	0.684	0.1649	7.5

The dimensions in table 3 does not include any wall material such as bricks. To calculate the total width of the trench one would have to include the width of the bricks and consider the angle α.

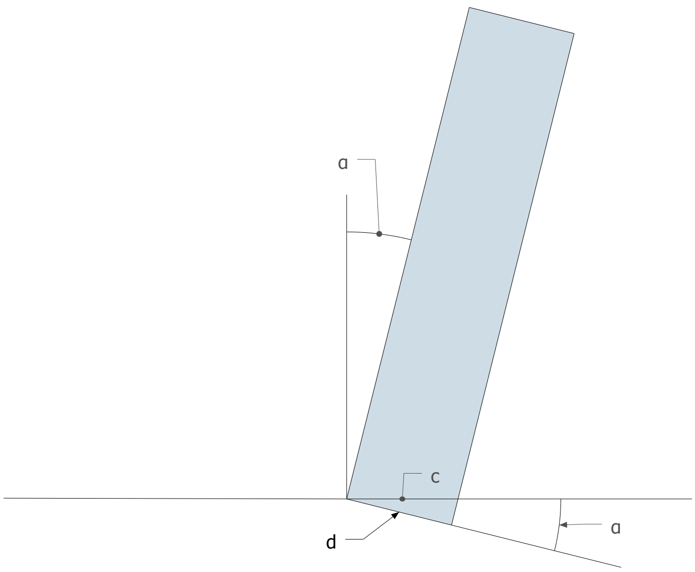

Figure 7: Illustration of the trenchside, where the blue block is a brick.

From figure 7 one can see that one must include the width, $2c$, when considering the width of the trench. If one know the width of the brick, (d), and the angle, (α), one can calculate, c, with the following equation:

$$c = \frac{d}{\cos \alpha} \tag{4.1}$$

Now the total width of the hole that must be dug for the trench is known. That is the bottom and top width, b, a, and the width of the building material, c, which gives the total result of $2c + b$ at the bottom and $2c + a$ at the top.

4.11 Combustion of Biogas

The purpose of this section is to get an idea of the amount of biogas needed for cooking in a normal household.

According to McAllister et al. (2011) one can assume that air consists of 21% O_2 and 79% N_2. The balanced stoichiometric combustion of methane mixed with air is as follows (McAllister et al. 2011; Khandelwal and Gupta 2009):

$$CH4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 + Energy \tag{4.2}$$

A general stoichiometry combustion for a hydrocarbon fuel, $C_\alpha H_\beta O_\gamma$, with air can be expressed as (McAllister et al. 2011):

$$C_\alpha H_\beta O_\gamma + \left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right)(O_2 + 3.76N_2) \rightarrow \alpha CO_2 + \frac{\beta}{2}H_2O + 3.76\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right)N_2 \tag{4.3}$$

where α is the number of carbon atoms, β is the number of hydrogen atoms and γ is the number of oxygen atoms.

McAllister et al. (2011) claims that the amount of air that is required for combustion of a stoichiometric mixture is called *theoretical* or *stoichiometric* air. However, McAllister et al. (2011) explains that in practice, fuels are often combusted with a different amount of air than the stoichiometric ratio. This is because there may be leakages or other factors that need to be compensated for. The fuel-air ratio, f, for a combustion is given by

$$f = \frac{m_f}{m_{air}}, \tag{4.4}$$

where m_f and m_{air} are the average masses of fuel and air. Rewriting eq (4.4) for the stoichimetric mixture it becomes

$$f_s = \frac{M_f}{\left(\alpha + \frac{\beta}{4}\right) \cdot 4.76 \cdot M_{air}}, \tag{4.5}$$

where M_f and M_{air} are the average masses per mole for the fuel and air.

Table 4: Properties of methane, carbon dioxide and air([1](Khandelwal and Gupta 2009), [2](The Engineering ToolBox 2014c), [3](McAllister et al. 2011), [4] (The Engineering ToolBox 2014a).

Property	Methane	Carbon dioxide	Air
Molecular weight [g/mol]	16.04[1]	44.01[1]	28.97[2]
Heating value [MJ/kg]	55.5[3]	-	-
Heating value [kJ/mol]	286[3]	-	-
Density[kg/m^3][3]	0.668[4]	1.842[4]	1.205[4]

The molecular weight of methane and air is 16.04 and 28.97 g/mol respectively. For methane $\alpha = 1$, $\beta = 4$ and $\gamma = 0$. Inserting this in eq (4.5) gives

$$f_s = \frac{16.04}{\left(1 + \frac{4}{4} - \frac{\gamma}{2}\right) \cdot 4.76 \cdot 28.97} = 0.0582 \tag{4.6}$$

which implies, that if there would only be methane in the biogas the FAR_s would be

$$\frac{Air}{Methane} = \frac{1}{0.0582} = 17.19. \tag{4.7}$$

Which says that for every mass of methane there must be 17.19 mass of air. But biogas usually have a composition of 60% methane and 40% carbon dioxide (with minor traces of other substances, see table 2) (Kavuma 2013).

The amount of energy that is required to heat up a subject from one temperature to another is given by the following equation:

$$Q = c_p \cdot m \cdot dT \ kJ. \tag{4.8}$$

where m is the mass of the subject and dT is the change in temperature (The Engineering ToolBox 2014b). The specific heat of water is 4.187 kJ/kgK (The Engineering ToolBox 2014d). The amount of heat that is required to heat 1 kg water from 20°C to 100°C is calculate from equation (4.8)

$$Q = 4.187 \cdot 1 \cdot 80 = 334.96 \ kJ/kg. \tag{4.9}$$

To boil a pot with 5 kg of water, from $20°C$ to 100°C would require:

$$5kg \cdot 334.96 \ kJ/kg = 1674.8 \ kJ \tag{4.10}$$

of heat. Sasse et al. (1991) states that a typical biogas stove has an efficiency of 55%. If the biogas stove has an efficiency of 55 % one need to compensate for that and add:

$$\frac{1674.8 \ kJ}{0.55} = 3045.1 \ kJ \tag{4.11}$$

of extra heat. So how much biogas is needed to boil 5 l of water? As can be see from table 4 the heating value for biogas is 55.5 MJ/kg. Hence, the amount of methane needed is given by

$$\frac{3045.1 \ kJ}{55.5 \cdot 10^3 \ kJ/kg} = 0.055 \ kg \tag{4.12}$$

Dividing this with the density ($0.668 kg/m^3$, from table 4) and including the assumption that methane represents 60% of the biogas composition

$$\frac{0.055}{0.0668 \cdot 0.6} = 1.37 \ m^3 \tag{4.13}$$

thus the estimated volume of biogas needed to heat 5 kg of water to 100°C is 1.37m^3 .

5 Study Site

The biogas system was installed at a household in the village of Sait, 17 kilometers outside of Zomba. There are currently two adults and one child living in the household. The area where the digesters were placed is located around 3 meters from the household kitchen and two thirds of the area is shaded from the sun for most of the day. The household has one fully grown cow, one calf, one pig, and 6 goats from which the needed feeding material can be obtained. The information about the construction site is summarized in table 5.

Table 5: Information about the site.

Category	Measure
Inhabitants	2 adults, 1 child
Animals	1 cow, 1 calf and 6 goats
Distance between digester and kitchen	4-6 m
Altitude	800 masl

5.1 Weather

The study was carried out from the 15th of June until the 7th of August 2014, which is during the winter season in Malawi. During this period of time Malawi experience very little rainfall and the lowest temperatures of the year (Department of Climate Change and Meteorological Services 2006). The mean temperature for Zomba during a general year is shown in figure 8.

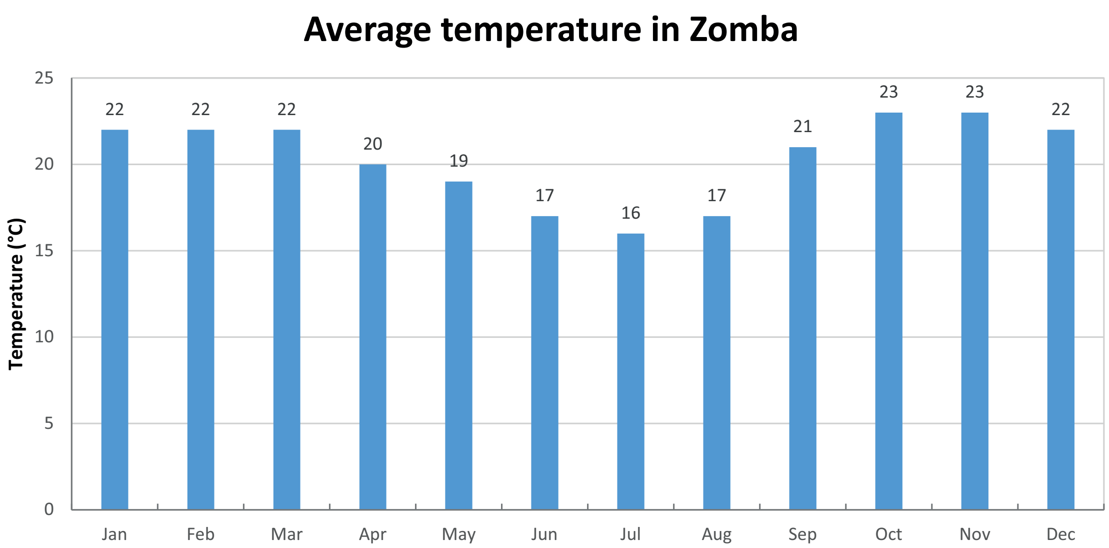

Figure 8: Monthly average temperatures in Zomba (Weatherbase 2014).

As can be seen in the diagram above the average temperatures during the months June, July, and August are the lowest of the year with a temperature in July reaching as low as 16 °C. This has effects on the installed biogas system since the microorganisms in the digesters are effected by the temperature. Where a higher temperature would normally result in more effective microorganisms and by that, an increase in biogas production.

6 Method

The following section explains how the work was carried out, i.e. how the biogas system was constructed and how the measuring process was carried out.

6.1 Digesters

Three old digester tubes were used, taken from the previous study mentioned in section 3. Two of the digesters were however found to be malfunctioning because of holes, hence two new ones were built to replace them. The digesters were constructed out of double layers of polyethylene plastic tubes with a thickness of 100 microns. Both ends of the tubes were sealed with 75 mm PVC pipes, acting as inlets and outlets for the slurry. At a distance of 1.5 m from the ending of the inlet of the digester a pipe was connected to transfer the produced biogas to the storage. The dimensions of the digesters, measured from where the polyethylene plastic tubes connect to the inlets and outlets, are shown in table 6.

Table 6: Dimensions of polyethylene tube.

Dimension	Measure
Length	3.9 m
Circumference	1.2 m

For pictures of the digester construction process see Appendix figures 1 to 3.

6.2 Trenches

From section 4.10 it is possible to see the minimum circumference Martí-Herrero and Capriano (2012) calculated for the dimension of the trench. Since the plastic tube only had a circumference of 1.2 m the dimension was approximated from the smallest circumference and was decided in such a way that the trenches had the dimensions given in table 7.

Table 7: Dimensions of trenches.

Length (m)	Heigh(mm)	Top width (mm)	Bottom width (mm)	Angle (°)
3.9	290	310	230	7.5

Since these dimensions are based on the circumference of the plastic tube, it is necessary to include the dimensions of the bricks that will be used as well. The bricks that were used were 5 cm thick.

From eq (4.1) it is possible to calculate the total top and bottom width of the trench. This means that, at minimum, the following width has to be included, both at the bottom and the top:

$$2 \cdot \frac{50}{\cos 7.5} = 100.86 \approx 100\text{mm}$$

One must also include space to put cement at the walls. At the top one may lay the bricks down as seen in figure 9, which is the approach chosen in the study. Figure 9 is an illustration of the model used to construct the trenches.

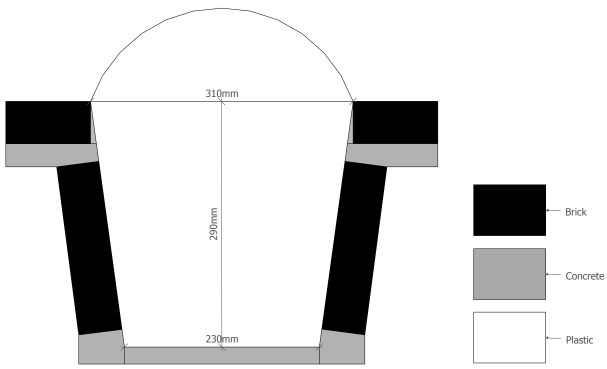

Figure 9: Cross section of trench and plastic tube including bricks and cement.

Pictures of the construction of the trenches are to be seen in Appendix figures 4 to 8.

6.3 Gas Storage Bag

The storage bag was, like the original digesters, reused from the previous study mentioned in section 3. The storage bag was constructed in the same way as the digesters, but with a length of 2 m. The ends of the storage bag were sealed with bamboo pieces and a gas outlet was attached close to the upper end of the bag. The bag was then hung vertically outside the kitchen wall. See figure 9 in the Appendix for a picture of the storage bag.

6.4 Mixing of Slurry

The feed material was mixed with water to make a fluent slurry of the animal manure. A ratio of 1 animal manure to 3 water was used in accordance with the theory under section 4.8. Three different feed materials were used: cow, goat and a mix of 50 % cow and 50 % goat. The tube, originally containing feed material from cow dung, never started to produce gas. Because of this the tube was emptied and refilled with a new feed material consisting of a new mix of cow and goat manure, on the 25th of July. The mixing was made one day in advance of filling the tubes in order to let the feed material soak prior to the decomposition in the tubes. Unwanted materials such as straw, stones and dirt were removed before the mixing and a stick was used to refine the animal manure. For pictures of the process of mixing and treating the slurry see Appendix figures 10 to 13.

6.5 Hydraulic Retention Time

In order to chose the correct HRT, factors discussed under section 4.9 were considered. However, when choosing HRT for a rural biogas system one has to consider that the HRT should be chosen in such a way that it is convenient for the user. In the study a HRT of 48 days was chosen because this allowed the user to fill one bucket of 16 l of slurry every third day in each of the tubes. Although a longer HRT would be preferable since the operating temperature was lower than 30°C. An important factor is that the outside temperature will be higher during the rest of the year as compared to when the study was completed and a HRT of 48 days would then probably suffice.

6.6 Gas Volume Measurement

The idea of the gas volume measurement was to make the biogas from the digesters fill a container of known volume on its way to the storage. The container was then emptied into the storage bag before the container was filled once again. By counting the times the produced biogas filled the container, the total volume of the produced biogas was estimated.

The container was constructed by using a five litre plastic bottle. The bottom of the bottle was removed and the bottle was then placed top-up in a larger bucket filled with water. The lid to the bottle was attached to the pipes transferring the biogas from the digesters to the storage via a loose movable hose. On either side of the hose's connection to the pipes was a valve. By opening the valve between the digesters and the measuring device and closing the valve between the measuring device and the storage bag, the biogas from the digesters made the plastic bottle rise in the water. Marks were made on the plastic container indicating each litre that was being filled up. When the container was full, i.e. contained four litres of biogas, the valves were switched from open to closed and from closed to open so when forcing the container back down, the biogas went back through the loose hose and filled up the storage bag. The procedure was then repeated until the digesters were empty. See figures 14 and 15 in Appendix for pictures of the gas volume measurement.

6.7 Gas Quality Measurement

A small hole had been made in the container for the gas volume measurement, but it was taped over with transparent sticky tape. When the container was filled with biogas, a syringe was pierced through the sticky tape and five milliliters of biogas were collected and then the hole was taped over again (see Appendix figure 16). The quality of the biogas was then estimated using a Dr. Einhorn's Fermentation Saccharometer, mentioned in the section 4.4 (see Appendix figures 17 to 18).

6.8 Biogas Composition

The IR-spectrophotometer IRPrestige21 by Shimadzu Corporation was used to determine the composition of the biogas produced in the digesters. The gas was trapped inside a syringe at the site and then transported back to a lab at Chancellor College where the spectrophotometry was carried out (see Appendix figure 19).

6.9 pH Level Measurement

The pH level was measured with the help of the portable pH meter HI 991301, fabricated by Hanna Instruments. Samples for the pH measurements were taken from the outlets, inlets, and from the feed material for each digester (see Appendix figure 20).

6.10 Temperature Measurement

The temperatures in the three digesters were measured with the help of the portable data logger CR10 made by Campbell Scientific. The data logger was powered by a battery, which was connected to and charged by a solar panel at the site. The data logger had a pre set program which collected the temperatures every ten seconds, calculated the maximum, minimum, average, and reference temperature and saved the results once every ten minutes. The saved data could then be downloaded to a computer via a cable (see Appendix figure 21). The data logger continued to collect the desired data without interruptions.

6.11 Biogas Stove

A biogas stove was constructed from an old burner originally made for burning alcohol. The alcohol burner was found at the local market and was modified to fit the biogas system, with dimensions calculated by following the calculations explained by Fulford (1996). Figure 10 shows a blueprint of the constructed burner with the used dimensions specified.

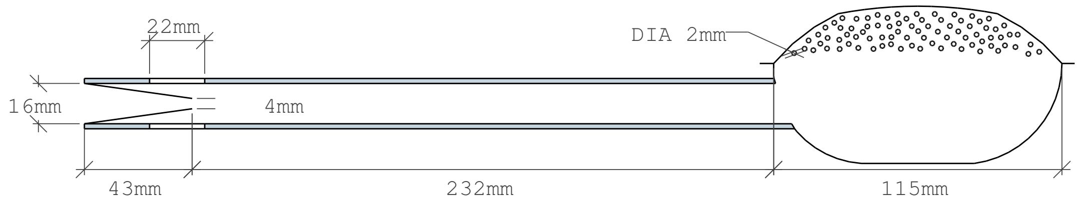

Figure 10: Sketch of the constructed biogas burner.

Besides constructing the biogas burner, a support frame with four legs was designed and constructed in order to allow a pot to be placed above the burner. For pictures of the burner and support frame see Appendix figure 22 to 24.

7 Results

All three original tubes were filled and started on the 26th of June but the first gas volume measurements were carried out on the 4th of July for one of the tubes where gas had been produced. As mentioned in the method section 6.1, two of the tubes were malfunctioning because of holes, and hence the tubes started to produce gas at different times. As mentioned in subsection 6.4, one of the tubes was emptied and refilled with a new feed material consisting of a new mix of cow and goat manure, on the 25th of July. That new slurry is referred to as New Cow/Goat in the figures below.

Table 8: Time until start of gas production for the different tubes.

Tube	Days until start of gas production
Cow/Goat (50/50)	8
Goat	23
Cow	no gas production
New Cow/Goat (50/50)	5

NOTE: The start of gas production is determined from the day that enough gas had accumulated in order for the gas to create a gas bell on the top of the tube and it was possible to carry out a volume measurement.

The gas production from New Cow/Goat had a very short starting time which is probably due to the fact that slurry from the, at the time, working tubes was used in the startup process and hence the microorganisms were already active gas producers.

7.1 Produced Biogas

The amount of gas produced differed between the three digesters, as well as the time when the gas production started. In figure 11 and table 10 the amount of produced biogas is presented.

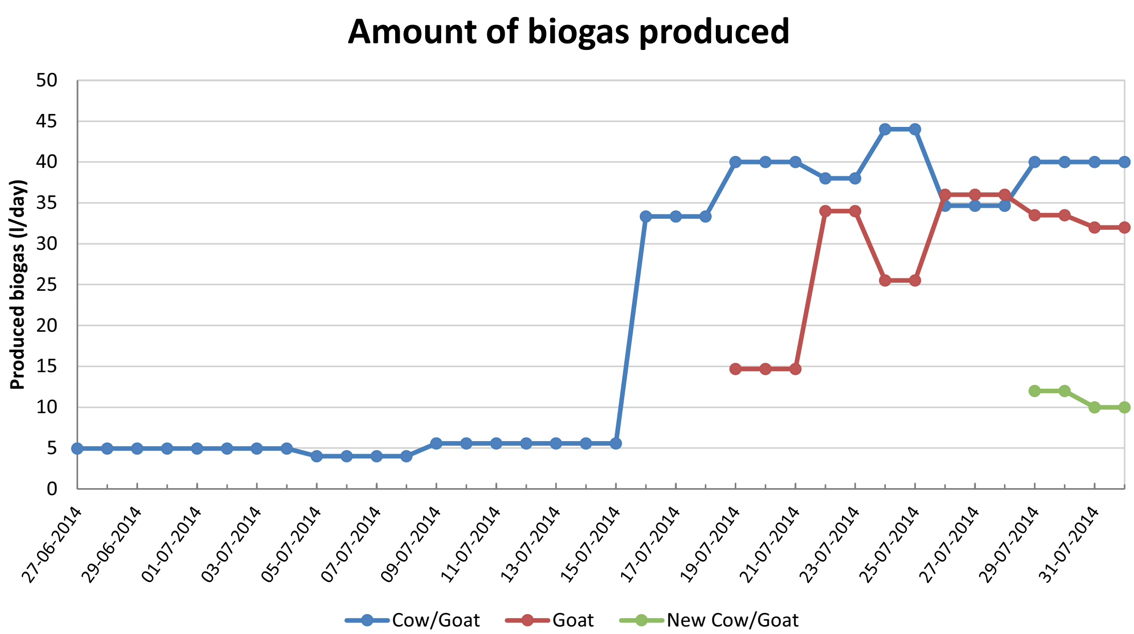

Figure 11: Obtained amounts of gas from conducted measurements.

As illustrated by figure 11 the amount of biogas produced is highest in the Cow/Goat mix but this was most probably because the gas production started earlier in that tube. It is hard to conclude which of the feed materials cow, goat or, mix of cow/goat manure that is most suitable for use in a tubular biogas digester. This is because the tube with only cow manure malfunctioned and never started to produce gas. The reason for this was not because biogas can not be produced from cow manure but rather because of difficulties with the process (see subsection 7.3). It is also hard to draw any conclusions concerning the feed material because of the short time of operation. The production from goat manure and the mix of cow/goat manure (blue line) are fairly similar which would indicate that both of the materials are equal with respect to amount of gas production, see figure (11). However, it is important to emphasise that the mix of cow/goat manure might have an advantage in the form of the microorganisms in tube which are adapted to digestion of both cow and goat manure. This would make the mix the preferable choice because it could handle interchanging between the two feed materials, which is useful in case of temporary shortages in one of the materials.

The quality of the produced gas was fairly similar and consistent no matter from which feed material it was produced. The quality varied between 60 % and 82 % content of methane, as seen in figure 12 and table 10.

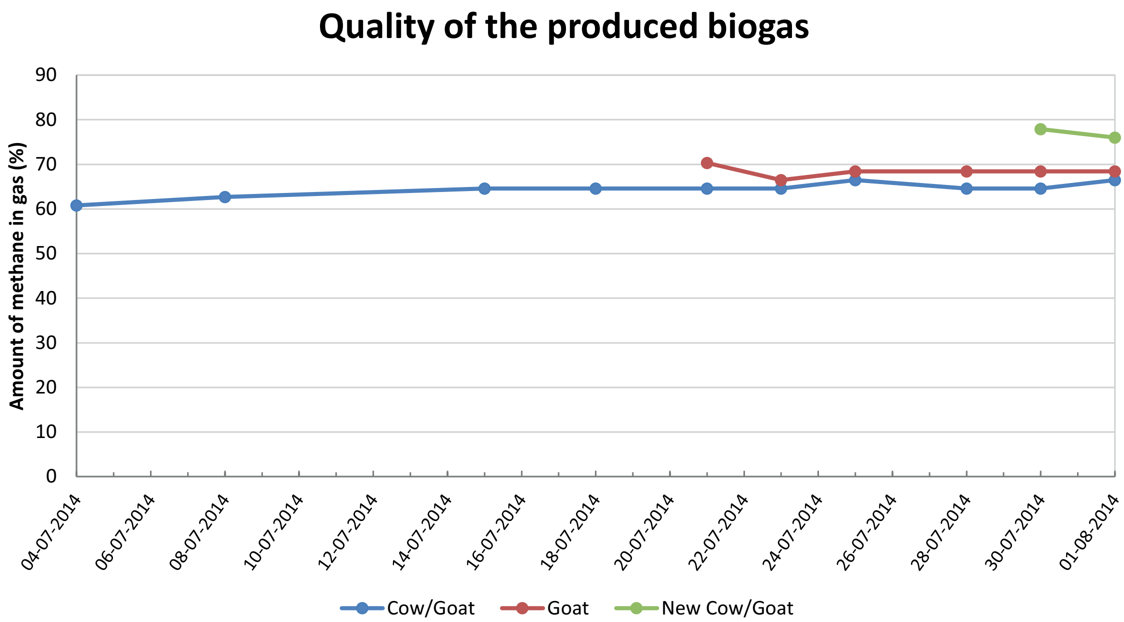

Figure 12: Obtained qualities of gas from conducted measurements.

It is noticeable that the amount of methane in the biogas is as large as it is since it normally reaches levels of between 60 - 70 % (see section 4.3). The reason for the high methane content is probably that the measuring method used is not very precise. When the carbondioxide is dissolved in the sodium hydroxide not only methane is left and there was no way of determining how much of other substances that were present in the gas. If one assumes that 5 % of the presumed methane actually is other substances, table 9 below can be set up.

Table 9: Amount of methane in the biogas if 5 % is assumed to consist of other substances. Worth to remember is that the digester containing New Cow/Goat was filled on the 25th of July.

Date	Cow/Goat quality [%]	Goat quality [%]	New Cow/Goat quality [%]
4/7	61	-	-
8/7	63	-	-
15/7	65	-	-
18/7	65	-	-
21/7	67	70	-
23/7	65	67	-
25/7	67	68	-
28/7	65	68	-
30/7	65	68	78
1/8	67	68	76

The values in table 9 are all in the range between 60 - 70 % except for the New Cow/Goat mix. These values are more in accordance with theory and probably represent a more realistic picture of the methane content. The reason that the New Cow/Goat still has values close to 80 % is most likely because the digestion process was not fully up and running when the measurements were made and air might still have been present in the tube.

Table 10 shows all the measurements for the biogas quality and the biogas production for the three working tubes.

Table 10: Biogas quality and biogas volume from the three digesters.

	Cow & goat		Goat		New Cow/Goat	
Date	quality [%]	volume [liters]	quality [%]	volume [liters]	quality[%]	volume [liters]
4/7	64	40	-	-	-	-
8/7	66	16	-	-	-	-
15/7	68	39	-	-	-	-
18/7	68	100	-	-	-	-
21/7	68	120	74	44	-	-
23/7	68	76	70	68	-	-
25/7	70	88	72	51	-	-
28/7	68	104	72	108	-	-
30/7	68	80	72	67	82	24
1/8	70	80	72	64	80	20
Average:	67.8					

The biogas volumes stated in table 10 are the volumes measured during the stated date. Those volumes were then used to calculate the values shown in figure 11.

7.2 Temperature

The temperatures in the different tubes differed a bit with the highest temperature in the tube containing the mixed slurry of Cow/Goat, as seen in figure 13. This is because that tube was exposed to sunlight during a larger part of the day compared to the other two.

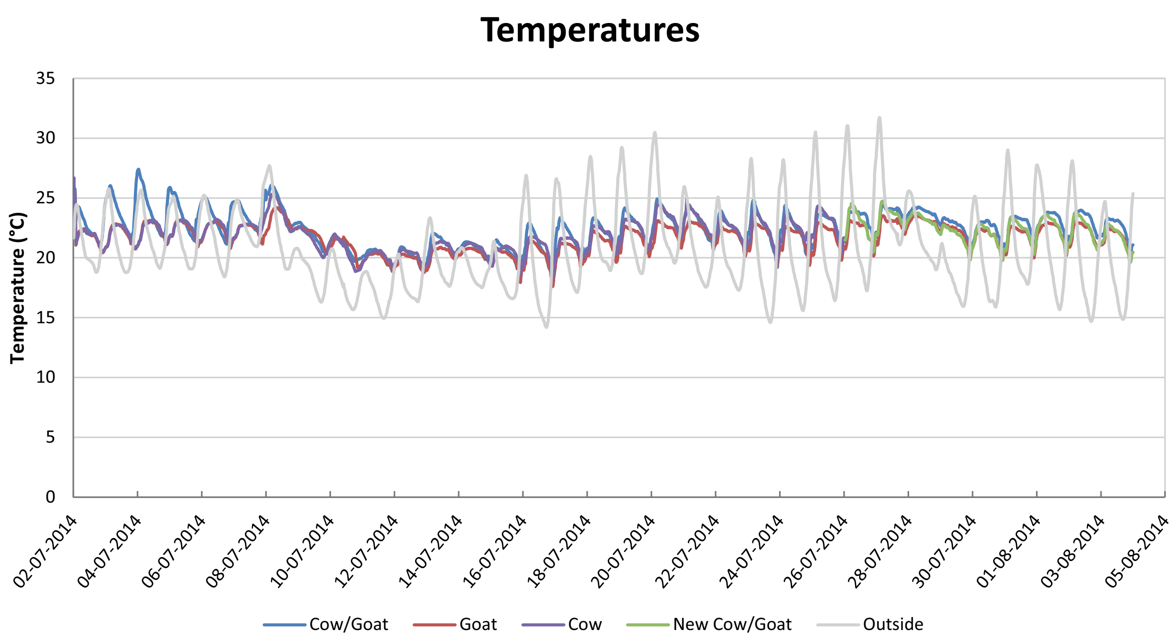

Figure 13: Obtained temperatures from conducted measurements.

The fact that the temperature is slightly higher in the Cow/Goat tube is probably one of the reasons that it started to produce biogas before the other tubes and also a reason to why it produced more biogas once the digestion process was up and running. This really shows the importance of the temperature in a digestion process and tells us that the placement of the tubes should be made so that they receive a maximum amount of sunlight (assuming a non transparent tube material is used). Generally it can be said about the temperatures that they are bit low and it would be preferable if they reached an average of around 30 °C. Considering that the study was conducted during the coldest month(s) in Malawi and the average temperature is around 5 °C higher (see section 5.1 during the other months, an average temperature of 30 °C is possible.

7.3 pH

As seen in figure 14, the pH level in the tube containing cow manure was too low, reaching a minimum of pH 6.2. However, from the 25th of July, when the digester was refilled, the feed materials in all three digesters stabilized at a pH between 7 and 8.

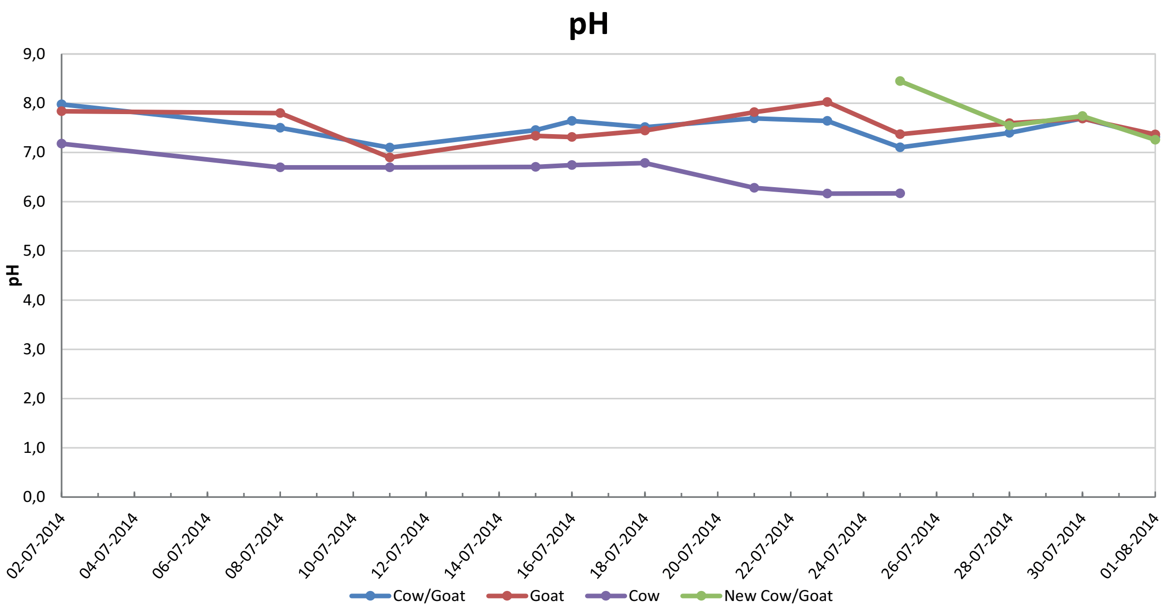

Figure 14: Obtained pH levels from conducted measurements.

The tube called Cow was originally filled with stomach content from cows and not with cow manure, which is why the pH was so low. This shows the importance of choosing a starting material of good quality and preferably a startup material from another already working biogas digester.

7.4 Gas Composition

In addition to the saccharometer an spectrophotometric analysis was done to determine the composition of the biogas. The different spectrophometric analyses of the different gases are presented in figures 15 to 17.

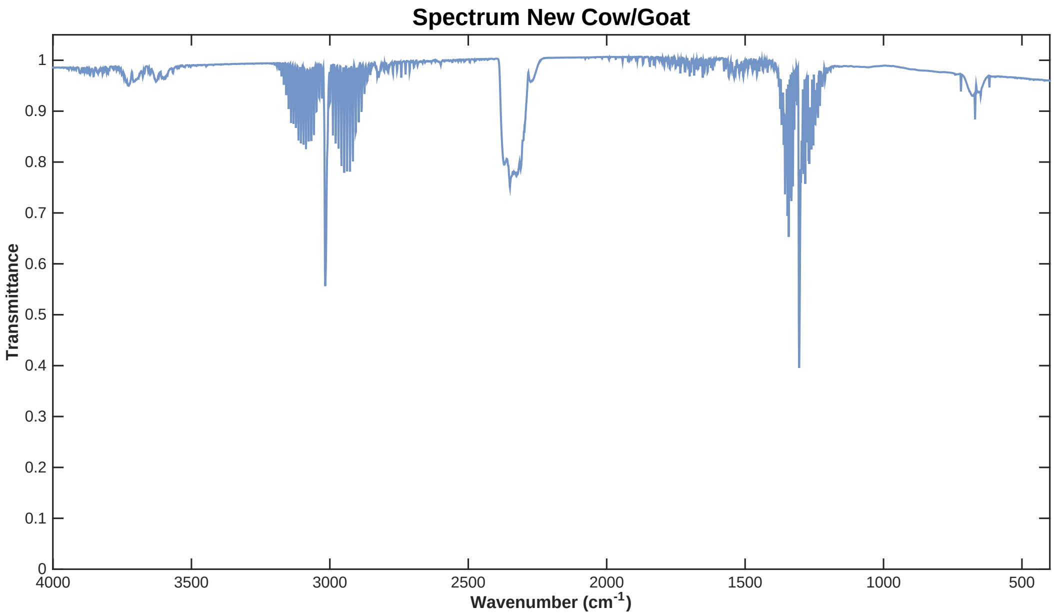

Figure 15: Spectrum of Cow/Goat.

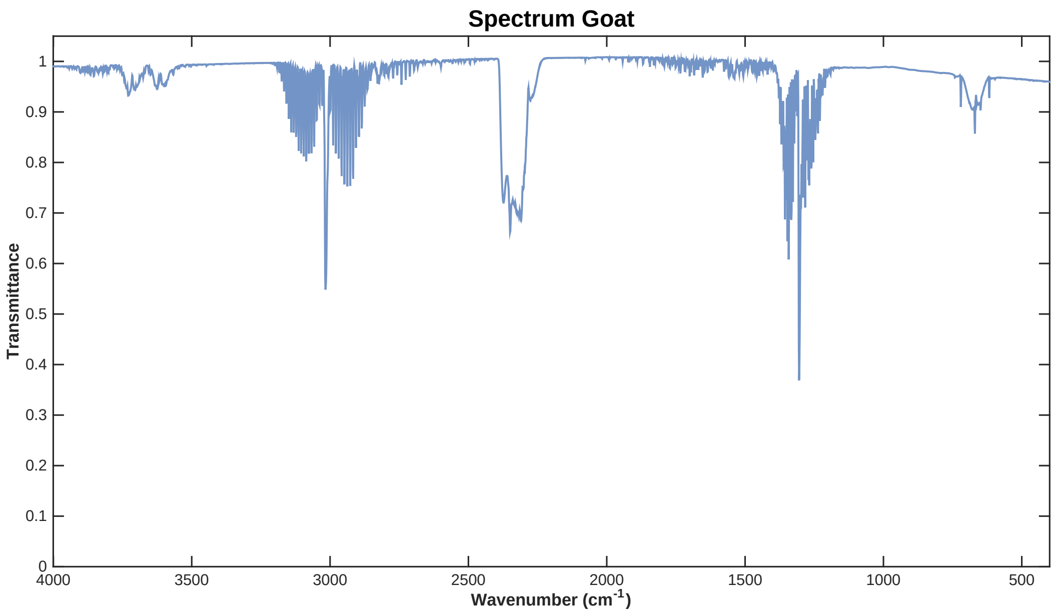

Figure 16: Spectrum of Goat.

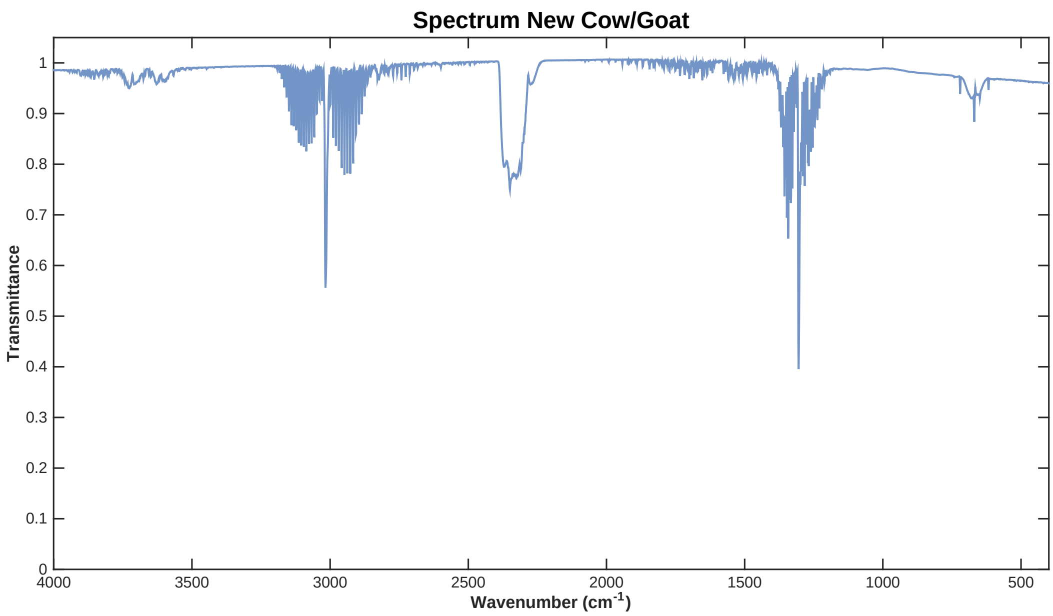

Figure 17: Spectrum of New Cow/Goat.

From the figures (15-17) above one can conclude that there are methane and carbon dioxide by comparing with the reference spectrums in section 4.5. Unfortunately it is impossible to say if there is any hydrogen sulfide in the samples. It may be no hydrogen sulfide at all or it is hiding behind the peaks from the methane and carbon dioxide peaks.

7.5 The System as a Whole

The system was up and running in the beginning of August 2014. The constructed stove was working and the family was able to use their own produced biogas to cook food. However, there were some problems with the pressure in the system caused by a too small total biogas volume. The pressure in the system decreased as soon as the burner was started and manual pressure was after a couple of minutes needed in order to keep the flame burning. This also means that there will not be sufficient gas to use the biogas stove for cooking every meal. For pictures of the completed system see Appendix figures 25 to 28.

8 Errors

The following section brings up potential sources of errors that may have affected the results.

8.1 pH

The measurements of the pH levels were done very close to the inlets and outlets, which might have influenced the results. The best would have been to measure the pH level in the middle of the digesters, but that was not possible during this study. Also the pH meter had an accuracy of $\pm$ 0.01 which effects the measured pH levels.

8.2 Temperature

The temperatures were measured fairly close to the inlets of the digesters, which might have influenced the results. This is because the sun shined more on the inlet-side of the digesters than on the outlet side.

8.3 Volume Measurement

The measuring technique used was quite imprecise and it was difficult to know when the digesters were empty. The fact that the measuring technique was imprecise could mean that both more or less biogas has been produced and it is hard to estimate in which direction the real results would be. However, the circumstance that the digesters were not always completely empty would imply that a larger amount of biogas had been produced. There might also have been air leakage in the pipe system when the low pressure in the measuring device forced the gas to flow from the digesters, which in that case would yield a higher biogas production estimate than the actual amount produced.

8.4 Trenches

When the trenches were dug, they were not horizontal and thus the liquid substance was not equally distributed in the plastic tube. This affect the total volume of the liquid in the plastic tube due the angle of the trench tilt made the substance gather in the end of the tube. As a consequence the total volume was limited to when the liquid substance started to drip from the outlet. If the bottom of trenches would have been horizontal the system could have held more liquid substance and the resulting biogas production would have increased.

9 Discussion

A working biogas system with three tubular polyethylene biogas digesters was installed and tested in accordance with the aim of this study. Even though the study as a whole can be regarded as a realization of the aim there are some aspects that need to be addressed. The study was carried out during a short period of time compared to the time needed for a biogas process to be sufficiently evaluated. This means that the biogas process did not have time to truly stabilize and that long term system parameters could not be determined. Ideally the system monitoring and measuring should have been carried out for a full year in order to see the effects of the temperature change and how the process behaved depending on the different feed materials.

One aspect to take into account is the fact that this study was done during the months of June to August, i.e. the Malawian winter. This means that the amount of produced biogas during this period of time will not be representative for the full year, the production will in fact be higher during the rest of the year than during the time of this study. Besides the fact that the biogas production will be higher, this will also most likely have positive effects on the pressure in the system and would allow the system to be used more often, during longer times and possibly at a higher rate without the need of manual pressure to keep the burner burning. Another aspect, related to temperature, is the fact that the temperatures differed quite a lot between the three different tubes even though they were placed next to each other. This was probably because the sun shone more on the digester containing Cow/Goat manure due to shadowing from trees on the other two tubes. This might be one of the factors that made this digester start its production first, and can also explain why this digester also produced the largest amount of biogas.

As mentioned in the introduction, Malawi suffers from substantial deforestation because of the widespread use of wood and charcoal as energy sources for cooking. This has a negative impact both on the climate and the Malawian people. Alternative energy sources are greatly needed to help Malawi adapt to and mitigate the situation at hand. The performed study shows that tubular polyethylene biogas digesters are a viable alternative to ease the situation. The technology has the advantage of being able to reduce the use of charcoal and wood which in turn will allow the forest to recover, if TPBDs are implemented at a large scale. This will help to restore the forest carbon sink as well as decrease the carbon dioxide emissions released from burning solid fuels. It is important to not only recognize the positive effects the technology has on the climate but also the benefits it can bring to the people. Cooking food is often done in a small room with a lack of ventilation which means that a thick mist of smoke, emitted from burning solid fuels, is formed. This smoke is then inhaled by the people in the room which has serious health effects on the on the human body. When cooking food on a biogas stove almost no smoke is emitted which greatly decreases the chance of catching smoke related deceases. Another benefit is that the material needed for the digestion process often can be found in a close proximity of the household because of the manure that is used comes from the animals at the household. This means that there is no need for long walks to gather wood or to get charcoal which would be an improvement for the family living at the household. The animal manure used in the biogas process is also a free resource which implies reduced costs for buying charcoal or wood. Although it is necessary to remember that the construction and installation of the biogas system is not for free.

One more positive thing with a biogas system is that the process enhances the manure with respect to its use as a fertiliser. This can help improve the harvest for the household and reduce cost for chemical fertilisers. It can also be noted that the Tubular Polyethylene Biogas Digester will not be the only solution to the problem with deforestation in Malawi but it most definitely can be one part of the solution next to other renewable energy sources such as solar power and wind power.

The implementation of TPBDs in Malawi could face possible constraints associated with economic, infrastructural, and cultural issues. The process of acquiring all the needed parts for the installation of a biogas system, is associated with high investment costs for a household which could hinder the whole process of installation. In the case with charcoal it gives rise to small part payments over a longer period of time and are hence easier to handle for a farming household that does not have money saved but rather receives it during harvest and spends it evenly over the year. A large one time payment could mean that no money is left for the time until next harvest. A solution to this could possibly be to establish an organisation which sells the TPBDs on an installation plan which would allow the household to benefit from using the biogas as an energy source while at the same time using the money normally spent on other cooking fuels to pay the TPBD system. An issue associated with the infrastructure is the availability of polyethylene plastic needed to create the tube. As of right now it is manufactured only to order and for other purposes than for being used to construct TPBDs. In order for the technology to spread it is necessary that the material is readily available at retailers and preferably the material needs to be made tougher and non-transparent.

Cultural issues are related with the fact that the technology is unknown and that there is a lot of tradition associated with using charcoal and wood as cooking fuels. To face these issues it is important to use education as a means of spreading knowledge about the benefits a TPBD can bring and to involve the community when implementing a biogas system. Education about the system is also important during the installation of the system since the household will later take care of its operation. To establish contact between the households that installs the systems and an organisation who has knowledge about how they operate could also be a good idea to keep the systems running and to gain further knowledge about the technology.

10 Conclusions

As a whole the study carried out was successful and a tubular polyethylene biogas digester system was implemented at a rural household using locally available materials. The study and the conducted testing shows that a TPBD very well can be used as a part of the solution to reduce deforestation and support climate change mitigation and adaptation in Malawi. The technology also has several other advantages mentioned in the discussion above but further research and development is necessary in order to implement TPBDs at a large scale. It is also important to note that next time a Tubular Polyethylene Biogas Digester is constructed in Malawi it should be dimensioned after the household's need and utilise a starting material from already decomposed manure or a running biogas process. Regarding the feed materials the results show that during this study the mix of cow/goat was the feed material that performed best and also preferred from the aspect of material interchangeability. Although, noticeable is that the tube with cow manure malfunctioned and the tube with goat manure was in the end of the study, working almost as well as the ones with the mix of cow and goat.

11 Future Projects

To continue the development of tubular polyethylene biogas digesters in Malawi more research and further implementations of the technology are needed. A possible area for research would be to evaluate and to map out the techniques potential for climate change mitigation. The next step in evolving and establishing the technology would be to implement a large scale digester that has the required dimensions to supply a household with sufficient biogas for cooking. In this implementation an economic evaluation would be relevant in order to be able to bring the technology to the people in Malawi. An economic evaluation that proves to the public that a TPBD is affordable and less costly than solid fuels in the long term is would be of great importance.

11.1 Recommendations for Future Projects

The following section brings up our recommendations to any research projects concerning the development of tubular polyethylene biogas digesters or other similar biogas technologies.

11.1.1 Startup Feed Material

Be sure to use a good startup material. A good startup material with an acceptable pH-level and active microorganisms is crucial for the gas production to start in a reasonable time. Preferably, use material from an already up and running biogas digester or material that has already started to decompose.

11.1.2 Construction Material

The best would be to always use new materials for the construction, especially when the system is supposed to be up and running for several years. Some polyethylene tubes used in this study turned out to be torn and broken, and the risks for leakage are always bigger when using old materials. It is also important to protect the digester tubes from outside effects with fencing and possibly roofing.

11.1.3 Trenches

The trenches turned out to have a slight inclination, resulting in a less amount of feed material in the digester tubes and a lesser amount of biogas being produced. To avoid this issue, one should make sure to construct the trench bases absolutely horizontal. It is also important to make sure that the walls and bases of the trenches are smooth in order to avoid damage to the plastic tubes.

11.1.4 Measuring of pH

Try to figure out a way to measure the pH-levels as close to the center of the digesters as possible. There might be a risk that the pH-levels just inside the inlets and outlets differ a bit from the rest of the material inside the tubes.

11.1.5 Sandbags for Trenches

To keep the costs down, it might be interesting to look at the possibility of building the trenches out of bags of sand instead of bricks. The bags are also softer and might decrease the risk for holes in the digester tubes.

11.1.6 Dimensions

It is good to make sure that the dimensions of the digester tube are big enough to produce the needed amount of biogas from the feed material that is to be utilized. Using one big biogas digester compared to additional small ones would be recommended because of the work and material needed. In section 4.11, it in concluded that the ideal amount of gas needed to heat 5 l of water to 100 degrees is $1.37m^3$, which is a lot more than this system contains as a whole.

11.1.7 Placement of Digesters

The amount of biogas produced is to a large extent dependent on the outside temperature and placing the digesters in a non-shaded area is preferable. If using a transparent material be sure to cover the tube with a non-transparent material or to build a roof over the digester in order to avoid algae formation due to direct sun exposure.

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Appendix: Pictures of the System

Digesters

Figure 1: Dismantling of old digesters.

Figure 2: Emptying of slurry from an old digester.

Figure 3: Fastening of PVC pipe to work as outlet of the newly made digester. Rubber bands from car tires is wrapped around in order to prevent leakage of slurry.

Trenches

Figure 4: Measuring of trenches to ensure correct dimensions.

Figure 5: Dug out trenches ready to be cemented.

Figure 6: Cementing of trenches to ensure a flat ground level.

Figure 7: Trench with bricks on the side walls.

Figure 8: Newly made ending of a trench which allows the outlet of the pipe to be raised to the correct level.

Storage Bag

Figure 9: The storage bag was hung from the celling outside of the kitchen. When the picture was taken the storage bag contained around 200 litres of biogas.

Mixing of Slurry

Figure 10: The cow stomach waste used to fill one of the tubes for the first time. This material was undigested by the cows and later emptied from the digester since it gave rise to a decreasing pH. This is the type of material one would want to avoid using as starting material for a biogas process.

Figure 11: Pounding of goat manure as a pretreatment before digestion.

Figure 12: Filling of the tubes for the first time.

Figure 13: A funnel was made in order to simplify the process of filling the digesters. The slurry is a mix of cow and goat manure with added water .

Gas Volume Measurement

Figure 14: The gas volume measurement ready to be used.

Figure 15: The upside down container was manually raised in the larger bucket and therby creating a suction that pulled the biogas from the digesters to the gas volume measuring device.

Gas Quality Measurement

Figure 16: The gas sample was collected from the gas volume measuring device using a small hole in the upside down container.

Figure 17: The gas was injected from the syringe into a Dr. Einhorn's Fermentation Saccharometer.

Figure 18: On this picture it is clearly visible how much methane is in the biogas since the methane forms a bubble at the top of the Dr. Einhorn's Fermentation Saccharometer and the carbon dioxide is dissolved in the solution.

Biogas Composition

Figure 19: Gas sample in the spectrophotometer ready for analysis.

pH Level Measurement

Figure 20: Extraction of sample from digester outlet to be brought back to the lab for further analysis.

Temperature Measurement

Figure 21: A computer and an external battery was brought to the site in order to collect the data from the data logger. On this picture one can also see the solar panel on the roof used to power the data logger.

Biogas Stove

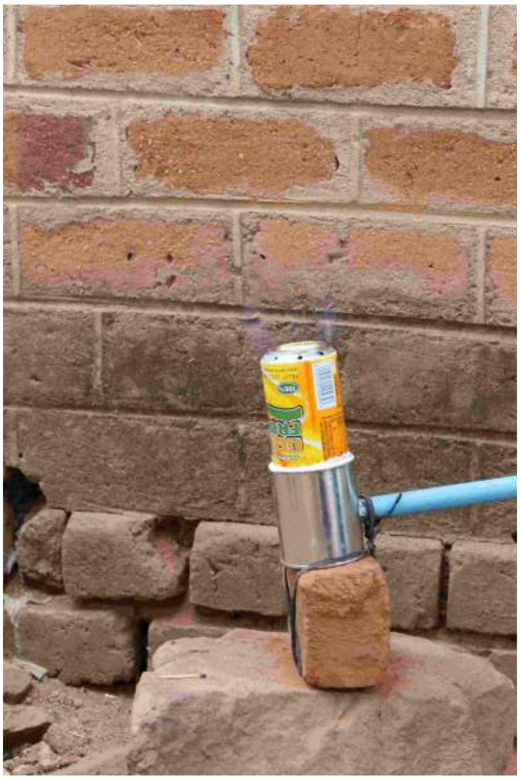

Figure 22: The first prototype of the burner with which we were able to test that a burnable gas was being produced in the digestion process.

Figure 23: The later designed biogas burner with air and gas intake.

Figure 24: The complete stove with support frame. The biogas enters from a pipe connected to the main system outside the kitchen wall.

The System as a Whole

Figure 25: The three biogas digesters with piping.

Figure 26: Biogas digesters with pipes leading to the storage bag and the kitchen.

Figure 27: Full biogas digester tube containing the mix of cow and goat slurry.

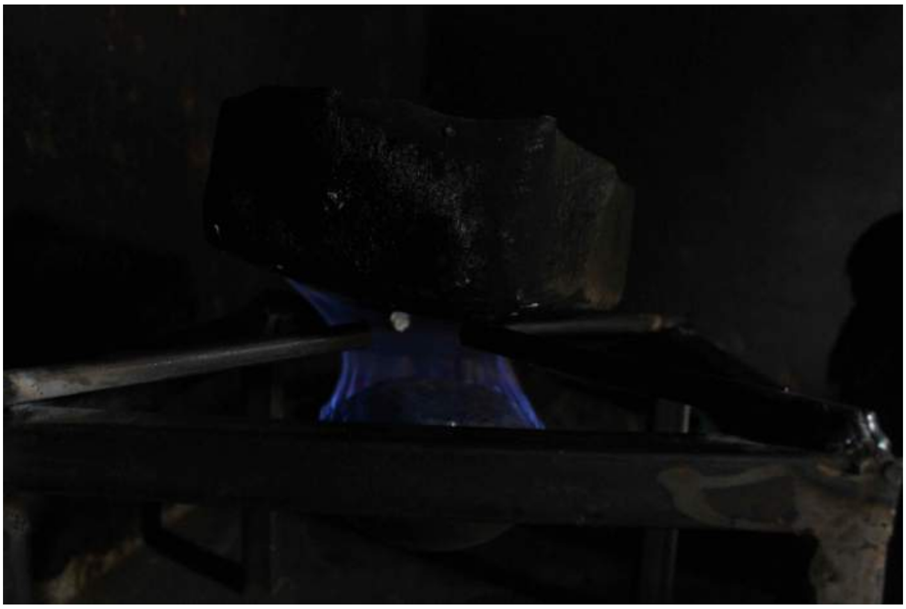

Figure 28: Clear blue flame burning from the biogas burner inside the kitchen. Ready to be used for cooking.

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