Manure Energy Exploitation

The Use of Biogas to secure Water Supply in Developing Countries

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Abstract

This thesis has investigated the feasibility to produce electricity for water pumping in developing countries by using a simple biogas reactor system with an internal combustion. This was done by visiting Katulani Secondary School (SS) in Kitui, Kenya. Here a biogas reactor fed with pig manure produces biogas currently used for cooking. A grid connected water pump owned by the school is also located here. Data collection through measurements and interviews was done during 8 days. 10 tests gave an average methane content of 57.9 %. This resulted in a lower heating value of 4.94 kWh/m³ based on ambient conditions. 9 tests showed average hydrogen sulfide and ammonia concentrations in the gas of 2,000 ppm and 5 ppm respectively.

The results of this work showed that the pigs at Katulani SS do not currently produce enough manure to cover the cooking demand of about 12 m³ biogas. Biogas can therefore not in addition be used for water pumping before measures are taken to increase the feedstock quantity. Measures could be to change fodder type, increase number of pigs, improve slurry mixture or apply co-digestion.

At an obtained gas production of about 17.1 m³ biogas per day, 5.1 m³ biogas is available to be used in an engine. This thesis shows that at a required water supply of 5 m³ per day, an otto gas engine could be chosen if the compression ratio of the engine is increased. The otto engine has the advantage that it can run solely on biogas. A pilot-injection engine could also be chosen. This engine might be more suitable due to its ability to run at lower biogas volumes and to pump more water at the same volume of biogas compared to otto engines. A minimum diesel injection of 15 % would cost 9.81 Kenyan shillings (KES)/m³ water.

The results of the thesis shows that there is a potential for using biogas in a low-complex system for pumping water at low costs compared to using grid electricity. At the same time, there is additional synergy effects as pork meat, quality manure fertilizer and alternatively through taking advantage of the engine exhaust.

Content

List of acronyms

A/F – Air/fuel ratio
AT – Autotransformer
BG – Biogas
COD – Chemical oxygen demand

DM – Dry matter
DOL – Direct on-line
Eq. – Equation
FF – Fresh Feedstock
HRT – Hydraulic retention time
HTSA – Help to Self-help in Africa
KES – Kenyan shillings (1 KES = 0.07 Norwegian kroner 28.05.2013)
LHV – Lower heating value [kWh/m^3]
LHV' – Lower heating value [kJ/kg]
M.a.s.l. – Meters above sea level
N – Number of moles
n/a – Not available or not applicable
NDIR – Non-dispersive infrared
NTP – Normal temperature and pressure (0 ˚C, 101.3 kPa)
O/L – Overload
O/M – Oxygen/methane ratio
OLR – Organic loading rate
Sfc – Specific fuel consumption
SS – Secondary School
VS – Volatile solids
WB – Wheel barrow

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1 Introduction

The introduction starts with some background information about the challenges regarding cooking and water availability in Kenya and Kitui in specific, before presenting the research objectives with related research questions. The obtained user requirements are listed based on interviews and experience from the site Katulani SS. Key assumption and limitation are then presented before a short literature review on earlier work in the field and a report outline.

1.1 Background

In rural areas of Kenya, and other comparable countries, there are huge challenges regarding energy supply. Conventional fossil fuels are steadily getting more expensive at the same time as they contribute to global climate change. Deforestation is a consequence of a growing demand for wood used as timber and for cooking. At the same time cooking by using wood or charcoal have major negative health effects due to flue gasses in the kitchen.

The water situation in many African countries is also harsh. Many places, water cannot be taken for granted. Kitui is a small town 160 km east of Nairobi with about 60,000 inhabitants. For most of the inhabitants here, water can either be bought at the store at limited opening hours or provided by using water pumps which are most commonly driven by fossil fuels or grid electricity. Either way, it is not cheap. As climate changes and deforestation continues the water situation keeps getting worse.

The Grimstad based organization Help to self-help in Africa (HTSA) aims to create environmental friendly and locally profitable biogas facilities in Kenya and Tanzania that are easily operated and replicable. These facilities are mainly pig farms and biogas reactors driven on the pig manure. In the existing biogas reactors, supported by HTSA, the biogas is currently only used for cooking. One of these is the facility at Katulani Secondary School (SS) in Kitui which is the site of investigation. Here, an existing 4 kW submersible water pump is considered to be connected to an engine driven on the excess biogas from the biogas reactor.

In addition to the mentioned advantages from biogas facilities, more synergy effects are accomplished in the local community. For instance waste products which are better as fertilizer compared to raw manure. Another outcome is pork meat, which is rare in this area of Kenya. Also local value will be created by hiring locals for the operation and construction of the facility as well as using local materials.

1.2 Problem statement

1.2.1 Research objectives

Objective 1: Establish the requirements for average daily biogas volume for cooking purpose, average daily water demand and system for water treatment, distribution and use.

Objective 2: Estimate feedstock quantity needed to produce enough biogas for cooking and water pumping at a selected school. Perform technical and economic analyses.

Objective 3: Design water supply systems with different levels of complexity for a selected school based on experience from the existing biogas reactor at Katulani SS.

Objective 4: Suggest improvements to an existing or planned biogas powered water supply system.

1.2.2 Research questions

To reach the objectives of the thesis, some important questions need to be answered to determine the characteristics of the system.

- What are the approximate sizes of the pigs and how much feedstock do they produce?
- Based on the location, which measures to enhance the biogas production could be taken?
- What are the concentration of the corrosive substances hydrogen sulfide, ammonia and water vapor in the gas?
- What is the methane fraction of the biogas?
- What are the environmental conditions of temperature, atmospheric pressure and humidity?
- How is the configuration of the pump system that already exists at Katulani SS?
- What are the total head and water flow of the existing water supply system?

1.3 User requirements

The requirements that must be satisfied to integrate a biogas engine are found by questioning the principal at Katulani SS Fred Muia [1] and the organization HTSA. The six most important requirements obtained are listed below:

R1. Cover the cooking demand for a total capacity of 340 students and staff.
  - This requirement must be satisfied before water pumping using biogas can be a reality.

R2. Cover a total water demand of at least 5000 liters per day.
  - The volume is based on approximations of current drinking water for student and staff, pigsty and biogas plant. It does not include water for sale.

R3. Reliable system
  - Low maintenance and long life span of the system components are important factors since skilled labor is limited. The system should be a long term solution.

R4. Back-up alternative
  - It is crucial to be prepared for break downs at worst-case scenario droughts.

R5. Profitable
  - The school will not go through with a project that does not save costs.

R6. Replicable
  - One of the main principles for the organization HTSA is that it must be easy to spread the knowledge about how to construct the system, making the Kenyans self-dependent from foreign interference.

1.4 Key assumptions

The results are only based on 9 – 10 measurements over 6 days in March 2013. These measurements are assumed to represent the average operation parameters of the reactor and the average ambient climate conditions. The fuel prices are based on own observations at local fuel stations in Kitui Town and are assumed to be an average.

1.5 Key limitations

The thesis focuses on a one stage fixed dome plant fed by pig manure to produce biogas and a 4 kW electrical submersible pump as the power consumer as these are the materials that are available for investigation.

Only 4-stroke internal combustion engines in combination with a generator are considered as a power producer, due to their low complexity and reliability. This eliminates other options as gas turbines, 2-stroke engines, wankel engines, stirling engines and thermo electric generators. A turbo charger is likewise not considered due to high complexity, high costs and low reliability.

In addition, only engines modified from either otto or diesel engines are considered due to their high availability in Kenya.

1.6 Literature review

Books about biogas from waste matter[2] and engines for biogas[3] give thoroughly knowledge suitable for this thesis. Many of the assumptions made in this thesis are based on these two books.

In addition, a feasibility report[4] from HTSH written before the construction start of the biogas facility at Katulani Secondary School provides some interesting information.

1.7 Report outline

This thesis starts with general information about biogas based water pumping. This is to get a basic understanding of the measurements results and solutions. A case study is further presented with mostly focus on the biogas facility at Katulani Secondary School. Also the area and the town of Kitui are presented in this part aiming to give understanding of issues and possibilities that are characteristic for the specific location. The materials and methods are further presented to give a view on how the measurements were done before the section of measurement and estimation results. Here, all the measured results are presented along with obtained estimation results based on the measurements. In the solution part, measures to increase gas production are presented along with a comparison of relevant engines and alternative solutions. In the conclusion, summarize of the obtained results are given along with some recommendations and future work prospects.

2 Biogas based water supply

This chapter of the thesis presents basic knowledge about a submersible water supply system with an internal combustion engine driven on biogas. It ends with a table of the key values retrieved from this chapter that are used in later calculations.

2.1 Biogas

When solar irradiation hits the earth, some of it is absorbed and stored. Through photosynthesis, carbon dioxide and water are combined in an endothermic reaction to produce oxygen and organic matter in the form of glucose.

Humans can exploit the stored energy in organic matter in numerous ways. One of the cleanest and most environmental friendly ways is through biogas conversion. Biogas is produced in the absence of oxygen in a bacterial decomposition process called anaerobic digestion. The biogas produced is the waste product in the respiration of these bacteria. This happens naturally in swamps, in sediments of freshwater and saltwater, in the digestion channels of humans and animals, etc. [5].

In a dry state, biogas consist of approximately 55 – 70 vol.-% methane, 30 – 45 vol.-% carbon dioxide, 1 – 2 vol.-% hydrogen, ammonia, hydrogen sulfide and smaller traces of gases as oxygen, nitrogen and carbon monoxide[5]. This content varies according to different sources and their composition. More fat in the substrate give larger methane content and vice versa. Methane and hydrogen are normally the only combustible parts of this gas[5].

Methane is a gas without any smell or color which makes it hard to detect. It is the simplest form of alkanes and is the main component of natural gas [5]. The explosion limit of methane in air is 4.4 vol.-%. An overview of the properties of methane and other components of biogas are given in table 2.1. The biogas properties depend on the methane content, the atmospheric pressure and the temperature [6]. Methane is also a gas that contributes to global warming when let out to the atmosphere. It is 21 times more effective as a greenhouse gas compared to carbon dioxide[2].

Table 2.1 Properties of some gases at NTP conditions [7]

	Dry Biogas*	**Natural gas**	**Methane**	**Carbon dioxide**	**Hydrogen sulfide**	**Carbon monoxide**	**Hydrogen**
Chemical symbol	-	-	CH_4	CO_2	H_2O	CO	H_2
Lower heating value [kWh/Nm³]	6	10	10	-	-	3**	3
Density [kg/Nm]	1.2	0,7	0.72	1.85	1.44	1.57	0.09
Relative density to air	0.9	0.54	0.55	1.19	1.19	0.97	0.07
Ignition temperature [˚C]	700	650	600	-	270	605	585
Explosive area [vol.-%]	6 – 12	4.4 – 15	4.4 – 16.5	-	4.3 – 45.5	10.9 – 75.6	4 – 77
* Methane 60 vol.-%, carbon dioxide 38 vol.-% und other gasses 2 vol.-% **At 25 ˚C [8]							

Threating methane as an ideal gas, the density (ρ) can be found from the proportional relation to pressure(Pr) and reverse proportional relation to temperature(T) using equation 1 with normal temperature and pressure (NTP) conditions of 273 K and 101.3 kPa[3]:

$$\rho_{CH_{4(actual)}}\left[\frac{kg}{m^3}\right] = \rho_{CH_{4(NTP)}} \cdot \frac{Pr_{gas} - Pr_{water}}{Pr_{NTP}} \cdot \frac{T_{NTP}}{T_{actual}} \left[\frac{kg}{m^3}\right], \qquad [eq.1]$$

where:

$\rho_{CH_{4(NTP)}}$ – Density of methane at NTP conditions [kg/m³] as seen in table 2.1.

$\mathrm{Pr_{gas}}$ – Total pressure of the gas [kPa]

$\mathrm{Pr_{water}}$ – Actual partial pressure of water vapor [kPa]

$\mathrm{Pr_{NTP}}$ – Pressure at NTP condition: 101.3 kPa

$\mathrm{T_{NTP}}$ – Temperature at NTP condition: 273 K

$\mathrm{T_{actual}}$ – Actual temperature of gas [K]

The actual lower heating value (LHV) of the biogas (BG) is obtained based on the density and the methane content as seen below[3]:

$$\mathrm{LHV_{BG}}[\frac{\mathrm{kWh}}{\mathrm{m^3}}] = \%\mathrm{V_{CH_4}} \cdot \rho_{\mathrm{CH_{4(actual)}}} \cdot \mathrm{LHV'_{CH_4}}[\frac{\mathrm{kJ}}{\mathrm{kg}}], \qquad \text{[eq.2]}$$

where:

$\mathrm{LHV_{BG}}$ – Lower heating value of biogas [kWh/m³]

$\mathrm{LHV'_{CH_4}}$ – Lower heating value of methane [kWh/m³]

$\%\mathrm{V_{CH_4}}$ – Volume percentage or mole percentage of methane in the gas [%]

The average power (P) produced from the biogas can be found by knowing the LHV, the efficiency (η) or losses, and the volume of the biogas in relation to the operation time.

$$\mathrm{P_{produced}} = \frac{\mathrm{V_{Biogas}} \cdot \mathrm{LHV_{BG}} \cdot \eta_{\mathrm{tot}}}{\mathrm{t}} [\mathrm{W}], \qquad \text{[eq.3]}$$

where:

η_{tot} – Efficiency of power conversion

t – Time duration of power production [s]

$\mathrm{V_{Biogas}}$ – Total volume of consumed biogas [m³]

If the gas has had no drying treatment it is almost always saturated with water vapor since the temperature of the biogas outlet is usually lower than inside the digester. By knowing the gas temperature and the relative humidity, the partial pressure of the water vapor can be found by using figure 2.1[3].

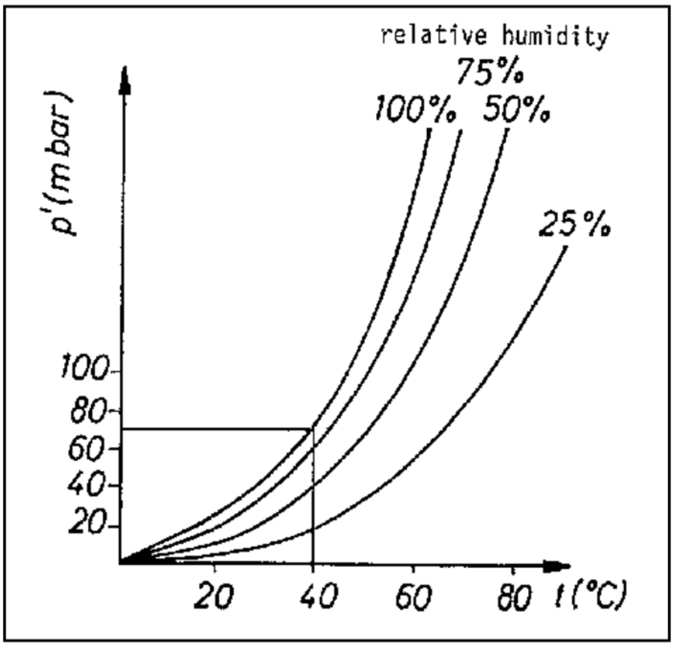


Figure 2.1 Relative humidity and partial pressure of water vapor in biogas[3]

The vapor content of the gas can be found in figure 2.11. As the biogas is not cooled after combustion in the case at Katulani SS, no energy is lost in condensing the water in the product gas. Therefore, the lower heating value (LHV) is repeatedly used in this thesis.

2.1.1 The biogas production process

The biogas process can be divided into hydrolyses, acidogenesis, acetogenesis and methanogenesis.

Hydrolyses is the process which brake down long-chain molecules as protein, carbohydrate and fat polymers, into smaller molecules or monomers as glucose, xylose and amino acids. Lignin is the only part of the organic matter that cannot decompose under anaerobic conditions. The duration of decomposing depends on the complexity of the molecules[5].

The second stage is the acidogenesis or fermentation process. Here about half of the monomers and long-chain fatty acids are broken down to acetate. 20 % of the monomers are converted to carbon dioxide while 30 % is broken down to short-chain volatile fatty acids (VFA) and alcohols [9]. This is under the assumption that the process is bacterial balanced[5]. VFAs and alcohols cannot be converted directly into methane and therefore has to go through an intermediate step called acetogenesis. Here they are converted to the methanogenic substrates acetate, hydrogen and carbon dioxide [9].

The third stage is the methanogenesis where methane is produced. It is this process which requires anaerobic conditions. Under balanced conditions 70 % of the methane comes from degradation of acetic acid, while 30 % comes from carbon dioxide and hydrogen. Inhibition of one of these two processes leads to inhibition of the other.

Table 2.2 Energy yield of methanogens [5]

Source	Process	Energy yield [kJ/mol CH_4]
Hydrogen	$4H_2+CO_2 \rightarrow CH_4+2H_2O$	- 131
Formic acid	$4HCOOH \rightarrow CH_4+3CO_2+2H_2O$	- 145
Methanol	$4CH_3OH \rightarrow 3CH_4+CO_2+H_2O$	- 105
Acetic acid	$CH_3COOH \rightarrow CH_4+CO_2$	- 36

The methanogen bacteria have the slowest growth rate of the bacteria in the digestion process only about one fifth of the acid forming bacteria. The energy yield of methanogens from the exothermic decomposition is seen in table 2.2.

The gas potential of raw protein, raw fat and carbohydrates can be seen in table 2.3.

Table 2.3 Gas potential of feedstock content [9]

Substrate	[Liter gas/kg total solids]	Methane [%]	Carbon dioxide [%]
Raw protein	700	70 – 71	29 - 30
Raw fat	1,200 – 1,250	67 – 68	32 - 33
Carbohydrates	790 – 800	50	50

As seen in table 2.3, fat contributes the most in the biogas production process, while proteins give higher methane percentage in the produced gas. It is common that the conversion ratio from animal manure to methane and carbon dioxide is between 30 – 60 %[5].

2.1.2 Optimal digestion conditions

It is important that the feed-in of organic matter occurs slowly with low variations and at the same rate as organic acids are removed from the digester. If not, the methane producing bacteria, or methanogens, will not be able to adjust to the growth rate and fully exploit the fatty acids. The pH value will then decrease along with the gas production and refilling of the digester may be a necessary consequence[10]. The pH value will also decrease if the organic acids produced are not removed soon after they are formed [5].

The more continuous the reactor is fed the more stable the living conditions of the bacteria become and a more stable gas production is accomplished. Another way to operate the reactor is by so-called "batch-filling". Here, the process consists of first filling the reactor, then gathering the biogas and emptying the reactor when gas production stops. It is necessary to leave some substrate after the emptying so that bacteria are left to secure the initiation of the next fermentation process [10].

Ideally metanogenesis and the acetic acid production should be separated from hydrolyses and the other acids due to the diverse bacteria cultures, which thrives at different pH values. In a simple biogas reactor with one digestion tank, a compromise must therefore be done. [10]. The pH value is dependent on the partial pressure of CO_2 and on the concentration of alkaline and acid components in the liquid phase [9]. Methanogens need nutrients to be able to grow. Some of the most important are nitrogen, phosphorus and potassium. Nitrogen content is often measured in relation to carbon. This C/N ratio should be less than 30/1 for not limiting the process[5].

All feedstock should be mixed into small pieces before entering the digester. This is to increase the relative surface area. The smaller the pieces the more gas produced since bacteria can attack the material more easily. This requires external work before the input either by hand or machines and results in a faster decomposition of the feedstock. To avoid a floating surface layer and sedimentation of suspended solids at the bottom of the digester, stirring could be applied inside the digester. The stirring should be done slowly to avoid decrease in gas quality and preferable continuously[10].

The organic loading rate (OLR) is the rate at which the feedstock is added and is measured in the daily chemical oxygen demand or kg COD/day. OLR and COD is further explained in [5]. The hydraulic retention time is the average duration time of the fermentation process for the substrate. Organic loading rate and hydraulic retention time must be balanced in relation to each other. This relation is dependent on the reactor temperature and in many practical applications on the time it takes for the substrate to reach a level where it is not profitable to keep it in the reactor any longer for optimal biogas production [10]. This is because the gas production will peak and then decrease before the organic matter is fully digested as seen in figure 2.2. A high gas production which is evenly produced during the day is often preferred.

The hydraulic retention time (HRT) can be found by the relation of liquid volume of the digester and the daily process flow rate:

$$\mathrm{HRT} = \frac{\text{Liquid volume}}{\text{Process flow rate}}[\text{days}] \qquad [\text{eq.4}]$$

Table 2.4 gives examples of some climates and countries in relation to average HRT used for low complexity biogas facilities.

Table 2.4 HRT suitable in different countries when using low complexity biogas facilities [3]

Climate	**Country examples**	**HRT**
Hot tropical plains	Sudan, Cameroon, Sri Lanka, Indonesia, Venezuela, central America	30 – 40 days
Hot but with slightly cooler winters	India, Thailand, Philippines, Kenya, Ethiopia	40 – 60 days
Temperate and with distinct cooler winters	China, Korea, Turkey	60 – 90 days

As seen in table 2.4, a HRT between 40 – 60 days could be expected in Kenya. The gas yield is dependent on the HRT. As seen in figure 2.2 with an example at 30 ˚C, the production rate is high at the beginning but then slowly decreases until there is almost no gas production. Pig manure is not shown in this figure but would have a curve slightly above cattle manure in figure 2.2.

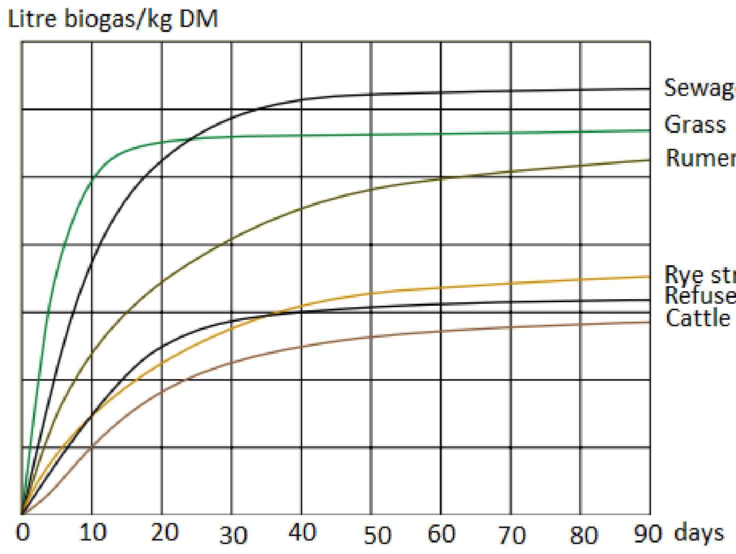


Figure 2.2 Biogas production compared to HRT at 30 ˚C [5]

The temperature and temperature variations have a large influence on the biochemical process and thereby also the HRT. Increased temperature gives higher rate of gas production. The temperature change should though be kept to a minimum to maintain ideal living conditions for the bacteria. The higher temperature, the lower temperature change can be tolerated. For 37˚C the temperature change should not exceed ± 2˚C[5].

Large amount of fat in the feedstock gives a large amount of long-chain fatty acids. A Large amount of protein, in turn, gives a large amount of ammonium and ammonia. Ammonia is toxic to the bacteria in high concentrations and at the same time a source of nitrogen, which is essential for bacteria growth. The balance of ammonia and ammonium becomes important, as ammonium is not that toxic. This relation is dependent on pH value and temperature. Higher pH and temperature gives more ammonia instead of ammonium. Slurry usually has a high concentration of ammonia. Other substances as heavy metals, salts and micronutrients are also necessary in the process, but have a negative effect in high concentrations. Antibiotics and disinfectants can also be found when using animal waste. These have to be kept low since their purpose is to kill microorganisms[5].

2.1.3 Water input

For degradation to occur the water content must be 50 % or above. In biogas pumps with a direct feed-in the water content should be at least 85 %[5]. Some of this water demand, or all of it, could be covered by the natural water content in the manure and urine. The pipe where the biogas flows out could also be designed upwards so that water condensate is drained back into the digester. Water efficiency may be crucial in arid areas.

2.1.4 Feedstock

There are plenty of possibilities for using different types of organic matter for use in an anaerobic biogas reactor. The most familiar are animal manure and slurry, agricultural residues and by-products, digestible organic wastes from food and agro industries, organic fraction of municipal waste, sewage sludge and dedicated energy crops[9]. Animal manure and slurries have some additional advantage compared to the other alternatives due to a naturally content of anaerobic bacteria, high water content, low price and high accessibility. However, animal waste has a relatively low methane yield. Therefore it should be mixed with other substrates with higher methane yield. Examples of common additives to manure and slurry are: Oily residues from food, fishing and feed industries, alcohol wastes from sugar and brewery industries, cultivated energy crops [9] and animal left-over from slaughter houses. The quality of the input manure is highly dependent on the fodder quality used to feed the animals [10]. Figure 2.3 shows the biogas and methane yield of different feedstock materials arranged from highest biogas yield to the lowest. A tendency of increased methane content in the gas can be observed as the gas volume production decreases.

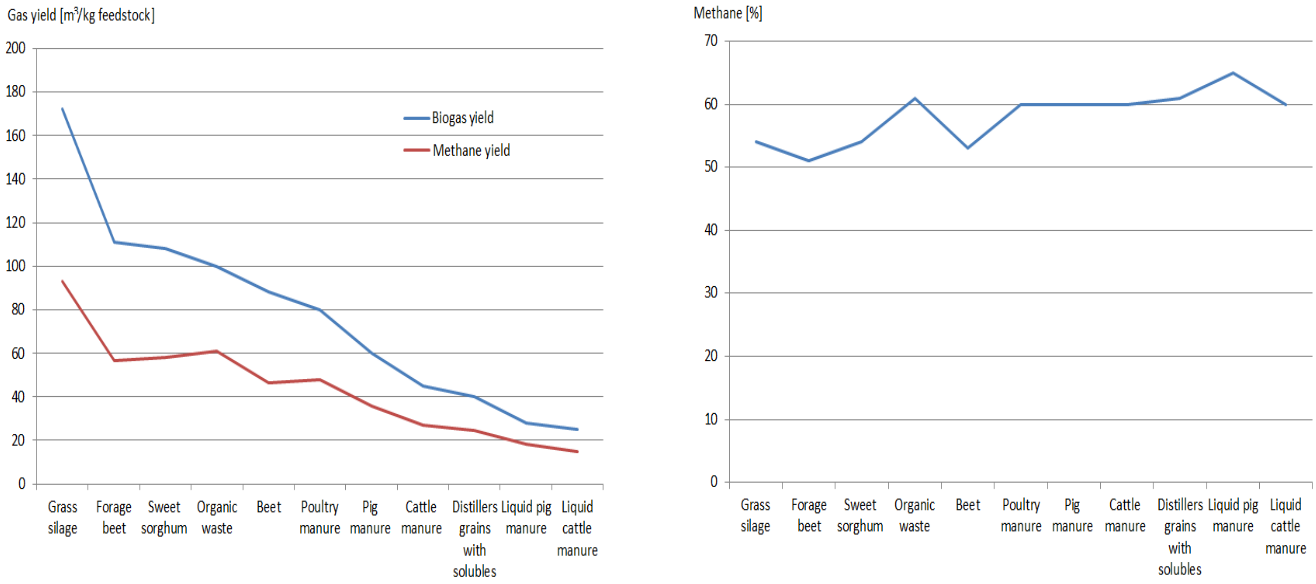


Figure 2.3 Biogas yield and methane yield [9]

The properties of pig manure largely depend on type and amount of feeding, the animal size and the environment. It can therefore be difficult to estimate. From [2] the production rate and water content are obtained in relation to the stage of life, gender and size of the pigs in table 2.5. Relevant cow categories for Katulani SS are also included in this table.

Table 2.5 Manure production of pigs at different stages of life and cattle [2]

	Weight [kg]	**Liquid manure production[liter/day/animal]**	**Dry matter content [%]**
Young pig	< 12	0,5	2.5 – 13
Young pig	12-20	1	2.5 – 13
Young pig	20-45	3	2.5 – 13
Young pig	45-60	4,5	2.5 – 13
Young sow	<90	4,5	2.5 – 13
Sow	>90	4,5	2.5 – 13
Sow with piglets		14	2.5 – 13
Feeder Cattle		50	7 – 17
Young cattle		25	7 – 17

The density of the manure is vital to be able to convert volume values into mass values and vice versa. In [11], the density of separated pig manure with 30 % DM is investigated by using a specific gravity bottle while the density of urine was found by using a hydrometer. The results are shown in table 2.6.

Table 2.6 Density of pig manure [11]

	Variation range [kg/m³]	Average value [kg/m³]
Density manure (30 % DM)	1,090 – 1,175	1,130
Density urin	1,007 – 1,023	1,016

The density values in table 2.6 are obtained from farms in Great Britain. There might be differences regarding the DM content in developing countries that are not accounted for in this thesis. This is in specific due to different types of feeding.

2.1.5 Digestate

The digestate that comes out from the biogas reactor output is more homogeneous than before the reactor. This results in a more evenly distribution of the nutrients on the field. The manure contains little viable seeds, as these are killed in the biogas process. This eliminates the need for chemical pesticides. Most of the nitrogen in the manure is in the form of ammonium which is easily available for the plants. These are factors that increase the speed of the manure effect and the size the of the crop [10]. The biogas process reduces the odour of the manure. A low decomposition ratio can be indicated by the odour of the output manure [10]. The manure output could also be diluted and used as feed in a fish pond.

2.1.6 Small-scale biogas plants

Small-scale biogas plants at low costs are often without an automatic stirring, heating system or any advanced monitoring system. They are made from locally available materials as cement and plastic bags[12]. It must be completely sealed to limit heat dissipation and avoid oxygen entrance. Due to the necessity of heat for an efficient process, this simple construction is most suitable in warm tropical or subtropical climates.

Varies types of biogas plants exist. The design depends on local climate, frameworks, energy availability and affordability. For the purpose of this study, simple small-scale plants are described. These plants use feedstock from household and small farming activity. The biogas produced is commonly used for cooking and direct lightning. In addition to being simple and inexpensive, these plants are also robust, easy to operate and require little maintenance. It may be operated by adding slurry once per day and remove the same volume slurry towards the output. The slurry removed has been digested to some degree, but not fully digested. When the reactor is not stirred in simple biogas digesters a large volume of substrate would most likely be needed to be removed 2 – 3 times per year[9].

The fixed dome plant in figure 2.4 is the reactor type most commonly used in Kenya [13]. It origins from China and has the advantage of no movable parts. The gasholder is placed on top of the underground digester. When gas is produced, the manure is pushed towards a compensating tank. The mixing chamber is similar to the floating drum plant described later, but in addition the fixed dome has a third chamber called the expansion chamber. This chamber works as regulation for the digestion. When biogas is produced, liquid manure is pushed into the expansion chamber and when it is used this slurry is pulled back. When the volume of gas is produced it will expand and push the slurry towards the outlet, where it floats up and drains out of the expansion chamber[14]. The slurry is transported to the digester by means of gravity. Due to the higher location of the input than the output, the slurry is pushed towards the output chamber when pressure in the digester increases and not towards the input. A figure of a fixed dome can be seen in figure 2.4 with the dimensions for an 8 m³ digester or dome. The flow of the fixed dome plant is shown to the right.

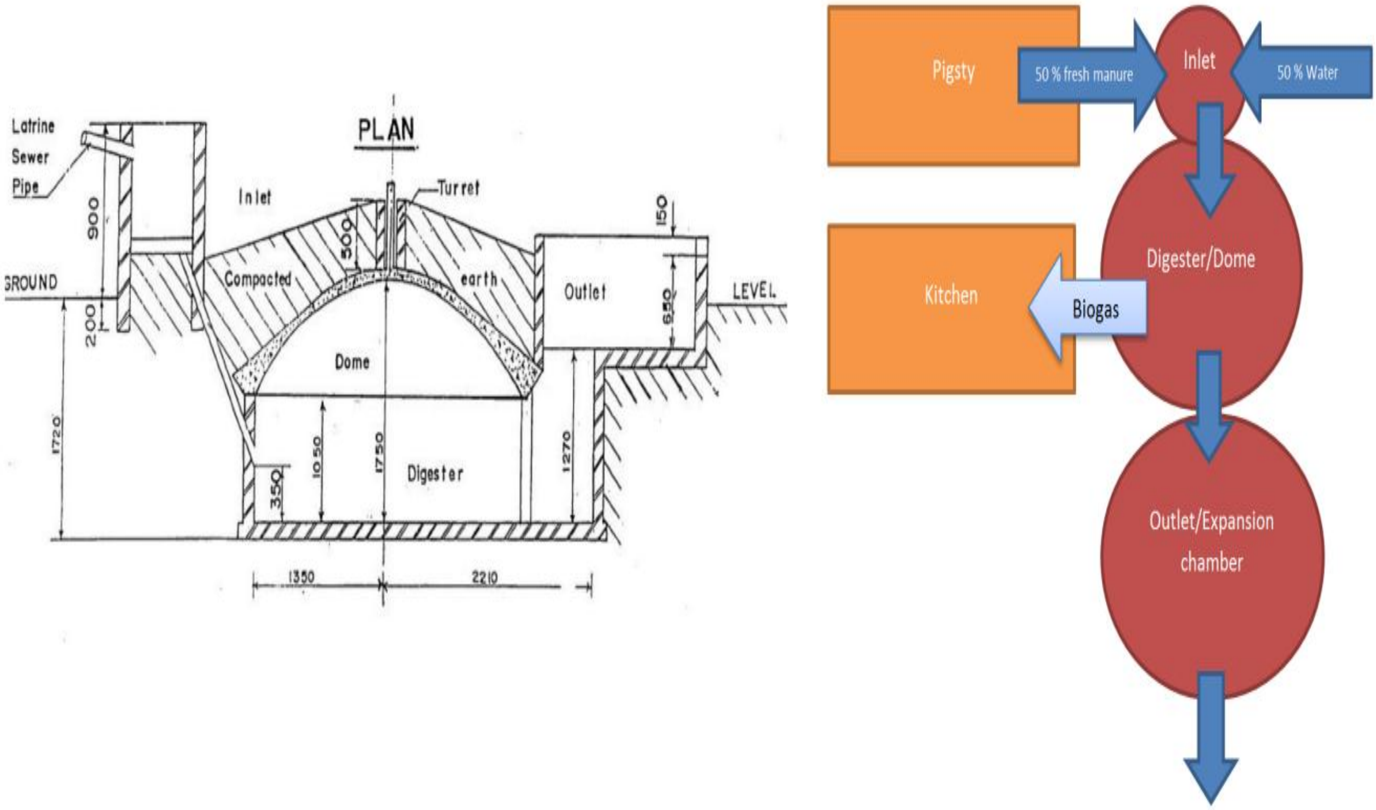


Figure 2.4 Fixed dome plant [13] and a flow chart showing the mass transport in the plant

The floating drum plant in figure 2.5 is very common in India. It has the same input system as the fixed dome. But the digester has a floating steel drum on top of the slurry or on a water jacket. The drum rises and sinks according to if gas is produced or consumed. This moving tank gives a visually understanding of how the plant works. The steel material used in this plant gives higher costs and more maintenance. The same flow chart as in the fixed dome applies for the floating drum, except there is no need for an expansion chamber as the movement of the tank produces the necessary pressure. Below is a sketch of an 85 m³ floating drum plant.

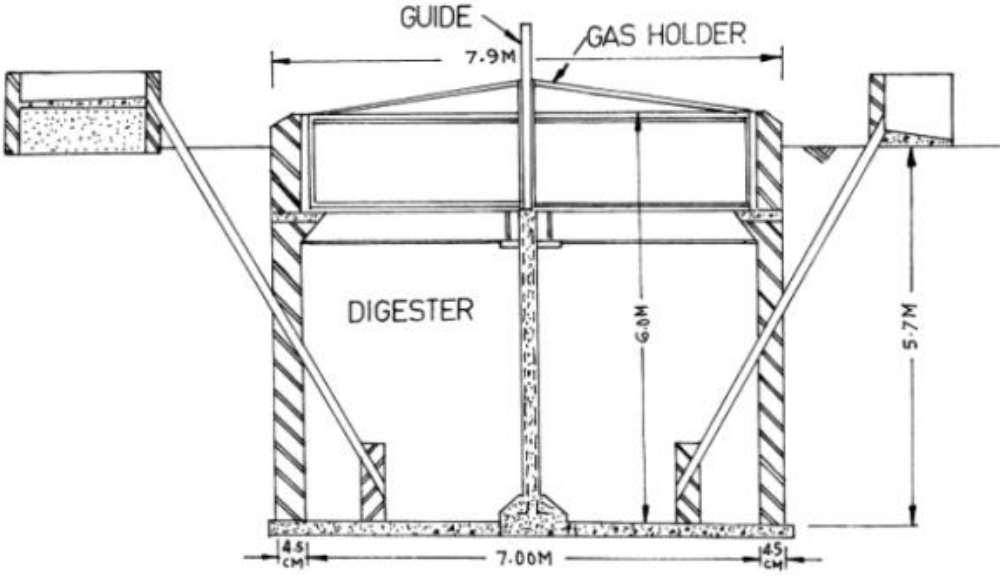


Figure 2.5 Floating drum plant [14]

A comparison between the floating drum and the fixed dome at 48 m³ is given in table 2.7.

Table 2.7 Comparison floating drum and fixed dome plant [13]

Issues	**Floating drum 48 m³**	**Fixed dome 48 m³**
Durability	>30 years	>30 years
Average cost of installation	480,000 – 600,000 KES	500,000 – 700,000 KES
Effective gas volume	n/a	9.7 m³
No. Of cows for effective feeding	17 – 22	17 – 22
Total amount of feeds per day	200 kg	200 kg
Ease of use	Easy	Very easy
Mantenance	Every 3 – 4 days	Minimal
Tehcnical problems	Some	Very few

Methods using plastic in the design are also available. The drawback of these types is the use of plastic as it is not a sustainable material and must be bought from a manufacturer. The lifespan of these plants are also reduced.

The rubber-balloon plant consists of an expendable balloon partly buried beneath the ground with weights on a platform covering the top. The mass of the weight depends on the operating pressure required[15]. Pipes transfer the slurry in and out by gravity from higher to lower altitude. The balloon concept could also be applied to an existing fixed dome plant as an external storage shown later.

A similar concept as in the fixed dome plant is applied in the plastic tubular digester seen in figure 2.6. However, a tubular plastic with a cylindrical volume is used as digester containing the biogas and the slurry in this case. In the pipeline from the digester there is a safety vent consisting of a T-bend with a bottom submerged into water. At too high pressure in the system, the biogas escapes through the water [12]. The life expectancy is about half compared to the fixed dome and floating drum design [13]. A simple illustration is shown in figure 2.6.

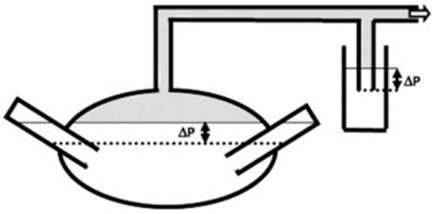


Figure 2.6 Plastic tubular digester with water safety vent [12]

2.2 Gas installation

The pipes from the digester to the stoves may be galvanized steel pipes which are corrosion resistive and have low costs. It can also be PVC which are made out of plastic and are therefore flexible but also more expensive. This choice may depend on the location of the kitchen in relation to the digester[4].

Drainage is needed to condensate water in the pipes. If the kitchen is located at a higher elevation than the digester and the piping is at a straight slope, no water trap is needed since the condensed water will drain back to the digester. In other cases, one or more water traps are needed. These are located at local bottom points of the pipe system, where the water would else gather and block the gas flow. It is crucial that there is no leakage in the pipes, since biogas can be explosive in mixtures with air. However, when buildings have a high degree of ventilation, an explosion is unlikely [4].

The pressure loss must be kept below the driving pressure of the gas to be able to flow towards the output without the use of a blower or fan. A pressure loss is unavoidable and is caused by pipe friction, vents, bends, injector nozzles of the biogas stoves and other armatures and fittings. A moody chart specified for gas installations is found in appendix figure A.1 and can be used to find the friction factor of the gas pipes. The procedure of finding the pressure loss in gas pipes is the same as in water pipes, which will be discussed later.

There exist a large number of gas burners on the market. These have to be chosen based on gas volume and the cooking pans. Usually it is necessary to modify the stove before it can be used for biogas [4]. Around 9 – 17 % of the biogas reacts with air. If too much biogas is mixed with the air, the combustion becomes incomplete. This is unwanted since it lowers the efficiency and produces toxic gases as carbon monoxide and soot/carbon particles. Usually the biogas is burned with too much oxygen than the stoichiometric ratio to avoid producing these gases. To mix the air and fuel properly, about 50% of the air is often mixed before it is burned in a flame [16].

The burner has a designed operating pressure. The operating pressure in the digester should hence be above this pressure to overcome friction in the pipes and valves[17]. The efficiency of domestic biogas stove is typically between 1.2 and 5.5 kW with an efficiency of 55 %[16].

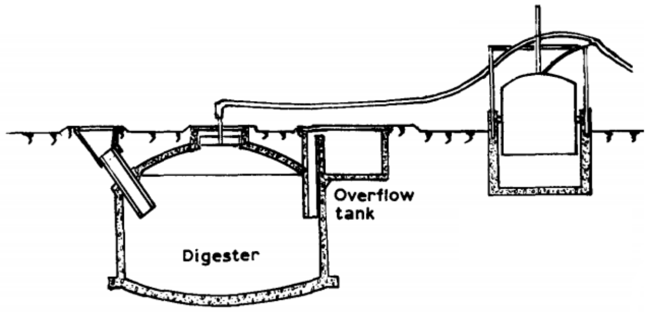
2.3 Gas storage

Biogas storage bag can be done in several ways, but the easiest ways are shown in figure 2.7.

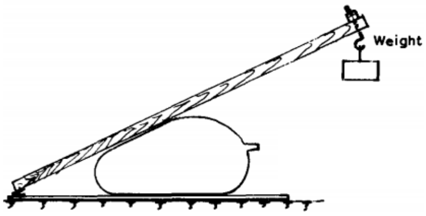
The separated floating biogas storage tank is a type of storage which combines a fixed dome plant without the expansion chamber, with a separated tank which applies the floating digester concept. The tank flows up and down as biogas is produced and consumed. A close to constant pressure can be obtained with this storage. However, it is an expensive construction and requires maintenance as steel is likely to be used[17].

Another way is a biogas storage bag placed on the ground that is regulated by placing weight on top of it during gas consumption, while removing the weights during production. A plate can be used to couple the weights[17]. These bags exists up to 25 m³[2].

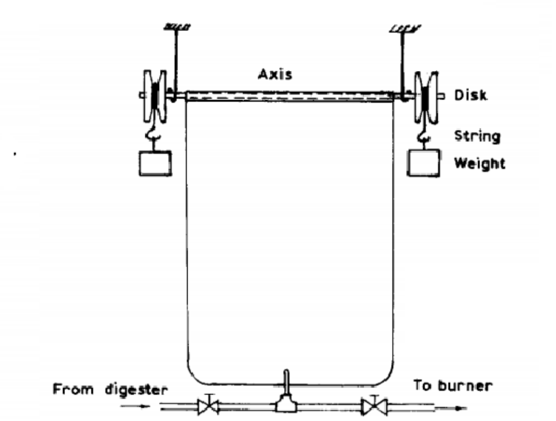
Another type of storage consists of a bag with a small axis connected to two pulleys, a string and two weights. The bag is compressed by the two weights which are wound up the bag due to gravity. The weights are removed when the gas is not used. The vent is then automatically opened and leads gas into the bag from the digester. The bag is made from a red mud plastic which is soft and has low permeability for gas. The axis and the pulleys can be made of wood. This is a not an expensive storage and it is easy to make [17]. More complex types of the hanging bag within tanks do also exist. These can store volumes up to 3000 m³ at low pressure[2].



Separated floating biogas storage tank



Biogas storage bag



Hanging bag storage

Figure 2.7 Simple gas storage concepts [17]

The biogas can also be stored at medium or high pressure in steel pressure tanks. This is out of the scope of this thesis due to high complexity, operation costs and high energy consumption.

2.4 Heat and power generation

The easiest way to use biogas for energy purposes is by directly burning it for cooking or lightning. This is very common in developing countries at small farms. Simple gas treatment may be needed in those cases as for instance condensation, particle removal, compression, cooling or drying[9].

In more developed countries, combined heat and power generation (CHP) is regarded a very efficient way of utilizing biogas. The total efficiency of a CHP plant may be up to 90 %, whereas 35 % of it in the form of electricity [9]. Some of this electricity is usually used for process purposes such as pumps, control systems and stirrers. The heat may be used for heating of water or rooms or to heat up the digester to increase the biogas yield. The heat can also be used to generate additional electricity through either stirling generator, thermo electric generator, etc. In warm climates, the heat could be exploited in air-conditioning or in a fridge or freezer by using a heat-cooling coupling system.

2.4.1 Combustion process

The most important gas in the biogas that is involved in the combustion process is methane. Therefore, the methane content in the gas is of high importance. Hydrogen contributes but the content is negligibly. The other gases absorb energy in the form of heat. The energy content of a molecule can be found by examining the bounding energy between the atoms in each molecule. By doing so the values in table 2.8 are obtained.

Table 2.8 Bond energy of some molecules [18]

Substance	Chemical name	Total bond energy [kJ/mole]
Methane	CH_4	1640
Oxygen	O_2	988
Carbon dioxide	CO_2	1598
Water	H_2O	1840

To break bonds, energy must be supplied. Energy is produced when making a bond.

The fuel consumption in internal combustion engines can be expressed in normal cubic meter per kilowatt hour, or m^3n/kWh. To be able to choose the dimension of an engine, the actual biogas consumption is crucial to know.

Chemical reaction of a complete stoichiometric combustion with a clean oxygen intake is,

$$\mathrm{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O} \qquad \text{[eq.5]}$$

When air enters the combustion, some of the nitrogen that enters can be oxidized into nitrogen dioxide if high enough temperature. Dry air contains about 79.1 % nitrogen which means that 3.78 moles nitrogen is added for each mole of oxygen at ideal gas conditions. Sulfur content can also give sulfur dioxide. At incomplete combustion with shortage oxygen, carbon monoxide may be produced instead of carbon dioxide.

In spark ignition engines a methane content between 5 – 15 vol.-% in mixture with air is necessary for properly being ignited. Methane has a high octane number of 120[8]. Hence, biogas burns at a slow velocity. Methane and biogas are hard to ignite and stable against knocking, meaning an even compression and combustion in the displacement volume can be obtained. An increment of the compression ratio is therefore possible without causing the described knocking problems [6].

Lubrication oils that are ash-poor and insures a long-term high alkalinity should be used in gas engines. This is to avoid wear of the cylinder head of the engine due to sulfuric acid created from hydrogen sulfide[2]. Methods of hydrogen sulfide treatment are presented later.

In [3] it is stated that for an internal combustion engine capacity decrease by 10 % for every 1,000 meters above sea level (m.a.s.l.) due to lower air pressure. In [19] the capacity of a diesel engine typically drops 3.5 % for every 300 meters above 150 m.a.s.l. That gives approximately a 9 % drop at 1000 m.a.s.l. The diesel engine also drops 2 % for every 5.5 ˚C above 30 ˚C and if a turbo charger is used it drops 3 %. The performance also drops 6 % at 100 % relative humidity[19]. The temperature and humidity decrease in [19] is assumed to apply also for otto engines. In appendix table A.7 there is shown the relation between the recommended diesel engine capacity and the rated submersible motor for different temperatures and elevations.

The overall efficiency of an engine can be expressed as [3]:

$$\eta_{\mathrm{overall}} = \frac{1}{\mathrm{sfc}} = \frac{\mathrm{P_{out}} \cdot \mathrm{t}}{\mathrm{LHV} \cdot \mathrm{V'}} \left[\frac{\mathrm{kWh_{mech}}}{\mathrm{kWh_{fuel}}}\right] \qquad \text{[eq.6]}$$

where:

sfc – Specific fuel consumption $[\mathrm{kWh_{fuel}}/\mathrm{kWh_{mech}}]$

LHV – Lower heating value of fuel [kWh/m³]

V' – Volume of fuel per day [m³/day]

t – Time duration [hours]

$\mathrm{P_{out}}$ – Mechanical power from engine [W]

The volumetric fuel consumption (fc_{vol}) is found by[3]:

$$\mathrm{fc_{vol}} = \frac{\mathrm{sfc} \cdot \mathrm{P_{out}}}{\mathrm{LHV}} \left[\frac{\mathrm{m^3}}{\mathrm{s}}\right] \qquad \text{[eq.7]}$$

Internal gas engines can be classified into gas-otto engine, gas-diesel engine and pilot-injection engine. Natural gas could be used in all three of them as a back-up solution and in the start-up phase if the digester needs to be heated up.

2.4.2 Gas-otto engine

For applications lower than 100 kW the gas-otto engine may be used. This engine is designed to operate according to the thermodynamic otto cycle. Surplus air is usually added to limit the carbon monoxide emission caused by an incomplete combustion. This results in some reduction in the power output, but which can be compensated for by the use of a turbocharger. The minimum methane requirement for this engine is normally around 45 vol.-% [9].

The modification of a petrol engine into a gas engine is uncomplicated. The carburetor must simply be replaced by an air/gas mixer, a venturi mixer or alternatively a simple mixing device if the operation is at constant speed and load. The piston position in the displacement volume is dependent on the speed of the burning process which is slower for biogas. The point of ignition must consequently be adjusted 10 – 15 ˚ earlier. This can be provided by standard ignition systems which usually has a wide range of adjustments[3].

It is an advantage to increase the compression ratio compared to petrol operation. This will increase power output, increase start-up capability and reduce gas consumption. An otto engine usually runs on a compression ratio of 6 to 9.5, which could be increased to 10 – 12 for biogas applications. The cylinder volume should then be decreased by machining of a part of the head sealing surface and replace it by a high compression head. Changes on the piston, the combustion chamber shape and a thinner cylinder gasket could also be done. The modifications could reduce the engine life span of an otto engine as it is designed for lower compression ratios[3]. How the thermal efficiency is effected by the compression ratio can be seen in the equation for thermal efficiency for otto engines[20]:

$$\eta_{\mathrm{thermal}} = 1 - \frac{1}{\left(\frac{V_{\max}}{V_{\min}}\right)^{k-1}} \qquad \text{[eq.8]}$$

where:

k – Polytropical constant for air at 300 K

$V_{\max}$ – Maximum displacement volume where piston is in bottom dead center

$V_{\min}$ – Minimum displacement volume where piston is in top dead center

A compression increase to 7 – 10 would eliminate the petrol as a back-up solution due to knocking. If the carburetor is retained and the pressure kept low enough, a petrol back-up solution could be available as back-up. However, petrol and biogas cannot be used at the same time as the combustion would become too rich[3].

The volumetric efficiency is lower when using biogas instead of petrol as it takes up more volume on behalf of air. When petrol evaporates it also has a cooling effect on the air and fuel mixture which increases its density and the following mixture volume that is sucked in [3].

In an otto engine an excess air ratio of 1 ± 0.1 must be maintained. This means an approximate stoichiometric air fuel ratio which gives almost non excess air or fuel. The inlet ducts are designed for petrol and cannot allow more air in. Hence, the total fuel energy in the mixture becomes less than in petrol operation and subsequently also the power output. This decrease is more significant than when using gas diesel engines, which have an air intake larger than necessary at medium and low speeds. The power decrease needs to be considered when choosing a proper engine [3].

The gas mixture supplied to the combustion chamber is controlled according to the power demand. This is done by operating a butterfly valve between the mixer and the inlet of the engine. Closing the butterfly valve gives a reduced air/fuel mixture at lower pressure in the combustion chamber. This causes a further reduction in power output, mean effective pressure and higher specific fuel consumption. A better solution to this valve control is to use a higher capacity engine and operate at medium speeds and an open valve[3]. The effect of operating at medium speed is seen in the figure below.

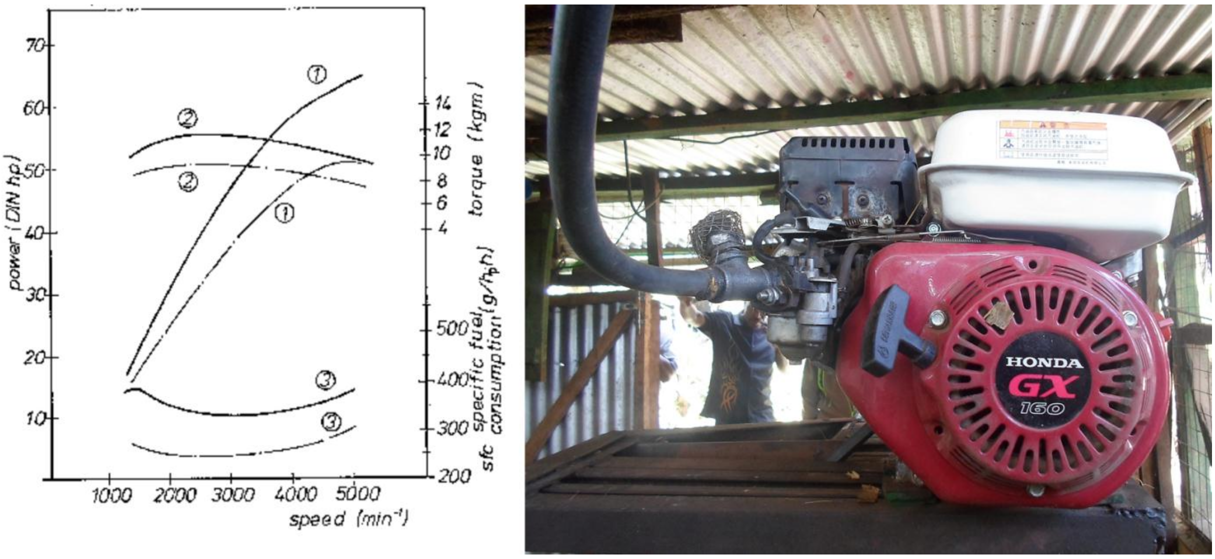


Figure 2.8 Comparison between gas (dotted line) and petrol (straight line) operation in otto engine [3] and a picture of a 3.6 kW gas otto engine.

As seen in the picture to the left in figure 2.8 above of comparison of petrol and methane, the most effective operation with the lowest specific fuel consumption is at medium speed and power. 1 is the power output, 2 is the torque while 3 is the specific fuel consumption.

The picture to the right in figure 2.8 shows an originally 3.6 kW 4-stroke SI engine converted into a gas engine for the purpose of chopping straws at a floating drum biogas plant in Thika, Kenya. As is common for small engines, it has a recoil starter, meaning that it has to be started manually by pulling the handle. The biogas flows into the engine through the black hose seen to the left.

2.4.3 Gas-diesel engine modified from diesel engine

At applications higher than 100 kW, a diesel engine modified to work on the otto cycle are often used instead of a otto engines designed for petrol operation[9].

The gas operation requires extensive modifications and requires the availability of a number of parts and equipment as well as a skilled mechanic and great precision work. The injection pump and nozzle must be replaced by a mixing device as a venture mixer or pneumatic control valve that supplies constant air/fuel mixture. The compression ratio must also be reduced from 15 – 21 to 10 – 12 and an ignition system with an ignition distributer, ignition coil, spark plugs and an electric supply as for instance a battery must be mounted. If the ignition distributer can be connected to the camshaft, the original speed governor can be retained to control speed and power. The control rack can be connected to the valve before the gas mixture. When these changes mentioned are made, the engine can run on neither diesel nor petrol. The compression decrease is achieved by doing the opposite process as described for compression increase in otto-gas engine in the previous chapter[3].

2.4.4 Pilot-injection gas engine

The application of the pilot-injection gas engine, also called duel fuel engine, is often used in tractors and heavy duty vehicles. Biogas is mixed in an external chamber with a surplus of air before it is compressed in the combustion chamber [9].

A normal diesel fuel injection system supplies diesel fuel. The volume of diesel fuel necessary for ignition is about 10 – 20 % of the volume that would be used if it was working on diesel alone. When operating at partial load, the biogas input is regulated, while all other parameters are unchanged. The airflow should not be controlled since a reduction would reduce the power and efficiency due to reduction of pressure and main effective pressure and could even lead to failure of self-ignition. A lean mixture up to a stoichiometric value of 4 is possible[3].

During duel fuel operation of the diesel engine, biogas contribution between 0 – 85 % has almost the same fuel performance as if operated on 100 % diesel. At biogas contribution of more than 85 %, the mixture can have difficulties to ignite and the engine may stall and eventually stop rotating[3].

The inlet channel and manifold of the diesel engine are dimensioned to deliver excess air to the engine for maximum performance at rated power. Due to the space the biogas occupies and the required air input, the total fuel input is lower at maximum performance than operation solely on diesel. This is however a smaller decrease than in petrol engines. For operation at medium and low speed the air inlet is larger than necessary and the power output will only be slightly lower than in diesel operation[3].

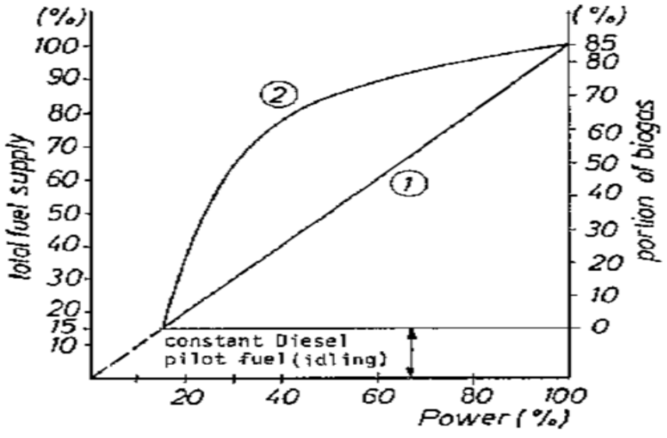


Figure 2.9 Operation of pilot-injection engine at different biogas supply fractions. Total fuel is marked as 1 while portion of biogas is marked as 2 [3].

The figure above shows the total fuel compared to the portion of biogas when diesel injection and the sfc are constant.

All diesel engines are equipped with a governor that controls speed and power by adjusting the diesel fuel injection. This governor should be used to control the required power output when there is not enough biogas to cover the demand. Then additional diesel fuel can be injected without cutting the supply of biogas[3].

Diesel fuel can also be used alone, which can be an advantage if the engine drives a water pump in arid and rural areas. On the other hand, this engine cannot operate without diesel which makes it reliable on a stable diesel supply and increase operation costs. It is also recommended to check upon the injector nozzle every 500 hours of operation. This is because when the fuel injection is below 10 % – 15 % of its normal value, the injector may overheat[3].

2.4.5 Alternative electricity generation

A micro gas turbine could be used for applications up to 200 kW. Here, air is pushed into the combustion chamber of the turbine and mixed with the biogas. The mixture is burned which increase temperature and pressure. The exhaust gas is released through the turbine which drives which drives both the generator and the inlet compressor through separated shafts. Some of the exhaust heat is used to preheat the gas mixture before combustion. The costs of micro gas turbines are higher than for internal combustion engines, but future work may change this[9].

Fuel cells can be used to convert biogas directly into DC electricity by an electrochemical reaction. A fuel cell consists of several cells coupled in parallel to increase the total voltage output. The main structure of the cell is an electrolyte layer in contact with porous electrodes on both sides. The negative anode at one side, while the positive cathode at the other. In a biogas configuration the biogas is typically fed continuously to the anode while oxygen or air is fed continuously to the other. The costs of this technology is too high compared to combustion engines[9].

Stirling engines are based on the stirling cycle. Here an external combustion leads to a gas expansion which increases the volume in the cylinder and moves a piston. The engine use the heat generated from the combustion, and the gas quality and methane content have therefor lower requirement than an internal combustion engine. The electrical efficiency is approximately 24 – 28 % and the exhaust temperature about 250 – 300 ˚C. The effect is usually up to 50 kW. The engine has low wear and maintenance costs but the low efficiency limits practicality.

2.5 Gas treatment

To avoid wear due to corrosion and deterioration of lubrication oil in an internal combustion engine, requirements for the gas quality are necessary. One of the most critical gases is hydrogen sulfide ($\mathrm{H_2S}$). This is a toxic gas with an uncomfortable odor and when it reacts with water creates sulphur acid which is highly corrosive. Biogas from animal manure usually contains between 1,000 – 3,000 ppm hydrogen sulfide which is above the requirements of most conventional engines. Since hydrogen sulfide production varies, over-dimension of the gas treatment equipment is necessary [9]. Several desulphurization methods can be used. The decision should be based on the hydrogen sulfide concentration, the required concentration for the gas application, variations in hydrogen sulfide production, assessment of failure consequences and the costs and amount of required maintenance and operation management [21]. Accurate hydrogen sulfide concentration that different methods apply for are found in table A.3 in the appendix. A graph showing a rough overview of the methods application ranges are shown below in the two figures:

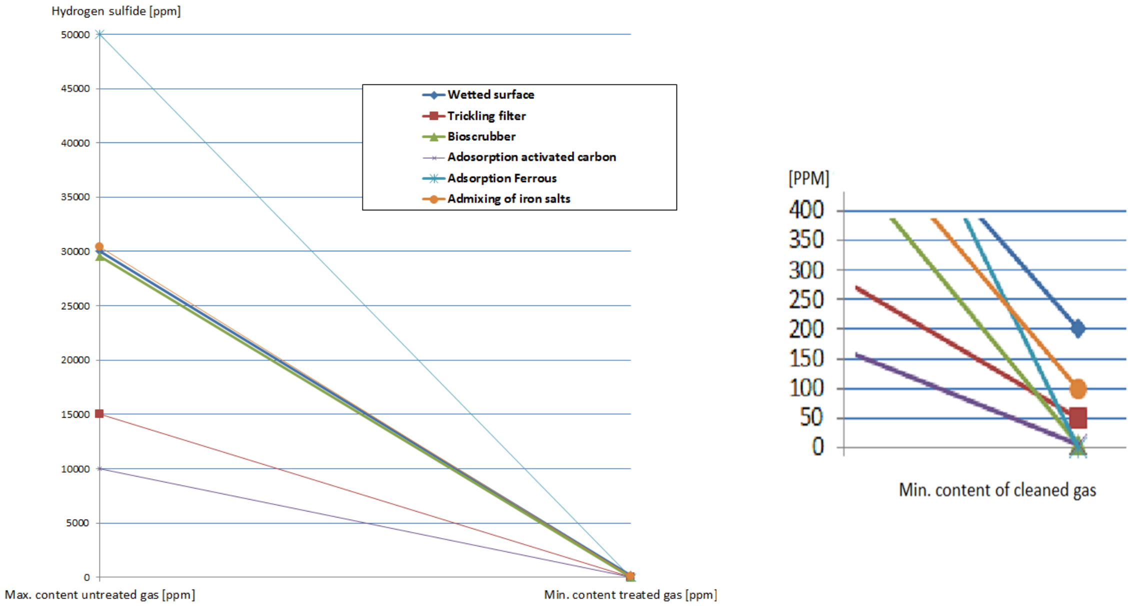


Figure 2.10 Effect of varies methods of desulphurization.

2.5.1 Biological desulphurization

During biological desulphurization a small volume of air or oxygen is injected into the raw biogas. Then, solid sulfur (S) or liquid sulfurous acid ($2H_2SO_3$) is produced instead of the unwanted hydrogen sulfide. The reaction process can be seen bellow.

$$2H_2S+O_2 \rightarrow 2H_2O+2S$$

$$2H_2S+3O_2 \rightarrow 2H_2SO_3$$

Because of the acidity of the reaction products corrosion may be an issue. The produced sulfur is collected and mixed with the digestate to improve the fertilizer product. Sulfur needs a special type of bacteria called Sulfolobus to be produced from hydrogen sulfide. These bacteria is present in the substrate since it consists the necessary nutrients [9]. The bacteria thiobacillus is also present which produces sulfuric acid [22].

Internal biological desulphurization inside the digester is a simple method that can be done by using small compressors to inject air. In this way aerobic zones in the gas space are created. The reaction appears in the gas space or on the walls of the digester. If a floating layer exists the reaction can also occur on this surface [9].

External biological desulphurization is done after the injection of oxygen by either a trickling filter, bioscrubber or a combination of both. The trickling filter has a biofilm which grows on a packed bed. For growth of microorganisms, nutrients must be supplied by recirculating a liquid through the filter. A bioscrubber discharges liquid droplets which absorbs hydrogen sulfide. Further, the resulting sludge is led to a reactor with microorganism growth where hydrogen sulfide is separated into sulfur and water. The effluent is recirculated and discharged over the bioscrubber again. These methods can remove high amounts of H_2S but has a low adaptability to fluctuations [22] .

2.5.2 Chemical desulphurization

In chemical desulphurization a substance is added in the process to chemically remove or avoid the unwanted gas from mixing with the output biogas. Such methods requires operational costs for buying chemicals, but the transportation costs could be limited if it is available in the local community.

Admixing of iron salts as iron chloride ($FeCl_3$) and iron sulfate ($FeSO_4$) to the digester or in a tank before the digester results in precipitation of sulfur in the form of iron sulfide (FeS). Iron sulfide is removed from the digester along with the digestate. In addition, ammonia is removed from the gas and also added to the digestate. Both are valuable as fertilizers. This is a simple method of desulphurization with low investment costs [21]. The disadvantages are the low effectiveness and control ability of the gas quality output. Therefore, this method could be preferably used in combination with other technologies.

In the case of a bioscrubber, instead of using water as scrubbing medium, a caustic solution could be used as for instance sodium hydroxide (NaOH). An oxidizer, often hydrogen peroxide (H_2O_2), is also added to oxidize the absorbed hydrogen sulfide into sulfur or sulfate (SO_4^{2-}). This method is suitable when dealing with high fluctuations in the hydrogen sulfide content, as the chemical addition can be easily controlled. With this method a concentration of 5 ppm hydrogen sulfide can be obtained [21]. Hydrogen sulfide concentration in raw untreated gas that this applies for is not found.

2.5.3 Adsorption on metal oxides and activated carbon

Adsorption of hydrogen sulfide can occur on metal surfaces as iron oxide (FeO), zink oxide (ZnO) or copper oxide (CuO). When hydrogen sulfide is adsorbed it is bound as metal sulfides, while water is produced and released. When the adsorber is fully loaded it must be replaced by a new plate [22].

Activated carbon is highly porous charcoal. The adsorption at an activated carbon surface is usually done while adding some additional oxygen to produce sulfur solid which sticks more to the surface. The overall costs for this method are high, but results in hydrogen sulfide concentrations a bellow 1 ppm. Therefore, it is only used in the final stages of processes where the required hydrogen sulfide concentration is particularly low [22].

2.5.4 Drying for water removal

Very often, biogas is saturated with water vapor after the digester. At the same time, some of the common gas cleaning methods, as the bioscrubber and the trickling filter, adds water after the digestion process if the gas is not already saturated. Water vapor may condense in pipes when passing from high to low pressure or cooled by the ambient air or ground. This may lead to corrosion or gas blockage. Most biogas applications, for example gas engines, have maximum requirements for relative humidity.

The design of the pipes can avoid some water related difficulties. As mentioned earlier drainage can be done by leading the water either back to the digester in a straight slope, or alternatively a water trap can be used to lead the water directly into the soil beneath [4]. The pipes could also be placed underground to increase the cooling effect and hence the water removal. A stable foundation is required since a moving ground could affect the angle of inclination. Unwanted substances as water soluble gases and aerosols will also be decreased during the water condensation. A more effective, but at the same time more expensive method, is using an electrical cooler [9]. To decrease the relative humidity without affecting the absolute humidity, the water can be heated up after a cooling process. The figure below shows the effect of cooling and preheating on the relative humidity.

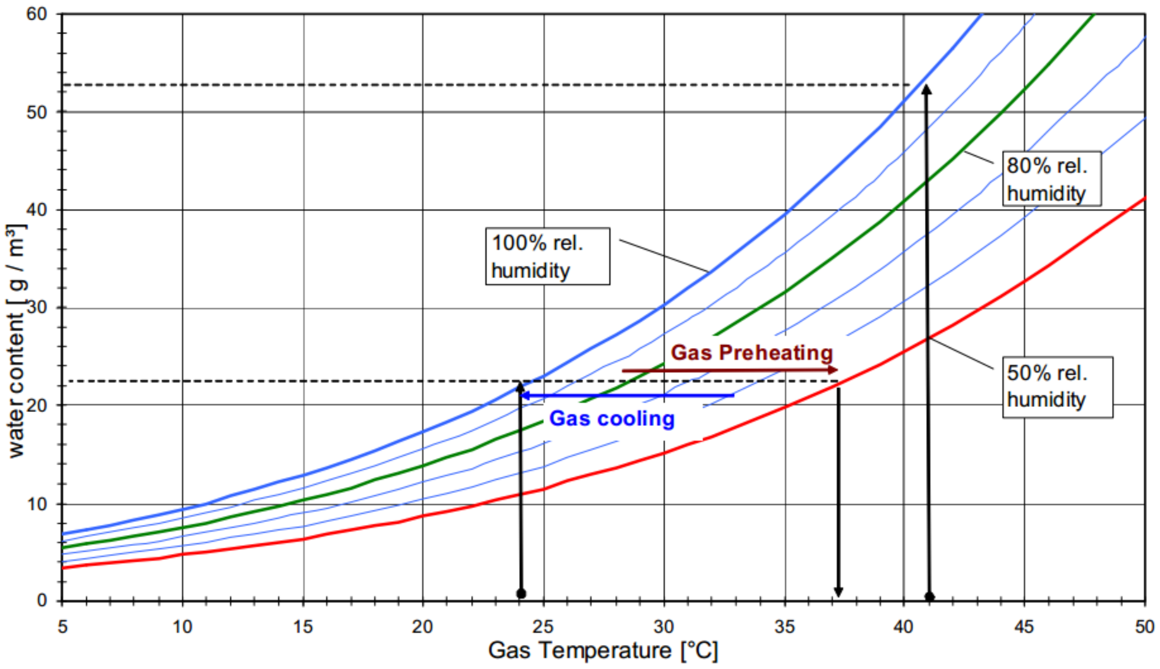


Figure 2.11 Water content in biogas at different relative humidities [21]

This figure can also be applied for finding the absolute water content in the gas when knowing the gas temperature and the relative humidity.

2.5.5 Ammonia removal

Ammonia is corrosive and may lead to emission of Nitrogen dioxide when combusted. Since the concentration is usually low, measures are often not needed. Ammonia could be removed by any water scrubbing method or by condensation of water, but also by the admixing of iron salts method [21]. Using the latter method, the nitrogen is converted into a liquid ammonium form, which increases its quality as a fertilizer as mentioned earlier.

2.6 Water pumping

2.6.1 Groundwater source

Groundwater makes up 97 – 98 % of all liquid fresh water on the planet. It can be found almost everywhere including deserts, but the distance down to the groundwater source varies. The water quality is often very high compared to surface water. It usually has an even temperature, low content of organic matter substances and a low content of microorganisms. On the other hand it may have more magnesium and calcium, which may be a problem if too high concentrations. Many countries are deeply dependent on their groundwater source, especially arid areas. If the drainage into the groundwater source is lower than the water pumped up, the water supply will be unsustainable [23] .

2.6.2 Well design

A screen allows only water into the pump and should be placed against the optimum aquifer zone. A casing is needed to keep the borehole open by avoiding collapse. On the outside of a screen, gravel pack around the whole borehole should be placed to avoid fine sand corns to enter the pump. The grain size should be between 2 – 4 mm diameters[24].

2.6.3 Electrical submersible pump

An electrical submersible pump is commonly used for fresh water supply. It is a thin single-stage or multi-stage centrifugal pump that is vertically lowered into the borehole. A stage in a centrifugal pump consists of an impeller that rotates the fluid as it is moved from the inlet suction to the outlet discharge inside the hollow and stationary cavity. The velocity is converted into pressure energy in the cavity due to increase in the cross sectional area of the pipe[25]. The more pressure needed the more stages are used. The pump is chosen based on required flow and the head. The total head depends on the water level in the well, the lift up to discharge and discharge pressure and the total losses[19].

The pump output necessary can be found by[26]:

$$P_{out} = Pr \cdot Q'[kW] = h_{tot} \cdot g \cdot \rho \cdot Q'[kW], \qquad \text{[eq.9]}$$

where:

Q' is the flow rate [m^3/h]

ρ – Water density [kg/m^3]

h_{tot} – is the total head [m]

g – Gravitational acceleration [m/s^2]

A centrifugal pump has a connected shaft with bearings connected to a motor. In an electrical submersible pump the motor can either be connected to the pump via a mechanical shaft or the motor can be hermetically sealed and submerged together with the pump. In the case of the latter type, the motor and cable must be designed to operate under water [19].

The most common electrical motor today is the AC induction motor, which has to run at a small lag in motor speed compared to synchronous speed to produce a driving torque. The synchronous motor speed can be found by:

$$n_{sync}=\frac{60 \cdot f_{grid}}{\text{pole pairs}}[rpm] \qquad \text{[eq.10]}$$

where:

f_{grid} – Grid frequency [Hz]

Pole pairs – number of pole pairs in the motor

The most common AC induction motors are the squirrel cage and wound rotor. For 3 phase applications at constant speed drive with no continuous low-speed running, an AC induction motor is suitable[27]. To protect it against overload, surges and phase failure a circuit breakers and thermal protector (O/L relay) should be present[19]. Phase loss relay and water level control of tank and source control could also be added for further protection.

During start-up of the pump, the locked rotor current, or starting current, is often 5 – 7 times the rated current for about 0.1 second and the starting torque can be twice the operation value[28]. If the load is high there should be some device to protect the grid or other equipment against surges.

The simplest way is to couple the motor directly to the grid through for instance a contactor. This is called direct-on-line (DOL) starting and is the way to produce the least heat if it supplies a low inertia load up to 45 kW. The starting current is not decreased but the motor life span is long due to low heat generation[19].

A D/Y starting connects a Y-configuration during start-up and switches automatically over to a D-connection after a fixed duration of time. This reduces the voltage and torque and therefore also the current during start-up. However, for small pumps with low inertia, speed will be lost during the transition between Y and D connection resulting in a current spike. Also only duel voltage motors with six leads can be used.

An autotransformer (AT) could be used instead of a D/Y starter. As the motor speed increase, the taps in the transformer is changed to increase the voltage supplied to the motor. The AT reduces the distribution side current with the squire of the voltage ratio, unlike the other starting methods were this current varies directly[29]. As the AT is connected as a choke coil during the tap change the motor will be connected to the power supply the whole time and thereby not loose speed[19].

For constant-speed motors, soft starting could be used for reducing the voltage and torque and hence also the current. Control of the phase-angle is here applied and the control section sets the operating and protective parameters[19]. For variable-speed motors, a frequency converter could be used to control the speed. This is very accurate, but is overkill for constant-speed applications[19]. Another method of reducing start-up current is to couple a resistor or reactance in series with the motor[29]. This method will waste much energy through heat.

2.6.4 Pumping conditions

To find the optimum pump and the most efficient pumping rate, the pumping characteristic must be compared to the system characteristics. The pump characteristics are given by the manufacturer, while the system characteristics can be found by finding the total head at different flow rates. The total head is found by summing the losses due to the friction, fittings and the height.

The friction head is found by the following steps. First, the relative roughness (e) of the pipe must be found by the relations between the absolute roughness (k) of the internal surface of the piping and the inner diameter (d) of the pipe[26]:

$$e=\frac{k}{d} \qquad \text{[eq.11]}$$

Secondly, the Reynolds number (Re) can be found by[26]:

$$\mathrm{Re}=\frac{v\rho d}{\mu}, \qquad \text{[eq.12]}$$

where:

v – Speed of fluid [m/s]

μ – Viscosity of fluid [kg/m·s]

ρ – Fluid density [kg/m^3]

By knowing the Re and the relative roughness, a moody chart for water pipes can be read to find the friction factor at different flows. A moody chart specified for water pipes can be found in figure A.4 in the appendix. Knowing the friction factor, the equation below can be used to find the friction head[26].

$$h_f=f\left(\frac{l}{d}\frac{v^2}{2g}\right) \text{ [m]}, \qquad \text{[eq.13]}$$

v – Speed of the water flow [m/s]

l – Length of the pipe [m]

d – Inner diameter of the pipe [m]

2.6.5 Generator

To convert the mechanical power from an internal combustion engine into electrical energy a generator is needed.

These generators are often given with properties at standard environmental conditions. If these conditions are not fulfilled at the given location the installed capacity is reduced. For a standard generator with three-phases, internal regulation a continuous torque and a DOL start-up, the following decrease can be expected[19]:

- 5 % for every 5 ˚C above 40 ˚C.
- 2.5 % for every 300 meters above 1000 meters above sea level.

For a 3-phase submersible pump, the generator must be able to handle a voltage reduction of 35 % during start-up. By dimensioning according to table A.7 in the appendix and taking the location into account, the voltage dip will not be larger than 10 % and the life expectancy will not be reduced[19].

Generators can either be externally or internally regulated. In external, the output voltage is regulated. When motor voltage decrease during start-up, the output voltage of the generator is increased. In the internal, an extra winding in the generator stator is used to sense the output current and adjust the output voltage correspondingly. The internal regulation has better efficiency than the external, requiring less generator installed capacity [19].

Generators are usually dimensioned according to the apparent power (S) they need to deliver. The apparent power is a function of the power factor $cos\varphi$ which is determined by the power consuming equipment.

$$S_{el} = \frac{P_{el}}{\cos\varphi}[VA] \qquad [eq.14]$$

If no efficiencies are given in the product description, generators can be assumed to have an efficiency of 90 % from mechanical power P_{mech} from the engine shaft to the electrical actual power P_{el}[3].

For isolated operation synchronous generators are normally chosen on behalf of asynchronous generators. Due to the phase shift, the generator produces reactive current, which is compensated for by a power factor controller. The generator should also be equipped with an off-load switch and a control device that adjust the frequency, voltage and phasing within the tolerated limits[2].

2.7 Summary key values

The values obtained from this chapter are general cases and should be considered as assumptions. These values are used in later calculations.

Table 2.9 Summary of key values chapter 2

Potential methane yield	0.37 m^3/kg DM
Common degradation rate animal manure	30 – 60 %
Density pig manure with 30 % DM content	1.13 kg/l
Optimal HRT in Kenya in general	40 – 60 days
Efficiency small otto engine	25 %
Efficiency small pilot-injection	30 %
Generator efficiency	90 %

3 Case Study

To get an insight of the specific case of Katulani SS, the area of Kitui County is presented. This aims to give basic knowledge about the issues and possibilities in the area. Katulani SS is also presented with special focus on the biogas reactor and the water pump located at the school.

3.1 The Republic of Kenya

Kenya is located in Eastern-Africa at 1 00 N and 38 00 E. It borders to Somalia, Ethiopia and South-Sudan to the north Uganda to the west, Tanzania to the south and the Indian Ocean to the east. Nairobi is the capital and the country has an area of 580,367 m². The climate varies from tropical along the coast to dry in the inland. The population is above 44 million divided into several ethnical groups. Non-dependent of ethnical grouping, 82.5 % of the population is Christian. Kenya was a British colony until 1963. The national languages are therefore English and Kiswahili. The country consists of 7 provinces and 47 counties[30].

3.2 Kitui County

3.2.1 Location

Kitui County is one of the 47 counties in Kenya. It covers an area of 30,497 km² in the central south-east part of the country. The county is divided into four districts: Kyuso, Mwingi, Kitui and Mutomo. The main city in the county is Kitui Town located in Kitui district about 130 km east from Nairobi [31] and about 1,400 meters above sea level[1].

3.2.2 Demography

Kitui County had in 2009 a population of 1,012,709 inhabitants. This gave a population density of 33 people/km² which is low compared to the average of 74.1 people/km² in Kenya. 447,613 of the inhabitants are living in the Kitui district. 48 % of the inhabitants are men and 52 % are women [32]. During the last years the population has increased drastically, and the percentage of people between 0 – 14 is 46.6 %. Only 5.2 % are 65 years or above. The inhabitant growth rate per year is 2.2 % taking into account the born and death ratio and the immigration and emigration ratio. The number of households is 205,491 which gives 5.4 people/household on average [33].

The ethnic groups in the Kitui area are mostly Akamba, but there are also groups of Swahili and Somali. The Akamba tribe lives in the countries of Kitui and Machakos in Kenya. Traditionally, they were agriculture and cattle farmers. Before the colonization they were engaged in trading between the inland and the coast. They had no centralized political organization at the time. After the colonization, they started working at the European's farms and in the cities. Today they are an active political group [34].

3.2.3 Topography and Climate

The altitudes in Kitui range from 400 meters to 1,800 meters. The central part consists of hilly ridges, separated by low lying areas between 600 – 900 meters of elevation [35].

The area is semi-arid, meaning that only short grass which is resistant to drought is able to grow without any artificial irrigation. The annual precipitation in different parts of the country is between 500 – 1,050 mm and usually falls during the rainy season in April/May and November/December. The rain is highly unreliable and often falls in a few intensive storms[35]. There are large local differences in precipitation due to factors like topography. The driest areas in Kitui are in the eastern and southern parts. Occasionally rain season is absent causing severe drought.

Almost all the county area is the drainage basin belonging to Tana River flowing at the north-west county borders to Meru and Embu. The Tana River is Kenya's largest river. It flows through Tana River County before it discharges into the Indian Ocean. Athi River marks the district boundary to Machakos to the west and Taita Taveta to the south. According to [1], there are two permanent rivers in the county: Tana river and Athi river.

The temperatures vary between 14 ˚C and 34 ˚C and peaks between January and February and between June and September [33]. The annual average solar radiation in this area of Kenya is approximately between 5.5 – 6 kWh/m²/day [36]. This is the total amount of shortwave radiation received from above by a surface horizontal to the ground.

There is not much wind in this area of Kenya, less than 100 W/m² at 50 m.a.sl.[37]. Some windmills connected to water pumps can be seen but are rare. No geothermal power is generated in this area, although Kenya is the largest geothermal producer owing to the Rift Valley in the west of the country.

3.2.4 Industry

Cotton is the only large industry in the county. Farmers can deliver their harvest at a cotton ginnery which is located in Kitui Town. Other agriculture products are livestock products, maize, beans, sorghum, pigeon peas, cowpeas, cassava and millet [33]. Irrigated agriculture takes only place along river banks. Mostly the agriculture is rain fed and during periods of drought farmers are dependent on relief food from donors [35]. Main industries are livestock keeping, tobacco, coffee, mangoes and commercial businesses [33]. Other industries commonly seen are local artifacts as carved wooden figures and woven baskets.

A 500 km² area stretching through Kitui and Mutito was discovered to contain one of the richest coal reserves in the world. Iron ore and gemstones reserves also exist in the county[33].

3.2.5 Water availability

There are not many water sources in the Kitui. Seasonable rivers occur during the rainy season but do not last for long and soon dry out. Some of them have dams to store the water for a longer time typically for use in irrigation. Water from rivers can also be used for washing purposes or livestock water, but rarely for human drinking water.

The water delivered by Masinga dam goes through a thoroughly cleaning process while the water from the boreholes is regarded clean and is not treated. In Kitui town old cement pipes from the colonial time is still in use and only partly replaced by new pipes made of plastic. The joints between the new and old pipes cause leakage [35]. The rate of leakage is unknown.

The water from the pipe system can be bought at water stations located several places around the area with opening hours from 8 am to 6 pm each day. It usually cost 2 KES for 20 liters in the outskirt of the city while in Kitui Town the price is 3 KES for the same amount of water. This water stations usually close during dry season due to a lower water surface limit in the reservoir. Water can also be bought in ordinary stores for a price of 35 KES for a 1 liter bottle.

Kitui town has currently no sewage system, but construction is ongoing.

3.2.6 The Masinga reservoir

The Masinga reservoir is the largest man-made lake in East Africa operated by the Kenyan electricity company KenGen. It belongs to Tana River and is located at the border between the two counties of Embu and Machakos about 121 km north east from Kitui Town [31].The inflow is highest during the rainy season, but there will also be inflow during dry periods due to snow melting from Mount Kenya. According to KenGen the capacity of the reservoir is approximately 1.433 billion m³ with a siltation of 10 %. This means that the actual water volume is 1.29 billion m³ due to fine particles that takes up space [35].

Figure 3.1 Masinga Dam showing submersible pump and pipe line towards Kitui.

The lower limit of the water level in the reservoir is governed by the Masinga Dam Hydro Power plant’s ability to generating electricity. The water distribution in the pipes is shut down so that no water from the pipe lines flows if this limit is exceeded. This happens usually every dry season.

Masinga Dam delivers 9,000 m³ of drinkable water each day. Construction is ongoing to double this water flow. The pipes will then stretch further past Kitui Town.

The water goes through a treatment process before it enters the pipelines. First the water is roughly filtered for large objects before it is pumped up to a raw water tank by a submersible pump. A chemical house makes a solution of chlorine, aluminum sulfate and soda ash ($\mathrm{Na_2CO_3}$) by adding it to a water flow through gravity dozers that are manually operated. Chlorine is used as disinfection, aluminum sulphat as coagulation and soda ash to raise the pH value of the water. The decided concentration of the different chemicals is based on daily laboratory tests. There is typically more dirty water in rainy season, thus more chemicals added. The solution from the chemical house and the water is combined in a mixing chamber. The mixture goes then into a flocculation basin, which gives the water time to react with the added chemicals. After this basin the water goes through a rapid sand filter to filter out larger particles. The last stop before it is pumped to the pipelines is in the clear water tank where additional chlorine is added.

Despite that Masinga water is treated for drinking water quality, it is common practice to boil the water from the pipes before drinking.

3.2.7 Sand dams

In 2006 there were about 500 constructed sand dams in the central part of Kitui. These dams are constructed under rivers that normally dry out during drought season. The riverbed is filled with sand to increase the natural aquifer. In this way the water can be provided for a longer time period [35].

3.2.8 Power production and electricity distribution

The state-owned Kenya Electricity Generating Company is the leading electricity producing company in Kenya and produce about 80 % of the total electricity consumption.

In 2009 Kenya had an installed electric capacity of 1.706 million kW. From this, 43.8 % comes from hydro plants, mostly located in Tana River. 43.3 % comes from fossil fuels while other renewable sources as geothermal and wind power have 12.9 % of the total installed capacity. The country has no grid connected solar plants or nuclear power plants [30]. The only grid connected power production in Kitui County is three hydro plants in Tana River. The country has never had any petroleum production. However, oil reserves have just recently been discovered in northern parts of the country.

The frequency in Kenya alternates at 50 Hz, and has normal voltage output of 240Δ/415Y volts. The grid is unreliable and outages occur often. Outside the city, grid connection is not common. Off-grid solar cells can be seen, but is too expensive for most people.

The electricity price does not change much and is governed by the price of fossil fuels. The current fuel prices in March 2013 where around 109 KES for diesel, 119 KES for petrol and 90.1 for kerosene as seen in figure 3.2.

Figure 3.2 Fuel prices Kitui area March 2013

3.3 Help to Self-help in Africa (HTSA)

HTSA is a small Grimstad based NGO that aims to create profitable and environmental friendly businesses in Africa containing pig farming, biogas reactor and water supply systems. They started their work in 2006 and have since than established a biogas reactor in Kiabakari Bible School in Tanzania and Katulani SS in Kitui, Kenya. At Katulani, a water supply system has also been established. The organization has established a great network of people in the Kitui area and is currently planning two more biogas reactors and water supply systems in the area [38].

The organization has also supported the education of people in the area which among other has resulted in a particularly skilled biogas constructor who has built about 70 biogas reactors between 2009 and 2012 [38].

3.4 Katulani Secondary School

Katulani SS is located outside the center of Kitui Town. The school is a boarding school with about 300 students and a capacity of 320 students mostly between the age of 13 and 18. Secondary school is not for every one and only the best students from primary school are enrolled.

The school is opened approximately 22 days a month and 10 months a year[39]. There are about 10 people working at the school. Some of the facilities at Katulani SS are science lab, computer lab and a football field and volleyball court outside. Two cows and several chickens are freely wandering around in the school yard, while pigs are kept in the pigsty. Electricity is provided from the grid to the main building. In the image of Katulani SS in figure 3.3, the water pump can be seen as the white squire down to the left, while the pig house is the larger white building to the right in the picture. More explanations are given in the map in figure 3.7.

Figure 3.3 Image of Katulani SS dated 10. June 2013 and retrieved from Google Earth

3.4.1 Pigsty design

The capacity of the house is about 150 pigs [1] and can be seen as a floor plan in figure A.3 in the appendix. The pigsty itself has an area of 18.9 x 7.2 m with a 0.8 meter aisle that is wide enough for a wheel barrow to get through [39]. It is divided into 11 pig bins and one room for storage. The pigs are arranged in each pig bin after age, with an exception of the sow which feeds the small piglet in a family bin. In those cases, a 0.2 meter high wood shelf is placed around the edges of the bin to protect the piglets against the heavy mother. Each bin has its own water trough.

The pigs are trained to defecate in an outer compartment, so that the dung can be easily shoveled. For this purpose, channels are located along the outside of the pig pens with a depth of 40 cm and width of 60 cm[4].

3.4.2 Pig feed

The pig feed is crucial for both the pig growth and the biogas production. Pigs are omnivorous, but do they get stomach issues this may cause death. Therefore, antibiotics are added to the fodder. Two main components in most pig feed are maize and soy [39].

Kitui is a dry area, but pig food can still be bought from a local store in Kitui Town and costs 1,700 KES/bag. One bag weighs 70 kg but the content of this feed is unknown [39]. The feed is supplemented by left-over vegetables from the local market close to the school.

Feed that guarantees satisfies Kenyan standardized pig nutrition values can alternatively be bought from Nairobi, about a four hour drive from the school. The price of this feed is 2,300 KSh/bag. A truck can carry about a hundred bags of 70 kg each trip. Buying as many bags as possible would reduce the transportation costs [39].

3.4.3 Slaughtering

Pigs that were finished for slaughtering had an average living weight of around 45 – 50 kg after 5 month. The pigs are mostly sold to a slaughter house in Nairobi for 198 KES/kg. They can also be sold to a local slaughter house for a price of 250 – 300 KES/kg but the market is not that large in this area.

It is desired to establish a slaughter house at the school to increase the revenue. This may also produce entrails that can be added to the digester for increased biogas production. A slaughter house requires an electricity consuming freezer and good hygienic conditions.

3.4.4 Biogas digester

The dung is shoveled onto a wheel barrow and brought to the inlet of the biogas digester. This is done at pig keeper’s choice although there are channels on both sides of the pigsty that can be used for pushing the dung to the inlet. According to pig keeper Nicodemus [40], a number of 3 full wheel barrows with pig manure are filled into the reactor. This is done from Monday to Friday and not during the weekends[39].

The inlet to the digester is a hollow rectangular solid made out of concrete as seen to the right in figure 3.4. The dung is mixed with 50 % water in the inlet space to make a slurry[40].

The tools used for the mixing into slurry are a wood stick and a y-shaped wood device with a net in between. A hollow cylindrical lid with a wood handle and closed bottom is lifted when the slurry is mixed. The slurry is then sucked into the digester. The dung from the two cows is also collected from around the school yard and supplied to the digester.

The digester is made out of locally produced concrete. The liquid working volume of the digester is 48 m^3 and the effective gas volume is 9.7 m^3[13].

The over-pressure in the tank should be 4.9 kPa at minimum slurry volume in the digester and 14.7 kPa at maximum slurry volume [39]. The only part visible from above ground is the top cylinder with the gas pipe outlet as seen in the middle in figure 3.4. On top of the digester cylinder is a small water chamber which indicates if there is any leakage by the presence of bobbles.

Figure 3.4 Biogas facility at Katulani SS. Output chamber is shown to the left, biogas output in the middle and slurry input with mixing device to the right

The output tank to the left in figure 3.4 is a shallow basin with a wall stretching diagonally across the basin. When gas is produced, the volume of the gas expands in the digester. This expansion pushes the slurry towards the output basin where it flows out through a pipe at a certain height. The slurry does not go back to the inlet due to the higher altitude of the input than the output basin. When gas is used the slurry height of the output basin sinks and the gas flows out through the piping. A HRT of 60 days was recommended in the report of recommendation by [13]before the building of the plant at Katulani SS, this is within the expected HRT seen in table 2.4.

The distance from the biogas digester to the kitchen is about 12 meters. Galvanized steel pipes with a diameter of ¾ inch leads the gas to the digester beneath the ground. The pressure loss in the pipe line is designed not to exceed a 0.4 kPa pressure loss [4]. That is much less than the minimum driving pressure of 4.9 kPa from the digester. A vent outside is located close to the digester. This vent is covered by a blue bucket to avoid student sabotage. A water trap is placed closed to the kitchen, which drains the water that is condensed into liquid state due to the cooling effect of the ambient ground.

3.4.5 Kitchen

The kitchen consists of 3 large wood stoves and 4 biogas burners. Two of the biogas burners have 4 rings where the biogas comes out through small holes. Depending on the pan size and the amount of gas needed this 4 rings can be shut on and of independently to adjust the gas consumption. To create the desired burning from the stove, it has to be ignited manually.

Figure 3.5 Two of the four biogas stoves at Katulani SS

A PVC hose with a diameter of ¾ inch leads the gas from the steel pipe outside to the burner through a vent inside the kitchen. This hose is easy to decouple. Gas will then flow out in the room if the vent inside the kitchen and the vent outside the digester are open. Since the kitchen has good natural ventilation, there is no explosion hazard.

From [4] a maximum biogas flow of 2 m^3 at the steel pipe and PVC hose diameter of ¾ can be expected. Katulani SS aims to consume biogas for cooking for 6 hours at full biogas flow from 8 am to 2 pm every day. This gives a maximum gas flow of 12 m^3 during those hours.

As stated by [41] about 35 – 45 % of the food cooking is done by using biogas. Fire wood contributes to the rest of the heating process. The fire wood is usually of the type acacia and costs about 6,000 KES/ton. Katulani SS had in 2012 a total fire wood cost of 120,000 KES. The burning of wood lets out flue gases in the kitchen which makes it a health issue to work there due to no chimney.

Alternatively, charcoal could be bought at the local market for about 150 KES for a bag with a volume of approximately 40 liter. Charcoal is not measured in weight at the local market since this is easy to manipulate by adding water. Charcoal gives a cleaner combustion than fire wood, but 70 to 80 % of the energy disappears during the production[42]. Kerosene and LPG are also widely used for cooking. Kerosene is commonly used in urban areas while LPG is more common among wealthy people in both urban and rural areas[13].

3.4.6 Water pumping system

The grid connected water pumping system was established in Mars 2012. The borehole is 176 meters deep and the pipe 1 ½ inch in diameter [39]. According to the pump entrepreneur Paul Kariuki[43], the installed pump is a Grundfos SP5A-44 multistage submersible pump with a rated flow at 5 m^3/h and an additional check valve included. The pump supplies on average 9,000 liters each day [1], and is submerged together with a 4 kW three-phase squirrel cage induction motors of the type MS 4000. This motor runs at 2875 rpm and 415 V.

A reliable pump is crucial since maintenance requires trained people to do the job. The amount of water allowed to pump by the government is 20,000 liters daily. The main tank is located beside the entrance of the school at the roof of the control room, about 2.5 above ground. The tank itself has a capacity of 20,000 liter and is about 3 meters high. The distance between the main tank and borehole is approximately 50 meters. From the main tank the water is led to the kitchen, the principles house, the staff room, the dormitory, the science lab and to a tank outside the pig house. This tank outside the pig house is 1.3 meter high, has a capacity of 2,500 liters [1] and is 2.4 meter above ground to give pressure for the hose in the pigsty. For the pigsty and the digester approximately 1,400 liters are assumed to be needed each day for pig consumption and mixing into the biogas digester inlet. This water can partly be gathered from the tank containing surface water. About 5,000 liters from the borehole is assumed used by the student and staff for drinking. The water quality of the ground water is considered safe for human drinking without any treatment. When the school has surplus water, it is sold to the local community for 2 KES per 20 liters, which is the same price as at the local water stations.

3.4.7 Control panel

A power cable from the control station to the pump site goes beneath the ground. The power is connected in a delta connection without neutral at about 415 V. Outside the control box, the voltage and ampere is monitored and shown in a display. The control box has several functions and components:

An ABB block contactor for direct on-line (DOL) starting is used[44]. It switches the power by using a manual Andeli circuit breaker at a lower power circuit[45]. An ABB thermal overload (O/L) relay is connected to protect against current overloads, phase imbalance and phase loss[44]. In the case of too high temperature in the motor, the O/L relay opens the switches in the 3 pole Gold Plus miniature circuit breaker. This circuit breaker is coupled in the series with the supply before the contactor and the motor[46].

A Lovato phase sequence and phase loss relay is connected which monitors the voltage of the motor. Without this relay the phase sequence could be reversed and further revers the motor, or in the case were one of the circuit breakers trips, the motor may not start or draw the necessary current from the two other phases. Both cases could damage the motor and the pump[47].

Additionally, a floatless relay of the type AFR-1 is connected. This relay is connected to two sensors. One of the sensors is located down the borehole to monitor the water level. The submersible pump could be damaged if the level of the water sinks below the pump. Another sensor monitors the water level of the main tank so the pump does not waste energy by trying to pump water to a full reservoir[48].

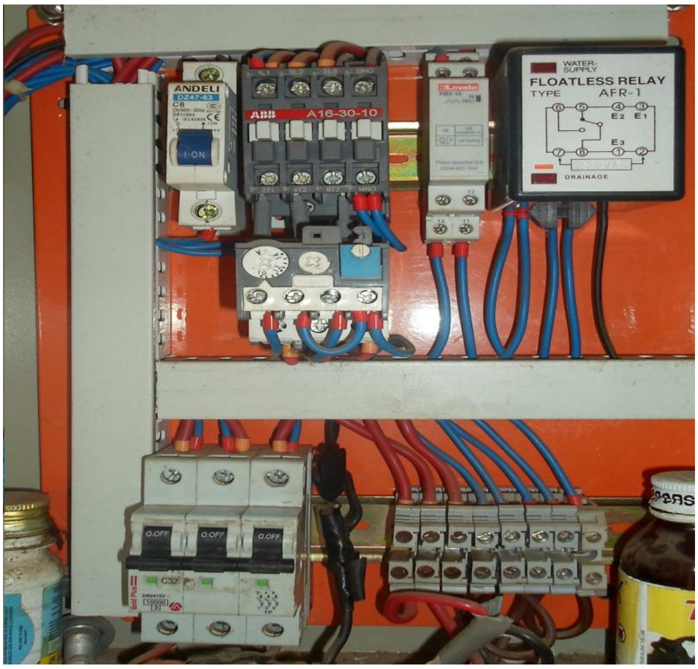


Figure 3.6 Control panel for water pump

In figure 3.4 is the control box in the control panel for the water pump at Katulani SS.

3.4.8 Other water sources

Usually, the borehole belonging to the school provides enough drinking water so that the school is self-supplied. But other water sources are available in this area. Water from Masinga Dam can be bought from the local water station for 2 KES per 20 liters or 100 KES/m^3[1]. In 2012 Katulani SS had total water expenses of 63,000 KES, due to operation start-up in March and some operational problems[41].

The water can also be carried by donkeys from the river located three kilometers from the school. A donkey normally carries 80 liters on its back. This is not a reliable water source since the river often dries out. However, water can still be found in dried rivers after digging 2 – 3 meters downwards[42]. Roof water is designed to be collected into tanks from five of the building in the school yard. Only 4 of them are currently in use. This surface water from the roof and the river is primarily used for cleaning and livestock purposes. Drinking water is usually cooked when taken from the roof tanks or the river.

3.4.9 Electricity supply

The average electricity rate in 2011 and 2012 was 19 KES/kWh plus fixed charge of 120 KES/months according to the economist Mumo[41] at Katulani SS. The school had in 2012 a total electricity consumption of 7,762 kWh with an annual electricity cost of 147,500 KES and a fixed charge of 1,440 KES. This is included electricity for the water pumping. Except for water pumping, electricity is manly used for lightning. No heaters or air conditioning devices are used at the school facility.

The electricity in Kenya is highly unreliable. [41] estimated the failure period during rainy season to be 45 %. Included in this percentage is every Thursday during a rainy season where electricity is cut-off due to maintenance. Outside the rainy season he estimated about 25 % failure rate.

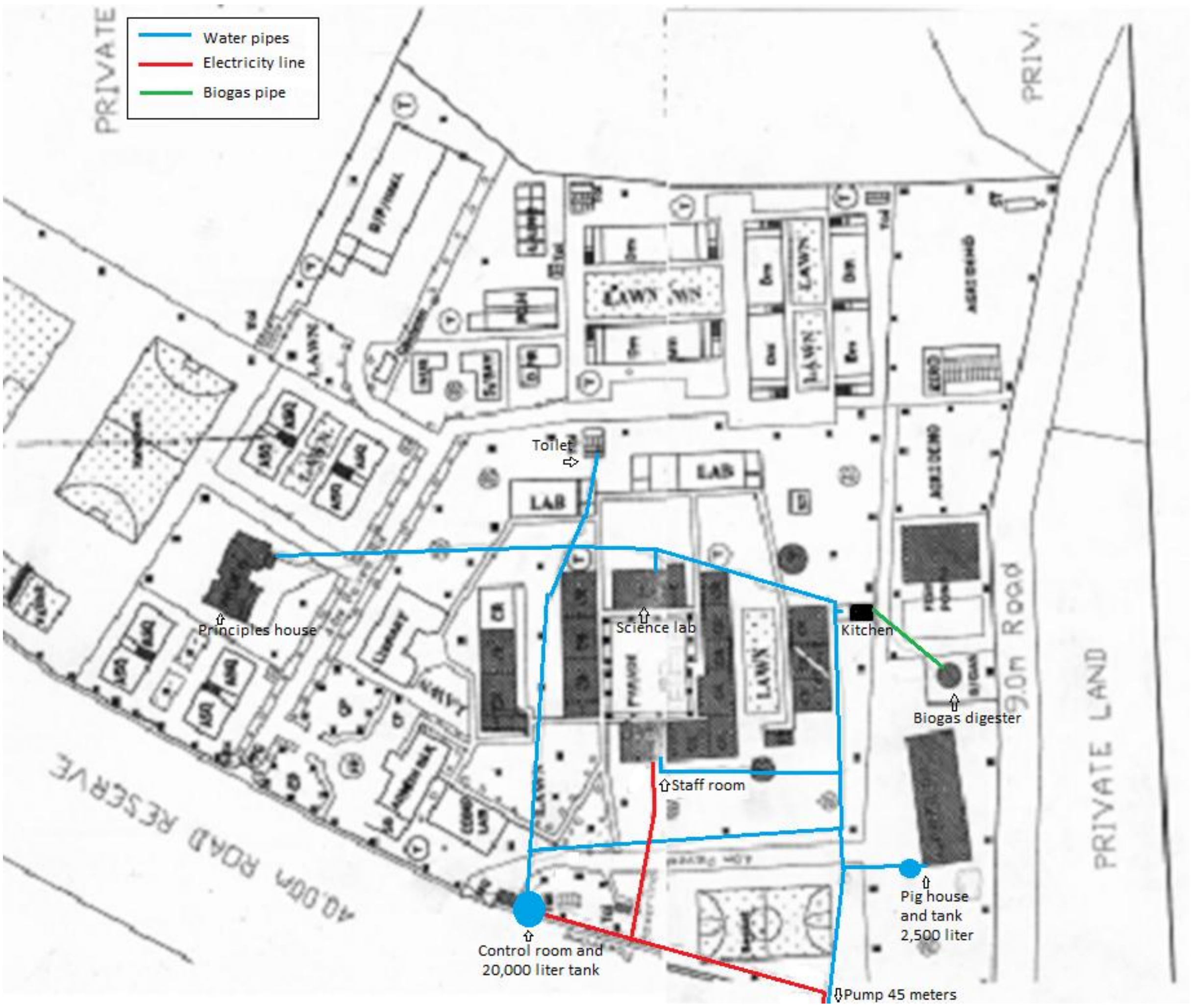


Figure 3.7 Map Katulani SS with existing buildings (black) and planned future buildings (white) [31]

3.5 Discussion

The method used to collect data about the biogas reactor and the pump in the case study has been by questioning local staff and the HTSH organization members. Some measurements were taken regarding size of wheel barrow and tank size and height above ground.

Since the pig keeper[40] uses a shovel and a wheelbarrow to carry the dung, some of the valuable urine is lost. The urine could contribute to the biogas process and at the same time lower the volume of necessary added water. No other organic materials were used in the input feedstock. This has the potential to increase the gas production rate.

The biogas fraction of the fuel for cooking was found particularly low, only 35 – 45 % of the total cooking demand[41]. By own observations of the biogas facility and the kitchen this seems reasonably as 3 large fire wood stoves were more used than the biogas due to biogas shortage.

The number of pigs is only 58 % of its designed capacity. Increasing the amount would increase income in addition to producing more manure. The slaughtering weight was about 45 – 50 kg at an age of 5 months. This is low compared to common practice and will without doubt have an effect on the average size of the pigs and thereby also the manure production rate. As pigs are sold for a higher price locally than in Nairobi, work can be done to increase the awareness about pig meat in the area.

The water pump setup was explained in the previous chapter. A 4 kW Grundfos SP5A-44 multistage submersible pump with a rated flow of 5 m^3/h is used at a depth of 176 meters and pipe diameter of 1 ¼ inch. It pumps about 9,000 liters each day, but the used water at the school is only 5,000 liter per day. This means that about 4,000 liters are sold to the local community. The electrical control panel connected to the pump is sophisticated and needs to be handled by skilled electricians when failure occurs.

Knowing the size of the biogas pipes, the amount possible biogas transportation from the digester to the kitchen during 6 hours was found to be 12 m^3. As the biogas facility was constructed to cover the school's entire cooking demand and thereby enable a removal of the fire wood stoves, it can be assumed that 12 m^3 is the total cooking demand. Assuming that fire wood stoves cover the remaining cooking demand of about 60 %[41].

The high failure rate of the Kenyan grid points out another reason for securing a stable water supply independent from the grid.

Table 3.1 Summary of key values from chapter 3

Number of pigs	87 pigs
Capacity of pig house	150 pigs
Effective gas volume	9.7 m^3 BG
Digester fluid volume	48 m^3
Operating pressure of digester	4.9 – 14.7 kPa
Water added into total slurry	50 % of total slurry
Max BG flow in pipes	2 m^3/hour
Gas pipe diameter	¾ ’’
Designed pressure loss of the gas pipe	0.4 kPa
Distance biogas digester and kitchen	12 meters
Diesel price	109 KES/liter
Electricity price	19 KES/kWh + 120 KES/months
Pump rated power	4 kW
Water pipe diameter	1 ½ ’’
Depth borehole	176 meters
Maximum water volume allowed to pump	20,000 liter
Hours of cooking necessary	6 hours

4 Materials and methods

The samples used for the gas measurements were taken from the hose in the kitchen, which was directly coupled between the biogas digester and the stove. The measurement equipment is listed in the sub chapters.

The methods of the research were primarily gas concentration measurements and interviews. The hose connected to the stove was decoupled before the measurements were taken. In this way, the biogas flowed freely through the hose when the vent inside the kitchen and the vent outside the digester were open.

4.1 Riken RX-415

Riken RX-415, seen in figure 4.1, is an instrument that can be calibrated to measure oxygen and either methane or hydro carbons concentrations. It has a detection system based on non-dispersive infrared (NDIR) method[49].

A 1 meter long hose and a probe were coupled to the instrument before start-up. When the instrument was ready, the probe was placed at the biogas hose outlet until a stable value was shown in the display. The instrument was calibrated against methane by Martin Bruusgaard AS. The oxygen sensor has a lifespan of approximately one year[49] and was out of order at the time of the measurements. This did not affect the methane measurements.

The instrument was turned on by following the instruction manual procedure. The display showed “0.0 % LEL and 20.9 % when it was on. LEL is an abbreviation for “lower explosion limit” which is at 100 % LEL. If other numbers were shown in the display, the instrument should be adjusted by applying fresh air according to the procedure in the instruction manual.

Figure 4.1 Riken RX-415 with hose and probe

4.2 Dräger-Tubes with Pump Accuro

The Dräger-Tube method is simple gas analyze methods used to identify the concentrations of different gases.

The Pump Accuro to the left in figure 4.2 is a hand pump iused together with Dräger tubes and does not require an external energy source. It draws 100 ml ±5% per stroke when the pump body is pressed together completely [50]. The exhaust valve is closed during the opening phase of the blows so that the gas sample flows through the connected Dräger Tube. After the complete opening of the pump body into its original position the suction process is finished. The end of a stroke is shown by a pressure controlled stroke indication located in the pump head. This indicator turns into a white color when the stroke is ended. The number of strokes is also automatically counted.

The glass of the tubes is broken on both sides before the tube is connected to the pump with the arrow sign pointing towards the pump inlet.

During measurements in the biogas hose, the tubes were placed into the hose during the complete stokes. It was important not to take the tube out of the hose before the stroke indication had turned white. Good lighting is necessary but direct sunlight should be avoided since UV radiation may affect the color of the tube.

Reading of the tubes should be done straight after the measurement is done, the color of the tube changes over time so keeping the tube as a proof is no use. If the color indication is slanting, the correct value must be the average between the long and the short discoloration. If the color indication becomes more diffuse towards the end, the point used is where the discoloration is just visible before it faints [50].

Figure 4.2 Dräger Tubes, pump accuro and tube-glass breaker

4.2.1 Ammonia 5/a

Optionally choose between 10 strokes pumping for approximately 10 seconds to measure between 5 to 70 ppm, or 1 stroke in 10 seconds to measure between 50 to 600 ppm. The reaction principle is

$$\mathrm{NH_3{+}pH\ indicator} \rightarrow \mathrm{Blue\ reaction\ product}$$

The standard deviation is between $\pm$ 10 to 15 % and other basic amines substances such as organic amines may be indicated as well. However, the indicator is not affected by hydrogen sulfide around 2000 ppm. The ambient conditions should be between 10 to 50 °C and the absolute humidity less than 20 g H_2O /m^3 [50].

During the measurements taken, 10 complete strokes were taken for each test.

4.2.2 Hydrogen Sulfide 100/a

The measuring range is between 100 to 2,000 ppm which is done by one stroke for approximately 30 seconds. The reaction principle is

$$\mathrm{H_2S + Pb^2 \rightarrow Pb^{2+} + 2H^+}$$

The standard deviation is between $\pm$5 to 10 % and the color changes from white to brown. The ambient conditions should be between 0 to 40 °C and the absolute humidity between 3 to 40 g H_2O/m^3 [50].

4.2.3 Hydrogen sulfide 0.2 %/A.

The measuring range is between 0.2 to 7 % and is done after 1 stroke followed by 2 desorption strokes in clean air for approximately 2 minutes. The reaction principle is:

$$\mathrm{H_2S + Cu^{2+} \rightarrow CuS + 2H^+}$$

The standard deviation is between 5 to 10 % and the color change from pale blue to black. The ambient conditions should be between 0 to 60 ˚C and the absolute humidity less than 40 mg H_2O /liter [50].

4.3 Delta Ohm Hygrometer HD 8501 H

Gas temperature was measured by Hygrometer HD 8501 H with a temperature range between 50 – 150 ˚C to. Humidity can also be measured with this device, but this function was out of order at the time of the measurements. An interchangeable temperature penetration probe was used and placed into the biogas hose at the kitchen. A stable temperature value was then found after 10 – 15 seconds.

4.4 Prologue Wireless Weather Station IW004

This weather station measures relative humidity, temperature, atmospheric pressure. This data is measured by a sensor and shown on a LCD display. Since the hygrometer HD 8501 H measures only temperature, the relative humidity and atmospheric pressure results are taken into consideration from this weather station device. According to the product sheet an accuracy of 1 % can be expected[51].

4.5 Interviews

Three persons from the school staff contributed to the data collection in this thesis. These are the pig keeper Nicodemus[40], the economist Mumo [41] and the principle of the school Fred Muia[1]. From the organization HTSA, the members Johannes Markhus[39] and Helge Underland[4] have contributed to the data collection.

5 Measurement and estimated results

This chapter presents the results of the gas measurements and the estimated feedstock input. From this, further calculations of the gas output and water pumping are made based on the data collection. A discussion of the results will be presented at the end of this chapter including a table of the key results.

5.1 Measured gas content and environmental conditions

In table 5.1, the results directly obtained from the measurements are shown. Hydrogen sulfide (H_2S) is shown in two separated columns. The first column shows results measured by the tube Hydrogen sulfide 0.2 %/A, and the second measured by Hydrogen Sulfide 100/a.

Table 5.1 Measurement results of gas concentration and environmental conditions

	Date [2013]	**Time**	**CH4 [vol.-%]**	**H2S [vol.-%]**	**H2S [ppm]**	**NH4 [ppm]**	**Temp. gas [˚C]**	**Humidity ambient air [%]**	**Temp. ambient air [˚C]**	**Atm. pressure [hPa]**
Test 1 Day 1	Sunday 24.03	15:20	59.0	n/a	n/a	n/a	33.6	37	32.5	892
Test 2 Day 3	Tuesday 26.03	11:00	59.5	0.2	>2,000	n/a	33.4	55	30.0	898
Test 3 Day 3	Tuesday 26.03	17:15	57.0	0.2	>2,000	6	35.6	49	34.5	892
Test 4 Day 4	Wedensday 27.03	08:45	57.0	0.21	>2,000	3	25.2	66	24.4	897
Test 5 Day 4	Wedensday 27.03	19:35	56.5	0.2	>2,000	5	32.0	48	31.5	884
Test 6 Day 5	Thursday 28.03	08:25	57.0	0.2	>2,000	3	25.0	69	24.5	897
Test 7 Day 5	Thursday 28.03	14:30	58.0	0.2	n/a	8	34.7	58	34.3	897
Test 8 Day 6	Friday 29.03	09:00	59.0	0.2	n/a	3	24.2	75	21.9	899
Test 9 Day 6	Friday 29.03	18:40	57.0	0.2	n/a	5	29.2	62	28.1	883
Test 10 Day 7	Saturday 30.03	19:55	59.0	0.2	n/a	4	29.3	70	28.4	899
Average results			**57.9**	**0.2**	**>2,000**	**5.2**	**30.2**	**59**	**29.0**	**894**

Only 5 measurements were taken with Hydrogen Sulfide 100/a as the results clearly showed a hydrogen sulfide concentration above the measurement range of this tube. It was therefore considered sufficient to only use the Hydrogen sulfide 0.2 %/A.

The average methane content was measured to 57.9 vol.-% and varied between 56.6 vol.-% and 59.5 vol.-%. For animal manure 60 % content could be expected[5]. The methane concentration showed a tendency to decrease slightly during the period of measurements.

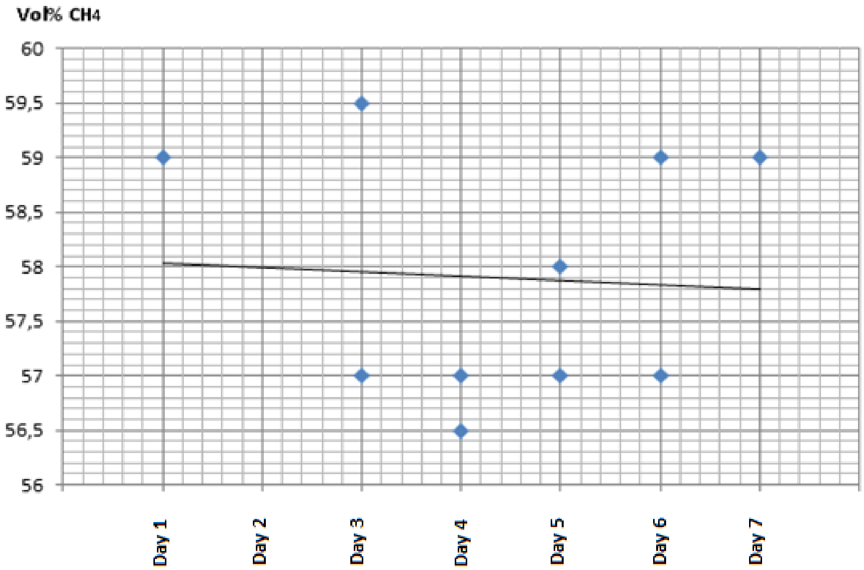


Figure 5.1 Methane average value

The methane concentration also showed a tendency to decrease during the day. This is shown in table 5.2 and figure 5.2 where the measurements are divided into morning, mid-day and evening. The column to the right in the table is the average results during each time period.

Table 5.2 Methane concentration in relation to time of the day

	Time	Test results of methane concentration				Average test result
Morning	8 am – 12 pm	59.5	57.0	57.0	59.0	58.1
Mid-day	12 pm – 6 pm	59.0	57.0	58.0		58.0
Evening	6 pm – 8 pm	56.5	57.0	59.0	59.0	57.9

The measurement from Sunday (day 1) and Saturday (day 7) were done in the mid-day and in the evening. They still showed a relatively high methane concentration. According to Uno Andersen [52] from Bioforsk, the methane production is usually stable in a continues biogas process. The methane variations could therefore be a result of external factors as an uneven feeding of the reactor. The reactor is not fed during weekends[39]. Other external reasons for methane decrease could be for instance ambient temperature change, which should not be more than ± 2˚C[5], rainfall, or alternatively the use of silicon hoses or some types of rubber hoses[52]. Only a PVC hose is used at Katulani SS, which should not have an effect on the methane production.

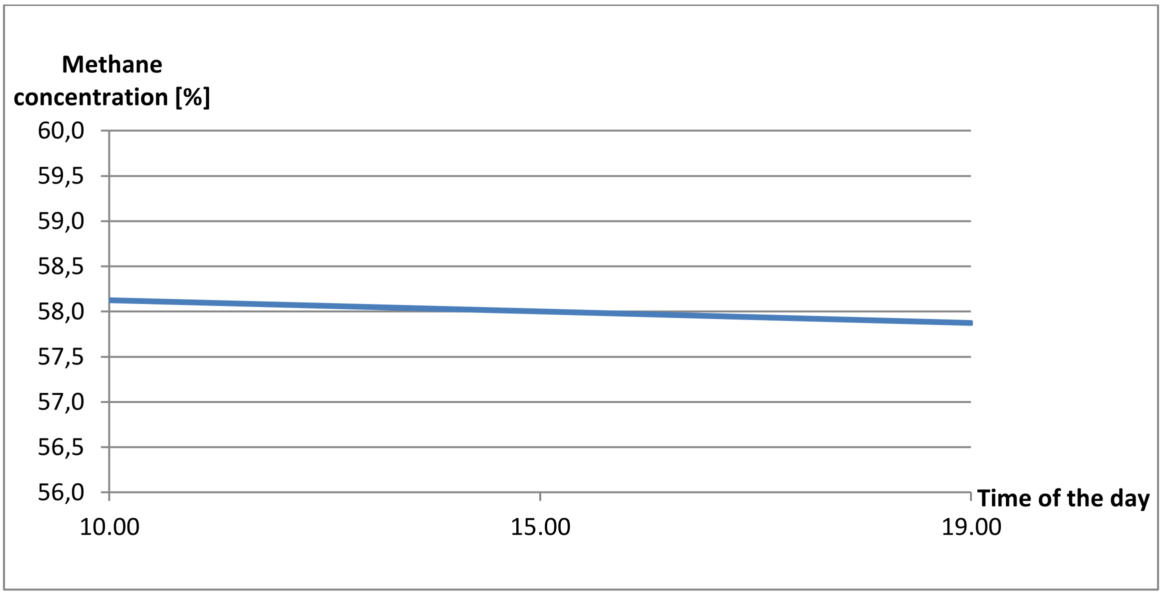


Figure 5.2 Methane concentration in relation to time of the day

5.1.1 Balanced combustion reaction

To balance the combustion reaction the water amount needs to be determined. By knowing the average gas temperature of the measurements to be 30.2 ˚C and assuming the gas to be saturated, the partial pressure of the water can be found in figure 2.1 to be 4.1 kPa and the density to be 0.031 kg H_2O/m^3 biogas (BG) from figure 2.11.

The density of methane decreases proportionally with higher temperatures and lower pressures. The over-pressure of the digester varies between 4.9 and 14.7 kPa. The actual total pressure in the digester is the atmospheric pressure added by the average over-pressure at 9.8 kPa.

The new density is thereby found by using equation 1:

$$\rho_{CH_{4(actual)}} = \rho_{CH_{4(NTP)}} \cdot \frac{P_{actual} - P_{water}}{P_{NTP}} \cdot \frac{T_{NTP}}{T_{actual}} \left[\frac{kg}{m^3}\right]$$

$$\rho_{CH_{4(actual)}} = 0.72\,\frac{kg}{m^3} \cdot \frac{(89.4-4.1)\ kPa + 9.8\ kPa}{101.3\ kPa} \cdot \frac{273\ K}{303.2\ K} = 0.61\ kg/m^3$$

By knowing the methane concentration, the actual density of methane and the water content, the mass of water per mass of methane can be found to be 0.088 g H_2O/g CH_4.

$$\frac{m_{water}}{m_{methane}} = \frac{0.031\frac{kgH_2O}{m^3\ BG}}{0.61\frac{kg\ CH_4}{m^3 CH_4} \cdot 0.579\,\frac{m^3 CH_4}{m^3 BG}} = 0.088\,\frac{kg\ H_2O}{kg\ CH_4}$$

Thereafter, from a periodic table the molar mass of methane can be found to be 16.04 g CH_4/mole CH_4 and for water 18.02 g H_2O/mole H_2O. From this, the moles of water per mole of methane can be found.

$$\frac{n_{water}}{n_{methane}} = 0.088\,\frac{gH_2O}{gCH_4} \cdot \frac{16.04\frac{g\ CH_4}{mole\ CH_4}}{18.02\frac{g\ H_2O}{mole\ H_2O}} = 0.078\,\frac{mole\ H_2O}{mole\ CH_4}$$

In the further balancing of the combustion reaction, biogas is considered an ideal gas at 30.2 ˚C, which means that the molecular forces between the molecules of the biogas are not taken into account. The volume percent and the mole percent are therefore identical when considering the reactant side of the combustion[20].

The water content per biogas can then be found to be:

$$0.078 \frac{\mathrm{m^3\ H_2O}}{\mathrm{m^3\ CH_4}} \cdot 0.579 \frac{\mathrm{m^3 CH_4}}{\mathrm{m^3 BG}} = 0.045 \frac{\mathrm{m^3\ H_2O}}{\mathrm{m^3\ BG}} = 0.045\ \frac{\mathrm{mole\ H_2O}}{\mathrm{mole\ BG}}$$

If negligible the oxygen, hydrogen, ammonia and other trace elements of the gas, the rest of the mole fraction would be carbon dioxide:

$$\mathrm{n_{CO_2}} = 1 - 0.579\ \mathrm{CH_4} - 0.002\ \mathrm{H_2S} - 0.045\ \mathrm{H_20} = 0.375\ \mathrm{CO_2}$$

The resulting gas component fractions can be seen in figure 5.3.

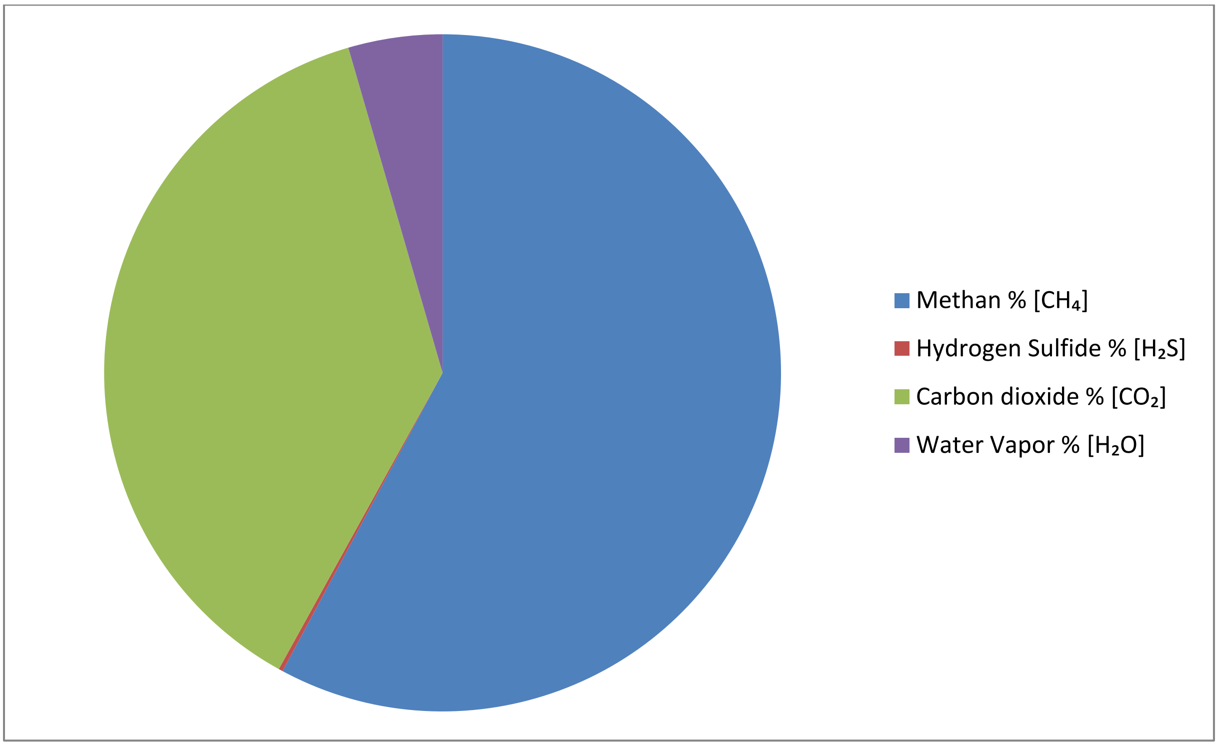


Figure 5.3 Gas concentration obtained when negligible hydrogen, oxygen, ammonia and other trace elements. Methane and hydrogen sulfide are measured directly.

The hydrogen sulfide content in relation to the methane content would be 0.003 $\mathrm{m^3\ H_2S/m^3\ CH_4}$ or mole H_2S/mole CH_4 at ideal gas conditions. Likewise the carbon dioxide would be 0.649 mole CO_2/mole CH_4.

The argon content in the air is treated as nitrogen along with other trace gases in the air. If the nitrogen content of air is assumed to be 79.1 % and oxygen 20.9 %[20], 3.78 moles of nitrogen is necessary for each oxygen atom when air is mixed with biogas in the mixing chamber of the engine. If the combustion reaction is balanced according to 1 mole of methane the following chemical equation is obtained:

$$CH_4 + 0.649\ CO_2 + 0.003\ H_2S\ + 0.078\ H_2O\ + xO_2 + 3.78\ xN_2 \rightarrow\ yCO_2 + 0.003\ H_2S + zH_2O + 3.76xN_2$$

The nitrogen and hydrogen sulfide content is assumed not to react and is therefore the same at both sides. To simplify the reaction these two gases are not considered.

As seen in equation 5, the oxygen needed for a stoichiometric combustion reaction is 2 moles per mole of methane. The simplified combustion reaction can thereby be set up to be:

$$CH_4 + 0.649\ CO_2\ + 0.078\ H_2O\ + 2O_2 \rightarrow\ 1.649\ CO_2 + 2.078\ H_2O$$

Since the biogas itself in reality contains a small volume of oxygen, the input oxygen needed from the air is slightly lower. The small hydrogen fraction could also participate in the combustion and release energy. If high enough temperature hydrogen sulfide and nitrogen could react with oxygen and give emission of sulfur dioxide and nitrogen oxides. Carbon monoxide could be present if incomplete combustion.

5.1.2 Fuel-air ratio

For a complete combustion an oxygen-methane ration (O/M) of 2:1 is needed according to equation 5 for a stoichiometric combustion. Since air contains 20.9 % oxygen[20], and the biogas contains 57.9 % methane. The total air-fuel ratio (AF) becomes:

$$A/F = \frac{\frac{n_{O_2}}{\text{Vol\% } O_2(\text{air})}}{\frac{n_{CH_4}}{\text{Vol\% } CH_4(\text{biogas})}} = \frac{\frac{2\text{ mole } O_2}{0.209\text{ mole } O_2/\text{air}}}{\frac{1\text{ mole } CH_4}{0.579\text{ mole } CH_4/\text{biogas}}} = 5.54\frac{\text{mole air}}{\text{mole biogas}}$$

That is equivalent to about 18 vol.-% fuel at stoichiometric combustion.

5.1.3 Lower heating value

Standard properties of methane at 0 ˚C and 101.3 kPa are shown in table 2.1. However, to find the actual lower heating value, the actual pressure, methane content and density must be taken into account.

By summing up the bond energy between the atoms in the chemical reaction, the enthalpy of the combustion reaction of one mole of methane can be found. The bond energy of the molecules is provided in table 2.8.

$$\Delta H = 1640\frac{\text{kJ}}{\text{mole } CH_4} + \frac{2\text{ mole } O_2}{\text{mole } CH_4}\cdot 494\frac{\text{kJ}}{\text{mole } O_2} + \frac{(0.636-1.636)\text{mole } CO_2}{\text{mole } CH_4}\cdot 1598\frac{\text{kJ}}{\text{mole } CO_2} + \frac{(0.088-2.088)\text{mole}H_2O}{\text{mole } CH_4}\cdot 920\frac{\text{kJ}}{\text{mole}H_2O} = -810\frac{\text{kJ}}{\text{mole } CH_4}$$

The negative sign means that this is an exothermic reaction that releases energy. Further, the energy content per mass of methane can be found to be:

$$LHV'_{CH_4} = \frac{810\frac{\text{kJ}}{\text{mole } CH_4}}{16.04\cdot 10^{-3}\frac{\text{kg } CH_4}{\text{mole } CH_4}} = 50{,}499\frac{\text{kJ}}{\text{kg } CH_4}$$

Taking the pressure and methane concentration into account, the following lower heating value of the biogas at the given location is obtained from equation 2:

$$\mathrm{LHV_{biogas}} = 0.579\,\frac{\mathrm{mole\ CH_4}}{\mathrm{mole\ biogas}} \cdot 0.61\,\frac{\mathrm{kg\ CH_4}}{\mathrm{m^3 CH_4}} \cdot 50{,}499\,\frac{\mathrm{kJ}}{\mathrm{kg\ CH_4}} = 17{,}795\,\frac{\mathrm{kJ}}{\mathrm{m^3 biogas}} = 4.94\,\frac{\mathrm{kWh}}{\mathrm{m^3\ biogas}}$$

The contribution from hydrogen is very small and therefore not added in the heating value. The heating value of 4.94 kWh/m^3 is quite low compared to table 2.1 where the value is 6 kWh/Nm^3 at NTP conditions. This difference is due to the low air pressure at the altitude of Kitui, the gas being saturated with water vapor and a slightly lower methane content.

A lower heating value of 4.94 kWh/m^3 would give 9.9 kW at a gas flow of 2 m^3/hour. Since 4 stoves are installed, the average stove effect would therefore be 1.4 kW each if 55 % stove efficiency is assumed as in [16].

5.2 Pig quantities and manure production

The pig keeper at Katulani SS gave an estimate over the sizes of the pigs as seen in the table [40]. The number of pigs were counted to be 87 and the pigs were categorized into 15 different groups were each group consists of pigs with approximately the same weight and living in the same pigpen. From this the average weight of the pigs could be found to be 19.4 kg.

Table 5.3 Pig pen number and sizes [40]

Weight category	Pigpen number	Number of pigs	Average weight [kg]
1	1	9	5
2	2	1	150
3	2	1	200
4	3	1	70
5	3	7	1
6	4	8	12
7	5	12	7
8	6	2	150
9	7	2	80
10	7	7	2
11	8	9	4
12	8	1	7
13	9	18	7
14	10	1	70
15	11	8	40

Pigs above 60 kg are counted to be 8, while the remaining 79 pigs are below 60 kg. 72 % of the pigs are between 1 to 10 kg.

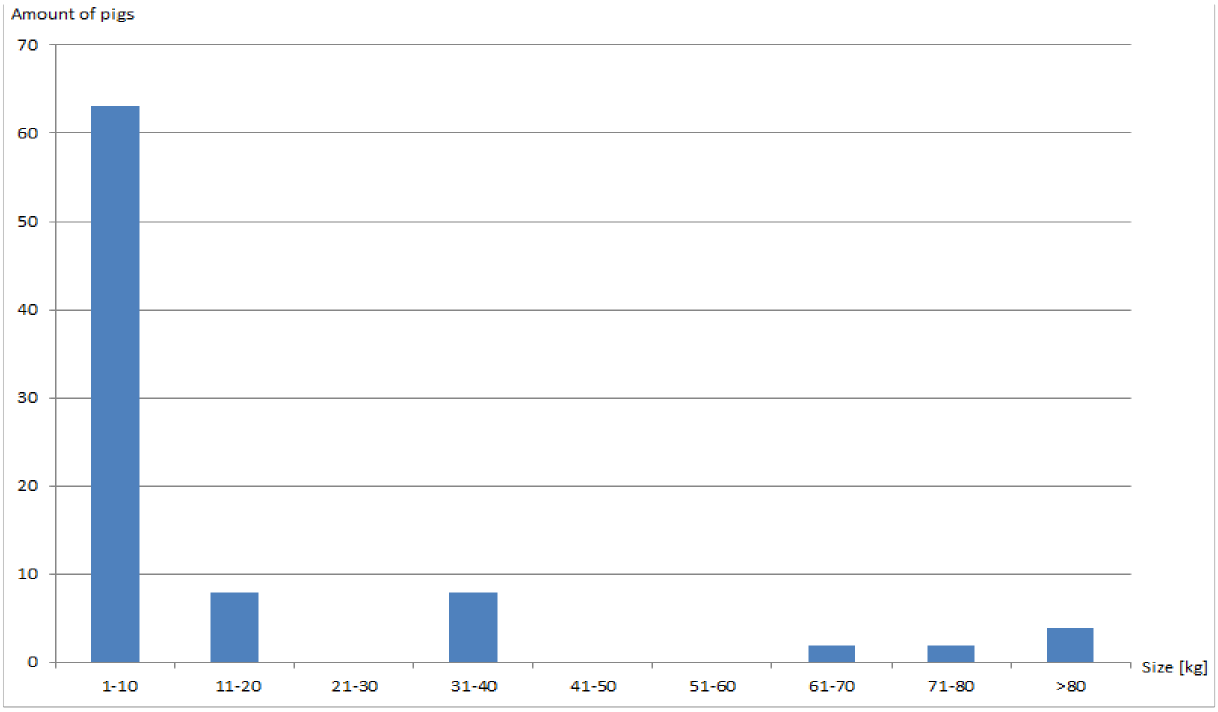


Figure 5.4 Pig weight distribution

5.3 Feedstock size

Pig manure from 87 pigs and 2 cows are used as feedstock in the biogas reactor at Katulani SS. Two methods of estimating the size of the daily feedstock volume is used and will be described in this chapter.

The first method is based on knowing that the pig keeper feed the reactor with three wheel barrows a day. Knowing the volume of the wheel barrow, the daily manure input can be found. The top surface was measured 55x75 cm, the bottom surface 45x45 cm and the height 22 cm. The volume of a wheel barrow (WB) is then found by dividing the wheel barrow into a trapezoid and two triangles.

$$V_{WB} = c(a+b) \cdot \frac{h}{2} + (c-d) \cdot b \cdot \frac{h}{2}$$

$$V_{WB} = 0.45(0.45+0.75) \cdot \frac{0.22}{2} m^3 + (0.55-0.45) \cdot 0.75 \cdot \frac{0.22}{2} m^3 = 67.7\ liter$$

Three wheel barrows per day make this a total of 203 liter manure per day. The wheel barrow used can be seen in figure 5.5. Based on the size of the wheel barrow, 2.33 liter fresh manure/day is produced per pig in average.

Figure 5.5 Wheel barrow used to carry the manure at Katulani SS

Since feedstock should contain about a maximum of 15 % dry matter, the water content in the input feedstock is assumed to be 85 % in total as water added to the manure should be 50 %[13, 40]. Based on this information, the current DM content is calculated to be 30 % in the manure. 25 – 30 % is confirmed as likable values in [7, 11, 53, 54] for separated manure. Some urine is however probably mixed into the manure at unknown volume. The water content, and thereby the dry matter content, is difficult to estimate, as it depends on several factors such as feed, water consumption, local climate, pigsty system and the volume of urine mixed.

The density of the total manure depends on the fraction of DM and moisture. The density of water is assumed to be 1 kg/liter while the DM content is regarded as 30 % of the density found in table 2.6. The urine contribution to the dry matter is negligible. From that, a daily mass of manure per day becomes 229 kg/day from the 3 WBs. That is equivalent to 69 kg DM/day when assuming 30 % DM. The cow manure is not included in these values.

The second method of estimating the daily manure volume is by considering the sizes of the pigs and use a standardized manure table as in table 5.4[2]. Manure from the two cows is included in this table, but with a 50 % collection rate added as the cows often wanders freely around the school yard which makes it difficult to collect all the produced cattle manure.

Table 5.4 Animal manure production

	Live weight animals [kg][2]	Liquid manure production[liter /day/animal] [2]	% Manure collection rate	DM %*[2]	Number of animals	Liter DM/day	Liter manure/day
Young pig	< 12	0.5	100	13	56	3.6	28.0
Young pig	12-20	1.0	100	13	8	1.0	8.0
Young pig	20-45	3.0	100	13	8	3.1	24.0
Young pig	45-60	4.5	100	13	0	0	0
Young sow	<90	4.5	100	13	3	1.7	13.5
Sow	>90	4.5	100	13	4	2.3	18.0
Sow with piglets		14.0	100	13	1+7	1.8	14.0
Feeder Cattle		50.0	50	17	1	1.4	8.5
Young cattle		25.0	50	17	1	0.7	4.2
Total					89	15.9	118.2
* DM could be any value between 2.5 % and 13 % for pigs and 7 % – 17 % for cows [2].							

By using the method of the standardized manure table, the total manure production per day becomes 118.2 liter when 13 % DM in is used. In a scenario of 13 % moisture, no additional water would be necessary to add into the digester.

The density from table 2.6 at 1.13 kg/liter with 30 % DM can be used if the manure volume obtained is recalculated to contain 70 % water instead of 87 % Water. By assuming a proportional relation and interpolate between 100 % water with density of 1 kg/liter and manure with 70 % water with 1.13 kg/liter, a density of 1.06 kg/liter at 83 % water content is found. Then, the DM content from the table 5.4 becomes 16.29 kg DM/day. The total manure volume at 30 % DM would be 54.3 liter/day.

The manure volume result obtained from the standardized manure production in table 5.4 differs significantly compared to the manure production obtained from the wheel barrow (WB). The manure volume obtained from the table after adjusting for the water content is not even enough to fill one WB. This indicates that the manure estimations by using table 5.4 are not correct. This could partly be explained if too low pig weight estimations were made. Another reason could be that straws might be added to the manure in the WB or that the moisture content of the WB manure was considered too low.

In the further calculations, the manure input of 203 liters obtained from the WB is used as current fresh feedstock (FF) input. This is used with an assumed 30 % DM content.

5.3.1 Hydraulic retention time

The volume of the liquid space in the tank is 48 m³. The average HRT, shown in eq.4, is found by using the manure volume obtained from the WBs and add water in the ratio 1:1 into the total slurry:

$$\mathrm{HRT}=\frac{\mathrm{V_{liquid}}}{\mathrm{V'_{slurry\ in}}}=\frac{48000\ \mathrm{liter}}{203.0\,\frac{\mathrm{liter\ FF}}{\mathrm{day}}+203.0\frac{\mathrm{liter\ water}}{\mathrm{day}}}$$

$$\mathrm{HRT}=118\ \mathrm{days}$$

The input slurry volume is the total input of water and manure. The slurry volume necessary to gain a HRT of 60 days, which is within the range of table 2.4, would be:

$$\mathrm{V'_{in}} = \frac{\mathrm{V_{dig}}}{\mathrm{HRT}} = \frac{48000\ \mathrm{liter}}{60\ \mathrm{days}} = 800\,\frac{\mathrm{liter}}{\mathrm{day}}$$

A HRT suitable for the location would give the highest gas yield. If a shorter HRT is preferred more slurry need to be added.

800 liter of slurry would require a manure supply of 400 liter/day at 30 % DM or about 6 WBs. At 15 % DM in the total slurry this gives 136 kg DM/day. In the further calculations of optimum biogas production, 800 liters of slurry with 15 % DM is used. This volume could be higher as the range of the HRT is as low as 40 days for Kenya in table 2.4. However, 60 days HRT is also recommended by [13] for the location of Katulani SS.

5.3.2 Gas production and potential

The value of the biogas yield has been found to vary slightly between different sources as it varies considerably depending on the content. According to [5] and [2] the average potential biogas yield from pig slurry is 0.37 $\mathrm{m^3}$ gas/kg DM. By using the daily DM content the potential gas yield becomes:

$$\mathrm{V'_{BG}}[\frac{\mathrm{m^3gas}}{\mathrm{day}}] = \mathrm{Manure}\left[\frac{\mathrm{kg\ DM}}{\mathrm{day}}\right]\cdot 0.37\,\frac{\mathrm{m^3gas}}{\mathrm{kg\ DM}}$$

The biogas yield varies according to composition of the dry matter. The process is not fully digested and therefore this volume will be somewhat lower. As explained in [5], it is common for animal manure to be 30 – 60 % digested in a biogas digester. As gas yield depends on costs and complexity of the plant, a gas yield efficiency (η_{digester}) of 30 – 40 % of its potential rate could be assumed for a simple fixed dome plant. Maximum profitability operation is not a limiting factor for the digestion process in the case of Katulani SS. But complexity is. The slurry is for instance not mixed inside the digester nor heated which would have increased the gas production.

At Katulani SS a long HRT are currently used, which will give a somewhat higher gas yield per DM in to the digester. At 100 % degradation the gas output would be:

$$\mathrm{V'_{BG}}[\frac{\mathrm{m^3gas}}{\mathrm{day}}] = \mathrm{Manure}\left[\frac{\mathrm{kg\ DM}}{\mathrm{day}}\right]\cdot \eta_{\mathrm{digester}}\cdot 0.37\,\frac{\mathrm{m^3gas}}{\mathrm{kg\ DM}}$$

$$\mathrm{V'_{BG}} = 203\,\frac{\mathrm{liter\ FF}}{\mathrm{day}}\cdot 0.30\,\frac{\mathrm{kg\ DM}}{\mathrm{kg\ FF}}\cdot 1.13\,\frac{\mathrm{kg\ FF}}{\mathrm{liter\ FF}}\cdot 0.37\,\frac{\mathrm{m^3gas}}{\mathrm{kg\ DM}} = 25.5\ \mathrm{m^3gas/day}$$

At a degradation rate of 30 % the gas production becomes:

$$\mathrm{V'_{BG}} = 203\,\frac{\mathrm{liter\ FF}}{\mathrm{day}}\cdot 0.30\,\frac{\mathrm{kg\ DM}}{\mathrm{kg\ FF}}\cdot 0.30\cdot 0.37\,\frac{\mathrm{m^3gas}}{\mathrm{kg\ DM}}\cdot 1.13\,\frac{\mathrm{kg\ DM}}{\mathrm{liter\ DM}} = 7.6\ \mathrm{m^3gas}/day$$

This would cover 63 % of a cooking demand of 12 $\mathrm{m^3}$/day. That is a higher percentage than 35 – 45 % cooking coverage estimated by [41]. The reason for this difference can be inaccuracy regarding the actual gas consumption or it might be that the actual gas production is inhibited by for instance a surface layer on top of the slurry inside the digester due to poor mixing.

If a 40 % efficiency is used due to a long retention time of 118 days and a good mixing job before feedstock entering is done, the gas production would become 10.2 m³/day, covering 85 % of the cooking demand.

Using a HRT of 60 days as recommended in [3, 13], 800 liters of input slurry are needed, which gives 400 liter FF/day with 30 % DM . The daily gas volume obtained at an efficiency of 30 % is:

$$V'_{\mathrm{BG}} = 400\,\frac{\text{liter FF}}{\text{day}} \cdot 0.30\,\frac{\text{kg DM}}{\text{kg FF}} \cdot 0.3 \cdot 0.37\,\frac{\mathrm{m^3 gas}}{\text{kg DM}} \cdot 1.13\,\frac{\text{kg DM}}{\text{liter DM}} = 15.1\ \mathrm{m^3 gas/day}$$

The degradation rate is crucial to be able to determine the gas output. It is highly dependent on the complexity of the biogas facility. A complex digester could include process heating or stirring or two separated tanks with different pH values for optimal digestion of the different stages of the fermentation. Complex fermentation methods are outside the scope of this thesis. The gas produced is shown in relation to the degradation rate in figure 5.6 at constant potential gas yield of 0.37 m³/kg DM. The degradation rates are within the expected range between 30 – 60 % for animal manure.

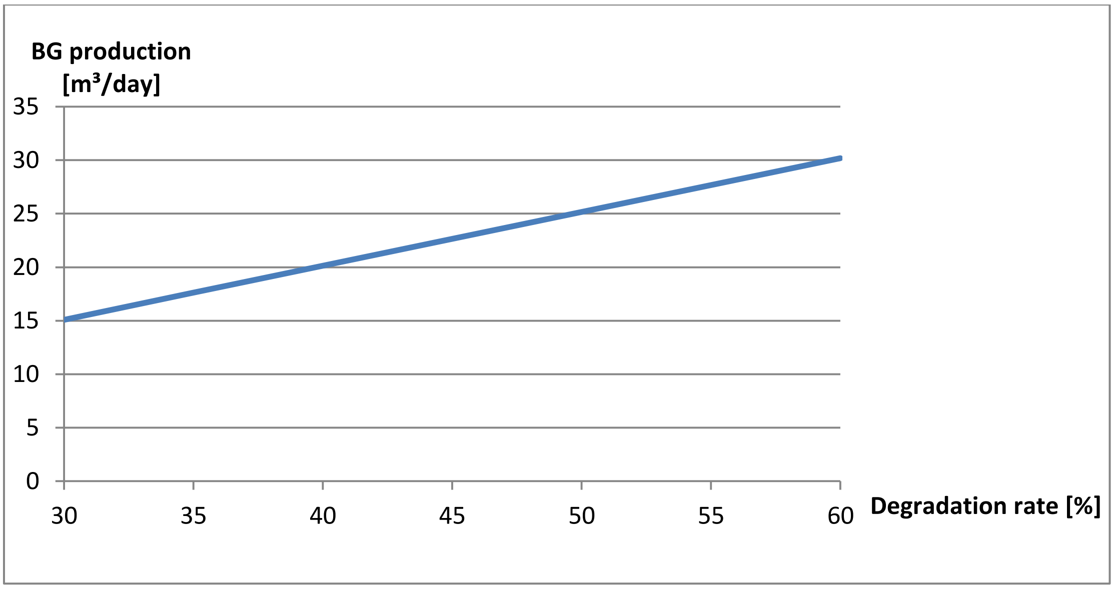


Figure 5.6 Biogas yield at different degradation rates when using a potential gas yield of 0.37 m³/kg DM from 400 liter pig manure.

At a cooking demand of 12 m³/day and degradation rate of 30 %, the remaining biogas to be used in an engine when using a HRT of 60 days and 400 liters of pig manure per day would be 3.1 m³ BG/day.

5.4 Water pumping

5.4.1 Total head

The total head consists of the sum of the losses due to pumping height, friction, outlet pressure and the fittings. The values used for the total head calculations can be found in the table 5.1. The outlet pressure and the location of the pump in relation to the water surface are not taken into account during the following calculations.

Table 5.1 Key data for total head calculations

Parameter	**Value and unity**
Pipe diameter (d)	0.0381 meters or 1 ½ inch [39]
Pipe cross-sectional area (A)	0.00114 m² [39]
Total pipe height (h)	176.5 meter [39]
Total pipe length (l)	231.5 meter [39]
Absolute roughness of cast iron pipe (k)	0.0000216 meters[26]
Gravitational acceleration (g)	9.81 meter/second
Water density (ρ)	988.2 kg/m³*[55]
Water viscosity (μ)	0.001 kg/ms[55]
Loss in vent [m]	0.15 meters[56]
Loss in 90 ˚ bends [m]	0.63 meters[56]
*Density used by Grundfos in pump specifications seen in figure A.1 in the appendix	

The total head is the sum of the friction head, the height difference and the losses in the bends and vents. There are three bends from the pump to the tank at 90˚. The losses due to the bend fittings are assumed to be 3 x 0.63 m. One valve is located at the pump site, which is assumed to be a gate valve with a fitting loss of 0.15 m.

First the friction head needs to be calculated. The relative roughness (e) can be found according to equation 11:

$$\mathrm{e} = \frac{\mathrm{k}}{\mathrm{d}} = \frac{0.0000216\mathrm{m}}{0.0381\mathrm{m}} = 0.006$$

The Reynolds number (Re) is found according to equation 12, where Q' is the water flow:

$$\mathrm{Re} = \frac{\mathrm{v}\rho\mathrm{d}}{\mu} = \frac{\mathrm{Q}'\rho\mathrm{d}}{3600\mathrm{A}\mu} = \frac{\mathrm{Q}'\cdot 988.2\frac{\mathrm{kg}}{\mathrm{m}^3}\cdot 0.0381\ \mathrm{meter})}{3600\frac{\mathrm{s}}{\mathrm{h}}\cdot 0.00114\ \mathrm{m}^2\cdot 0.001\frac{\mathrm{kg}}{\mathrm{ms}}} = 9175.9\cdot\mathrm{Q}'$$

Knowing the water flow and the relative roughness, the friction factor can be found by using the turbulence flow curves in the moody diagram in figure A.4 in the appendix. The friction loss is found by equation 13:

$$\mathrm{h_f} = \mathrm{f}\left(\frac{\mathrm{l}}{\mathrm{d}}\frac{\mathrm{v}^2}{2\mathrm{g}}\right) = \mathrm{f}\mathrm{v}^2\cdot\left(\frac{231.5\mathrm{m}}{2\cdot 9.81\frac{\mathrm{m}}{\mathrm{s}^2}\cdot 0.0381\mathrm{m}}\right) = \mathrm{f}\mathrm{v}^2\cdot 309.7\frac{\mathrm{m}^2}{\mathrm{s}}$$

The values of the friction factor (f) and the velocity (v) vary with the water flow and can be seen in figure A.4 in the appendix.

The resulting system characteristics are shown in figure 5.7.

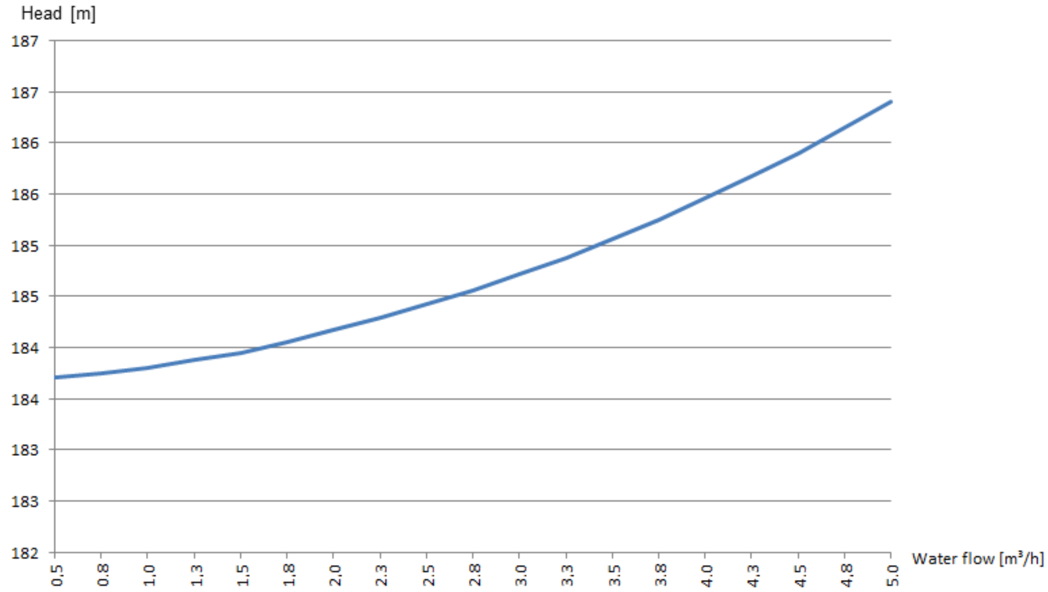


Figure 5.7 System characteristics

5.4.2 Maximum and optimal flow

The restriction for volume of water allowed to be pumped by the government is set to 20 m^3/day. To pump 20 m^3 at a rated flow of 5 m^3/h would take:

$$t_{\text{rated}} = V \cdot Q' = \frac{20\ m^3}{5\ \frac{m^3}{h}} = 4 \text{ hours}$$

In figure A.1 in the appendix, the pump efficiency and the total pump and motor efficiency can be read at about 58.0 % and 45 % respectively.

The highest flow rate according to the pump characteristic in figure A.1 is at 6.75 m^3/h would give a pumping duration at of:

$$t_{\text{min}} = V \cdot Q' = \frac{20\ m^3}{6.75\ \frac{m^3}{h}} = 2.96 \text{ hours,}$$

or 2 hours and 58 minutes. This operation would only give pump efficiency of 39 % and total efficiency of 30 %.

The most energy saving way to operate the pump can be showed by comparing the pump and the system performance curves. The point where the curves cross is the balancing operation point.

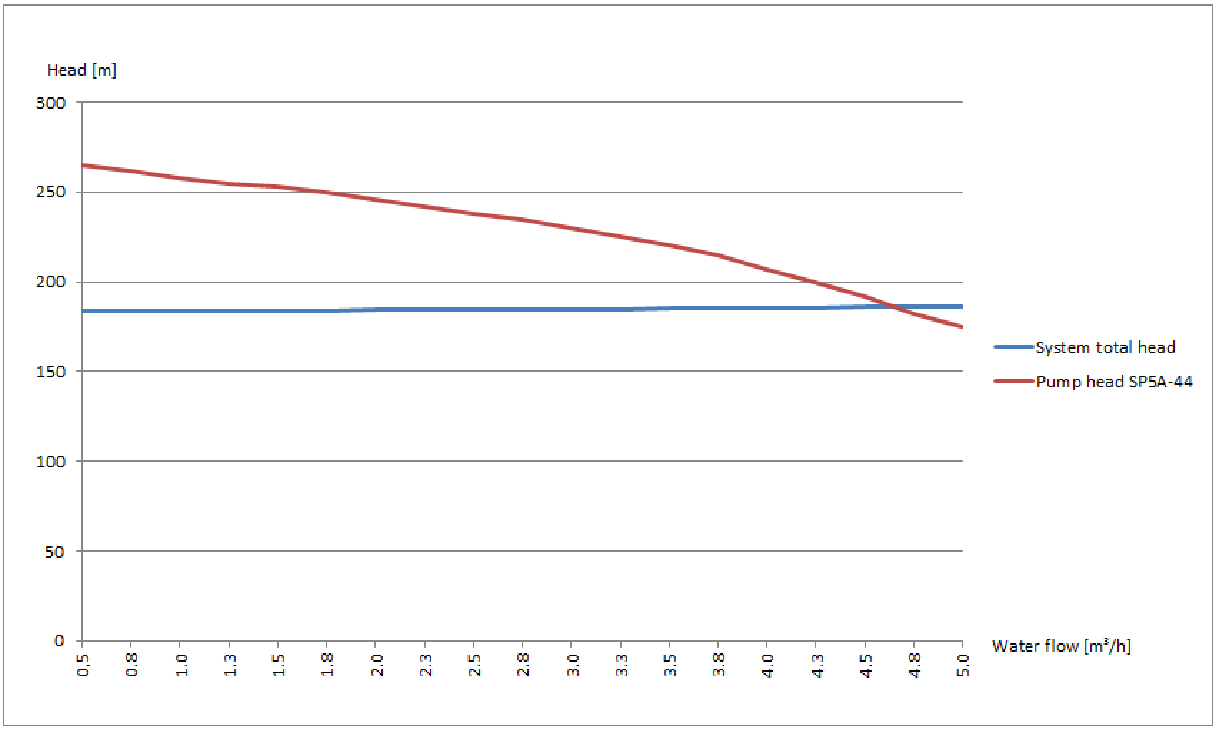


Figure 5.8 System and pump characteristics for SP5A-44 from Grundfos

The optimal point is around 4.6 m³/h at a head of 187 m. As shown in figure A.1, the balance point is close to the optimum operation point at 4.5 m³/h which means the point of maximum pump efficiency regarding electric power input in relation to mechanical power output. The maximum pump efficiency is 58.6 % and the total efficiency including the motor (η) is 45.7 %.

$$\mathrm{t_{optimum}} = \mathrm{V} \cdot \mathrm{Q'[h]} = \frac{20\ \mathrm{m}^3}{4.6\,\frac{\mathrm{m}^3}{\mathrm{h}}} = 4.3\ \text{hours},$$

or 4 hours and 20 minutes. As the optimum and the balancing point are almost the same, the optimum efficiency is also used for the balancing operation point. The power requirement for the motor ($\mathrm{P_{out}}$) can then be found according to equation 9:

$$\mathrm{P_{out}} = \frac{\mathrm{head_{tot}} \cdot \mathrm{Q'} \cdot \mathrm{g} \cdot \rho \cdot \eta_{\mathrm{pump}}}{3600} = \frac{187\ \mathrm{m} \cdot 4.6\,\frac{\mathrm{m}^3}{\mathrm{h}} \cdot 998.2\,\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 9.81\,\frac{\mathrm{m}}{\mathrm{s}^2}}{3600\,\frac{\mathrm{s}}{\mathrm{h}} \cdot 0.586} = 3{,}993\ \mathrm{W}$$

Due to the efficiency of the motor of $\mu_{\mathrm{motor}} = \frac{\mu}{\mu_{\mathrm{pump}}} = 0.779$, the motor must have a power supply of:

$$\mathrm{P_{in}} = \frac{\mathrm{P_{out}}}{\mu_{\mathrm{motor}}} = \frac{3993\ \mathrm{W}}{0.779} = 5.1\ \mathrm{kW}$$

If the pump operates with more power than necessary, water will be thrown into the tank at high speed and hence power would be wasted. The balancing operation point of the pump will be used in further calculations as this is the point with the least wasted power. This minimizes the volume of biogas necessary for the purpose of water pumping.

5.4.1 Biogas flow in pipe

By using equation 1 the density of carbon dioxide becomes 1.56 kg/m³ when assumed to be an ideal gas. When negligible H_2S and other trace gases, the total density of biogas can be calculated to be:

$$\rho_{BG} = \text{vol}\ \%\ CH_4 \cdot \rho_{CH_4} + \text{vol}\ \%\ CO_2 \cdot \rho_{CO_2} + \text{vol}\ \%\ H_2O \cdot \rho_{H_2O}$$

$$\rho_{BG} = 0.579\frac{m^3 CH_4}{m^3 BG} \cdot 0.61\frac{kg\ CH_4}{m^3 CH_4} + 0.375\frac{m^3 CO_2}{m^3 BG} \cdot 1.56\frac{kg\ CO_2}{m^3\ CO_2} + 0.031\frac{kgH_2O}{m^3 H_2O} = 0.97\frac{kg\ BG}{m^3 BG}$$

A constant density in the pipe is assumed for simplicity of calculations. The viscosity of biogas at 30 ˚C is assumed to be 0.0000171 Pa·s retrieved from [16]. The atmospheric pressure, water vapor and methane content are not taken into account in the calculations of the viscosity.

The pressure loss in the biogas pipe is dimensioned to be 0.4 kPa and the pipe used is ¾ ʺ galvanized iron with an absolute roughness of 0.0005 m[26]. At a flow rate of 2 m³/hours and by using the same formulas as used in the water pumping chapter, the relative roughness and the Re can be found to be:

$$e = \frac{k}{d} = \frac{0.0005\ m}{0.0191\ m} = 0.0262$$

$$Re = \frac{v\rho_{BG}d}{\mu_{BG}} = \frac{\frac{2\frac{m^3}{hour}}{3600\frac{s}{hour}\cdot 0.00029\ m^2} \cdot 0.97\frac{kg}{m^3} \cdot 0.0191\ m}{0.0000171\ Pa\cdot s} = 2011$$

At a relative roughness of 0.0262 a Re above 3500 gives turbulent gas flow according to the moody chart for gas installations in figure A.5 in the appendix. The gas flow becomes laminar at Re numbers below 3500. By finding the friction factor in the moody chart and multiplying the gravity acceleration and the density of biogas into equation 13 the pressure loss due to the pipe roughness becomes:

$$\Delta p_{loss} = f\left(\frac{l}{d}\frac{v^2\rho_{BG}}{2}\right)$$

$$\Delta p_{pipe} = 0.0318\left(\frac{16\ m}{0.0191\ m} \cdot \frac{\left(\frac{2\frac{m^3}{hour}}{3600\frac{s}{hour}\cdot 0.00029\ m^2}\right)^2 \cdot 0.97\ kg/m^3}{2}\right) = 47\ Pa$$

A pipe length of a 16 meters is assumed when adding the 12 meter length of the pipe with 4 meters of height variation as the pipe is located underground.

As the designed pressure loss should be 0.4 kPa. The losses in the 2 vents, the bends, the water trap, the PVC tube, the stove, the outlet and additional armatures and fitting would be:

$$\Delta p_{additional} = \Delta p_{total} - \Delta p_{pipe} = 0.4\ kPa - 0.047\ kPa = 0.353\ kPa$$

The loss in the PVC tube is treated as constant for different gas flows to simplify the calculations. By knowing the pressure loss due to the pipe friction and the additional constant pressure loss, the pressure losses at different gas flows are roughly found as seen in figure 5.9.

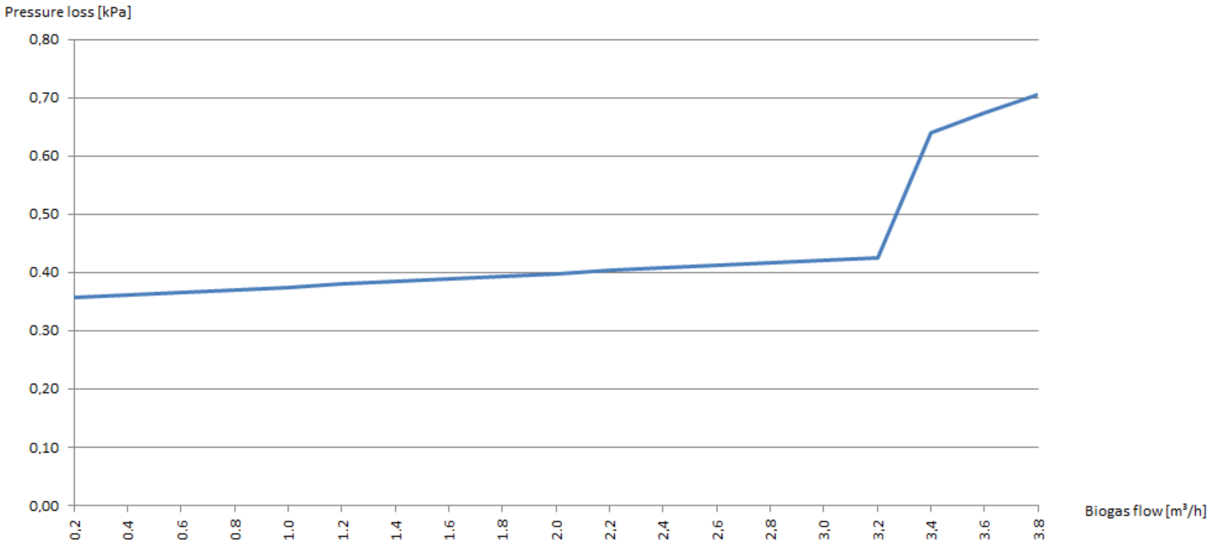


Figure 5.9 Pressure loss in gas pipe at different biogas flows

At 3.4 m^3/hour the flow becomes turbulent and the friction due to the roughness of the pipe consequently increases as seen by the steep change in pressure loss in figure 5.9. A table of the pressure losses can also be found in table A.9 in the appendix.

5.5 Discussion

The gas measurement results showed relatively low methane content at 57.9 % with a decreasing tendency towards the evenings. Animal manure have commonly a methane content of 60 % in dry biogas[5]. As this gas is likely to be saturated with water vapor it would be expected a lower methane content than 60 %. The lower methane content could also be explained by a higher fraction of carbohydrates instead of proteins and fat in the manure as shown in table 2.3. The methane production could also be inhibited by a temperature variation of more than ±2 ˚C which is likely due to ambient temperature fluctuations.

The content of the hydrogen sulfide and ammonia were found to be about 2,000 ppm and 5.2 ppm respectively. Usually the hydrogen sulfide content varies more than the measurements shown and could therefore go higher. However, the desulphurization methods presented in this thesis are suitable for hydrogen sulfide content in untreated gas up to 10,000 and 50,000 ppm. More measurements should therefore not be necessary and the method chosen should be based on the required minimum concentration. For engines, this might be below 100 ppm hydrogen sulfide. Based on the measurements, the ammonia content is lower than most application requirements and do therefore not need treatment.

The ambient average conditions at the time of the measurements were 29 ˚C, 59 % relative humidity and 89.4 kPa. The high relative humidity was likely due to the start-up phase of a rainy season in Mars/April. The ambient pressure is lower than at sea level as expected at higher elevation. The average atmospheric pressure obtained through the measurements was 89.4 kPa. An expected atmospheric pressure of 86.6 kPa at 1,400 m.a.s.l was found in [20].

The sizes of the pigs are based on approximate guessing from [40] and is hence not accurate. The resulting average weight of 19.4 kg of the 87 pigs could only be seen as an indication. By the writers own observations there very many small piglets and the pigs looked skinny. There might be an issue of malnutrition or under nutrition which should be considered. However, that is outside the scope of this thesis. It might also be the high number of piglets was due to the timing of the visit and that the average size is usually higher. However, it is known that the pigs are slaughtered after 5 months at a living weight between 45 – 50 kg which is a relatively low weight compared to common practice.

The statement from [40] of 3 WB is not accurate as the WB might not be completely filled. Still, it gives a useful indication. The biogas output from the calculations was higher than expected. [41] estimated that the biogas covered 35 – 45 % of the total cooking. The calculations gave a 63 % contribution. This could indicate that the calculated gas production is too high, or that the assumed consumption is too low.

Also the moisture content of the manure is uncertain. Even though there were not observed straw in the pig pens with the purpose of absorbing moisture, this could have been added. This would have explained the different results obtained from estimating the expected manure production based on the pig sizes, and the volume found by measuring the WB.

Based on the desired dry matter content fraction of about 15 % of the total slurry input, the added volume of water of about 50 vol.-%, fresh pig manure of 25 – 30 % DM from various literature sources [7, 53, 54], the drying effect of the hot air as well as the author’s own observations, it was reasoned that a 30 % DM content could be assumed. The urine contribution of the total manure is accordingly assumed low, and the DM content could therefore be somewhat lower. The DM content is fundamental for the resulting gas production.

Due to the unknown urine contribution to the total manure composition, measurements of this fraction should be conducted for more certain results. This could be done by measuring the weight of manure samples and dry them to compare the weight difference between the wet and dry sample. However, since the total dry mater fraction into the digester should ideally be 15 vol.-% of 800 liters the desired dry matter content of 120 liter/day is determined, regardless of the water content in the fresh manure.

The density of the dry matter content varies according to the feed, gender and size of the pigs. As seen in the calculations, small changes of this value have high impact on the gas production. As the density is varying depending on several factors, more investigation on the manure composition should be done for more accurate results. This could be done by using a specific gravity bottle as explained in [11]. Another way could be to dry samples of the pig manure until 100 % DM remains. These methods would be representable as long as the feed input and size of the pigs do not change considerably.

Based on the 30 vol.-% DM in the manure and the density of pig manure, a total DM content per day of 69 kg is obtained. This mass of DM per day defers from the mass obtained from the wheel barrow by almost ¼. This strongly suggests that either pig size estimation are too low, the moisture of the manure is too low, a considerable amount of straw is added to the manure or a combinations of these factors.

The total pumping head was found to be 187 meters with a flow rate at 4.6 m^3/h and a total efficiency of 45.7 %. More accurate distance measurements could be done, but has not a significant impact on the resulting head. Taking into account the water surface level would reduce the total head as it would give additional input pressure to the water flow in the pipe and reduce the necessary pressure produced by the pump.

By knowing the maximum cooking requirements to be 12 m^3 and using a pump power input of 5.1 kW, the necessary biogas volume and power conversion methods for the pumping fueled by biogas can be determined.

Table 5.5 Summary of key values from chapter 5

Obtained heating value at measured methane content, water content and atmospheric pressure.	4.94 kWh/m^3
Current slurry volume into the reactor including 50 % water addition	406 l/day
Current manure volume or fresh feedstock (FF) produced based on wheel barrow (WB) per day.	203 l/day
Current dry matter produced based on WB with 30 % DM content.	69 kg/day
Current HRT based on WB per day.	118 days
Current gas production at gas yield of 0.37 m^3/kg DM and a degradation rate of 30 %.	7.6 m^3/day
Optimal manure volume produced HRT at 60 days.	400 liters/day
Optimal dry matter produced based on WB and 60 days HRT.	136 kg DM/day
Optimal gas production at gas yield of 0.37 m^3/kg DM, a degradation rate of 30 % and a HRT of 60 days.	15.1 m^3/day
Water pump power input at balancing point of operation.	5.1 kW
Duration of daily pumping at balancing point of operation.	4.3 hours/day
Density of the biogas	0.97 kg/m^3

6 Solutions

Before an engine can be connected to the biogas digester, the biogas production needs to be enhanced. Proper mixing is important before the feedstock enters, but in spite of that there are few low-complex measures to increase efficiency of the digester known to the author. Therefore, feedstock size must be enlarged and the possibilities for co-digestion should be investigated.

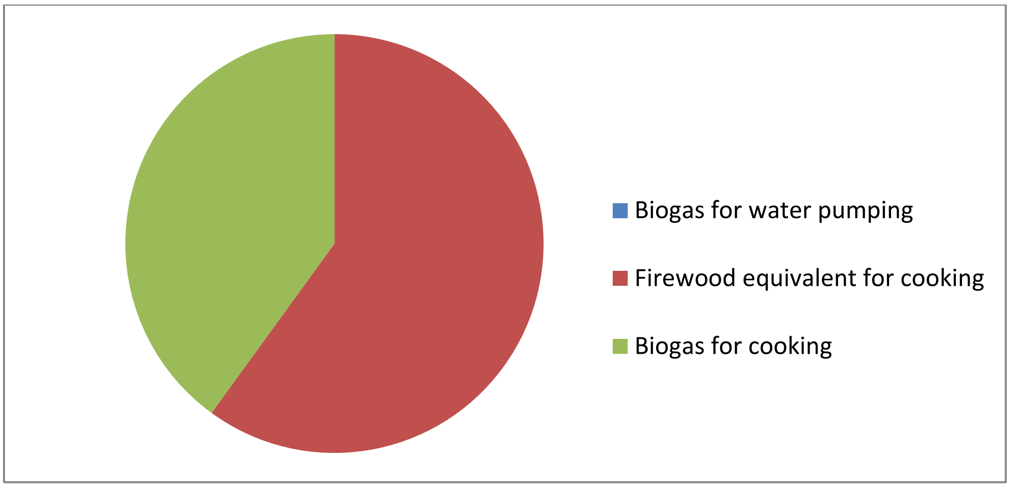


Figure 6.1 Current biomass distribution at Katulani SS

Figure 6.1 shows the current biomass distribution, where the energy content of the fire wood used today is converted into biogas equivalents. Figure 6.2 shows a visional scenario when increasing biogas production to 17.1 m³/day. That is a gas production increase of 125 %. This could be obtained by for instance increasing the number of pigs combined with co-digestion as will be shown in this chapter.

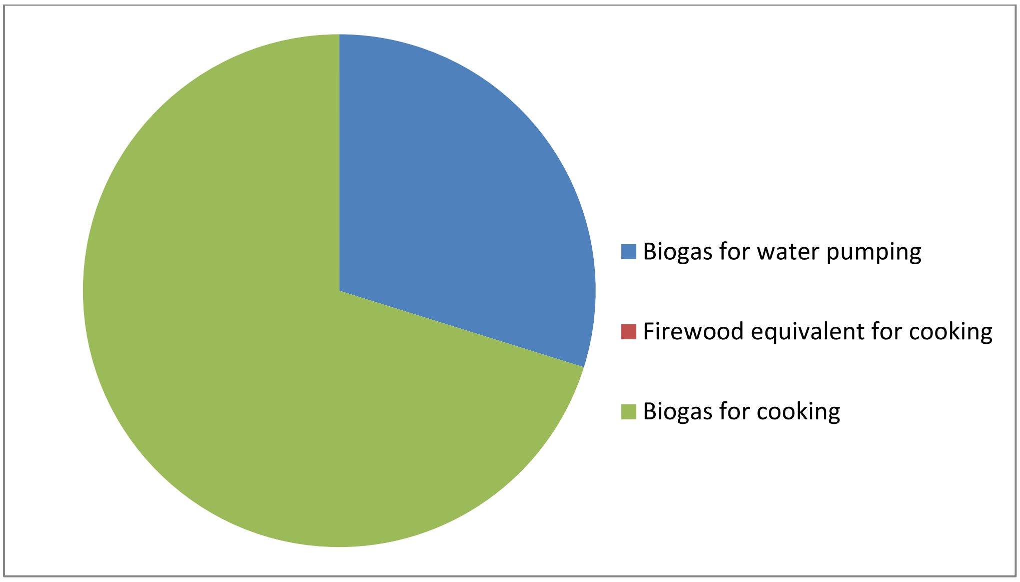


Figure 6.2 Visional biomass distribution at Katulani SS

Further, a comparison of the otto engine and pilot-injection engine are made based on the obtained gas potential and water supply results from chapter 5. Alternative solution will also be mentioned before a discussion of the suggested solutions at the ending of this chapter.

6.1 Increase of biogas production

The manure volume produced per day that is necessary can be accomplished by increasing the number of pigs to the capacity of the pig house at 150 while at the same time increase the average size of the pigs without decreasing the slaughtering age. Increasing the number of pigs to 150 would give 350 liter manure at the current production rate.

As 400 liters is desired for a HRT of 60 days, the remaining 50 liters of manure could be covered by increasing the average size of the animals either by prolonging the slaughtering age, which is currently about 45 kg, or increase feeding assuming the pigs are able to eat more fodder and gain more weight. However, this would only lead to the gas potential of 15.1 m^3/day at 30 % DM content if the 60 days HRT is desired.

Based on available resources in the area, the fresh feedstock [FF] chosen for comparison is slaughtering house waste, cattle manure, poultry manure, maize silage, grass silage and fruit waste in figure 6.3. Synergy effects of mixing different organic matters are not considered. It is assumed the same degradation rate of 30 % for each substrate, although this is highly dependent of the lignin content of the substrate[2]. A comprehensive list of substrates can be found in [2]. All addition of the organic matters would increase the biogas production, given that the substrates do not replace a substrate with a higher biogas yield. This is shown in figure 6.3 where the average biogas yield of sorghum gives a lower biogas output if replacing pig manure. The corresponding table used for the calculation can be found in table A.8 in the appendix.

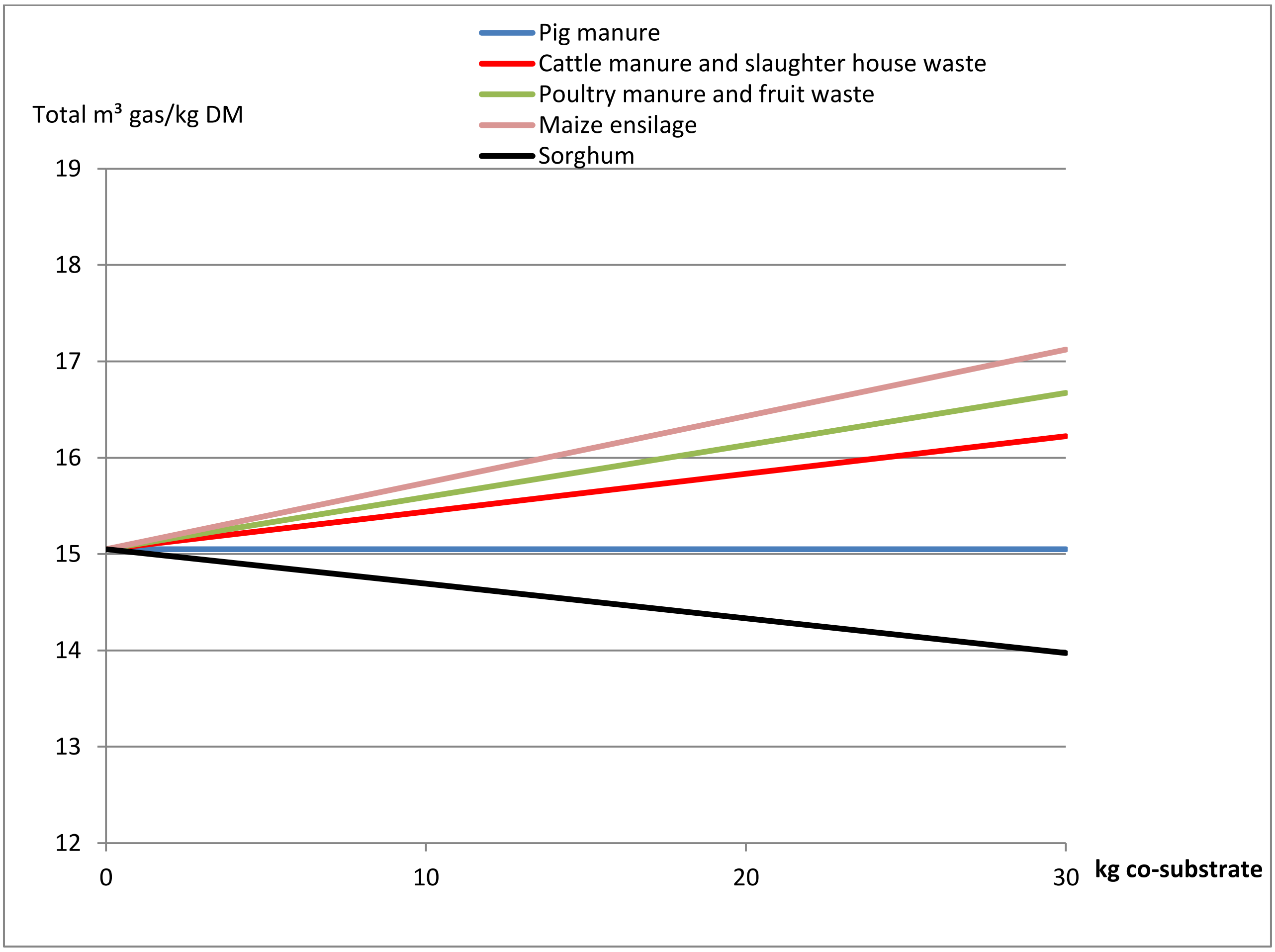


Figure 6.3 Effect of replacing pig manure by a co-substrate at constant total dry matter input to the digester

Figure 6.3 shows that by using 30 kg DM of for instance maize ensilage instead of 30 kg DM pig manure, the biogas production could be increased from 15.1 to 17.1 m^3 gas per day at the same mass of feedstock input to the digester. That is in total 106 kg DM pig manure and 30 kg DM maize ensilage. Poultry manure and fruit waste would increase it to 16.7 m^3/day by doing the same.

Maize ensilage is pre-fermented to break complex ingredients before entering the biogas reactor. This is to increase methane production. To avoid loss of VS as well as mold infestation that would have an antibiotic effect in the digester, the ensilage should be compressed and covered[2].

The methane production change should also be taken into account since this gas determines the heating value. By knowing the densities and the different methane percentage the heating value can be adjusted accordingly. In the cases of the examples above the manure types in general has a methane content of 60 % in the biogas product, while maize has 52 % and fruit 67 %[5]. The methane concentrations obtained when using sorghum or slaughter house waste is unknown to the author.

6.2 Power generation

6.2.1 Engine power generation limitations

To find the engine output limitations, the biogas production rate of 17.1 m³/day obtained from 106 kg DM pig manure, 30 kg DM maize ensilage and 85 % water is used. This gives a biogas volume of 5.1 m³ to be used in the engine after the cooking requirement is withdrawn. The heating value and the water pumping hours for optimal performance are known from earlier calculations. The efficiencies is assumed to be 25 % for a small otto engine and 30 % for a small pilot-injection engine[3]. The otto engine modified from diesel is not considered due to its unsuitability for power ranges below 100 kW[9].

The mechanical power production for an otto engine can thereby be found by equation 6:

$$\mathrm{P_{otto}} = \frac{\mathrm{V_{Biogas} \cdot LHV \cdot \eta_{tot}}}{\mathrm{t}}\ [\mathrm{kW}]$$

Where η_{tot} equal the product of engine and generator efficiencies.

$$\mathrm{P_{otto}[kW]} = \frac{5.1\,\frac{\mathrm{m^3}}{\mathrm{day}} \cdot 4.94\,\frac{\mathrm{kWh}}{\mathrm{m^3}} \cdot 0.25}{4.3\,\frac{\mathrm{h}}{\mathrm{day}}} = 1.5\ \mathrm{kW}$$

For a pilot-injection engine the efficiency is 30 %. The power output would thereby be 1.7 kW. However, maximum 85 % of the total energy output is supplied by biogas, while the remaining power comes from diesel. Therefore, the total mechanical power output of the engine becomes:

$$\mathrm{P_{diesel}[kW]} = \frac{1.7\ \mathrm{kW}}{0.85} = 2.0\ \mathrm{kW}$$

Which means that diesel contributes with 0.3 kW to the power output, when operating at the biogas input limit. The energy content of light diesel fuel is found to be 9.21 kWh/liter[20]. The specific fuel consumption is found by equation 6 to be 3.33 kWh fuel/kWh mechanical power output ($\frac{\mathrm{kWh_{fuel}}}{\mathrm{kWh_{mech}}}$). By using equation 7, this in turn gives a diesel fuel consumption of:

$$\mathrm{fc_{vol\ diesel}} = \frac{\mathrm{sfc \cdot P_{diesel}}}{\mathrm{LHV_{diesel}}}$$

$$\mathrm{fc_{vol\ diesel}} = \frac{3.33\frac{\mathrm{kWh_{fuel}}}{\mathrm{kWh_{mech}}} \cdot 0.3\ \mathrm{kW}}{9.21\,\frac{\mathrm{kWh_{fuel}}}{\mathrm{liter}}} = 0.11\ \mathrm{liter/h}$$

This means 0.47 liters of diesel for a day with 4.3 pumping hours at 2 kW mechanical power output. At a diesel price of 109 KES/liter the costs become 52 KES/day. As the diesel contribution to the energy content can be increased, a shortage of biogas could easily be compensated for, but at a higher operating cost. The following diesel consumption and fraction in relation to the total mechanical power output is shown in figure 6.4 and 6.5.

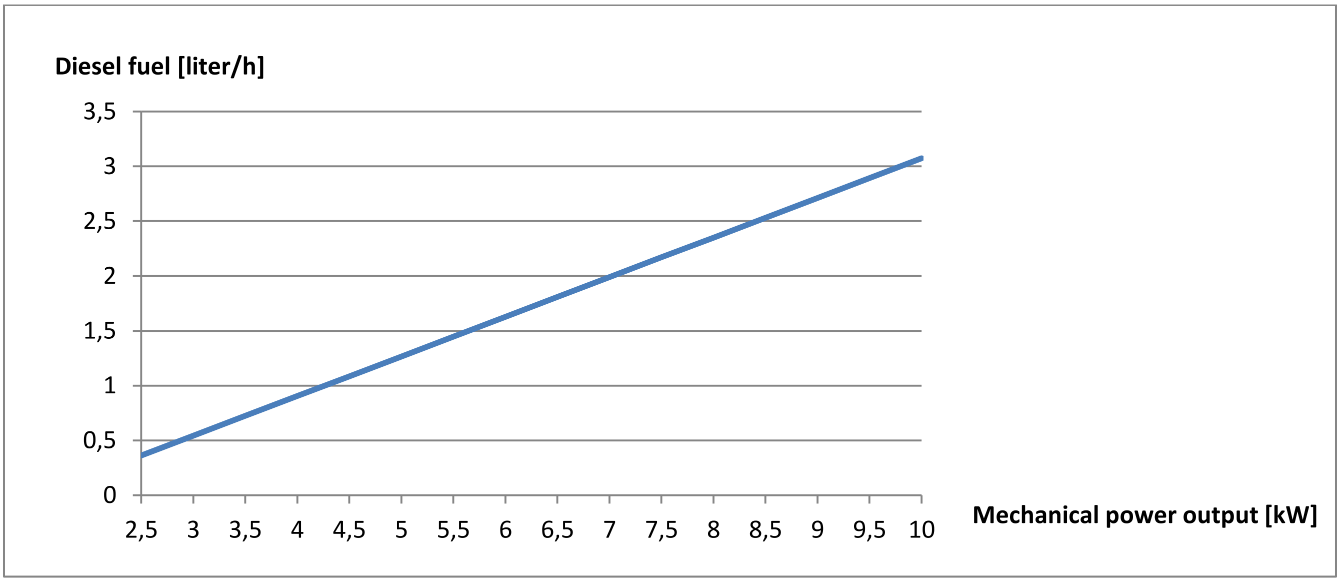


Figure 6.4 Diesel fuel consumption at different power outputs when 5.1 m³ biogas/day is supplied.

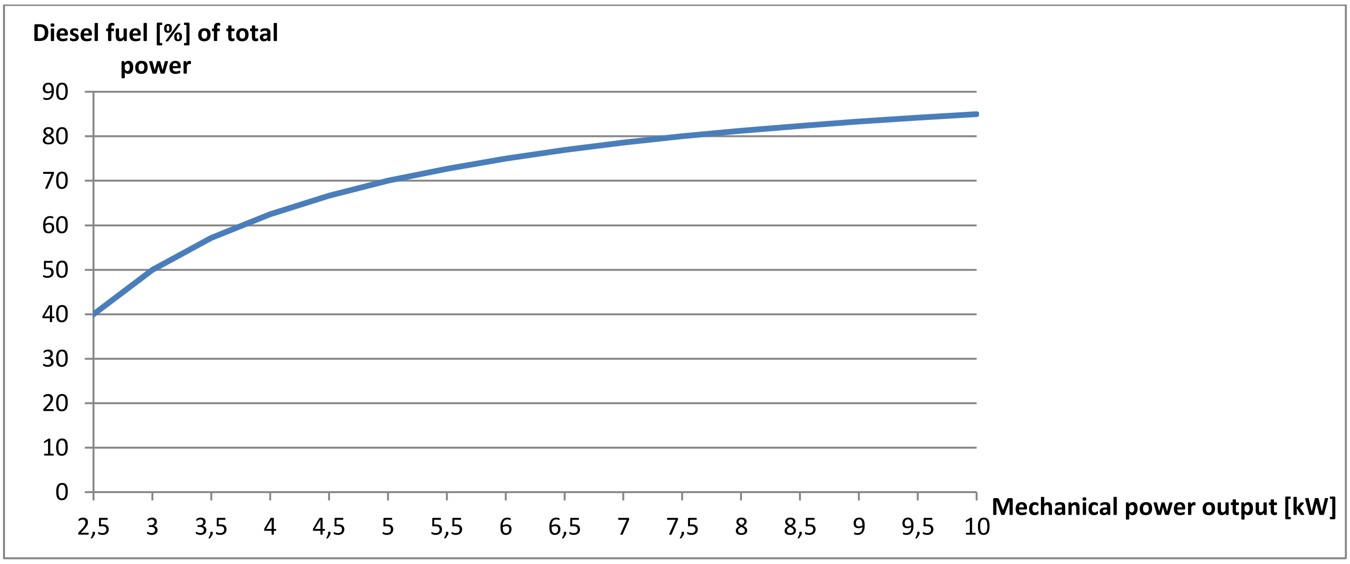


Figure 6.5 Diesel fuel fraction at different power outputs when 5.1 m³ biogas/day is supplied.

As an increasing volume of diesel need to be added for every increase in the diesel fraction of the total fuel input, the curve in figure 6.5 becomes under proportional.

For pumping 20,000 liters, the engine must operate on 5.9 kW for 4.3 hours. At a biogas volume available of 5.1 m³ per day this would result in a diesel consumption of 1.52 liters per hour based on equation 7. That gives a biogas contribution of 24 % of the total mechanical energy consumption.

6.3 Technical requirements

6.3.1 Engine and generator

The engine should operate on medium power output to be the most efficient. According to table A.7 in the appendix this is more than twice the rated capacity of the pump. The deration of the engine is 3.5 % for every 300 meters above 150 meters. At the altitude of Katulani SS at about 1400 m.a.s.l. this becomes 14.6 %. The generator and cables are assumed to have a total efficiency of 90 %. The generator deration is about 3.33 % for 1,400 as it decreases with 2.5 % every 300 meters above 1000 meter in altitude.

The power factor ($\cos\varphi$) of the pump is found to be 0.77 at 417 V and 50 Hz as retrieved from the data sheet[55]. The required apparent power capacity of the generator must therefore be dimensioned according to this.

By using table A.7 in the appendix for recommended generator and diesel engines, and taking the elevation and temperature into account, the following technical requirements are obtained.

Table 6.1 Technical requirements for engine and generator at given pumping characteristics

Key parameter at 1,400 m.a.sl.	**Value**
Power demand pump	5.13 KW
Engine capacity	11.5 kW
Generator actual power capacity	12 kW
Generator capacity apparent power	16 kVA
Voltage	415 V
Frequency	50 Hz
Power factor ($\cos\varphi$)	0.77
Speed of engine	1500 rpm [2]
Operating point engine	5.9 kW*
*Losses from cables and generator included.	

6.3.2 Water volume pumped

The water required at the school is only about ¼ of the maximum water volume allowed to pump at 20,000 liter. By pumping less than the maximum volume the biogas volume requirements would fall drastically. In table 6.2 is a comparison of the gas required for pumping between 1 m^3 and 20 m^3 water per day. The results are shown for an otto engine and for a pilot-injection engine with 15 % and 20 % diesel injection. The table assumes that the water pump is operated on the balancing operation point. The required cooking demand of 12 m^3 BG/day is withdrawn from the total biogas production of 17.1 m^3 BG/day giving 5.1 m^3 BG/day available for water pumping.

Based on table 6.2, almost 5,000 liters of water required can be covered with an otto engine without compression increase at a gas volume available of 5.1 m^3. Pilot-injection engines will be able to pump more water at the same volume of biogas. For pumping the max capacity of 20,000 liters of water per day, 14.7 m^3 biogas with 15 % diesel fuel, or 13.8 m^3 biogas and 20 % diesel fuel could be used. The pilot-injection engine can also pump water at lower biogas volumes by increasing the diesel power contribution.

Table 6.2 Water volume pumped at varying availability of biogas

Water volume [m^3 water/day]	Pumping hours per day	Gas volume with otto engine [m^3 BG/day]	Gas volume with Pilot-injection engine 15 % diesel		Gas volume with pilot-injection engine 20 % diesel	
			Biogas [m^3 BG/day]	Diesel consumption [liter/day]	Biogas [m^3 BG/day]	Diesel consumption [liter/day]
1.0	0.2	1.0	0.7	0.09	0.7	0.13
2.0	0.4	2.1	1.5	0.19	1.4	0.27
3.0	0.6	3.1	2.2	0.28	2.1	0.40
4.0	0.9	4.1	2.9	0.38	2.8	0.54
5.0	**1.1**	**5.2**	**3.7**	**0.47**	**3.5**	**0.67**
6.0	1.3	6.2	4.4	0.59	4.1	0.80
7.0	1.5	7.3	5.2	0.66	4.9	0.94
8.0	1.7	8.3	5.9	0.76	5.5	1.07
9.0	2.0	9.3	6.6	0.85	6.2	1.21
10.0	2.2	10.4	7.4	0.95	6.9	1.34
11.0	2.4	11.4	8.1	1.04	7.6	1.48
12.0	2.6	12.5	8.8	1.14	8.3	1.61
13.0	2.8	13.5	9.6	1.23	9.0	1.74
14.0	3.0	14.5	10.3	1.33	9.7	1.88
15.0	3.3	15.6	11.0	1.42	10.4	2.01
16.0	3.5	16.6	11.8	1.51	11.1	2.15
17.0	3.7	17.7	12.5	1.61	11.8	2.28
18.0	3.9	18.7	13.2	1.70	12.5	2.41
19.0	4.1	19.7	14.0	1.80	13.1	2.55
20.0	4.3	20.8	14.7	1.89	13.8	2.68

6.3.3 Costs

The costs of water pumping are indicated for the 4 alternatives otto engine, pilot-injection engine with 15 % and 20 % diesel, and electricity from the grid. 4.6 m^3/hour is assumed as water flow as this is the balancing operation flow. The operating power at the balancing pumping point has earlier been found to be 5.9 kW in the case of Katulani SS. Since the value includes generator losses the power withdrawn from the power grid would be somewhat lower, and is here set to 5.4 kW. This assumes 5 % loss in the cables. Further an electricity price of 19 KES/kWh and a diesel price on 109 KES/liter are assumed.

Table 6.3 Cost comparison otto and pilot-injection engine

	Otto engine	**Pilot-injection engine (15 % diesel)**	**Pilot-injection engine (20 % diesel)**	**Grid electricity**
Investment costs [KES]*	600,000	600,000	600,000	0
Cost fuel [KES/m³ water]	0	9.81	14.17	0
Costs electricity [KES/m³ water]	0	0	0	22.30
Maintenance [KES/m³ water]	+	+	+	n/a
Lubrication [KES/m³ water]	+	+	+	0
Manpower operation [KES/m³ water]	+	+	+	0
Lifespan	4,000 hours*[3]	10 – 20,000 hours[3]	10 – 20,000 hours[3]	Unlimited
Availability factor [%]	n/a	n/a	n/a	55 – 75[41]
* Appropriate price set by HTSA[39]				

Considered annual water consumption of 5,000 liter/per day, 22 days a month and 10 months a year the total water demand would be 1,100 m³. The minimum operation costs would then be:

- Otto engine: Maintenance, lubrication oil and labor hours.
- Pilot-injection engine with 15 % diesel: 10,790 KES/year plus maintenance lubrication oil and labor hours.
- Pilot-injection engine with 20 % diesel: 15,590 KES/year plus maintenance lubrication oil and labor hours.
- Grid electricity: 24,540 KES/year.

As the mechanical power needed for pumping 20,000 liter per day is 5.9 kW for 4.3 hours, the necessary diesel injection at 5.1 m³ BG/day would be:

$$\mathrm{fc}_{\mathrm{vol\ diesel}} = \frac{3.33\,\frac{\mathrm{kWh}_{\mathrm{fuel}}}{\mathrm{kWh}_{\mathrm{mech}}} \cdot (5.9-1.7)\mathrm{kW}}{9.21\,\frac{\mathrm{kWh}_{\mathrm{fuel}}}{\mathrm{liter}}} = 1.52\,\frac{\mathrm{liter}}{\mathrm{h}},$$

That is 6.5 liter during 4.3 hours at a water flow of 4.6 m³/hour. This would give a total cost of 712 KES/day. The corresponding costs using grid electricity would only give about 446 KES/day.

6.4 Alternative configurations

6.4.1 Increase pressure in otto engine

Methods of increasing the compression ratio are described earlier. The aim is to increase ideal thermal efficiency of the engine. Other parameters such as the combustion rate and heat loss will have a minor impact, but for simplicity of calculations, they are not considered in this calculations[57].

In [57] a 4.4 kW and 1,500 rpm otto engine modified from diesel is used in experiments which determined the efficiency increase due to higher compression ratios. Here it was found that an increase in the compression ratio from 9.3 to 15 would increase the peak break thermal efficiency from 23 % to 26.8 %, or 0.67 % per unity of compression ratio on average. Between 13 and 15 there were less effect than between 9.3 and 13. The increase above 13 particularly increased the emissions of nitrogen oxide and hydro carbons. [57]. The effect on the ideal thermal efficiency by increasing the compression ratio is shown in the figure 6.6.

It is assumed an overall efficiency of 25 % at a compression ratio of 7.5 which appear to be a common case[3]. At 25 ˚C the polytropical exponent of air is about 1.4 [20]. As the A/F ratio is 5.54 at the calculated heating value of the biogas at Katulani SS, the majority of the mixture is shown to be air. For simplification reasons the polytropical value (k) is therefore chosen to be 1.4 in equation 8 for ideal thermal efficiency:

$$\eta_{\text{thermal}} = 1 - \frac{1}{\left(\frac{V_{\max}}{V_{\min}}\right)^{1.4-1}}$$

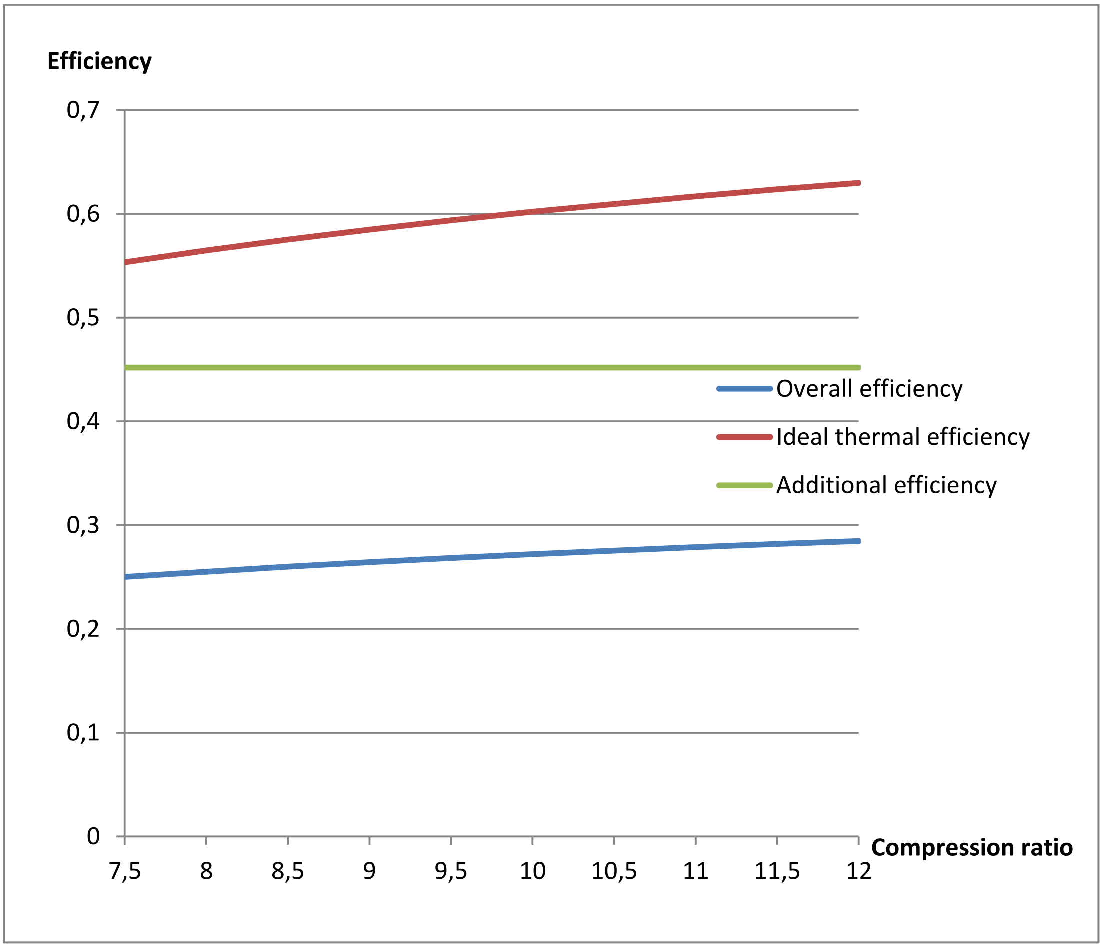


Figure 6.6 Otto engine efficiency at different compression ratios

As seen in the figure, the ideal thermal efficiency increases at higher compression ratios. An increase from 7.5 to 12 would result in an ideal thermal efficiency increase from 55 % to 63 %. The effect on the overall efficiency would be an increase from 25 % to 29 %. This efficiency increase is expected to be somewhat lower due to heat losses[57]. 28 % efficiency is therefore assumed, which gives a sfc value of 3.57 $\frac{\text{kWh}_{\text{fuel}}}{\text{kWh}_{\text{mech}}}$. The impact of the compression increase, from 7.5 to 12, on the required biogas volume can be seen in the comparison below.

Water volume [m³ water/day]	Pumping hours	Gas volume with otto engine with 25 % efficiency [m³ gas/day]	Gas volume with otto engine with 28 % efficiency [m³ gas/day]
1.0	0.2	1.0	0.9
2.0	0.4	2.1	1.8
3.0	0.6	3.1	2.8
4.0	0.9	4.1	3.7
5.0	**1.1**	**5.2**	**4.6**
6.0	1.3	6.2	5.6
7.0	1.5	7.3	6.5
8.0	1.7	8.3	7.4
9.0	2.0	9.3	8.3
10.0	2.2	10.4	9.3
11.0	2.4	11.4	10.2
12.0	2.6	12.5	11.1
13.0	2.8	13.5	12.1
14.0	3.0	14.5	13.0
15.0	3.3	15.6	13.9
16.0	3.5	16.6	14.8
17.0	3.7	17.7	15.8
18.0	3.9	18.7	16.7
19.0	4.1	19.7	17.6
20.0	4.3	20.8	18.6

By doing measures to increase the compression ratio in an otto engine, the required water volume of 5,000 liters can be pumped by 4.6 m³ BG/day instead of 5.2 m³ BG/day. However, one should bear in mind, that this would eliminate the possibility to use petrol as a back-up fuel in case of biogas shortage. Another disadvantage is that the modification is likely to decrease to lifespan of the engine[3].

6.4.2 Gas storage

Using gas storage gives the possibility to look at the total annual production during the year. Storage is only an option if the gas production often exceeds the effective gas volume of 9.7 m³. As the school is only opened 5 days per week, this gives approximately 22 days per month. Due to school vacations, it is opened 10 month per year. At a gas production of 17.1 m³/day, the total annual gas remaining after the cooking becomes:

$$\mathrm{V_{remaining}} = 17.1\,\frac{\mathrm{m^3\ total\ gas}}{\mathrm{day}} \cdot 365\,\frac{\mathrm{days}}{\mathrm{year}} - 12\,\frac{\mathrm{m^3 cooking\ gas}}{\mathrm{day}} \cdot 17.1\,\frac{\mathrm{days}}{\mathrm{month}} \cdot 10\,\frac{\mathrm{month}}{\mathrm{year}}$$

$$\mathrm{V_{remaining}} = 4{,}190\,\frac{\mathrm{m^3\ gas\ remaining}}{\mathrm{year}}$$

This is gas that is not accounted for in the previous calculations and that would go to waste into the atmosphere without any storage.

This gives 11.5 m³/day of additional biogas every day if spread evenly over the year which could have been used for water pumping. At this biogas volume available, 16.6 m³/day could in theory be pumped every day by a pilot-injection engine operating on 15 % injected diesel.

Assuming a continues vacation of 50 days and a constant water flow of 20,000 liter/day throughout this period, the storage necessary when using a pilot-injection engine at the lower limit of 15 % diesel injection would be:

$$V_{\text{tank}}[\text{m}^3] = ((V_{\text{production}}[\frac{\text{m}^3\text{BG}}{\text{day}}] - V_{\text{water pumping}}[\frac{\text{m}^3\text{BG}}{\text{day}}]) \cdot [\text{days}]) - V_{\text{BG digester}}[\text{m}^3\text{BG}]$$

$$V_{\text{tank}}[\text{m}^3] = \left(\left(17.1\ \frac{\text{m}^3\text{BG}}{\text{day}} - \frac{(0.85 \cdot 5.9)\text{kW} \cdot 4.34\frac{\text{h}}{\text{day}}}{4.94\,\frac{\text{kWh}}{\text{m}^3} \cdot 0.3}\right) \cdot 50\ \text{days}\right) - 9.7\ \text{m}^3$$

$$V_{\text{gas}} = 111\ \text{m}^3$$

For storage over weekends while at the same time pumping 20,000 liters/day would not require storage as the gas chamber of the fixed dome would store up to 9.7 m³. Storage for 10 days would require a storage volume of 24 m³.

6.4.3 Applicable start-up methods

The figure below shows an rough indication on the effect of the different starting methods based on figures from [19].

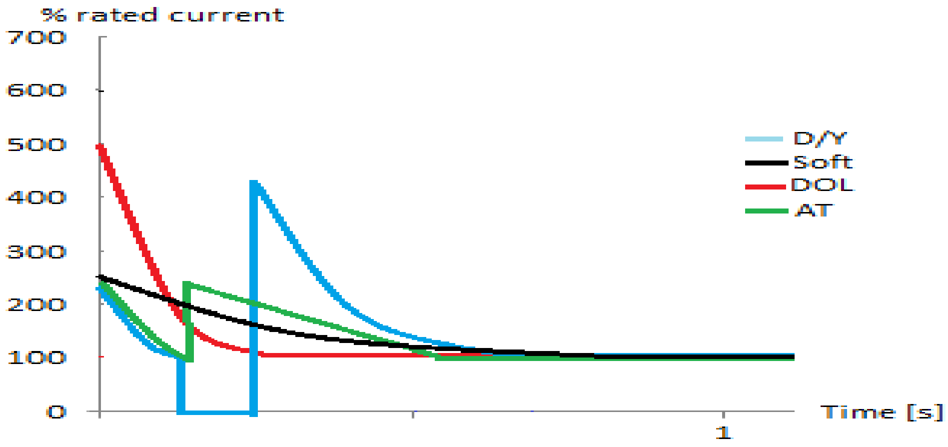


Figure 6.7 Comparison of pumping start-up methods

The Y/D starting is not suited as explained earlier. Instead an autotransformer (AT) could be used. The AT reduces the distribution side current with the square of the voltage ratio, unlike the other starting methods where this current varies directly. The engine and generator capacity requirements are thereby reduced by 20 %[19]. This results in table 6.4.

Table 6.4 Engine and generator capacity requirements when AT starting

Engine capacity	8 kW
Generator actual power	10 kW
Generator apparent power	14 kVA

In [29] the purchase price between starting methods are compared . The AT was considered relatively expensive compared to DOL start. The price could be compensated for by using a less expensive generator and engine.

6.4.4 Utilization of waste heat

To increase the efficiency of the plant, as much as possible of the wasted engine heat could be used for heating purposes.

At an engine output of 5.9 kW at efficiency of 30 % for a pilot-injection engine, a power input of 19.7 kW must be supplied. This means that the wasted power is 13.8 kWh per hour of water pumping. If pumping 20,000 liters, this would give 85.1 kWh of waste heat in total. In addition comes generator and cable losses of 0.8 kW.

Small piglets ideally need a temperature of 30 ˚C [2] and the temperature in Kitui County can go down to 14 ˚C. By pumping the excess heat through pipes to their pig bin, some additional heat could contribute to decrease piglet mortality and deceases. Other uses could be to dry the liquid manure into fertilizer or drying of products as hay. A more complex solution is to use the heat in an absorption refrigerator for cooling purposes during night[2]. If necessary, the waste heat could also be used to heat up the gas after cooling and thereby decrease the relative humidity as seen in figure 2.11.

The degree of heat that can be used depends on the cooling medium, the required cooling degree and the losses to the ambient air.

6.4.5 Carbon dioxide

The carbon dioxide that is normally let out into the ambient air could also be taken advantage of, which would give an additional environmental effect. By leading the exhaust gas into a greenhouse, plants could take advantage of better growing conditions. In addition, the exhaust contains water which would decrease the needed water supply.

Some investments and maintenance when using this method would be expected. Industries usually add 20 – 50 g CO_2/m^2h. The issue of flue gasses, cooling and toxic compounds should be investigated[58].

6.5 Discussion

The result of the measurements showed a stable hydrogen sulfide level. However, these results are uncertain due to a limited number of measurements. Therefore a safety margin should be added, which means that the desulphurization equipment should be able to filter the hydrogen sulfide from a higher concentration than measured down to the level set by engine manufacturer. This requirement does not eliminate the use of any of the desulphurization methods. If more measurements are taken and the level of hydrogen sulfide is shown to be stable, a biological filter could be a suitable choice.

The solution chosen should be based on required water volume. An otto engine does not reach the lower limit of 5,000 liters at an available biogas volume of 5.1 m^3. A pilot-injection engine with 15 % diesel injection could pump almost 7,000 liters per day at 5.1 m^3 BG available.

According to the calculations, it would not be possible to reach required water volume without adding a co-substrate. At 30 kg maize ensilage addition the biogas production would be 17.1 m^3/day. The maize would only contribute with 22 % of the total input. A small decrease in the methane fraction of the gas would be expected due to the high content of carbohydrates in maize[2]. For simplicity, this factor is not considered in the calculations. It would however have a small negative effect on the obtained heating value. This in turn, would increase the gas volume necessary to pump the same volume of water.

The gas yields of the co-substrates are uncertain and could therefore not be taken for granted. Analysis of the relevant substrates should be done for accurate results. Potential consequences for the food or fodder supply in the area should also be assessed as the use of certain co-substrates in the biogas reactor might impose competition to these industries. If using animal residues from a slaughter house, the hygienic risk must be taken into account. Proper hygienization measures must be determined that meet national laws. Special care must be taken if the waste product is to be used as a fertilizer[2]. It might involve high temperatures for the hygienization process. As buying electricity from the grid is not desired, it might be worth investigating using the waste heat from an engine for this purpose.

Another additional advantage of increasing the number of pigs and their sizes would be the increased income from pig meat. As Nairobi is only about a 3 – 4 hour drive from Katulani SS, a large enough market for pig meat is expected. In addition, a slaughter house could be established at the school yard to decrease costs related to transportation. This would produce waste that could be used as co-substrate in the digester if proper hygienised. The economic effects of these measures are out of the scope of this thesis.

Based on the required 5,000 liter water per day, 6 hours school per day and water pumping at night for 1.1 hours, the gas flow during an ordinary day could be approximated in figure 6.8.

Figure 6.8 Visional gas flow when biogas covers cooking and water pumping demand.

At a gas production rate of 17.1 m³/day there is a high potential for gas storage even when pumping at maximum water flow each day. Large storage facilities would be necessary to store the entire surplus gas volume over long vacations. Therefore, it is more realistic to store it just over 3 – 10 days in small scale storage solutions. On the other hand, this might create a problem of wasted methane gas into the atmosphere during longer vacations.

Since Katulani SS already has an electricity connection, it might be easier to generate electricity and sell the surplus electricity to the grid as this would require low investments and in addition generate an income. Some measures to be able to deliver grid power quality would be necessary. It could also be considered to use the surplus biogas to drive a tractor by filling the surplus gas on smaller tanks. Using a pilot-injection engine for this purpose is a common practice in developed countries[9].

Table 6.5 Summary of key values from chapter 6

Optimal gas production at gas yield of 0.37 m³/kg DM, a degradation rate of 30 % and a HRT of 60 days with feedstock 106 kg DM/day pig manure and 30 kg DM/day maize.	17.1 m³ BG/day
Available biogas for water pumping at a total biogas production of 17.1 m³ BG/day	5.1 m³ BG/day
Necessary mechanical engine output at required water volume of 5,000 liters	5.9 kW
Biogas necessary for pumping 5,000 liter with otto engine	5.2 m³ BG/day
Biogas necessary for pumping 5,000 liter with otto engine with increased compression ratio from 7.5 to 12	4.6 m³ BG/day
Biogas necessary for pumping 5,000 liter with pilot-injection engine with 15 – 20 % diesel fuel injection	3.7 – 3.5 m³ BG/day
Price of water when using otto engine	0 KES/m³ water
Price of water when using pilot-injection engine with 15 – 20 % diesel fuel injection	9.81 – 14.17 KES/m³ water
Price of water when using grid electricity	22.30 KES/m³ water

7 Conclusions

The thesis has described a biogas reactor system where the surplus biogas (BG) is used in an internal combustion engine to generate electricity for water pumping in developing countries. The requirements for cooking and water pumping were found for the case of Katulani Secondary School (SS). Based on these requirements, a gas otto engine and a pilot-injection engine at 15 % and 20 % fuel injection were compared. Alternative configurations as an increased compression ratio in the gas otto engine, a different pump start-up method and the use of the engine exhaust were also discussed.

The investigation was done during 8 days by taking measurements of the biogas composition and the ambient conditions at Katulani SS, taking measurements of necessary dimensions of the biogas facility and by interviewing the staff at Katulani SS and the members of the organization Self to Self-help in Africa. Based on the measured methane concentration of 57.9 % and the ambient conditions found, the lower heating value was obtained to be 4.94 kWh/m^3.

The thesis has found that the biogas facility at Katulani SS currently do not produce enough biogas to be able to cover both the cooking and the water supply requirements. The feedstock volume should be increased to about twice the current volume to obtain an advised HRT of 60 days. That means 800 liter slurry input with 15 % dry matter (DM) content. The feedstock increase could mainly be done by increasing the pig manure volume, either by a higher number of pigs or alternatively try to change the fodder type and fodder amount. The slaughtering weight was found to be particularly low at about 45 kg and could be increased as larger pigs produce more manure than smaller pigs. 800 liter slurry with 15 % DM based on pig manure was found to equal 136 kg DM pig manure which would give 15.1 m^3 BG/day at a potential gas yield of 0.37 m^3 BG/kg DM and a degradation rate of 30 %.

In addition to increase the pig manure, a co-substrate could be added based on local resources available. The co-substrate should not replace pig manure into the digester if a lower biogas yield is obtained from it. By for instance using a mixture of 106 kg DM pig manure, 30 kg DM maize and 85 % moisture, a biogas volume of 17.1 m^3/day can be obtained based on the assumptions made in this thesis.

At a total biogas production of 17.1 m^3/day and a cooking demand considered to be 12 m^3 BG/day, 5.1 m^3 is then left to be used in an engine. At a daily water demand of 5,000 liters at the school, this biogas volume is slightly too low to be used in a gas otto engine without increased compression ratio. However, by using a pilot-injection engine with for instance 15 % diesel fuel, a water volume of almost 7,000 liter can be supplied daily. A higher water volume can be supplied if increasing the diesel injection. However, the diesel consumption should be kept low to keep the costs of the water pumping to a minimum. A diesel injection of 15 % would cost 9.81 KES/m^3 water.

A pilot-injection engine could be most suitable due to its ability to take advantage of low volumes of biogas in combination with diesel fuel. It satisfies both the cooking and water demand, and can also give enough power to pump the daily maximum volume limit set by the government. This would require 76 % diesel at a biogas volume of 5.1 m^3 available per day.

Regardless of the choice of engine, utilization of the waste heat should be considered as this would increase the overall efficiency of the engine. As a low complex solution with several positive synergy effects, the concept of using biogas for water pumping by using an internal combustion engine could have the potential to expand in developing countries.

7.1 Recommendations

There is not enough biogas production at current moment. The author recommends that the production increase to about 17.1 m^3/day. Then, sufficient biogas is available to drive a pilot-injection engine with 15 % diesel injection and still supply a surplus water volume of 2,000 liter that can be sold to the local community. A pilot-injection engine is a safe choice, as this engine could run in the range from 0 to 85 % biogas. It is not advised to frequently run the engine at much higher diesel fuel fractions than 15 – 20 % due to costs and the environmental concerns both locally and globally that fossil fuels represents. At Katulani SS, the grid electricity should still be connected to the pump as a back-up solution. Engine failure would then be no issue at worst case scenarios. In this way, Katulani SS can work as a test facility to gain experience that can be valuable if similar water pumping systems at locations without grid connection are to be established.

According to the calculations, a modified otto engine does not reach the minimum required water volume at the biogas volume of 5.1 m^3/day available, although very close. But a modified otto engine should still be considered at Katulani SS as the grid could be used as a back-up solution when there is shortage of biogas. This would give a close to no-cost water pumping solution if enough biogas is available and might bring down the overall expenses.

In other cases where grid connection or other power sources are not available, an otto engine with increased compression ratio might not be a good solution because back-up might become an issue.

7.2 Future work

Due to restriction from the Norwegian food administration “Mattilsynet” no samples of the manure was allowed to be imported from Kenya for composition analyses as pathogens may be a potential hazard. The analyses should therefore be done in Kenya. From this, more exact values of the manure production can be found, based on accurate measurements of the dry matter content, density and nutrition value. This in turn, would give more accurate values of the biogas yield potential and degradation rate. The way the sampling is done is important as it has impact on the result.

Better estimate on the actual biogas consumption could be done by finding the installed capacity of the burners and time the duration in operation. In this way, it might be necessary to correct the biogas volume available for use in an engine.

An assessment of the local resources in the Kitui area could be done to find which organic matter would be most suitable as a co-substrate in the biogas reactor. Factors to be considered could the availability, treatment possibilities as well as potential consequences in the local community by using this substrate. The potential gas yield of the substrate and its degradation rate, necessary treatment and synergy effects when mixing with pig manure could be considered by composition analyses.

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Appendix

Table A.1 Comparison otto and pilot-injection engine [3]

	Pilot-injection gas engine	Gas Otto
Compression ratio (VDC+VC)/VC	15 – 18	10 – 12
Excess air ratio	1.3 – 4.0	0.9 – 1.3
Specific fuel ratio	0.55 – 0.75 m^3/kWh + diesel (10 – 20 % of only diesel operation)	0.65 – 1.0 m^3/kWh
Efficiency	30 %	Large: 30 % Small: 25 %
Temperature after compression	600 – 900 ˚C	400 – 600 ˚C
Pressure after compression	3,500 – 6,000 kPa	1,500 – 2,000 kPa
Exhaust temperature	500 – 700 ˚C	500 – 900 ˚C
Common speed ratio	1,300 – 3,000 rpm	1,500 – 5,000 rpm
Ignition type	Self-ignition of pilot fuel injected into a hot compressed mixture of air and gas which is ignited by the pilot fuel afterwards just before piston reaches TDC.	As in an ordinary otto engine by a spark plug.
Control	A small diesel fuel is injected to facilitate ignition. Variation of the amount of fuel gas supplied to the mixing device is used for variation of power output. The airflow is not controlled to maintain a high pressure and ignition temperature.	Variation of admission of the air/fuel mixture by a throttle valve between the venture mixing valve and the engine inlet. Throttling reduce actual suction pressure of engine, therefore also the absolute compression and efficiency.
Manual control (M)	The governor/injector system is fixed and supplying the pilot fuel	By setting the lever of the throttle. Load and speed

	amount only. The gas valve at the mixing chamber is set to achieve the required speed/power.	variations require an appropriate regulation of the throttle.
Automatic control (A)	Using the same mechanism above. The gas valve is however operated by a governor or an actuator of an electronic system.	Needs additional equipment as a **separately mounted mechanical governor** to operate the throttle or by using an electronic speed sensor with control unit and actuator to operate the throttle.
Constant speed and constant load: generator with constant load and frequency	M: Simple mixing chamber with manually operated control valve.	M: Fixed setting of gas and air or the throttle if a venture is used.
	A: Not necessary at constant load.	A: Not necessary at constant load.
Constant speed and varying load: Generator with constant frequency and a pump with varying electricity demand due to varying capacity and head.	M: Adjust gas valve to mixing chamber whenever load changes. Needs an operator nearby to adjust the gas flow. Without adjustment load variations are compensated by variations in diesel fuel supply automatically. Substitution of diesel fuel by biogas is however reduced.	M: When load changes, manually adjust gas/air valve if mixing valve or venturi if venture mixer.
	A: Simple mixing chamber with gas valve operated by control system. The pilot fuel injection is fixed adjusted.	A: Mixing valve with butterfly valve operated by control system. Speed governor or electronic control system operating the butterfly throttle of mixing device.
Varying speed and varying load: Drive of diverse machinery.	M: Adjust gas valve in accordance with required load/speed. Needs an operator nearby to adjust the gas flow. (Without adjustment load variations are compensated by variations in diesel fuel supply automatically. Substitution of diesel fuel by biogas is however reduced.)	M: Adjust throttle valve in accordance with required load/speed.
	A: Fixed setting of pilot fuel injection. Electronic control system or speed governor with	A: Mechanical governor or electronic control with practicable mode of set point adjustment.
Source: [3]		

Table A.2 Pumping system characteristics

Water flow [m³/h]	Mass flow [kg/h]	Velocity [m/s]	Reynolds number	Friction factor	Friction head [m]	System total head [m]	Pump head [m]
0.50	494.2	0.12	4,590	0.00975	0.0449	183.7	265
0.75	741.3	0.18	6,884	0.00850	0.0880	183.7	260
1.00	988.4	0.24	9,180	0.00800	0.1472	183.8	257
1.25	1235.5	0.30	11,474	0.00750	0.2157	183.9	255
1.50	1482.6	0.37	13,770	0.00710	0.2940	183.9	253
1.75	1729.7	0.43	16,064	0.00700	0.3945	184.0	250
2.00	1976.8	0.49	18,360	0.00690	0.5079	184.2	246
2.25	2223.9	0.55	20,655	0.00675	0.6289	184.3	242
2.50	2471.0	0.61	22,950	0.00660	0.7591	184.4	238
2.75	2718.1	0.67	25,245	0.00650	0.9046	184.6	235
3.00	2965.2	0.73	27,540	0.00635	1.0517	184.7	230
3.25	3212.3	0.79	29,834	0.00625	1.2149	184.9	225
3.50	3459.4	0.85	32,129	0.00620	1.3977	185.1	220
3.75	3706.5	0.91	34,424	0.00615	1.5916	185.2	215
4.00	3953.6	0.98	36,719	0.00610	1.7961	185.5	208
4.25	4200.7	1.04	39,014	0.00605	2.0110	185.7	200
4.50	4447.8	1.10	41,309	0.00600	2.2359	185.9	192
4.75	4694.9	1.16	43,604	0.00600	2.4913	186.1	183
5.00	4942.0	1.22	45,899	0.00595	2.7374	186.4	175

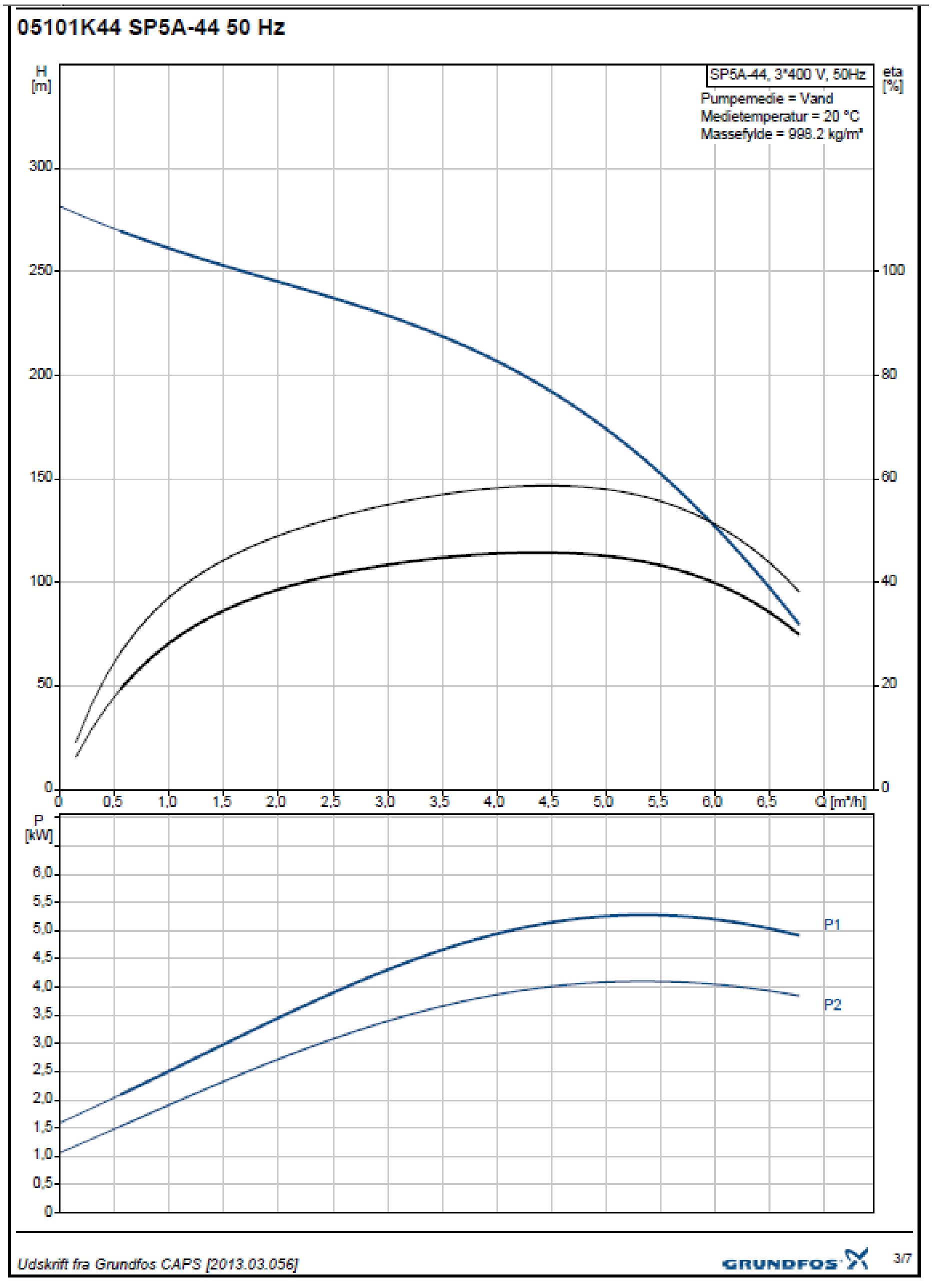

Figure A.1 Pump characteristics SP5A-44 from Grundfos. The picture above shows the pump curve, pump efficiency and the total efficiency of the pump and motor. The figure below shows the electrical power input (P1) and the pump output (P2) [55].

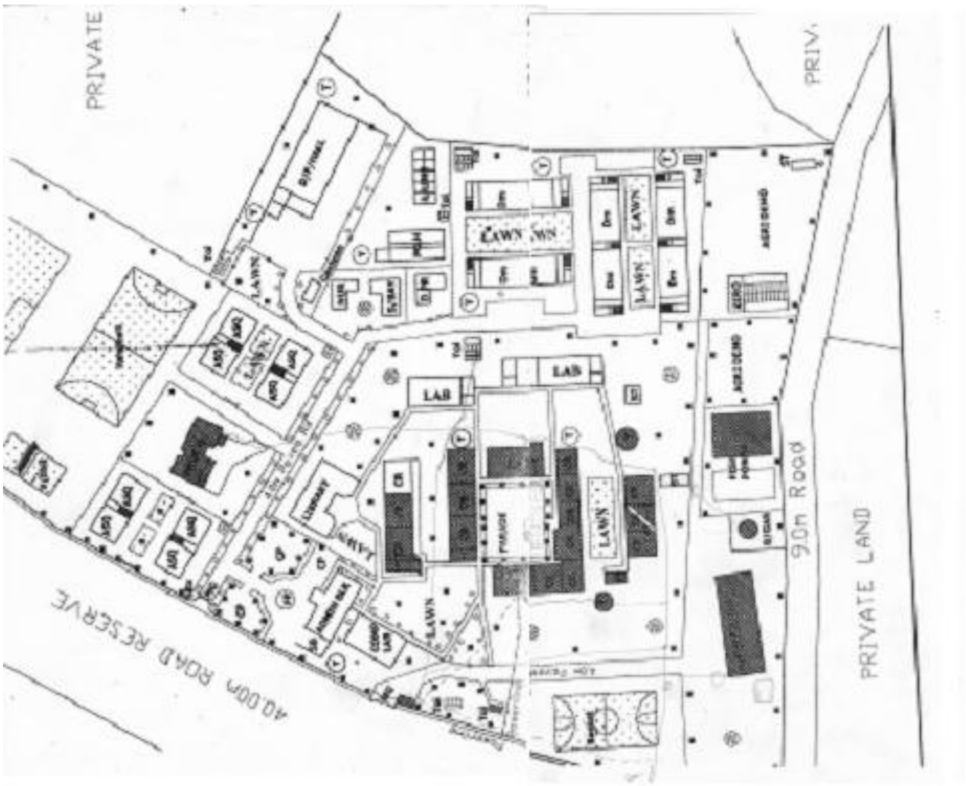

Figure A.2 Map Katulani SS with existing buildings (black) and future planned buildings (white) [1]

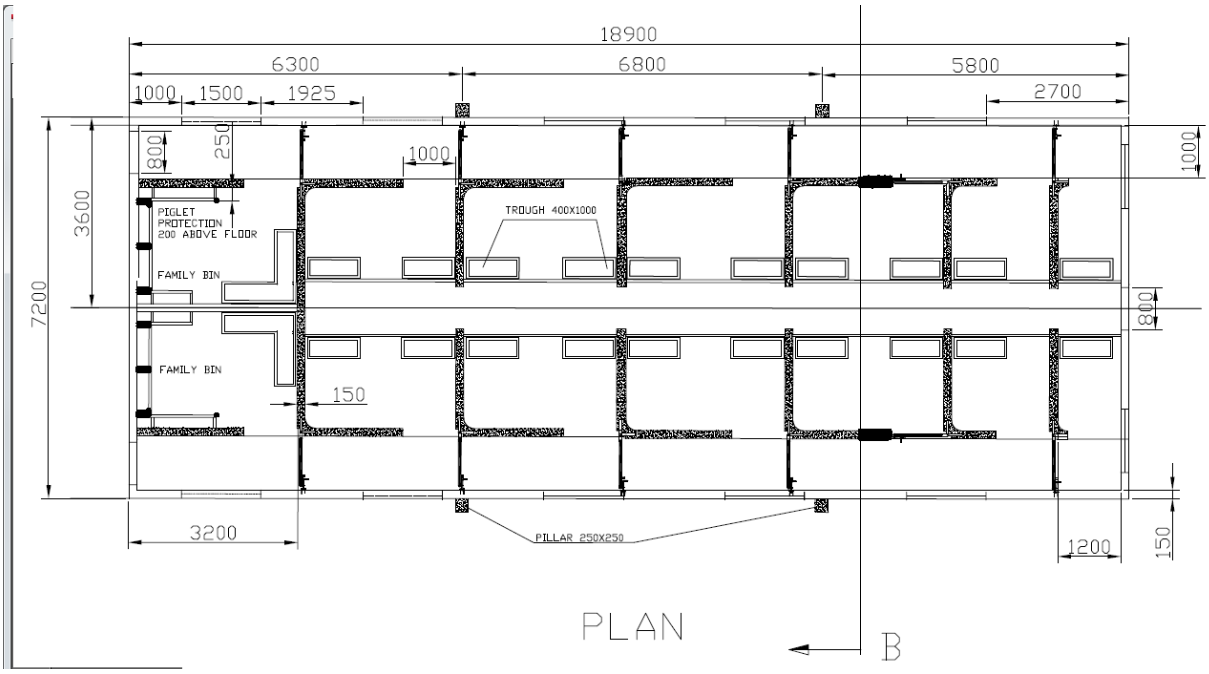

Figure A.3 Floor plan of pigsty at Katulani SS[39].

Table A.3 Desulphurization methods [21]

	Biological			**Adsorption**		**Chemical admixing**
Overview of desulphurization technologies	**Wetted surface**	**Trickling filter**	**Bio-scrubber**	**Activated carbon**	**Ferrous**	**Iron salts**
Separable substances	H_2S	H_2S, NH_{32}	H_2S, NH_3	H_2S	H_2S	H_2S, NH_3
Content in raw untreated gas max [ppm]	30,000	15,000	30,000	10,000	50,000	30,000
Content in clean gas min [ppm]	200	50	5	5	1	100
Content in clean gas max [ppm]	500	100	50	5	100	150
Temperature [˚C]	>20	25 – 37	25 – 37	25 – 70	25	
Air injection [vol.-%]	8 – 12	2 – 12	Yes	1 – 2	Yes	No
Products	Sulfur	Sulfur	Sulfur and Sulfur carbonate	Sulfur and depleted activate carbon	Sulfur and cleaning componds	Iron sulfid
Investment costs	Very high	Low	Very high	Very high	High	Very high
Operating costs	High	Low	Low	Very low	Very low	Very low

Table A.4 Effect of diesel injection

%diesel of energy contribution	**% BG of energy contribution**	**Total power [kW]**	**Power diesel [kW]**	**Diesel [l/h]**
15.00	85.00	10.7	1.6	0.89
13.24	86.76	10.5	1.4	0.77
17.18	82.82	11.0	1.9	1.05
20.78	79.22	11.5	2.4	1.32
24.08	75.92	12.0	2.9	1.60
27.12	72.88	12.5	3.4	1.88
29.92	70.08	13.0	3.9	2.15
32.52	67.48	13.5	4.4	2.43
34.93	65.07	14.0	4.9	2.71
37.17	62.83	14.5	5.4	2.99
39.27	60.73	15.0	5.7	3.26
41.23	58.77	15.5	6.4	3.54

Table A.5 Biogas and methane yields [9]

Feedstock	Biogas yield [m^3/ton fresh feedstock]	CH4 yield [%]	%CH4 /(m^3 Biogas/ton fresh feedstock)
Maize silage	202	52	0.26
Grass silage	172	54	0.31
Forage beet	111	51	0.46
Sweet sorghum	108	54	0.50
Organic waste	100	61	0.61
Beet	88	53	0.60
Poultry manure	80	60	0.75
Pig manure	60	60	1.00
Cattle manure	45	60	1.33
Distillers grains with solubles	40	61	1.53
Liquid pig manure	28	65	2.32
Liquid cattle manure	25	60	2.40

Table A.6 Effect of adding organic matter to feedstock [7]

Feedstock [FF]	DM [%]	Biogas yield [m^3/kg FF]*	Methane yield [%]*	[m^3 Biogas per 10 kg]	[m^3 Biogas per 20 kg]	[m^3 Biogas per 30 kg]	[m^3 Biogas per 40 kg]
Pig stomack content	13.5	40		65 0.06	0.12	0.18	0.24
Cattle manure	25.0	45	60	0.07	0.13	0.20	0.27
Pig manure	22.5	60	60	0.09	0.18	0.27	0.36
Poultry manure	32.0	80	60	0.12	0.24	0.36	0.48
Maize silage	27.5	185	52	0.28	0.56	0.83	1.11
Grass silage	37.5	185	54	0.28	0.56	0.83	1.11
Fruit waste	35.0	265	67	0.40	0.80	1.19	1.59
* Average values of original values are used							

Table A.7 Engine and generator requirements at different motor ratings

Submersible pump motor rating [kW]	Generator rating [kW]		Diesel engine at DOL start and 100 % relative humidity [kW]			
			Max. 150 m.a.s.l.		Max. 750 m.a.s.l.	
	DOL start	AT start	30 ˚C	40 ˚C	30 ˚C	40 ˚C
0.25	1.5	1.0	1.2	1.3	1.4	1.4
0.37	2.0	1.5	2.0	2.1	2.3	2.3
0.55	2.5	2.0	2.5	3.1	2.8	2.9
0.75	3.0	2.5	3.0	3.1	3.4	3.4
1.1	4.0	3.0	4.0	4.2	4.5	4.6
1.5	5.0	4.0	5.0	5.2	5.6	5.7
2.2	7.0	6.0	7.0	7.3	7.8	8
3.7	11.0	9.0	10.0	10.4	11.1	11.5
5.5	16.0	12.5	14.0	14.6	15.6	16.0
7.5	19.0	15.0	17.0	17.7	19.0	20.0
11	28.0	22.0	25.0	26.0	28.0	29.0
15	38.0	30.0	35.0	36.0	39.0	40.0
18.5	50.0	40.0	45.0	47.0	50.0	52.0
22.0	55.0	45.0	50.0	52.0	56.0	57.0
30.0	75.0	60.0	65.0	68.0	72.0	75.0
37.0	95.0	75.0	83.0	86.0	92.0	95.0
45.0	110.0	90.0	100.0	104.0	111.0	115.0
55.0	135.0	110.0	120.0	125.0	133.0	137.0
75.0	185.0	150.0	165.0	172.0	183.0	189.0
90.0	220.0	175.0	192.5	200.0	215.0	220.0
110.0	250.0	200.0	220.0	230.0	244.0	250.0
132.0	313.0	250.0	275.0	290.0	305.0	315.0
150.0	344.0	275.0	305.0	315.0	335.0	345.0
185.0	396.0	330.0	365.0	405.0	405.0	415.0

Table A.8 Biogas yields of chosen feedstock

Feedstock	Biogas yield [m³/DM]	Average DM content in FF [%]	Degradation rate [%]	Weight of substrate [kg] of 800 liter slurry with 15 % moisture					
				0 kg	10 kg	20 kg	30 kg	40 kg	50 kg
Pig manure	0.37	13.5	30	15.1	15.1	15.1	15.1	15.1	15.1
Cattle manure	0.50	25.0	30	15.1	15.4	15.8	16.2	16.6	17.0
Poultry manure	0.55	22.5	30	15.1	15.6	16.1	16.7	17.2	17.8
Maize ensilage	0,60	32.0	30	15.1	15.7	16.4	17.1	17.8	18.5
Sorghum	0.25	27.5	30	15.1	14.7	14.3	14.0	13.6	13.3
Fruit waste	0.55	37.5	30	15.1	15.6	16.1	16.7	17.2	17.8
Slaughterhouse waste	0.50	35.0	30	15.1	15.4	15.8	16.2	16.6	17.0

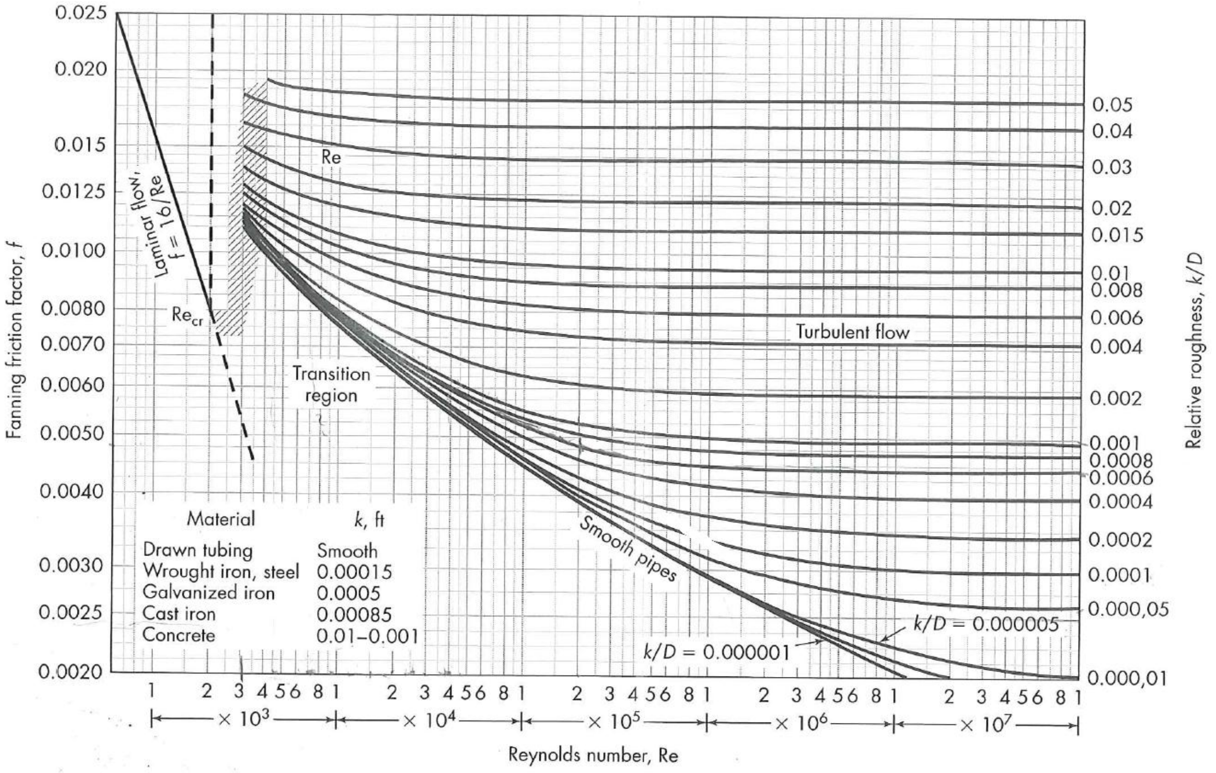

Figure A.4 Moody chart for water pipes

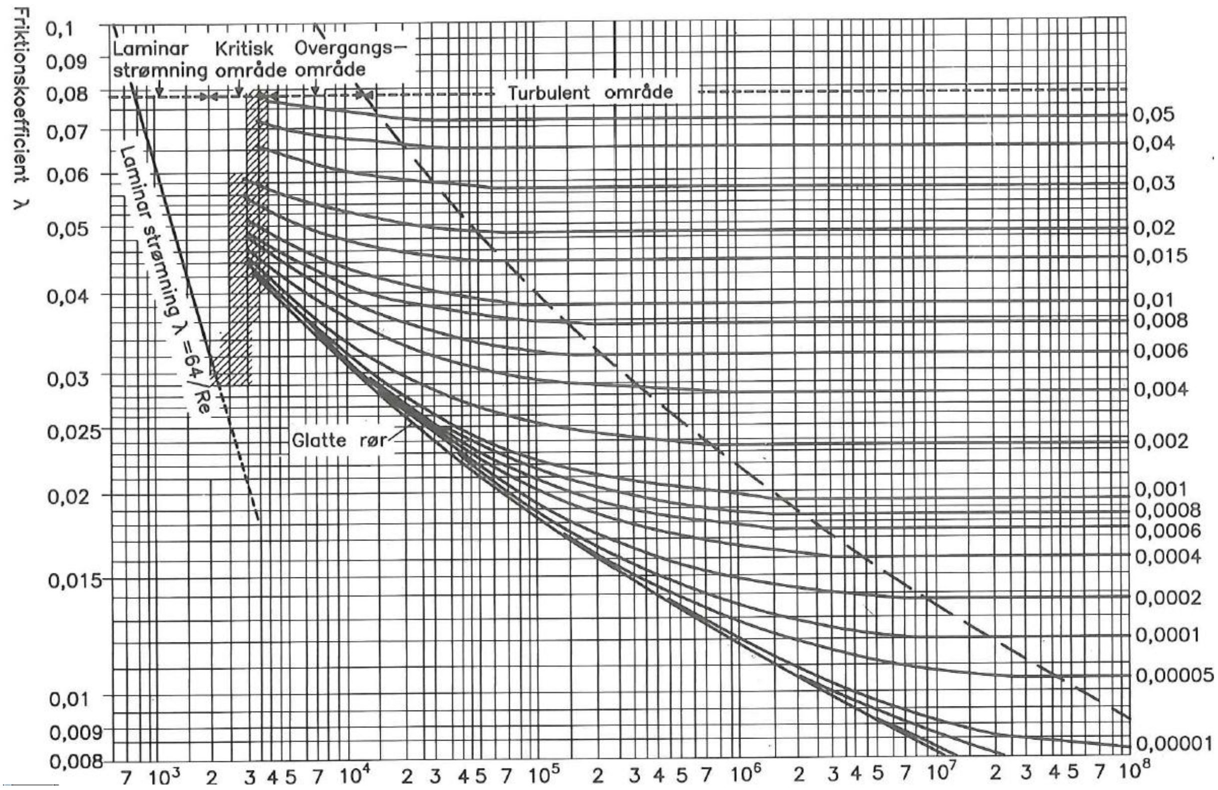

Figure A.5 Moody chart for gas installations

Table A.9 Biogas pressure drop calculations

Biogas flow [m³/h]	Mass flow [kg/h]	Gas velocity [m/s]	Reynolds number	Friction factor	Friction pressure drop [kPa]	Total Pressure drop [kPa]
0.2	0.19	0.19	210	0.304	0.0047	0.36
0.4	0.39	0.39	420	0.152	0.0093	0.36
0.6	0.58	0.58	631	0.101	0.0140	0.37
0.8	0.78	0.78	841	0.076	0.0186	0.37
1.0	0.97	0.97	1,051	0.060	0.0233	0.38
1.2	1.16	1.16	1,261	0.051	0.0279	0.38
1.4	1.36	1.36	1,471	0.044	0.0326	0.38
1.6	1.55	1.55	1,681	0.038	0.0372	0.39
1.8	1.75	1.75	1,892	0.034	0.0419	0.39
2.0	1.94	1.94	2,102	0.030	0.0466	0.40
2.2	2.13	2.13	2,312	0.028	0.0512	0.40
2.4	2.33	2.33	2,522	0.025	0.0559	0.41
2.6	2.52	2.52	2,732	0.023	0.0605	0.41
2.8	2.72	2.72	2,943	0.022	0.0652	0.42
3.0	2.91	2.91	3,153	0.020	0.0698	0.42
3.2	3.10	3.10	3,363	0.019	0.0745	0.43
3.4	3.30	3.30	3,573	0.065	0.2872	0.64
3.6	3.49	3.49	3,783	0.065	0.3220	0.67
3.8	3.69	3.69	3,993	0.064	0.3533	0.71