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Biogas Technology on Uzi Island, Zanzibar: A Feasibility Study

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Abstract

With realization of the finite quantity of fossil fuels and improved study on the effects of global climate change there has been an increasing demand for energy production from renewable, sustainable sources in developed and developing nations alike. The population of Tanzania relies overwhelmingly on biomass as a source of primary energy, with such impacts as deforestation and negative health effects. Biogas generation is a renewable energy technology that utilizes organic waste sources to produce a methane-rich gas suitable for cooking and lighting with the potential to replace current unsustainable energy sources and provide several environmental and socioeconomic benefits. A biogas feasibility study was conducted in the village of Uzi, Zanzibar through local surveys, a waste generation audit, and creation of a pilot biogas system. Currently, biogas technology is not feasible in Uzi due to economic and realistic barriers. Methods of financial aid such as government subsidy, microfinance, and a carbon credit system need to be explored in order to realize the potential of biogas technology in Uzi.

1. Introduction

1.1 **Rationale**

The global production and consumption of energy is one of the most important and pertinent issues currently facing the international community. With realization of the finite quantity of fossil fuels and improved study on the effects of global climate change due to greenhouse gas emissions, there has been an increasing demand for energy production from renewable, sustainable sources. This fact is no less true for developing nations as it is for their developed counterparts, despite a drastic imbalance in per capita energy consumption rates. Biogas generation is a renewable energy technology that utilizes organic waste sources to produce a methane-rich gas suitable for cooking and lighting purposes (Lansing, et al., 2008). This technology has the potential to replace current unsustainable energy sources and provide several environmental, social, and economic benefits.

1.2 Energy Use in Tanzania

In Tanzania, the use of biomass accounts for 92.1% of the total energy supply, with the remaining portion supplied by fossil fuels, a small amount of hydroelectricity, and less than one percent of renewable sources such as solar photovoltaic, wind, and biogas (Lohri, 2009). Nationwide there is an electrification rate of 10%, resulting in electricity access for 39% of the urban population and only 2% of the rural population. Approximately 79% of total energy consumption in Tanzania is on the domestic level (Lohri, 2009). Table 1 gives specific information on household energy source and consumption statistics.

Table 1. Tanzania Household (HH) Energy Statistics (Mwakaje, 2008)

Type of energy used in HH sector	*% of total HH energy consumption*	*Purpose of energy used*
Biomass fuels (charcoal&firewood)	97.7	Cooking, heating, lighting
Petroleum fuels	2.0	Kerosene for lighting and cooking
Electricity	0.3	Lighting, powering the radio and in a few cases cooking
Solar, biogas, wind	0	Lighting, cooking

A 2007 Human Development Report found that for cooking purposes 60% of the total population uses fuel wood, 35% uses charcoal, and the remaining 5% uses electricity, liquefied petroleum gas or other sources. However, in rural areas the use of fuel wood is significantly higher, accounting for about 87% of energy used for cooking (Watkins, 2007). The typical rural household uses a three-stone setup for cooking (three large stones of equal size placed together with the wood and fire inside and cooking pot on top), which only has an efficiency of 10-15%. Furthermore, it is estimated that the average low-income Tanzanian family spends roughly 35% of total income on energy costs (Otte, 2009).

1.3 Environmental Implications

Although biomass is technically a renewable energy source, the current rates of production and consumption in Tanzania are highly unsustainable. Domestic dependence on fuel wood and charcoal result in an estimated yearly per capita consumption of $1m^3$ of forest area, or an average of 7kg of fuel wood daily per rural household (Schmitz, 2007). Tanzania's total forest area was estimated to be 352,600 km^2 in 2005, or about 40% of the total land area; in the fifteen years between 1990 and 2005 an estimated 62,800 km^2 of forest area was harvested, resulting in an average annual deforestation rate of 1% (Lohri, 2009). Similarly, the United Nations Development Program reports an annual biomass consumption of 36 million m^3, leading to 91,000 hectares of forest area lost each year (Watkins, 2007). Although the harvest of biomass for charcoal and wood fuel is not the sole cause of deforestation, it plays a significant role in the continuing loss of forest cover. Charcoal production is particularly damaging because it takes about 6kg of wood to make 1kg of charcoal (Lohri, 2009).

Deforestation has widespread effects in terms of environmental degradation; these include increased rates of soil erosion, decline in quality and quantity of soil base, loss of pollutant buffering capacity, decreased nutrient cycling, increased desertification, loss of biodiversity, and inconsistent weather patterns (Murphy, 2001; Neto et al., 2010). Combustion of charcoal and fuel wood results in greenhouse gas and solid particulate matter emissions that perpetuate global climate change and contribute to ambient air pollution (Neto et al., 2010).

1.4 Social Implications

The social impacts of fuel wood and charcoal use take two main forms: negative health effects due to constant exposure to toxic fumes, and the time and labor intensive duty of fuel wood collection. These effects fall almost entirely on women and children, as they are the ones assigned cooking and household duties in the local culture. Most rural families cook indoors or in semi-ventilated areas, which creates significant amounts of indoor air pollution. This exposure to biomass fumes has many documented health effects including acute respiratory infections, chronic obstructive pulmonary disease, asthma, tuberculosis, cancer, cataracts, blindness, and low birth weight (Otte, 2009; Neto et al., 2010). The United Nations Development Program estimates that more than 500,000 people in Sub-Saharan Africa die annually from exposure to indoor air pollution from biomass combustion (Otte, 2009).

For families that cannot afford or opt not to purchase biomass for cooking, fuel wood collection is a daily obligation. The average daily collection load in Sub-Saharan Africa is 20kg, but amounts as high as 38kg have been recorded (WEO, 2006). This labor has potential negative health effects but the major issue is with time consumption, as many women and children spend multiple hours each day collecting fuel wood. A study in the Rungwe district of Tanzania found that women spent an average of 3-4 hours per day collecting firewood (Mwakaje, 2008). For children this has a negative impact on education through decreased school attendance. The main effect on women is the loss of time that could be used for income-generating activities such as seaweed cultivation, tailoring and food preparation. The end result is a larger burden of labor and decreased opportunity for economic empowerment of women (Otte, 2009).

1.5 Economic Implications

Decreases in the fertility of agricultural land due to the effects of erosion from deforestation are estimated to result in an annual reduction of Tanzania's gross national product by 0.5-1.5% (Lohri, 2009). More efficient energy technologies provide better services at lower long-term costs, promoting economic development by enhancing the productivity of labor and capital (WEO, 2006).

1.6 Potential of Biogas Technology

Biogas generation takes advantage of anaerobic digestion to degrade organic waste into a combustible gas and nutrient-rich effluent. This biogas can be combusted in simple single-burner stoves for cooking purposes and also be used to power special biogas-modified lighting units. Because the technology is relatively simple, inexpensive and only requires freely available organic waste as an input, it has the potential to provide sustainable, renewable energy to alleviate the dependence on biomass fuel sources in developing nations. Furthermore, biogas technology is well-suited to the tropical/sub-tropical climate of Tanzania and has the capacity to provide energy to rural villages where electricity and other energy sources are scarce, with the added benefit of production of liquid effluent suitable for agricultural fertilization. With widespread dispersal and proper management, biogas technology has the potential to greatly reduce the aforementioned environmental, social, and economic impacts of biomass consumption.

1.7 Study Objectives

This study was conceived with two main objectives in mind. The first objective was to conduct a feasibility study concerning domestic-scale biogas generation in the rural village of Uzi, Zanzibar. Information was to be obtained through formal and informal surveys on energy use, cooking habits and attitude towards biogas technology, as well as a study of average household organic waste production. The second objective was to construct, commission, and monitor a domestic biogas digester at a small research center in Uzi as a pilot system for local research, education, and outreach.

2. Study Area

2.1 Zanzibar

Zanzibar is an archipelago in the Western Indian Ocean consisting of two main islands, Uguja and Pemba, located approximately 30km off the coast of mainland Tanzania. Zanzibar is a semi-autonomous nation and forms one half of the United Republic of Tanzania. Unguja is about 50 miles long and 24 miles wide, located between 5-6° South and 39-40º East (Fales & O'Hare, 2010).

2.2 Uzi Island

Uzi is an island located at the coordinates 6°18′- 6°24′ S and 39°23′-39°26′ E, connected to the southwest of Unguja by a narrow isthmus of tidal mangrove swamp. Uzi has an area of 15.6km² and a population of about 3,000 (Nowak et al, 2009).

The Uzi Island Research Center was started in the early 1990's by Aliy Abdurahim Aliy and Iss-Haka Hussein Abdullah as a place for local environmental research and conservation efforts. The center consists of one building with three rooms for hosting visitors. Several foreign students and volunteers come to conduct research and help with local environmentally and socially themed projects annually, mostly through connection with the German organization World Unite! (Aliy Abdurahim Aliy, personal communication, 5/2/2011).

3. Biogas

3.1 Background

Biogas generation technology consists of the biochemical degradation of complex organic material into simple organics and dissolved nutrients, with a methane-rich gas and nutrient-rich liquid as byproducts. A basic biogas system consists of a digestion tank with pipes for waste input and effluent 'slurry' output, and a gas collection reservoir (Amigun et al, 2007). Waste can be loaded on a daily basis, as in the method of continuous digestion, or loaded in larger amounts at larger time intervals in a process called batch digestion (Residua, date unknown). The technology can be applied on varying scales, from domestic to industrial, and is able to process such varied substrates as food waste, animal waste, agricultural residues, sewage sludge, industrial waste, and slaughterhouse waste (Murto et al., 2004). It is also possible to mix multiple waste types together in a process called co-digestion. Theoretically, any material that contains carbohydrates, fats, proteins, cellulose, or hemicellulose as main components can be processed through anaerobic digestion. However, the main polymer of wood, lignin, is resistant to anaerobic digestion and only produces minimal amounts of biogas so woody substrates should be avoided (Bruni et al., 2010). Although a wide range of materials can be processed through anaerobic digestion each substrate has varying methane output values that depend further on external factors such as temperature, pH, and particle size.

3.2 Technical Information

The driving principle of biogas generation is the natural process of anaerobic digestion. Anaerobic digestion, or biomethanization, consists of four stages as described below and shown in Figure 1.

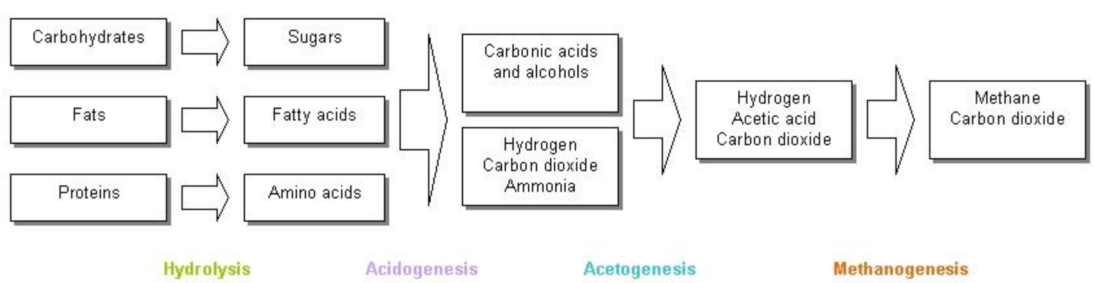
Hydrolysis: Insoluble organic polymers such as proteins, fats, carbohydrates, and cellulose are broken down by enzymes produced by hydrolytic bacteria, leaving simple sugars, amino acids, and fatty acids remaining (Slater, 2007).

Acidogenesis: Acidogenic bacteria further degrade the sugars, amino acids, and fatty acids, producing volatile fatty acids, carbon dioxide, hydrogen sulfide, and ammonia (Slater, 2007).

Acetogenesis: Simple molecules and volatile fatty acids are degraded by acetogenic bacteria, producing acetic acid, carbon dioxide and hydrogen (Slater, 2007; Lohri, 2009).

Methanogenesis: Methanogenic bacteria convert acetic acid and hydrogen into methane and carbon dioxide. These bacteria have a slower growth rate than those in the previous stages, so their metabolism level is rate-limiting in the anaerobic digestion process (Lohri, 2009).

Figure 1: The 4 stages of anaerobic digestion



Anaerobic digestion occurs in three temperature ranges: psychrophilic (< 30ºC), mesophilic (30-40 ºC) and thermophilic (50-60 ºC), with the highest rates of biogas production occurring in the mesophilic and thermophilic ranges (Yadvika et al., 2004). The pH of the digester is mainly affected by the production of carbon dioxide and volatile fatty acids; digestion occurs at a pH range of 5.5-8.5, however the optimal range is between 6.8 and 7.2 (Yadvika et al., 2004; Slater, 2007).

Biogas composition consists of methane (45-80%), carbon dioxide (20-40%) and small amounts of hydrogen sulfide, water vapor, ammonia, nitrogen and hydrogen, with composition varying with substrate characteristics and digester conditions (Jingura, 2009). Table 2 shows the typical biogas composition of the organic fraction of solid waste, as measured by Mata-Alvarez. Generally, biogas has an energy content of 6.0-6.5 kWh/m³ or 18.6-26.04 MJ/ m³, and one cubic meter has the approximate fuel equivalent of 0.6-0.65 liters of oil (Lohri, 2009; Amigun et al., 2007). Biogas with a methane content of 45% or higher is combustible (Lohri, 2009).

Table 2. Typical components of biogas from the organic fraction of municipal solid waste (Lohri, 2009)

Components	Concentration (by volume)
Methane (CH_4)	55-60%
Carbon dioxide (CO_2)	35-40%
Water	2% (20 °C) – 7% (40 °C)
Hydrogen Sulphide (H_2S)	20-20'000ppm (2%)
Ammonia (NH_3)	0-0.05%
Nitrogen (N_2)	0-2%
Oxygen (O_2)	0-2%
Hydrogen (H_2)	0-1%

3.3 Uses

There is a wide range of primary and secondary uses for biogas system products. Biogas uses include cooking, lighting, ambient air and water heating, conversion into electricity in a generator, combined heat and power (CHP) generation, refinement into natural gas and vehicle fuel, and food and fruit preservation. Biogas slurry uses include organic soil basal and top dressing, foliar liquid fertilizer, feedstock for fish, pig and earthworm farming, biopesticide application, and as a culture solution for edible mushroom cultivation and soilless cultivation (Chang et al., 2011). However, the majority of these uses require some form of further processing and energy input, which is typically not feasible on a domestic scale. For a rural, household-size biogas generation system the main uses of biogas are for direct cooking and lighting in biogas-modified appliances, while digester slurry can be used as a nutrient-rich fertilizer for enhancement of crop growth.

3.4 Benefits

The foremost benefit of a domestic biogas generation system in rural developing areas is the production of a renewable and sustainable energy source, along with the resulting environmental and socioeconomic improvements of biomass dependence alleviation. After the initial investment is recuperated there is the potential for partial or complete elimination of fuel costs, as well as a potential source of income generation through effluent slurry sale as fertilizer.

A benefit unique to biogas generation as a renewable energy technology is the potential for improved solid waste management and domestic hygiene conditions. In most rural areas in Tanzania there is no form of municipal solid waste management and household waste is generally either thrown outside of homes, placed in unplanned communal dumpsites, or burned in small piles. When organic waste is left to rot it produces emissions such as methane that contribute to global climate change, while also attracting insect pests and disease vectors. When waste is burned harmful emissions and solid particulates are released, affecting local air quality and producing greenhouse gases. If this organic waste is used as input for a biogas system energy can be produced while simultaneously improving solid waste management, essentially converting trash into fuel. Similarly, when animal excrement, typically cow dung, is used as a substrate it also serves to lower methane emissions and helps to reduce eutrophication of local water sources through reduced nutrient leaching (Walekhwa et al., 2009).

Household hygiene and sanitation can be improved by connecting a toilet to a domestic biogas system and taking advantage of the fact that human feces is a suitable substrate for anaerobic digestion. This human waste can then be co-digested with other substrates such as food and animal waste; a popular system in use in southern China successfully combines a household toilet with waste from a pigpen in a biogas digester (Chen et al., 2010). This type of human waste system has the potential to improve domestic hygiene and reduce the occurrence of infectious diseases while also protecting local ground and surface waters from human fecal contamination from pit latrines (Chen et al, 2010).

3.5 Limitations

One of the most important limitations of a domestic biogas system is the need for a suitable climate for anaerobic digestion, around 30ºC. Although it is possible to create a self-heated system or use a solar greenhouse to raise ambient temperatures (Kumar et al., 2008), this is largely unfeasible for rural areas in developing nations. Therefore, the utilization of domestic biogas systems is typically limited to tropical and sub-tropical regions.

To maintain optimum performance and achieve maximum biogas yield certain system process parameters such as pH, carbon to nitrogen ratio and organic loading rate must be continually monitored. The scientific equipment and knowledge to achieve this is rarely available in developing rural areas, so it is likely that most biogas systems will operate at less than optimum performance levels.

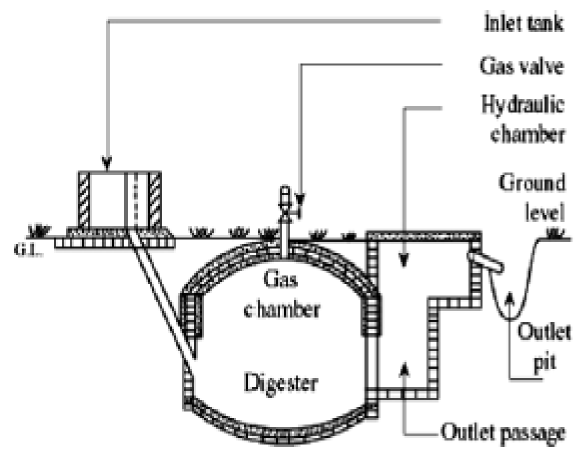
3.6 Types of small scale systems

There are four main designs of domestic biogas systems currently in use in Tanzania.

Fixed-Dome System

The fixed-dome system or "Chinese model" is constructed partially underground and consists of a concrete dome-shaped digestion chamber, waste mixing chamber, inlet pipe, slurry overflow chamber, and slurry output pipe (See Fig. 2) (SEDC, 2011). The fixed-dome system can be constructed in various sizes, from 3 to 50 m³. This system has a long life expectancy and the potential for large waste capacity, but cracks and leaks are an issue. The initial investment is high and requires the work of skilled masons. Because of the large waste input requirement and high initial investment, this system is generally not feasible for households without livestock.

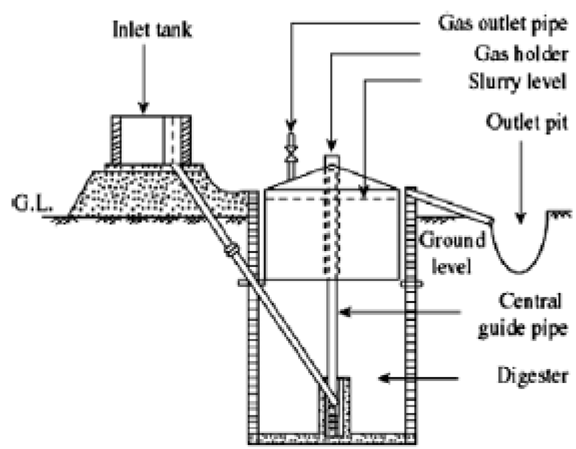
Figure 2: Fixed-dome system (Amigun et al, 2007)



Floating-Drum System

The floating-drum system or "Indian model" is constructed partially underground and consists of a concrete digestion chamber with a gas reservoir that rises along a central guide pipe with gas production (Amigun et al, 2007) (Fig.3). The benefit of this system over the fixed-dome model is that the floating-drum reservoir provides a visual reference of current gas levels. However, similar issues with high cost, requirement of skilled labor, and maintenance are present.

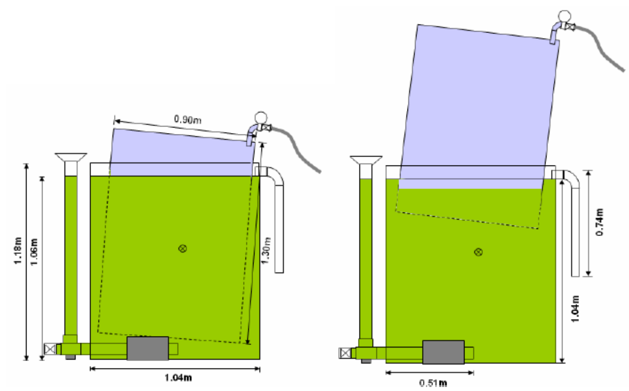
Figure 3: Floating-drum system (Amigun, 2007)



Floating-Tank System

The floating-tank digester system consists of a high density polyethylene (HDPE) water tank as a digestion chamber, with a smaller tank inverted and placed inside the larger tank that acts as a reservoir chamber, rising with gas production (See Fig. 4). Standard plumbing tubes connected to the digestion tank act as input and overflow pipes. This system is relatively inexpensive and can be built with locally available materials, but the design leads to gas recovery inefficiency (Lohri, 2009).

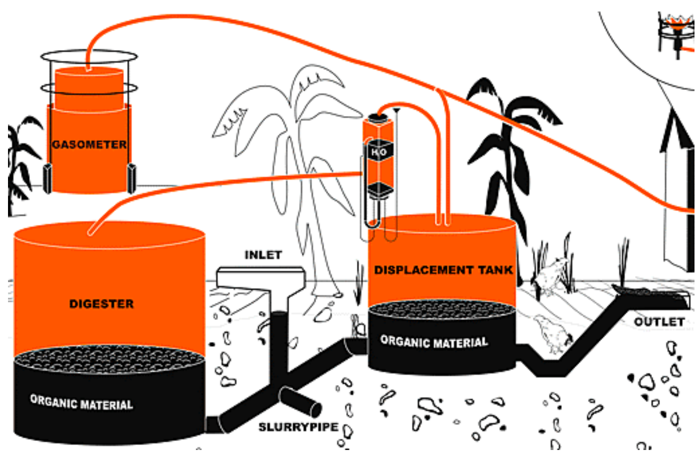
Figure 4: Floating-tank system (Lohri, 2009)



Supergas System

The Supergas system was designed by the Danish Organization DANTAN and consists of a HDPE digester, slurry displacement tank and gas reservoir connected to a hydraulic valve (See Figure 5). The system operates under high pressure with the goal of achieving more in-tank mixing and a resulting higher rate of gas production (Kirknaes, 2009). Benefits include a high rate of gas production and recovery, but there is a high cost of construction and design complexities make maintenance difficult and expensive.

Figure 5: Supergas system (Kirknaes, 2009)



3.7 History of Biogas in Tanzania

This section is meant only to be a brief introduction to biogas technology in Tanzania, as a complete review of the topic is beyond the scope of this study; for more comprehensive reviews see Mwakaje (2007) and Schmitz (2007).

Biogas generation technology was first introduced into Tanzania in 1975 when the Small Industries Development Organization (SIDO) built 120 digesters of the floating-drum design in the Arusha region. In 1982 the parastatal organization Center for Agricultural Mechanization and Rural Technology (CAMARTEC) was formed and partnered with the German Agency for Technical Cooperation (GTZ) to form the Biogas Extension Service, with the goal of increasing biogas technology research and dissemination in the country. The project adapted the Chinese fixed-dome design to local conditions in $12m^3$ $16m^3$, $30m^3$, and $50m^3$ sizes. Between 1983 and 2005 CAMARTEC built 707 of these digesters, mainly in the Arusha region. Other organizations involved in biogas technology promotion and research include the Tanzanian Traditional Energy and Development Organization (TaTEDO), Evangelical Lutheran Church in Tanzania (ELCT), Tanzania Commission for Science and Technology (COSTECH), and the government Ministry of Energy and Minerals. (Lohri, 2009; Mwakaje, 2007; Schmitz, 2007).

3.8 Current Status of Biogas in Tanzania

The major development in biogas technology and dissemination in Tanzania in recent years has been the creation of the Tanzania Domestic Biogas Program (TDBP). The program was formed in 2008 and is a joint effort between the Netherlands Development Organization (SNV) and CAMARTEC, along with other governmental and non-governmental organizations (SNV, 2008). One of the major program goals is to install 12,000 biogas systems of the CAMARTEC modified fixed-dome model, reaching 72,000 people (SNV, 2008). To date 1,368 of these systems have been built throughout Tanzania (TDBP, 2011).

A literature review concluded that the only existing biogas systems currently in use in Zanzibar were constructed by the Danish organization DANTAN in partnership with the local non-governmental organization Zanzibar Livestock Welfare and Development Organization (ZALWEDA) from 2006-2008. This specially designed "Supergas" system is described in section 3.6. Six systems have been built in the following locations: Chukani, Jumbi, Kitope, Mpapa, Tunguu, and Chumba Viamboni (Salim Bashuaib, personal communication, 3/30/11).

3.9 ARTI-TZ

The Appropriate Rural Technology Institute-Tanzania (ARTI-TZ) is a non-profit organization started in 2007 with the goal of disseminating renewable energy technologies in Tanzania and promoting environmental and socio-economic awareness. In regard to biogas, ARTI-TZ has its own design of a floating-tank biogas digester that is sold in varying sizes. The biogas system used for this project was modeled after one of these systems with the support of ARTI staff.

4. Methods

4.1 Village Survey

The first component of the feasibility study conducted was a formal survey of local people in the village of Uzi, Zanzibar. The aim of the survey was to assess fuel wood and charcoal usage and expenditures, cooking habits, and attitudes toward biogas technology (See Appendix 1 for the complete survey). The survey was conducted orally in Swahili by the researcher with the help of a translator on April 10th, 2011. Thirty women were surveyed; only women were chosen for the survey because they are in charge of cooking and fuel collection duties in the local culture.

4.2 Household Food Waste Audit

The goal of this component of the feasibility study was to measure the daily production of organic kitchen waste produced on a daily basis in Uzi households. Five houses were chosen for daily waste collection over a period of one week, from April 22nd to April 28th, 2011. The houses were not randomly chosen; houses were identified with the help of a local villager and the first five households willing to participate in the audit were selected, without regard of any further household information.

4.3 Pilot Biogas System

4.3.1 Construction

The construction of the pilot biogas system was based on the ARTI-TZ design of a floating-tank digestion system (See Figure 4). The digestion chamber consisted of a 1500L SimTank high-density polyethylene water tank and the gas collection reservoir was a similar 1000L SimTank tank. The tops of the water tanks were removed with a jigsaw, leaving the insides exposed. An input pipe was constructed with 3-inch PVC piping and a 3-inch plastic elbow joint, connected near the bottom of the 1500L tank. An effluent pipe was constructed using 2-inch PVC piping and a 2-inch elbow joint placed 1.28m high along the 1500L digestion tank. A 2-inch valve cap was placed near the bottom of the digestion tank as an emergency output or draining valve. The total cost of construction was 532,000 TZS. The system was constructed on April 7th, 2011.

4.3.2 Commission

The biogas system was started with 100L of slurry from an existing local cow dung-based biogas digester. This was combined with 120L of a cow dung and water mixture, mixed in equal parts. The cow dung was collected around the village of Uzi and ranged from fresh to a few days old. This 220L slurry, cow dung and water mixture was meant to serve as a bacteria inoculum to expedite the anaerobic digestion process. The remaining digester volume was filled with tap water over a period of two days.

4.3.3 Substrate

The intended substrate for this floating-tank system was organic kitchen waste. The waste material that was fed into the system was acquired from local households participating in the household food waste audit. Accepted organic waste included fruit and vegetable peelings, over-ripened fruit, rice, ugali (mashed corn meal), cassava peelings, potato peelings and other organic items. Fish and meat bones were removed before feeding because they do not degrade under anaerobic conditions. Mango pits were removed when possible to reduce the risk of input pipe clogging.

4.3.4 Waste Preparation

Three different food waste preparation methods were tried to reduce food particle size in order to expedite digestion rates. First, a small hand-powered meat-grinder was used. This machine broke after two days of use, so preparation was switched to hand-cutting with a knife and cutting board. Finally, a local tool called a majani was used, which is basically an enlarged version of a mortar and pestle used to mash the food waste. This method was used for the majority of substrate preparation.

4.3.5 Feeding Regimen

After inoculum input the system was left alone for a period of four days to allow for bacterial growth. After this period the system was fed with two kilograms of cassava flour over two days as a high-energy feed to aid with bacterial growth, as per the instructions of ARTI-TZ. The digester was fed one kilogram of food waste on 4/19/11 and the feeding regimen was slowly increased to the target daily amount of five kilograms by 4/28/11. ARTI-TZ gives a suggested daily feeding rate of 5-6kg of wet-weight food waste for a 1500L floating-tank digestion system (Dennis Tessier, personal communication, 4/1/11). Food waste was mixed with effluent slurry when fed in order to reduce the amount of fresh water introduction with the aim of concentrating the bacterial population. Each feeding was followed by 20-40L of slurry input as a way to flush the input pipe and aid with mixing inside the digester. The system was fed or flushed with slurry twice daily, at 8 am and 8pm.

4.3.6 Gas Production Monitoring

Gas production was monitored twice a day, at 8 AM and 8 PM. An improvised measurement system was used to measure gas production; the gas reservoir tank was marked from the top down at one inch intervals. Measurement was taken by measuring the level of the bottom of the reservoir tank in an upright position at its intersection with the top of the digester tank.

4.3.7 Stove Testing

Stove testing was conducted by measuring the rate of gas usage over set periods of time. In order to calibrate the measurement system the current reservoir tank level was measured, the stove was run at full power for a set time, and the reservoir tank level was measured again. The resulting decrease in tank level in inches was used to calculate the average stove burn time in minutes per inch.

Water boiling tests were conducted to measure the average time it took to boil one liter of water at varying gas pressures. The three pressures were gas reservoir tank only, 6kg placed on top of the reservoir tank, and 12kg placed on top of the reservoir tank. Time was stopped when the water reached a full boil.

5. Results

5.1 Village Survey

The breakdown of local cooking fuel sources can be seen in Figure 6, with fuel wood consisting of the large majority of biomass used. Of the respondents who used fuel wood, 77% acquired it through daily collection and 22% purchased it locally (Figure 7). Fuel wood was purchased and used in units of one 'mzigo', which is a bundle of approximately 15kg of varying wood types. The local price of one mzigo ranged from 1,200-1,500 Tanzanian Shillings TZS. All charcoal was purchased; the unit was one 'polo', which is an approximately 50kg bag with a local price range of 6,000-6,500 TZS per bag. The current exchange rate is 1,511 TZS for 1 U.S dollar (5/5/11).

The fuel wood consumption average was 1.5 mzigos (approximately 22.5kg) per week, while charcoal consumption averaged 1.6 polos (approximately 80kg) per month. Using the average price of 1,350 TZS, fuel wood expenditures would be 8,100 TZS/month and 97,200 TZS/year. Using the average price of 6,250 TZS for charcoal, expenditures would total 10,000 TZS/month and 120,000 TZS/year. For fuel wood this expenditure only applies to those who purchase rather than collect wood.

Average time spent on fuel wood collection was 3 hours and 21 minutes per day; respondents said that just walking to the collection area took about 40 minutes (travel time was included in the total collection time).

The average time spent cooking per day was 1 hour and 53 minutes. Figure 8 shows that 28 of 30 respondents cooked inside, while only two cooked outside. Figure 9 shows respondent perceptions of the health impacts of fuel wood and charcoal use. Further informal conversations about health impacts indicated that the majority of villagers who thought biomass use was bad listed eye irritation due to fumes as the main reason. Two people said that biomass fumes also negatively impacted the quality of their homes due to smoke charring. The average number of children was 3.7, with a range of 0-10. All respondents answered that they currently do not use food waste and throw it outside of their homes or in small, informal dumpsites. One respondent did say that she fed leftover rice to her chickens.

None of the respondents had heard of biogas technology before. Attitudes towards the use of food waste, cow dung, and human waste in a biogas digester to produce cooking fuel are shown in Figures 10, 11 and 12.

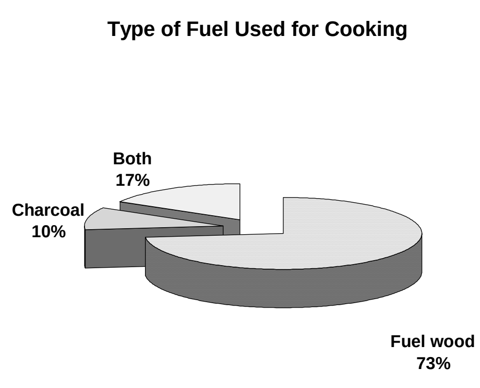


Figure 6.

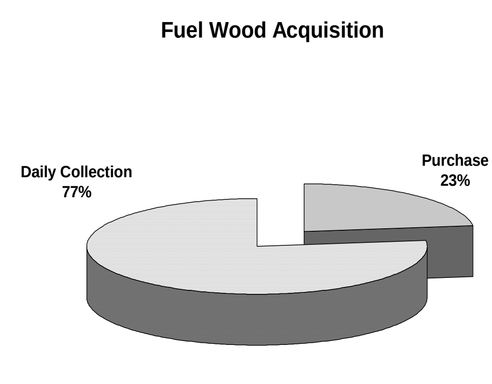


Figure 7.

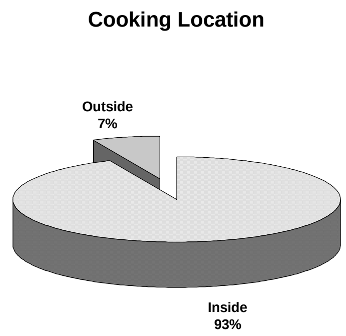


Figure 8. .

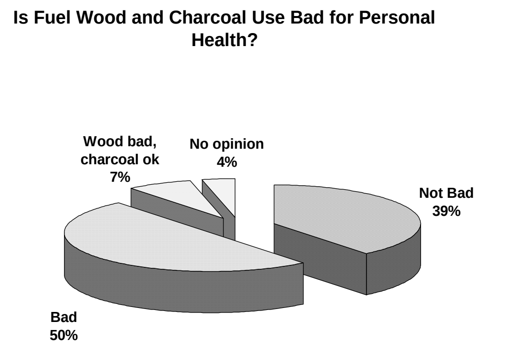


Figure 9.

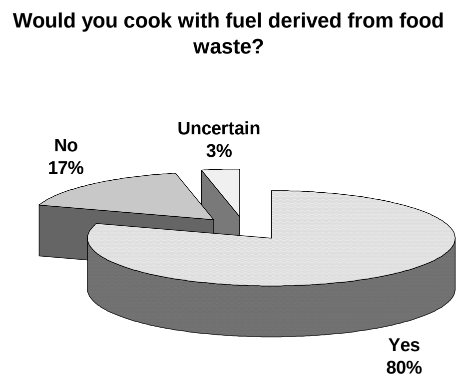


Figure 10.

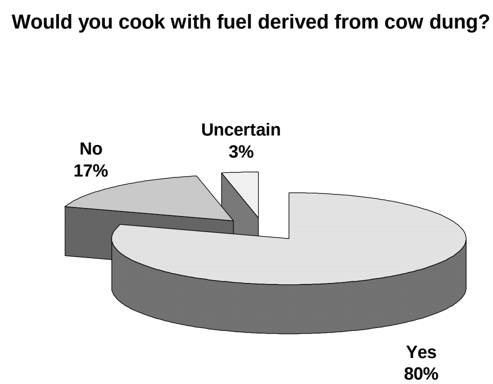


Figure 11.

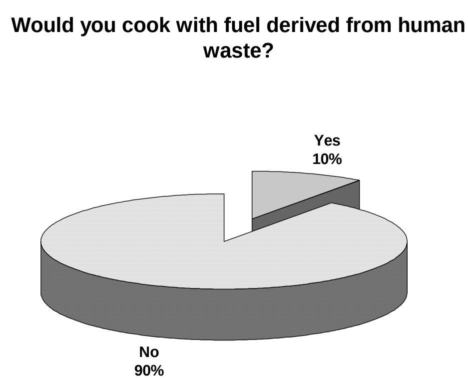


Figure 12.

5.2 Household Food Waste Audit

The results of the week-long food waste audit can be seen in Figure 13. The houses produced an average of 1.1kg, 1.9kg, 0.4kg, 1.2kg, and 1.3kg, respectively for houses 1-5. This indicates a total average of 1.15kg per household per day. The lowest daily amount collected was 0.25kg and the highest was 3.25kg. Visual observation showed the food waste to consist mostly of fruit peelings- mainly orange, lime, mango and papaya- and potato and cassava peelings.

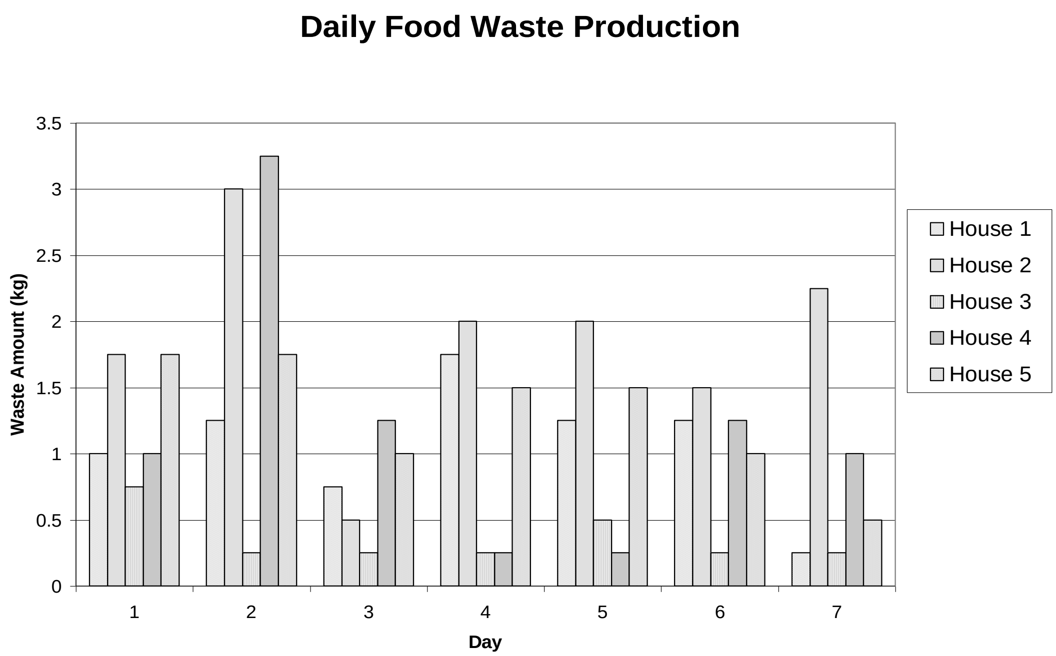


Figure 13.

5.3 Pilot System

5.3.1 Stove Testing

Table 3 shows the data produced through burn time measurement. As shown in Table 4, calculations give an average stove burn time of 8 minutes and 40 seconds per inch of gas reservoir tank height.

Burn Time (minutes)	Reservoir Tank Decrease (inches)
60	8.5
40	4.5
60	8
60	7
30	4
60	6.5
90	7
70	9
60	7.5
30	3.5
120	13

Table 3.

Table 4.

Total Burn Time	Total Change in Gas Reservoir Height	Average Burn Time in Minutes per Inch
680 minutes	78.5 inches	8.6624 (8 min 40secs)

The results of the water boiling tests are shown in Table 5.

Table 5.

Tank Pressure	**Test 1**	**Test 2**	**Average**
Tank Only	9 min	9 min 30secs	9 min 15secs
6kg	9 min 30secs	8 min 45secs	9 min 37.5secs
12kg	6 min 20secs	6 min 40secs	6 min 29.7secs

5.3.2 Gas Production Monitoring

Figures 14 and 15 show the gas production in inches of reservoir tank rise and minutes of burn time per 12-hour period, respectively, for the elapsed measurement period. Hour 0 represents the measurement period start time of 8 PM on 4/21/11, and hour 228 is 9.5 days later at 8 AM on 5/1/11. The gaps in the data indicate days when stove testing was performed and uninterrupted production data could not be obtained. Doubling the average production rate of 6.19 inches per 12-hour period gives a daily gas production average of 12.38 inches or 1 hour and 47 minutes of burn time.

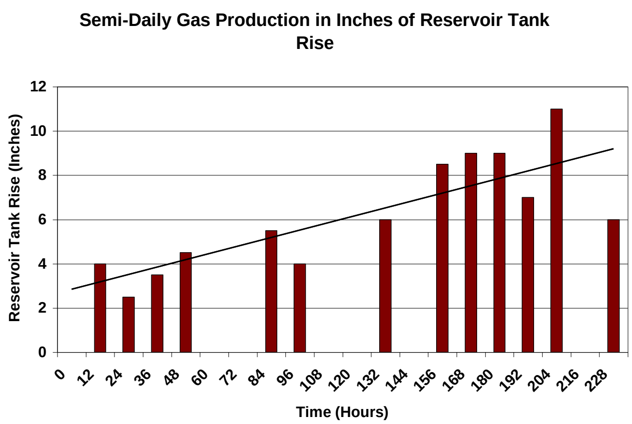


Figure 14.

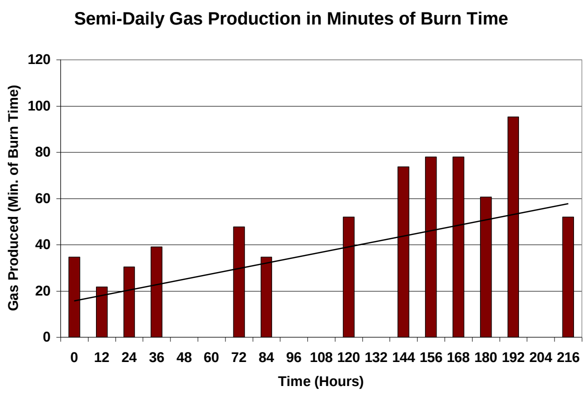


Figure 15.

6. Discussion

6.1 Biogas Feasibility in Uzi

6.1.1 Cooking

Survey results gave an average daily cooking time of 1 hour and 53 minutes; using the average of the daily gas production data indicates that 95% (1 hour and 47 minutes) of this cooking time could be supplied by this biogas system. However, the gas production data shows a clear trend of increase with time so it can be assumed that the actual daily biogas production rate would be significantly higher over the long term. This is because the data collected over the study period only encompasses the initial, start-up phase of the biogas digester. Previous research shows that gas production continues at an increasing rate during the initial phase until digester bacteria populations have stabilized with feeding rates while production rates plateau (Lohri, 2009). Using the value of the highest rate of 12-hour gas production measured during the study period, 11 inches, a daily gas production value of 3 hours and 10.5 minutes of burn time is given. This would provide 169% of the average daily required cooking time for one household.

6.1.2 Waste Generation

The average daily household waste production rate of 1.15kg would only be enough to provide 23% of the suggested 5kg amount of daily feeding material for the biogas system. At this rate of production it would take five households to generate the optimum amount of waste for system feeding.

6.1.3 Biomass Replacement

Assuming a rate of gas production sufficient to cover 100% of daily cooking needs, approximately 90kg per month and 1080kg per year of fuel wood per household would be saved from consumption. For charcoal the savings would be 80kg per month and 960kg per year.

If 1kg of fuel wood is equal to 438g of CO2 equivalent emissions (Bajracharya, 2010), then it can be calculated that 473.04kg of CO2 emissions would be saved annually per household with complete replacement of fuel wood.

6.1.4 Economic Feasibility

As mentioned in section 5.1, the annual cooking fuel expenditures for fuel wood and charcoal users was 97,200 TZS and 120,000 TZS, respectively. Considering that the cost of all biogas system components was 532,000 TZS, the amortization period would be 5.5 years and 4.4 years for fuel wood and charcoal users, respectively. However, the commercial price of a 1500L floating-tank system from ARTI-TZ is 895,000 TZS for parts, installation, and three months of service. This higher price would increase the amortization periods to 9.2 and 7.5 years for fuel wood and charcoal users, respectively.

6.2 Assessment

Based on these calculations, a 1500L floating-tank biogas system is not currently feasible on the domestic level in Uzi. One of the most important factors affecting feasibility is the fact that 77% of villagers surveyed collect wood rather than purchase it. This makes it extremely difficult to promote a biogas system based on economic benefits- if there are no fuel costs to be removed, there is no direct money to be saved. An effort could be made to promote the system based on possible income generation through increased time for profit-making activities and effluent sale, but the long amortization rate removes the possibility for any immediate or short-term gains. Further, it has not yet been established if there is a market for digester effluent as fertilizer on Uzi or the rest of Zanzibar.

For the portion of the population that does purchase cooking fuel, the local biomass prices are relatively low which again makes economic promotion difficult because the amortization period is too long. Lohri (2009) found that the average price of one polo (50kg) of charcoal in Dar es Salaam, mainland Tanzania, was 30,000-35,000 TZS, meaning that a similar amount in Uzi is five times less expensive. A list of current charcoal and fuel wood prices in Zanzibar could not be found, but it is probable that Uzi is on the low range of the price spectrum. The reason for this is that the majority of charcoal production and fuel wood harvesting occurs locally on the island, eliminating transport costs and middlemen. These fuel prices are likely to increase as local resources become scarce which would make biogas systems more attractive, but waiting for that time to come would have serious environmental and social implications.

Another important and limiting factor is the low rate of daily household organic waste generation. A biogas system could be planned on a multi-home level, but the daily cooking time and subsequent fuel substitution would be greatly reduced. Also, the families would have to share a stove to cook because the biogas in floating-tank systems is generally not under enough pressure to be able to support multiple fuel lines.

6.3 Potential Solutions

6.3.1 Waste Generation

In regard to the problem of insufficient waste generation, there are two main solutions. The first is to build a smaller biogas digester that has a lower input requirement. Previous research has shown that a similar floating-tank system with a 1000L digester and 750L gas reservoir produced a daily average of 289L of biogas, or about one hour of burn time, when fed with 2kg of food waste per day (Lohri, 2009). This would be enough to supply 53% of daily average cooking needs, but would only be viable for a low percent of the population that produces 2kg of food waste daily and would still likely remain economically unviable due to low cooking fuel prices.

The second solution to the problem of insufficient organic waste generation is to supplement the digester with other waste sources. Households that own cattle would likely be able to meet the 5kg daily input target with ease, as just one cow produces several kilograms of manure per day. Similarly, households with goats or a large amount of poultry could use the resulting manure. For households without livestock, the only realistic option of waste supplementation is to connect a toilet to the biogas digester. Assuming a daily average of 500g of feces production per person (Makhanu, date unknown), a family of six would be able to supplement a biogas system with 3kg of waste, covering 83% of the suggested feeding requirement. Although this would not completely fulfill the feeding requirements, it would still allow for a significant rate of gas production. However, the village survey showed that 90% of villagers did not approve of using human waste to generate cooking fuel so this proposal would be met with strong opposition. Local education on the low risk and high potential benefit of human waste use could be used as a tool to reverse this opposition.

6.3.2 Economic Viability

The largest current barriers to biogas system economic feasibility in Uzi are the high initial system cost and the long amortization period. Although personal system construction and commission is possible, the lack of biogas knowledge and experience in Uzi would make this option unrealistic and unadvisable. This means that a commercial system would be more appropriate, but would have a resulting increase in initial investment and amortization periods. Therefore, the most realistic ways to improve the economic viability are with the help of government subsidies, microfinance institutions, and aid from international governmental and non-governmental organizations. The government could be lobbied to provide financial support on the basis of preserving the environmental integrity of Uzi Island as a potential site for future tourism and resulting revenue. There is currently no tourism on the island, but the potential is high and a small eco-tourism project is currently in the initial stages of construction (Aliy, personal communication, 4/5/11). This option would require local survey and discussion to see if the people of Uzi would be willing to exchange the burden of fuel collection with the burden of tourism. A microfinance program would allow villagers to loan the money for initial system investment and slowly pay it back as the financial benefits of the biogas system are realized. Lastly, a type of carbon credit system could be introduced where developed nations fund biogas systems and get a certain amount of carbon credits for the resulting reduction in local deforestation and biomass emissions. Without some form of financial support the biogas potential in Uzi is very low.

6.4 Pilot System

6.4.1 Potential Improvements

The biggest place for improvement with the 1500L floating-tank system is with biogas capture. A large difference in the diameters of the digestion and gas reservoir tanks leads to biogas collection inefficiency as the exposed digester surface area releases biogas directly into the air. The easiest way to improve this would be to use closer-fitting tanks, however the tanks are only manufactured in certain pre-set sizes. Therefore, other gas collection designs such as water casings and flexible plastic bags should be considered. There is also a need for a simple yet precise gas reservoir measurement system to let users know the exact amount of gas and resulting burn time in the reservoir.

6.4.2 Potential Side-Effects

The risk of explosion due to biogas leakage and accumulation does exist but is extremely unlikely. The open-air architecture of most homes in Zanzibar would prevent most gas from accumulating, preventing explosion and potential health effects from inhalation (Lohri, 2009).

An increase in insect presence and larvae were observed in and on the digester, although they could not be quantified or identified. Previous research with a similar digester and climate in Dar es Salaam showed that 80-90% of larvae were of the family *Psychodidae*, which do not bite and are not serious disease transmitters. 10-20% of the larvae were of the genus *Culex* which are mosquitoes that are a human nuisance and vector of filarial parasites, however these larvae can be eliminated by stirring the exposed digester fluid occasionally (Lohri, 2009).

During the study period it was observed that chickens fed on disposed food waste. Although there was no way to confirm what percent of the diet it constituted, there is a possibility that using food waste for a digester rather than dumping would negatively impact local poultry populations and resulting egg production.

If biogas systems were implemented on a large scale in Uzi there would be a decline in fuel wood and charcoal demand, which could cause unemployment and anger due to industry crash.

6.5 Study Limitations

6.5.1 Pilot System

The most apparent limitation to this study is the short research period. Biogas systems typically take 2-3 months before bacterial populations stabilize and produce consistent amounts of gas. This meant that statistically significant gas production data could not be obtained.

Lack of sophisticated equipment meant that important parameters such as pH, temperature, biogas composition and flow rate, organic loading rate, chemical and biological oxygen demand, and effluent characteristics could not be analyzed. However, this lack of sophisticated equipment is likely representative of the vast majority of potential rural biogas households.

The lack of a gas flow meter meant that an improvised system of biogas production measurement had to be created. While this system was suitable for very basic measurement, inconsistencies and slight errors in the data are likely.

6.5.2 Village Survey

Although the survey only asked basic questions, it was conducted by the researcher with only three months of Swahili language practice. A ‘translator’ was present, but his low level of English proficiency prevented effective communication. Because of this there may be errors in the village survey data due to miscommunication.

6.5.3 Household Waste Collection

The household waste was only able to be measured with a handheld spring scale with an upper limit of 25kg. This resulted in a significant lack of measurement precision, as values had to be estimated in quarter-kilogram increments.

6.6 Suggestions for Further Research

A survey of households in Uzi with cattle would provide important information pertaining to the possibility of waste supplementation possibilities. A more in-depth survey about local attitudes towards human waste use for biogas would help provide information that could be turned into an education/outreach program, with the goal of changing local perceptions and widening waste supplementation sources. A continuation of pilot biogas system feeding and monitoring with more sophisticated equipment would provide more accurate gas production and process parameter information that would be valuable as pioneering data for biogas technology in Uzi.

An in-depth study of the charcoal and fuel wood industries in Uzi, including harvest rates, deforestation rates and price fluctuations could help to provide more convincing information endorsing the benefits of biogas technology. An in-depth review of current governmental policy towards alternative energy technologies in Zanzibar could help provide information on possibilities of action for promoting biogas technology through the legislative and judicial systems. Finally, the possibility government subsidy, microfinance and a carbon credit system in Uzi needs much further exploration.

7. Conclusion

Biogas technology has the potential to provide numerous environmental and socioeconomic benefits, such as reduced rates of deforestation, improved indoor air quality, and more time for income-generating activities. However, a 1500L capacity floating-tank digestion system is not yet feasible on Uzi Island. Economic factors such as a high initial investment cost, low current biomass fuel prices and a long period of amortization combined with the realistic factor of insufficient daily organic waste production and the social factor of disapproval of human waste use for cooking are the main barriers to biogas implementation. Proposed solutions include financial support through government subsidies, microfinance systems and a carbon credit system, waste input supplementation through use of animal and human wastes, increased local biogas technology education, and biogas system design changes.

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Appendix 1: Village Survey Questions

1. Unatumia nini kupikia- kuni au makaa?
--- Kuni- Unatafuta au nunua? Unatafuta kwa saa ngapgi?
2. Unatumia ngapi kwa siku/wiki/mwezi?
3. Unalipa pesa ngapi kwa kuni/makaa?
4. Unapika kwa saa ngapi kila siku?
5. Unapika ndani ya au nje ya nyumba yako?
6. Una watoto ngapi?
7. Unafikiri kupika kwa makka na kuni ni mbaya kwa afya?
8. Umesikia kuhusu biogas?
9. Ni sawa kutumia takataka za vyakula kutengeneza umeme kupika?
10. Ni sawa kutumia mavi wa ng'ombe kutengeneza umeme kupika?
11. Ni sawa kutumia mavi wa binadume kutengeneza umeme kupika?
12. Sasa, unafanya nini kwa takataka za vyakula?

1. What fuel source do you use to cook?
--Fuel wood- do you buy it or collect it? How long do you spend collecting each day?
2. How much fuel wood/charcoal do you use per week or month?
3. How much do you pay for fuel wood/charcoal?
4. How many hours a day do you cook for?
5. Do you cook inside or outside?
6. How man children do you have?
7. Do you think cooking with fuel wood or charcoal is bad for health?
8. Have you ever heard of biogas?
9. Is it ok to use food waste to create cooking fuel?
10. Is it ok to use cow dung to create cooking fuel?
11. Is it ok to use human feces to create cooking fuel?
12. Currently, what do you do with your food waste?