



Manual for the construction and operation of small and medium size biogas systems



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ANNEX A: Table for diesel engine / dual fuel testing

1 INTRODUCTION

1.1 Context

This installation manual for biogas systems has been prepared within the context of the biogas project carried out in Bilibiza, Gabo Delgado, Mozambique. It was implemented by ADPP farmers club and FACT Foundation. This pilot project is an unique experience in Mozambique, since it is one of the few biogas examples using biogas for cooking and electricity production.

The introduction and promotion of biogas systems that supply gas and alternative electricity for institutions in rural areas will actively contribute to the reduction of greenhouse gas emission and deforestation, and lead to improved health and sanitation, and cost reductions.

1.2 Intended readers

This manual has been prepared to support practitioners with the installation of small- and medium scale biogas systems. In particular, this manual will be used by ADPP to support the operation of their floating dome- and plug flow systems. The manual describes 2 digester types that can be installed by individuals with little or no background in biogas technology. It is intended for application in developing countries, in households or institutional setting.

1.3 Reading guide

This manual starts with an introduction to biogas and the required conditions. Next, the planning of installations is discussed, followed by instructions on how to construct a plug flow system and a floating dome system. Subsequently, start-up procedures, troubleshooting and maintenance, and gas transport and usage are discussed. The final chapter presents the cost-benefit analysis of different system scenarios.

On the basis of this sequence, the reader will follow a step by step description of biogas, how it is installed, usage and what costs and revenues can be expected.

2 BIOGAS OVERVIEW AND REQUIRED CONDITIONS

2.1 Introduction to biogas

Biogas refers to a gas resulting from the anaerobic digestion of organic waste, such as animal waste, kitchen waste, sewage or slaughter waste. It is a process of natural decomposition (digestion) of any organic substance of animal or plant origin due to the activity of anaerobic bacteria, that function in a non-oxygen environment.

Biogas is composed of methane (CH₄), carbon dioxide (CO₂), water vapour (H₂O), and may have small amounts of other gases like hydrogen sulphide (H₂S) and nitrogen (N₂). The methane represents the largest part (typically 55-65%) which gives the gas a calorific value of about 20 MJ/m³. This energy allows biogas to be used as a fuel for cooking and lighting; it can also be used for electricity generation through a gas engine, or co-fuelled in diesel generators to reduce diesel consumption.

Within biogas technology, there are different type of digesters available that can be used for anaerobic digestion. In the context of developing countries, the following system types are most suited for small- and medium scale biogas production:

- Fixed dome model
- Floating dome model
- Plug flow model

The fixed dome model is a straightforward form of digester, constructed underground of brick or concrete. Millions are already constructed for household use (scale up to approx 10m³), especially in Asia but lately also in Africa. Since extended information is available about fixed dome systems¹ (such as the SNV biogas programme), this manual focuses on the plug flow model (chapter 4) and the floating dome model (chapter 5).

2.2 Advantages biogas

Biogas is a useful energy source that can be produced in any areas with sufficient access to feedstock and water. Biogas offers a good option for the disposal of organic waste. Disposal of agro-processing waste and manure encourage better sanitation on farms.

Biogas technology offers an ideal solution for both consumptive usage on household level as productive usage on small- and medium enterprise or industrial level. It provides an opportunity for direct use as for cooking and lightning, and after conversion into a secondary form of energy, such as electricity or mechanical power.

Biogas technology qualifies as renewable energy technology. Plant material and manure is decomposed in the digester by bacteria into biogas and slurry. As these materials are produced in short cycles, they are renewable and carbon-neutral.

Besides producing the biogas, anaerobic digestion also results in a nutrient rich fertilizer (slurry) as organic by-product. Except for the gas, nothing gets lost and nutrients can be brought back to the field.

¹ Such as the SNV domestic biogas programme (www.SNV.org).

2.3 Demand for energy

For determining the appropriate biodigester size, it is recommended to estimate the energy consumption per person per day. The energy demand of any given household, SME, or village should be the sum of all current and future consumption (i.e. hours of cooking, lighting, cooling, power generation). Next step is to determine if sufficient feedstock is available to cover the energy demand. The biomass supply can be determined on the basis of the an inventory of kitchen waste, livestock, agricultural residues or pest plants. More detailed information on calculating energy demand is discussed in chapter 3.

2.4 Requirements for biogas production

1. Access to feedstock

In rural areas with access to agricultural residues, farmers that keep zero-grazing pigs (>10 heads) or dairy cattle (>3 heads), or access to large quantities of kitchen waste (>5kg/day) the conditions are in place for installing household biogas units.

2. Access to water

Water is needed by the anaerobic bacteria to survive, but also to improve the properties of the material. Feedstock is mixed with water to obtain a low solid content, which is called slurry. This allows the slurry to easily flow through the system, and the gas to escape from the digesting mass. Generally, water is added to the mixture until the slurry consist of 10-15% solids.

3. Digester temperature

Digester temperature is an important factor in biogas as it influences the productivity of the anaerobic bacteria. The bacteria involved in the process are mesophilic bacteria that are active in the range of 20–37°C. They are most productive around 33-37°C; at lower temperatures, the bacteria become less active which slows down the digestion process.

4. Proper management

Gas production depends upon digester temperature, fermentation or retention time and the feedstock material. However, a biogas unit will only yield good results if it is properly maintained. Daily supply of feedstock and water is essential for a good operation of the biogas system.

2.5 Inputs

There are many different types of biomass that can be used for biogas production, but also many that are less suitable or downright unsuitable. Determining the suitability of certain (mixes of) biomass for digestion requires a more detailed assessment. General guidelines for assessing the feedstock are:

- Start-up digestion process: to start up the digestion process, a culture of mesophilic bacteria is needed. These bacteria can normally be found in fresh manure.
- Manure: Any type of manure of animals that is easy to collect can be used as feedstock (cow, pig, chicken).
- Kitchen waste: starchy kitchen waste (such as cooked rice, maize porridge, bread, beans) which can be easily mixed with water, provides an excellent feedstock. Note that non-organic waste (plastics), bones, and too fibrous waste (peels, shells) are not suitable for digestion.
- Agro (processing) residues: there are several types of agro (processing) residues that are suitable for digestion. Examples are press cakes and fruit skins.

- Aquatic weeds: weeds such as water hyacinth are nutrient rich feedstock suitable for digestion. Cutting the water hyacinth in small particles is necessary for a well-working biogas process.
- Energy plants: there are various plants that are suitable for digestion, and can be grown for this purpose. Examples are Euphorbia tirucalli, A shrub that grows in semi-arid tropical countries and are widely spread in Africa; or fast growing grass species such as elephant grass (*Pennisetum purpureum*) or Guatemala grass (*Tripsacum laxum*) that commonly occur in large parts of Africa.



Figure 2-1 Elephant grass



Figure 2-2 Euphorbia tirucalli

The following should be avoided:

- Fibrous materials, such as dry stalks and leaves, branches, maize cobs, rice husk, wood should be avoided. Bacteria's will have difficulty in breaking down the material, which leads to poor digestion.
- Chemicals: antibiotics, disinfectants and other chemical parts that are present in the slurry can seriously affect, or even stop the digestion process.

2.6 Using digester effluent as fertilizer

In the digester, feedstock is converted to biogas and effluent. The effluent is rich in plant nutrients and undigested organic matter and can be used to improve the fertility and structure of the soil in gardens and fields. Therefore slurry is an effective fertilizer that can improve the growth of crops.

3 BIOGAS INSTALLATION PLANNING

Planning a biogas system requires a number of steps to be taken. Provided that there is a certain amount of feedstock (animal dung or other organic wastes) available nearby, the first step is to determine what the gas is going to be used for, and what amounts of gas are needed. From this, the required amount of feedstock and water can be determined and the system size can be calculated. Finally, a suitable location for the plant can be identified.

3.1 Gas requirements

Most small biogas systems produce gas for meeting household energy demands (cooking and lighting), although the use of the gas for power production (electricity or mechanical power) is starting to develop. Both will be briefly discussed below.

1. Household energy

Household energy that can be provided by biogas concerns mainly fuel for cooking and lighting. For both purposes, the existing energy use should be taken as a reference.



Figure 3-1 Cooking on a 3-stone fire

Biogas requirements for cooking can be estimated on the basis of the current fuel type, fuel consumption, and stove equipment used. For different combination, approximate fuel-to-biogas replacement values can be found in Table 3-1 below. For example, if a household currently uses 8 kg of woodfuel per day, cooking on 3 stones, the daily biogas need would be $8 \times 0.21 = 1.7 \text{ m}^3$ of biogas per day.

Table 3-1 Approximate cooking fuel replacement values

Fuel / stove	Fuel NCV	stove efficiency	replacement
Wood 3-stone	15 MJ/kg	10%	0.21 m ³ /kg wood
Wood improved	15 MJ/kg	20%	0.43 m ³ /kg wood
Charcoal	25 MJ/kg	30%	1.07 m ³ /kg charcoal
Kerosene	38 MJ/l	40%	2.17 m ³ /l kerosene
Butane gas	45 MJ/kg	45%	2.89 m ³ /kg butane

Biogas requirements for lighting can be estimated using the number of lights and the number of hours of lighting needed. Biogas lamps come in various sizes but an average consumption rate is some 100 litres (0.1 m³) of biogas per hour, so for one lamp used for 4 hours per day the gas requirements would be $1 \times 3 \times 0.1 = 0.3 \text{ m}^3$ per day.

2. Power production

For using biogas for the production of power (mechanical or electric), there are essentially three options: using a biogas engine / generator (spark plug engine); modifying a gasoline engine / generator to run on biogas; or using biogas in combination with diesel in a diesel engine / generator.

Biogas engines run on biogas only, so the full electricity demand should be covered by biogas. The gas requirements depend largely on the size and type of the engine, the capacity at which it is used, and biogas quality. It can range from about 1.5 m³/kWh for a small generator (<5 kW) running at partial load to 0.6 m³/kWh or less for a large generator (>50 kW) at optimum load, both running on biogas with a typical Net Calorific Value (20 MJ/m³). In case of a small generator covering an electricity demand of e.g. 8 kWh/day, the biogas consumption would be $8 \times 1.5 = 12 \text{ m}^3$ of biogas per day.

Note that gas gensets are available from about 1 kWe upward, and running such engines at very low loads results in low efficiency and more frequent engine failure. For individual households, such engines are often too large.

Gasoline engines can be modified to run on biogas, as the basic spark plug combustion technology is the same. It requires placing a biogas/air mixing device between the carburettor and the air filter, or replacing the carburettor altogether. The rated capacity of the engine is usually derated with some 20-50%, depending on (a.o.) engine type and biogas quality. The efficiency is similar to that of a biogas engine so the same gas consumption per kWh can be used for calculations

Diesel engines can be run to some extent on biogas; it should be understood that some amount of diesel (at least 20%, but for proper injector cooling 40% is recommended) is always required for the engine to run. Biogas can thus replace a large amount of diesel consumption but cannot fully replace it. Assuming that there is an existing diesel set in operation, one can estimate the biogas consumption from the current diesel consumption, using a maximum replacement of 60% of the diesel and a replacement value of about 2.5 m³ biogas per litre diesel. So when daily diesel consumption is 5 litres, the biogas requirements would be $5 \times 60\% \times 2.5 = 7.5 \text{ m}^3/\text{day}$.

3.2 Feedstock requirements

There are many different types of biomass that can be used for biogas production, but also many that are less suitable or downright unsuitable. Determining the suitability of certain (mixes of) biomass for digestion requires a more detailed assessment; in this chapter we briefly look at cow dung, jatropha presscake and kitchen waste.

Cow dung. In the case of cow dung, one can use a biogas yield of approx 40 litres (0.04 m³) per kg of fresh dung. So at a daily gas requirement of 2 m³ gas per day, the daily fresh dung requirements are $2 / 0.04 = 50$ kg. As one cow produces some 10 kg of fresh dung per day, the dung of 5 cows would be needed. For 12 m³ of gas per day, the dung requirements would be 300 kg/day, requiring the dung from 30 cows. The dung needs to be thoroughly mixed with water (typically 1 litre per kg of fresh dung) in order to arrive at a suitable slurry, in this case 50 litres (2m³ gas) or 300 litres (12m³ gas) per day.

Jatropha press cake. If available, jatropha presscake can be added to boost the gas production. The gas yield per kg cake depends on the amount of oil still inside, but for first estimates one can produce 400 litres (0.4 m³) of biogas per kg cake. For a stable process it is recommended to use it in combination with animal dung, e.g. replacing half the dung with press cake. For 2 m³ of biogas per day one would then need 25 kg of dung (producing half of the gas) plus 2.5 kg of press cake. Note that the water requirements are slightly different: the presscake is very dry and each kg requires some 7 litres of water. In this case, some 43 litres of water are required per day. For 12 m³ of gas, one could use 150 kg of dung and 15 kg of presscake, with 258 litres of water.

Kitchen waste. Different types of kitchen waste (particularly food scraps – bread, rice, maize, cassava, vegetables) can be used as feedstock. The gas yield depends heavily on the actual composition and the amount of water in the waste, but as an average one can use 200 litres of biogas per kg of waste. Here also, adding dung is recommended: for 2 m³ of biogas per day one would then need 25 kg of dung plus 5 kg of kitchen waste. The water requirements of kitchen waste are approx 2 litres per kg, so the total water input would be 35 litres per day. For 12 m³ of gas this would be 150 kg of dung, 30 kg of kitchen waste and 210 litres of water.

NB for both the presscake and the kitchen waste, the amount of dung in the mix could be reduced gradually, although gas production stability should be monitored closely. The dung adds certain spore elements to the digester that might not be available in the other feedstocks; in time this could lead to a reduction of gas production.



Figure 3-2 Jatropha presscake



Figure 3-3 Kitchen waste

3.3 System sizing

The proper digester size can be determined as follows:

1. The volume required for the digesting slurry is at least 50 times the daily input (where one kg of input is usually taken as 1 litre). So for 2 m³ biogas per day, with a daily input of 100 litres of slurry (50 kg dung + 50 l water), the required volume is at least 50 x 100 = 5000 litres (5 m³). In case of the dung-and-cake mix, with a daily input of some 70 litres of slurry (25 kg dung + 2.5 kg of cake + 43 l of water) the required volume would be 50 x 70 = 3500 litres (3.5 m³).
2. In case of a flexible PVC digester, biogas is stored inside the bag; a typical volume of one day of biogas production is reserved. So in both the described cases, 2 m³ of volume would be required for gas storage. In case of a floating dome digester, the volume of the gas holder would need to be at least 2 m³.

3.4 Selecting appropriate technology

There are many types of biogas systems, in various scale ranges and with varying complexity. Within the Mozambique project, low complexity digesters with sizes upto approx 100 m³ are being considered. As such, systems with heating and stirring devices are not included in the selection. In the mentioned scale range, the most common systems are fixed dome, floating dome and plug-flow digesters. The table below gives an overview of the main advantages and disadvantages of each type, in small (<10m³) and medium size (10-100m³)

	Small (<10m ³)			Medium (10-100m ³)		
	FXD	FLD	PFL	FXD	FLD	PFL
Technical life	++	+	0	++	+	0
Investment costs	--	--	+	--	--	++
Space requirements	+	+	-	+	+	-
Local material availability	+	+	--	+	+	--
Construction skills	--	+	++	--	+	++
Removable	-	-	+	-	-	+

Notes: FXD = fixed dome; FLD = floating dome; PFL = plug flow



Figure 3-4 Large (50m³) fixed dome systems in Rwanda (<http://www.smartinnova.com/index.php?p=re-biogas>)



Figure 3-5 Small floating dome system in India (<http://home.btconnect.com/engindia/biogas.htm>)

3.5 Selecting a location

There are several criteria for determining the suitability of a certain location for biogas production.

1. Availability of feedstock and water. The most important criterion is that sufficient feedstock and (fresh) water must be available year-round in the direct vicinity of the proposed biogas site. Preferably, both water and feedstock availability should be in excess of the required amount, in order to safeguard a continuous supply. Note that starting up a digester requires a multitude of feedstock and water to be made available in a short period of time.
2. On the proposed site, the digester should be placed near the place of end-use of the gas. There should be sufficient space around the digester, and access to the inlet and outlet for adding feedstock and removing slurry. A nearby place to apply or process (compost) the slurry is an advantage.
3. The proposed terrain should be fit for excavation: rocky grounds should be avoided. Terrain height differences should be taken into consideration: plug-flow digesters should be placed horizontally. It might be possible to use gravity for easier digester feeding, e.g. by positioning the digester downhill from stables or latrines.

4 CONSTRUCTION OF PVC PLUG-FLOW BIOGAS SYSTEMS

Installation of a PVC plug flow digester is relatively straightforward. It requires some level of technical skill but no specialist skill. Having selected the proper bag size, the main activities are, in consecutive order:

1. Excavation
2. Reinforcement of ditch sides
3. Installation of bag, inlet and outlet
4. Installation of gas system
5. Construction of roof
6. Start-up

4.1 Selection of PVC bag

Having determined the daily gas requirements and the digester volume, the measures of the bag should be determined. For this purpose, calculation programmes can be used that have the required slurry- and gas contents of the bag as main inputs, and the bag length and width as output. The table below gives an indication of the measures for three sizes of bags.

Table 4-1 Digester bag measures

Digester size	6 m ³	20 m ³	60 m ³
Bag length	9.00	12.70	21.00
Bag width	1.90	2.70	3.80

The bag should be made from fibre-reinforced PVC of at least 850 g/m². It should have inlet- and outlet sleeves on the short ends, large enough for 110mm PVC pipes. The bag should be fitted with one or more 1" gas connections on top.



Figure 4-1 PVC Bag inlet flange



Figure 4-2 PVC bag gas connection

4.2 Excavation

First step in the installation procedure is the selection of a site. The site should be large enough for the digester bag, the in- and outlet of the digester, and some additional space in order to walk around the installation. It should be as close as possible to the place where the gas is going to be used, in order to avoid large gas lines. The ground should be flat, and must be fit to excavate (e.g. no rocky underground).

As an indication, the following minimum space requirements can be used:

Table 4-2 Minimum digester space requirements

Digester size	6 m ³	20 m ³	60 m ³
Space length	15 m	20 m	25 m
Space width	4 m	5 m	6 m

After selection of a suitable location, a ditch will need to be excavated in which to place the digester bag. The sand from the ditch should be put around the ditch to create a low wall thus increasing the effective depth of the ditch. A sketch of the ditch is provided in Figure 4-3 below; measures for the different digester sizes are provided in Table 4-3 below.

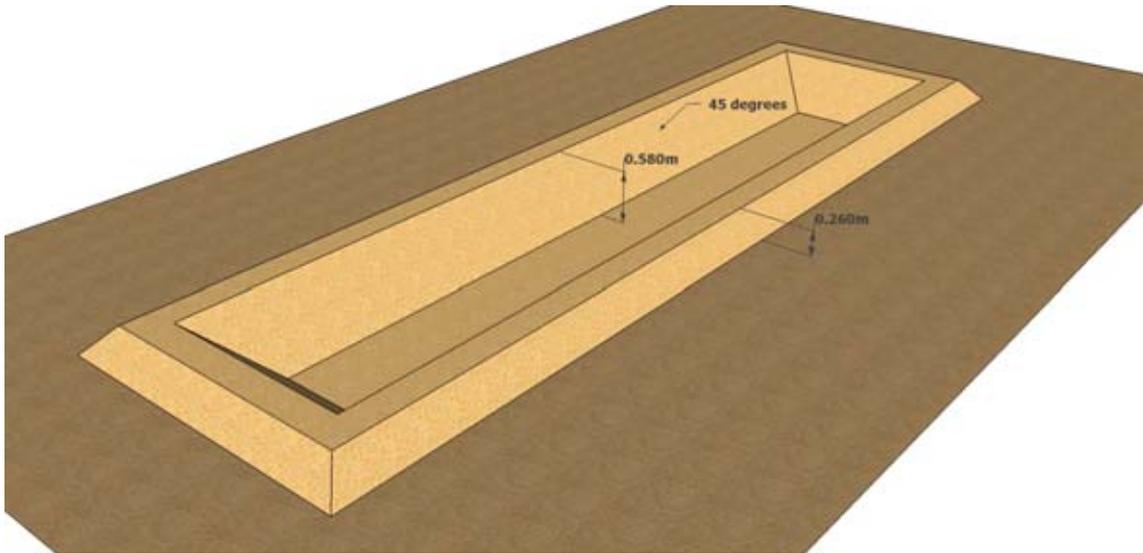


Figure 4-3 Basic layout for digester ditch

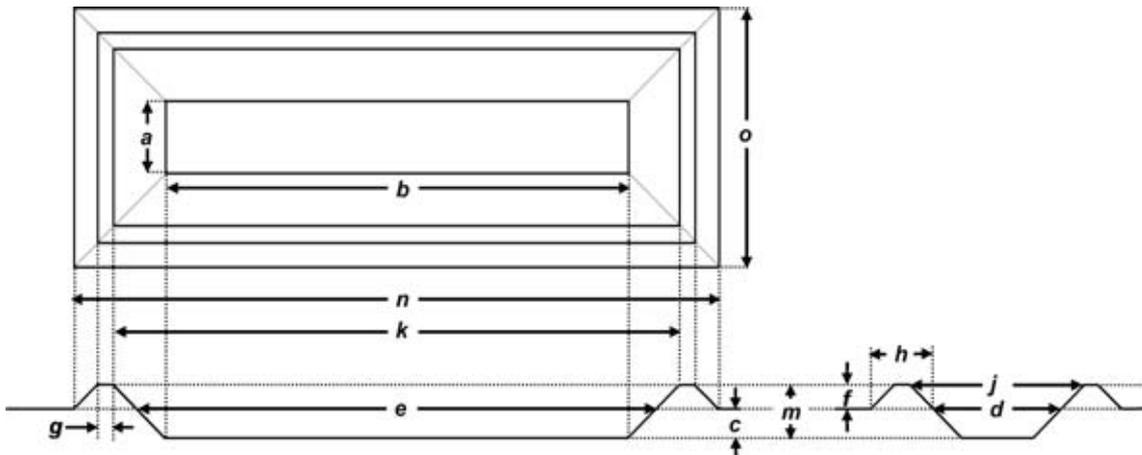


Figure 4-4 Measures of digester ditch

Table 4-3 Measures for digester ditch (in metres)

Digester size	6 m ³	20 m ³	60 m ³
a. ditch base width	0.69	0.96	1.36
b. ditch base length	7.41	10.78	15.30
c. ditch base depth from ground level	0.28	0.36	0.48
d. full ditch width at ground level	1.24	1.68	2.33
e. full ditch length at ground level	7.97	11.50	16.27
f. wall height from ground level	0.21	0.31	0.47
g. wall top width	0.30	0.30	0.30
h. wall total width	0.72	0.93	1.25
j. ditch width at top level	1.66	2.31	3.27
k. ditch length at top level	8.38	12.13	17.22
m. ditch depth from top level	0.49	0.68	0.96
n. total length	9.28	13.18	18.49
o. total width	2.55	3.35	4.55

In placing the ditch, please remember to leave space for inlet and outlet before and after the digester (both approx 2 metres).

The ditch should be dug in two phases:

1. First, a ditch with vertical walls should be dug, with the dimensions of the bottom of the ditch. Start with marking the corners and sides of the ditch with pegs and rope. Then the ditch can be dug, putting the sand from the ditch far enough from the edge of the ditch, i.e. there where the walls will be made. Regularly measure the depth of the ditch in several places, in order to prevent digging too deep.
2. After that, the sides of the ditch should be scraped off diagonally, arriving at the eventual dimensions of the ditch. The angle should be approx 45 degrees in order to prevent caving in.



Figure 4-5 Excavation of a 6m³ digester ditch

Care should be taken that the bottom and sides of the ditch do not have pointy rocks sticking out. Any rocks that could potentially damage the digester bag should be removed.

If this is impossible, e.g. when it concerns large rocks that cannot be practically removed, counter measures should be taken:

- Rocks in the bottom of the ditch could be covered with a thin layer of fine sand;
- Rocks sticking out from the sides should be blanketed by a sturdy cover (e.g. rice bags or equivalent) before placing the digester bag in the ditch.

Although it is not absolutely necessary for the functioning of the digester, it is recommended to reinforce the sides of the digester ditch, in order to avoid erosion, facilitate maintenance and provide a solid base for roof construction and gas line. For this purpose, cement tiles should be prepared that can be placed around the top interior of the ditch, and on top of the walls. The size of the tiles can be selected according to the size of the digester; a typical tile size would be 30 x 60 cm (5cm thickness). It is recommended to construct a mould – this facilitates the production process and results in uniformly shapes tiles.

Note that the strength of the tiles can be optimised by following a few simple guidelines:

1. Using a good mix of cement and sand: at most 4 parts of sand on one part of cement.
2. Using plastic sheets on which to place the tiles during hardening, in order to prevent the surface to take the water from the cement mix
3. Placing the tiles in the shade during hardening; in addition it is recommended to frequently spray the hardening tiles with water.

Over all, it should be considered that cement tiles and bricks do not harden by drying! Cement needs sufficient water in order to harden; as such, evaporation of water should be minimised.

Usually a single row of tiles suffices but larger digesters could be fitted with two rows.

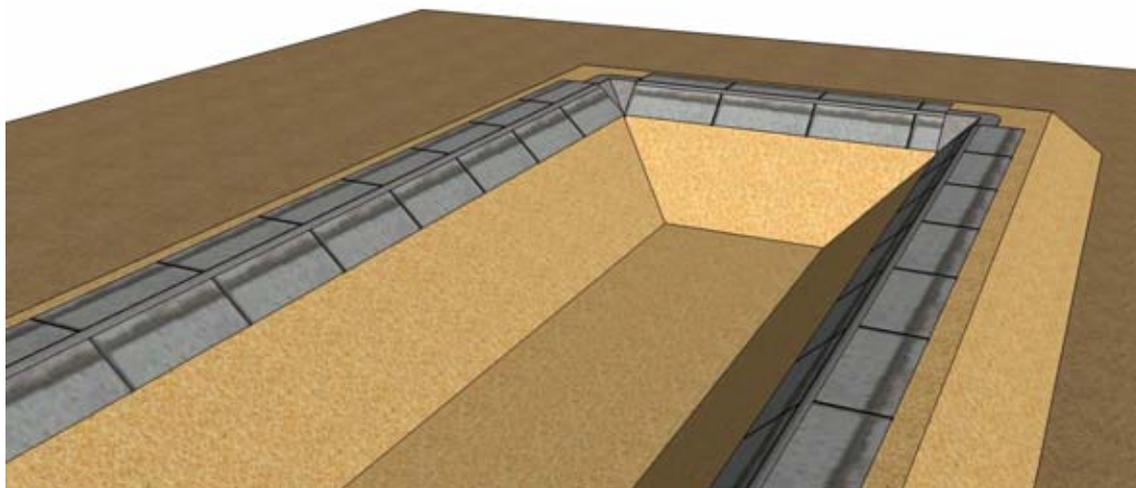


Figure 4-6 Placement of reinforcements



Figure 4-7 Placement of reinforcements for a 60m³ digester

4.3 Roof construction

Prior to placing the digester, it is recommended to construct a simple roof over the digester bag, to shield it from direct sunlight and reduce strong temperature fluctuations of the bag contents. Basically, any type of roofing can be constructed; main considerations being:

- **Strength and durability.** The roof construction should have a lifetime of several years, and be able to withstand mechanical stress, particularly due to wind.
- **Costs.** The construction costs should be limited, and its maintenance/repair should be low-cost. Use of locally available materials might be preferred.
- **Resistance to direct sunlight.** The roofing material should be able to withstand direct sunlight so some types of plastics should be avoided.

One possible solution is to construct a steel structure from cement iron. The structure is made up of iron arcs, connected by horizontal rods (welded). This structure can then be covered by e.g. plastic sheets or natural materials (e.g. thatch or bamboo).



Figure 4-8 Roof construction of cement iron (60m³ digester)



Figure 4-9 Roof cover (60m³ digester)

Some specific point for this roof construction:

1. The shape of the arcs should be a segment (e.g. one third) of a circle. In the case of a 60m³ system (see Table 4-3) the arcs should cover a width of approx 3.3m. The arcs can be made from iron lengths of 4.4m (including 2x0.2m for the arc foundation in the walls). The roof height is then approx 0.95m from the top of the wall.
2. The iron arcs should be founded in cement, just outside of the ditch reinforcement. A typical spacing for the arcs is 1m.
3. The horizontal rods should be welded to the arcs. Welding should be done **before** the bag is placed in the ditch!
4. The iron should be painted with anti-corrosion paint. If plastic sheets are to be used as cover, it is recommended to wrap the irons with duct tape in order to prevent the sheeting to be worn.
5. it can be considered to leave part of the sheeting hang loose, holding them down with weights attached to the sides. This way, the wind can lift them up, which reduced the mechanical stress on the structure and the sheeting.

4.4 Digester bag installation

When the ditch and main roof construction are complete, the bag can be placed inside. Make sure that the gas connection is on top! Inlet and outlet pipes are made of 110 mm PVC pipe; the edges of the pipes should be well rounded in order to avoid punctures. The pipes should run to a depth of approx 75% of the ditch.



Figure 4-10 Digester bag (60m³) placed inside the ditch

A connection should then be made between the bag and the gas line. A flexible hose of at least ¾" (preferably larger) should be used for this. The length should be minimised in order to reduce pressure drops.

When all connections have been made, an (optional) pressure test can be done to assure gas tightness of all connections. The digester inlet and outlets should be solidly blocked, e.g. with plastic bottles and plastic bags. The main valve should be closed; the pressure relief bottle should be filled such that the hose is emerged in at least 15cm of water. Also, the water level in the pressure meter should be verified.

Then, a compressor should be connected to the system, e.g. to the condensate trap T-piece. The digester bag will be filled with air; after that the pressure will quickly build up. At the maximum pressure, the gas relieve system will start to kick in, and air bubbles will escape through the hose inside the bottle. The pressure meter will show a pressure of 15 cm water. At this point the compressor can be turned off. All connections (including the gas system and the in-and outlet connections to the digester bag) should be sprayed with a soap-water mixture from a spray bottle. Any gas leaks will cause bubbles, and should be repaired.

After the pressure test, the in- and outlet should be de-blocked, allowing all the air to escape from the bag (don't forget to reinstall the condensate trap!). Filling of the bag with dung and water can start as soon as the bag is completely empty.



Figure 4-11 Pressure testing of a 12m³ digester. The bottle provides a protection against over pressure.

4.5 Inlet and outlet construction

The inlet and outlet tubes should be connected to inlet- and outlet structures that will facilitate feeding the digester and recovering the outgoing slurry. Preferably, these structures should be built when the digester is already in operation, so that the PVC pipes will have set according to their position to the digester bag.

The inlet consists of an elevated cement structure (see Figure 4-12) in which the inlet pipe ends up. If it is used also for mixing, its height should be limited in order to avoid height lifting of water and feedstock. its content should match the total volume of material going in each day (or half day, in case of multiple feeding).

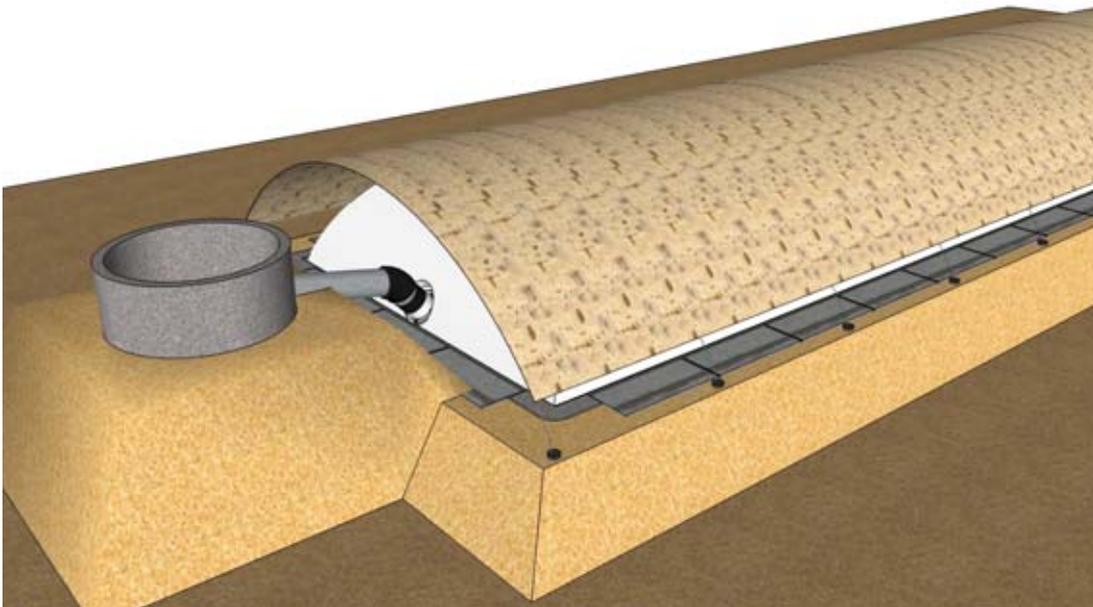


Figure 4-12 Inlet structure

For the outlet, the most important is to cut the PVC pipe such that slurry will exit during feeding under normal operating conditions. I.e. the pipe should be cut approx 5-10 cm above the intended filling height of the digester bag. It is recommended to cut the pipe only after the actual operating level has been reached. Use a stick to gauge the level of digester effluent inside the outlet pipe, and saw off the pipe at that level. NB if the pipe that doesn't reach the outlet basin, a prefab 45 degree bend can be added to the outlet pipe to extend its length.

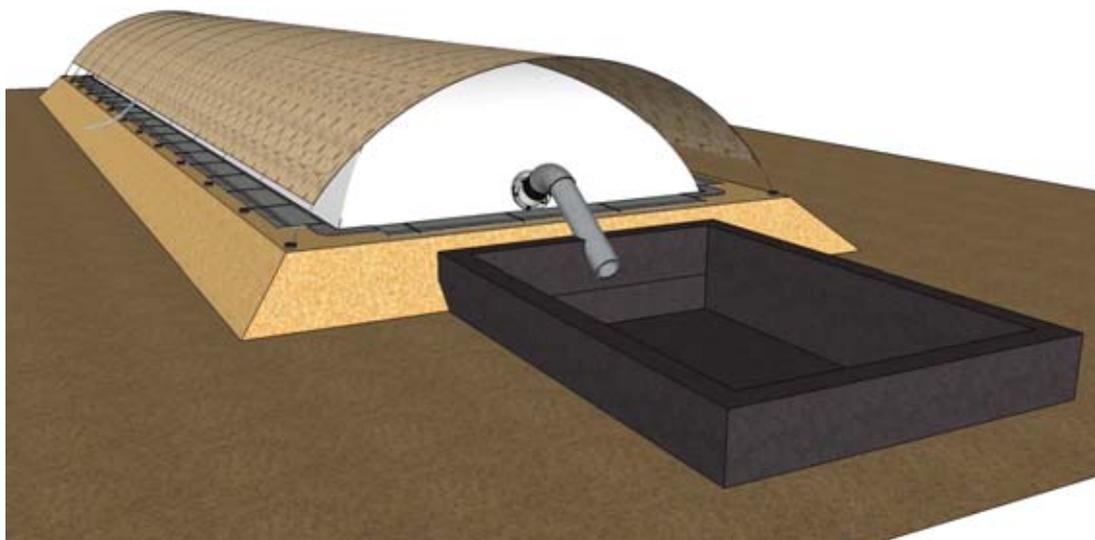


Figure 4-13 Outlet structure

The outlet structure (see Figure 4-13) is less critical: it can be a low reservoir in cement, holding the contents of a daily feed.

5 CONSTRUCTION OF FLOATING DOME BIOGAS SYSTEMS

The floating dome system developed originates from India. It consist of a underground reactor in brick or concrete, and a gas holder in metal or plastic that floats on top (the floating dome). Due to the practical size of the gas holder, this type is generally not constructed beyond the household scale (approx 15m³). In India, a metal floating dome is often used as gas holder. Because of limited availability and high material costs, such system are not typically used in Africa. The so-called “Sintex” water tanks are easily available in Africa, and is a practical alternative.

Advantages of a floating dome system:

- Robust design, very long lifetime (>20 years) if properly constructed
- Straightforward masonry work
- Locally available materials (cement, sand, bricks, piping, hoses, water tank)
- Constant and elevated gas pressure

Disadvantages of a floating dome system:

- Relatively large costs; due to high costs of the gas holder and the cement
- Limited scale; large biogas systems would require several smaller units (e.g. 4x15m³)
- Cannot be moved
- In case of using a metal tank, metal parts susceptible to corrosion, requiring frequent maintenance

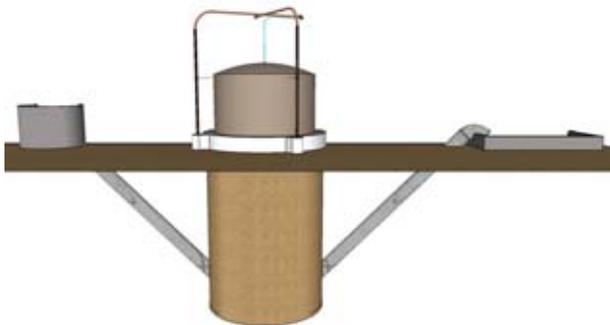


Figure 5-1 Schematic overview of inlet, reactor, outlet.



Figure 5-2 Floating dome system

5.1 System description

Daily input of feedstock is inserted in the inlet and moves from there to the reactor through a PVC pipe. The produced biogas escapes from the reactor and is stored in the dome that floats on top of the reactor. The floating dome will be pushed up when gas volume increases. The gas leaves the system through a gas connection that connects the floating dome to the gas user. After gas consumption, the floating dome goes down again. When the reactor reaches full capacity, the surplus slurry leaves the system through the outlet.

5.2 Installation

Selection of the site

First step in the installation process is the selection of the site. The site should be big enough to install the reactor, the inlet and the outlet, and it should have enough additional space to deliver the feedstock, do the feeding, and do maintenance. As an indication, the dimensions of the site should be at least 4 x 15 m for a single (12m³) system.

Furthermore, the installation should be close to the place where the gas will be utilized, to avoid covering long distances and gas pipes with large dimensions. The site should be flat and suitable for excavation work (avoid rocky soils or high ground water level).

The reactor

Next step will be the building of the reactor. The design followed in this manual refers to floating dome digester size of 6m³ and 9m³. The following materials are needed to construct the reactor:

Table 5-1 List of materials

Digester size	6 m ³	12 m ³
Cement bags (50kg)	37	45
Sand and water		
Bricks 10x10x20cm (made from cement)	900	1100
Water storage tank	2,5m ³	5m ³
PVC pipe 110mm	3.5 m	3.5 m

As the digester wall will be made of brick, it is recommended to start arranging a supply of bricks. This could either be burnt clay bricks of good quality but in absence thereof, cement bricks can be made using a mould (see Table 5-3). When preparing the bricks, please adhere to the following guidelines:

1. Using a good mix of cement and sand: at most 4 parts of sand on one part of cement.
2. Using plastic sheets on which to place the tiles during hardening, in order to prevent the surface to take the water from the cement mix
3. Placing the tiles in the shade during hardening; in addition it is recommended to frequently spray the hardening tiles with water.



Figure 5-3 Brick mould

Then, the dimensions of the excavation work need to be defined. The dimensions of the reactor pit should be outlined using poles and rope. From a fixed point in the centre of the circle, the same distance is measured with the rope to each of the poles. Depending on the size of the water tank, the diameter of the reactor is defined. The water tank should be able to freely float within the reactor so there should be some space available between the outside of the tank and the reactor walls.

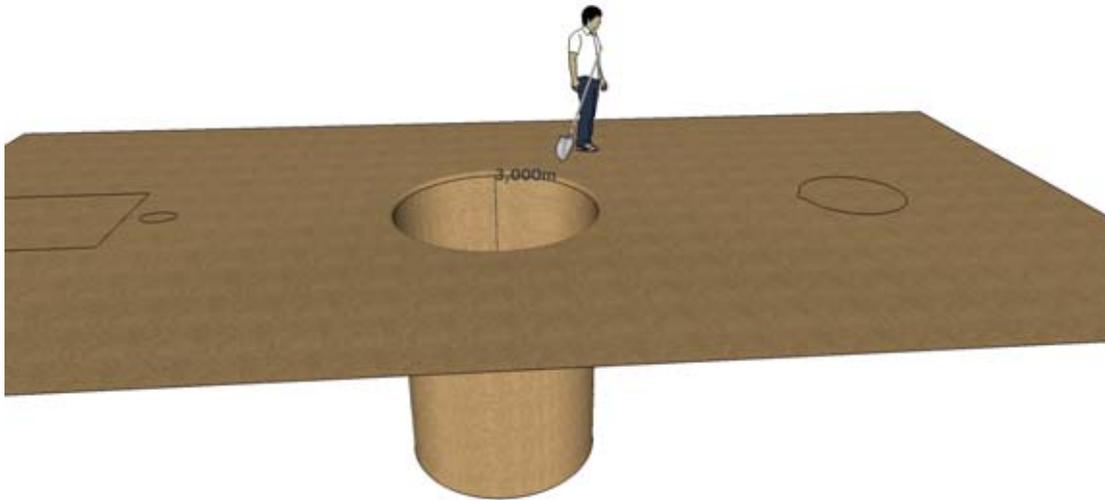


Figure 5-4 Excavation works

Table 5-2 shows the dimensions of the excavation work. For a 6m³ system, the radius from the centre to the circumference of the circle is 1.50m; For a 12m³ system, the radius is 1.70m. The depth of the reactor for both systems is identical, 3m. It is important that the walls of the reactor are excavated and levelled out well to prevent crooked walls of the reactor tank.

Table 5-2 Excavation measures

Digester size	6 m ³	12 m ³
Radius gas holder	1.20 m	1.40 m
Inner radius reactor wall	1.23 m	1.43 m
Outer radius reactor wall (10 cm bricks)	1.40 m	1.60 m
Minimum radius excavation	1.50 m	1.70 m
Depth of reactor (from ground level)	3.00 m	3.00 m

The bottom of the reactor should be level. It should be covered with plastic sheets, and a concrete floor of at least 5cm thickness should be made, with a steel pipe in the centre to facilitate the wall construction – this pipe should be removed when the walls are finished, and the hole carefully filled with cement. The floor should be allowed to harden for at least 2 days before the construction of the walls can start. To be able to connect the pipes well into the reactor, it is necessary to already position the pipes during the building process of the reactor.

During the construction of the walls of the reactor, it is extremely important that the masonry is perfectly straight and perfectly round, otherwise the gas holder will get stuck. The masonry should preferably be done by an experienced mason; during brick laying, the distance to the centre of the pit and the straightness of the wall should be monitored constantly! The wall should be built all the way up to approx 0.2 cm above ground level.

After finishing the reactor walls, a separation wall of 80cm height is constructed inside the reactor. The separation wall will facilitate better decomposition of the feedstock. It will keep the freshly fed feedstock longer in the inlet compartment, and thus avoid that fresh feedstock directly flows to the outlet and leaves the system without being decomposed. Distance between the inlet and the separation wall should be 0.5m in case of the 12m³ systems and 0.5m in case of the 6m³.

As soon as the separation wall is finished, the interior of the reactor (floor and walls) should be plastered with a layer of 1-2cm of water-tight cement (1 part cement and 1 part sand). Note that the reactor and inlet- and outlet connections need to be water proof and air tight to avoid gas- and water leakages.



Figure 5-5 Reactor pit with 2 inlets and 1 outlet



Figure 5-6 Constructing the separation wall

Table 5-3 Digester dimensions

Digester size	6 m ³	12 m ³
Distance between reactor floor and the bottom part of the in- and outlet pipe	0.3 m	0.3 m
Thickness of the reactor floor	5 cm	5 cm
Distance between reactor wall and outside end of the inlet and outlet pipes	1.67 m	1.67 m
Height of reactor wall above ground level	0.2 m	0.2 m

Connecting the floating dome

The floating dome functions as the gas storage. The biogas bubbles up from the slurry in the reactor into the dome, where it is stored until usage.

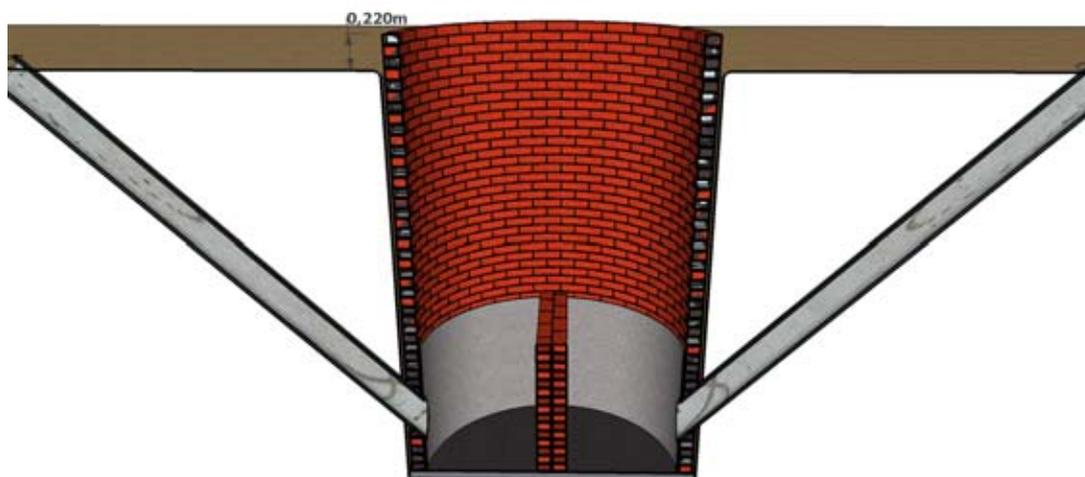


Figure 5-7 Profile reactor biodigester

In case of using a plastic water tank as floating dome, the top of the tanks needs to be cut off. This open part of the tank will float on top of the slurry. Do not cut out the top of the tank completely, since this will make the tank very unstable and lose its round shape.

To facilitate a stable position of the floating dome on top of the reactor, it is necessary to establish a support frame that guides the dome in its movement. Figure 5-8 gives an example of an external frame in which the floating drum can easily move up and down. It can be made from 3/4" galvanised steel pipe. A structure of loops connects the top of the gas holder to the frame

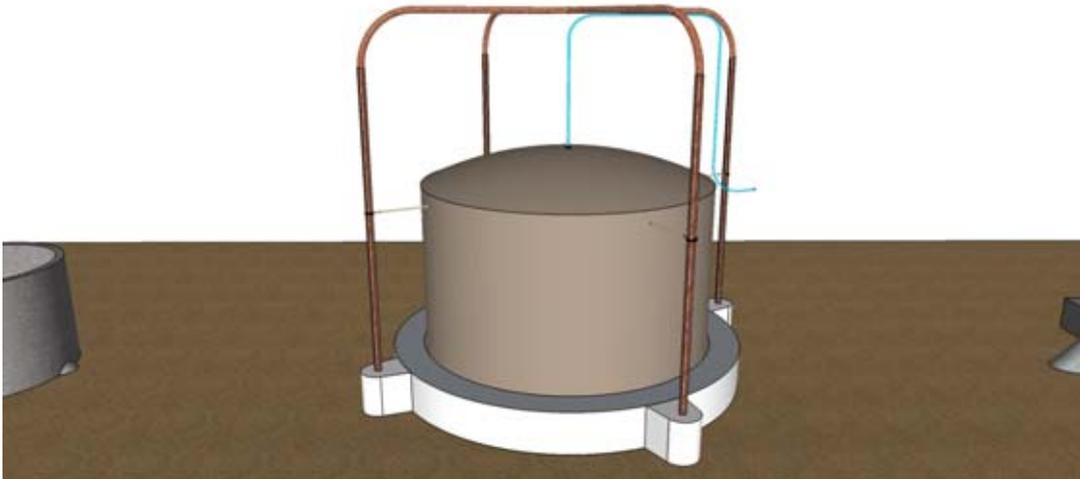


Figure 5-8 External support frame

A gas hose is connected on top of the tank. The gas hose is interrupted with a valve. Please refer to section 0 for determining the size of the gas line pipes. For connecting a generator, usually at least 1" galvanized pipe is recommended. For other biogas applications, such as lamps and cooking stoves, 3/4" PVC pipes can be used.

5.3 Inlet and outlet

As can be seen in Figure 5-9, the PVC inlet- and outlet pipe are fitted into the wall at 30cm from floor level. The distance between the reactor wall and the extreme end of the pipes should be 167cm. This means that the inlet- and outlet pipes should have a length of at least 350cm.



Figure 5-9 Inlet pit on right side, outlet tank on left side



Figure 5-10 Inlet, reactor and outlet

After finishing the reactor walls, the inlet pit and the outlet tank can be constructed. The construction of the in- and outlet do not follow strict criteria, as long as the guidelines with regard to pipe lengths and levels are followed:

General guidelines for constructing the inlet:

- The inlet pipe should be at least, 10cm above the reactor wall. This will guarantee a smooth flow of feedstock mixture from the inlet pit into the reactor.
- If the inlet is to be used for mixing, its contents should be at least the daily input: 100 litres for the 6m³ digester, and 200 litres for the 12m³ digester. Table 5-4 shows possible dimensions.
- A round shape facilitates the feedstock mixture to easily flow into the system.
- Take into consideration that the daily operator of the system can easily discharge the feedstock into the inlet and keep it clean.

General guidelines for constructing the outlet

- The top of the outlet pipe needs to be about 10cm lower than the top of the reactor wall. This will guarantee that surplus slurry will leave the reactor as soon as it is full, since the pressure of the gas will push the surplus through the outlet pipe.
- The dimensions of the outlet should allow storage of at least a daily amount of feedstock, since this amount of slurry will leave the system. It is recommended to make the outlet big enough to store the slurry for a longer period. Table 5-4 shows possible dimensions.
- A PVC bend is connected to the end of the outlet pipe.

Table 5-4 Dimensions inlet- and outlet tank

Digester size	6 m ³	12 m ³
Inlet pit radius	0.40m	0.50m
Inlet pit depth	0.30m	0.40m
Outlet pit width	1.00m	1.50m
Outlet pit length	1.50m	2.00m
Outlet pit depth	0.50m	0.50m



Figure 5-11 Inlet pit



Figure 5-12 Outlet tank

6 OPERATION AND MAINTENANCE

6.1 Digester start-up

For the start-up of a digester, different methods exist². A proven method is to fill the digester to **half** the required level with a mixture of animal dung (cow or pig) and water, in a ratio of 1 kg of dung with 5-10 litres of water. This batch should be left for approx 2 weeks for the process to have started, after which the feeding of daily mixtures can start.

Alternatively, the digester can be started by filling it up with water to **half** the required level and start feeding it with the standard daily mixture. This method is considered safer but also takes more time.

Note that at lower temperatures, acid forming bacteria may outgrow methane producing bacteria, increasing the possibility of the digester to turn sour. In such a case, it is recommended to use more water (e.g. 10-20 litres per kg of dung) or revert to the water-only method.

In either case, it is recommended to use only dung for start-up, and to wait with adding other substrates until the digester is producing a stable amount of gas. Even then, it is recommended to slowly increase the amount of co-substrate, adding 20% of the eventual amount for at least one week, then increasing it to 40% in the week after that, until the full 100% is reached.



Figure 6-1 Filling of a 12m³ digester

Initially, mainly CO₂ is produced, so any gas produced in the first weeks will not burn. If after one month the gas still does not burn, it is recommended to (partly) deflate the gas storage. The methane content of the gas inside the storage will then increase much faster.

² See for example http://www.appropedia.org/Biogas_start_up

When the digester has been started up with half the amount of water and/or dung, it will take approximately one month of feeding before it is filled with to the required level. At this moment, sufficient gas will have built up to pressurise the gas storage with sand bags. At this point, the outlet pipe can be cut to the required length.

6.2 General operation and maintenance

Typical daily operations activities include preparing and adding the daily mixture, daily checkup of the system, and managing the digester effluent. For reference: normal operation of a 12 m³ digester takes approximately 1 hour each day.

Preparing and adding the daily mixture

The digester should be fed at least once per day. Easiest is to mix inside the inlet structure. Close the inlet pipe, e.g. with a plastic bottle and plastic bag. Make sure that neither bottle or bag goes into the inlet, as they might cause blockages. In case the needed amount is more than fits into the bucket, feed in two or three equal parts.

Measure the correct amount of dung, co-substrate (if applicable), and water. Co-substrate should be as fine as possible: when using e.g. kitchen wastes, it should be cut in small pieces before adding it to the mix. Water should have the ambient temperature, in order to prevent temperature shocks when adding the mix to the digester. It may be best to fill a container of water each day, for use in the next day's mixture. The ingredients should be put in the inlet bucket, allow to soak for 15-30 minutes, and then mixed thoroughly by hand. Any dry lumps (e.g. from the animal dung) should be broken and soaked thoroughly. When the mixture is a uniform slurry, pull the plug from the inlet to let the mixture flow into the digester.



Figure 6-2 Daily feeding of a 12m³ digester

Daily check-up

Each day, the whole biogas system should be checked for irregularities (tears or cracks in bag or hoses, tightness of hose clamps). The water level inside the pressure relieve system should be checked (hose to be emerged in 15 cm water). The pressure should be checked (approx 5 cm water), and the amount of water in the pressure meter. Check the level of

water in the condense trap, and empty the bottle if necessary. Check the state of the roofing. Clean the system regularly.

Every three months, all of the connections in the system should be checked for gas-tightness. Use a spray-bottle with soap and water to spray all connections (including digester in- and outlet, and all gas connections upto the main valve).

Managing digester effluent

While adding the daily mixture, a similar amount of digester effluent will flow out of the digester outlet. The effluent is a potent fertiliser, containing all the nutrients present in the original inputs, and can be used in fields and gardens. The main drawback is the high water content (>90%) which makes it impractical to transport over large distances. This issue can be partially resolved by leaving the effluent in the open, so that part of the water can evaporate during the day. As such, it is best to first remove the effluent of the day before, and then feed the digester, to prevent the fresh (wet) effluent to mix with the partially dried effluent from the day before.

Alternatively, the effluent can be added to compost. It will increase its nutrient value and provide the required amount of moisture for the composting process.

6.3 Trouble shooting

After start-up procedure, there is no gas production

- The digester may have gone sour. Flush out the digester with a large amount of water (twice the digester contents) and start it again.

There is gas after start-up, but it doesn't burn

- The gas that is produced in the first weeks after start-up is mainly carbon dioxide (CO₂) and it takes a while for the methane content to rise to a level that can sustain a flame. Let most of the gas inside the digester escape; after a few days the methane content of the gas will have sufficiently increased to arrive at quality biogas.

There was gas after start-up, but it stopped

- The bacteria inside the digester may have died due to high acidity, antibiotics, or poison. Flush out the digester with a large amount of water (twice the digester contents) and start it again.

There is gas, but it flows very slowly

- There may be too little weight on the digester bag (plug flow), or the gas holder may be stuck (floating dome). Check the pressure of the gas and add sand bags if necessary.
- Check the gas pipe system for blockages.

There is gas, but it is much too little to supply my daily energy needs

- Do you feed it enough? Gas production can be increased by adding co-substrate. Please discuss with an expert which types may be appropriate for you.
- Was the digester size properly assessed? If not, you may need a larger system.

Never use any sharp objects in an attempt to remove blockages in the in- and outlets of PVC digesters, as this can easily lead to punctures in the bottom of the bag!

7 GAS TRANSPORT AND USAGE

7.1 Gas line

Regardless of the type of biogas system and the nature of the end use, some sort of gas transportation infrastructure will be required in order to get the biogas from the digester to the end user. In most cases this is a single pipe in metal or PVC, with a facility to remove condense water at the lowest point.

Choosing pipe material

Typically, biogas pipes are made of either galvanised steel or PVC. Both are durable and resistant to corrosive substances in biogas. Specific considerations of each type:

- Galvanised steel pipes are more expensive than PVC pipes
- PVC pipes are easier to install than steel pipes, with screw fittings or glue
- PVC is susceptible to UV; direct sunlight should be avoided.
- Galvanised steel pipes can contribute to gas treatment (condensation of water vapour when placed underground).

Choosing pipe diameter

Main parameters³ when choosing a pipe diameter are the gas line length, the maximum gas flow, and the maximum pressure drop over the gas line at that maximum gas flow. Table 7-1 gives an overview of the minimum pipe sizes (in inch) at different lengths and maximum gas flows, for galvanised steel pipes. The permissible maximum pressure drop is 2 mbar.

Table 7-1 Minimum pipe diameter (inch) for different gas flows and pipe lengths

Maximum gas flow (m ³ /h)	Pipe length (m)				
	10	20	30	40	50
0.5	0.75	1.00	1.00	1.00	1.25
1.0	1.00	1.25	1.25	1.50	1.50
1.5	1.25	1.50	1.50	2.00	2.00
2.0	1.50	1.50	2.00	2.00	2.00
3.0	2.00	2.00	2.00	2.50	2.50
4.0	2.00	2.00	2.50	2.50	2.50
5.0	2.00	2.50	2.50	2.50	3.00

Note that the maximum gas flow is determined by the capacity of the biogas appliance. For example:

- A typical (single) household consumes approx 0.4 m³ biogas per hour; at a distance of 20 m between the biogas system and the stove, the pipe diameter should be at least 1".
- A Large (double) biogas stove consumes approx 4 m³/h of biogas per hour; at a distance of 10 m the pipe diameter should be at least 2".
- A 7.5 kW diesel engine running at 50% load, and 60% biogas, consumes some 3 m³/h of biogas; at a distance of 40m, the pipe diameter should be at least 2.5".

³ Other parameters are the relative gas density and the pipe friction – which is slightly higher for galvanised steel than for PVC

NB using smaller pipe diameters than indicated in the table might very well work, but then the pressure drop over the pipes will be larger so the biogas pressure will need to be increased in order to compensate.

The connection between the biogas system and the gas line is usually made of flexible tube (e.g. water hose). Care should be taken that this pipe does not collapse, as a collapsed hose may cause considerable pressure drops.

Configuring and constructing the gas line

When configuring the gas line, the following issues are important:

- The gas line should contain few as possible low points where condense water can accumulate. Usually, at least one low point will be required; this point should be fitted with a condense trap (see below). All the other pipes should decline towards that point.
- Try to avoid placing gas lines across (intensively used) paths
- When using gas in engines, it is recommended to remove (some of) the water vapour in the gas. This can be done by using (sections of) steel pipe buried underground, so that the gas is allowed to cool.

Any bends and junctions in the gas line should preferably be made using threaded pipe fittings; the pipes should then be fitted with pipe threads using appropriate tools (see Figure 7-1). Always apply sufficient amounts of teflon tape on any thread in order to avoid gas leaks!



Figure 7-1 Tools for making pipe thread



Figure 7-2 Threaded pipe fittings

Alternatively, pipes can be connected using pieces of flexible hose. Make sure that hoses do not collapse. Always use hose clamps to fasten the hose to the pipe. When connecting two pieces of flexible hose, use a short piece of hard tube (PVC or metal) that fits inside the flexible tubes to be connected, and use hose clamps to fasten both ends.

At least one valve should be placed in the gas system either on the digester side, the end-used side, or (preferably) both. Standard ball-valves can be used.

After the gas line has been put in place, it is recommended to test it for gas tightness. All connections but one should be carefully blocked. Blow into the pipe and keep the pressure on it for a minute or so. If the pressure has not dropped noticeably, the line can be considered gas tight.

Condensate removal

In the lowest point of the gas tubing, condensate may build up over time, which should be trapped in order to prevent it from blocking the pipe. At this point, a T-piece should be put in the tube, with one of the legs pointing downwards. A manual or automatic removal device can be connected there (see Figure 7-3).

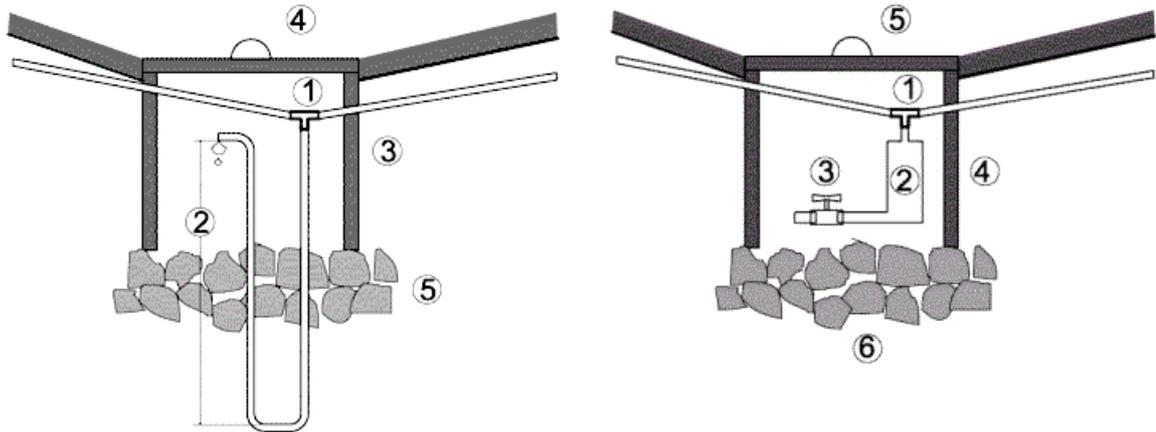


Figure 7-3 Automatic and manual condensate traps

(source: http://www.cd3wd.com/CD3WD_40/BIOGSHTM/EN/APPLDEV/CONSTRUCT/PIPING.HTML)

Pressure relieve system

Flexible PVC digesters operate at a much lower pressure than fixed-dome digesters (typically, up to 10 mbar). Although a well-constructed bag can withstand that pressure several times over, it is recommended to apply a safety relief system. This avoids damage to the bag; moreover, it avoids digestate to be pressed out of the bag when the gas pressure rises.

A simple pressure relieve system consists of a water bottle with a gas tube inserted, emerged in water for about 15 cm (see Figure 7-4). At elevated gas pressures (>15 mbar), the gas can escape through the hose and the water into the atmosphere. **This system should be placed in a well-ventilated area only!** It should be connected to the gas piping system before the first valve (on the biogas system side), using a T-piece and hose clamps.

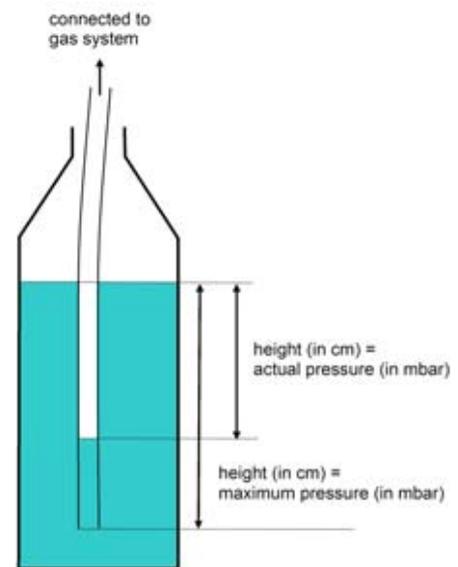


Figure 7-4 Pressure relieve system

7.2 Measuring devices

Gas production. The most straightforward way of measuring gas production is by placing a gas counter in the gas line. Normal G2.5 or G4 natural gas counters (e.g. from China) can be used for this. Please note the following:

- Gas meters have minimum and maximum gas flow rates; for a G2.5 meter this is 25 and 4000 l/h, respectively. Also, a small pressure drop (typically 1-2 mbar) is noticeable at the point where the counter mechanism is set in motion.
- Most gas meters are fitted with fine thread that do not allow direct connection of regular fittings. Special brass fittings are usually required in order to connect them to standard (3/4") connectors.
- Condensate can be trapped inside. It is recommended to regularly disconnect and turn over the gas meter to empty it.



Figure 7-5 Gas counter (G2.5)

Gas pressure. For measuring gas pressure, a simple manometer can be constructed by connecting a u-shaped piece of transparent hose filled with water (see Figure 7-6) to the gas line. The U of the hose should have a height of at least 30 cm, and the water level should be approx 10-15 cm from the bottom. As pressure builds up, the water level in one of the two legs will drop, and in the other it will increase. The pressure (in mbar or cm water) is equal to the height difference of the water in the two legs of the hose.

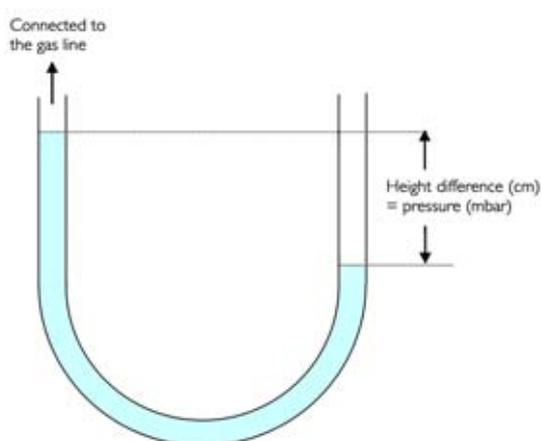


Figure 7-6 Pressure meter (manometer)

Gas composition. For a reliable determination of the composition of the biogas (e.g. for determining its methane content or H₂S content), sophisticated and expensive equipment is required⁴. When using the gas for cooking and lighting, such analyses are not necessary: methane contents are usually in the 55-65% range (burning the gas is the actual test) and H₂S does not do any harm. Only in the case of using the gas in engines, H₂S is an issue: it

⁴ E.g. Sewerin Multitec 540 (<http://www.sewerin.com/cms/en/products/gas/landfill-and-biological-gas/multitecr-540.html>) or Status Scientific PGD3-IR (<http://www.status-scientific.com/pgd3-infrared-series.cfm?a=uk&page=yes>)

should be kept below 200 ppm and this might require cleaning measures (see section 7.5 below).



Figure 7-7 Gas meter, pressure relieve system, gas pressure meter, and main valve

7.3 Biogas stoves

Cooking is by far the most common type of biogas end-use. There are dedicated biogas-stoves available on the market in most countries where (household) biogas systems are being promoted – Chinese made but also local craftsmanship. They come in various sizes: from small household size with 1-2 kW power ($\sim 0.5 \text{ m}^3/\text{h}$), to large institutional stoves with a power of more than 10 kW ($>4 \text{ m}^3/\text{h}$).



Figure 7-8 Small household stove



Figure 7-9 Large double stove

Gas stoves work with the following principle (see Figure 7-10): gas is first mixed with a small portion of air (primary combustion air). This is achieved by pressing the gas through a small orifice, thus creating a gas jet. This gas jet creates a slight underpressure when

directed in a tube, which causes a flow of air. The mix of gas and primary air flows out of the burner head where it burns in the open air (secondary combustion air).

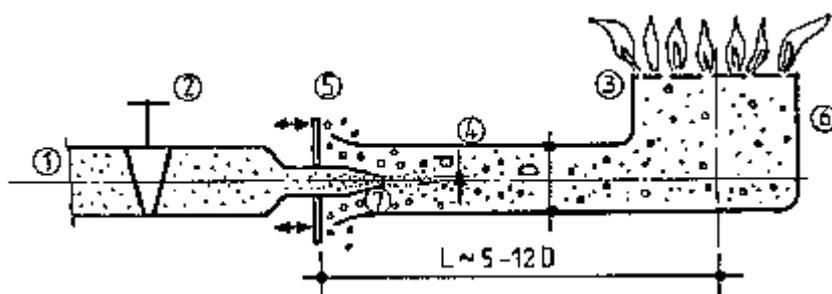


Figure 7-10 Schematic representation of a gas burner
(<http://collections.infocollections.org/ukedu/en/d/Jg32bie/6.5.html>)

It should be understood that biogas stoves are very similar to LPG (butane) stoves but that there are some specific differences that need to be considered:

- LPG requires far more air per volume of gas than biogas (approx 3 times more). This has consequences for the mixing ratio of primary air.
- LPG is distributed in pressurised bottles; the pressure is reduced before the gas enters the burner, but it is still in the order of 20-30 mbar. This may be considerably higher than the pressure at which biogas is supplied.

Stove power

When selecting a stove, it is important to determine the required power: a too small stove will increase cooking time in comparison to the traditional way of cooking. For this purpose, a boiling test can be done on the traditional way of cooking: measuring the time (t in minutes) that it takes to boil a (common) pan with a known amount of water (V in litres). Be sure to put a lid on the pan to minimise evaporation. The stove output power (P in kW) is equal to $5.2 \times V / t$. So if it takes 8 minutes to boil 2 litres of water, the output power equals $5.2 \times 2 / 8 = 1.3$ kW.

The gas throughput of the stove (Q in m^3/h) can be calculated from the required power by the following calculation: $Q = 0.45 \times P$. So if the required stove output power is 1.3 kW, the stove should have a gas flow of $0.59 \text{ m}^3/\text{h}$.

Gas pressure

Also make sure that the stove pressure matches the biogas pressure as near as possible. The stove will function at a lower power if the gas is supplied at a lower pressure. The eventual stove output (P_{actual}) can be calculated from the rated stove power (P_{stove}), the rated biogas pressure (p_1) and the actual biogas pressure (p_2) with this equation: $P_{\text{actual}} = P_{\text{stove}} \times \sqrt{p_2 / p_1}$. So if the rated stove power is 1.3 kW at a biogas pressure of 16 mbar, and the actual biogas pressure is 8 mbar, the actual stove power will be 0.9 kW.

7.4 Biogas lamps

Similar to cooking stoves, biogas lamp function similarly to other gas lamps. The gas and primary air are pre-mixed and injected in a wicket, where it is combusted. Ignition can either be manual or electrical, with a battery powered spark. A typical biogas lamp consumes some 0.1 m^3 of gas per hour, which would be comparable to a 40W electric light bulb.



Figure 7-11 Biogas lamp

7.5 Use in engines and generators

As indicated in section 3.1, biogas can be used for mechanical or electrical power production by using it in a diesel or spark plug engine. There are some general issues and specific issues that need to be considered when using biogas for this purpose.

General considerations

A first issue to be considered is gas conditioning. As much as possible, water vapour should be removed by cooling of the gas, e.g. by leading it through a buried steel pipe. More importantly, if large quantities of Hydrogen Sulphide (H_2S) are present in the gas, these should be reduced as it may cause corrosion of engine parts. This can be done by leading the gas through a container with rusty iron shavings or pellets (see Figure 7-12). Larger engines require larger desulphurisation units. The shavings should be regularly replaced or regenerated (washed).

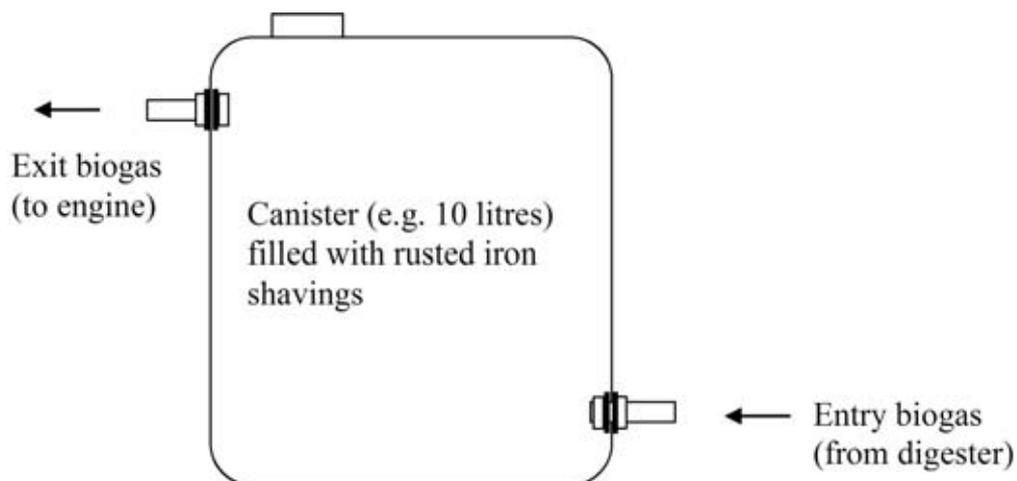


Figure 7-12 Schematic representation of a desulphurisation unit

Regardless of the measures against H_2S , it is recommended to change engine oil more frequently. The Sulphur causes the engine oil to turn acid, which attacks the metal parts of the engine's interior.

The dimensioning of the gas line should be considered. Engines may consume considerable quantities of gas: a 20 kW spark plus engine can consume in excess of 15 m³/h of biogas – in order to limit the pressure drop over 10m of piping to 5 mbar, a 2.5” pipe should be used.

Engine testing: after having successfully connected an engine or generator, it is recommended to run a full test. This means that the engine should be loaded to its full power, which may require a heavy electrical load. Large electric loads can be created using immersion water heaters (typically some 1 kW each). When testing a three-phase generator, it is recommended to connect equal numbers of heaters to each phase.

Diesel engine

In order to supply biogas to a diesel engine, a connection should be made between the gas line and the air inlet of the engine. The combination of under pressure created by the engine and over pressure of the digester result in a considerable gas flow, provided that the pressure drop over the gas supply system is sufficient.

The recommended way to make the connection is to drill a hole in the air inlet pipe (just under the air filter, and welding a threaded pipe (e.g. a hollow thread end) to the air inlet pipe on this point. See Figures below for the process. Note that the air inlet must be removed from the engine, in order to avoid iron shavings to get into the engine cylinder!



Figure 7-13 Marking a center point



Figure 7-14 Drilling the hole



Figure 7-15 The hole in the air inlet pipe



Figure 7-16 Welding the thread to the inlet



Figure 7-17 Finishing the thread connection



Figure 7-18 The valve connection to the air inlet

After the air inlet pipe has been put back onto the engine, a valve can be connected to the thread, and subsequently a hose can be connected to the valve. Make sure that the hose is not allowed to collapse, and that all connections are gas tight (i.e. using teflon tape on threads, and hose clamps on hoses).



Figure 7-19 The gas system connected to the diesel engine, in a test setup.

The engine is now ready to be operated on diesel and biogas. It should be started normally, with the gas valve closed. Once it is running smoothly, the gas valve can be opened carefully. If the engine starts knocking, there is too much gas and the valve should be slightly closed until the knocking stops. Note that there may be different settings for the gas valve at different engine loading rates!

For verifying the gas consumption rate and diesel replacement rate, a test can be performed as follows:

1. The following measuring equipment should be present:
 - a stop watch
 - a gas counter (usually a standard G4 meter suffices)
 - scales for measuring diesel consumption (1g precision),
 - a kWh counter (optionally)
 - a kW meter
 - a frequency meter
 - electrical loads (e.g. immersion heaters) allowing electrical loading upto the typical loading rate of the generator / engine.
2. The diesel should be supplied from a removable fuel tank. The tank should be set up such that it can be weighed using the scales.
3. First, the diesel consumption of the generator / engine should be determined in the base case, i.e. without biogas. This should be done at zero load, (typical) half load and (typical) full load. The procedure is as follows:
 - Start the engine, and let run idle.
 - Connect the electrical load (in case of half and full load tests)
 - Measure and note the kW of the connected electrical loads
 - Measure and note the frequency of the generator
 - Measure and note the weight of the fuel tank and its contents
 - Start the stop watch and let the engine run for 5 minutes
 - Measure and note the weight of the fuel tank and its contents
 - The fuel consumption at the specific load (and frequency) can be calculated as follows: $\text{Consumption (l/h)} = \text{fuel consumed (g)} \times (60 / \text{time (min)}) / 850$
4. The tests should be repeated with the gas valve opened; measuring and noting the gas counter reading directly before and after the test start. Make sure that the dual fuel tests are carried out at the same loads as in the diesel only test! The diesel consumption can be calculated as above; the gas consumption (m^3/h) = gas consumed (m^3) x (60 / time (min)).
5. For each loading rate, the percentage of diesel replaced and the replacement rate (l/m^3) can be calculated:
 - Diesel replacement (%) = $1 - \text{diesel consumption with gas (l/h)} / \text{diesel consumption without gas (l/h)}$
 - Diesel replacement rate (l/m^3) = $(\text{diesel consumption without gas (l/h)} - \text{diesel consumption with gas (l/h)}) / (\text{biogas consumption (m}^3/\text{h)})$
6. Optionally, for each test, the efficiency of the engine can be calculated: Efficiency (%) = $(\text{load (kW)} \times \text{time (min)}) \times 60 / (\text{diesel consumption (l/h)} \times 10 + \text{biogas consumption (m}^3/\text{h)} \times 5.5)$.

In Annex A there is a table that can be used for the measurements.

Spark plug (biogas) engine.

This type of engine has already been modified to operate on biogas⁵, so it is merely a matter of connecting the gas supply line to the engine.

⁵ Modifying gasoline engines is delicate work; it has not been included in this manual.

8 COST-BENEFIT ANALYSIS

For the purpose of the cost-benefit analysis, the costs of producing biogas with two small (6m³) and one large (60m³) biogas system have been determined, in order to make a comparison with the financial benefits of a number of biogas applications. The figures are based on actual costs incurred during digester installation in rural Mozambique, although some modifications have been made to correct location-specific costs (e.g. transport).

8.1 Biogas production costs

Investment costs

The investment in the different biogas systems is presented in Table 8-1 below. Note that some cost items are depending on the location of the biogas system, particularly transportation costs.

Table 8-1 Investments in different biogas systems

System / cost component	Unit	FD 6m ³	PF 6m ³	PF 60m ³
Biogas system size	m ³	6	6	60
Daily biogas output	m ³ /d	1.5	1.5	15
Reactor costs	EUR	279	359	1,529
Cement / sand	EUR	448	95	178
Connections	EUR	168	190	793
Labour	EUR	329	97	246
Transport	EUR	147	205	891
Start-up (water and dung)	EUR	68	68	675
Total system costs	EUR	1,439	1,014	4,312
Total costs per m ³ system	EUR/m ³	240	169	72

Note: FD = floating dome; PF = plug flow

The table shows that on a smaller scale, plug flow systems are somewhat cheaper than floating dome systems, particularly due to the smaller cost of cement and labour. Further, the plug flow systems show a considerable scale advantage: at a factor 10 scale increase, the investment costs increase with a factor 4.25. It should be noted that the scale advantage is very limited in the case of floating dome systems, as large systems would require a modular setup that has very limited scale advantages.

Financial costs

The investment costs presented above can be translated to annual costs by defining depreciation and a (fictional) interest rate on the investment. The resulting annual costs are presented in Table 8-2 below. A 10 year depreciation rate and 10% interest rate are used in the calculations.

Table 8-2 Financial costs

System / cost component	Unit	FD 6m ³	PF 6m ³	PF 60m ³
Total system costs	EUR	1,439	1,014	4,312
Annual depreciation	EUR/a	144	101	431
Interests	EUR/a	90	64	271
Total financial costs	EUR/a	234	165	702

Operational costs

Table 8-3 below lists the typical operational costs of the three different types of digester.

Table 8-3 Operational costs

System / cost component	Unit	FD 6m ³	PF 6m ³	PF 60m ³
Labour	EUR/a	159.69	159.69	319.38
Animal dung	EUR/a	37.33	37.33	373.30
Organic waste	EUR/a	62.22	62.22	622.16
Water	EUR/a	199.09	199.09	1,990.91
Maintenance	EUR/a	43.18	30.42	129.35
Total operational costs	EUR/a	458.32	458.32	3,305.74
Total costs (per day)	EUR/d	1.26	1.26	9.06

The figures in the table are calculated with the following assumptions:

- Labour is calculated at a going rate of 3.5 EUR/d, the approximate official minimum wage in Mozambique. Daily labour requirements are 1 h/d for the smaller systems and 2 h/d for the larger unit.
- Dung costs are calculated at a rate of 30 EUR/t which is based on actual price of dung ex transportation fee. It is assumed that dung represents 50% of the input material.
- Organic waste (e.g. jatropha presscake) is assumed to have a price of 50 EUR/t.
- Water costs are calculated at a rate of 10 EUR/m³.
- Maintenance is calculated as a fixed percentage (3%) of the initial investment per year.

The table shows that water is a major cost item for all systems. For the smaller systems, labour is the second largest cost item. Feedstock and maintenance are relatively small cost items.

Total costs

The figures presented above combine in the total cost overviews presented in Table 8-4 below.

Table 8-4 Total costs of biogas production

System / cost component	Unit	FD 6m ³	PF 6m ³	PF 60m ³
Financial costs	EUR/a	234	165	702
Operational costs	EUR/a	458	458	3,306
Total costs	EUR/a	693	623	4,007
Total costs	EUR/m ³	1.26	1.14	0.73

Main conclusions that can be drawn are that on a smaller scale, plug flow systems are slightly cheaper than floating dome systems, due to the smaller investment (financial) costs. The scale advantage of the plug flow reactor is considerable: biogas production costs are 36% lower in the large scale case.

8.2 Value of the biogas

The eventual value of the produced biogas largely depends on the type of end use of the gas, and on the specific nature of practices it changes. Using biogas as a cooking fuel may result in less benefits in comparison to its use as an engine fuel; however, replacing fuelwood that is used inefficiently (e.g. on a 3-stone cooking fire) may result in

considerable wood savings, and thus in higher returns than when a more expensive cooking fuel like charcoal is being replaced.

Table 8-5 presents an overview of a number of fuels that can be replaced with biogas.

Table 8-5 Approximate cooking fuel replacement values

Fuel / stove	Replacement biogas	Fuel price	Financial return
Wood 3-stone	0.21 m ³ /kg wood	0.11 EUR/kg	0.52 EUR/m ³ biogas
Wood improved stove	0.43 m ³ /kg wood	0.11 EUR/kg	0.26 EUR/m ³ biogas
Charcoal	1.07 m ³ /kg charcoal	0.21 EUR/kg	0.20 EUR/m ³ biogas
Butane gas	2.89 m ³ /kg butane	1.59 EUR/kg	0.55 EUR/m ³ biogas
Diesel	2.5 m ³ /l diesel	2.21 EUR/l	0.88 EUR/m ³ biogas

8.3 Analysis

For the analysis of costs and benefits of the different biogas systems, first a distinction will be made to the specific conditions of a biogas system as far as these have a consequence on the actual expenses on its operation. Small household systems for example will likely use their own feedstock resources (dung, kitchen waste) and water source, which will then not result in expenses on these cost items. Also, when family labour is used for the operation of the unit, there might be no cost involved as alternative costs of this labour is usually low. Larger systems on the other hand, could be placed near animal farms (no dung expenses) or institutional kitchens (no expenses on organic waste).

A further issue is the valorisation of the digestate as an organic fertiliser. Although there might be little market for this, the replacement value of the slurry could be considered equal to possible costs for the dung. In some cases, the slurry is actually sold at a higher price than the comparable amount of dung.

In order to take these conditions into consideration, the biogas production costs are calculated not only as the complete amount, but also in case there are no expenses on feedstock and water, and in case there are no expenses on feedstock, water or labour. The resulting costs are shown in Table 8-6 below.

Table 8-6 Investments in different biogas systems

System / cost component	Unit	FD 6m ³	PF 6m ³	PF 60m ³
Total costs	EUR/a	693	623	4,007
Total costs (ex fs / water)	EUR/a	437	355	1,150
Total costs (ex fs / water / labour)	EUR/a	277	195	831
Total costs	EUR/m ³	1.26	1.14	0.73
Total costs (ex FS / water)	EUR/m ³	0.80	0.65	0.21
Total costs (ex FS / water / labour)	EUR/m ³	0.51	0.36	0.15

In Figure 8-1 these costs are plotted in a bar diagram, and the financial returns from the different biogas applications are added as lines. Basically, the figure shows for each biogas application under which condition the benefits are larger than the costs: this is the case where the corresponding bar remains **below** the red line of the specific biogas application.

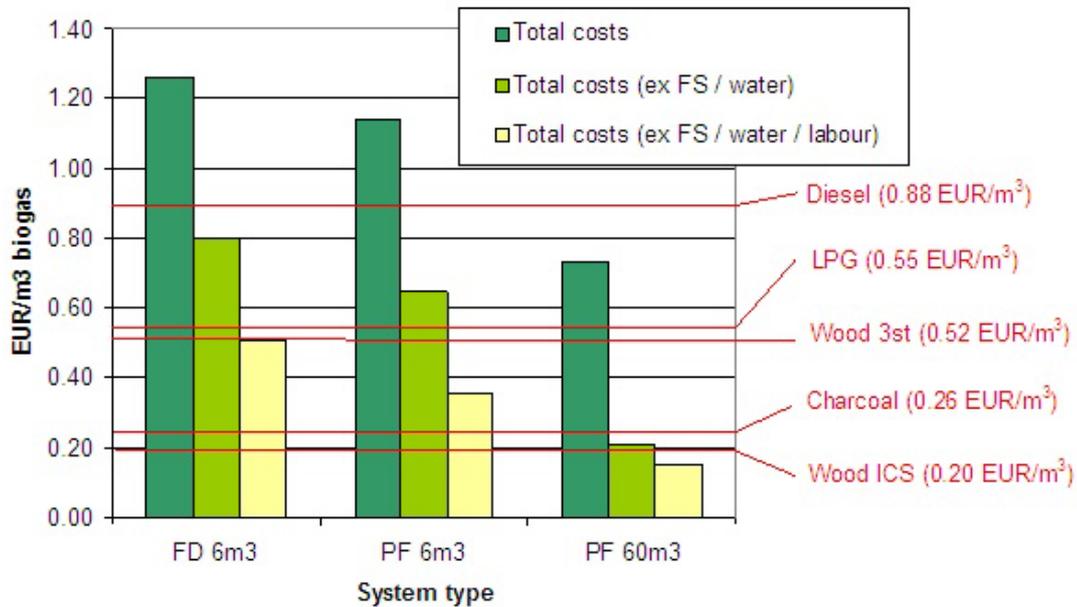


Figure 8-1 Costs and benefits of different combinations shown in one diagram

8.4 Conclusions

The following conclusions can be drawn on the costs of biogas systems:

- On the 6m³ scale, investment costs of plug flow systems are somewhat lower than those of floating dome systems.
- Plug flow systems show a considerable scale advantage with respect to investment costs and operational costs.
- Water is a major operational cost item for all systems. For the smaller systems, labour is the second largest cost item. Feedstock and maintenance are relatively small cost items.

With respect to the comparison of costs and benefits of biogas production:

- Replacing diesel in a diesel engine is feasible in all cases except in the two small-scale biogas cases when all costs are accounted;
- Replacing LPG or fuelwood used on 3 stones is feasible for smaller systems if feedstock, water and labour are not accounted for; for the large unit, labour costs can be covered by the benefits.
- Replacing charcoal is only feasible for a large scale biogas unit when feedstock and water costs are not accounted for.
- Replacing fuelwood in an improved cooking stove (ICS) is possible only when using a large biogas system, and then only when feedstock, water and labour are not accounted for.

Annex A: Table for diesel engine / dual fuel testing

Test:	Load (kW)	Time (min)	diesel1 (g)	diesel2 (g)	biogas1 (m ³)	biogas2 (m ³)	diesel cons (l/h) ¹	gas cons (m ³ /h) ²	diesel replaced (%) ³	Replacement rate (l/m ³) ⁴	Efficiency (%) ⁵
1. Diesel, no-load					-	-		-	-	-	
2. Diesel, half load					-	-		-	-	-	
3. Diesel, full load					-	-		-	-	-	
4. Dual, no-load											
5. Dual, half load											
6. Dual, full load											

¹ Diesel consumption (l/h) = (diesel1 (g) – diesel2 (g)) x (60 / time (min)) / 850

² Biogas consumption (m³/h) = (biogas1 (m³) – biogas2 (m³)) x (60 / time (min)).

³ Diesel replacement (%) = 1 – diesel consumption with gas (l/h) / diesel consumption without gas (l/h)

⁴ Diesel replacement rate (l/m³) = (diesel consumption without gas (l/h) – diesel consumption with gas (l/h)) / (biogas consumption (m³/h))

⁵ Efficiency (%) = (load (kW) x time (min)) x 60 / (diesel consumption (l/h) x 10 + biogas consumption (m³/h) x 5.5)