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

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Abstract: *Energy access for all is the seventh Sustainable Development Goal (SDG) put forth by the United Nations in 2015. This initiative has been taken on by many non-governmental organizations (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 analyzing the feasibility of biogas projects for some rural communities. The method we describe enables both evaluation of digester designs for specific settings and determination of the scale, cost, and effectiveness of a biogas plant. For example, in a cooking application, 1* m^3 *of biogas can replace 1.3 kg of firewood (and the associated approximately 10 minutes spent collecting firewood). Such technology evaluation is critical for helping communities and organizations determine whether this type of project is well-suited for their settings. All too often, development project concepts are funded prematurely, before the realization 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 condensed, simplified written resource that enables development practitioners, volunteers and communities in a rural setting to readily evaluate whether a biogas energy solution is appropriate and sustainable for their setting before investing valuable resources and time into 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 preparations. This dependence on firewood in schools both impacts the time students spend working rather than studying and contributes to deforestation (Global Alliance for Clean Cookstoves, 2016). To evaluate the feasibility of biogas as an alternative fuel, we developed a methodology to enable development practitioners to determine the most appropriate type of biogas plant for their setting and to gauge the impact of sizing on fuel costs and yields from such a plant. Our intent is for development practitioners to be able to utilize our approach to determine if this type of energy development is appropriate for their specific application and setting.

This article presents our method of feasibility analysis and its application to a case study for sizing and costing of a community-scale biogas plant. 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 sizing a plant for a specific population of users and beneficiaries. A case study is performed for Matema Beach High School (MBHS), a government school of approximately 1,000 students in southwestern Tanzania where Richardson (lead author) lived and worked as a Peace Corps volunteer for two years. The analysis aims to determine if biogas would be an effective alternative cooking fuel compared to the currently-used firewood fuel. The analysis focuses on biogas digester type selection, basic costing of construction, and evaluating 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 while working 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). By evaluating the cost and effectiveness of systems before construction and implementation, this method can inform system design that will effectively utilize local resources, and it can also promote planning for system lifetime and sustainability. Because 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 while 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), and the UN 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).

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. The six most common plant designs are reviewed here based on their construction, operation, and maintenance.

(a) (b) (c)

(d) (e) (f)

Figure 1: 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].

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

2.1 Fixed Dome

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 initial material costs are low, the most substantial costs attributed to paying skilled masons and sourcing heavy machinery. The fixed dome chamber's gas-tightness depends on the skill of masonry available; average masonry would not create a gas-tight dome, so additional sealants or plastic liners could be used to prevent leakages. However, the use of additional sealants and liners can also contribute to the primary safety concern for a fixed dome plant, namely, the possibility of dome explosion if gas build-up is too high without proper depressurization through releasing or burning excess gases (Kuria and Maringa, 2008).

This continuous-feed digester can be variably sized with volumes ranging between 6–20 m^3. It has a long operational lifespan of 12–20 years with a daily output of 0.2–0.5 m^3 of gas per m^3 digester volume $\left[\frac{m_{gas}^3}{m_{volume}^3}\right]$. This quantity, output compared to digester volume, could be interpreted as a form 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 utilized by experienced biogas technicians who are familiar with the operations (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 create continuous substrate motion 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 influent 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 constructed as a brick-lined pit supporting a cylindrical steel drum. This design has a comparatively high initial cost because of the steel and machining needed, though construction is relatively simple and can be performed by local masons and metal workers (Cheng *et al.*, 2014). However, the reduced costs of average masons (compared to the skilled masons required for fixed domes) would be balanced by the additional cost of metal laborers. Inside the drum, a steel bar framework disturbs and breaks apart the scum layer (which forms at the top of waste accumulated in the digester) when the drum is rotated to enhance gas production (Kuria and Maringa, 2008). As the drum can move vertically with changes in gas levels, the plant produces constant-pressure gas, which is advantageous for cooking (Werner, Stöhr and Hees, 1989). The drum height is a visual indicator of gas storage levels and helps with ease of understanding by the user. The digester is sized from 6–100 m^3 to produce daily 0.3–0.6 $\left[\frac{m_{gas}^3}{m_{volume}^3}\right]$, interpreted as a 30–60% gas production efficiency. Its lifespan ranges from 8-12 years, lower than the fixed dome because of 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 valued more 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, and maintenance would be more frequent with rusting (Polprasert, Nukulchai and Rajput, 1982).

2.3 Earth-pit plant

The earth-pit plant design requires minimal materials: cement for pit lining, metal netting and plaster walls to prevent seepage, and a masonry ring. In addition, an external gasholder (metal or plastic) is recommended. The low cost of installation (comparatively $\frac{1}{5}$ the cost of a floating drum plant) is balanced by the shorter lifespan of 2–5 years. The continuous feed digester can be sized between 4–500 m^3 to produce daily 0.1–0.5 $\left[\frac{m_{gas}^3}{m_{volume}^3}\right]$, interpreted as a 10–50% gas production efficiency. Maintenance is minimal, typically consisting of occasional plaster repairs. Also, the overall strength of the digester is low because it lacks structural supports; this design is reliable in stable soil but must be situated above the groundwater table to avoid groundwater contamination and dilution of the water-waste slurry. Increased pressure can be achieved by weighing down the gas holder. The plant does not impose large safety concerns as the structure is not as gas-tight as a fixed dome plant and therefore is not as prone to explosions (Werner, Stöhr and Hees, 1989).

2.4 Ferro-cement plant

Ferro-cement biogas plants are constructed using cement mortar with steel wire mesh layers (Council of Scientific & Industrial Research, 2007). This digester has a low material input, but high-quality cement is required (Polprasert, Nukulchai and Rajput, 1982). The process of constructing a plant is theoretically easy to perform in rural areas, but a standard method has not yet been adequately time-tested (Cheng *et al.*, 2014). Also, careful handling of the ferro-cement structure is necessary during transport and construction to prevent damages, so it is recommended mostly where ferro-cement experience is present (Council of Scientific & Industrial Research, 2007).

Continuous daily operation yields 0.3–0.6 $\left[\frac{m_{gas}^3}{m_{volume}^3}\right]$ (interpreted as a 30–60% gas production efficiency) during operation and digesters can be sized from 4–20 m^3. The lifetime of a ferro-cement plant ranges from 6–10 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 the plant can be enhanced using an extra storage tank to prevent leakages and continually allow for production. The gas holder 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, explosions have not been reported with this type of plant, so the safety concerns are low (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). The cost of the bag is generally low (between 20 to 200 USD) though importation taxes for developing countries can double the cost. Because 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 because the plastic prevents seepage into or out of the digester; with masonry, seepage would be more likely to occur which, in areas where the groundwater table is high, could result in both the water-waste slurry becoming diluted and the groundwater being locally contaminated by human waste (Cheng *et al.*, 2014). The bags are easy to install and do not require masonry expertise, but require adequate slurry to be added for the bag to provide sufficient pressure (Cheng *et al.*, 2014). Low gas output pressures have been reported, thus weights can be placed on bags to increase pressure. In addition, tight seals are difficult to produce where piping joins the bag, even if sealants are available, so gas leakages are common. However, if gas production is high and not being used or stored, the bags can explode (Kuria and Maringa, 2008).

The bag volume is 4–100 m^3, lifetime is typically 2–5 years, and daily output is 0.3–0.8 $\left[\frac{m_{gas}^3}{m_{volume}^3}\right]$ (Werner, Stöhr and Hees, 1989), interpreted as a 30–80% gas production efficiency. Simple maintenance (sealing) is required if the bag is damaged or sliced, but sediment accumulation is very difficult to remove. The bag's strength is low; the thin plastic used commercially to manufacture bags is prone to damage from falling objects, people and animals, and in the scope of this study, non-traditional bag materials were not considered. In addition, this design demands shelter from direct sunlight and is greatly impacted by changes in temperature, which in turn is dependent upon the material and its color, and the resulting rates of heat transfer. The recommended mean temperature is greater than 20°C, so operation is poor during cold nights or winter.

2.6 Composite material digester

Composite material digesters are prefabricated and commonly used commercially. Made of fiberglass, carbon fiber and polyester, they are mainly manufactured remotely and imported to remote and rural areas such as the Tanzanian setting we considered. Composite digesters have high initial investments but do not require local masonry skill. A typical composite digester costs approximately 3000 USD, which may be 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 operation guidelines can lead to significantly reduced working efficiency (Cheng *et al.*, 2014). A general lifetime of composite digesters cannot be cited because the lifetime varies too much based on manufacturer and materials used, however, this type of digester typically has the longest lifetime of all those reviewed.

Composites have a high resistance to corrosion and are strong and durable, consistently holding high gas pressures. However, to ensure proper operation, they require technical and operational follow-up after implementation, which is often lacking in remote and rural environments. If the composites are instead manufactured locally in inexperienced plants, there is a safety-risk that lowquality digesters could malfunction. They are also prone to sinking into soft ground materials, but are tightly sealed so water seepage is not a problem (Cheng *et al.*, 2014).

2.7 Ratings for design criteria

In order to select an appropriate biogas plant design for effective operation at MBHS, we use the technology review to evaluate each digester's strengths and weaknesses over ten criteria (developed based on Kuria's design factors (Kuria and Maringa, 2008)). These criteria were selected to gauge the digesters' construction and operation within a specific environment, in our case the tropical and rainy climate of MBHS where temperatures average 24.9 °C and average annual rainfall exceeds two meters (*Climate: Kyela*, 2018).

1. STRENGTH – Can the design withstand the gas pressure from the water-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 could the plant have on the local environment and people?

Each digester is ranked over the criteria for the specific application of MBHS on a scale of 1 – 10, 1 being lowest and 10 being 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 weigh criteria differently based on the importance of each design and operational aspect with respect to local environments.

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*
1. Strength	8	8	7	8	5	9
2. Cost	7	6	8	7	8	4
3. Availability of materials	9	9	9	8	6	4
4. Ease of construction	5	8	8	5	6	4
5. Ease of operation	7	9	8	8	7	7
6. Ease of Maintenance	5	7	7	6	5	7
7. Reliability	7	8	6	7	5	8
8. Gas tight	6	7	6	7	5	8
9. Safety	5	8	7	7	7	9
10. Environment	8	6	6	8	8	7
TOTALS	**67**	**76**	**72**	**71**	**62**	**67**

The scoring shows that the floating drum design is rated as the most effective for the school's setting. However, we recommend two design changes to further enhance the digester's site-specific feasibility. First, the digester should incorporate a water jacket so that the drum would rise and fall within the water instead of the slurry (see Fig. 2). The jacket both enhances hygiene by removing operator contact with the slurry and prevents the drum from becoming stuck and unable to rise or fall in the floating scum. Second, a roofing structure (not shown) should be constructed over the plant to prevent rain from both diluting the slurry and causing continual corrosion. These modifications impact the plant's ease of operation, maintenance, safety, and applicability in the local environment while only adding modest costs. Within the design criteria, this would allow for at least a three-point scoring increase, because the four criteria with increased ratings would only be countered by one criterion with a reduced rating.

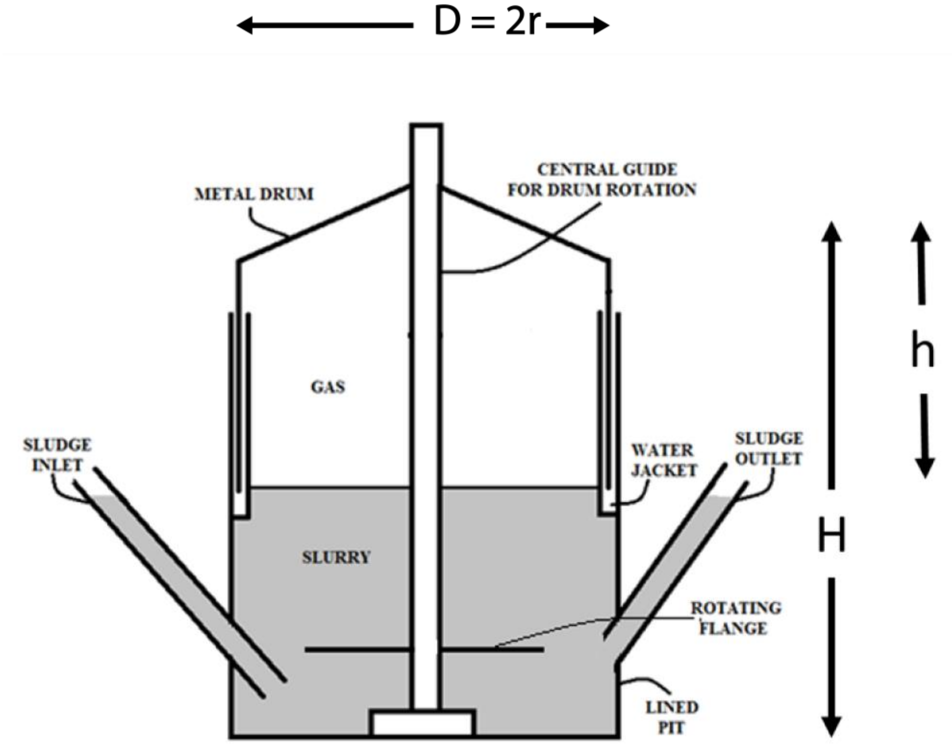

Figure 2: Schematic of the floating drum biogas digester (not to scale).

3 FIELD DESIGN METHODS

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 feces) (Fry, Merrill and Merrill, 1973). This estimate was used in modeling the boarding-students' (advanced-level) waste production, and the waste of day-students (ordinary-level) was estimated to be half of the daily average, based on the proportion of their day spent at school (from 6:30 am to 5:00 pm). These assumptions were limited because they did not reflect diet or environmental factors (and capturing local data on waste production was outside the scope of this research); they were used to simplify the model. The students were then assigned to the bathroom that they predominantly use to estimate the waste deposits daily into 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; a pump would require electricity (which is inconsistent in the village and costly when provided by a generator), maintenance (with both technical expertise and sanitary precautions) and be an additional system cost. This additional cost would not only require initial capital, but operational fuel costs are particularly high in this area because of a lack of local access to petrol. The proposed biogas plant location and bathroom locations are labeled on a campus map in Figure 3.

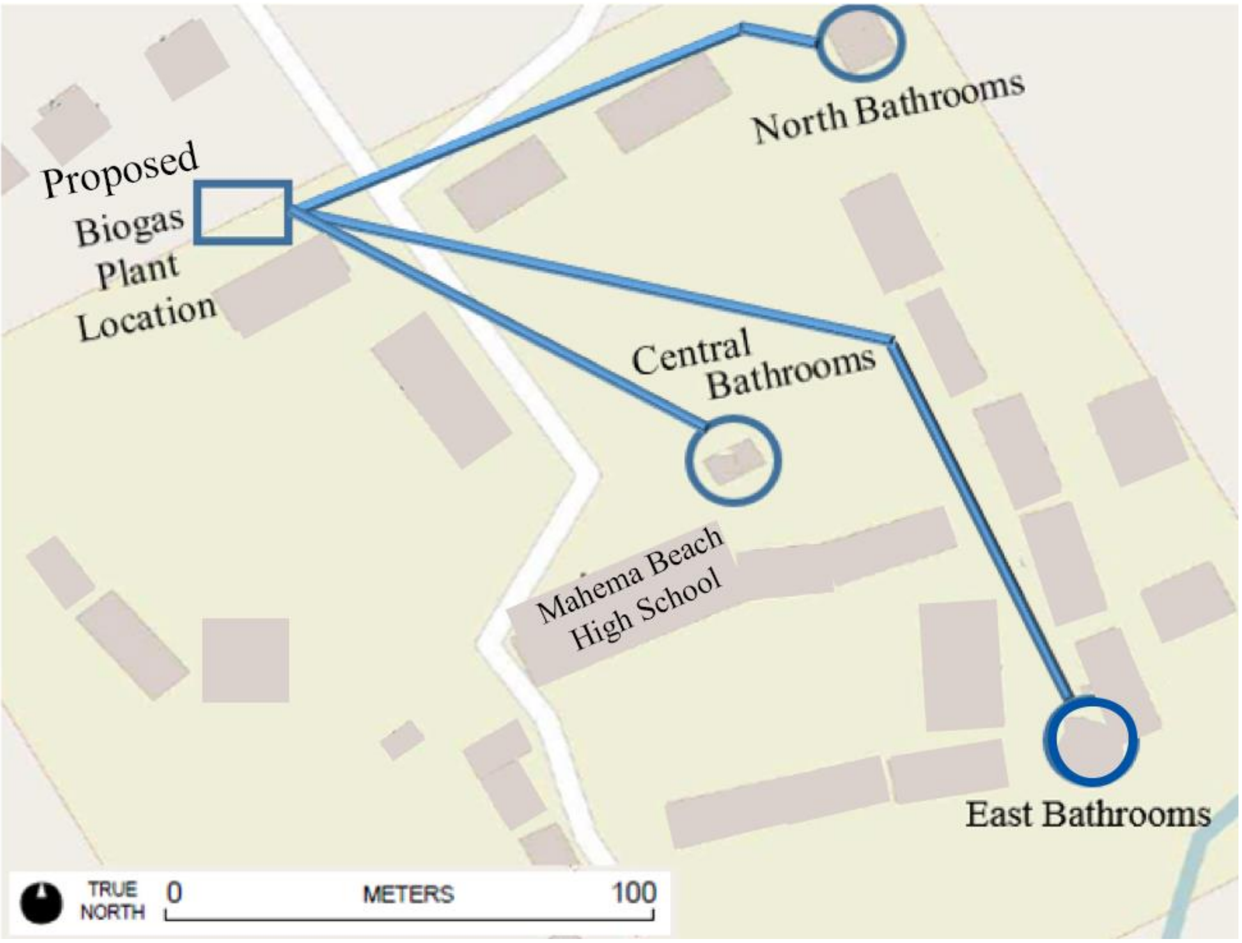

Figure 3: Bathroom and proposed biogas plant locations on MBHS's campus with piping routes. (This map was created using fieldpapers.org, an open-source tool to create atlases from Google Maps.)

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 in addition to all female students. To include multiple design sizes based on varied daily waste production, the bathrooms were considered independently, grouped in combinations, and grouped entirely together in each of the design calculations. The calculations made for MBHS biogas plant can be found organized into tables in the appendix of this paper.

4 DESIGN RESULTS

4.1 Sizing the digester

The digester volume is based on the amount of waste fed daily into the system and the chosen retention-time of waste in the plant. Retention-time is the period needed for feedstock to decompose (in this instance, human waste) (Wellinger, Murphy and Baxter, 2013). Recommendations for 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 range of 20 – 100 days is used. Combining the estimated production of 1.22 kg of human waste (feces and urine) per person per day, with the estimated ~1000 kg/m^3 density of human waste slurry (Onojo et al., 2013) allowed us to calculate the volumetric daily feed rate of waste (*v)* [m^3/day]. Given that the digester must accommodate this daily input of waste over the entire retention period, volume (V_d) [m^3] is a function of the daily feed rate (*v)* [m^3/day] and the retention time (*R*) [days] (Kuria and Maringa, 2008). The basic equations used in our analysis are presented here. Further details and calculations are found in the Appendix.

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

After the necessary volume is determined, the dimensions of the digester can be calculated. Based on the literature of floating drum designs, the diameter of the digester (*D*) [m] is assumed to equal its height (*H*) [m] (Kuria and Maringa, 2008), and volume approximated as the volume of the cylinder only. This shows volume as a function of one dimension (*D*) and the function can be rearranged to solve for diameter.

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

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

4.2 Estimating the cost

A limiting factor for project feasibility is one of the system costs, construction of the plant, which predominantly relates to the cost of steel (for the metal drum) and piping. Although maintenance would be a reoccurring system cost, as it would with all plant types, the construction cost was calculated instead to determine the initial, limiting investment that would be required to develop the biogas plant. The cost of steel is a direct function of the digester surface area and unit price of the material. Given the radius of a metal drum (*r=D/2)* and the assumption that the metal drum height *(h)* [m] is approximately one half of the total masonry digester height (*H*) [m], visualized in Figure 2, we can calculate the area of steel needed (drum surface area [m^2], with the simplifying assumption of a flat-topped drum for area calculations). Then a local cost per m^2 of steel is used to determine the drum's cost.

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

We located and measured the predicted piping routes to be as direct as possible while limiting unnecessary pipe bends, and to not interfere with any existing structures on campus (Figure 3). These distances are coupled with the local cost per meter of PVC pipe to determine the total piping cost.

4.3 Comparing estimated cost and plant outputs

Finally, we compared the two major cost components with the plant outputs to evaluate economic feasibility. The primary outputs considered are daily biogas yields, equivalent number of meals made with the gas yields, equivalent mass of firewood saved daily, and time saved because of a reduction in time 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 choose a value of 0.02 m^3 gas per kilogram human excreta (Oxfam, 2008). The biogas yields are then compared to equivalent meals prepared using Oxfam's biogas generator design research which states that 0.3 m^3 of biogas is required to cook one meal (Oxfam, 2011). To determine how the gas output as a fuel source can be equated to firewood for cooking, we compared the energy content of biogas to that of firewood (Werner, Stöhr and Hees, 1989).

Lastly, the time saved from firewood collection by replacing wood with biogas is calculated using research on wood collection time performed 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/hour. Overall the plant outputs were calculated for each of MBHS's bathroom waste-input combinations and can be found in the appendix.

5 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 recognize that education and training would be required should any biogas digester system be installed, but did prioritize 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 was employed, the digester would range in volume from 12–60 m^3 depending on which septic tanks were connected. The cost of the two major components would range from approximately 3,000–10,000 USD, which does not include continual operational or maintenance costs; operational costs would include personnel supervision and monitoring of the plant, while maintenance costs would include cleaning and repairs of the digester and drum, and slurry removal and disposal as necessary during these processes. The plant would yield 2–12 m^3 biogas daily. This volume of gas corresponds to approximately 8–40 meals cooked, 3–16 kg firewood saved, and 0.4–2 hours of firewood collection prevented per day. Given the largest design (with all septic tanks connected) the biogas produced would not be able to replace cooking with firewood completely and would instead serve as a supplementary fuel.

6 CULTURAL CONSIDERATIONS

Before beginning to develop a biogas project, it is very important to understand how the fuel will be perceived locally, particularly if considering using human excreta as feedstock. If this practice is new to a community, it is important to acknowledge that a simplified characterization 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 design of a biogas system, 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, and noted 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 for effective diffusion of technology (Lee, Trimi and Kim, 2013). Since Tanzania is considered a collectivistic society (Hofstede, 2015), positive subjective evaluations by peers, or in other words the opportunity to see others adopting and liking biodigesters, is necessary for effective adoption of such systems. 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 such as this concept to successfully move forward, it is also critical to provide appropriate communication and education centered on how the plant operates hygienically and how biogas is a clean cooking fuel.

7 CONCLUSION

The digester design process shows that the plant at MBHS would have a very high initial cost of construction, even without incorporating the costs of additional materials, labor, 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 gas 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 rationalize the initial investments needed for the project, especially when other projects (such as dormitory and classroom construction) have already been prioritized in the school’s expansion budget. The prohibitive costs are partly associated with the specific floating drum design, but this type of digester was prioritized 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. Because 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 increase the health risk on campus, for example, by contaminating water sources.

Although the use of a biogas plant 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 plant 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 at the level of detail of the cost estimating procedure for a floating-drum digester in Kuria and Maringa (2008) but with the additional cost of training factored in. Such level of detail is beyond our current scope. In addition, the barriers to cultural acceptance of biogas plants 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.

8 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.

9 REFERENCES

2015 International Plumbing Code (2015) *International Code Council*. Available at: https://codes.iccsafe.org/public/document/code/550/9794943 (Accessed: 2 May 2018).

Cheng, S. *et al.* (2014) ‘Development and application of prefabricated biogas digesters in developing countries,’ *Renewable and Sustainable Energy Reviews*. Elsevier, 34, pp. 387–400. doi: 10.1016/j.rser.2014.03.035.

Climate: Kyela (2018) *Climate Data*. Available at: https://en.climate-data.org/location/26733/ (Accessed: 15 May 2018).

Council of Scientific & Industrial Research (2007) *Ferrocement Applications*. Ghaziabad.

Fry, L. J., Merrill, R. and Merrill, Y. (1973) ‘Methane Digesters For Fuel Gas and Fertilizer with Complete Instructions for Two Working Models,’ *The New Alchemy Institute*, (3), pp. 1–58. Available at: http://large.stanford.edu/courses/2010/ph240/cook2/docs/methane_digesters.pdf.

Garmin Ltd. (2016) *Garmin GPSMAP 64 Owner’s Manual*. Olathe. Available at: http://static.garmin.com/pumac/GPSMAP64_OM_EN.pdf.

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

Hofstede, G. (2015). *What about Tanzania?* The Hofstede Centre. Retrieved from http://geert-hofstede.com/tanzania.html.

Khatavkar, A. and Matthews, S. (2013) *Technical Brief: BIO-LATRINES*. Nairobi. Available at: https://www.pseau.org/outils/ouvrages/practical_action_bio_latrines_2013.pdf.

Kuria, J. and 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*, 3(1), pp. 9–40.

Lee, S. G., Trimi, S. and Kim, C. (2013) ‘The impact of cultural differences on technology adoption,’*Journal of World Business*. Elsevier Inc., 48(1), pp. 20–29. doi: 10.1016/j.jwb.2012.06.003.

Mittal, S., Ahlgren, E. O. and Shukla, P. R. (2018) ‘Barriers to biogas dissemination in India: A review,’ *Energy Policy*, 112(January 2017), pp. 361–370. doi: 10.1016/j.enpol.2017.10.027.

Mshandete, A. M. and Parawira, W. (2009) ‘Biogas Technology Research in Selected Sub-Saharan African Countries – A Review,’ *African Journal of Biotechnology*, 8(2), pp. 116–125. doi: 10.1080/07388550902823674.

Onojo, O.J. et al. (2013) ‘Estimation of the Electric Power Potential of Human Waste Using Students Hostel Soak-Away Pits,’*American Journal of Engineering Research*, 2(9), pp. 198–203.

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

Oxfam (2011) *Design, construction and maintenance of a biogas generator*. Oxford.

Peace Corps (2018) *Resource Library, PCLive*. Available at: https://pclive.peacecorps.gov/pclive/index.php/library (Accessed: 21 May 2018).

Polprasert, C., Nukulchai, W. K. and Rajput, V. S. (1982) ‘A Ferrocement Digester : Biogas and Biomass Production,’ *Journal of Ferrocement*, 12(1), pp. 25–34.

Preston, K. M. (2012) *Fuelwood Collection and Consumption: A Case Study in Lupeta, Tanzania*. Michigan Technological University. Available at: https://www.mtu.edu/peacecorps/programs/forestry/pdfs/katie-preston-thesis-final.pdf.

Wellinger, A., Murphy, J. and Baxter, D. (2013) *The Biogas Handbook*. 1st Edition. Oxford: Woodhead Publishing.

Werner, U., Stöhr, U. and Hees, N. (1989) *Biogas plants in animal husbandry*. Deutsches Zentrum für Entwicklungstechnologien.

Zhu, J. (2015) *Sustainable Development Knowledge Platform, United Nations Department of Public Information*. Available at: https://sustainabledevelopment.un.org/?menu=1300 (Accessed: 30 April 2018).

10 APPENDIX

Table A1: Calculations of the daily feed rate into the biogas digester.

	North Bath-rooms	Central Bath-rooms	East Bath-rooms	North & Central Bathrooms	North & East Bathrooms	Central & East Bathrooms	All Bath-rooms
# Advanced-Level students	180	10	70	190	250	80	260
# Ordinary-Level students	0	170	280	170	280	450	450
(A-level student waste)/day [m^3]	0.00122						
(O-level student waste)/day) [m^3]	0.00061						
Daily feed 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	340	480	370	590

Equations Used:

*Daily feed rate [m^3/day]= (#A-level students) * (daily waste per A-level student) + (#O-level students) * (daily waste per O-Level student)* (A1)

Note: daily waste per person estimated as 1.22 kg (Fry, Merrill and Merrill, 1973); density of human slurry estimated as 1000 kg/m^3 (Onojo et al., 2013)

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

	North Bath-rooms	Central Bath-rooms	East Bath-rooms	North & Central Bathrooms	North & East Bathrooms	Central & East Bathrooms	All Bath-rooms

$V_{d,1}$ $at\ R = 20\ days$ $[m^3]$	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:

$$volume\ [m^3] = (\#days\ for\ retention) * (daily\ feed\ rate) \tag{A2}$$

$$H, D\ [m] = \sqrt[3]{\frac{4*volume}{\pi}} \tag{A3}$$

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

	North Bath-rooms	Central Bath-rooms	East Bath-rooms	North & Central Bathrooms	North & East Bathrooms	Central & East Bathrooms	All Bath-rooms
length of piping needed [m]	106	85	200	191	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 $[m^2]$	7.42	4.85	8.23	9.85	12.43	10.55	14.37
amount of steel needed for drum 2 $[m^2]$	11.78	7.70	13.06	15.63	19.73	16.75	22.82
amount of steel needed for drum 3 $[m^2]$	15.44	10.08	17.11	20.48	25.85	21.95	29.90
amount of steel needed for drum 4 $[m^2]$	18.71	12.22	20.73	24.81	31.32	26.59	36.22
amount of steel needed for drum 5 $[m^2]$	21.71	14.18	24.05	28.79	36.34	30.85	42.03

cost per unit steel [\$/m^2]	\$ 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:

$$(cost\ of\ piping)[\$] = (length\ needed) * (unit\ cost\ per\ length) \tag{A4}$$

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

$$cost\ of\ steel\ drum\ [\$] = (steel\ needed\ for\ drum) * (unit\ cost\ of\ steel) \tag{A6}$$

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

Table A4: Comparison of the energy content of biogas vs. firewood.

Fuel Type:	Energy Content	Per unit measure
Biogas	25 [MJ]	1 [m^3]
Wood	19 [MJ]	1 [kg]

Equations Used:

$$(equivalent\ mass\ of\ firewood)[kg] = \left(\frac{25}{19}\right) * (volume\ of\ biogas)[m^3] \tag{A8}$$

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

	North Bath-rooms	Central Bath-rooms	East Bath-rooms	North & Central Bathrooms	North & East Bathrooms	Central & East Bathrooms	All Bath-rooms
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:

$$gas\ yield\ per\ day\ [m^3] = 0.02 * (daily\ mass\ of\ human\ waste\ [kg]) \qquad \text{(A9)}$$

$$estimated\ meals\ made\ with\ gas = \frac{gas\ yield\ per\ day}{0.03\ [m^3]} \qquad \text{(A10)}$$

$$Time\ saved\ [hour] = \frac{equivalent\ mass\ of\ firewood}{8.2\ [\frac{kg}{hr}]} \qquad \text{(A11)}$$