Community-Level Resource Development and Management, Part 2: A Transferable Approach to Feasibility Analysis for Biogas as an Alternative Cooking Fuel

Megan M. Richardson
School of Mechanical, Industrial and Manufacturing Engineering,
Humanitarian Engineering Program,
Oregon State University, Corvallis, OR, USA

Kendra V. Sharp* PhD
School of Mechanical, Industrial and Manufacturing Engineering,
Humanitarian Engineering Program,
Oregon State University, Corvallis, OR, USA
kendra.sharp@oregonstate.edu

*corresponding author

ABSTRACT: *Energy access for all is the seventh Sustainable Development Goal (SDG) put forth by the United Nations in 2015. This sustainable development goal has been taken on by many non-governmental organisations (NGOs), national governments and communities alike. Traditional Sub-Saharan African approaches to cooking often rely on three-stone fires (or other open wood fires). The smoke from these open cooking fires is known to cause significant adverse health impacts. Thus, access to cleaner energy sources is especially important to improve cooking conditions. One alternative cooking fuel is biogas, which has the advantages of smoke reduction, and decreased reliance on and impact of firewood collection. In this article, we develop a method of analysing the feasibility of biogas projects for some rural communities. The method we describe enables both evaluation of small-scale anaerobic digester designs for specific settings and determination of the scale, cost, and effectiveness of a biogas digester. For example, in a cooking application, 1 m³ of biogas can replace 1.3 kg of firewood and the associated time (approximately 10 minutes) spent collecting firewood. Such technology evaluation is critical for helping communities and organisations determine whether this type of project is well suited for their settings. All too often, development project concepts are funded prematurely, before the realisation that the implemented technology does not function properly or is unsustainable for specific applications. The feasibility analysis we describe is a contribution to the literature, because it provides a condense and, simply written resource to enable development practitioners, volunteers and communities in a rural setting, evaluate sustainable biogas energy solutions prior to investment and implementation.*

KEYWORDS: *Alternative fuel, biogas, cooking fuel, digester, energy, Tanzania*

1 INTRODUCTION

Without access to alternative fuels, students in rural areas around the world spend time away from the classroom collecting firewood to contribute to meal preparation. Dependence on firewood in schools impacts the time students spend on study and contributes to deforestation (Global Alliance for Clean Cookstoves, 2016).

Alternative fuels such as biogas can potentially reduce the issues associated with firewood collection and use in rural settings. Biogas is defined as the mixture of gases (predominantly methane and carbon dioxide) that is generated from the degradation of organic material in oxygen-free or anaerobic environments. Biogas can be generated and stored in specialised vessels known as anaerobic digesters or biogas digesters.

We developed a methodology for development practioners to evaluate the feasibility of biogas as an alternative fuel source to firewood. The methodology allows practitioners to determine biogas digester type, sizing and resulting biogas yields. The methodology also allows for an assessment of the impact of biogas digester sizing on fuel costs. Our intent is for development practitioners to utilise our approach to determine if this type of energy generation technology development is appropriate for their application and setting.

This paper presents feasibility assessment methodology and its application to a case study for sizing and costing of a community-scale biogas digester. We investigate the feasibility of using human waste to power the plant, with regards to both sanitary and social constraints, and detail the process of plant sizing for a specific population of users and beneficiaries. Matema Beach High School (MBHS), a government school of approximately 1,000 students in southwestern Tanzania, is utilised as a case study for this methodology. The analysis aims to determine if biogas is an effective alternative cooking fuel compared to firewood fuel. The analysis focuses on: biogas digester type selection, basic cost of construction, and evaluating the biogas yields of the chosen design, along with local acceptability.

We developed this analysis method by collating information from other resources and distilling key points into a condensed and accessible format that can be used by practitioners. Our primary goal is to aid development practitioners and volunteers in evaluating the feasibility of biogas infrastructure in rural settings. Currently, volunteers have many educational resources related to community development, but lack thorough technical resources related to energy development (Peace Corps, 2018). Determining the cost and effectiveness of energy systems prior to construction and implementation can inform sustainable system design including the use of local resources and appropriate long-term planning of system maintenance. As this method requires minimal technical background to use, it is ideal for practitioners outside of academia who do not have access to databases and libraries whilst working rurally. The development of simple-to-use evaluation and planning methods for schools is particularly important as it aligns with national and global initiatives. The Tanzanian government has promoted renewable energy development through policy and funding, particularly in rural areas (Mshandete and Parawira, 2009). Likewise the United Nations (UN) organisation has pushed for reduced reliance on non-renewable fuels by promoting access to affordable, reliable, sustainable and modern energy for all in its Sustainable Development Goals (Zhu, 2015).

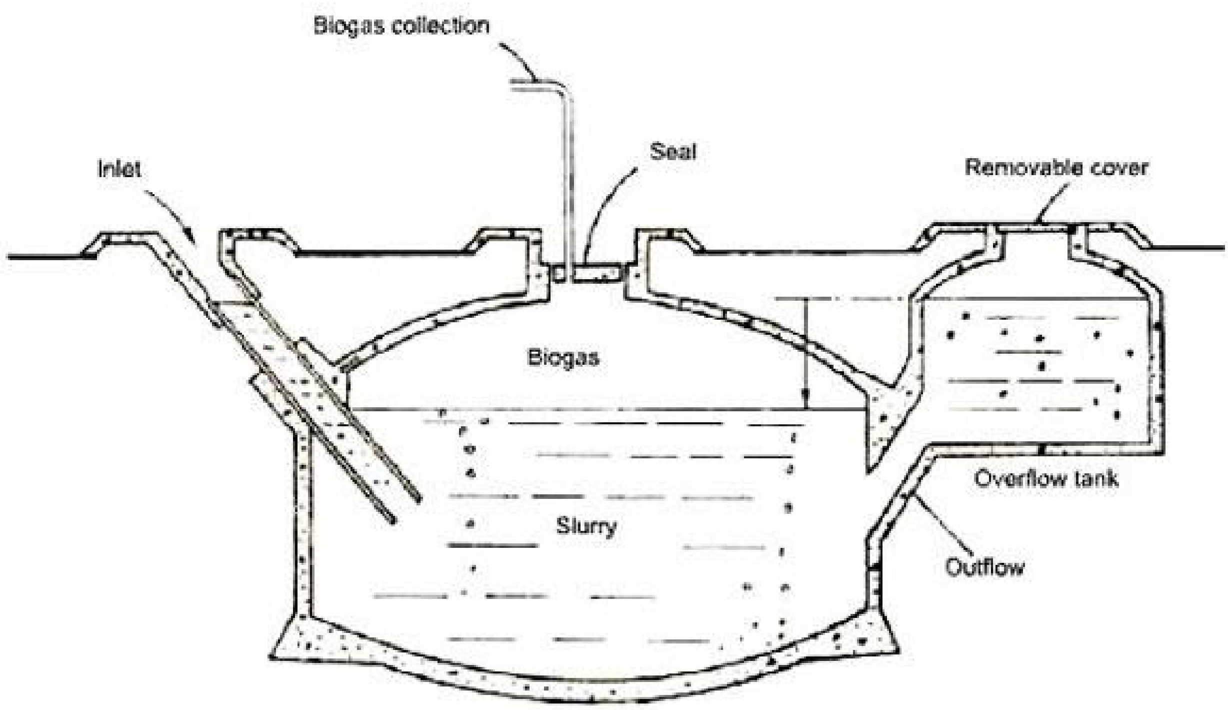

Figure 1: *Simple fixed-dome biogas digester* (*Li, and Ho,* 2006)

2 BIOGAS TECHNOLOGY REVIEW

We begin a feasibility analysis by determining which type of biogas digester would operate most effectively in the school's environment.

As described above, biogas can be generated from the fermentation or digestion of organic materials by specialised bacteria that exist in oxygen-free (anaerobic) environments. Organic wastes include: human and animal excreta, food waste, garden waste or other liquid organic wastes (e.g. fats and oils).

Biogas digesters are specialised vessels that enable the generation, capture and storage of generated biogas. Biogas digesters are designed for two specific functions – digestion or fermentation of the input waste in an oxygen-free "digestion" chamber, and collection of the generated flammable gas in the gas holder or gas storage chamber. A general biogas digester design is shown in Figure 1 to illustrate those two functions.

The six most common biogas digester designs commonly seen in rural development settings are reviewed here based on their construction, operation, and maintenance.

2.1 Fixed Dome

A fixed dome biogas digester (Figure 1) is a conical brick and mortar wall construction with fixed concrete shell roofing that acts as an immovable biogas holder.

The fixed dome plant is constructed using locally available materials: brick and mortar, concrete for shell-roofing, PVC piping, and is partially buried under a layer of soil (Kuria and Maringa, 2008). The cost of materials is low with the greatest costs attributed to the use of highly skilled masonry labour and the use of heavy machinery. The gas-tightness of the fixed dome chamber is dependent on the skill of masonry available; average

Figure 2: *Applications of the six most common biogas digesters*: (*a*) *fixed dome*[1]; (*b*) *floating drum*[2]; (*c*) *earth-pit*[3]; (*d*) *ferro-cement cage*[4]; (*e*) *balloon*[5]; *and* (*f*) *composite material*[5].

Notes:

[1] *https://commons.wikimedia.org/wiki/Commons:Reusing_content_outside_Wikimedia,*

[2] *https://energypedia.info/wiki/File:Floating_drum_mauretania.jpg,*

[3] *https://kendallpermaculture.com/2013/07/05/biogas-project-update-may/,*

[4] *https://www.sciencedirect.com/science/article/pii/S1364032114001968 and*

[5] *http://www.build-a-biogas-plant.com/balloon-digester/*

masonry does not create a gas-tight dome and additional sealants or plastic liners must be used to prevent leakages. The use of additional sealants and liners creates a risk to safety due to the possibility of dome explosion due to gas pressure build-up if no suitable depressurisation, venting and flaring of excess gas is allowed for (Kuria and Maringa, 2008).

The fixed dome digested is continuous-feed digester that can vary in size with volumes ranging between 6 to 20 m^3. Typical operational lifespans are between 12 to 20 years with a specific biogas production rate of 0.2 to 0.5 m^3 of biogas per m^3 digester volume $m_{gas}{}^3/m_{volume}{}^3$. The specific biogas production rate can be interpreted as a kind of efficiency; the gas production efficiency compared to the digester volume would be 20–50%. However, gas produced is not visibly indicated to the user and fluctuates in pressure. Fixed-dome plants are recommended only if they will be utilised by experienced biogas technicians who are familiar operating the technology (Werner, Stöhr and Hees, 1989).

Minimal regular maintenance is required as no metal or moving parts are involved in the design; instead, daily additions of influent generates the mixing requirement to break-up scum and enhance gas production (Werner, Stöhr and Hees, 1989). However, if repairs are needed, the only access to the digester is through the influent and effluent chambers. Therefore repairs are difficult to perform, and cracking could lead to irreparable leaks and structural damage (Cheng et al., 2014).

The overall strength of the brick and mortar structure is high. In terms of reliability, the amount of gas produced relates directly to the mass of the waste provided; gas produced will not be released at a constant pressure, which could negatively impact the cooking application.

2.2 Floating drum

The floating drum digester is an underground cylindrical or dome-shaped construction containing an internal moving gas holder (Figure 3).

The digester is typically constructed as a brick-lined pit supporting a cylindrical steel floating drum. The drum can either float directly above the fermenting waste slurry or in a water jacket. The biogas generated is collected in the gas drum that rises and falls in accordance with the volume of gas generated.

The floating drum design has a comparatively high initial cost due to the steel and machining needed for its construction, however the overall construction is simple and can be performed by local masons and metal workers (Cheng et al., 2014). The reduction in cost for the use of average masonry skill in comparison to the skilled masonry

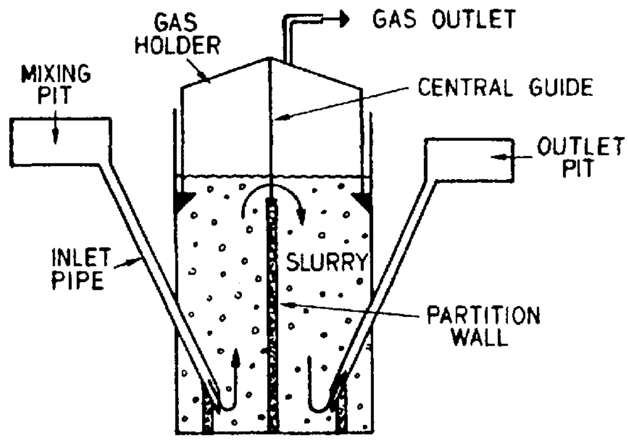

Figure 3: Cross-section of simple schematic of floating drum biogas digester (Marchaim, 1992)

required for fixed dome digesters is balanced by the cost of skilled metal labour.

The drum is rotated to encourage enhanced biogas production. Inside the drum, a steel bar framework disturbs and breaks apart the scum layer formed at the top of the accumulated waste as the drum is rotated (Kuria and Maringa, 2008). As the drum can move vertically with changes in gas levels, the plant produces biogas at constant pressure, which is advantageous for cooking (Werner, Stöhr and Hees, 1989). The drum height is an easily interpretable visual indicator of gas storage levels to the user.

The digester is sized from 6 to 100 m^3 with an expected specific daily biogas production rate of 0.3 to 0.6 $m_{gas}{}^3 m/m_{volume}{}^3$. This can be interpreted as 30 to 60% gas production efficiency. The digester lifespan ranges from 8 to 12 years, this is lower than the fixed dome due to the effects of corrosion on the drum (Werner, Stöhr and Hees, 1989). Chemical additives could potentially mitigate the effects of corrosion without significant impact on the digestive process; however, investigating such possibilities was beyond the scope of this study.

During maintenance and cleaning, the metal drum can be removed for ease of access into the digester. Regular maintenance requirements include drum painting (for optimal sealing), rust removal, and dislodging the drum if it gets stuck in floating scum and cannot rise. The metal structure provides high strength and reliability (Kuria and Maringa, 2008). This type of digester is recommended when reliability is of greater importance than cost. The interior painting helps to ensure that the digester is gas-tight, and its movement with gas production prevents the possibility of a plant explosion. Within a local environment that experiences heavy and cyclic rainfall, it is possible for rain to seep into the pit, with the maintenance frequency increasing with rust build up (Polprasert, Nukulchai and Rajput, 1982).

2.3 Earth-pit digester

The earth-pit plant digester (Figure 4) is a design that is suitable for stable soils where masonry walled digester designs are not required. The earth-pit plant is typically an earthen pit lined with a thin layer of cement, with or without steel mesh reinforcement, to prevent seepage of the digester contents to the surrounding soil(Werner, Stöhr and Hees, 1989). The edge of the pit is reinforced with a ring of masonry that serves as the anchorage point for the gas holder. The gasholder construction material can vary, is it typically either a metal construction or plastic sheeting. Where plastic sheeting is used, the sheeting is attached to a wooden frame that extends down into the fermenting slurry and anchored in place to counteract buoyancy(Werner, Stöhr and Hees, 1989).

The earth-pit is a continuous feed digester that is typically sized between 4 to 500 m^3, with a daily production rate of 0.1 to 0.5 $m_{gas}{}^3m/m_{volume}{}^3$, or a 10 to 50% gas production efficiency.

The earth-pit plant design requires minimal construction materials: cement for pit lining, metal netting and plaster

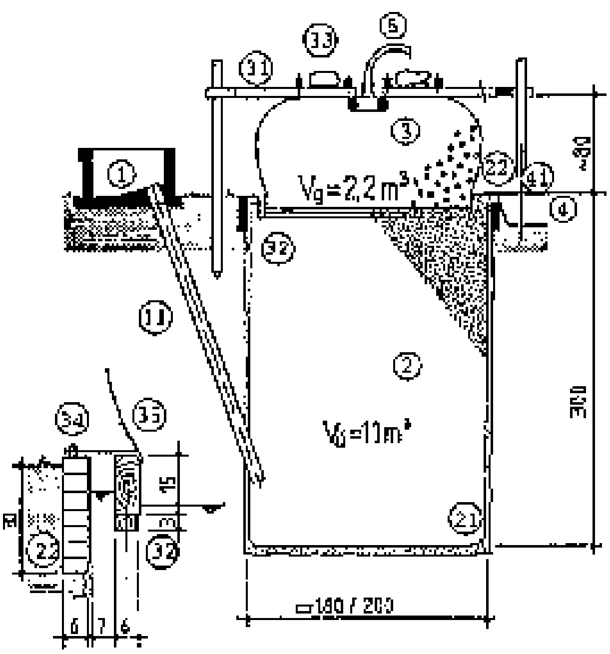

Figure 4: Earth pit biogas digester with plastic sheeting gasholder. 1. Mixing pit, ll Fill pipe, 2 Digester, 21 Rendering, 22 Peripheral masonry, 3 Plastic-sheet gasholder, 31 Cuide frame, 32 Wooden frame, 33 Weight, 34 Frame anchorage, 35 Plastic sheeting, 4 Slurry store, 41 Overflow, 5 Gas pipe (OEKOTOP in (Werner, Stöhr and Hees, 1989))

walls to prevent seepage, and a masonry ring. In addition, an external gasholder (metal or plastic) is recommended. The cost of installation is the lowest of the technologies described in this paper (approximately one fifth of the cost of a floating drum plant) however this is in turn balanced by a short operational lifespan of 2 to 5 years. The overall structural integrity of the digester is low as it lacks structural supports. Despite the design being suitable in stable soil conditions, it must be situated above the groundwater table to avoid groundwater contamination and dilution of the waste slurry. Maintenance of the plant is minimal, typically consisting of occasional plaster repairs.

Increased biogas pressure can be achieved by weighing down the gasholder. The plant does not impose as immediate a risk of explosion as the fixed dome construction as the structure is not gas-tight (Werner, Stöhr and Hees, 1989) however appropriate design safety features for biogas handling must still be maintained.

2.4 Ferro-cement plant

Ferro-cement biogas digesters are cast-in-situ structures constructed using cement mortar with steel wire mesh layers (Council of Scientific & Industrial Research, 2007) (Figure 5). Ferro-cement digesters can be self-supporting singular or multiple compartment chambers or earth-lined pit chambers. The compartment chambers allow for the containment of the fermenting waste and biogas collection. Inlet and outlet piping are provided to facilitate entry of the waste to be fermented and removal of the digested sludge and biogas venting and piping is provided for access to the stored biogas.

The ferro-cement digester doesn't require high volumes of construction material however the required quality of cement for construction is high (i.e. ferrocement) (Polprasert, Nukulchai and Rajput, 1982). The constructing of the plant is theoretically easy in rural areas however a standardised method has not yet been adequately time-tested (Cheng et al., 2014). Careful handling of the ferro-cement structure is necessary during transport and construction to prevent damage, therefore the applicability of this technology is mostly recommended in communities where ferro-cement experience is present (Council of Scientific & Industrial Research, 2007).

Continuous daily operation yields a biogas production rate of 0.3 to 0.6 $m_{gas}{}^3m/m_{volume}{}^3$ (or 30 to 60% gas production efficiency) during operation, and digesters are typically sized between 4 to 20 m3. The operational lifetime of a ferro-cement plant ranges from 6 to 10 years (Werner, Stöhr and Hees, 1989). Scum accumulation can reduce gas production, which can be maintained by mixing and withdrawing portions of the slurry. Ferro-cement has a greater crack-proof property than regular cement, so the overall strength is high. The reliability of

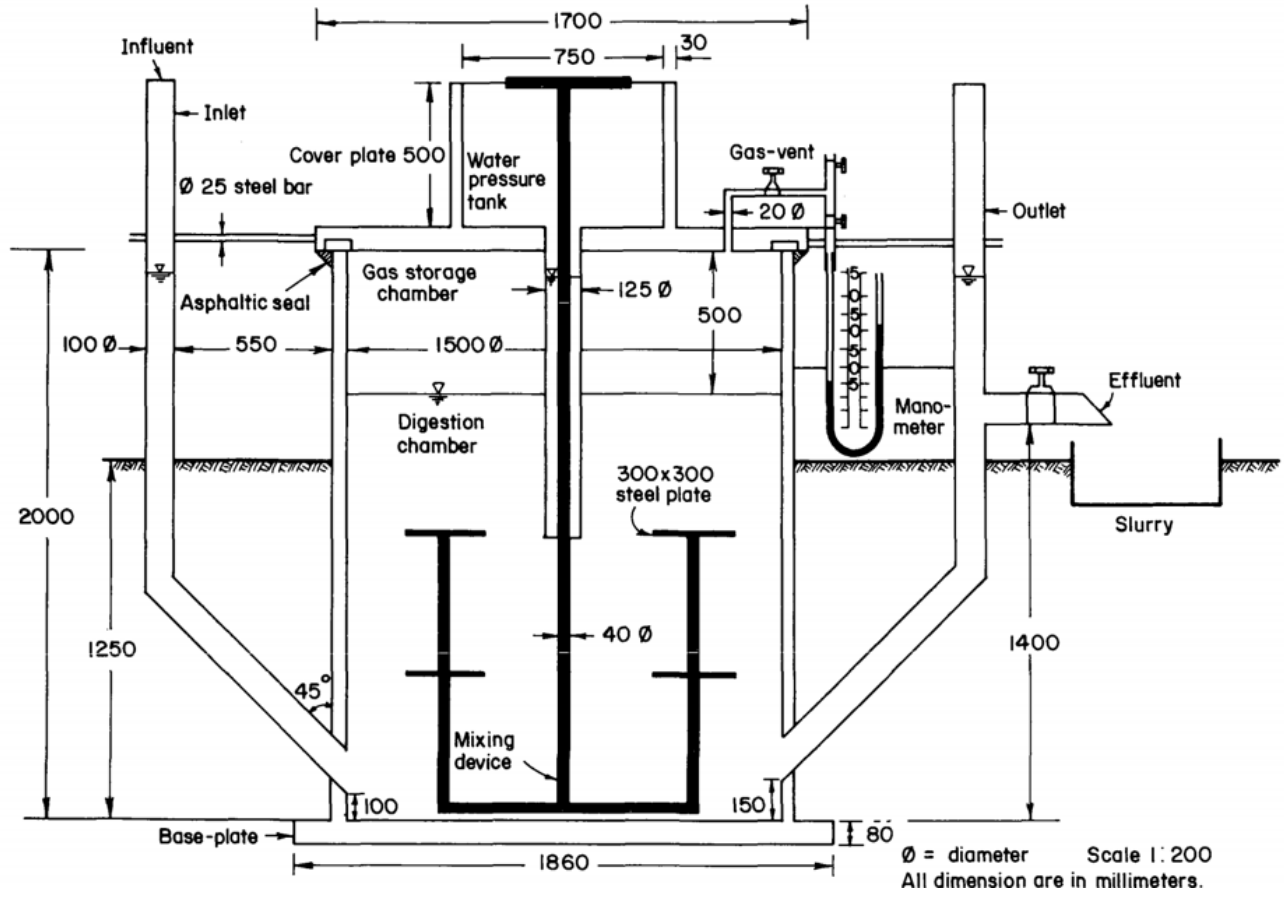

Figure 5: *Schematic of Ferro-cement biogas digester cross section Kanok-Nukulchai and Robles-Austriaco,* 1985)

the plant can be enhanced using an extra storage tank to prevent leakages and continually allow for production. The gasholder requires special sealing measures to prevent leakages, and excessive pressure could cause leakages at seals. However, ferro-cement seals are tighter than in regular cement, so leakages are expected to be lower than a fixed dome plant. Lastly, as there are no known explosions reported from the operation of ferro-cement biogas digesters, this type of construction can be considered to generate a lower risk of explosion than fixed dome plants. (Polprasert, Nukulchai and Rajput, 1982).

2.5 Bag digester

Bag digesters (also known as balloon digesters or low-cost polyethylene digesters) are long, cylindrical plastic bags placed into trenches, lined with compacted sand and mud (Kuria and Maringa, 2008) (Figure 6).

The cost of the bag is generally low (between $20 to $200 USD) though importation taxes for developing countries can double the cost. AS they are easy to transport, bag digesters are well suited for remote areas where construction materials are difficult to acquire and transport. In addition, bags are a good solution when the groundwater table is high as the plastic prevents seepage into or out of the digester. This is in contrast to masonry construction where wastewater seepage is more likely to occur; this is most problematic for areas with high groundwater tables where risk of groundwater contamination high (Cheng et al., 2014).

The bags are easy to install and do not require masonry expertise, but do require adequate waste to be added for the bag to provide sufficient pressure (Cheng et al., 2014). Where low pressure gas output is reported weights can be placed on bags to increase pressure. As air-tight seals are difficult to produce where the piping joins the bag despite the use of sealants, gas leakages are common. If gas production is high and the produced gas is not utilised or stored, the bags can explode (Kuria and Maringa, 2008).

The bag volume is typically 4 to 100 m3 with an expected lifetime between 2 to 5 years. Estimated daily output from digesters of this technology is 0.3 to 0.8 $m_{gas}^3 m/m_{volume}^3$ (or 30 to 80% gas production efficiency) (Werner, Stöhr and Hees, 1989).

The bag is simple to maintain with most repairs consisting of sealing works should the bag be damaged or ruptured. Sediment accumulation in the bag is very difficult to remove. The bag's structural integrity is low; the thin

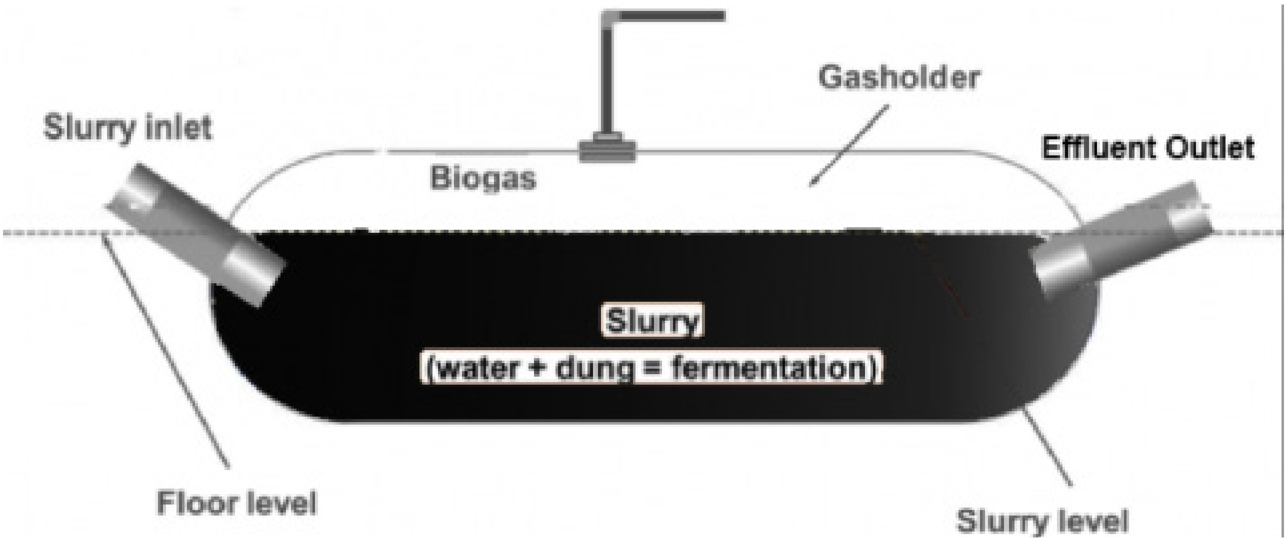

Figure 6: *Bag biogas digester schematic* (*Massachusetts Institute of Technology Impact Labs, n.d.*)

plastic used commercially to manufacture bags is prone to damage from falling objects, people and animals. The scope of this study did not consider non-traditional bag materials. This design requires shelter from direct sunlight and is impacted by changes in temperature, which in turn is dependent upon the material and its colour, and the resulting rates of heat transfer. The recommended mean temperature is greater than 20°C, so biogas production rates are poor during cold nights or winter.

2.6 Composite material digester

Composite material digesters are prefabricated and commonly used commercial technologies. Made of fiberglass, carbon fibre and polyester, they are mainly manufactured remotely and imported to remote and rural areas such as Tanzania. Composite digesters have high initial investment cost but do not require local masonry skill. A typical composite digester costs approximately $3,000 USD, which may be cost prohibitive in terms of upfront capital available, for example, at MBHS. The prefabricated designs are only available in select volumes.

Operation is theoretically simple, but a lack of operational guidelines can lead to significantly reduced working efficiency (Cheng et al., 2014). The typical operational lifetime of a composite digesters cannot be easily estimate as the lifetime varies based on the manufacturer and construction materials used, however, of the digester technologies reviewed in this study, the composite material digester is assumed to have the longest operational lifetime.

Composite material digesters have a high resistance to corrosion and are strong and durable, with the ability to hold consistently high gas pressures. To ensure proper operation, composite material digesters require technical and operational follow-up inspections post implementation, which is often lacking in remote and rural environments. Additionally, if the composite material digesters are manufactured locally in inexperienced manufacturing plants; the risk of producing malfunctioning low-quality digesters is greater. Composite material digesters are also prone to sinking into soft ground material. Seepage of wastewater into the groundwater table is minimised due to the tight sealing construction (Cheng et al., 2014).

2.7 Ratings for design criteria

In order to select an appropriate biogas digester design for MBHS, we used the technology review methodology developed as part of this study to evaluate each digester's strengths and weaknesses against the following ten (10) defined criteria:

1. *Strength* – Can the design withstand the gas pressure from the waste slurry?
2. *Cost* – What is the overall cost of materials, construction, training and ongoing maintenance?
3. *Materials* – Are materials locally available?
4. *Ease of Construction* – What level of skill is required for plant construction?
5. *Ease of Operation* – How easily will a local user be able to operate the plant?
6. *Ease of Maintenance* – What degree of maintenance will be regularly required?
7. *Reliability* – Can the plant consistently function as needed?
8. *Gas-tight* – Can the design withstand gas leakages?

9. *Safety* – Is it safe to operate the plant, both for the user's health and physical safety?
10. *Environment* – Can the plant withstand the local environmental conditions? What health impacts can the plant have on the local environment and people?

These criteria were developed based on Kuria's design factors (Kuria and Maringa, 2008). The criteria were selected to gauge the digesters' construction and operation in specific environmental conditions; in our case MBHS is a tropical and rainy climate where temperatures average 24.9°C, with average annual rainfall exceeding two (2) meters (Climate-Data.org, 2018).

Each digester is ranked over the criteria for the specific application of MBHS on a scale of one (1) to ten (10), with 1 being the lowest and 10 being the highest. We based the scores on evaluating the author's experience in the local environment and conversations with future plant users against the definition of each of the criteria across each digester design. In this study, each criterion was weighed equally, but in future investigations, it would be possible to weight the criteria based on the importance of each design and ease of operation in the local environmental context.

The scoring shows that the floating drum design is rated as the most effective design for MBHS. However, we recommend two design changes to further enhance the digester's suitability. Firstly, the digester should incorporate a water jacket so that the drum rises and falls within the water instead of the fermenting waste slurry (Figure 7). The jacket both enhances hygiene by removing operator contact with the waste slurry and prevents the drum from becoming stuck in the floating scum on the slurry surface. Secondly, a roofing structure (not shown) should be constructed over the plant to prevent rain from both diluting the slurry and causing corrosion. These modifications impact the plant's ease of operation, maintenance, safety, and applicability in the local environment whilst only adding slight cost. Reassessing the design with respect to the design criteria above, this would allow for at least a three-point increase in score from 76 to 79, with a decrease in one point in the "operation", "maintenance", "safety" and "environment" criteria and increase of one point in the "cost" criteria.

We began the design process by estimating the school's daily waste production, which is a function of the number of students and their daily toilet use. Waste estimates for students, all aged in their teens and twenties, were based on an adult producing an average 1.22 kg of waste per day (urine and faeces) (Fry, Merrill and Merrill, 1973). This estimate was used in modelling the boarding-students' (advanced-level) waste production. The waste of day students (ordinary-level) was estimated to be half of the

Table 1: *Ranking of the six most common biogas digesters over selected design criteria*

Design Criteria	***Fixed Dome***	***Floating Drum***	***Earth-Pit Plant***	***Ferro-Cement Plant***	***Bag Digester***	***Composite Material Digester***
Strength	8	8	7	8	5	9
Cost	7	6	8	7	8	4
Availability of materials	9	9	9	8	6	4
Ease of construction	5	8	8	5	6	4
Ease of operation	7	9	8	8	7	7
Ease of maintenance	5	7	7	6	5	7
Reliability	7	8	6	7	5	8
Gas-tight	6	7	6	7	5	8
Safety	5	8	7	7	7	9
Environment	8	6	6	8	8	7
TOTALS	67	76	72	71	62	67

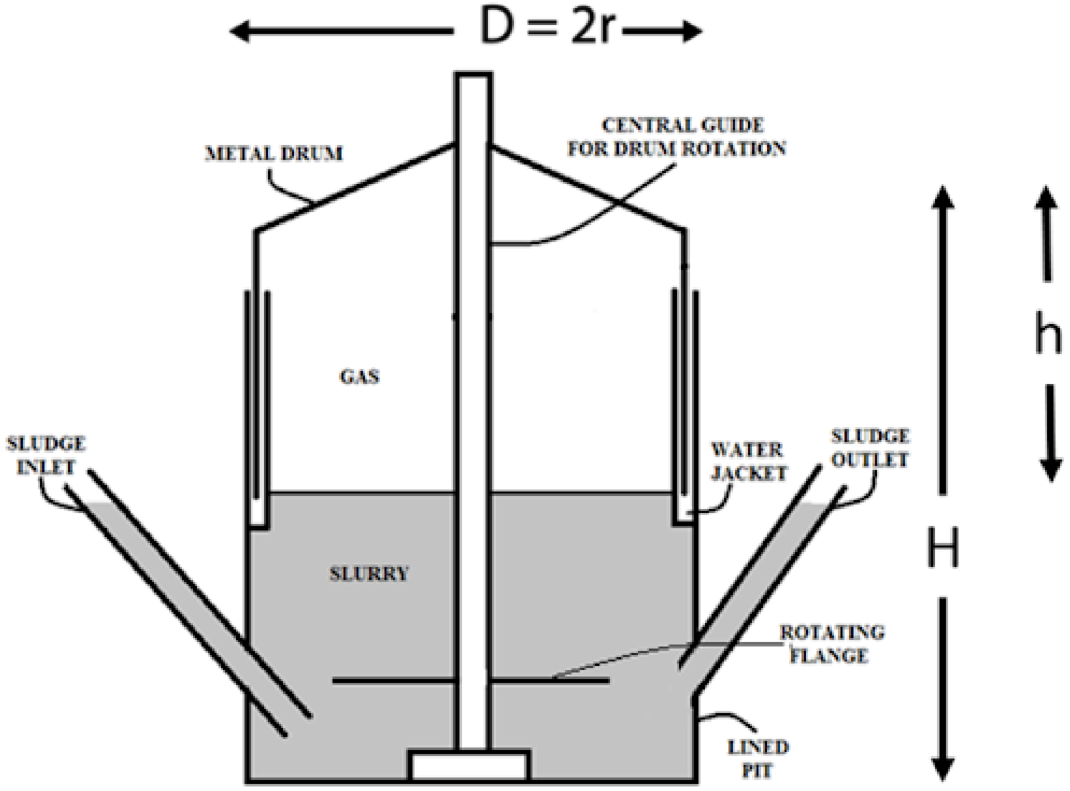

Figure 7: Schematic of the modified floating drum biogas digester (not to scale)

advanced-level student daily average, based on the proportion of time spent at school (6:30AM to 5:00PM). These assumptions are limited as they do not reflect diet or environmental factors; capturing local data on waste production was outside the scope of this research.

The students were then assigned to the bathroom that they predominantly use to estimate the daily waste flow to each septic tank. Only the bathrooms at elevations higher than the anticipated digester location would be incorporated into the system design to eliminate the need for a pump. Inclusion of pumps in this design was deemed unfeasible due to inconsistent electricity supply in the local village and high maintenance requirements and low resource abilities (both technical expertise and good sanitary practice) to service the maintenance requirements. Inclusion of generators for electricity production was deemed cost prohibitive both from a capital and operational perspective owning to high costs of petrol and lack of local access to petrol. The proposed biogas digester location and bathroom locations are labelled on the campus map in Figure 8.

The distance and change in elevation between each bathroom and the plant location were determined using a Garmin GPSMAP 64ST (Garmin Ltd., 2016). The slope was calculated for each pipe route and when compared to the International Plumbing Code, we saw that each value exceeded the code's recommendation for horizontal drainage pipes (2015 International Plumbing Code, 2015). Therefore, the locally available pipe was found able to accommodate the flow, and intermediate pumps or tanks were not deemed necessary.

The North Bathrooms were associated with dormitories, the Central Bathrooms accommodated dormitory students and a limited number of day students, and the East Bathrooms were used by a dormitory of students, and all female students. To include multiple design sizes based on varied daily waste production, the bathrooms were considered independently, grouped in combinations, and grouped together in each of the design calculations. The calculations made for MBHS biogas digester can be found into Table A1 to Table A5 in APPENDIX A.

3 DESIGN RESULTS

3.1 Sizing the digester

One of the important parameters for digester sizing is the hydraulic residence time. The hydraulic residence time is the average time the waste spends inside the digestion vessel. The hydraulic residence time is correlated to two parameters: the digester volume and the organic loading rate as shown in Equation 1. The organic loading rate is defined as the amount of waste fed to the system on a daily basis (Kuria and Maringa, 2008).

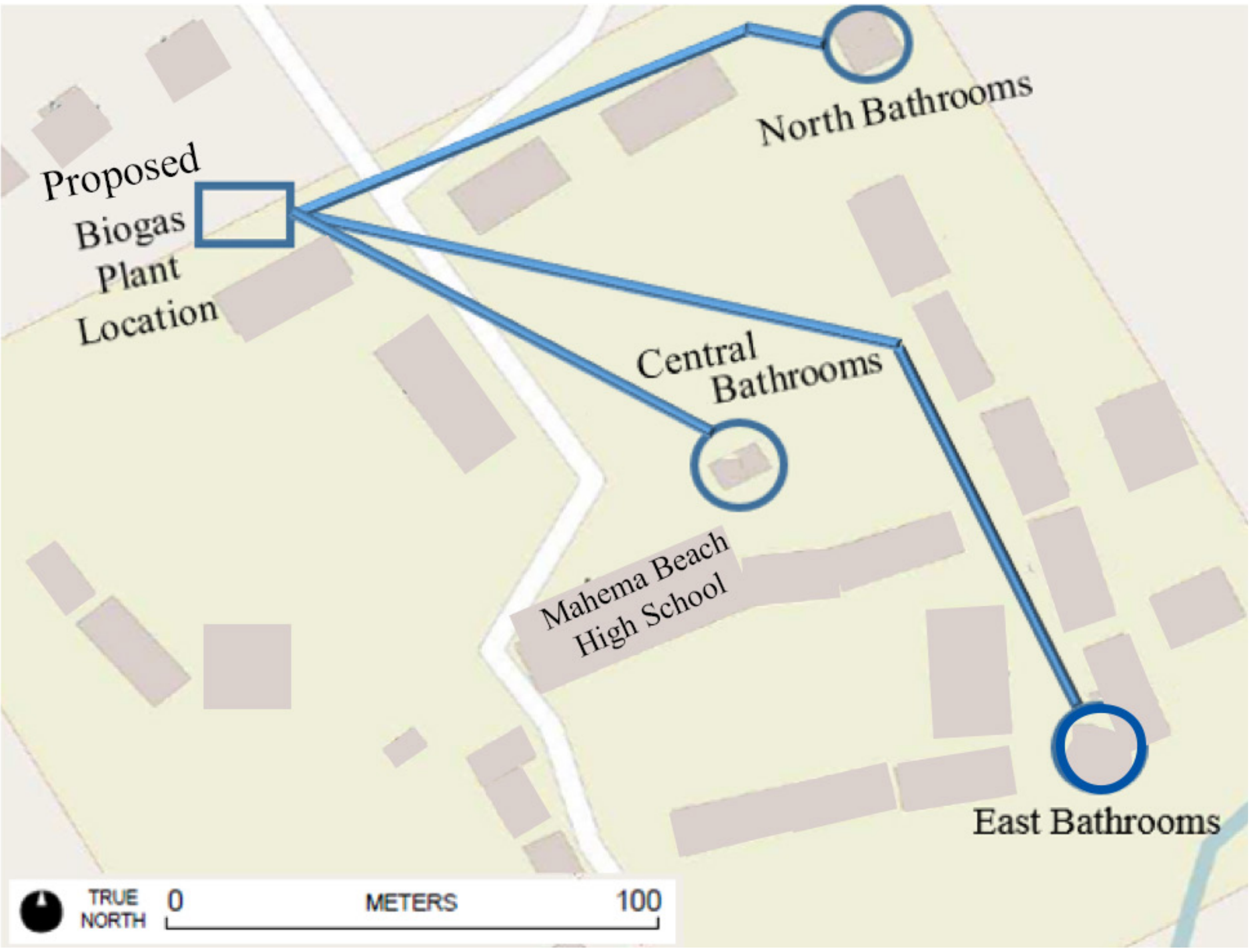

Figure 8: *Bathroom and proposed biogas digester locations on MBHS's campus with piping routes. Note*: (*This map was created using fieldpapers.org, an open-source tool to create atlases from Google Maps.*)

$$R = \frac{V_d}{v} \tag{1}$$

where:

R = Hydraulic retention time [days]

V_d = Digester volume [m^3]

v = Organic loading rate [m^3/d]

Recommendations for design retention time vary, but 100 days is strongly recommended for human excreta to ensure the safety of operators when removing the waste from the digester (Khatavkar and Matthews, 2013).

To determine the impact of retention time on scale and cost, a design retention time of 20 to 100 days is used. Combining the estimated production of 1.22 kg of human waste (faeces and urine) per person per day and assuming a density of approximately 1,000 kg/m3 for human waste slurry (Onojo et al., 2013) allowed us to calculate the organic loading rate of (v) (m3/day). The basic equations used in our analysis are presented here. Further details and calculations are found in APPENDIX A.

After the required volume is determined, the dimensions of the digester can be calculated. Based on the literature of floating drum designs, the volume of the digester is approximated as a cylinder, with the diameter of the digester (D) (m) is assumed to be equal to the height (H) (m) (Kuria and Maringa, 2008). Equation 2 below represents volume as a function of the diameter (D) only. Equation 3 shows the rearrangement of Equation 2 to solve for diameter.

$$V_d = \frac{\pi D^2 H}{4} = \frac{\pi D^3}{4} \tag{2}$$

$$D = \sqrt[3]{\frac{4V_d}{\pi}} \tag{3}$$

3.2 Estimating the cost

A limiting factor for project feasibility is the construction cost, which is predominantly related to the cost of steel and piping.

The cost of construction was calculated to determine the initial, limiting investment that would be required to develop the biogas digester. For the purposes of this assessment, the maintenance cost is treated as an ongoing system cost and not an influencing factor for initial investment requirements.

The cost of steel is a direct function of the digester surface area and unit price of material. Given the radius of a metal drum r=D/2 and the assumption that the metal drum height (h) is approximately one half of the total masonry digester height (H) (Figure 7), we can calculate the area of steel required (Equation 4), assuming the digester can be approximated as a flat-topped drum. The local cost per square meter (m^2) of steel is used to determine the total cost of the drum.

$$Surface\ Area = 2\pi rh + r^2 \tag{4}$$
$$= 2\pi\left(\frac{D}{2}\right)\left(\frac{H}{2}\right) + \pi\left(\frac{D}{2}\right)^2$$
$$= 3\pi\left(\frac{D^2}{4}\right)$$

We designed the pipe routes to be as direct as possible and limited unnecessary pipe bends to minimise interference with existing structures on campus (Figure 8). The total piping cost was calculated from the total design length of the piping and the local cost per metre of material.

3.3 Comparing estimated cost and plant outputs

We compared the two major cost components with the plant outputs to evaluate economic feasibility. The primary plant outputs are: total daily biogas yield, the equivalent number of meals made with the gas produced, the equivalent mass of firewood saved per day, the time saved spent collecting firewood.

The daily gas yield is a function of the average gas yield per kilogram of human excreta [m^3/kg] (Werner, Stöhr and Hees, 1989), the mass of excreta produced daily by students [kg/person], and the number of students at school. In the scope of this study, the gas yield rate was assumed to be constant. Based on Oxfam's research on biogas yield from human excreta, we chose a value of 0.02 m^3 gas per kilogram human excreta (Oxfam, 2008).

The equivalent meal numbers produced is calculated from the total daily biogas yield assuming a certain volume of biogas consumption per meal generated. We utilised Oxfam's biogas generator design research value of 0.3 m^3 of biogas required per meal generated (Oxfam, 2011).

The equivalent firewood saving was determined we compared the energy content of biogas to that of firewood (Werner, Stöhr and Hees, 1989). The time saved from firewood collection by using biogas as cook fuel was calculated by using research on wood collection times in Southern Tanzania (Preston, 2012). Based on Preston's (2012) data on hours spent collecting firewood per year and mass collected per year, we estimate the average rate of firewood collection to be 8.2 kg per hour.

Plant outputs for each of the MBHS's bathroom waste-input combinations were calculated. The results of these calculations can be found in APPENDIX A.

4 DISCUSSION

The feasibility study suggested that the floating drum biogas digester would be the most suitable design for the school based on its safety during operation (both physical and with regards to sanitation) and the current lack of multi-year biogas management experience at the school. We recognise that education and training would be required should any biogas digester system be installed, but did prioritise ease of entry to technology adoption in our evaluation process.

The major costs in constructing this type of plant include: the material costs of the steel used for the digester drum and the piping connecting the septic tanks to the digester. If the recommended retention time of 100 days is employed, the digester would range in volume from 12 to 60 m^3, depending on the number of septic tanks that are connected. The cost of the two major components would range from approximately $3,000 to $10,000 USD, which does not include continual operating or maintenance costs. Operating costs include personnel supervision and monitoring of the plant; maintenance costs would include cleaning and repairs of the digester and drum, and slurry removal and disposal as necessary.

It is estimated that a plant of this configuration would yield approximately 2 to 12 m^3 biogas daily. This volume of biogas corresponds to approximately: 8 to 40 meals cooked, 3 to 16 kg firewood saved, and 0.4 to 2 hours per day of time gained from not requiring firewood collection. Given the largest design (with all septic tanks connected) the biogas produced would not be able to replace cooking with firewood completely, but would serve as a useful supplementary fuel.

5 CULTURAL CONSIDERATIONS

Prior to developing a biogas project, it is important to understand how the fuel generated will be perceived locally, particularly if considering the use of human excreta as feedstock. If this practice is new to a community, it is important to acknowledge that a simplified characterisation of biogas digester processes is essentially "cooking with human waste," which can be seen as unclean and undesirable. The acceptance of such a practice can be opposed by cultural barriers related to social stigma, religion, health practices and institutional knowledge (Mittal, Ahlgren and Shukla, 2018).

Even with an optimal and well-functioning biogas digester design , cultural barriers can prevent plant operation from succeeding. Lee et al. (2013) studied technology adoption in cultures that varied in terms of degrees of collectivism. Lee at al. noted for effective diffusion of technology there is a relationship between cultural values and the importance of the level of perceived innovation versus the level of positive subjective evaluations of the technology by peers (Lee, Trimi and Kim, 2013). Since Tanzania is considered a collectivistic society, positive subjective evaluations by peers, or the opportunity to see others adopting and liking anaerobic biodigester designs, are necessary for effective adoption of such systems (Hofstede, 2015). Thus, it is important to know if existing biogas infrastructure can be found locally and how people perceive different waste materials as fuel. For a biogas project to successfully move forward, it is critical to provide appropriate communication and education centred on how the plant operates hygienically and how biogas is a clean cooking fuel.

6 CONCLUSION

The biogas digester design process shows that the plant at MBHS would have a high initial cost of construction, even without incorporating the costs of additional materials, labour, and transportation. The high costs are a function of the local prices of steel and piping and the large spread of the school's campus. The biogas yield produced would not be sufficient to entirely replace cooking with firewood, so biogas would most likely only serve as a supplementary cooking fuel.

Given a current lack of biogas management experience at the school, it would be difficult to both ensure proper maintenance and to rationalise the initial investments needed for the project, especially when other projects (such as dormitory and classroom construction) have already been prioritised in the school's expansion budget. The prohibitive costs are partly associated with the specific floating drum design, but this type of digester was prioritised in part because of the sanitary measures it employs; we did not feel that installing fencing around a biodigester was sufficient for our level of risk tolerance. As a biodigester at MBHS would be operated in a school environment with approximately 1,000 students present, it would be unethical to recommend a system that could potentially increase the health risk on campus, for example, by contaminating water sources.

Although the use of a biogas digester for fuel production is not ideal for this specific school setting, it could be feasible in alternative environments. Key factors that influence the feasibility are the proximity of toilets (less piping is required if they are grouped more closely together), availability and cost of steel, and demand for biogas (based on the number of people supported by cooking). For instance, in a hospital or health clinic setting, the buildings include more densely located toilets with many outpatients who use these facilities but are not fed on-site. The inpatient population that would be served meals would be a smaller fraction of the total waste-producers, so cooking with firewood could potentially be replaced entirely. We do note that the installation of any type of biogas digester would require training for operation and maintenance to ensure that users are working with a safe and sanitary energy source.

Future work to further develop this methodology could relate to developing case studies around designs of the other types of digesters. It would be helpful to collate more detailed cost estimation procedures for all types of digesters, for example including the additional cost of training for operation and maintenance of the digesters. Such level of detail is beyond our current scope.

The barriers to cultural acceptance of biogas digesters should be further investigated as they will vary dependent on the specific community and culture in which the plant would be employed. These cultural considerations are extremely important with regards to community cooperation and endorsement and should not be overlooked.

7 ACKNOWLEDGEMENTS

Thanks to Matema Beach High School's students, teachers and staff for collaborating to develop this research initiative, specifically Headmaster Solomon Mwaipopo and Richardson's project counterparts: Kava Ilombo and Gertruda Ruhele. The Peace Corps community in Tanzania provided continual support throughout my service, and special thanks are given to Oregon State University's School of Mechanical, Industrial and Manufacturing Engineering for their support of the Peace

Corps Master's International program and my research both on campus and abroad.

8 REFERENCES

2015 International Plumbing Code (2015) *International Code Council*, viewed 2 May 2018, https://codes.iccsafe.org/content/IPC2015PDF

Cheng, S, Zifu, L, Heinz-Peter, M, Elisabeth-Maria, H, Ruiling, G & Xuemei W 2014, 'Development and application of prefabricated biogas digesters in developing countries,' *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 387–400, doi: 10.1016/j.rser.2014.03.035.

Climate-Data.org 2018, *Kyela Climate*, Oedheim, viewed 15 May 2018, https://en.climate-data.org/location/26733/

Council of Scientific & Industrial Research 2007, *Ferrocement Applications,* Structural Engineering Research Centre (Council of Scientific and Industrial Research, Ghaziabad, https://www.ircwash.org/sites/default/files/161-7880.pdf

Fry, LJ, Merrill, R & Merrill, Y 1973, 'Methane digesters for fuel gas and fertilizer with complete instructions for two working models' *The New Alchemy Institute*, vol. 3, pp. 1–58, viewed: http://large.stanford.edu/courses/2010/ph240/cook2/docs/methane_digesters.pdf

Garmin Ltd 2016, *Garmin GPSMAP 64 Owner's Manual,* Olathe, https://www8.garmin.com/manuals/webhelp/gpsmap64/EN-US/GPSMAP_64_OM_EN-US.pdf

Global Alliance for Clean Cookstoves, 2016, *Safe Access to Fuel and Energy (SAFE)*, WPF Climate and Disaster Risk Reduction Program, Rome, http://www.safefuelandenergy.org/about/index.cfm.

Hofstede G 2015, *What about Tanzania*? The Hofstede Centre, https://www.hofstede-insights.com/country-comparison/tanzania/

Kangmin, L & Ho MW 2006, *Biogas China*, Institute of Science in Society Report, http://www.i-sis.org.uk/BiogasChina.php

Kanok-Nukulchai, W & Robles-Austriaco, L 1985, *Ferrocement Biogas Digester – Do it Yourself Series Booklet No.* 6, International Ferrocement Information Center, Bangkok

Khatavkar, A & Matthews, S 2013, '*Technical Brief*: *BIO-LATRINES*', Practical Action, Nairobi, https://www.pseau.org/outils/ouvrages/practical_action_bio_latrines_2013.pdf

Kuria, J, & Maringa, M 2008, 'Developing simple procedures for selecting, sizing, scheduling of materials and costing of small bio–gas units,' International Journal for Service Learning in Engineering, vol. 3, no. 1, pp. 9–40

Lee, SG, Trimi, S & Kim, C 2013, 'The impact of cultural differences on technology adoption', *Journal of World Business*, vol. 48, no. 1, pp. 20–29, doi: 10.1016/j.jwb.2012.06.003.

Marchaim, U 1992, *Biogas processes for sustainable development,* Food and Agriculture Organization of the United Nations (FAO), Rome

Massachusetts Institute of Technology (MIT) (n.d.), *Impact Labs – Bag biogas digester*, https://impactlabs.mit.edu/bag-biogas-digester

Mittal, S, Ahlgren, EO & Shukla, PR 2018, 'Barriers to biogas dissemination in India: a review,' *Energy Policy,* vol. 112, pp. 361–370, doi: 10.1016/j.enpol.2017.10.027.

Mshandete, AM & Parawira, W 2009, 'Biogas technology research in selected Sub-Saharan African countries – a review,' *African Journal of Biotechnology*, vol. 8, no. 2, pp. 116–125, doi: 10.1080/07388550902823674

Onojo, OJ, Chukwudebe, GA, Okafor, ENC, Ononiwu, GC, Chukwuchekwa, N, Opara, RO & Dike, DO 2013, 'Estimation of the electric power potential of human waste using students hostel soak-away pits,' *American Journal of Engineering Research*, vol. 2 no. 9, pp. 198–203

Oxfam 2008, *Septic Tank Guidelines, Oxfam Technical Briefing Notes,* https://policy-practice.oxfam.org.uk/publications/septic-tank-guidelines-126711.

Oxfam 2011, *Design, construction and maintenance of a biogas generator, Oxfam Technical Briefing Notes,* Oxford, https://policy-practice.oxfam.org.uk/publications/design-construction-and-maintenance-of-a-biogas-generator-136537

Peace Corps 2018, *Resource Library*, PCLive, viewed 21 May 2018, https://pclive.peacecorps.gov/pclive/index.php/library

Polprasert, C, Nukulchai, WK & Rajput, VS 1982, 'A ferrocement digester : biogas and biomass production,' *Journal of Ferrocement*, vol. 12, no. 1, pp. 25–34

Preston, KM 2012, 'Fuelwood Collection and Consumption: A Case Study in Lupeta, Tanzania', Master's Thesis, Michigan Technological University, https://www.mtu.edu/peacecorps/programs/forestry/pdfs/katie-preston-thesis-final.pdf

Wellinger, A, Murphy, J & Baxter, D 2013, *The Biogas Handbook*, 1st edn, Woodhead Publishing, Oxford

Werner, U, Stöhr, U & Hees, N 1989, *Biogas plants in animal husbandry*, Deutsches Zentrum für Entwicklungstechnologien, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn

Zhu, J 2015, *Sustainable Development Knowledge Platform, United Nations Department of Public Information,* New York, viewed 30 April 2018, https://sustainabledevelopment.un.org/?menu=1300

9 APPENDIX A

Table A1: *Calculations of the organic loading rate into the biogas digester*

Parameter	Bathroom						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
# Advanced-Level students	280	10	70	190	250	80	260
# Ordinary-Level students	0	170	280	170	280	450	450
(A-level student waste)/day m3				0.00122			
(O-level student waste)/day) m^3				0.00061			
Organic loading rate, v, m^3/day	0.22	0.12	0.26	0.34	0.48	0.37	0.59
Daily mass of waste [kg]	220	120	260	240	480	370	590

Equations used:

$$\textit{Organic loading rate, } v\ [m^3/day] = (\textit{No. of A-level students}) \times (\textit{Daily waste per A-level student}) + (\textit{O-level students}) \times (\textit{Daily waste per O-level student}) \quad (A1)$$

Note: daily waste per person estimated as 1.22 kg (Fry, Merrill and Merrill, 1973); density of human slurry estimated as 1,000 kg/m^3 (Onojo et al., 2013)

Table A2: *Calculations of the necessary digester volume as a function of desired retention time*

Parameter	Bathroom						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
$V_{d,1}$ at R = 20 days [m^3]	4.39	2.32	5.12	6.71	9.52	7.44	11.83
$V_{d,2}$ at R = 40 days [m^3]	8.78	4.64	10.25	13.42	19.03	14.88	23.67
$V_{d,3}$ at R = 60 days [m^3]	13.18	6.95	15.37	20.13	28.55	22.33	35.50
$V_{d,4}$ at R = 80 days [m^3]	17.57	9.27	20.50	26.84	38.06	29.77	47.34
$V_{d,5}$ at R = 100 days [m^3]	21.96	11.59	25.62	33.55	47.58	37.21	59.17
H_1, D_1 [m]	1.77	1.43	1.87	2.04	2.30	2.12	2.47
H_2, D_2 [m]	2.24	1.81	2.35	2.58	2.89	2.67	3.11
H_3, D_3 [m]	2.56	2.07	2.69	2.95	3.31	3.05	3.56
H_4, D_4 [m]	2.82	2.28	2.97	3.25	3.65	3.36	3.92
H_5, D_5 [m]	3.04	2.45	3.20	3.50	3.93	3.62	4.22

Equations used:

$$\textit{volume}\ [m^3] = (\textit{No. of days for retention}) \times (\textit{Organic loading rate}) \tag{A2}$$

$$H_x, D_x = \sqrt[3]{\frac{4 \times volume}{\pi}} \tag{A3}$$

Table A3: *Costing calculations for the piping and steel required to construct a floating drum digester*

Parameter	**Bathroom**						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
Length of piping needed [m]	106	85	200	190	306	285	391
Unit cost of piping [$/m]				$3			
Cost of piping [$]	$318	$255	$600	$573	$918	$855	$1,173
Amount of steel needed for drum 1 [m²]	7.42	4.85	8.23	9.85	12.43	10.55	14.37
Amount of steel needed for drum 2 [m²]	11.78	7.70	13.06	15.63	19.73	16.75	22.82
Amount of steel needed for drum 3 [m²]	15.44	10.08	17.11	20.48	25.85	21.95	29.90
Amount of steel needed for drum 4 [m²]	18.71	12.22	20.73	24.81	31.32	26.59	36.22
Amount of steel needed for drum 5 [m²]	21.71	14.18	24.05	28.79	36.34	30.85	42.03
Cost per unit steel [$/m²]				$200			
Cost for the drum 1 [$]	$1,485	$970	$1,645	$1,969	$2,486	$2,110	$2,875
Cost for the drum 2 [$]	$2,357	$1,539	$2,612	$3,126	$3,946	$3,350	$4,563
Cost for the drum 3 [$]	$3,088	$2,017	$3,422	$4,096	$5,171	$4,389	$5,980
Cost for the drum 4 [$]	$3,741	$2,443	$4,146	$4,962	$6,264	$5,317	$7,244
Cost for the drum 5 [$]	$4,341	$2,835	$4,811	$5,758	$7,269	$6,170	$8,406
Total cost 1 [$]	$1,803	$1,225	$2,245	$2,542	$3,404	$2,965	$4,048
Total cost 2 [$]	$2,675	$1,794	$3,212	$3,699	$4,864	$4,205	$5,736
Total cost 3 [$]	$3,406	$2,272	$4,022	$4,669	$6,089	$5,244	$7,153
Total cost 4 [$]	$4,059	$2,698	$4,746	$5,535	$7,182	$6,172	$8,417
Total cost 5 [$]	$4,659	$3,090	$5,411	$6,331	$8,187	$7,025	$9,579

Equations used:

$$\textit{Cost of piping}\ [\$] = (\textit{Length needed}) \times (\textit{Unit cost per length}) \tag{A4}$$

$$\textit{Steel needed for drum}\ [m^2] = 3\pi \times (\textit{diameter of digester})^2 \div 4;\ \textit{top assumed to be flat} \tag{A5}$$

$$\textit{Cost of steel drum}\ [\$] = (\textit{Steel needed for drum}) \times (\textit{Unit cost of steel}) \tag{A6}$$

$$\textit{Total cost}\ [\$] = (\textit{Cost of piping}) + (\textit{Cost of steel drum}) \tag{A7}$$

Table A4: *Comparison of the energy content of biogas versus firewood*

Fuel Type	**Energy Content (MJ)**	**Per unit measure**
Biogas	25	1 m^3
Wood	19	1 kg

Equations used:

$$\textit{Equivalent mass of firewood}\ [kg] = 25 \div 19 \times (\textit{Volume of biogas})\ [m^3] \tag{A8}$$

Table A5: *Calculations of the effectiveness of the biogas digester*: *gas volume, equivalent meals, and time saved*

Parameter	**Bathroom**						
	North	***Central***	***East***	***North & Central***	***North & East***	***Central & East***	***All***
Gas yield per day [m^3]	4.4	2.4	5.2	6.8	9.6	7.4	11.8
Estimate meals cooked with gas	14.7	8.0	17.3	22.7	32.0	24.7	39.3
Equivalent mass of firewood per day [kg]	5.8	3.2	6.8	8.9	12.6	9.7	15.5
Time saved (based on equivalent mass) [hour]	0.7	0.4	0.8	1.1	1.5	1.2	1.9

Equations used:

$$\textit{Gas yield per day}\ [m^3] = 0.02 \times (\textit{Daily mass of human waste})\ [kg] \tag{A9}$$

$$\textit{Estimated meals made with gas} = (\textit{Gas yield per day}) \div 0.03\ [m^3] \tag{A10}$$

$$\textit{Time saved}\ [hour] = (\textit{Equivalent mass of firewood}) \div 8.2\ [kg/hr] \tag{A11}$$