BIOMASS SYSTEM ANALYSIS

Study of Biomass System for the Polygeneration Unit (Work Package #155)

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General Definitions and Terminology

Anaerobic – without oxygen
Biomass—organic waste such as cattle, pig, or goat dung, food waste, or plant clippings
Digestate—the slurry that exits the digester; also known as effluent
Genset—refers to the biogas engine generator set
Feedstock—the waste, or biomass, that is added to the digester
Hydraulic Retention Time – the number of days the slurry remains in the tank
Methanogen—methane-producing bacteria
Slurry – a mixture of biomass and water
Total Solids – the dry matter in the feedstock
Volatile Solids –organic matter that can be converted into biogas

Abbreviations

AD – Anaerobic Digestion
AF – Anaerobic Filter
COD – Chemical Oxygen Demand
CSTR – Continuously Stirred Tank Reactor
HRT – Hydraulic Retention Time
OLR – Organic Loading Rate
OSC – Optimal Solids Content
PTD – Plastic Tube Digester
SRT – Solids Retention Time
TS –Total Solids
UASB – Upflow Anaerobic Sludge Blanket
VFA – Volatile Fatty Acids
VS – Volatile Solids
VSD – Volatile Solid Degradation

1 EXECUTIVE SUMMARY

The analysis is for the biomass subsystem of the polygeneration module that will be field tested in Kenya later this year. The biomass system includes the biomass digester and necessary fittings, biogas engine generator, the digester feedstock, and the effluent exiting the digester. This project features a literature study of biomass digesters; a market search for biomass digesters and biogas engine generators; design considerations for the digester system; and an outline of the integration of the best candidates into the polygeneration system.

Anaerobic digestion is a process by which organic material (volatile solids) is broken down in the absence of oxygen by bacteria to produce biogas with a high methane content. There are several different types of digesters that can host the process, including: batch reactors, floating drums, fixed domes, continuously stirred tank reactors (CSTRs), plug flow reactors (PFRs), anaerobic filters (AF), and up flow anaerobic sludge blanket reactors (UASBRs). Reactor systems can be separated into categories according to whether they are suspended or attached growth systems. Suspended growth refers to reactor systems that constantly have to regrow the anaerobes (bacteria used in anaerobic digestion) because the bacteria exit the digester with the effluent. Attached growth systems have the anaerobes permanently fixated to a medium inside of the digester. The liquefied slurry flows through the medium, gets digested, and flows out leaving the bacteria behind on the medium. The literature suggested that since the attached growth systems required influent with a solids content of 2-4%, the large water requirement would put a strain on Kenya's water resource. Also the attached growth system is more suited for flushed manure installments on large dairy farms as opposed to the scraped manure that will come from family cows in rural areas. For this reason, suspended growth systems were decided to be most well suited to the polygeneration project.

In order to further reduce the water footprint, dry digestion was explored as an alternative to wet digestion. In dry digestion the feedstock can have a solids content of 20-40% while wet digestion requires a solids content of <15%. Overall, dry digestion would be well suited for the purpose of the polygeneration unit because of the reduced water footprint and the more robust nature of the dry digestion process which demands a lesser amount of pre- and post treatment of the slurry. Also, the effluent will be closer to the usable fertilizer state than the wet digestion effluent because it will not have to be dehydrated prior to use. Of the digesters usually coupled with dry digestion, the plug flow reactor with a Dranco design would be the best reactor system to use for the polygeneration unit. This design is closest to the Indian floating dome household digesters. Unfortunately, the Indian floating dome household digesters found in the market search were not suited for powering an electricity generator. When coupled with dry digestion plastic tube digesters (PTDs) are horizontal plug flow reactors. Plastic tube digesters have been used as complete mix reactors (wet digestion) in various rural locations in Bolivia, Tanzania, Kenya, Honduras, Cameroon, etc. Even though dry digestion has not been tested in these areas, the concept of the plastic bag digester is familiar and the products are readily available for purchase, unlike the Dranco plug flow design.

For this reason the market search focused on plastic tube digesters and biogas engines. A 16 m^3 PVC digester kit and a 1.2kW biogas engine by Biogas Australia were chosen to be the best package, at a total price of €2300 including shipping to Mombassa and all of the fittings necessary for operation.

The review found that there are a number of factors that should be taken into consideration during the system design. These include preserving the oxygen free environment by preventing tearing, constant digester temperature, total solids content, volatile fatty acids accumulation, volatile solids degradation, carbon-nitrogen ratio, feedstock acidity, hydraulic retention time, organic loading rate, gas production rate, and gas consumption rate (engine). The total solids and volatile solids content of the feedstock, prevention of volatile fatty acid accumulation, and proper organic loading are some of the factors that require the most attention.

Future considerations and research for the biomass system encompass (1) a market search for a Dranco designed plug flow reactor; (2) using feedstock other than cow dung and incorporating co-digestion; (3) heat recovery; (4) uses for output slurry; (5) incentivizing dung collection.

2 INTRODUCTION

The purpose of this project was to analyze the biomass system of the polygeneration project. The analysis included a literature survey of engines and digesters and a market search for the system components. It should be used as a resource by the SELECT students and Polygeneration Research group for furthering the work on the next polygeneration prototype. Later this year, the team plans to build a unit that will be field tested in a rural Kenyan village. Therefore, the leading motivation for this research is rural electrification, not natural disasters and emergency situations. The biogas system suggested in this report is intended to power a micro-grid or battery charging station.

The other part of this project was a literature study of different anaerobic digestion systems, feedstock types, and the effects of certain operational parameters of digesters. The generator set component of the biogas system is more time tested, so an extensive literature review of this technology was not undertaken. The market search results are a compilation of the specifications and product information of a number of biogas engine generators and digesters available for purchase. The products found on the market were compared with each other according to the objectives and criteria outlined in POY Group A's Final Report (Syed et al., 2013). One biomass digester and one biogas engine generator were selected as the best candidates for the biogas system that will be installed in the next polygeneration unit. Lastly, I describe some parameters and options that are worth further consideration and investigation.

3 OBJECTIVES

1. Study KTH's next demo container for Kenya (functions, specifications)
2. Literature survey on biogas engines and biomass digesters
3. Market search for biogas engines and biomass digesters suitable for the polygeneration container
4. Selection of a candidate
5. Outline of physical integration
6. Outline of functional integration

4 THE BIOGAS SYSTEM

The biogas system analyzed in this report includes the feedstock, anaerobic biomass digester, and the biogas engine generator. The flow of the system is modeled in Figure 1 below and mapped onto the diagram in Figure 2.

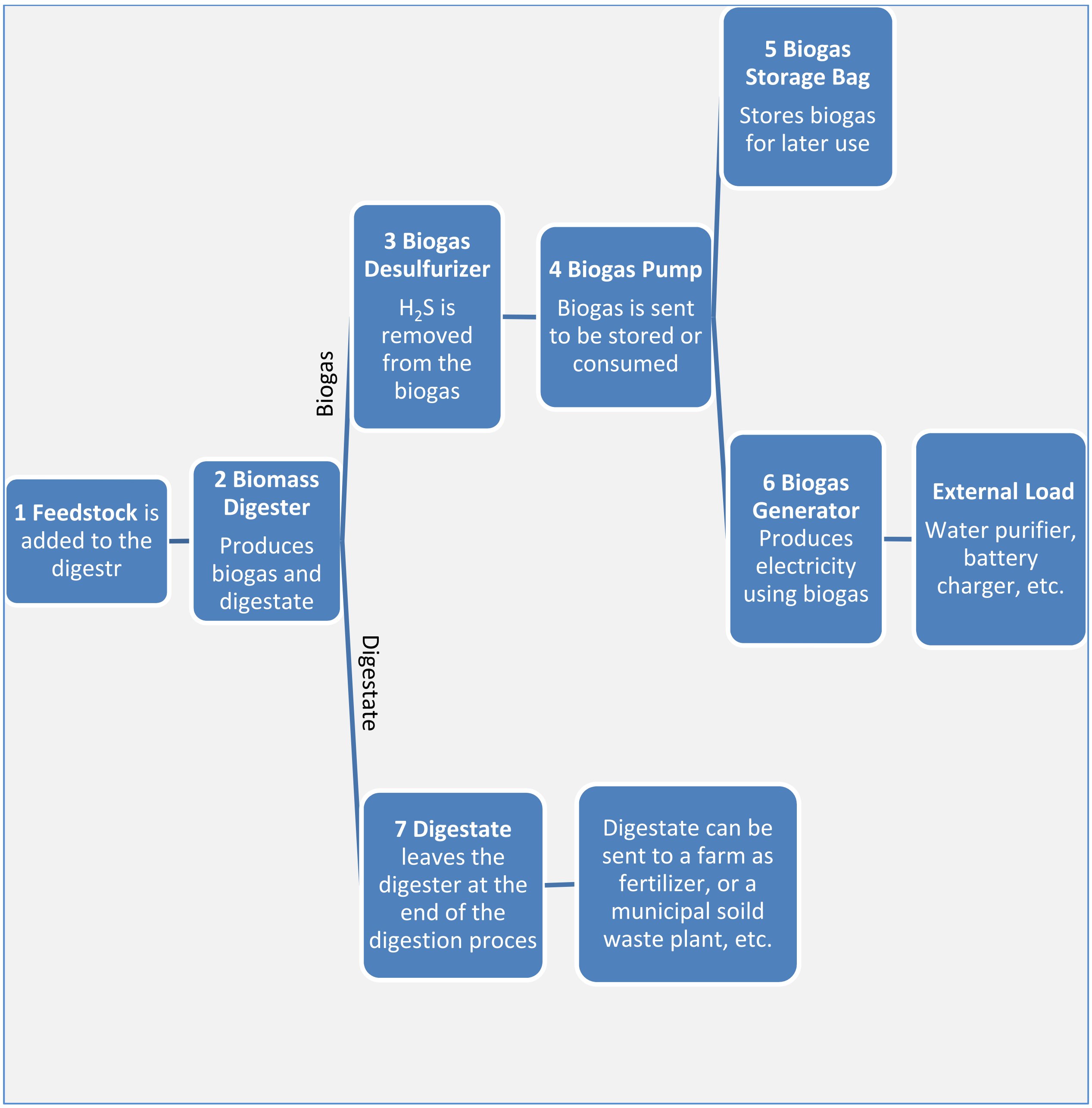


Figure 1 – Flow chart of the biogas system used in the polygeneration unit

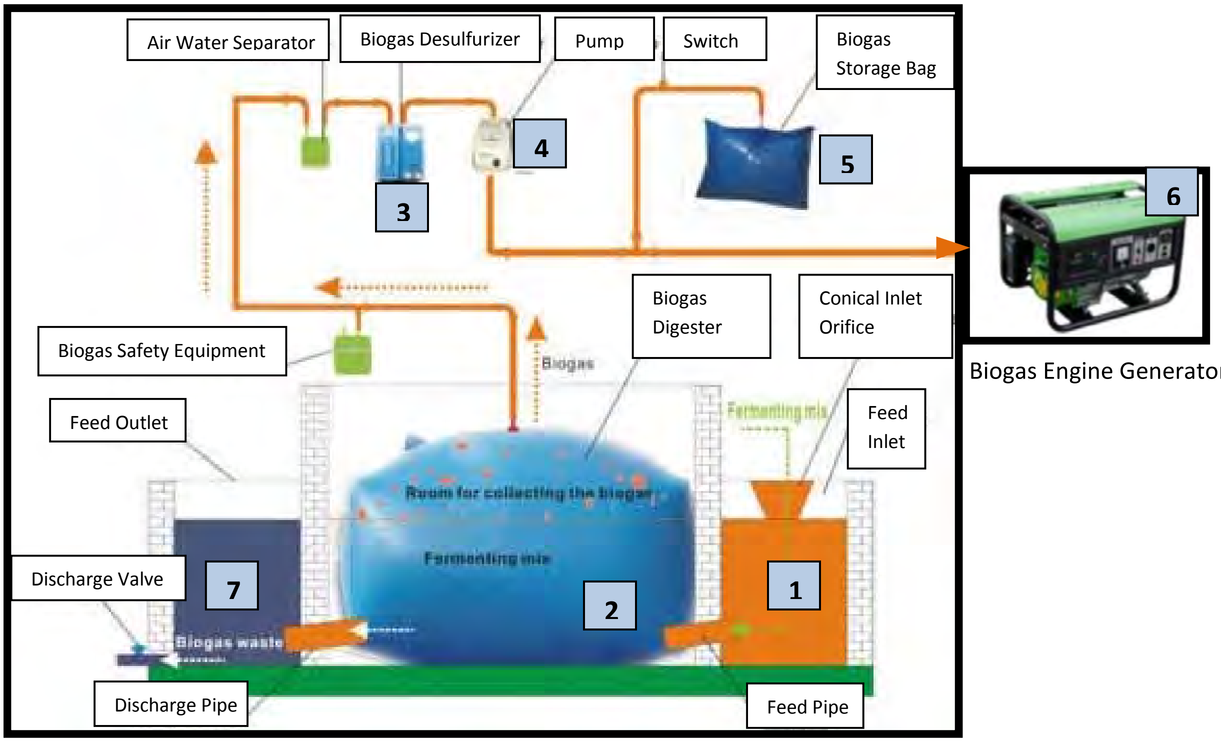


Figure 2 – Diagram of a plastic tube digester biogas system

5 THE ANAEROBIC DIGESTION PROCESS

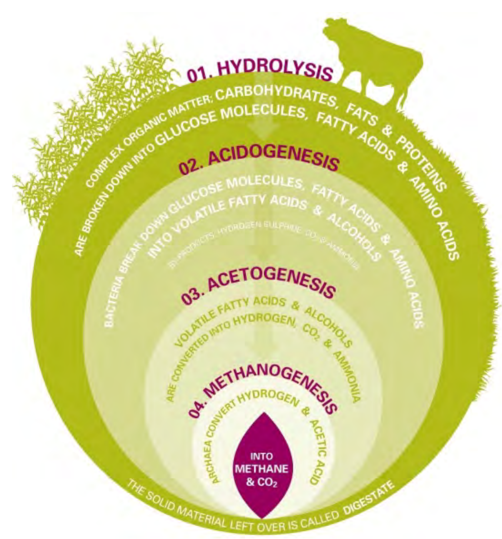


Figure 3 – Process of Anaerobic Digestion
Source: Anaerobic Digestion & Biogas Association

Anaerobic digestion is a process by which organic material (volatile solids) is broken down by bacteria in the absence of oxygen to produce biogas with a high methane content. Anaerobic bacteria are naturally occurring and do not need to be separately added to the digester, but it does require the addition of inoculates to jump start the bacteria growth (Leggett, Graves, & Lanyon). Biogas is about 55% methane, 40% carbon dioxide, and 5% water vapor, hydrogen sulfide, and ammonia, with a heating value of about 600 BTU/ft^3 (Leggett et al.; Singh, 1971). This gas can later be burned to produce energy for cooking, heating, electricity generation, gas lighting, etc. Acidogenesis is the first major step in the digestion process, followed by methanogenesis. In acidogenesis, acid bacteria convert more complex organic molecules into volatile fatty acids, or volatile solids.

In the second stage, these simpler compounds are processed by methane-forming anaerobes to produce biogas and effluent.

Not all volatile solids are digested, however, due to the sensitive nature of the methane-producing anaerobes (Singh, 1971). Maximizing the percentage of VSD will maximize the amount of biogas harvested from the incoming feedstock. In reactor systems using animal waste especially, methanogenesis is the limiting step (Lyberatos & Skiadas, 1999). Thus, choosing a reactor system that has an optimal environment for the finicky methane-forming bacteria is crucial for biogas production; not to mention that undigested volatile solids are the source of the residual odor in the digestate.

6 ANAEROBIC DIGESTION TECHNOLOGY

Biomass digesters are employed to host the anaerobic digestion process that outputs biogas. There are many different biomass reactor designs, but essentially a biomass digester is a heated tank into which raw organic material is added, digested, and subsequently released as effluent along with the biogas. The simplest reactor system is the batch reactor. More complicated designs use features such as stirring, excess heating, multiple tanks, etc. to maximize volatile solid degradation (VSD). According to (Nasir, Mohd Ghazi, & Omar, 2012)), various bioreactor systems have been used to digest cow manure, including batch reactors, semi-continuous reactors, one- and two-stage systems, UASB, AF, and CSTR.

In accordance with the criteria outlined for this upcoming polygeneration prototype the biomass digester should be easy to install, requiring little technical expertise and only 1-2 people for assembly. Also, all of the materials and tools needed should be included in the container. Keeping this in mind, I did a rough comparison of reactor systems based on a few categories.

6.1 Types of Biomass Reactor Systems

Batch Reactors—the reactor is filled with feedstock all at once. When a batch completes the anaerobic digestion process, the batch is removed and a fresh serving of feedstock is added. There is no daily input or output for this reactor system. The batch reactor has a very simple design and daily feedstock is not needed.

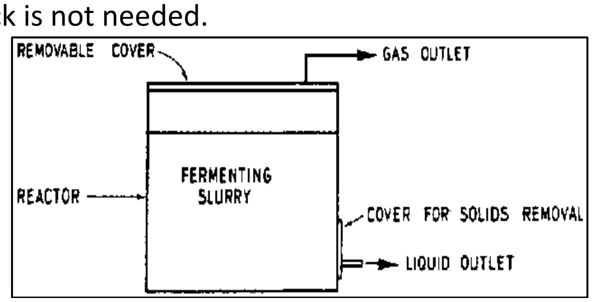


Figure 4 – Batch Reactor

Plug flow reactors—these reactors usually host dry anaerobic digestion. The high solids (20-40% TS) waste flows like a plug through the tank. The flow is semi-continuous with a HRT of 20-30 days. The reactor itself can be an in-ground tubular tank or a covered, concrete-lined trench. Digestion takes place under mesophilic conditions and fibrous solids are removed post-digestion so the reactor can handle scraped manure operations (Wilkie, 2005). The plastic tube digester under dry digestion circumstances is an example of a plug flow reactor.
Plug flow reactors are generally inexpensive ("Promoting BIogas Systems in Kenya: A feasibility study," 2007).

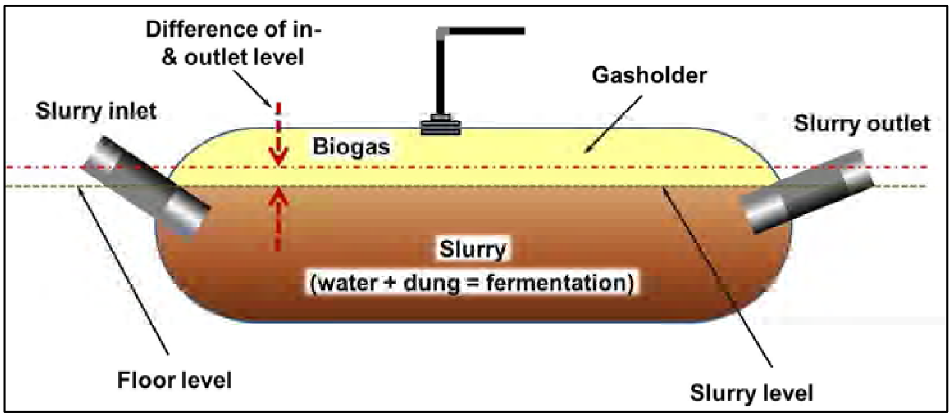


Figure 5 – Plastic tube type plug flow digesters

Fixed Dome (Chinese) Digester—a fixed dome digester consists of an underground tank. Part of the tank is used to store biogas and the rest of the tank holds the material to be digested. These digesters use a suspended-growth system and usually also use wet digestion. The installation is very complex.

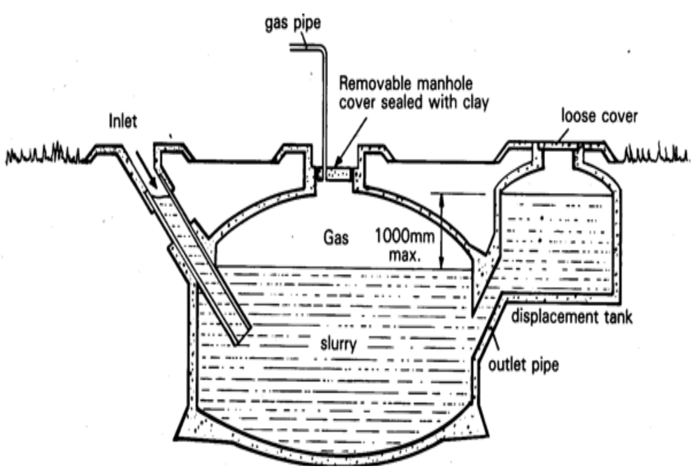


Figure 6 – Fixed dome digester

Floating Drum (Indian) Digester—in a floating drum digester, the gas is trapped beneath a movable “drum”, i.e. the top of the digester. The floating drum is a bit smaller than the entire tank and “floats” in the slurry contained in the digester. The floating drum digesters pictured below are household biodigesters and the biogas is used for cooking; the biogas produced is not sufficient for electricity generation according to one of the manufacturers. However, larger floating drum digesters are able to provide a sufficient supply of biogas for electricity generation ("Promoting BIogas Systems in Kenya: A feasibility study," 2007).

Figure 7 – Household floating drum digesters

Fixed-film Reactor—bacteria is immobilized on a fixed screen or other media within the tank. This prevents washout of anaerobic bacteria, shortening the retention time. This system operates with a total solids content of < 2% and a hydraulic retention time of 2-4 days. At such a low total solids content, this system is best for flushed-manure operations. Because these reactors are only used for wet digestion, fibrous solids must be removed pre-digestion to prevent clogging. Also, only smaller amounts of sand and silt are permitted (Wilkie, 2005). Upflow anaerobic sludge blanket reactors (UASB) and anaerobic filters (AF) are examples of a fixed-film reactor system.

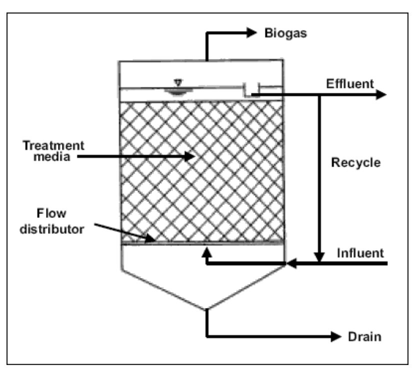


Figure 8 – Schematic of the up flow anaerobic filter process.

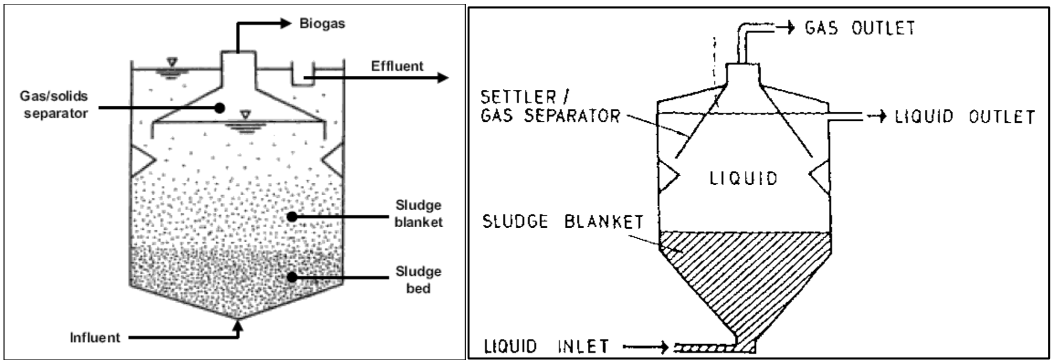


Figure 9 – Upflow anaerobic sludge blanket

Continuously stirred tank reactors (CSTR)—these reactor systems use mechanical agitation, effluent recirculation, or biogas recirculation to mix the contents of the digester. Mixing ensures that heavier contents do not settle to the bottom and that anaerobes are evenly distributed throughout the substrate. Mixing also prevents foaming, but too much agitation can stress the microorganisms (Rajendran, Aslanzadeh et al. 2012). Fibrous solids are removed either pre- or post-digestion and the reactor is meant to handle substrate with a solids content of 3-10%. The CSTR is usually coupled with mesophilic temperatures and the HRT varies from 20-25 days (Wilkie, 2005).

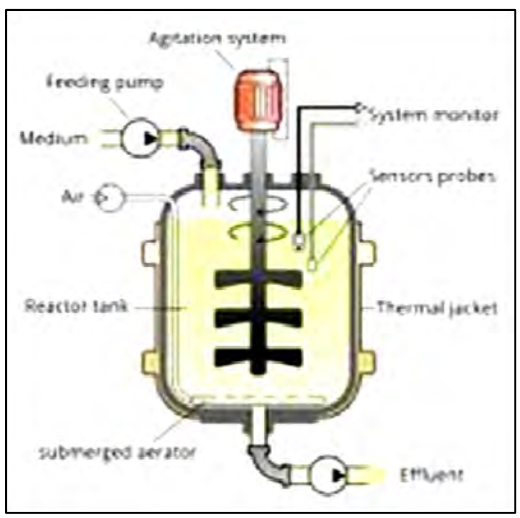


Figure 10 – Continuously stirred tank reactor

Semi-Continuous—in a semi-continuous system, slurry is loaded into the digester perhaps once per day. A continuous reactor system is more compatible with a flushed manure disposal system, because then the substrate could be continuously pumped into the digester. The opposite of a continuously loaded reactor system is a batch reactor system.

One-stage System—in one-stage systems, acidogenesis and methanogenesis take place in the same tank which can be counter-productive because the pH levels are lowered during acidogenesis. Methanogenic bacteria are very sensitive to changes in pH level—as well as temperature—therefore a large decrease in pH could lower the amount of methane that results from the digestion process (Singh, 1971).

Two-stage System—Two-stage systems seek to avoid the possibility of decreased yield by using two separate tanks. In the first tank, acidogenesis takes place and methanogenesis takes place in the subsequent holding tank. Two-stage systems degrade about 9% more volatile solids than one stage systems, and thus reportedly have a methane yield 6-8% higher. (Nasir et al., 2012)

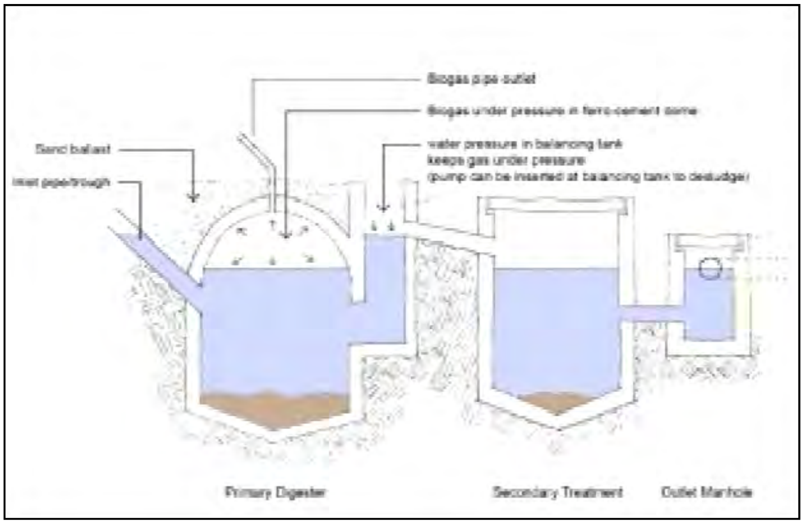


Figure 11 – Two-stage System

6.2 Attached vs. Suspended Growth

Biomass reactors can have suspended- or attached-growth systems. In suspended-growth, the anaerobes are continually growing and exiting the digester with the substrate. These systems tend to have much longer retention times than their counterparts because the slurry must remain inside of the tank long enough for the anaerobes to grow *and* digest the substrate. Methanogens grow slowly and double every 5-16 days, thus a HRT of at least 10-15 days is necessary for a suspended growth system (Rajendran, Aslanzadeh et al. 2012). "*If the rate of the bacteria lost from the digester with the effluent slurry exceeds the methanogen growth rate, the bacterial population in the digester will be washed out of the system. Washout is avoided by maintaining a sufficient residence time for solids, and thus bacterial cells remain in optimal concentration within the digester*"(Marchaim, 1992). In high-rate attached-growth systems, the bacteria are attached to a medium which remains inside of the digester. As incoming substrate flows through the medium inside of the tank, the attached anaerobes digest the organic material. When effluent exits the attached-growth system, it does not carry the anaerobes out with it as is the case with the suspended-growth systems set up (Lyberatos & Skiadas, 1999). Because the anaerobes remain inside of the digester, the retention times are much shorter

(0.2-2 days) and time since time is not needed to continuously grow replacement bacteria. A lower HRT means a smaller digester volume can be used.

Attached growth systems begin producing biogas much more quickly than suspended-growth reactors, but the solids content of the influent is 2-4% as opposed to 6-14% for the latter. The incoming slurry must be able to flow through the medium without getting clogged hence the low TS content. Feeding manure into an attached growth system would require pre-treatment of the manure to remove any fibrous solids or large particles that might clog the digester, which would increase the temporal maintenance cost. A significantly larger amount of water would be needed to make the slurry 2-4% TS as well. Kenya already has problems with water shortages and severe droughts, so choosing a system that minimizes water usage would be in the best interest of the project. Apart from the water requirement, attached growth systems are significantly more complex and so someone with lots of technical expertise would have to manage the digester construction and maintenance (Marchaim, 1992).

6.3 Dry Digestion vs. Wet Digestion

Dry digestion handles substrate with a solids content of 20-40% while wet digestion deals with material that has <15% TS. Unlike wet digestion that uses diluted slurry, dry digesters can process organic material in its original state (i.e. without dilution) (Vandevivere). Only material with TS of >50% require some dilution (Oleszkiewicz and Poggi-Varaldo 1997). The lower water footprint makes dry digestion much more appealing than wet digestion for use in the polygeneration module's biomass system. However, some manures such as dairy manure have a natural solids content of 15% making it more suitable for a wet digestion system. If dry digestion was used then substrate with a very high solids content would have to be added to the manure in order to increase the solids content.

Since dry digestion can handle substrate with a high total solids content, it is sturdier than wet digestion because "impurities such as stones, glass, or wood do not cause any hindrance" (Vandevivere). The ability to handle large items such as these makes the pretreatment of feedstock for dry digestion much less involved than the pretreatment for wet digestion which requires the feedstock to be transformed into a slurry. This transformation includes adding water as well as removing any large or fibrous particles. The table below shows the advantages and disadvantages of a dry digestion system.

Table 4.3. Advantages and disadvantages of one-stage 'dry' systems.

Criteria	Advantages	Disadvantages
- Technical :	- No moving parts inside reactor - Robust (inerts and plastics need not be removed) - No short-circuiting	- Wet wastes (< 20 % TS) cannot be treated alone
- Biological :	- Less VS loss in pre- treatment - Larger OLR (high biomass) - Limited dispersion of transient peak concentrations of inhibitors	- Little possibility to dilute inhibitors with fresh water
- Economical & Environ-mental :	- Cheaper pre-treatment and smaller reactors - Complete hygienization - Very small water usage - Smaller heat requirement	- More robust and expensive waste handling equipment (compensated by smaller and simpler reactor)

Figure 12 - Advantages and disadvantages of dry digestion. ***(Source: Vandevivere)***

The challenges of dry digestion lie in handling, pumping, and mixing the solid streams rather than inhibition to the chemical processes of anaerobic digestion. Economically speaking, wet digestion is more appealing because cheaper equipment such as centrifugal pumps and piping can be used to move the slurry. In dry digestion, more expensive pumps that are powerful enough to move highly viscous streams are required. Despite these challenges, the total investment cost of dry digestion is similar to that of wet digestion when the pretreatment, dewatering equipment, and internal mixing are factored into the wet digestion process. Environmentally dry digestion is much better than wet digestion because dry digestion has a water consumption footprint about ten times less than that for wet digestion (Vandevivere). Less water also means that less evaporation must be done with the output slurry because the digestate resulting from dry digestion is already similar to the manure form. Also under thermophilic conditions, the plug flow reactor results in the complete hygenization of waste, thus the effluent will not contain any harmful pathogens (Baeten and Verstraete 1993).

Plug flow designs are characteristic of dry digestion, while complete mix reactors are usually used with wet digestion. Plug flow designs are simpler because of the absence of mechanical mixing devices used in CSTRs, but the absence of these devices makes mixing fresh feedstock with the fermenting feedstock challenging. In the digestion process, mixing ensures that the anaerobes are evenly distributed throughout the substrate, guaranteeing adequate inoculation. Mixing also prevents over acidification which can decrease the pH level such that methanogenesis is inhibited. There are several plug flow reactor designs shown in Figure 12 that seek to address the problem of mixing solid waste.

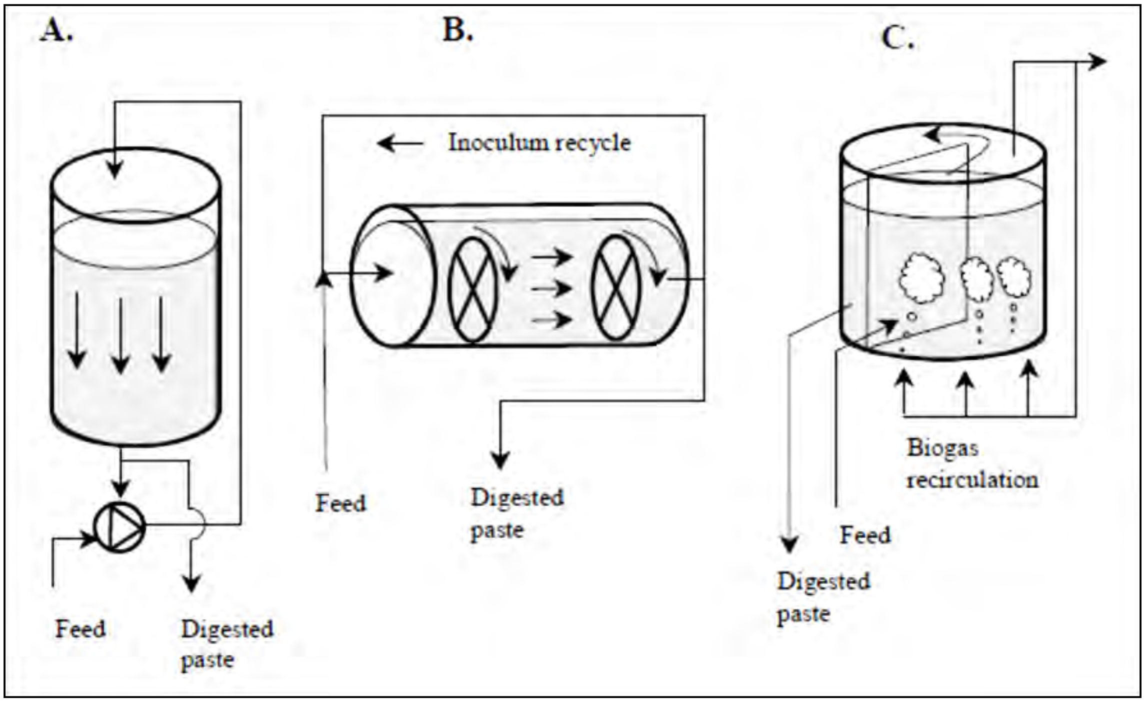


Figure 13 - Plug flow reactor systems used in 'dry' digestion.
(A) Dranco design (B) Kompogas and BRV design (C) Valorga design

The first design is the Dranco (DRy ANaerobic COmposting) design, pictured above in Figure 12A. This design mixes fresh substrate with the already fermenting mass by diverting some of the effluent back into the influent stream and then pumping the mixture the digester. In the Kompogas design pictured in Figure 12B, plug flow occurs horizontally and slow rotating impellers are used to mix the feedstock inside of the digester. The total solids content of the waste in this reactor must be maintained at about 23% to prevent settling of heavier substrate to the bottom of the tank. The Valorga design injects high-pressure streams of biogas into the substrate every quarter hour in order to mix the waste. One drawback of this last design is that the biogas inlet holes can become clogged.

Overall, dry digestion would be well suited for the purpose of the polygeneration unit because of the reduced water footprint and the more robust nature of the dry digestion process which demands a lesser amount of pre- and post treatment of the slurry. Also, the effluent will be closer to the usable fertilizer state than the wet digestion effluent. If the total solids content of the cow manure is 15% then another type of waste with a higher solids content must be added. This works out in the end because according to Nasir et al. (2012), co-digestion of cow manure with another substance leads to higher biogas yields. One challenge of using dry digestion with a plastic tube digester would be ensuring that the substrate is

mixed properly and flows through the reactor. If the Dranco design can be manipulated such that a pump is not needed, then gravity will ensure that the substrate flows down to the outlet. With semi-continuous loading the person loading the digester for the day could add some of the out coming digestate with the fresh manure that was collected prior to loading the mixture into the digester.

6.4 Plastic Tube, Fixed Dome, and Floating Drum Digesters

Suspended-growth systems include plastic tube digester, batch reactors, plug flow digesters, floating drums, fixed domes, and CSTRs. Between these digesters, plastic tube digesters have the shortest lifetime and are the least durable ("Promoting BIogas Systems in Kenya: A feasibility study," 2007). On the other hand, they are more likely to have their substrate warmed by the sun and they are the easiest to install (Marchaim, 1992). They are not as permanent as the other digesters and this is most appropriate for the emergency energy module that is not meant to be permanent either. It would probably be better to use a floating drum or fixed dome digester for the rural electrification situations save for the fact that bricks are heavy and would take up too much space in the digester. Thus, plastic tube digesters will fit best inside of the container. They are also the cheapest which makes them the best choice for the prototype. The hydraulic retention time is extremely long, suggesting that the team might have to wait a few weeks before having a steady enough supply of biogas to do tests. Below in Figure 13 is a summary of the most common digesters in Kenya.

\ Type of biogas digester Issues	Floating drum -16m^3	Fixed Dome - 16m^3	Plastic Tubular Digester 9 m^3
Average cost of installation (€)	1188-1403	712-1426	399
Ease of use/operation	Easy	Very easy	Easy
Perception	A bit dirty, but good	Very good	On trial
Efficiency	Needs time	Needs time	Works faster
Ease of installation	Simple to Complex	Very complex	Simple
Durability	At least 30 years	At least 30 years	15 years (est)
Contractors needed to install	2-3	4-6	1
Technical problems reported	Some	Very few??	Quite a few
Extension/technical support	Limited	Some	A little
Minimum cattle/TLU needed	3-4	2-4	2
Maintenance	Every 3-4 years	Minimal (only feeding digester)	Unknown
Numbers installed	>1000	300-800	150 – 200

Figure 14 – Comparison of Most Common Digesters in Kenya *(Source: Kenya Feasibility Report)*

The CSTR model would require electricity to run the mixer. Technically some of the electricity generated by the biogas system could be used to power the digester, but then the system would have to produce more energy to reach the target capacity.

The polyethylene tube type digester being considered for the Kenya prototype features a simple, semi-continuous, suspended growth reactor system. This system is less sophisticated because it does not provide extra heating aside from the heat provided through insulation and there is no stirring. However, since they have already been used in Kenya, **I agree with the team that the plastic tube digester is the best reactor system to use with the polygeneration unit for rural electrification at this time because the market search for a Dranco design plug flow reactor was not fruitful. The other suspended growth reactors are more complex and require advanced technical knowledge for installation. Also, the plastic tube digester is the easiest to transport and fit into the container. However, if the horizontal plastic tube digested is coupled with dry digestion, then some settling and VFA accumulation – inhibitors to the digestion process – may arise due to the lack of mixing. The market search is for horizontal plastic tube digesters, but vertical plug flow reactors (Dranco) using dry digestion should be seriously considered.**

7 BIOMASS DIGESTER DESIGN CONSIDERATIONS

All anaerobic digesters host the same process of anaerobic digestion, but individual designs are adjusted to maximize the amount of biogas produced or the percent of volatile solids that are destroyed. The design considerations discussed are with respect to a PTD. The adjustments are made to create conditions that encourage activity of both acid- and methane-forming bacteria, including (Wilkie, 2005):

- An oxygen free environment
- A relatively constant digester temperature of about 35°C
- A consistent supply of organic matter, where the input material has a solids content of about 6-8% (Singh, 1971); (Rajendran, Aslanzadeh, & Taherzadeh, 2012)
- A pH level between 6.5 and 7.6 (Labatut & Gooch, 2012; Leggett et al.)
- Carbon-nitrogen ratio of about 13:1-28:1 for the raw material fed into the digester (Nasir et al., 2012; Rajendran et al., 2012)

7.1 Oxygen Free Environment

Preserve the anaerobic environment. In the Honduras Digester Manual (Brown, 2004), the constructors positioned the inlet and outlet buckets on a steep incline (Figure 4), such that the substrate would act as a stopper to prevent air from coming into the digester. The exact nature of the digester chosen will differ from the Do-It-Yourself model that is described in the Honduras manual, but the main idea is still the same: the slurry level in the digester must be above the height of the inlet/outlet connection so that no air can enter. In general, the digester should also be protected from rips and tearing to preserve the anaerobic environment.

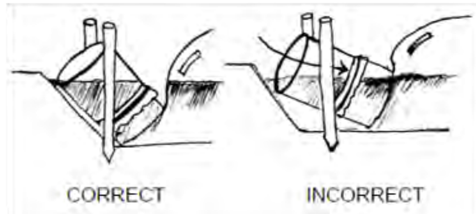


Figure 15 – Proper configuration of the digester inlet and outlet
(Source: Honduras Biodigester Construction Manual)

Protection from tearing. PTDs are susceptible to puncture and not as durable as the floating and fixed dome counterparts; however, setting up a fence around the perimeter of the digester can help reduce the risk of puncture by an animal or wandering child. Also, measures should be taken to reduce the amount of friction between the digester and the ground, especially if the trench is set in concrete or brick.

Maintenance during the rainy season. According to a review of plastic tube digesters in Tanzania (Atkins, Fuchs, Hoffman, & Wilhelm, 2008), farmers with PTDs in dirt trenches had to put in up to 2-3 more hours of maintenance per day due to erosion of the dirt trench. March to May generally constitutes the rainy season in Kenya, thus during these times maintenance of the PTD may prove to be as difficult for people in Kenya as it was for the people in Tanzania. Depending upon the maintenance cost during the rainy season, it may be worthwhile to set the trench in concrete and brick before placing the digester in it. According to the contact for Biogas South Africa, it would take 1 week for 1 brick layer and 5 laborers to construct a brick lined trench and install the PTD. Whether or not the investment cost is less than the maintenance cost depends upon the lifetime of the PTD. The team should be mindful of the rainy season in Kenya when planning the trip to test the demo container.

7.2 Constant Digester Temperature

Options for heating the digester. As aforementioned, the methane-producing bacteria require a fairly constant temperature for maximum biogas production. According to a study on household digesters (Lyberatos & Skiadas, 1999) and another concerning dairy manure digestion (Wilkie, 2005), a temperature of 35°C (mesophilic conditions) is optimal; but while the average temperature in Northern Kenya is about 20-40°C, it is 22-30°C along the coast and even lower in Nairobi (Muli & Saha). Several options are available for heating the digester (Singh, 1971):

(a) Having a black digester can provide some solar heating.

(b) Insulate the digester by lining the trench with a 50-100cm layer of straw or wood shavings.
(c) Circulate hot water throughout the outside of the digester.
(d) Use a CHP unit to redirect the excess heat from the electrical generator to the biomass digester. However, a CHP is mainly appropriate for more extreme weather conditions.

7.3 Constant Supply of Organic Matter

Dung Collection. The plastic tube digester (plug flow reactor system) is usually coupled with a scrape waste management system as opposed to one that utilizes flushing (Wilkie 2005). People will have to scrape the dung from the ground and bring it to the polygeneration unit for digestion. According to Wilkie and Burke neither plug-flow nor complete-mix reactors are suitable for dairy farms using sand bedding and scraped manure because the sand and silt can have a negative impact on the digestion process (Burke, 2001; Wilkie, 2005). Housing cattle in zero-grazing units with concreted floors would prevent sand and silt from being scraped up with the dung (Gichohi, 2009). Kenya has been encouraging the use of zero grazing units ("Promoting BIogas Systems in Kenya: A feasibility study," 2007) so if these units increase, then dung harvest will be much simpler.

Creating the Feedstock. According to the literature, the optimal solids content of the slurry is 6-8% for greater volatile solids reduction (Barker 2001; Singh 1971; Rajendran, Aslanzadeh et al. 2012). The solids content of dairy cow manure is usually about 10-15%, therefore, the manure has to be mixed with water to reach the OSC for wet digestion. Wilke claims that plug-flow reactors can handle 10-14% total solids in the slurry. If this number is closer to the optimal value for the PTD, then water would not have to be added to the manure in order for it to be digested. The OSC for dry digestion ranges from 20-40% TS so cow manure would have to be mixed with a material that had a higher TS content. Note that the solids content of manure varies depending upon the type of cow.

Loading the Digester (OLR). A mix of fresh cow manure should be loaded into the digester at the optimal OLR. The OLR should be outlined in the installation manual provided by the manufacturer. The organic loading rate is the amount of VS or COD per unit volume of the digester, thus the amount of feedstock needed to satisfy the OLR depends upon the composition of the feedstock as well as the size of digester. The starter batch of slurry should include some rumen, which slightly accelerates anaerobe growth and biogas production (Budiyono, Widiasa, Johari, & Sunarso, 2010). Rumen can be acquired from the stomach contents of a cow at a local slaughterhouse. It acts as an inoculate to enhance the growth of anaerobic bacteria. In order to prevent washout of anaerobic bacteria, some of the effluent can be mixed with the fresh manure prior to being loaded into the digester.

Removing output slurry. The slurry should exit the digester at the same rate that it is input because this is a semi-continuous reactor system with zero mass accumulation (after the initial batch). In a digester, gravity pushes the digestate out of the tank. In the case of plastic tube digesters, the digester is placed inside of a slanted trench so that the substrate slowly moves toward the exit until it is pushed out.

7.4 Acidity and C-N Ratio

Type of Cow. The solids content, volatile solids content, pH level, and C-N ratio of manure depends upon the type of cow and the amount of biogas produced depends specifically on the amount of volatile solids in the manure not just the amount of manure itself. The percent of volatile solids in the manure varies enough between different types of cows that this parameter requires attention. Live weight of the cow is used to determine the amount of total solids – and thus volatile solids – that a cow will produce. In Kenya, the main livestock are dairy cows that are zero grazed (Matiri & Kiruiro, 2009). Only 20% of the national milk production comes from large-scale dairy farming; the rest comes from small-scale farms. The most common breeds are Friesian and Ayrshire with some Guernsey, Jersey, and East African Zebu as well ("Promoting BIogas Systems in Kenya: A feasibility study," 2007). Once the type of cow is determined, better biogas production estimates can be made using the Matlab code (addressed later and found in the Appendix).

Acidity. The digester must be held at a pH level between 6.5 and 7.6 in order optimize anaerobic digestion. The methanogens are sensitive to acidic conditions, so a lowered pH level will result in a lower biogas yield. Problematic acidic conditions are caused by accumulation of volatile fatty acids in the digester. Accumulation happens when excess volatile fatty acids are loaded into the digester or a toxic substance that has a very low pH is introduced into the feedstock. Generally In order to prevent a drop in pH, there must be enough buffer capacity (alkalinity) in the system. For anaerobic digestion the bicarbonate ion (HCO_3^-) acts as the buffer to keep the system in the optimal pH range. Fortunately, cow manure has a typical pH of 7.4 and provides enough buffering capacity to keep the digestate in the optimal range (Labatut & Gooch, 2012). When experimenting with co-digestion of manure plus other substances (food waste, etc.), the pH level of the feedstock should be measured with a pH meter to make sure that the acidity is not below the optimal range. The amount of volatile fatty acids is an early indicator of digester upsets, and thus should be checked weekly during the testing period.

Labatut and Gooch (2012) measured the VFA by distilling a sample and doing a titration of the distillate with sodium hydroxide 0.1 N to pH 8.3. If monitoring during the testing period in Kenya reveals the eventual stability of the acidity levels in the substrate, then consumers should not be concerned about measuring the acidity levels in the same manner *as long as they follow the digester loading instructions – outlined in our digester manual – carefully.*

Carbon-Nitrogen Ratio. A C-N ratio of 13:1-28:1 is optimal for anaerobic digestion. According to a study reviewed by (Nasir et al., 2012), cow manure has a ratio of about 5.8:1 which is below the optimal range. Co-digestion of cow manure with readily biodegradable organic matter is suggested to raise the C-N ratio. During the field testing period in Kenya, this parameter should be measured when experimenting with co-digestion of cow manure. Once the optimal loading ratio of cow manure to the additional substrate is determined, the C-N ratio should not have to be monitored by the consumer. Again, the consumer must make sure to follow the loading instructions provided in the operational manual very carefully.

8 MARKET SEARCH METHODS AND RESULTS

Search engines Alibaba.com, Lulusoso.com, Made-in-china.com, and environmental expert.com were used to locate prospective digester and engine models. Some of the engines and digesters had already been found by previous students working on the biomass system. Since the two students had already contacted some of the manufactures to get specifications for the models that they found, I went back to the site and double checked these numbers but I did not re-contact suppliers about the same product. Once I found a suitable product based on the 3.6kWh electricity output, I contacted the supplier for more detailed specifications. Most of the suppliers replied, but not all of the information requested was provided. Some of the suppliers gave me official specification sheets or quotes which can be found in the Appendix.

Just like the SELECT team, I found it difficult to find and contact African biogas system manufacturers. The GTZ commissioned Feasibility Survey found that there are at least three companies involved in the installation of PTDs in Kenya: Pioneer Technologies Limited, Modeline Electrical and Mechanical Engineers, and Biens Limited ("Promoting BIogas Systems in Kenya: A feasibility study," 2007). Pioneer Technologies, a local plastics company, is regarded as the company that started to distribute PTDs on a large scale in Kenya. I tried to contact Pioneer Technologies but was unable to do so. However, I was able to contact BiogasSA and Biogas International—headquartered in Johannesburg, South Africa and Nairobi, Kenya, respectively—about polyethylene tube digesters. I received specifications from BiogasSA, but I was unable to procure more information about the Flexi Biogas System by Biogas International. BiogasSA offers biogas gensets, but they are actually manufactured by PUXIN. This suggests that

BiogasSA digesters are compatible with PUXIN gensets. Preferably all of the components of the biogas system should be purchased from the same manufacturer however one goal of the project is to buy as many materials locally as possible. Therefore, if a suitable local digester kit is available, then it is better to buy the engine and digester from separate companies even if the Chinese companies offer digesters as well.

In general, it is best for the digester to be purchased from a local manufacturer because the digester performance is more dependent upon environment conditions (including feedstock type) than the biogas generator. Also, the shipping costs will be minimized.

8.1 CRITERIA FOR KTH's NEXT DEMO CONTAINER

Overall, the goal of the polygeneration unit is to produce electricity and clean water for people in rural Kenya. The main criteria (below) taken under consideration in choosing the best biogas engine and anaerobic digester candidates are among those outlined in the SELECT Group A Final Report and the Subsystem Integration Report by the WP2 team.

Main Criteria for the Biomass System

- Produce 3.6kWh/day
- Low Cost
- Fit into container (Dimensions and weight)
- Relatively easy installation (minimal time and technical expertise required)

General

- Cost and lead times for shipping the solution from Stockholm to Kenya must be considered.
- The contained solution will not be connected to the main grid.
- Assembly, disassembly, start up and maintenance must be possible without any external electricity.

Electricity

- Voltage and frequency must comply with local standard for all electrical equipment used.
- 50 Wh/day per person has to be provided.
- Equipment should be obtained locally if possible
- Storage of energy should be considered.

Other

- It must be possible to fit all equipment into a standard container for transport.

- No more than two persons should be required to assemble/disassemble the production unit.
- All tools required for assembly/disassembly must be included – if not available locally
- Simple technical documentation and an operation manual as well as an assembly and disassembly guide ("IKEA type") must be provided.
- Recycling of certain components of the contained solution must be considered.

8.2 COMPARISON CRITERIA

Comparisons were based on the following criteria and other areas of interest. See the Comparisons Excel sheet in the Appendix for the complete compilation of all the specifications for all of the engines and digesters found during the market search. Choices were made based on the following criteria.

Biomass System Criteria (Syed et al., 2013)

- Produce 3.6kWh/day
- Low Cost
- Fit into container (Dimensions and Weight)
- Relatively easy installation (minimal time and technical expertise required)
- Local manufacturer (preferably Kenyan)

Biogas Engine-Generator Set Criteria:

- Lowest gas consumption rate
- Electrical standards compatible with the region
- Low Cost
- Local supplier, reputable company (safety certification)
- Engine specifically made for biogas

Biomass Digester Criteria:

- High Gas Production
- Kit includes all fittings
- Low Cost
- Ease of Installation
- Local Manufacturer (preferably in Kenya)
- Ease of connection to the engine

8.3 MARKET SEARCH CONCLUSIONS

8.3.1 Best Biogas Engine

First Choice

The **1.2 kW JQ2500BG/LPG – B Biogas Generator** supplied by **Biogas Australia** is my first choice.

Figure 16 – Biogas Australia 1.2kW generator

The engine would only run for three hours to supply 3.6kWh of power per day. Biogas Australia also offers a 0.5kW and 3.5kW size, so if the load needs to be adjusted we can change the engine size without switching companies.

The engine has a low gas consumption rate of 0.7 m^3 biogas/kWh. This gas consumption rate is lower than the 1.217 m^3 biogas/kWh rate of the Puxin 1.2 genset. Note that the gas consumption rate was calculated using the 1.46m^3/hr specification given in the email from PUXIN.

$$1.217m^3 \text{ biogas/kWh} = (1.46m^3 \text{ biogas/h})/(1.2 \text{ kW})$$

According to my calculations (see MATLAB code in Appendix and calculation below), 2.52 m^3 of biogas is required to run the engine per day compared to the 4.38 m^3 of biogas required to run the PUXIN 1.2 kW engine. Less gas required translates into less cow dung required per day. This will decrease the temporal costs associated with collecting the cow manure using a "scrape" collection method.

Biogas Australia is familiar with using heat recovery to warm plastic tiles to keep young animals warm, such as baby piglets. If we choose to pursue the idea of combined heat and power, this company would be familiar with the procedure and be able to give advice on the system set up. Also, they supply digesters, meaning that both major components of the biomass system could be bought from them.

The biogas generators are supplied by Greenpower, a.k.a. Shanghai Chenchang Power Technology Co. Ltd. These are not mainstream engines, but as a company they advertise a number of certifications shown below including China National Accreditation Service for Conformity Assessment (CNAS), Conformité Européenne (CE), United States Environmental Protection Agency (EPA), GOST-R Certification in Russia, Rostechnadzor Permit, California Air Resources Board (CARB), and the Australian Gas Association (AGA) as well as Electromagnetic

Compatibility (EMC) . In light of these certifications, this engine has a stronger guarantee of being safer than the ACME engine.

<u>Second Choice</u>

The **AM1500BG 1kW biogas generator set by Wuhan Acme Agro-Tech Co.** was chosen to be the second best genset candidate based on its low price and low gas consumption rate. It has an investment cost of **€320** and a gas consumption rate of $0.7m^3$ biogas/kWh according to a quote supplied by the manufacturer upon email request. Just like for Biogas Australia, the low gas consumption rate makes it considerably more desirable than the PUXIN engine. The generator is tailored for biogas only and outputs a current at 230V and 50Hz, which is the standard for Kenya; thus the electricity generated should be highly compatible with the appliance loads there. Lastly, ACME produces a 2kW and 3kW version of this generator set, so if the electricity load on the biogas system needs to be increased in the future we can easily do so.

Figure 17 – ACME 1kW Biogas Generator

<u>Note</u>: Shengdong new Energy Technology Co. (€435), Guangzhou Dingfeng (€600), and Juangsu Hopepower New Energy have prices and gas consumption rates comparable to ACME, but they were not ranked for various reasons.

Shengdong new Energy Tech was not ranked because the user manual provided for the generator set seemed inadequate. However, I do not know what the user's manual for the ACME engine will look like. Also, ACME offers biogas digesters suggesting that the company is more familiar with the entire biomass system.

I did not get a reply from Guangzhou Dingfeng Machinery Co. nor Juangsu Hopepower New Energy, therefore this engine was not ranked. If I could not get a response, then it might be difficult working with the company in the future. Both Kristel and I have been in contact with Leo Liu from ACME and while I did not find that many safety standard certificates, they do have many manufacturing/economic/business certificates and awards unlike Shengdong who had none available.

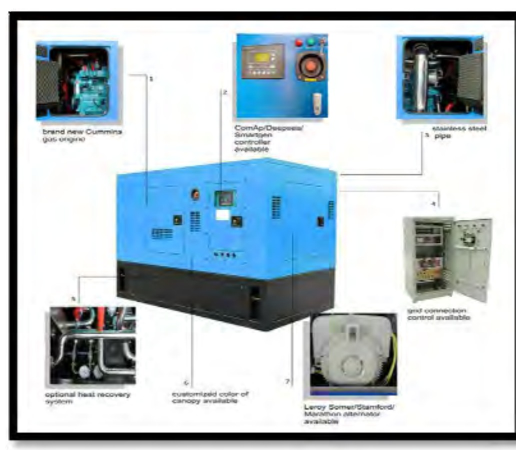
<u>Third Choice</u>

The **RTA2B 2kW Biogas Genset** by **Chengdu Rare Tech Co., Ltd.** has a lot of good options and quality parts. Also it is one of the few companies advertising compliance with the CE standards. The generator will output a current at 230V and 50Hz which is the standard for Kenya, thus the electricity generated should be highly compatible with the appliance loads there. Turnkey projects are offered for construction of a biogas plant in European locations but not in Africa. Also, the gas consumption rate of 0.73-0.81 is similar to Biogas Australia and ACME. About 2.92 m^3 of biogas is required to produce 3.6 kWh of energy. The downside of this engine is the high price: €1890 (excluding shipping).

Standard Configuration of Generator Set:

- Raretech new gas engine
- Alternator (PMG, anti-condensation function etc available)
- Control system by Smartgen/Deepsea/ComAp controller
- Venturi mixer
- Electronic ignition system, including ECU, spark plug, high-voltage electricity wire, ignition timing switch, ignition coil and wires
- Electronic speed governing system, including controller and actuator
- Air filter, oil filter
- Silencer
- Corrugated pipe
- Engine repair kit
- Gas engine book manual, alternator book manual, controller book manual
- Genset Operation and maintenance manual
- Related drawings
  Certificate of Quality
- Test report and other necessary accessories

Figure 18 – Chengdu Rare 2kW Biogas Generator



Options:

- Soundproof enclosure
- CHP/Heat recovery system to recover heat from jacket water and exhaust manifold
- Grid connection system by ComAp/Deapsea controller
- Paralleling running system
- Gas leakage alarm system
- Emission control: controlled three-way catalytic converter in the exhaust stream

- Remote genset running online monitor
- Automatic transfer switch (ATS)
- Maintenance-free storage battery 12V DC for starting and power supply control
- Battery charger 12V DC

Latest Design Choice

The most recent biomass system design proposal suggests the use of a **PX-BG 1.2 kW Biogas Genset** from **Shenzhen Puxin Technology Co. Ltd.** This engine has an appealing size and price but the gas consumption rate of 1.2 m^3/kWh makes it less desirable. As aforementioned, at this rate 4.38 m^3 of biogas is required to run the engine for 3 hours per day.

8.3.2 Best Anaerobic Digester

Best Value

If either the 1.2 kW Biogas Australia genset or the 1kW ACME genset is used to reach the target capacity (3.6 kWh/day), then the accompanying digester must produce at least 2.52 m^3 of biogas. The **DIY 16 m^3 PVC Digester Kit** from **Biogas Australia** reports the highest gas production rate of 6.2 m^3 biogas/day. At this rate, the digester would be able to produce an adequate supply of biogas to keep the genset running for up to about 7-8 hours a day.

Figure 19 – Biogas Australia 16m^3 Digester

Biogas Australia Genset

(4 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1.2kW)]$^{-1}$ = 4.7 hours/day (5.6 kWh)

(6.2 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1.2kW)]$^{-1}$ = 7.4 hours/day (8.8 kWh)

ACME Genset

(4 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1 kW)]$^{-1}$ = 5.7 hours/day (4 kWh)

(6.2 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1 kW)]$^{-1}$ = 8.8 hours/day (8.8 kWh)

If it is only run for the 4 hours that we are aiming for right now, then the excess biogas produced that day will amount to a full day's supply that could be used during peak hours. The 6.2 m^3 production rate is most likely an overestimate of a maximum production under ideal conditions, so if the rate turns out to be lower, suppose 4 m^3, the amount of biogas produced will still be adequate for the day's supply.

This digester also has a fairly simple installation process and an adequate kit. The kit includes the double membrane PVC biogas digester, pipes and fittings, biogas booster pump (electric), water separator, biogas purifier, safety relief valve, and single burner stove. The stove is not needed, so we can request a reduction in the price to have it omitted from the standard kit. They also offer a consultation service—at a cost—to help you to estimate the parameters of your biomass system so that you can choose the appropriate digester size out of the range offered: 6 m^3 to 50 m^3. The quote of €2300 includes the 16 m^3 soft digester with all fittings water separator, biogas purifier, and booster pump, a 20m^3 biogas storage bag (required for genset use), 1 1.2kW biogas genset (manual start), and sea freight to Mombassa, Kenya.

Lowest Price

The most economical digester would be the **Household Soft 10 m^3 Biogas Digester** from **Wuhan ACME.** The Household Biogas Digester System must be specifically requested as some of the biogas system parts (pump, desulphurizer, etc.) are sold separately. The system that ACME offers includes one 10 m^3 soft biogas digester, biogas fittings (pressure meter, desulfurizer, pipes, etc.), 1 m^3 biogas storage bag, and one 15W biogas pump for a total of €245. Since this digester has an estimated production rate of 2-4 m^3, it would be advisable to assume the lower estimate and buy two digesters to supply the engine's needs.

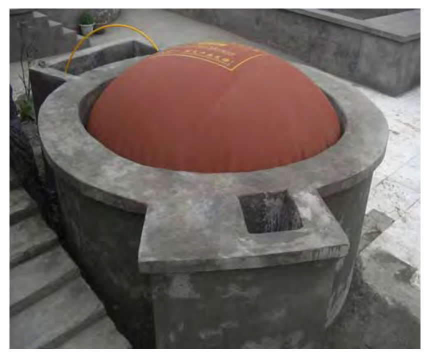


Figure 20 – ACME 10m^3 Digester

Biogas Australia Genset

(2 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1.2kW)]$^{-1}$ = 2.4 hours/day (2.8 kWh)

(4 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1.2kW)]$^{-1}$ = 4.7 hours/day (5.6 kWh)

ACME Genset

(2 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1 kW)]$^{-1}$ = 2.8 hours/day (2 kWh)

(4 m^3 biogas produced/day) x [(0.7 m^3/kWh) x (1 kW)]$^{-1}$ = 5.7 hours/day (4 kWh)

In order to keep a full day's supply of biogas in accordance with the criteria, at least three biogas storage bags are needed. The two digesters systems and the extra storage bag minus the second pump bring the digester package total to: (2 x €245) - €28 + €33 = **€495**.

Using multiple digesters in the system presents the problem of consistency and physical integration. First, it will be difficult to assure that the two digesters are loaded in the exact same way, so the percent methane of the biogas from one of the digesters might be different than the biogas from the other digester. If this is the case, then the mixed gas flowing into the genset could cause engine problems. Second, connecting the two digesters to two separate bags and biogas pumps and then to one engine means multiple pipe connections and more chances for biogas leaks. Also, it might not be feasible for the engine to accept biogas from both pumps at the same rate if the pipes from the two pumps are connected to the single pipe leading into the pump. In reality, having two digesters may not present problems, but it will most likely require additional effort to prepare the system.

Latest Design Choice

The **Chongqing Xinshui Machine Manufacture Series H H15-Q80 15m^3 PVC digester** was the digester of choice in the latest polygeneration system design proposal. It is a PVC tube type digester that produces 2 m^3 of biogas per day. Two digesters would be needed to meet the demands of the ACME engine for a total price of €**772**. This price includes the biogas digester, 25 m of pipeline, the joint, gas nozzle, safety valve, gas-water separate, biogas desulfurizer, PVC hoop, booster pump, and pipeline control switch. Having all of the fittings included with the digester ensures that the pieces will fit together properly. The downside to choosing this digester is the need for two digesters. Also, they do not provide a biogas storage bag in the package, so this will have to be purchased separately. Chongqing Xinshui Machine Manufacture Company was awarded a Certificate of Conformity of Quality Management System Certification from CNAB for the years 2004-2010.

Figure 21 – Chongqing Xinshui 15m^3 Digester

8.3.3 Best Digester-Engine Pairs**

***Please note that Biogas Australia is the only company to include the shipping cost in the price.*

#1 Biogas Australia: *€2300* incl. shipping to Mombassa

<u>Includes</u>: Biogas Australia digester & fittings, H_2O separator, H_2S scrubber, booster pump, 1 20 m^3 storage bag, 1.2 kW engine

<u>Total Package Size and Weight</u>: 0.93 m^3 and 103 kg

<u>Pros</u>: Both the digester and engine are supplied by the same company which assures that the pipes will all be included in the kit and they will all fit properly. They also offer a 0.5 kW, 1.2 kW, and 3.5 kW engine. Consultation service (at a cost) to help you with digester sizing.

Cons: The engine is not actually manufactured by Biogas Australia so it may take longer to get spare parts if needed. Large package size. Short lifetime (5 years).
Other Options: Biogas Australia is able to supply absorption chillers which utilize the heat from the exhaust system of a genset to provide refrigeration. The genset can also be fitted with a CHP unit.

#2 ACME: *€815* excl. shipping
Includes: 2 digesters & fittings, H_2S scrubber, pump, 3 ACME 1 m^3 biogas storage bags, 1 kW engine
Total Package Size and Weight: 2*(600x300x400) + (610x450x470) = 0.28 m^3 and 93 kg
Pros: All parts are manufactured by ACME. Lowest investment cost.
Cons: You need 2 digesters so you will have to make some alterations in order to connect two digesters with one engine.

#3 Chongquing digester + ACME 1 kW engine: *€1194* excl. shipping
Includes: 2 digesters & fittings, H_2O separator, H_2S scrubber, pump, 2 1m^3 ACME storage bag, 1 kW engine
Total Package Area: 2*(600x300x400) + (610x450x470) = 0.27 m^3 and >43 kg (engine weight only, digester size not provided)
Pros: Second cheapest option.
Cons: Products are from 2 separate companies so alterations will most likely be needed. 2 digesters required.

Latest Configuration = Chongquing digester + PUXIN 1.2 kW engine: *€1905* excl. shipping
Includes: 3 digesters & fittings, H_2O separator, H_2S scrubber, pump, 1 storage bag, 1.2 kW engine
Total Package Area: 3*(600x300x400) + (620x480x480) = 0.36 m^3 and >43kg (engine weight)
Pros: 10 year lifetime
Cons: Second most expensive. Products from 2 separate manufacturers and 3 digesters needed, so alterations will most likely be necessary.

9 SYSTEM INTEGRATION

This section outlines the integration of the Biogas Australia digester and engine into the polygeneration unit. The integration requirements were suggested in the 'WP2 – Subsystem Integration Strategy' report.

9.1 Electricity Standard

The standard for Kenyan electrical appliances is 220-240 V, 50Hz, and Type G British BS-1363 electrical outlets. The Biogas Australia 1.2 kW JQ2500BG/LPG – B biogas generator is a single phase brushless generator with an AC output at 50 Hz and 230 V. According to the integration strategy in the WP2 report, the AC output should be at 240V, therefore, an alternator may be needed to properly integrate this electrical system.

9.2 Package Size

According to the *Subsystem Integration Report* SELECT 2011, a standard container sized 6.1m x 2.44m x 2.6m (l x w x h) will be used. It can hold a net weight of 21600 kg. The digester package size and weight was given to be 1100 x 900 x 800 mm and 53 kg, but the genset package size was not provided. Based on the size and weight of the other 1-1.2 kW engines that I found, the size and weight of the Biogas Australia genset is estimated to be about 610 x 460 x 470 mm and 50 kg. This makes the **total package size 0.93 m^3 and 103 kg**. The weight is not significant compared to the gross weight that the container can hold, but this package will take up about 2.4 % of the total volume.

9.3 Safety

Special caution should be taken with regards to the following:

- Biomass and biogas storage
- Biomass feeding and handling (Use gloves)
- Engine high temperature
- Conditioning of gas including gas cleaning and safety valve
- Control systems
- Electrical configuration

The operational manuals provided by the suppliers will contain safety information that should be included in the overall safety guidelines for the container.

9.4 Environmental, safety standards and license

The biomass system should be configured such that it complies with all necessary safety and environmental standards. These standards will apply to engine emissions, digester emissions, safety of electrical configuration, and the quality of the digester effluent (solid waste). Since the container will be developed in Sweden and tested in Kenya, both Swedish and Kenyan emissions and environmental standards should be met. Some of the requirements will most likely be developed by the following governing bodies:

- Kenya Ministry of Environment, Water and Natural Resources <http://www.environment.go.ke/>
- Kenya Solid Waste Managements <http://www.unep.or.jp/ietc/GPWM/data/T2/IS_6_P_PolicyAndRegulations_Nairobi.pdf>
- Swedish Environmental Zones regulation <http://www.dieselnet.com/standards/se/zones.php#intro>

There are also general engine generator guidelines developed by China National Accreditation Service for Conformity Assessment (CNAS), Conformité Européenne (CE), United States Environmental Protection Agency (EPA), GOST-R Certification in Russia, Rostechnadzor Permit, California Air Resources Board (CARB), and the Australian Gas Association (AGA). If the engine complies with these, then it is more likely that they will comply with the Kenyan and Swedish environmental and electrical standards.

9.5 Installation

The system should be set up according to the instructions manual included with the kit provided by Biogas Australia. There are also a number of other manuals outlining the construction of polyethylene tube type biomass digesters that would be valuable supplementary material for the installation, including the Cameroon DIY manual (Harris, 2008) and the Honduras Gas Biodigester Information and Construction Manual for Rural Families by FUCOSOH (Brown, 2004).

The main set up of the Biomass Australia system is pictured in Figure 22. The biogas safety equipment, air water separator, biogas desulfurizer, pump, storage bag, and engine can be kept inside of the container, while the digester will be set up outside of the container. The demo container at KTH has the biogas system sectioned off from the rest of the container by a wall so that the systems operator will not be breathing in the fumes from the engine. This set up should be utilized in the next prototype for the same reasons. A hole will have to be cut into the door so that the biogas tube can be connected from the gas holder (outside) to the biogas pump (inside).

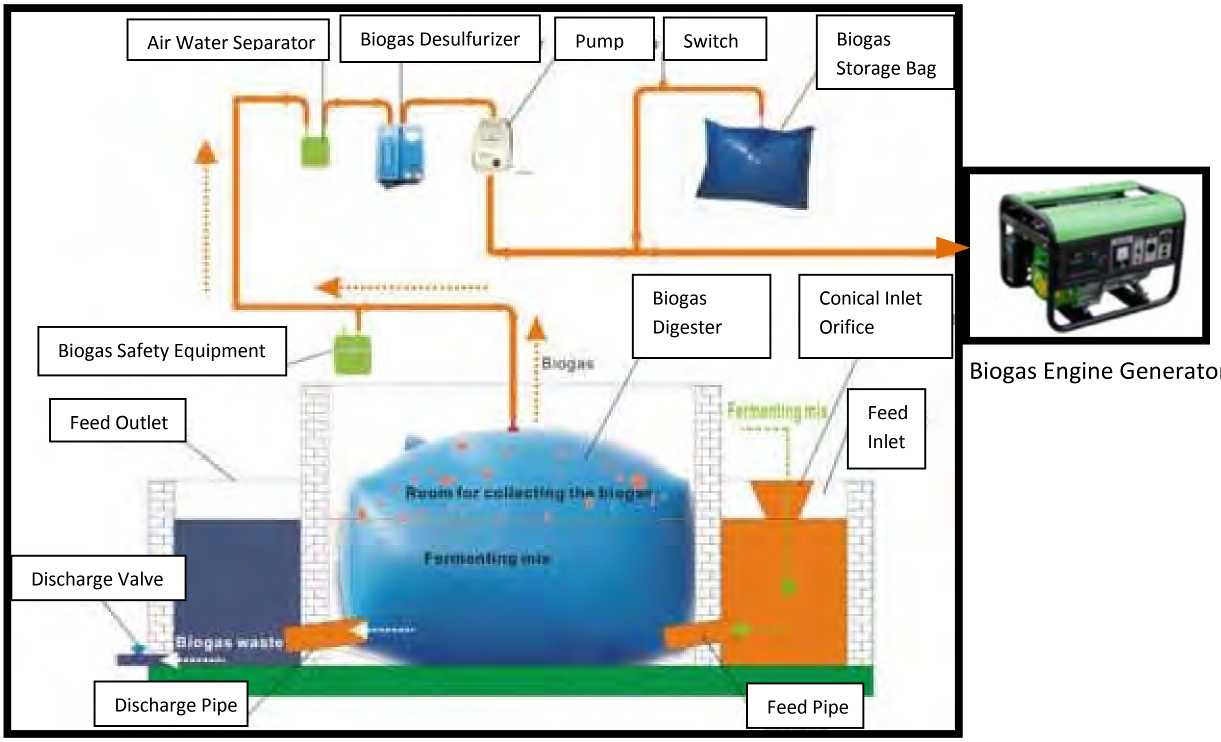


Figure 22 – Biogas Australia digester kit and engine set-up

9.6 Adequate Manual

The digester purchased will contain a manual outlining the construction of that specific digester. For the all-inclusive manual that will be created for the polygeneration unit, the authors should consult a few other manuals for polyethylene tube type digesters for extra tips and advice. There were a number of said manuals found during this project and previous work by the research team including the Cameroon DIY manual (Harris, 2008) and the Honduras Gas Biodigester Information and Construction Manual for Rural Families by FUCOSOH (Brown, 2004). The following needs to be addressed in the final manual:

- Connecting the biogas tube from the biodigester to the biogas storage bag to the biogas pump to the engine
- How to mix the manure and water
- How to properly load the digester
- How long it will take before biogas production can be expected
- Gas pressure required by the generator set

9.7 Monitoring Biogas Production

There is a Matlab script for anaerobic digestion optimization found during the review that might be available for purchase (Gaida 2011). The value of purchasing the Matlab Toolkit can be determined once more research is done on the unit functionality. In the meantime, the script created as part of this project can be used to do rough estimations of the amount of manure needed given the desired amount of electricity per day.

10 ANAEROBIC DIGESTION CALCULATIONS and PARAMETER JUSTIFICATIONS

A Matlab code was written that estimates the amount of manure and the number of cows needed to run the biogas engine. This script was designed to be flexible so that if some parameters of the systems are changed in the future the appropriate adjustments can be made in the code as well. The user can get a sense of the amount of resources required for a certain electrical capacity by going into the script and adjusting the desired electrical capacity ('Target') from 3.6kWh to the new quantity. In this code, I tried to take into account the percentage of volatile solids in the manure, type, breed, and live weight of the cows, and the gas consumption rate of the engine.

10.1 Motivation and Explanation

Not all of the manufacturers provided the hydraulic retention time or organic loading rates of their digesters which are needed to determine the amount of dung and number of cows needed to supply the digester. Since this information was not readily available, I tried bypassing the digester data by determining the amount of manure needed based on the gas production per kilogram of volatile solids added to the digester. Further research should be done to develop a reliable calculation that outputs the digester volume required given the amount of biogas needed in a given day. A Matlab Toolkit for anaerobic digestion was located but the author of the paper was not contacted and it is unclear whether or not the program is available for purchase (Gaida 2011). It might be worthwhile to invest in the program because customers will want biogas production estimates for their region. If there has not been enough data collected for different climates, then it might be difficult to provide a satisfactory estimate without a program.

10.2 Calculations

A combination of calculations and case study data was used to estimate the amount of manure and the number of cows needed to run the biogas engine. The literature survey of the anaerobic digestion process also informed the calculations needed to determine the amount of dung and water required to run a biogas genset. The calculations were done using Matlab and the code can be found in the Appendix. The calculations below explain the 'Alternate' portion of the code that is based on the gas produced per unit of volatile solids degraded (Barker, 2001). The 'Original' calculations (not described below) are based on the biogas yield per cow specification from the Kenyan Ministry of Agriculture.

The volume of biogas required to run the engine for the load of one day

Gas Required, m^3 = (Gas Consumption Rate, m^3/kWh) x (Target Capacity, kWh)

Total solids (dry matter) produced per cow. It is generally accepted that a ruminant produces 0.8% of its live weight as faecal dry matter in a day (Lekasi, Tanner, Kimani, & Harris, 2001)

TS per cow = 0.008 x (Live Weight, kg)

Calculate the amount of manure that a cow produces in one day.

Manure per cow, kg = (TS per cow, kg)/(TS content of cow manure)

Calculate the volume of biogas that can be expected from one cow.

Gas per cow, m^3 = (TS per cow, kg) x (%VS in faecal DM) x (%VS degradation/100) x (Gas per kg of volatile solids degraded in digester, m^3/kg VS)

Number of cows required.

Cows Required = (Gas Required, m^3) / (Gas produced per cow, m^3)

Calculate the total amount of manure required to run the engine.

TS Required, kg = (TS per cow, kg) x (# Cows Required)

Manure Required, kg = (TS Required, kg) / (TS content of cow manure)

The amount of water required to dilute the manure to the optimal solids content of the slurry.

H_2O Required, kg = [(TS Required, kg)/(OSC)] – (Manure Required, kg)

Total amount of slurry that must be added to the digester.

Slurry Required, kg = Manure Required, kg + H_2O Required

10.3 Parameter Justifications

Here I have defined a number of parameters of a biomass digestion and biogas engine system. Most of the parameters deal with the biomass anaerobic digestion process itself. It is very important that each parameter be carefully chosen to optimize the system productivity, but they should also be chosen to optimize the cost and economic aspects of the project. The feedstock parameters play a crucial role in determining the biogas production per day. For this reason, I examined the types of cows, different feedstock combinations, and types of biomass reactor systems in depth. Total volatile solids content and total solids content are two of the most important feedstock parameters needed to design the system.

Type of Cow = Friesian dairy cow
The most common cattle breed in Kenya is the Friesian dairy cow. Type of cow must be taken under consideration because dairy cow manure has a much lower percentage of total solids – and so volatile solids as well – compared to beef (Barker, 2001; Gichohi, 2009).

LiveWeight = 500 kg
Live weight depends upon the type of cow. Other common cows in Kenya include dairy cows Friesian, Ayrshire, Guernsey, and Jersey. These dairy cows weight 500-550kg, 450kg, 400kg, and 350kg respectively. Since Friesian cows have a weight ranging from 500-550kg, I chose to use the lower limit to account for the other cows in Kenya (Ouda, 2011).

TSC = 0.4
Total solids (also dry matter) content of cattle faeces is 40% and that of small ruminants is 50% (Lekasi et al., 2001).

GasVSD = 0.6861 m3 biogas/kg VS
This value for gas produced per kilogram of VS degraded was used in the James Barker calculations for a 1400lb Dairy Cow (Barker, 2001).

GasCow = 0.96 m3 biogas/cow/day
This value was taken from data compiled by the Kenya Ministry of Agriculture (Gichohi, 2009). I chose to use the data for the Garissa district in Kenya because it has an arid climate similar to that of the proposed Lodwar test site. It also seemed like the most rural option because it has a 50% poverty rate and 39.7% literacy level, and they are the farthest from a major city.

VSDPerc = 35%
From manipulation of James Barker calculations I found that a value of 35% was used for the percentage of VS that was degraded out of the total amount of VS added to the digester (Barker, 2001). Volatile solids degradation is estimated to be 40% for the digestion of dairy manure (Wilkie, 2005). I went with the smaller number because it is better to overestimate the amount of manure required than underestimate it.

VSTS = 0.76
This value represents the percentage of VS in TSC of manure. It is based on swine manure data from a study by Clemson University. I divided the volatile solids found in swine manure, 4.5 lb/AU/day, by the total solids found in swine manure, 5.9 lb/AU/day. This resulted in a percent volatile solids of about 76% (Chastain, Camberato, & Albrecht, 2001).

OSC = 0.08
Optimal solids content is 6-8% for maximum volatile solid degradation (Singh, 1971; Rajendran et al., 2012).

HRT and OLR
In the literature study, the hydraulic retention time and organic loading rate were reoccurring parameters (Nasir et. al, 2012). Thus, I tried using them to calculate the digester volume but without knowing the organic loading rate of the digester, I was not able to define a satisfactory relationship between the required amount of slurry, the HRT, and the necessary digester volume. Since only two manufacturers provided me with an organic loading rate and the rates of the studies in (Nasir et al., 2012)AD of LM varied over such a large range (1.9 – 20 kg VS/m^3 digester capacity/day), I did not feel comfortable estimating this parameter and using it to estimate the appropriate digester capacity. In a study referenced in Nasir et al., the methane yield did not significantly increase upon increasing the HRT from 20 days to 30 days, leading to the conclusion that HRT is not a significant operational parameter (Alkaya, Erguder, & Demirer, 2010). The HRT is actually dependent upon the optimal loading rate and how quickly the slurry moves through the digester. For suspended growth systems, an HRT of at least 10-15 days is required for adequate bacteria growth. Based on the study and the correlation between the HRT and the OLR, I decided not to use either of the two parameters and to determine the necessary digester capacity directly based on the gas production rates that the manufacturers provided me with. The gas production rates and corresponding capacities can be found in excel spreadsheet in the (Appendix—Market Search: Biomass Digesters).
<u>Reference</u> (Alkaya et al., 2010)

11 FUTURE CONSIDERATIONS and INVESTIGATION

The biogas digester and engine candidates were made based on the criteria outlined by POY Group A in their final report. The two candidates are the best for the next prototype in the Kenyan rural village but many other considerations should be taken when selecting the final biogas system. Insofar the intended use of the polygeneration project has been to provide rural electrification as well as serve as an emergency energy module after natural disasters. The biogas system chosen in this project might be too permanent to be effective in a natural disaster situation. There are a number of portable biodigester systems that could work, but it would still take a few days before a sufficient amount of biogas could be produced to run the biogas genset. A gasoline engine would be the most efficient in this case, though it would go against the goal for the unit to be 100% renewable.

11.1 Different Reactor Systems

An attached growth system should be considered for its low hydraulic retention time and ability to quickly digest a larger amount of substrate than the suspended growth system. The up flow anaerobic sludge blanket (UASB) and anaerobic filter (AF) reactor are just two examples of attached growth reactor systems that might be suitable for large-scale dairy farms with flushed manure systems (Nasir et al., 2012). They would also be useful if there was a very high demand for fertilizer because then more output slurry would be needed per day.

Below is a list of dairy farms that have Friesian cows. The farms would be good sites to test the polygeneration unit on a larger-scale operation. (Ouda, 2011)

1. Manera (Delamere Estates), Naivasha
2. KARI Naivasha, PO Box 25 Naivasha
3. KAR Lanet, PO Box 1275, Nakuru
4. Agricultural Development Corporation (ADC) Katuke Complex, PO Box 1392-30200 Kitale
5. Makongi Farm, PO Box 1320-30100 Eldoret
6. Kisima Farm, PO Box 19- 20107 Njoro
7. Gogar Farm PO Box 6-201080 Rongai
8. University of Nairobi Farm PO Box 29053-10202 Kabete
9. Sanctuary Farm PO Box 244-20177 Naivasha
10. Marimba Farm PO Box 32 Meru
11. ADC Olngatongo PO Box 680-30200 Kitale
12. Gicheha Farm, PO Box 236 Ruiru

11.2 Different Types of Feedstock

The compilation put together in the review by Nasir et al. (2012), the biogas yield for cow manure Is lower than the yield for swine or chicken. The lower biodegradability is due to the high amount of inorganic compounds and fibers left undigested after exiting the cow digestion system. According to Table 1 in a study by Nasir et al, pig and swine manure have resulted in a higher percentage of CH_4 in the biogas. Also, they have much shorter hydraulic retention times (HRT) which minimize reactor volume and ensure thorough mixing with an effective transfer of organic material for the active microbial biomass.

The conclusion of the review held that co-digestion improves biogas yield and bioreactor performance. Several studies concluded that co-digestion of manure with easily biodegradable organic waste yields a higher methane content (Nasir et al., 2012; Rajendran et al., 2012; Boe, 2006). Based on this conclusion, and the results of the review, the team should consider finding a feedstock supply that combines animal manure and perhaps human excretion, food scraps, or some type of plant clippings. Please note that mixing hog and chicken waste was not very effective and somewhat detrimental to the anaerobic digestion process (Nasir et al., 2012).

According to data collected by the Kenya National Bureau of Statistics (2010) goats, pigs, camels are other available livestock in Kenya.

11.3 Incentivizing Dung Collection

If the cows are free range, then collecting the dung will be challenging. If the system is for a couple of households, who is to say that one family will make sure to collect all of the dung while other families will fail to contribute dung yet continue to reap the benefits of electricity and clean water? Either there should be someone hired to collect dung, or people who input dung should get a discount on their electricity. They could also get an end of the month refund or something comparable based on how many kilograms of dung they contribute. You would only need a scale to check the weight of the feedstock and the person manning the container would keep records so that at the end of the month refunds could be awarded to families who contribute to the feedstock. This might help avoid the Tragedy of the Commons. On the other hand, it might be that the community members do not mind working together for the electricity and clean water generation.

If, however, the dung comes from cows that are on a large scale farm, then a flush system might be employed. If this is the case, then the feedstock supply will only depend on one large farm as opposed to collection by 25 different households.

11.4 Uses for Output slurry

The two main questions for the output slurry are:

1) What should be done with it? and

2) Who will be responsible for removing it?

In resource-poor regions of East Africa, cattle are more valuable for their manure and strength than their milk or meat because the dung is a nutrient rich fertilizer. Since fertilizer can be expensive for poorer families, there is a demand for a cheaper option in lower-socioeconomic regions. According to case studies of plastic tube digesters in Honduras (Brown, 2004) and household biogas digesters (Rajendran et al., 2012), the output slurry of the PTD is a clean, organic fertilizer that can be used for crop production. Burke 2001 suggests that the output slurry fertilizer can be sold to the public, nurseries, or other crop producers for some profit(Burke, 2001).

The KTH field team may want to see how many farms there are in the area and if they use manure as fertilizer. If there is a high demand, then sale of the output slurry might be a viable option and the profit could go toward the polygeneration unit maintenance. If someone is hired to man the unit, then he or she can sell the manure to local farmers. The farmers would have to come to the unit bringing their own containers to transport the slurry back to their farms. The reactor would get extremely messy if there was not a guaranteed demand for fertilizer.

Another option would be to have the sludge treated as municipal solid waste and disposed of at a nearby municipal waste unit. If the test region has a centralized sewage system in place and there is not a high enough demand for the slurry as fertilizer, then this could be a good option.

11.5 Biodiesel vs. Biogas

Biological waste from sugar cane, corn, etc. can be used to produce biodiesel. Biodiesel might be more suitable than biogas for natural disaster circumstances. For natural disasters, it will probably be necessary to transport the fuel in the container instead of producing it on site as is the case for rural electrification. I do not know the dimensions, weight, or logistics of transporting biodiesel or biogas, but it might be more cost effective and safer to transport biodiesel. The digester would not be needed, which would leave more space in the container for the fuel. If biodiesel proves to be more efficient than biogas, then this option should be considered for emergency situations.

11.6 Heat Recovery

Heat can be recovered from the exhaust pipe of the biogas engine. It was previously discussed as being used to heat the digester. This heat can also be used to provide central heating for houses, heating for livestock stables, newborn incubation units, refrigeration, etc.

12 FURTHER RESEARCH

Study the electrical compatibility of the generator set with the load appliance. I am not versed in enough electrical engineering to know which standards and requirements to look for in generator systems so someone should make sure that the engine I chose complies with the safety standards, from an electrical engineering perspective.

When you do field tests in Kenya, you will have to experiment with feedstock, loading rate, and water dung ratios to determine the maximum biogas production rate. There is only so much you can gain from calculations. In case studies of PTD installments in Kenya, Bolivia, Honduras, etc. the study concluded that failure of digesters is largely due to lack of proper loading (Brown, 2004). Thus, the operational manual for the polygeneration unit should have as detailed as possible instructions on how to properly load the digester and how long people can expect to wait before seeing steady biogas production.

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APPENDIX

Appendix A – List Of Specifications Requested Of The Manufacturer

Biogas Genset

a) Rated power (Boe)
b) Part Load Efficiency
c) Gas consumption (m3/kWh)
d) Biogas Conditions for the genset (Required methane content, %)
e) Lifetime (years)
f) Dimensions (mm x mm x mm)
g) Weight (kg)
h) Inlet pressure (kPa)
i) AC or DC?
j) Phase (single or three)
k) Speed (rpm)
l) Rated Voltage (V)
m) Rated Current (A)
n) Frequency (Hz)
o) Shipping time
p) Cost; Is it possible to buy a single genset?

Biogas Digester

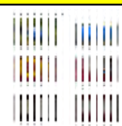
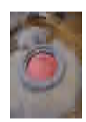
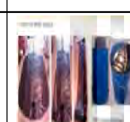
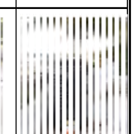
a) Gas production (m3/day)
b) Methanization Rate/Methane Content
c) Capacity (m3)
d) Lifetime
e) Temperature it can withstand
f) Optimal Feedstock (rice, corn husks, cow dung, etc.)
g) Water-Dung Ratio
h) Hydraulic Retention Time
i) Organic Loading Rate
j) Gas pressure
k) Inlet/outlet diameter and diameter of biogas pipe
l) Ease of installation (Technicians required? Moderate, difficult? How many people are needed? How long will it take?)
m) Safety: Fire resistant? Protection from rain needed? Easily punctured? UV resistant?
n) Package size (mm x mm x mm)
o) Package weight (kg)
p) Maintenance cost
q) Delivery time
r) Price
s) Other fittings:
    a. H_2S scrubber included? How much?

b. Gas storage bag: material, thickness, size, pressure, weight
c. Piping
d. Biogas pump: specifications and price for this

Appendix B – Comparison of Most Common Digesters in Kenya

\ Type of biogas digester Issues	Floating drum -16m^3	Fixed Dome - 16m^3	Plastic Tubular Digester 9 m^3
Average cost of installation (€)	1188-1403	712-1426	399
Ease of use/operation	Easy	Very easy	Easy
Perception	A bit dirty, but good	Very good	On trial
Efficiency	Needs time	Needs time	Works faster
Ease of installation	Simple to Complex	Very complex	Simple
Durability	At least 30 years	At least 30 years	15 years (est)
Contractors needed to install	2-3	4-6	1
Technical problems reported	Some	Very few??	Quite a few
Extension/technical support	Limited	Some	A little
Minimum cattle/TLU needed	3-4	2-4	2
Maintenance	Every 3-4 years	Minimal (only feeding digester)	Unknown
Numbers installed	>1000	300-800	150 – 200

Appendix C – Market Search: Biomass Digesters

Company	Biogas Australia Pty Ltd	BiogasSA (Biogas South Africa)	ACME	Chongqing Xinshui Machine Manufacture		Guangdohng Huizhou Biogas	Ecofys	Biogas International	Shenzhen Puxin Technology Co. Ltd.	Samuchit Enviro Tech Pvt Ltd
Model	DIY PVC Digester kit	DIY Biobag (PVC) Digester Kit	Household Soft Biogas Digester	Series M M15-K120	Series H H15-Q80	Family sized digester and plastic bag digester	Plastic Bag Digester	Flexi Biogas System	Portable Biogas plant	ARTI Household Biogas Kit
Capacity (m3)	16	20	10	15	15	8 (0.55mm thickness)	-	-	2	1
Gas Production (m3/day)	6.2 (rough estimate)	4-6	2-4	3	2	1.2-2.4m3/day (above 15°)	-	-	1.5	1
Price (EUR)	2300* (incl. Shipping)	1382 ex works	168	3860	386*	76	300	-		
Lifetime (years)	5	10 (15 if covered)	15	10	10	10	-	-		
Ease of Installation (Moderate, difficult)	1/2 day for 2 people	Simple; 1 week for 1 brick layer and 5 labourers	-	-	-	1/2 day for 2 people	Easy (0.5-1day)	1-2days		
Retention Time (days)	-	25	60	-	-	7-15	-	-		
Comments: Fittings and Accessories	Kit Includes: Double membrane PVC biogas digester, pipes and fittings, biogas booster pump (electric), water separator, biogas purifier, safety relief valve, single burner stove. *Price includes 1 16m3 digester with fittings, water separator, biogas purifier and booster pump; 1 20m3 biogas holder; 1 2kWh biogas genset, manual start; and shipping to Mombassa, Kenya.	Kit Includes: 20m3 PVC Bag, Gas pipe and fittings, digester pipe fittings & valves, pressure pump &desulfurizer, moisture trap &safety valve, Owners Manual with full installation and operation detail. (An extra gas storage back is not included because the gas is stored in the actual biobag)	Fittings and pump not included as in a kit, but they are available for purchase. (See 'Fittings' tab)	* Price includes fitting and pump.	*Price includes biogas digester, pipeline (25m). joint , gas nozzle, safety valve, gas-water separater, biogas desulfurizer, PVC hoop, booster pump, pipeline control switch	Digester package includes digester (cylindrical or rectangular), 2 clamps, special glue, 0.3 m2 extra PVC material, and 1 gas pipe.	Internal gas storage bag, no secondary gas storage needed	Includes: Flexi digester, suscreen micro greenhouse tunel Ramtons Whirlwind Technology 501 Double Burner Stove, piping and fittings (up to 30m/kit), training on maintenance and repair	The plant includes a PUXIN portable digester, a desulfurizer, a gas storage bag, a gas pump, a solar charger, as well as a gas pipeline and applicances	Along with the SET kit, we would have to provide a plastic tank (one commonly used for water storage). Also, the biogas is mainly used for cooking and might not be sufficient for energy generation
Picture										
Country Headquarters	Australia	Johannesburg, SA	China	China	China	China	Netherlands	Nairobi, Kenya	China	India

Appendix D – Market Search: Biogas Engines

Company manufacturing	Biogas Australia Pty Ltd	Chongqing Wangliyuan Agricultural	Anhui Fenghuo Renewable Energy CO.,LTD	Wuhan Acme Agro-Tech Co.	Shenzhen Puxin Technology Co. Ltd.
ENGINE MODEL	**Handy type JQ1600BG/LPG** Biogas Genset (Engine model CC152F)	**0,6kW**	**0,8kW**	**AM1500BG 1kW** Biogas Generator (Engine model AM168FG)	**PX-BG 1.2kW** Biogas Genset (Engine Model CC168F)
Max power (kW)	**0.5**	0.6	0.8	**1**	**1.2**
Investment Cost (EUR)	2300* (incl. Shipping)	765-1149	1934	320	517
Gas consumption (m3/kWh)	0.7m3/kWh	–	≤0.45	< 0.7m3/kWh	1.2 m3/kWh
Required Methane Content (%)	> 55%	–	–	> 60%	–
Lifetime (years)	–	–	–	–	–
Dimensions (mm)	–	"carton size"	435x340x400	610x450x470	6200X480X480
Weight (kg)	–	–	24.3	43	56
Inlet pressure (kPa)	2-12	–	–	0.6-1.2	–
Phase	Single	–	single	Single	Single
Cylinders	–	–	–	1	
AC/DC	AC	–	DC	AC	AC AC output: 220V 50Hz, DC output: 12V 8.3A
Starting System	Manual	–	–	Electric/Manual	–
Speed (rpm)	–	–	–	1500	–
Rated Voltage (V)	230	220/110	220/110	230	220
Rated Current (A)	–	–	3.6	12V 8.3A	8.3
Frequency (Hz)	50	50/60	50/60	50/60	50
Shipping time	–	1 week	34 days	10-15 days	1 month
Company replied to inquiry?	Yes	no	no	Yes	Previously contacted
Country of Origin	Australia	China	China	China	China
Standard Engine Configuration	Waterproof socket, AC circuit breaker, DC overload protection, V DC socket				
Other Comments	Size of connecting pipe: 9.5mm inside diameter, 15mm outside diameter *Price includes: 1 16m3 digester with fittings, water separator, biogas purifier and booster pump; 1 20m3 biogas holder; 1 2kWh biogas genset, manual start; and shipping to Mombassa, Kenya.		No longer available		They also have sizes 3, 4, 5, and 10 kW http://puxinbiogas.en.alibaba.com/productgrouplist-210329530-3/Biogas_generators.html?isGallery=Y

Company manufacturing	Biogas Australia Pty Ltd	Chongqing Xinshui Machine Manufacture	Chengdu Rare Tech Co., Ltd.	Shengdong New Energy Technology Co., Ltd.	Jiangsu Hopepower New Energy Development Co.,	Fuan Kinger Electrical Machinery Co.
ENGINE MODEL	**JQ2500BG/LPG-B** Biogas Genset (Engine model CC107F)		**RTA2B 2kW** Biogas Genset (Engine model R-D400) and optional CHP Unit	**2kW Biogas Genset** (Engine Model 168FB-B)	**HOPEPOWER HP2000-B** Biogas Genset	**KIGER LPG5500** Biogas Genset (Engine model LPG160) also have
Max power (kW)	**1.2**	**2**	**2**	**2**	**2**	**2**
Investment Cost (EUR)	2300* (incl. shipping)	232	1890	435	–	80-270
Gas consumption (m3/kWh)	0.7m3/kWh	2	0.73 - 0.81 m3/kWh	0.6 m3/kwh	0.33 m3/kWh	1.4-1.8 m3/kWh
Required Methane Content	> 55%	–	> 50%	–	–	–
Lifetime (years)	–	2	–	–	–	–
Dimensions (mm)	–	625X460X500	800x800x800	610x450x470	600x450x470	602x442x445
Weight (kg)	–	43	180	47	42	37
Inlet pressure (kPa)	2-12	3–8	1-5	> 5	–	–
Phase	Single	Single	Single	–	–	Single
Cylinders	–	–	1	1	1	–
AC/DC	AC	AC	–	DC (12V/8.3A)	AC	DC (12V/8.3A)
Starting System	Manual	–	Electronic	Manual (electric opt.)CDI Ignition system	Electronic	–
Speed (rpm)	–	3600	1500	–	3600	3600
Rated Voltage (V)	230	220	230	220/230	110/120/220/230/240	230
Rated Current (A)	–	12	8.7	–	–	25
Frequency (Hz)	50	60	50	50	50/60	50
Shipping time (month)	–	1 month	1-2 months	20 business days	–	1 month
Contacted?	Yes	Previously contacted	Yes	Yes	No	No
Country of Origin	Australia	China	China	China	China	China
Standard Configuration	Waterproof socket, AC circuit breaker, DC overload protection, V DC socket		CE	EPA and EC approved. Do not use the generator indoors nor in a humid environment. Generator must be on firma and flat ground.		
Other Comments	Size of connecting pipe: 9.5mm inside diameter, 15mm outside diameter *Price includes: 1 16m3 digester with fittings, water separator, biogas purifier and booster pump; 1 20m3 biogas holder; 1 2kWh biogas genset, manual start; and shipping to Mombassa, Kenya.		**2kW (RTS, RTT, RTI, RTC)** Biogas Genset (Cummins Biogas Generator (RTC)). CHP system is $2800 They have a ton of generators. They have a Cummins Biogas Generator (RTC). All of the generators are advertised as having the same info but I think the cummins is on the larger side so above are the specs		They also have 3kW, 5kW, 10kW, and 15kW	

Company manufacturing	KIGER	KIGER	KIGER	Wuhan Acme Agro-Tech Co.	Wuhan Acme Agro-Tech Co.	Shenzhen Puxin Technology Co. Ltd.
ENGINE MODEL	**2kW**	**2.5kW**	**2.8kW**	**ACME 2kW** Biogas Generator (They also have 1kW and 2kW)	**AM3500BG 3kW** Biogas Generator (Engine model AM190FG)	
Max power (kW)	2	2.5	2.8	**3**	**3**	**3**
Investment Cost (EUR)	200-270	200-270	200-270	519	672	935
Gas consumption (m3/kWh)	1.4-1.8	1.4-1.8	1.4-1.8	< 0.7m3/kWh	< 0.7m3/kWh	3.5
Required Methane Content (%)	–	–	–	≥ 60%	≥ 60%	–
Lifetime (years)	5years	–	–	–	–	15
Dimensions (mm)	595*445*460	595*445*460	595*445*460	710x710x600	700x525x560	620X480X480
Weight (kg)	41	42	44	93	81	93
Inlet pressure (kPa)	1.2-1.7	1.2-1.7	1.2-1.7	–	0.6-1.2	–
Phase	single	single	single	Single	Single	Single
Cylinders	–	–	–	1	1	–
AC/DC	AC	AC	AC	AC	AC	AC
Starting System	–	–	–	–	Electric/Manual	–
Speed (rpm)	3000	3000	3000	1500	1500	–
Rated Voltage (V)	220	220	220	230	230	–
Rated Current (A)	9	11	12	12V 8.3A	12V 8.3A	–
Frequency (Hz)	50	50	50	50	50/60	–
Shipping time	1 week	1 week	1 week	10-15 days	10-15 days	1 month
Contacted?	yes	yes	yes	Yes	Yes	Yes
Country of Origin	China	China	China	China	China	China
Standard Configuration						
Other Comments	Min 100 pieces	Min 100 pieces	Min 100 pieces	The above details are kind of sketch, based on alibaba not the original spec sheet (p.22)		

Company manufacturing	Jiangsu Hopepower New Energy	GUANGZHOU DINGFENG MACHINERY	Shenzhen Puxin Technology Co., Ltd.	Shanghai Better Industry Co., Ltd.	Biogas Australia Pty Ltd	Shanghai Better Industry Co.	KIGER	Weifang Heng An Imp&Exp Co.
ENGINE MODEL	**HOPEPOWER HP3000-B** Biogas Genset	**3kW**	**3kW**	**3kW**	**JQ6500BG/LPG-B** Biogas Genset (Engine model CC188F)	**BETTER BG350** Biogas Generator	**5kW**	**CFEM5K** Biogas Genset (Engine model CFQ188FE)
Max power (kW)	**3**	3	3	3	**3.5**	**3.5**	5	5
Investment Cost (EUR)	–	1225	1000 generators	766-3828	2300* (incl. shipping)	766-3828	200-270	915-1220
Gas consumption (m3/kWh)	0.33 m3/kWh	0.7 (m3/kWh)	3.5 (m3/kWh)	–	0.7m3/kWh	3.5m3/hour	1.4-1.8	0.7
Required Methane Content	–	–	–	–	≥ 55%	–	–	–
Lifetime (years)	–	–	15 years	–	–	–	–	–
Dimensions (mm)	700x525x580	700*525*560	620*480*480	–	–	–	690*515*565	675x510x550
Weight (kg)	72	75	93	–	–	–	72	190
Inlet pressure (kPa)	–			–	2-12	–	1.2-1.7	3
Phase	–	single	single	–	Single	Single	single	Single
Cylinders	1	–	–	–	–	–	–	
AC/DC	AC	AC	AC	–	AC	AC (DC output 12V)	AC	
Starting System	Electronic	–	–	–	Manual	–	–	
Speed (rpm)	3600	–	–	–	–	1500	3000	3000
Rated Voltage (V)	110/120/220/230/240	220	230	230	230	230	220	230
Rated Current (A)	–		8.3	8.3	–	8.3	20	10
Frequency (Hz)	50/60	50	50	50/60	50	50/60	50	50
Shipping time (month)	–	10 days	30 days	20-30 days	–	20-30 days	1 week	
Contacted?	No	yes	yes	yes	Yes	Yes	yes	Yes
Country of Origin	China	China	China	China	Australia	China	China	China
Standard Configuration					Waterproof socket, AC circuit breaker, DC overload protection, V DC socket			
Other Comments		http://www.weiku.com/products/8813800/Guangzhou_Biogas_generator_distributor_DF_3500BG.html			Size of connecting pipe: 9.5mm inside diameter, 15mm outside diameter *Price includes: 1 16m3 digester with fittings, water separator, biogas purifier and booster pump; 1 20m3 biogas holder; 1 2kWh biogas genset, manual start; and shipping to Mombassa, Kenya.		Min 100 pieces	Currently out of 5kW, they only have 10kW and 20kW

Company manufacturing	KIGER	KIGER	Weifang Naipute Gas Genset Co.	Shandong Lvhuan Power Equipment Co.	Weifang Huaxin Electric Motor Co.
ENGINE MODEL	**6.5kW**	**6.5kW**	**NPT 10GFT** Biogas Genset (Engine Model NQ15D1.5)	**LVHUAN LHBG10** Biogas Genset (Engine Model LH2100)	**HORIS HQ10GF** Biogas Genset (Engine Model HX2100DT)
Max power (kW)	6.5	6.5	10	10	11 (they offer
Investment Cost (EUR)	200-270	200-270	5035 per set	4222	
Gas consumption (m3/kWh)	1.4-1.8	1.4-1.8	0.6	(32% generating	
Required Methane Content			–	≥ 40	
Lifetime (years)			15-20	15-20	
Dimensions (mm)	690*515*565	690*515*565	1200x650x980	1450X700X1100	
Weight (kg)	75	75	380	700	
Inlet pressure (kPa)	1.2-1.7	1.2-1.7	2-50	5-20	
Phase	single	three	–	Three	Three
Cylinders			4	2	2.L
AC/DC	AC	AC	–	AC	AC
Starting System					
Speed (rpm)	3000	3000	1500	1500/1800	1500/1800
Rated Voltage (V)	220	220	400/230	400/230	220/380
Rated Current (A)	20	20	18	18	
Frequency (Hz)	50	50	50	50/60	50/60
Shipping time (month)	2 weeks	2 weeks	1 month	1 month	
Contacted?	yes	yes	No	Yes	No
Country of Origin	China	China	China	China	China
Standard Configuration					
Other Comments	Min 100 pieces	Min 100 pieces			Kind of sketchy

Company manufacturing	Olympian	Ettes Power Machinery Co.	Weifang Naipute Gas Genset Co.	Shandong Lvhuan Power Equipment Co.	Camda Biogas
ENGINE MODEL	**GEUG13S1** LP &Natural Gas Genset	**EC-18B** Biogas Genset (Cummins Engine 4BT3.9)	**NPT 15GFT** Biogas Generator (Engine Model	**LVHUAN LHBG20** Biogas Genset (Engine Model LH4100)	**KDGH-25-G** Genset
Max power (kW)	13	15	15	20	25/31; 33
Investment Cost (EUR)			6294 per set	6707	
Gas consumption (m3/kWh)			0.6	(32%	230g/kWh
Required Methane Content			–	≥ 40	
Lifetime (years)			15-20	15-20	
Dimensions (mm)	1348x710x1004	1950x1000x1350	1420x710x980	1650x720x1250	1800x710x1350
Weight (kg)	405	1010	460	750	900
Inlet pressure (kPa)		7-20kPa	2-50	5-20	
Phase	Single		Three	Three	
Cylinders	4	4.L	4	4	4 in-line
AC/DC			AC	AC	
Starting System					
Speed (rpm)	1500/1800	1500/1800	1500/1800	1500/1800	1500
Rated Voltage (V)			400/230	400/230	
Rated Current (A)			27	36	
Frequency (Hz)	50/60	50/60	50	50/60	
Shipping time (month)			1 month	1 month	
Contacted?	No	Yes	No	Yes	No
Country of Origin					
Standard Configuration					
Other Comments	PON POWER AB (SWEDEN) HVITFELDTSGATAN 15 GOETEBORG VASTRA GOTALANDS LAN, SE-411 20 Phone numbers: 46 31 60 64 90 GENERAL INFO http://www.cat.com/dealer-locator	They have nothing smaller	Smallest genset is 10kW	Partners with Puxin for biogas digesters.	

Appendix E – Quotes and Official Information from Suppliers

E.1 Biogas Australia Genset Specifications

Quotation for household biogas generators

Valid Date: 2011.1.1-2011.5.30

	Handy typeJQ1600BG/LPG	JQ2500BG/LPG-B	JQ6500BG/LPG-B
Series No.			
Types	Biogas genset	Biogas genset	Biogas genset
Fuel	**Biogas / CNG**	**Biogas/CNG**	**Biogas/CNG**
Rated Power	**500W 600W**	**1200W 1800W**	**3500W 4800W**
Maximum power	**600W 700W**	**1300W 2000W**	**4000W 5000W**
frequency	50HZ	50HZ	50HZ
DC OUT	12V 8.3A	12V 8.3A	12V 8.3A
Type of generator	single-phase brushless generator	Single-phase motor brush	Single-phase motor brush
Engine Model	CC154F	CC170F	CC188F
Bore x Stroke	54 x 38mm	70 x 54mm	88 x 64mm
Displacement	87cc	209cc	389cc
Igniting system	T.C.I.	T.C.I.	T.C.I.
Oil Capacity(L)	0.35	0.55	0.9
Size of connecting pipe	9.5 inside diameter,15mm outside diameter	9.5 inside diameter,15mm outside diameter	10.5 inside diameter,12mm outside diameter
Gas consumption(m^3/kw.h)	**0.7**	**0.7**	**0.7**
Standard Configuration	Waterproof socket AC Circuit breaker DC overload protection V DC socket	Waterproof socket AC Circuit breaker DC overload protection V DC socket	Waterproof socket AC Circuit breaker DC overload protection V DC socket
		With timer	**With timer**

Requirements for biogas fuel:

1- Content of methane should be over 55%

2- Pressure of biogas:2KPA ~ 12KPA

3- The biogas must be got rid of water,H2S by the biogas purify system before going to the biogas generator.

4- Can be used in parallel multi-machine,the power can reach to 10kw,20kw,30kw……（Need to use parallel machine）

E.2 Biogas Australia Digester Specifications

Soft biogas digesters			
Spec.(m^3)	Shape 	NO. of people supplied	Daily biogas Output (m^3) (Only for reference)
6	Cylindrical	3	2.4
8	Cylindrical	5	3.2
10	Cylindrical	6	4
12	Cylindrical	7	4.8
14	Cylindrical	8	5.6
16	Cylindrical	10	6.2
20	Cylindrical	12	7.3
25	Cylindrical	15	8.4
30	Cylindrical	17	9.2
40	Cylindrical	26	12.6
50	Cylindrical	28	14.2
Function	The equipment is specifically designed for producing biogas. It holds the fermenting mix (manure/grass clippings/sewage etc.) as well as acting as the storage for the biogas. The biogas can be used for lighting, cooking, generating etc.		
Packaging	Carton		

E.3 Wuhan ACME 1 kW Genset Quote and Specifications

WUHAN ACME AGRO TECH CO.,LTD.

ADD:Rm.17-01-0104,RongQiao City,JieFang AVE66#,Wuhan,China
Tel:0086-13125174870
Fax No: 0086-27-8331 5893
Email:leo@acmeagro.org
Http:www.acmeagro.org
Contact:Leo Liu

Quotation Of AM1500BG 1KW Biogas Generator	
1. Generator	
Model	AM1500BG
Type	Brush, copper wire, electric poles
Rated Frequency(HZ)	50/60
Rated Output Voltage(V)	230
Rated Power Output(KVA)	1
Max. Power Output(KVA)	1.2
Power Factor(cosΦ)	1
Method of Regulate Voltage	AVR
2.Engine	
Model	AM168FG
Type	Single cylinder, air cooled, four stroke,
Fuel Grade	Biogas, natural gas, liquefied gas, gas.
Bore×Stroke	68mm*54mm
Displacement(cc)	196cc
Gas Compression Ratio	<0.7
Ignition Method	Non-contact transistor
Starting Method	Electric/Manual
Noise Level at 7m distance	61dm
3.Other details	
Engine Switch	√
AC Circuit Breaker	√
DC Circuit Breaker	Optional
Fuel Gauge	√
Oil Alert System	√
Circuit Breaker Without Fuse	√
Accessory AC Plug	Optional
Electric Starter	√
Battery Tray	√
Dimensions(L×W×H)	610×450×470mm
Net Weight(kg)	41
Gross Weight(kg)	43
20FT/40FT/40HQ Container capacity	240/485/500
authentication	9001
4.Price	
Manual starting type	412USD
Electric Starting type	449USD

E.4 Wuhan ACME Household Biodigester Quotation

ACME AGRO GROUP LIMITED

WUHAN ACME AGRO-TECH CO., LTD.

ADD:Rm.17-01-0104.RongQiao City.JieFang AVE66#.Wuhan.China

TEL：+86-27-83315893 E-mail：leo@acmeagro.org Website:www.acmeagro.org

Membership of UNDP South-South Global Assets and Technology Center(SS-GATE)

Membership of China Council for the Promotion of International Trade（CCPIT）

Household biogas equipements with soft pvc digester

S/N	ITEM	UNIT	QTY	UNIT PRICE	AMOUNT
Necessary equipments					
1	10CBM SOFT BIOGAS DIGESTER	UNIT	1	$217.00	$217.00
2	BIOGAS FITTINGS	UNIT	1	$27.00	$27.00
3	1CBM BIOGAS STORAGE BAG	UNIT	1	$44.00	$44.00
4	15W BIOGAS PUMP	UNIT	1	$36.00	$36.00
TOTAL AMOUNT					**$324.00**
Optional equipments					
5	GAS STOVE(SINGLE)	UNIT	1	$15.20	$15.20
6	BIOGAS WATER HEATER	UNIT	1	$92.00	$92.00
7	BIOGAS RICE COOKER	UNIT	1	$46.00	$46.00
8	BIOGAS LAMP	UNIT	2	$9.00	$18.00

E.5 Chengdu Raretech 2kW Genset Specifications

RARE TECH CHENGDU RARE TECH CO., LTD
成都锐尔科技有限公司

Part 2 Technical Specifications

1) Specifications of Genset

Item / Model	RTA2B
Genset Specifications	
Prime Power (kVA/kWe)	2.5/2
Thermal Output @ Prime Rating (kW.h)	5.7
Rated Voltage (V)	230
Frequency (Hz)	50
Rated Current (A)	8.7
Voltage Stabilized Regulation	≤±1.5%
Voltage Instantaneous Regulation	≤±15%
Voltage Recovery Time (s)	≤0.5
Voltage Fluctuation Ratio	≤1%
Voltage Wave Distortion Ratio	≤5%
Frequency Stabilized Regulation	≤1%(adjustable)
Frequency Instantaneous Regulation	+/- 9%
Frequency Recovery Time (s)	≤8
Frequency Fluctuation Ratio	≤1%
Generator Insulation Class	H
Sound Level dB(A) @ 1 meter	≤85
Overall Dimensions(mm) (L*W*H) (for silent CHP unit)	800*800*800 Weight: 180kg
Sound Level of Silent Type	60 dB(A) @ 7 meters or 68 dB(A) @ 1 meter

2) Specification of Biogas Engine

Gas Engine Specifications	
Engine Model	R-D400
Type	4-cycle, single cylinder, water-cooling

Web: www.rarehightech.com
Email: poseidon@rarehightech.com Tel: 0086-28-83600053 Fax: 0086-28-83600050
Add: No. 619, Fuxing Ave, Qingbaijiang, Chengdu City, Sichuan Prov, China

CHENGDU RARE TECH CO. LTD

成都锐尔科技有限公司

Cylinder(s)	1
Bore x Stoke(mm)	80*80
Displacement (cc)	402
Compression Ratio	11.6 : 1
Rated Speed (RPM)	1,500
Mixer	Venturi
Ignition System	Electronic
Speed Governor	Electronic
Fuel	biogas (with CH4 content: > 45%)
Gas Consumption (m^3/kW·h)	100% of rated power: 0.73 m^3/kW·h 75% of rated power: 0.76 m^3/kW·h 50% of rated power: 0.81 m^3/kW·h (test is based on CH4 content 60%)
Idling Speed (rpm)	800±50
Oil Recommended	SAE 15W/40CD, gas special lube oil
Oil Consumption	≤0.35g/kW.h
The Highest Exhaust Temp. (℃)	≤550 (with water cooling exhaust manifold)

Appendix F – Matlab Code

```
% By: Niara Wright
% Biogas Yield Calculations
% Domain: KTH Polygeneration Research team

% Variable Definition

% DigV      = Minimum digester volume required
% GasVS     = volume of biogas yield per kg of VS
% GasPerCow = Volume of biogas yielded per day per cow
% GasProd   = Volume of biogas produced per day
% GasReq    = Volume of biogas required per day to run the engine
% HRT       = Hydraulic Retention Time (days)
% H2OV      = Volume of Dilution water needed to reach the optimal solids
% content
% Manure    = Mass of manure produced by one cow
% ManureV   = Volume of manure produced by one cow
% ManureReq = Mass of manure required to sustain electricity capacity
% OLR       = Organic Loading Rate
% OSC       = Optimal Solids Content of manure is 6-8% according to the
% literature.
% OVSC      = Optimal Volatile Solids Content of manure
% SlurryV   = total volume of slurry after dilution
% TSC       = total solids content of manure
% TSCow     = total solids content of manure/cow/day
% VSD       = Mass of volatile solids destroyed in digester
% VSManure  = Volume of VS produced by one cow
% VSDig     = Mass of VS inside of the digester
% VSDPerc   = % volatile solids degraded in digester
% VSPerc    = % volatile solids in manure (%)
% VSReq     = Mass of VS required for engine

conv = 0.1;       % m3 of digester volume per kg of slurry (estimated from POY)
GasVSD = 0.6861;  % m3 biogas/kg VS    INPUT VALUE: Based on type of cow
GasCow = 0.96;    % m3 biogas/cow/day      (from MinOfAgro)
% HRT = 25;       % days             INPUT VALUE: Digester spec
OLR = 4;          % kg VS/m3 digester   INPUT VALUE: Digester spec
```

```
OSC = 0.08;
TSC = 0.4;
VSDPerc = 40;
VSTS = 0.76;      % VS/TS (TS is 76% VS)
LiveWeight = 500; % kg

%% Original: Based on biogas yield per cow specification

% ENGINE
MaxPwr = 1.2;      % kW        INPUT VALUE: Biogas Australia 1.2 kW Genset
GasConsR = 0.7;   % m3/kWh     INPUT VALUE
Target = 3.6;     % kWh

Hours = Target/MaxPwr;        % Hours required to reach target capacity
GasReq = GasConsR*Target;      % Volume of biogas required per day (m3)

% DIGESTION
CowsReq = GasReq/GasCow;

TSCow = 0.008*LiveWeight;         % kg
TSReq = TSCow*CowsReq;            % kg
ManureReq = TSReq*(1/TSC);        % kg

H2OReq = (ManureReq*TSC)/OSC-ManureReq;   % kg
SlurryReq = ManureReq + H2OReq           % kg
DigV = SlurryReq*conv;                  % m3
fprintf('%0 .2f m3 of biogas are required to run the engine,\n thus you need a % d m3 digester
and % d cows to supply % d kg of manure each day. \n',...
   GasReq,ceil(DigV),ceil(CowsReq),ceil(ManureReq))


%% Alternate: Uses biogas yield per kg of VS added specification.
%This calculation takes into account the amount of volatile solids that are actually degraded
in the digester.

% ENGINE
MaxPwr = 1.2;      % kW        INPUT VALUE: Biogas Australia 1.2 kW Genset
GasConsR = 0.7;   % m3/kWh     INPUT VALUE
```

```
Target = 3.6;     % kWh

Hours = Target/MaxPwr;        % Hours required to reach target capacity
GasReq = GasConsR*Target;      % Volume of biogas required per day (m3)

% DIGESTION
TSCow = 0.008*LiveWeight;      % kg TS/cow
ManureCow = TSCow*(1/TSC);      % kg manure/cow
% GasCowCalc = TSCow*VSTS*GasVS
GasCowCalc = TSCow*VSTS*(VSDPerc/100)*GasVSD    % This would be used if the biogas yield is given per unit of VS destroyed not just VS added

CowsReqAlt = GasReq/GasCowCalc
TSReqAlt = TSCow*CowsReqAlt;           % kg
ManureReqAlt = TSReqAlt*(1/TSC);        % kg
H2OReqAlt = (ManureReqAlt*TSC)/OSC-ManureReqAlt;   % kg
SlurryReqAlt = ManureReqAlt + H2OReqAlt           % kg
DigVAlt = SlurryReqAlt*conv;                  % m3
% DigVAlt = (TSReqAlt*VSTS)/OLR;                  % m3

fprintf('Alternate: %0 .2f m3 of biogas are required to run the engine,\n thus you need a % d m3 digester and % d cows to supply % d kg of manure each day. \n',...
   GasReq,ceil(DigVAlt),ceil(CowsReqAlt),ceil(ManureReqAlt))
```