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Final Report:

The arbi Plug-Flow Digester in Tanzania

A medium-size Biogas Plant for Developing Countries

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The arbi Plug-flow Digester in Tanzania

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Imprint

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Abbreviations:

ABR	anaerobic baffled reactor
DM	dry matter (after drying wet biomass to constant weight)
HRT	hydraulic retention time (time the digestate remains on average inside the digester)
LR	loading rate (amount of OM fed daily per m^3 of reactor)
OM	organic matter (percentage of dry matter)
TSH	Tanzanian shilling

Abstract

On the area of the catholic monastery in Mivumoni in north-eastern Tanzania, a novel biogas plant has been planned and realized. The target was covering the energy need for cooking and laundry for around 500 persons after the final completion of the school extension. So far, only very small and simple biogas plants have been built generally in developing and emerging countries, digesting mainly highly diluted animal excrements, thus producing only little biogas per digester volume. Therefore it seemed to be reasonable to build in Mivumoni a plug-flow reactor, such as developed by W. Jewell (1980) in the 70-ties and adapted by Kompogas for the digestion of solid household wastes. An innovation of the Mivumoni plant is the "U"-shaped substrate flow allowing an easy re-inoculation as well as saving significantly expensive material for the construction of the digester walls.

The digester has a volume of 100 m^3 and is covered by a plastic film made out of fibre-reinforced PVC. Kompogas realized while digesting (semi-)solid wastes in pluf-flow reactors that it is advantageous to stir sporadically the digester content very slowly and radially in order to open some pathways for gas bubbles. Therefore, within the first half of the digester, a stirring device has been installed, which is rotated by means of a bike with a gear transmission ratio of minimal 40:1.

Compared to conventional biogas plants, the arbi plug-flow digester shows different, not negligible advantages, such as: 1. There is no restriction regarding the construction size; it closes the gap between small, simple plants and large industrial plants (scalable design). 2. The reactor is run preferably with biomass containing 12-20 % dry matter; this increases on the one hand the biogas yield per reactor volume significantly, reducing on the other hand the need to add (scarce) water while digesting solid waste such as residues from harvesting or market wastes, 3. In contrary to the completely mixed systems, in plug-flow systems the hydraulic retention time is defined within narrow confines, thus increasing the degradation and the specific gas yield. 4. Thanks to the defined retention time there is an optimal and reliable sanitation. 5. The "U"-shape permits easy re-inoculation, what allows increasing the loading rate without washing out the methanogenic bacteria. 6. In case of maintenance, there is an easy access into the interior by simply removing the cover. 7. The input of sediments is reduced lowering the rate of maintenance intervals.

The whole gas system of the Mivumoni plant is run at very low gas pressures of 2-3 mbar. This is possible because of using cheap sinter nozzles for cooking and for laundry. The low gas pressure has a positive effect reducing gas losses in the long pipelines in the case of a gas leakage.

Unfortunately, there is currently still a very low gas need in Mivumoni. Therefore it was not yet possible yet to test high loading rates without overproduction and air pollution by methane emissions. Analytical data on the present situation are presented. Taking account of the already existing practical knowledge, one may expect on a daily basis in Mivumoni more than 1.5 m^3 biogas pro m^3 reactor volume without further ado after increasing the loading rate. The price of one m^3 digester volume will be less than 200 US$ respecting the experiences made. This allows writing off the investments (including a gas motor) already after 3 to 6 years – depending on the local price structures and the available substrates - when producing electricity by the gas from a digester size of 100 m^3.

For economic reasons, it is recommended to produce in Mivumoni in addition to the heat also electricity. The project team shares the opinion that it is most important to construct biogas plants in developing and emerging countries, which can handle also solid biogenic wastes - in addition to the propagation of "cheap" mini-plants. This will permit to use the huge potential of waste, which has not already passed through the intestine of an animal, such as wastes from households, food markets and food industries, which today are dumped causing large environmental problems. In this context it seems to be reasonable to organize more seminars and congresses for a better exchange of knowledge and sensitisation for environmental protection.

Zusammenfassung

Auf dem Gelände des katholischen Klosters in Mivumoni im Nordosten von Tansania wurde eine neuartige Biogasanlage geplant und gebaut. Aufgabe war, im Endausbau des Klosters und der dazu gehörenden Schulen auf eine einfache Art die Energie zum Kochen und Waschen für etwa 500 Personen bereit zu stellen. Da in Entwicklungs- und Schwellenländern hauptsächlich sehr kleine Einfachanlagen in Betrieb sind, die vorwiegend mit stark verdünnten Exkrementen von Tieren betrieben werden und daher nur einen sehr kleinen Biogasertrag pro Fermentervolumen erzeugen, wurde der Bau eines Pfropfstromreaktors ins Auge gefasst, wie er schon von Jewell (1980) in den 70-er Jahren entwickelt und von Kompogas für die Behandlung fester Haushaltsabfälle angepasst worden war. Als Neuheit plante man einen „U“-förmigen Substratfluss, was eine einfache Rückimpfung ermöglicht und gleichzeitig Material für den Bau von Behälterwänden spürbar reduziert.

Der Fermenter hat ein Volumen von 100 m^3 und ist mit einer gewebeverstärkten PVC-Folie abgedeckt. In Anlehnung an Kompogas, wo sich zeigte, dass bei hohem Trockensubstanzgehalt es vorteilhaft ist, durch sporadisches, sehr langsames, radiales Rühren Wege für die Gasblasen zu öffnen, wurde in der ersten Fermenterhälfte ein Rührwerk installiert, das über ein Fahrrad mit einer Übersetzung von mindestens 40:1 angetrieben werden kann.

Der arbi Propfstrom-Fermenter hat gegenüber konventionellen Anlagen verschiedene, z.T. sehr grosse Vorteile: 1. Er ist skalierbar, also nicht in der Grösse beschränkt und kann daher die Lücke zwischen einfachen Kleinanlagen und industriellen Grossanlagen schliessen. 2. Der Fermenter soll vorzugsweise mit Biomasse, die 12-20 % Trockensubstanz aufweist, betrieben werden, was einerseits die Gasproduktion pro m^3 Reaktorvolumen stark erhöht und andererseits den Einsatz von (knappem) Wasser stark reduziert und so die Vergärung von festen Abfällen wie Ernteresten oder Marktabfällen ermöglicht. 3. Da – anders als in einem voll durchmischten Reaktor – die Aufenthaltszeit im Fermenter in engen Grenzen definiert ist, ist der biologische Abbau optimal und der Gasertrag erhöht. 4. Dank definierter Aufenthaltszeit weist der Fermenter eine optimale Hygienisierung auf. 5. Dank der „U“-Form ist Rückimpfen möglich, was erlaubt die Raumbelastung zu erhöhen ohne die methanbildenenden Bakterien auszuwaschen. 6. Durch Entfernen der Folie ist ein einfacher Zugang ins Innere möglich. 7. Der anorganische Sedimenteintrag (Kies, Sand etc.) wird reduziert, was das Intervall von Revisionen stark reduziert.

In Mivumoni wird das ganze System bei sehr niederen Gasdrücken von 2-3 mbar betrieben. Dies ist möglich dank des Einsatzes von billigen Sinterdüsen zum Kochen und Waschen. Der tiefe Gasdruck wirkt sich positiv aus bei den langen, verschiedentlich zusammengefügten Gasleitungen, wo immer die Möglichkeit eines kleinen Lecks besteht.

Unglücklicherweise ist der Gasbedarf in Mivumoni noch sehr klein. Daher konnte die Anlage noch nicht auf Volllast hochgefahren werden. Betriebsdaten über die aktuelle Situation werden vorgestellt. Unter Berücksichtigung des vorhandenen praktischen Wissens wird erwartet, dass in Mivumoni täglich ohne weiteres über 1,5 m^3 Gas pro m^3 Reaktorvolumen erzeugt werden können. Der Preis von einem m^3 Reaktor wird bei weniger aufwändiger Bauweise spürbar unter 200 US$ liegen, was erlaubt, bei Stromproduktion einen Reaktor dieser Grösse inklusive Gasmotor – je nach lokalen Preisstrukturen und Substratangebot – in 3 bis 6 Jahren zu amortisieren.

Es wird empfohlen, in Mivumoni neben Wärme auch Elektrizität zu produzieren. Nach Ansicht der Autoren ist es wichtig, dass sich die Entwicklungsländer und NGO’s von der einseitigen Propagierung von „billigen“ Kleinstanlagen lösen und auch Technologien einsetzen, die ermöglichen, das riesige Potential an - nicht vorgängig bereits durch Tiere verdauten - biogenen Abfällen zu nützen, welches zurzeit auf sehr stark umweltbelastenden Wegen entsorgt wird. In diesem Kontext ist es wichtig, den Erfahrungsaustausch mit Entwicklungs- und Schwellenländern durch Seminare und Tagungen zu fördern und die Menschen für Umweltprobleme zu sensibilisieren.

Initial position

The monastery in Mivumoni, Tanzania

In December 1966, the Tanzanian Franciscan sisters of the monastery “St. Anna” in Gerlisberg, Lucerne (Switzerland), founded their first settlement in Tanzania in Maua, at the slopes of Kilimanjaro. Further settlements followed in Arusha, Sanya Juu, Marangu and finally 2006 in Mivumoni.

Mivumoni (or on Google Earth: “Nivumomingi”) is located in the North-East of Tanzania, at the dirt road from Pangani to Muheza (see Appendix 6, p. 73: Pictures of Google Earth). With help from Switzerland, a little village has grown, where the sisters run a kindergarten, a school for adults, a hospital ward for the neighborhood as well as an ever growing farm, which is not only used for producing crops that can be sold on the market, but also for teaching and educational purposes. Today, the agriculture comprises a herd of about 180 cattle (including 7 milking cows), sheep, pigs, chicken, ducks and rearing of rabbits. On the fields grow different vegetables, pineapples, oranges, papaya, hibiscus as well as a plantation of teak and other woods.

The development of the agricultural site is supported – between others - by Richard “Richi” Balmer, a retreated engineer for tropical agriculture, and Leongard “Leo” Zitron, a retreated electrical engineer. Both live in Switzerland, but they spend several months each year at the monastery. Harald Frey, a Swiss architect living now in Tanzania, is engaged by the monastery and is responsible for the construction of the different buildings and the biogas plant.

The energy supply of Mivumoni

So far, Mivumoni has not yet been connected to the electrical grid of Tanzaniat; however, the connection is planned for the near future. In order to reduce the use of diesel for running a generator which generates the electricity necessary mainly for pumping the ground water and the liquid manure (see picture on the cover page), Leo installed photovoltaic panels on a roof charging batteries. Because the sisters needed a lot of firewood for cooking for themselves, the employees and for the boarding school, Richi had the idea to build a biogas plant to be run with the organic wastes of the farm.

In 2008, Richi established a contact to eBio, a company constructing biogas plants in Switzerland. In October 2008, eBio approached arbi in this context, because arbi had already built several biogas plants of different technologies in developing countries. Thereupon, a planning group was established, that met regularly. The group came to the conclusion that it was not reasonable to transfer Swiss technology 1:1 to Tanzania, because of the high costs of Swiss technology and also because of high risk of malfunction due to missing parts in case of trouble.

Looking at the simple reactor designs currently in use in developing countries, the group came quickly to the conclusion that a new design was necessary, which was able to handle larger amounts of substrate input than the “classical” plants in the tropics. Therefore it was decided to develop an “intermediate” plant, i.e. a technology in between high tech plants in Europe and very simple plants in developing countries. However, this needed some developing work, which was too expensive for the monastery. As the results of the working group showed a lot of open questions, arbi proposed to submit a demand for supporting a part of the developing costs by Repic (www.repic.ch), an interdepartmental platform of the Swiss government for supporting energy projects in developing and transition countries. Finally, Repic agreed to support the planning and construction of a biogas plant from April 2011 on. This report describes the construction and first experiences while operating the plant.

Biogas technologies in developing countries

In general, there is a warm climate in developing countries. This allows constructing simple biogas plants without heating the substrate to mesophilic temperature (~36° C). Because of missing infrastructure, such as stores to buy sophisticated technical parts, and because of lacking money, the biogas plants have to be as cheap as possible using construction materials, which are locally available. Due to the different education level in technology understanding it is advisable to build simple installations that can be easily understood, built and repaired.

In contrary to biogas plants in developed countries, these plants are usually (very) small and produce mainly biogas for cooking substituting charcoal, firewood, dried animal dung or kerosene. Because of the small sizes, producing electricity with co-generation is not possible – with the exception of some plants built by multi-national industries with European standards.

Subsequently, the biogas plant designs actually in use in developing countries will be described and their advantages and disadvantages will be discussed.

The Chinese fixed dome digester

The fixed dome digester – or also: “water pressure digester” – was originally developed in China. Today, it is spread all over the world in many different variations. Its main characteristic is a digestion chamber covered by a robust dome out of bricks, cement and/or concrete. There are an inlet and an outlet pit. The gas produced is stored within the dome, pressing the digestate up into the in- and outlet pits (red arrows in Fig. 1; the in- and outlet pits may be differently constructed depending on the design; e.g. the inlet pit may be deeper etc.).

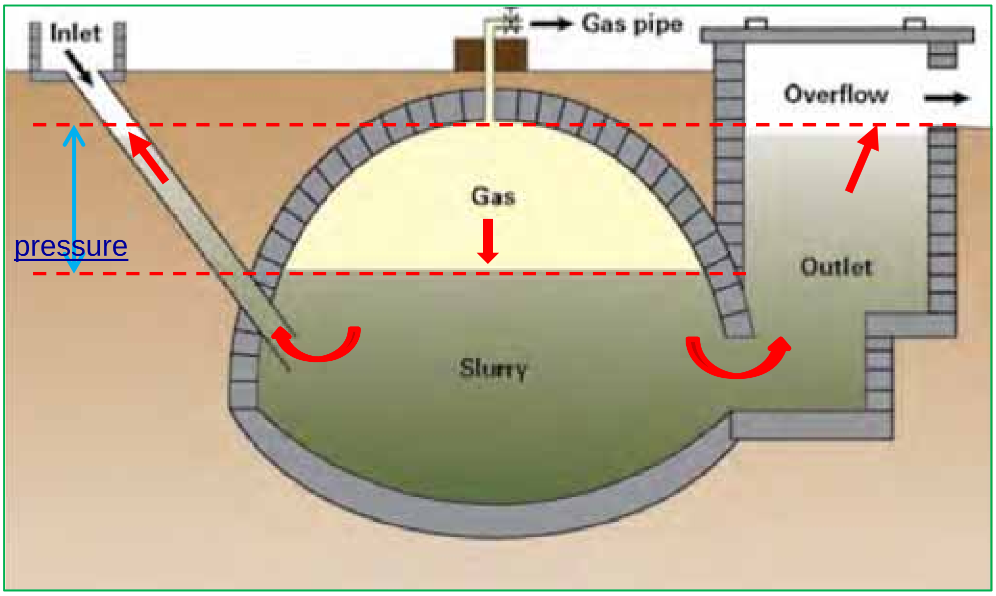


Fig. 1: *Cross section of one possible design of a fixed dome digester (Vögeli et al. 2014, modified)*

When gas is used, the levels in the in- and outlet pits sink and the level inside the digester rises. The gas pressure drops and may finally reach 0 mbar, when the digestate reaches the same level in all containers.

More than 10 million of such fixed dome digesters have been built in China. In Africa the number will be actually around 70’000 (extrapolation of data of Heedge (2015) for whole Africa including the north). This digester type is propagated in Africa, South-East Asia and South America by different development aid organizations, because it is cheap and may be constructed with local materials. Unfortunately, a very high percentage of the plants do not perform well or are even out of service. There are different reasons causing this fact:

The technical failure is mainly caused by the construction of the fixed dome, which has to be gas tight at different gas pressures: If biogas is produced during a period of no energy need, the slurry is pressed up into the pits by the gas accumulating in the dome, causing a very high gas pressure of up to 100 mbar or even more (Fig. 1). It is very difficult building a dome with local materials, which remains gastight under these ever changing pressure conditions: It is nearly impossible to prevent the formation of fine cracks in the wall of the dome during plant operation. These cracks may cause considerable gas losses depending on their sizes and the gas pressures.

The technically difficult construction of the dome (Fig. 2) is the reason that fixed dome digesters are limited in size: Very seldom the size of the digester exceeds 10 m^3; usually the digesters contain 4-8 m^3 of substrate diluted with water. If larger sizes are needed, several digesters have to be built.

Fig 2:
Construction of a large fixed dome plant
https://www.flickr.com/photos/gtzecosan/

The digesters are usually run with excrements of animals without agricultural wastes, such as straw, grass, leaves or peels of fruits, in order to hinder the formation of a (thick) scum layer inside the digester (solids ascending to the surface of the liquid by the help of little gas bubbles). However, excrements are ***not*** a good substrate for biogas plants; they show a very low gas yield in comparison to fresh organic matter, because they have already passed an intestine of an animal, where the easily degradable compounds have already been digested. In addition, for reducing the troubles with scum formation during operation, the excrements are usually diluted with water, what reduces their biogas potential even more (water does not produce any gas!).

Furthermore, it is hardly possible to prevent the accumulation of sediment within the digester. If – after 2-3 years – the sediments reduce the active size of the digester noticeably (or if a thick scum layer has been formed), the digester has to be cleaned out. This procedure is in most cases not an easy job, because the access into the digester is not comfortable at all….! This is another reason, why some installations stop being fully functional after a certain time.

Another reason for malfunctioning is poor understanding and training of the operators: Own FOS/TAC-measurements at three biogas plants in Bali, Indonesia, showed that two plants did not receive enough food, while the third one was overfed (Nett et al., 2014). All three plants could produce significantly more gas, if they were run properly. Table 1 shows the advantages and disadvantages of the fixed dome digester:

Fixed dome digester	
application	Manly for diluted animal excrements
advantages	
costs	Cheap
materials	Locally available; creates local jobs
disadvantages	
construction	Difficult to construct a dome that remains gastight over a lifespan. Special covering of the inside of the dome necessary (beeswax etc.)
access	Difficult access into the digester in case of scum or sediments (some design even no access!)
size	Limited in size, because: the larger the dome, the higher the probability of cracks
mixing	More or less completely mixed because of constant moving the substrate from the digester into the pits and back
hygiene	Not optimal because of mixing: some fresh material may be exported quite quickly, thus exporting pathogens before they are killed
water	Water necessary for dilution (problem in dry areas)
gas yield	Low because of: a.) mainly excrements, b.) dilution with water, c.) no defined retention time (some material remains too long and some too short inside because of mixing), d.) repeated contact of the digestate with oxygen when pressed into the pits
gas pressure	Varying: sometimes extremely high, sometimes (too) low
gas losses	High risk at high pressures
substrate	Not suited for particular compounds such as straw, vegetable wastes etc., which would increase the gas yield significantly (danger of scum formation)

Tab. 1: *Properties of a fixed dome digester*

The Indian floating drum digester

The floating drum (= floating dome) digester has been developed in India. The digester has a vertical cylindrical form and is built underground with in- and outlet pit. It is covered by a gasholder out of metal or of plastic floating in the digestate (Fig. 3). Within the gasholder, there may be some radius arms fixed at the central tube (blue lines, Fig. 3), which allow the destruction of a possible scum layer by turning the gasholder using the handles (Fig. 4). A construction of brickwork (pink in Fig. 3) holds the gasholder in the lowest, i.e. empty position and hinders at the same time the escape of too much gas between gasholder and wall.

In some (more sophisticated and thus more expensive) cases, the gas dome may float in a separate, concentrical containment filled with water in order to prevent gas bubbles escaping between the digester wall and the gasholder. However, that kind of construction shows the disadvantage that the scum layer destruction is impeded.

The gas pressure is constant; extremely high pressures as observed in fixed dome digesters do not occur (the pressure is given by the difference of the liquid level outside and inside the digester; see the dotted red lines in Fig. 3). The pressure may be defined according to the needs of the burners by putting the right amount of weight on the gasholder.

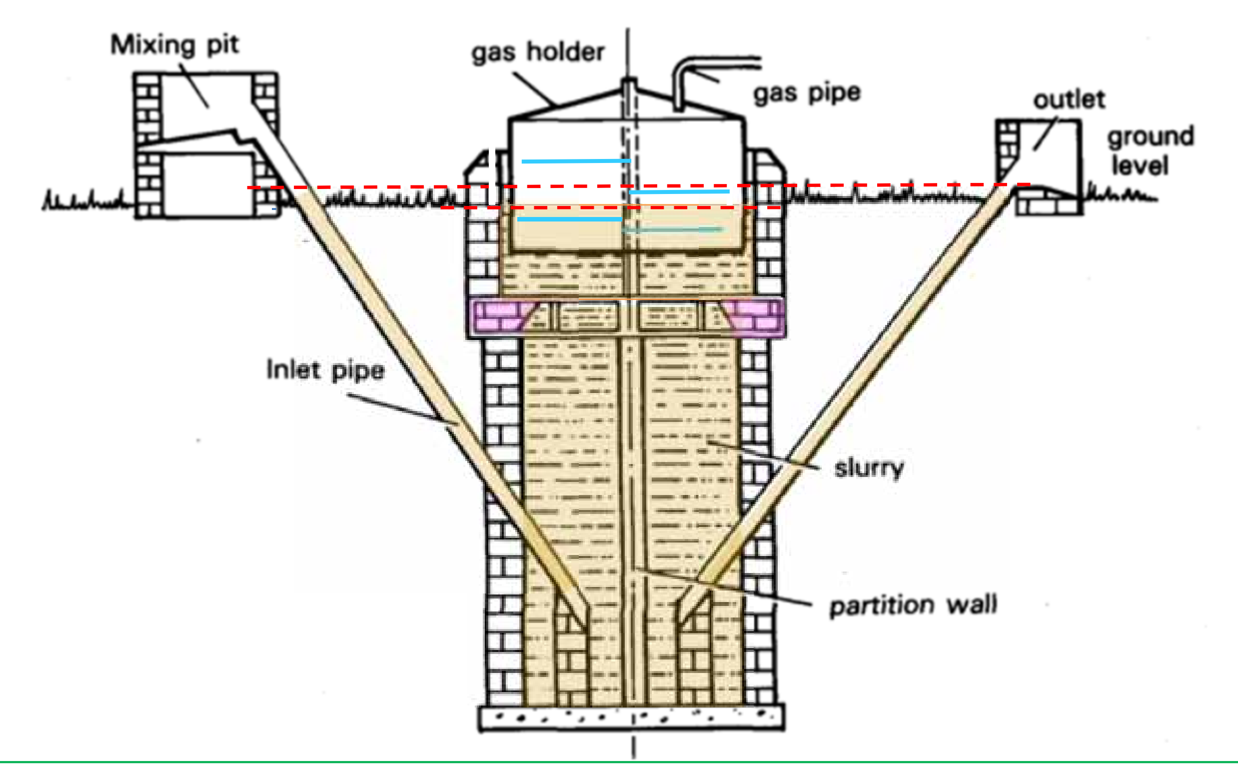


Fig. 3: *Cross section of one possible design of a floating dome digester (colors: see text; modified sketch of* http://www.fao.org/docrep/010/ah810e/AH810E13.htm*)*

The digester room may be separated by a partition wall impeding a shortcut of fresh material being exported too quickly after entering into the digester. Therefore, the hydraulic retention time is better defined than in a (+/- completely mixed) fixed dome reactor. Table 2 shows the advantages and disadvantages of the floating drum digester.

Fig. 4: *Floating drum digester with handles to turn around the gasholder for scum destruction* http://biogas-technology.blogspot.ch/2013/06/fixed-dome-digester-construction-manual.html

Floating drum digester	
application	Mainly diluted animal excrements including some solid particles
advantages	
size	Less limited than fixed dome (up to over 50 m^3)
substrate	May also treat substrate with particular carbon compounds (some straw etc.) because of the device for scum layer destruction
gas yield	Better because of small probability to have shortcuts of fresh input leaving to early and because of less limitation because of the substrate properties
gas losses	Minimal; eventually some between gasholder and wall
gas pressure	Constant and adjustable; very low, if desired.
gas reserve	Easy by looking at the position of the gas holder (in fixed dome: estimation observing the gas pressure)
access	Possible by removing the gasholder (however not very comfortable: relatively narrow and very deep)
hygiene	Better as less fresh material may be exported too quickly exporting pathogens before they have been killed
materials	Locally available; creates local jobs
disadvantages	
costs	Construction and especially the solid gasholder are relatively expensive; regular preventive maintenance of the gasholder causes operation costs due to the coating material and interruptions of the operation
longevity	Gasholders made out of metal have to be treated regularly against corrosion; plastic may be less stable and attacked by UV-light.

Tab. 2: *Properties of a floating drum digester*

Several variations of the fixed dome and the floating drum digester as well as hybrids of the two designs discussed have been built so far. Several new designs use - like the fixed dome digester - the work of the evolving gas for mixing. In Tanzania the German organization "Ingenieure-ohne-Grenzen" is developing a kind of rectangular fixed dome digester (Ingenieure ohne Grenzen, 2012) and the Dutch company SimGas BV has erected a factory producing small biogas plants out of solid plastic. Both designs press – when storing the gas – the anaerobic slurry into a pit, where there is contact with air (oxygen!).

Another design is "Supergas" from Superflex, a Danish development, which is a fully enclosed concept without contact to air. It is somehow a simple variation of the hydraulic reactor (AAT, 2015). The installation consists of two plastic balloons, where the slurry is pressed into the upper one and at a certain gas pressure a simple valve opens, allowing the gas to flow into the upper balloon and thus the slurry to flow rapidly back into the lower one mixing the content (von Borries, 2010).

Figure 5 shows a simple drum digester, which is distributed by TakamotoBiogas in Nairobi, Kenia (www.takamotobiogas.com). The farmer running the plant collects and loads dung mixed with water into the digester and uses the slurry for fertilizing his fields. He just pays for the biogas by loading credit on his cellphone. The biogas is piped through a gas meter updated by Schutter Energy Ltd., who alerts the farmer when the biogas credit is low. The plant is installed by the company. This concept is a nice example of combining low technology with high-tech solutions, which are available today, in order to find new models for financing a biogas plant (see www.youtube.com/watch?v=CWHOVbJtmqQ and .../watch?v=8ZM0fiwu0Is)

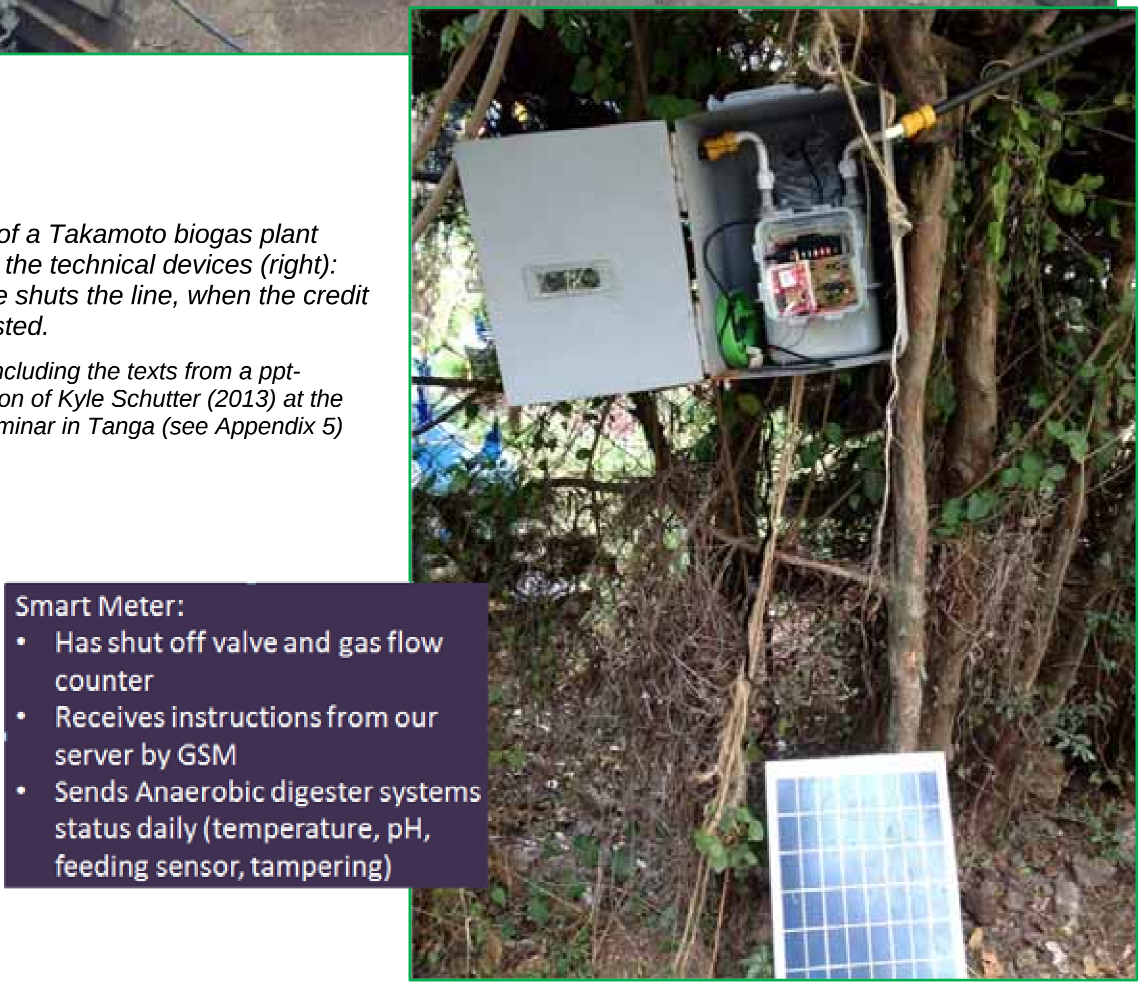


Fig. 5:

Pictures of a Takamoto biogas plant including the technical devices (right): The valve shuts the line, when the credit is exhausted.

Pictures including the texts from a ppt-presentation of Kyle Schutter (2013) at the biogas seminar in Tanga (see Appendix 5)

The anaerobic baffled reactor (ABR)

Anaerobic baffled reactors (ABR) are mainly used for sanitation reasons: The ABR is a – preferably long and rectangular - horizontal tank, where the substrate enters at one front side and leaves on the opposite one. The reactor is separated by several walls erected alternately from the ground and from the top forcing the scum layer and the sediment to remain inside enclosed in the segments.

The ABR shows a different retention time for the liquid (HRT = hydraulic retention time) and for the solids (SRT = solid retention time). The liquid passes quite quickly through the digester (red arrows, Fig. 6): The small compounds dissolved in the liquid are quickly degraded by the bacteria, which are kept back on the particles of scum and sediment allowing a short retention time for the liquid phase. The solids stay for a long time inside the digester until they are degraded, however.

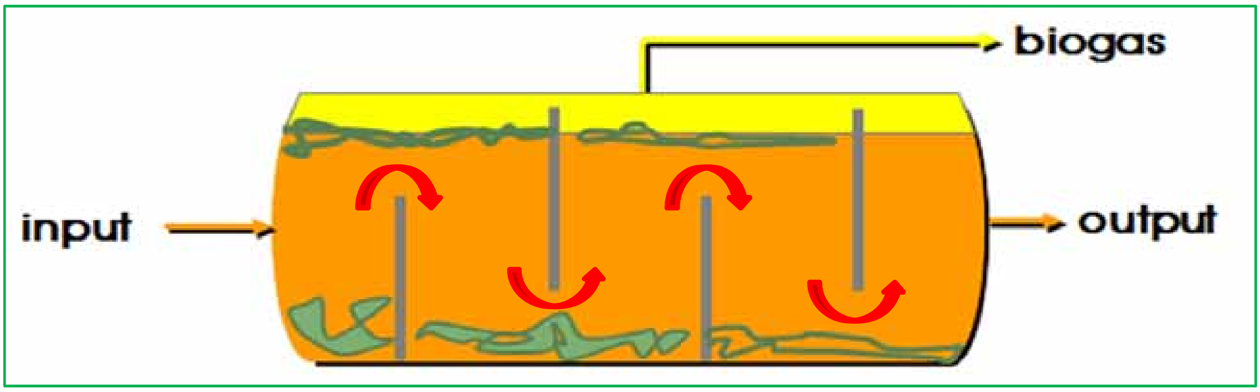


Fig. 6: *Sketch of an anaerobic baffled reactor (green: sediments and scum layer)*

Fig. 7: *Construction of an anaerobic baffled reactor in Ghana (http://www.germantoilet.org/en)*

A big advantage of the anaerobic baffled reactor is the fact that there is no mixing, i.e. it is a plug-flow reactor with different retention times for the liquid and the solids. The input enters on one front side, flows through the reactor and exits on the opposite side. This guarantees a minimal HRT, which is long enough to kill pathogens. Fixed within the sediments and within the scum layer, there are always enough bacteria to destroy the easily degradable compounds within the liquid that passes by. Table 3 sums up the properties of the ABR.

Anaerobic baffled reactor	
application	Especially human excrements (sewage with water)
advantages	
size	Not limited
substrate	Thin liquid phase with solid particles
gas yield	Uses the (evidently low) biogas potential of the substrate optimally, because the slowly degradable matter remains longer inside the digester than quickly degradable dissolved compounds
gas losses	Minimal
bacteria	No danger of exporting too many anaerobic bacteria at high loading rates, because always many bacteria are fixed within the solid matter
gas pressure	Constant
gas reserve	External (possibly balloon)
longevity	Good (but troubles inside the digester difficult to repair)
hygiene	Very good, because of plug-flow of the liquid phase, i.e. defined minimal HRT
materials	Locally available; bricks and much of cement.
disadvantages	
access	Difficult (many [gastight!] manholes necessary, if access has to be possible without destroying parts of the roof)
costs	Quite high because of reinforced concrete roof and many walls
operation	It must be taken care that no non-degradable material (such as sand, inorganic waste etc.) enters into the digester because of accumulation and thus reduction of active size

Tab. 3: *Properties of an anaerobic baffled reactor*

The tubular (plastic) digester

The tubular digester is a simple, flexible tube out of plastic (Polyethylene, PVC, rubber etc.), where the material enters on one front end and exits on the opposite one. I.e. it is a plug-flow digester. Because the tube has only three small openings, i.e. for the input and the output of the digestate and for the gas, the access to the interior is not possible. Therefore, it has to be taken care that there is no formation of scum layer and/or accumulation of sediment.

Tubular digesters are usually run with diluted manure. High loading rates by adding co-substrates (such as vegetable wastes etc.) and by reducing the retention time are not recommended, because of possible wash out of the bacteria and/or scum formation. Figure 8 shows a nice picture of a tubular digester covered with a roof against the UV-radiation of the sun for increasing the longevity of the photosensitive plastic. Table 4 summarizes the properties of the tubular digester.

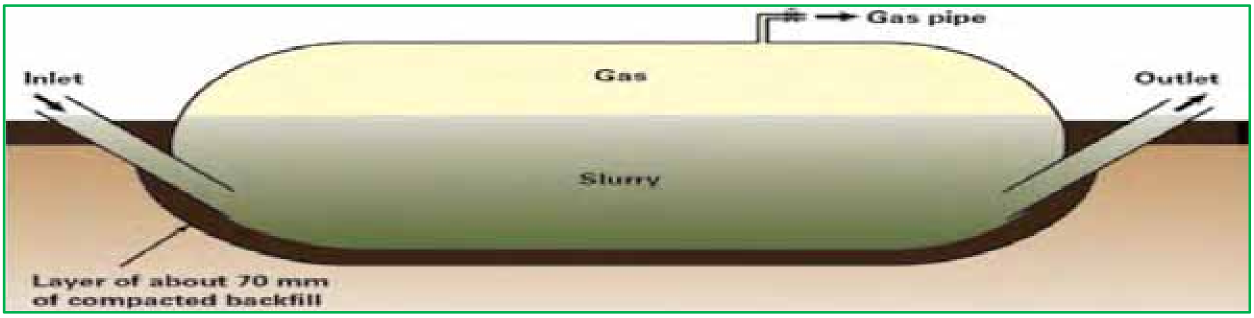


Fig. 8: *tubular digester (Urs Baier, zhaw Wädenswil)*

Tubular digester	
application	Mainly diluted animal excrements
advantages	
size	Limited, but larger sizes than fixed dome possible
substrate	Slurry without large particles
gas yield	Uses the (low) biogas potential of the substrate optimally, because of plug-flow design
gas losses	Minimal (eventually a bit larger with increasing age of the plastic)
hygiene	Good, because of plug-flow of the liquid phase, i.e. defined minimal HRT
costs	Moderate, if a (local?) company has the know-how to produce bags of good quality
disadvantages	
access	Not possible
gas pressure	Varying, if balloon is used for gas storage; eventually external storage necessary
longevity	Plastic of poor quality may be damaged by UV rays
operation	It must be taken care that no non-degradable material (such as sand, inorganic waste etc.) enters into the digester because of accumulation and thus reduction of active size

Tab. 4: *Properties of the tubular (plastic) digester*

The solid waste batch digestion

Solid wastes show in general a very high biogas potential for two reasons: On the one hand, they contain less water and thus a lot more (degradable) organic matter per kg and on the other one, they usually have not passed yet an intestine of an animal (or a human being), where the desired easily degradable compounds have been digested already and therefore are missing afterwards in the digester.

Worldwide, there is a lot of experience digesting sludge with high water content in sewage treatment plants. (There, the main reason is to reduce the sludge volume and not to produce gas!). Therefore, at the beginning of digesting new substrates, all the organic wastes were minced and diluted before “classical” liquid digestion. In Europe, solid waste digestion started only in the late 80-ties and 90-ties of last century; batch digestion such as developed by Ducellier and Isman (1946) was re-discovered in Germany only around 2000. In developing countries, solid waste digestion is not common yet.

arbi constructed already 1983-87 at the agricultural school of Nyamishaba at the Kiwu lake in Rwanda three batch digesters for digesting solid wastes, such as solid manure, straw, harvesting wastes, rotten fruits and vegetable wastes (Edelmann, 1987). Batch digesters are not continuously fed, but filled, closed and emptied after the digestion time of 4-5 weeks. At least three digesters are necessary in order to run them overlapping in regular intervals producing like this always more or less the same total amount of gas. A freshly filled digester is inoculated with bacteria within the liquid kept back behind a grid in one corner of the pit.

The digesters delivered mainly the energy to cook for the staff and the students of the school. The installation worked well until to the civil war in the 90-ies. Figure 9 shows some pictures of its construction and figure 10 a sight of the working plant.

Fig 9:

Top left: construction of 3 rectangular pits (one already working)

Top right: Water seal for the gas tight covering with a plastic membrane

Left: coating the bricks
(Edelmann 1987)

Fig. 10: *working batch digesters for solid wastes (right) at the agricultural school of Nyamishaba, Rwanda (Edelmann, 1987)*

Anaerobic batch digesters for solid wastes	
application	Al kind of (semi-)solid organic wastes (excluded woody material)
advantages	
size	Not limited (size can also be increased by adding more units)
substrate	Solid manure of cattle, swine, chicken etc.; wastes from harvesting, straw, rotten vegetables, fruits etc. (Dry matter content up to > 30-35%)
gas yield	High gas yield per m^3 of reactor and day
gas losses	Minimal (eventually some larger with increasing age of the plastic)
bacteria	Inoculation of the new batch with liquid of the previous digestion
access	No problem
longevity	Good, if chosen the right, UV-resistant material for the balloons (tissue reinforced PVC)
hygiene	Very good, because of defined retention time
costs	Relatively low: local bricks and labor; balloons of good quality may cost some money
fertilizer	There are fewer problems to bring out a solid digestate than a liquid one, which needs some infrastructure and needs more work for the same amount of minerals because of the higher water content.
disadvantages	
loading	Manual labor to fill and empty the pits; eventually bad odors, if the input material has been exposed to the sun for a longer time.
gas reserve	In Rwanda: external balloon with weight for the constant gas pressure; but optional use of the balloons covering the digesters

Tab. 5: *Properties of the batch digesters for solid waste digestion*

The plug-flow digester for semi-solid wastes

Reinhard Henning has built already in the 80-ties a large plug-flow reactor at a regional slaughterhouse combined with a feedlot in Ivory Coast (Henning, 1986). The project was funded by the GTZ, West Germany (German Agency for Technical Cooperation), today GIZ. The main objective was to generate electricity for the slaughterhouse by co-generation. A long pit was dug into the soil without any coating or plastering apart of the crown, where the covering was fixed (water seal). The loss of liquid became marginal after a short time of biological self-sealing with fibers present within the substrate. This method provided a significant reduction of the plant construction costs (Fig. 11). The cover of the pit was made out of expandable synthetic rubber sheeting, which acted as a variable size gas holder. The material was 1986 at the time of the final report still in good condition after two years of operation.

Fig. 11:

Digging the pit for a large plug-flow digester at the Ivory Coast with a water seal on top for the balloon (left)

Installation in operation (down).

(Pictures: R. Henning)

The installation was (and is still?) fed - besides of some manure of the cattle waiting to be slaughtered - with rumen contents and other slaughterhouse wastes, i.e. a mixture with a rather high dry matter (DM) content.

In Europe, plug-flow digesters for the digestion of substrate with more than 20% DM have first been developed by Dranco, a Belgish company. However, their vertical cylinder showed some problems (Edelmann and Engeli, 2003). In the 90-ties, the Kompogas process was developed (www.axpo-kompogas.com). This horzontal design shows very good results: There is an very gentle, slow axial mixing, which just helps escaping of gas bubbles and hinders a mixing of the digestate in direction of the flow (Fig. 12). Because this guarantees a well defined retention time, Kompogas shows excellent results for pathogen killing.

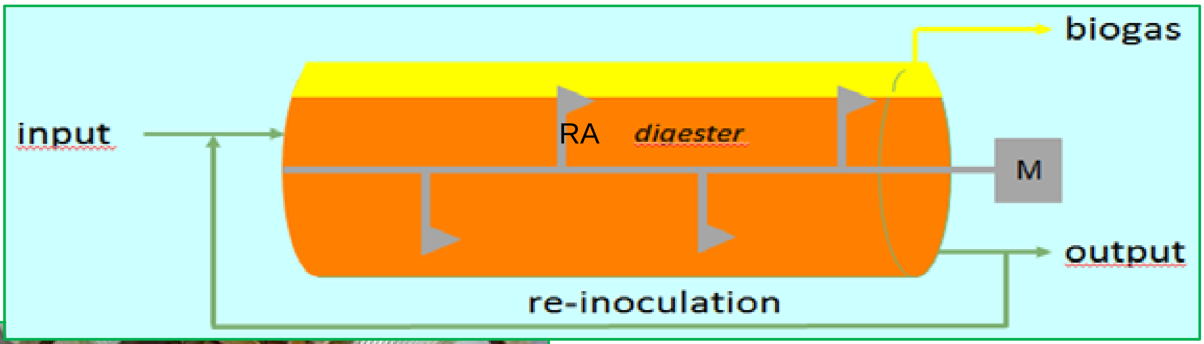


Fig. 12:

Scheme of the Kompogas process: M= motor, RA = intermittent slowly rotating arms (above)

Mixing arms within the digester (left)
(Picture: www.thoeni.com)

Because the anaerobic breakdown is done by a succession of three groups of bacteria (hydrolytic, acidogenic and methanogenic ones), at high loading rates re-inoculation of the fresh input with digestate rich in methanogenic bacteria is recommended: if not, there is the danger that the slowly growing bacteria – living mainly in the second half of the digester – are washed out and the digestion process breaks down.

Plug-flow digester for (semi-)solid wastes (model Ivory coast)	
application	Al kind of (semi-)solid organic wastes (excluded woody material)
advantages	
size	not limited
substrate	Solid manure of cattle, swine, chicken etc.; wastes from harvesting, vegetables, fruits etc. (Dry matter content 20-30%)
gas yield	High gas yield per m^3 of reactor and day
gas losses	Minimal (increasing with ageing of the rubber)
access	By taking away the balloon
hygiene	Very good, because of defined retention time
costs	Very low per m^3 of digester volume
disadvantages	
bacteria	Without re-inoculation danger of washing out the methanogenic bacteria at high loading rates
gas reserve	Within the balloon over the digestate; a good quality membrane out of expandable synthetic rubber may not be available locally at low prices

Tab. 6: *Properties of the plug-flow digester for solid waste digestion*

Biogas in developing Countries: Conclusions for the project

Summing up, it may be said, that

- Usually, in developing countries the locally designed biogas plants are (very) small.
- Very often there is lack of technological development, i.e. the same type of plant is multiplied without taking account of the local conditions.
- Usually, the plants are fed with diluted excrements of animals; the biogas technology is understood to be mainly a technology for rural regions. It is hardly believed to be a technology to treat the huge organic waste streams in urban areas in order to produce not only renewable energy, but also to reduce pollution of the water and of the air by closing ecological cycles while producing an organic fertilizer rich in inorganic nutrients.
- In order to prevent a scum layer, the input has to be diluted with (much) water – what reduces the biogas yield per volume and may also be a problem depending on dry seasons and region.
- The gas production is usually very low; it is used mainly for cooking, i.e. in general there is not enough gas for running a small co-generator for electricity production.
- Most of the installations show different disadvantages, such as difficult access into the interior in case of servicing, no constant or even partially very high gas pressure, risk of gas losses causing abandonment, unsatisfactory sanitation etc.
- Installations for digesting material with higher dry matter content are hardly built – despite of the fact, that these wastes show a significant higher biogas yield because of lower water content and because they have not passed an intestine of an animal already.

These considerations led to the intention to construct a cheap digester, which

- is not limited in size (10 to >100 m^3),
- provides an easy access into the interior in case of troubles,
- shows plug-flow properties for better degradation and optimal pathogen killing,
- is able to handle also higher dry matter contents (up to ~ 20%)
- takes into account the know-how acquired in Europe with solid waste digestion in plug-flow digesters (gentle mixing, re-inoculation etc.)
- avoids the import of too much sediment into the digester,
- may be operated at constant and low gas pressures in the whole gas line,
- gives an easy possibility to re-inoculate in case of high loading rates / low retention time,
- has a small external surface in relation to its volume and the pit is not too deep causing less work while constructing and less impetus by raising gas bubbles,
- low construction costs per volume of digester.

Therefore, the decision was taken to construct an “U”-shaped plug flow digester in Mivumoni. The idea was not totally new: arbi had been building a first, similar digester in Madagascar (FAO, 1988). It was one out of twelve different plant designs built in a project of FAO. Unfortunately, exactly that one could not be put into operation, because – implausible, but the truth! – all the about 120 cattle were stolen a few days before inauguration by the Dahl (criminal organization of Madagascar) and the owner was killed by a heart attack while pursuing the thieves on his horse.

A smaller, second one was built by M. H. Quispe in Peru after a sketch (Fig. 13) mailed by Hans Engeli to this loose contact. After a while, we received a short mail with a photo (Fig. 14) telling that the plant was running perfectly – but unfortunately there were no more data available, because the contact to Peru broke down after that mail.

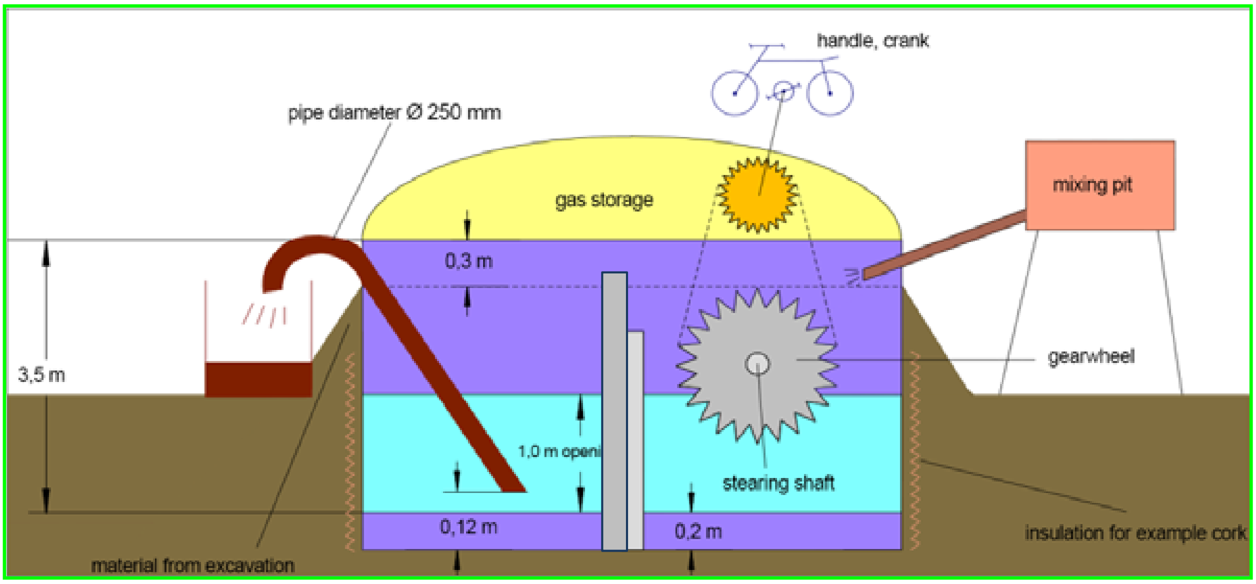
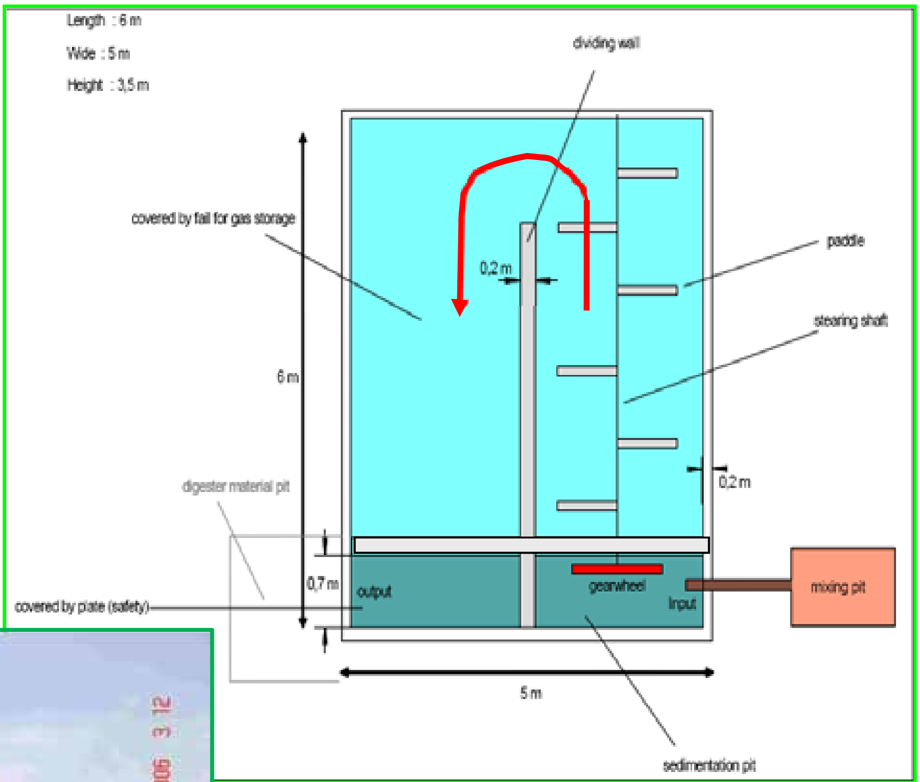


Fig. 13:

Sketches of the "U"-shaped plug-flow digester:

Above: cross section

Right: Top view: The light-blue part is the digester covered by a balloon and divided by a separation wall forcing the substrate to flow around the wall (red arrow) (Hans Engeli)



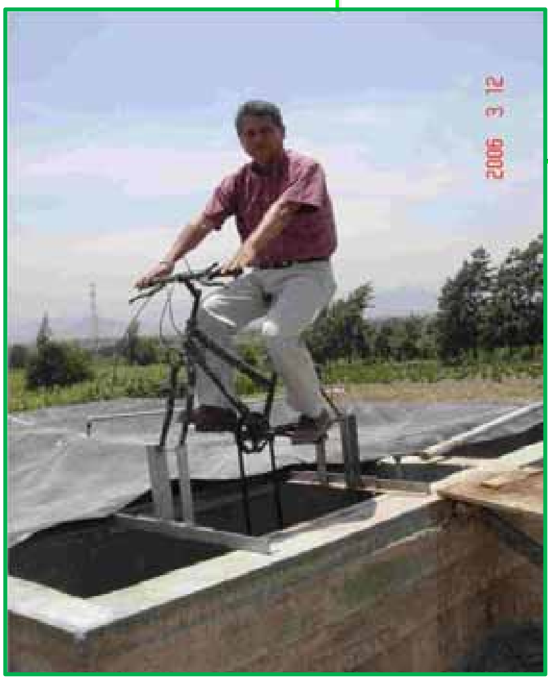


Fig. 14:

Photo sent back from Peru when finishing the construction: The digester half on the input side is gently moved (not stirred) by a stirring device driven by a bicycle

Planning and construction of the Mivumoni plant

Dimensioning of the plant

The dimensioning and planning of the plant was difficult, because the center of Mivumoni was (and is) to a large extent under construction. In addition, there was no telecommunication (phone, internet) possible with Mivumoni, i.e. questions had to be answered by the Swiss experts when visiting the site.

At the time of planning, the exact prospective number of people living on the site was not known in detail. It was estimated that in future it would be necessary to cook, wash and produce tea for up to 500 people (secondary school, school for housekeeping, sisters and local staff etc.). The energy need for heating water was estimated to be in the final stage of extension around **300 kWh/d or 50 to 55 m^3 of biogas**. It was not foreseen to produce electricity, because electricity for illumination is generated by solar panels and it was considered to be too dangerous combining the two grids.

At the same time it was difficult to estimate the amount of organic waste that would be available for feeding the plant. An open stable was already constructed at that time, but the herd was still small (about 50 animals at that time; today ~150) (Fig. 15). The cattle are outside on the fields during the day. They come back to the stable on the paved ground at night and for a short period at noon. The herd is supposed to grow to about 200 animals producing solid manure, when they are in the stable. In addition, there are sheep, chicken as well as rotten fruits and wastes from harvesting and cooking. But detailed estimations showed that there would be **far more biomass than necessary** on the area of the monastery.



Fig. 15:

The open stable with the cattle: The solid manure is collected daily from the paved ground.

The cattle are hybrids of a Swiss race and Zebus.

(Photos: Sabrina Huber and Richi Balmer)

In Switzerland, the "Kompogas" plug-flow-digesters produce per day up to 7.5 m^3 of biogas per m^3 of reactor volume (Edelmann and Engeli, 2005). These digesters treat wastes from household and garden at thermophile temperature (55°) with retention times of less than 20 days. In Tanzania the biogas yield will be smaller, because the biogas plant is not heated causing a slower degradation of the waste and thus a longer retention time of 30 to 40 days within the reactor. In addition, in Tanzania the wastes are not chopped to very small pieces by sophisticated machinery increasing the surface of the waste for bacterial attack. Nevertheless, with solid wastes containing much of (already "pre-digested") cow manure **biogas yields of more than 1 m^3/m^3 digester and day** are expected.

Considering these estimations, the decision was made to construct a **digester with 100 m^3 net volume**. This size is able to cover easily the heat needs of the monastery. It will most probably allow at a later time also increasing the gas production to around 150 m^3/day, if there will be a need for more electricity (by increasing the daily amount of feed, reducing the water content and keeping the bacteria concentration within the digester high by means of re-inoculation).

Positioning of the installation

The local situation in Mivumoni is not typical for developing countries: The stable is quite far from the (widespread) houses, where the biogas is used. Because the largest part of the input comes from the stable, it was decided to build the biogas plant next to it (Fig. 16). As a consequence, very long gas lines were (and will be) necessary to transport the gas to the users.

Fig. 16: *The biogas plant (protected by a fence) is positioned next to the stable (left). A masonry channel for liquid input connects the paved ground of the stable with the digester (blue arrow). When this picture was taken, the ditch for the gas line was not filled up yet. Coming from the biogas plant, it makes a turn (red arrow) and leads to the storing balloon next to the houses in the background (center). The digester is covered by a green balloon; on its right hand side, there is a pit (partially covered) for storing the digestate before it is brought out to the fields. (Photo: Rolf Lattmann)*

It was foreseen to run the plant at very low gas pressures (see further down). Therefore the gas storage in a balloon had to be placed near the users, i.e. near one kitchen and the washhouse (Fig. 17; K and W): Like this, the distances between the balloon and the ovens are short causing little pressure losses when much gas is used simultaneously, thus the gas flows quickly through the short pipes to the stoves. In consequence, the gas flows slowly and regularly within the very long line between biogas plant and the storing balloon (>150 m) causing nearly no pressure losses.

During this project, the gas line was realized from the digester to the storing balloon connecting the washhouse and a first kitchen. It is planned to connect also further kitchens (the ones of the staff, the guest house and of the new boarding school; see Figure 17).

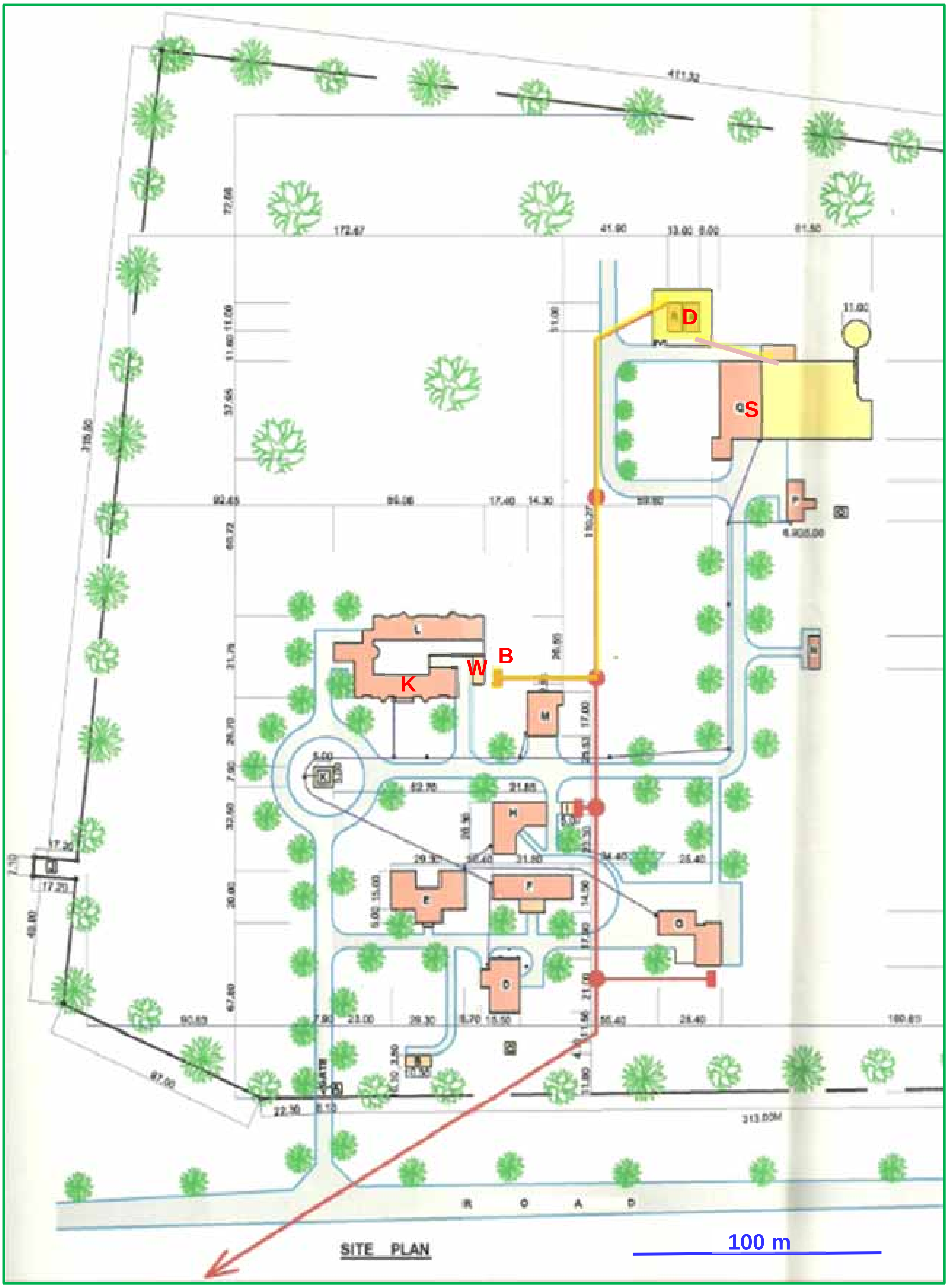


Fig. 17: *Site map of the monastery area. Realized in this project (yellowish on red lines): Digester including manure storage tank (D) and gas storage balloon (B) near the washhouse (W) and kitchen (K) including the gas line. Further lines are planned to two more kitchens and also to the new buildings on the other side of the road connecting Muheza and Pangani (new lodging of the boarding school currently under construction).*

Actually, the red flash should point straight down, as evident when looking at the Goggle Earth pictures in Appendix 6 on page 73!

Construction of the biogas plant

The digester

Typical for a plug-flow digester is a long shape with entry and discharge at the opposite front ends. Experiences showed that the vertical concept shows disadvantages (Edelmann and Engeli, 2005 a); plug-flow digesters are built preferably in a horizontal design. In an ideal plug-flow digester the material enters on one side into a tube or basin and progresses step by step pushed by new fresh material fed in its back until it reaches the exit (cf. Fig. 12). There is no mixing for- and backwards, respectively. This guarantees a nearly identical retention time within the reactor for all material; this is very advantageous, because there is no fresh material exported too early, thus increasing the biogas yield and ensuring that pathogens hardly can be brought out before having been killed.

As mentioned above, biogas is produced in a sequence of three groups of bacteria: the hydrolytic, the acidogenic and finally the methanogenic bacteria at the end of the chain. In a plug-flow digester, there is to some extent also a local sequence of the bacteria: The methanogenic bacteria - showing the longest doubling time - are concentrated towards the end of the digester (in contrast to mixed digesters, where everywhere all bacteria show the same concentration). At relatively low temperatures - such as averaged 26°C in Mivumoni – they may need up to more than a week for reduplikation. If the loading rate of a plug-flow digester is increased, more methanogenic bacteria may be exported than reproduced within the digester. That's the reason for re-inoculation (Fig. 12): At short retention times, a part (15-20%) of the digested material rich in bacteria is added to the fresh material guaranteeing that the anaerobic breakdown starts quickly and that there is no wash-out of bacteria.

In Europe, re-inoculation is done by pumping material back to the entrance. The **special feature of the arbi-digester** is the fact that inlet and outlet pits lay close together, because the digestate is flowing around a separation wall (Fig. 18). This allows **easy re-inoculation**.

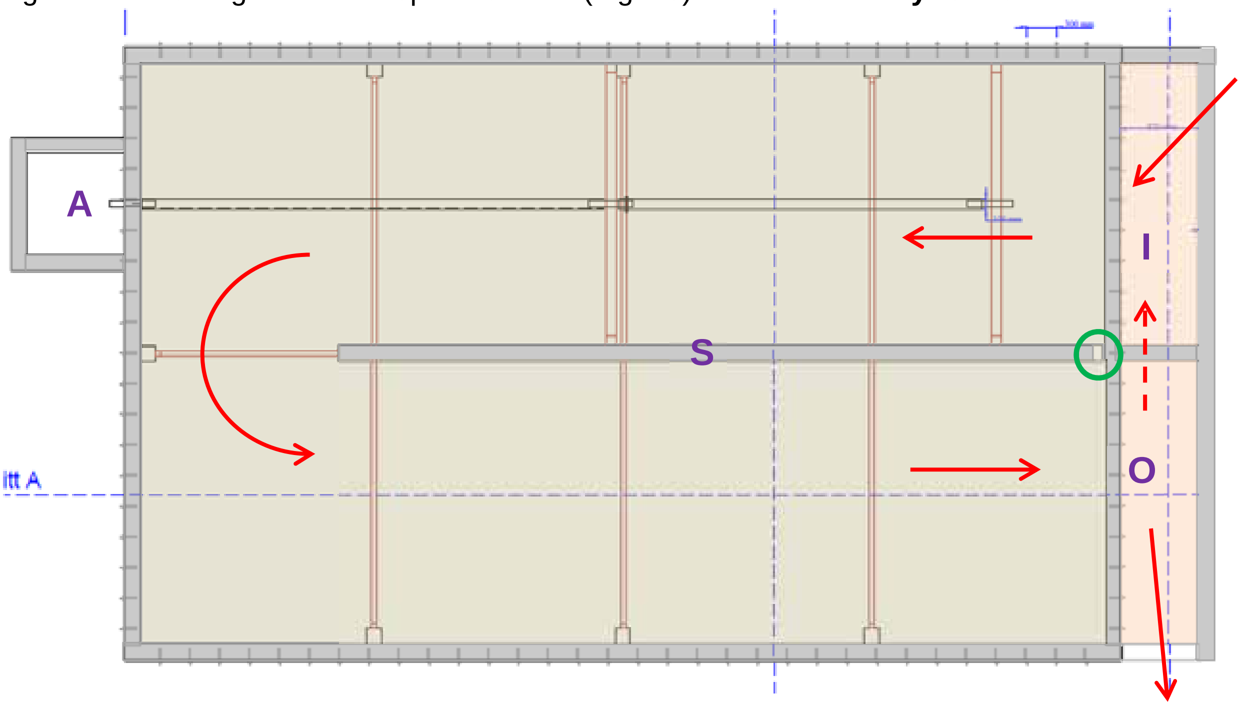


Fig. 18: *Top view of the arbi-digester: the fresh material is fed into the inlet pit (I), flows into the digester (light green), has to turn around the separation wall (S) and arrives finally to the outlet pit (O) and from there to the digestate storage pit. A small part may be put back into the inlet for re-inoculation and moistening, respectively. (A = pit for stirring mechanism; green ring and mechanism for stirring: see further down)* *(Edelmann, Engeli)*

But, besides of easy re-inculation there is a second advantage: the basin may be excavated in a rectangular form saving expensive walls, because a rectangle needs less walls per m^3 of volume than a long ditch. Furthermore, the separation wall may be constructed in a very light version, because there is the same pressure from both sides (the cheapest material possible; it has just to separate input from output material). Therefore, this **construction saves money**.

The outside dimensions of the digester (excluding the pits) are 10 x 6 m at a substrate depth of about 2 m. The separation wall is 7.8 m long. Deducing the volume of the walls, which are about 25 cm thick, it results a net volume of about 100 m^3 depending on filling level. At a net width of the two halfs of the digester of ~2.6 m (6m – 3 walls divided by 2) and a total length of both halfs of ~19 m it results a **ratio of length to width of about 7 : 1**, what seems to be reasonale for a good plug-fow behavior of the substrate.

In Mivumoni, the ground and the walls reactor had to be constructed in a solid way with local coral-bricks, armoring and mortar (Fig. 19). There was the faer of polluting the ground water, if the construction was not 100% manure-tight right from the beginning on. This increased the construction costs (see chapter “Conclusions”).

Fig. 19:

Construction of the reactor.

Top: ground foundation

Middle: In- and oulet pits are less deep than the reactor (see worker with red shirt)

Bottom: reactor (left) with openings for in- and output. Right: storage pit for the digestate.

(Photos: Rolf Lattmann)

What could be done better?

Because it was decided to build a high quality pilot plant for demonstration, however, for replication a more simple construction may be possible: just digging a basin, where only the two pits, the wall for the stirring device and the upper crown of the digester for fixing the plastic covering are masoned, i.e. using the self-sealing capacity of the ground by means of the organic fibers within the waste. This would save a large part of the construction costs (see chapter "conclusions")

The preparation of the input, sediment reduction

The solid manure is transported by wheelbarrow to the plant. Solid wastes such as kitchen wastes, are collected and brought to the platform in front of the inlet pit (Fig. 20). On the site, the wastes are collected in three differently colored buckets: Organic for the pigs (white), biogas (yellow) and Taka (black) for other waste to be burnt. There is a macerator driven manually or when indicated by a little electrical motor on the platform to mince very large pieces.

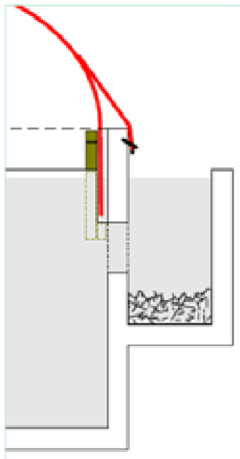
If necessary, urine from the stable or water from the roof (collected in the black cylindrical containers) may be added by buckets or through the channel connecting the paved ground of the stable with the platform (Fig. 20).

Fig. 20:

The buckets for waste collection and the platform in front of the inlet pit (below).

Above: The channel from the stable to the platform including the device for mincing (grey metal box; details see photo on top in the center). At the stable: containers for collections of water from the roof. (Photos: Sabrina Huber, Rolf Lattmann)

The pits are less deep than the digester. At the inlet pit, the opening leading into the digester does not reach the bottom of the pit, but starts only about 40 cm above the ground of the pit (Fig. 21, see also Fig.19). This allows to keep back some heavy sediments, such as sand and stones, before the material enters into the digester.



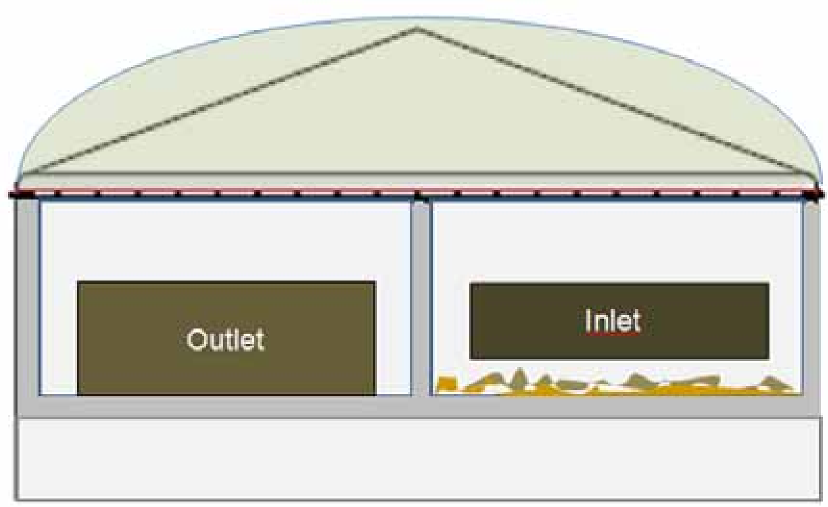


Fig. 21:

Top: Cuts of the digester at the front end: the opening of the inlet pit does not reach the ground of the pit, allowing heavy sediments to settle. Triangle: construction that hinders the balloon to touch the digestate and the stirrer, respectively.

Above: Sight into the inlet pit before its first operation. (Werner Edelmann)

Right: Excavation of sediments from the inlet pit on the occasion of a technical interruption of the operation (Photo Sabria Huber)

The fresh material is thrown into the inlet pit and mixed by hand using a long water tube, where to one end two small tubes of ~40 cm are welded in an "X"-shape (Fig. 22). Porportional to the amount of feed and depending on the loading rate, some digestate is ladled by a bucket from the outlet to the inlet pit, what adds besides of bacteria for re-inoculation also some moisture (during digestion occurs a liquefaction of the digestate).

Fig. 22:

The tool for mixing the different input fractions in the inlet pit with digested material from the outlet pit. (Rolf Lattmann)

What could have been done better?

In the rainy season, too much water was flowing from the paved ground via the channel into the digester diluting the substrates a lot too much and bringing a lot of sand from the paved ground, which accumulated – as planned – mainly in the inlet pit. The problem was solved by building a bypass conducting the much diluted urine into an already existing pit. This bypass reduces the sediment input significantly.

A reasonable tool to excavate sediments from the pit during normal operation is still missing (the sediments were taken out, when the digester had to be discharged to some extent for a modification of the stirring device.). It seems to be reasonable to foresee enough room for sediments and to take care at the same time to try to minimize the amount of sediments already before feeding the material.

The stirring device

As shown in Figure 12, Kompogas-digesters are equipped with an axial stirring device. But the solid waste is not stirred in the sense of intense mixing: the arms rotate from time to time very slowly (only 1-2 rpm), opening gently some ways for better letting escape the gas. The axial turning of the arms is rectangular to the flowing direction of the digestate, i.e. there is no mixing for- and backwards hindering the plug-flow behavior.

In Mivumoni it was decided to install a similar radial stirring device in the first half of the digester, were there are still a lot of solid particles being hydrolysed (Fig. 23); in the second half of the digester the material is already liquefied and homogenized and the gas can escape better. The device is driven by a bicycle. Figure 24 shows some details.

Fig. 23: *The stirring device of the first digester half: sights towards the input opening (left) and from the input side (right). The shaft is embeded on wooden supports (which resist well anaerobic conditions). The eight arms are put into (slow) operation for 5 minutes 2-3 times per day. The shaft is connected in a flexible way (little picture on the right side) with the axle driven by the bycicle* *(Photos: W. Edelmann and Rolf Lattmann)*

Fig. 24: *Sister Agnes – the responsible for the biogas plant – is stirring (left). The transmission ratio is by mistake only 4:1 instead of 40:1, i.e. there should be much larger gear rings on the axle.*

Unfortunately, by some misunderstandings the transmission ratio is not as recorded in several minutes at least 1: 40 (i.e. 40 times turning the pedals of the bike for one turn of the stirrer). At the same time – after an advice of a Swiss specialist for stirring manure - the axle turned by the bike was connected inside the digester in a flexible way with the shaft carrying the arms (despite of the fact that it is known that there should be as few as possible flexible parts within a biogas plant…!). This combination of faults led twice to a break down of the stirrer, because the high forces occuring at the (too) quick start of the stirrer caused the undocking of the shaft from the axle.

At the same time it is not favorable that the arms are not mounted by pairs facing each other, what caused additional forces on the (rather week) shaft, which therefore was bent (Fig. 25). Neverthesless, the idea to stirr the reactor content with high DM content by a bike seems to be feasible and a good solution after some modifications.

Fig. 25: *The shaft damaged because of uneven mounted stirring arms (lateral forces)*

What could be done better?

At this digester size and the very slow stirring speed, the gear rings outside the digester should be directly connected to a stronger, rigid shaft leading into the digester without any flexible connections.

Instead of welding the arms to the shaft as shown in Figure 23, it seems to be better to mount the arms by pair at a short distance (~15 cm) sighting in opposite directions. The orientation of the next pair of arms has to be preferably in an angle of 90° in comparison to the previous one. Like this the forces wanting to bend the shaft can be neutralized.

The transmission ratio should be **at least 40:1**. On the one hand, this provides more force while less hard biking and on the other one, the arms turn once or twice in a minute when turning the pedals of the bike at an agreeable speed.

The covering of the digester

As already mentioned above, the distance between digester and gas users is quite long in Mivumoni. Because the pressure loss is larger at high flow velocities and at long distances, the storage balloon had to be placed next to the users. As a consequence, the balloon covering the digester could not be used for storing gas; its single task is to be a gastight closure of the digester.

Both the balloons are made out of tissue-reinforced PVC containing a chemical protection against UV-radiation (Baur-Folien, 2015). This material shows good properties regarding permeability of methane, is relatively cheap and easy to repair by cold welding with special glue. The balloon covering the digester is protected by a wooden construction, which hinders the plastic falling into the digestate and avoids damaging the balloon by the arms of the stirrer in case of low gas pressure or revision (Fig's. 21, 23 and 26).

Fig. 26:

Right: "ready for take off !"

Below: filled with the first biogas. Next to the angle near the bike there is an inspection glass for observing the functioning of the stirring device. (R. Lattmann and W. Edelmann)

If it is intended to produce electricity with the biogas, as much of the H_2S within the biogas as possible has to be eliminated. By mounting additional (thin) wooden laths on the wooden beams, a surface could be prepared supporting the growth of bacteria oxidizing the hydrogen sulfide within the gas to elementary sulfur: Gas cleaning by pumping a very small amount of air (oxygen) into the biogas is the cheapest method to eliminate the H_2S from the gas to a large extent. However, this solution needs a constant electricity supply for the (small) pump.

A plastic foil strip welded to the balloon enters inside the digester all along its outside walls ~50 cm into the digestate hindering the gas to escape. It is trapped between the digester wall and the wooden support for the balloon (Fig. 27). There is a small slot between the separation wall and the wall at the entry/exit-side allowing the foil to dive into the digestate also there (green ring in Fig. 18).

The balloon was first screwed down by wooden laths and later by metal profiles on the outside of the masoned crown of the digester (Fig. 27).

Fig. 27: *Left: Inside the digester the foil strip welded to the covering dips about 50 cm into the digestate all around the outside walls (here with the architect Harald Frey on the picture).*

Right: The balloon is fixed by screwing it down with laths and metal profiles, respectively, on the outside of the crown. (Photos S. Huber and W. Edelmann)

This solution to fix the balloon (Fig. 27 and 28, left) seems not to be optimal, because the forces varied at different fixation points of the foil. This caused loosening of the foil at different points on the occasion of an overpressure situation.

A better technical solution to fix the covering with less stress could be to weld several strips outside on the foil, which enclose metal tubes. These tubes can be kept by hooks fixed in the wall. Mounting and removing of the cover will be a lot easier than opening all the screws.

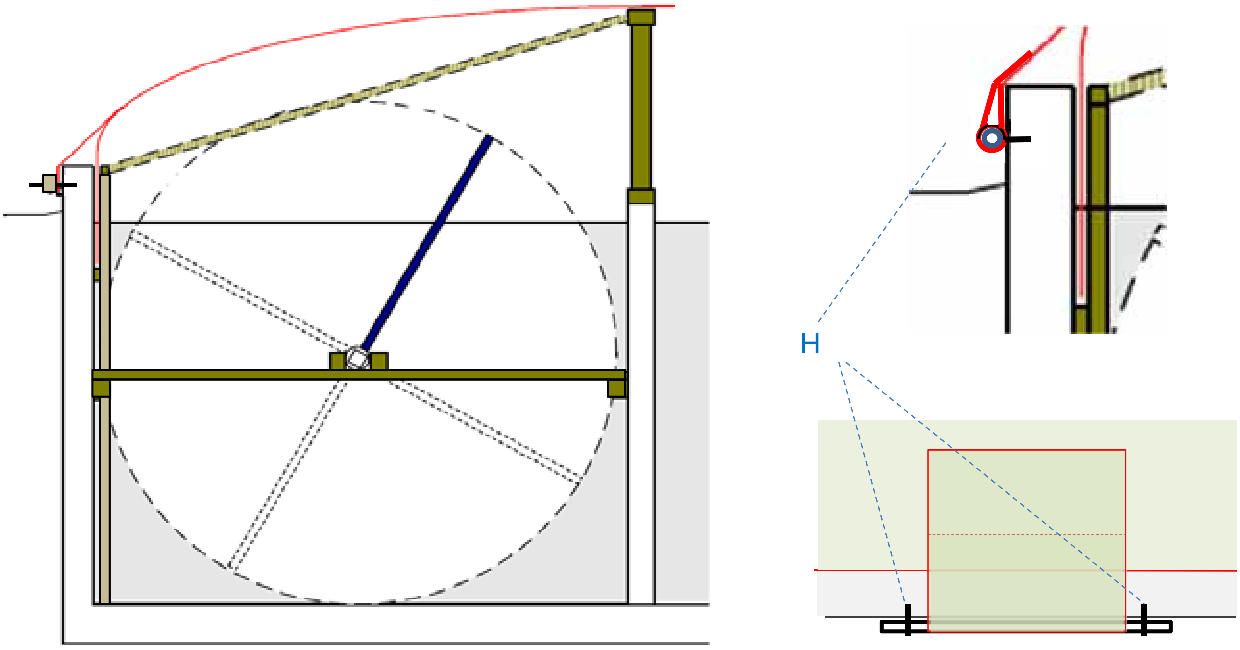


Fig. 28: *Left: Actually realized solution for fixing the cover of the digester.*

Right: Solution, which could be advantageous (hardly more expensive to fabricate): ~80 cm wide stripes are welded to the foil. They form shackles keeping water tubes of ~1 m, which are fixed on both sides by hooks (H) paved into the digester crown. Other solutions – also better than the one actually realized – seem also to be possible.

What could be done better?

The fixing of the balloon covering the digester should be constructed in a more stress-free way, which is also easier to mount and remove (for instance a solution with hooks instead of screws).

The gas line

Figure 29 shows a schematic diagram of the gas line: Coming from the balloon, the gas passes first a gas meter measuring the total biogas production. Then there is a device that serves on the one hand as condensate trap and on the other hand as pressure relieve valve: If the gas storage balloon is full and the production goes on, the gas escapes via a simple flare, where it can be burnt in order to reduce greenhouse gas emissions.

After this multi-purpose device there is the main valve: When it is closed, the digester or the balloon may be emptied (e.g. for a revision): If the digester has to be opened, the gas in the balloon is still at the disposal of the users and if the balloon has to be emptied, the gas from the digester will escape via overpressure valve (Fig. 30) and flare (Appendix 4, Fig. 4, p.68).

Between digester and users there is a long distance. After long discussions of pro's and con's it was decided to build an underground gas line out of locally available PVC tubes (diameter: 2'). There is less danger of damaging by men or animal; underground the line is well protected and does less impact the further development of the site. On the other hand, the costs were higher and there was the danger of clogging by condensate: Coming out of the digester, the gas is saturated with water vapor, which could condensate and accumulate at low points. Therefore, between digester and storage balloon overall four condensate traps were built, constructing the pipe with light decline towards the traps.

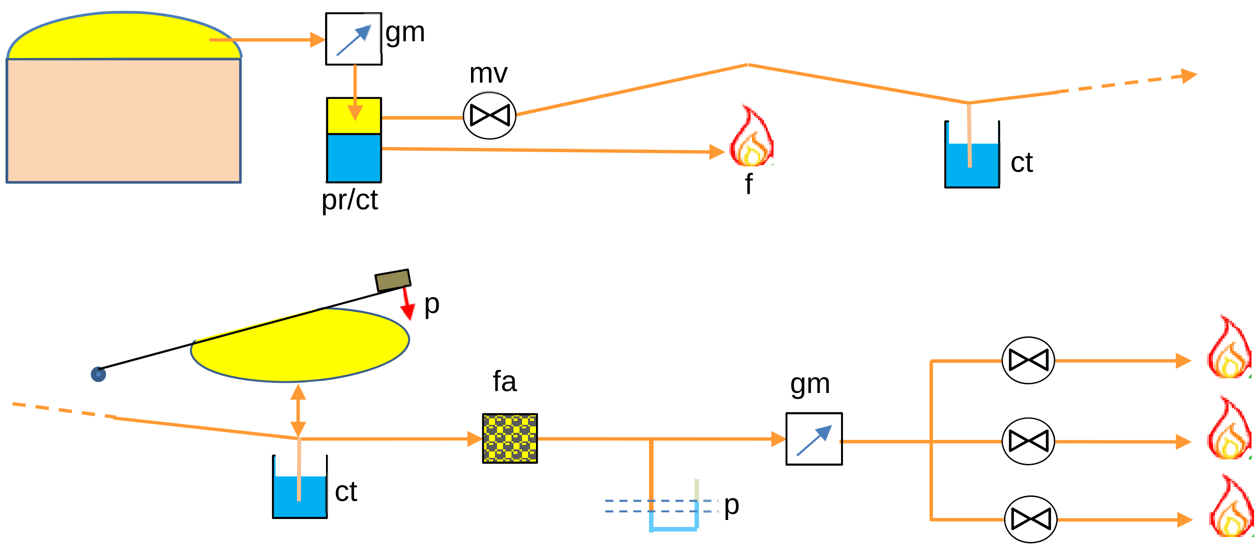


Fig. 29: *Schematic diagram of the gas line: gm: gas meter, pr: pressure relieve, mv: main valve, f: flare, ct: condensate trap, p: pressure of the system (generated by weights on the covering of the storage balloon), fa: flame arrester.*

Fig. 30:

Left: The gas passes through the gas meter to the main valve (mv) and into the ground towards the gas storage. Above the mv: a valve with a little hose for filling biogas bags.

In case of overpressure, the gas bubbles trough the water of the pressure relieve and escapes via the hose / tube to the left towards the flare. (W. Edelmann, S.Huber)

The device for pressure relieve could be improved (Fig. 31): Currently, there is a tap for regulation of the water level, i.e. the pressure necessary for blowing out the gas to the flare. The bucket is not transparent, what makes it difficult to keep the level at its optimal height.

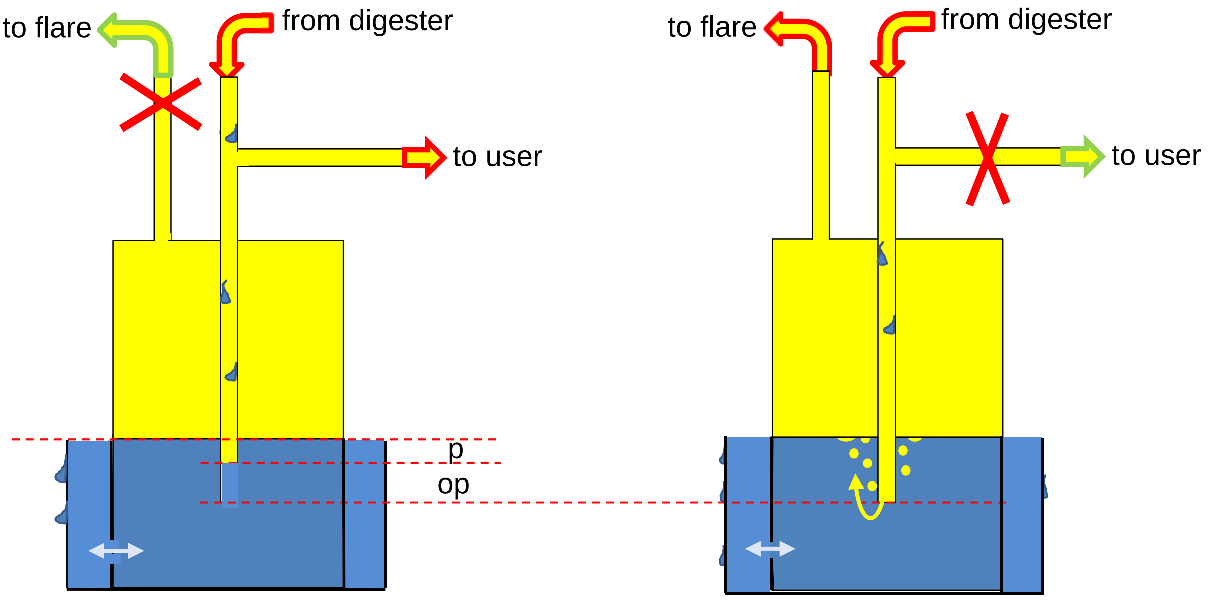


Fig. 31: *The pressure relieve device (acting also as condensate trap)*

Left: normal operation: The gas from the digester goes directly to the user. The systems pressure "p" (~2 cm) is defined by the weight on the gas storage balloon.

Right: The gasholder is full (or the main valve is closed for revision) and the pressure increases (overpressure "op"; ~4 cm), what lets the gas bubble towards the flare (total pressure on the balloon: p + op = ~2 + 4 = 6 cm water column = 6 mbar).

As shown in Figure 31, the tap (Fig. 30) should be replaced by a second, flat bucket with a larger diameter (open at the top). It defines the (blue) water level within the device, because there is a hole (light blue flashes) where water can pass . This will guarantee automatically the right over-pressure and can be easly controlled, if it should be necessary to add water (normally, condensate will replace evaporating water and surplus will flow out). The solution realized in Mivumoni shows the danger that condensate increases the level within the bucket increasing too much the pressure for the relieve damaging the balloons.

Because the condensate flows towards the deepest points, it was necessary to excavate and mason four 1,4 m deep chambers along the gas line declining by turns (Fig. 32 and also in Fig. 33 partially visible). At their bottom, a vertical branch of the gas line enters into a bucket filled with water. Intended was that this solution would be self-regulating in the sense that the condensate would make overflow the water in the bucket, which is open at the top. Unfortunately, this was not the case: Most of the water condensed already in the gas meter – which is at the *highest* point of the gas line with decline to both sides! – as well as in the first condensate trap. At the gas meter, a little tap had to be installed for regular emptying (cf. Fig. 3, Annexe 4, p. 67)

Fig. 32:
Chamber for a condensate trap (the picture was taken while constructing the gas line). (W. Edelmann)

The operation of the plant showed that here were too many traps. At the same time, they created problems: On the one hand, there is the danger of evaporation during the dry season, i.e. regular control is necessary. On the other one, during the rainy season, water was entering into the chamber creating the danger of blocking the line by submerging the bucket and the deepest point of the line. Therefore, the chambers had to be modified (waterproof caps and walls).

The gas storing balloon with a capacity of ~20 m^3 is close to a kitchen and the laundry. The weight (bricks) put on the covering of the storage balloon define the gas pressure in the whole system (Fig. 33, see also Fig. 5, p. 69 in Appendix 4). Also by fear of condensate, it was decided to conduct the gas line into the storage balloon at its deepest point – what was not ideal: As shown in the upper picture of Figure 33, the blue gas line comes from a condensate trap chamber and enters into a channel leading to the lowest center of the balloon. This rigid tube could not move sidewards inside the channel, when the balloon was changing position while inflating or decreasing. Therefore, the tube broke twice. Currently, the balloon is connected with a flexible hose. But regarding the fact that there is nearly no condensate any more, the connection would be better with a flexible hose at its side anyway.

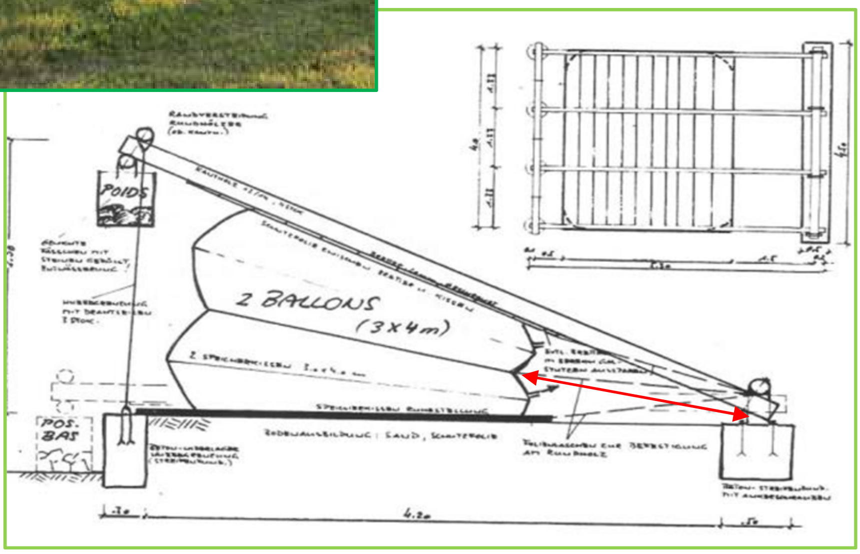
Fig. 33:

On top of the gas balloon, there is a heavy roof out of metal generating the (very low) gas pressure of the system.

The gas line comes from a condensate trap (foreground, left) and is conducted in a masoned channel to the center of the balloon – what caused problems… (broken tube in the small picture)

Above:The pressure of the system may be regulated by adding more or less bricks on the edge of the roof, i.e. next to the wall of the house (prying effect)
(W. Edelmann, S. Huber, R. Lattmann)

Right: Originally, it was intended to construct a less luxuries solution out of wood, such as realized in Rwanda. (Edelmann, 1987)



Coming from the balloon, the gas passes a simple flame arrester, i.e. a big can filled with pebble stones. Then there is a simple manometer, i.e. a branch with a flexible, transparent hose bent in “u”-shape and filled with some water (Fig. 34), where the users can read the gas pressure by measuring the difference of the water levels on the gas side and on the outside (atmosphere).

Fig. 34:

Installing the device to measure the pressure of the system: The lower part of the “U” will be filled with water containing some ink for better visibility and a scale will be fixed at the wall for easy determination of the difference of the levels.

*In Mivumoni, the optimal pressure of the system amounts to only **2 - 3 cm of water column**, i.e. 2-3 mbar.*

Finally, coming from the storage balloon there is a second gas meter measuring the amount of gas effectively used. In this gas meter, there were – as supposed - no problems with condensate.

What could be done better?

If installing a new gas meter (which are available free of charge at Swiss gas companies replacing old, still well working meters by new ones...!) after the digester, a little tap for dumping the condensate has to be foreseen right from the beginning on (cf. picture in Appendix 4, p. 67).

The overpressure release should be constructed in a “foolproof” way: No tap, but a solution as depicted in Figure 31 (or a “closed bucket in an open bucket”), where condensate flows out automatically and where it is evident, when water is missing.

The flare was constructed with a sinter nozzle, such as described further down. There was no pilot flame and the people forgot very often to light it…! It was intended to install a little pilot flame for automatic ignition, but the mechanic charged to do the work left the nozzle overnight outside his house, where it was stolen... – therefore there is no information available yet on the functioning of the improved design. But a solution has to be found, where surplus gas is lighted automatically.

The fear of the condensate was too excessive: two of the four condensate trap chambers could probably have been omitted constructing the second half of the gas line horizontally.

Regarding the chambers for the condensate traps one has to be aware of water penetrating possibly from the top, through the walls or the ground. (With heavy and long rain the groundwater table may raise almost to the ground-level).

The balloon should be placed a bit further away from the frame joint of the roof (as shown with the red arrow in the sketch of Figure 33) and the gas line has not to enter at the lowest point, if there are enough condensate traps in front of the balloon. (Eventually mounting a tap at the lowest point for sporadic voiding, if necessary).

The gas use in kitchen and laundry

After very good experiences in Rwanda with sinter nozzels (used usually as sound absorbers while blowing out overpressures), it was decided to equip lokal cooking stoves with nozzles. The nozzles, which are available in different sizes, are made of sintered stainless steel with a thread of aluminium and cost – depending on size – only a few dollars per piece (Fig. 35).

At the zhaw (Zürcher Hochschule für Angewandte Wissenschaften) two students wrote their bachelor thesis on the optimal functioning of these nozzles for cooking with biogas (Muther and Stähli, 2012). The abstract with some results of their work can be found in Appendix 1.

Fig. 35: *Top: The nozzles made of sintered stainless steel; right: the flare in its original modification (here without glass) (W. Edelmann, Bachofen AG, S. Huber)*

Bottom: Experiments done on the occasion of the bachelor works with an infrared camera to observe the distribution of the flame and the heat with different nozzole sizes, different distances between nozzle and pot as well different numbers of nozzles at varying distances.The blue barrel simulated a cooking pot (W. Edelmann).

As mentioned above, actually the biogas has to substitute for wood or charcoal used mainly for cooking and also for washing. Therefore, ovens, which are available on the local market, have been modified for dual use with biogas or with wood (Fig. 36). A piece of a pipe was equipped with a valve and a nozzle PSS 14 for big pots. For better regulation of the size of the flame, it was decided not to apply simple bucket-valves, as utilized in Rwanda (Edelmann, 1987, Fig. 37); the valves used here came from the local market. Two supports at the tube allow to keep the nozzle at its optimal position inside the oven. In order to avoid explosive mixtures of gas, it is recommended to ignite the flame outside the burning chamber.

Fig. 36:

Top:The nozzle at the end of a tube (including a valve and supporting feet) can be brought into the oven through the door designed for feeding wood (oven of the laundry).

Top right: There is a flame arrester.In the gas line in front of the furnace.

In the kitchen, besides of three pots equipped with nozzles (left), conventional biogas cookers are also in use (above; on the shelf).

(Edelmann, Huber)

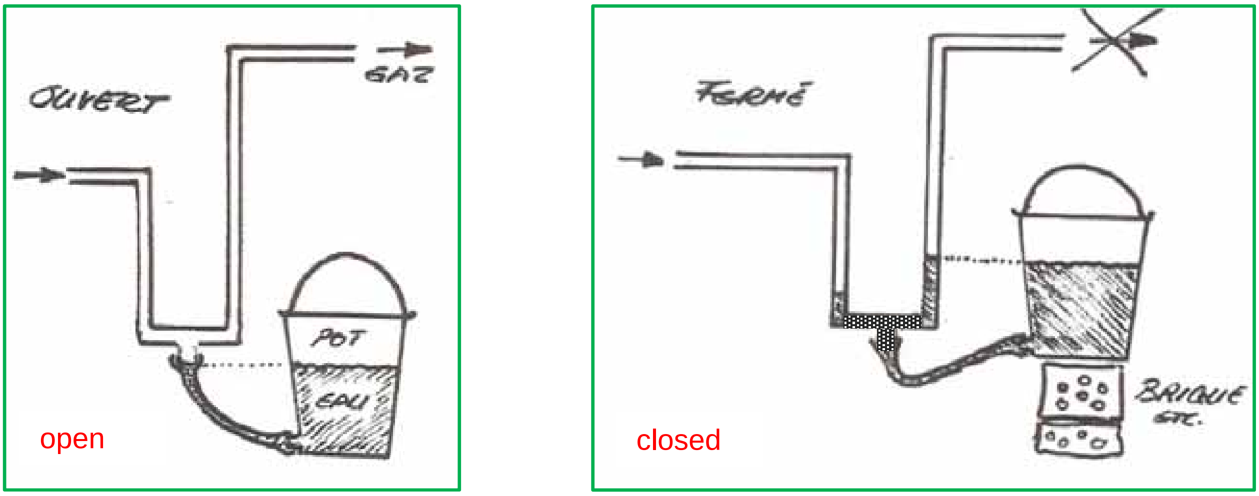


Fig. 37: *Simple "bucket-valve" as used in Rwanda: When the bucket filled with water is placed on the ground, the gas may pass. If elevated on some bricks, the water flows into the "u" of the gas line and the gas flow is blocked. This valve has the advantage of low costs, no danger of corrosion and of being 100% gastight (it could e.g. be applied for the main valve). (Edelmann, 1987)*

Unfortunately, the chimneys were constructed inadequately: On the one hand, they have to be long in order to generate a large upswing with the warm exhaust gas. The chimneys of the three cooking stoves in the kitchen are very much too short and even placed under the roof, causing extinction of the flame at some atmospheric conditions. On the other one, chimneys outperforming the roof should be equipped with a hat that increases the upswing (Fig. 38).

Fig. 38: *Left: Much too short chimneys at the kitchen (on the left after the blue tube a flame arrester in the gas line). Right: Because of the very low gas pressure in the system, i.e. quick extinction, it would be an advantage to mount hats rotating with the wind. (R. Lattmann)*

What could be done better?

The chimneys should be constructed in a way that the warm air shows enough upswing for not being pushed back into the combustion chamber, where the flame may be extinguished. Hats on the chimneys turning with the wind may be advantageous.

Operation of the plant

Start-up and first year of operation

The operation of the plant started in October 2012. The plant was filled with “solid” cow manure, which was diluted with very much urine and water from the roof of the stable. A good burning gas was available as soon as the level reached the foil of the covering, i.e. as soon as the installation was gastight.

As mentioned above, there were two interruptions of the operation because of malfunctioning of the stirrer caused by misunderstandings between the planning team (in Switzerland) and the construction team on site.

But besides of these (very short) interruptions of the operation, the installation is working well. The sisters were and are very happy about the biogas, which makes their life a lot more comfortable.

Regrettably – by another misunderstanding – the biogas plant was run always at relatively low dry matter (DM) contents. To a part this was caused by rain water (also from the paved ground at the stable) flowing during the rainy seasons via the channel directly into the digester. But – even more important - the people operating the plant had the traditional digestion in their mind (such as described in the chapter on the biogas technologies), i.e. they believed that the addition of water is good for the process, despite of the fact that water just increases the volume without producing any gas and increases the risk of scum formation.

It was the intention of the planning team to construct an **installation running at higher DM-contents**, i.e. DM (>)**>** 8-10 %. Already 1978, the Ecotope Group (Coppinger et al., 1978) found out that even in high cylindrical digesters (with high upswing by evolving gas bubbles) the danger of scum and sediment formation is very much reduced or even not existing any more at DM-contents of more than 8 – 10 %. William Jewell, the inventor of the plug-flow digesters, came to the same conclusion already in the 70-ties, running at the Cornell University, Ithaka (NY), a simple plug-flow digester similar to the one in Figure 11 (Jewell et al., 1980). Phase separation is less probable in a plug-flow reactor because it is much less high than a cylinder, what causes less gas/m^2 streaming upwards to the surface, where particles picked up on the way up may form a scum layer at the top. **At minimal ~10% DM, the viscosity of the substrate** (i.e. its “thickness”) **is high enough to prevent phase separation.** The upswing of the gas bubbles is not strong enough anymore to transport solid particles, such as fibers etc., up to the surface.

These facts show that it is ***not*** necessary to stir the reactor content in the sense of mixing and scum destroying. In contrary: mixing is ***not*** desired in order not to disturb the plug-flow behaviour. But a gentle opening of pathways within the “substrate-pudding” for an easier escape of the methane bubbles has shown to be advantageous while operating Kompogas-plants at high DM contents; therefore the only very slow, sporadic turning of the “stirring” device driven by the bike.

From the point of view “gas production” the dilution was not a problem, because there was (and is) not yet a high need for biogas: The number of students has not reached yet the planned level. Therefore, the loading rate of the plant has been extremely low, producing only as much gas as needed for the laundry and the kitchen connected to the gas grid. Because methane is a powerful greenhouse gas, it was not reasonable to produce more gas than needed.

Therefore, the amount of fresh material added was depending on the filling state of the storage balloon. And – as mentioned above – the manure was always diluted with much water.

Actual performance of the plant

Methods

In order to get more detailed information on the functioning of the plant, Sabrina Huber, a student of zhaw, went in summer/autumn 2014 for five months to Mivumoni for writing her bachelor thesis on the plant operation (Huber S., 2014).

In order to describe the operation, it was necessary to determine the running parameters of the plant using the infrastructure, which was locally available. For calculating values, such as hydraulic retention time (HRT), loading rate (LR), specific gas productions etc. in was necessary to determine the amount of substrate and its content of dry matter (DM) as well as of organic matter (OM), which was fed daily.

The amount of feed was determined by filling the manure into buckets and weighing them (Fig. 39). DM was measured by drying samples of about 200 g at ~105° C in a cheap (60$), small baking oven until weight was constant. OM is not as much varying as DM; one could take values from literature. Here, samples of DM were taken back to Switzerland for OM determination by measuring the volatile solids. At the same time the amount of liquid added (mainly urine from cattle and sheep) was measured.

Fig: 39:

Weighing the FM of the input and preparing the samples for DM determination. (S. Huber)

In addition, the total amount of gas and the effectively used amount were recorded daily at the two gas meters (as done already before). Further recordings concerned pH (pH-papers sensitive around the neutral range), temperatures of the digester as well as of the air among the shade.

For further details see Sabrina Huber (2014).

Results and discussion of the results

Sabrina Huber distinguished four phases while measuring 2014 the parameters of the plant.

As mentioned above, until summer 2014 the plant was running with a substrate, which was much too much diluted. Despite of the fact that the data on gas production, gas use and number of wheelbarrows fed were recorded, it was not possible to make a statement on the functioning of the plant at high DM-levels. At that time, the DM-content of the input was only about 6 – 7% (phase 1 = last 2 weeks before increasing the DM-content)

From phase 2 on, less liquid and 50 kg of rotten oranges were fed daily in addition to the cow manure. In phase 3 there was a (quick) re-starting after a technical interruption. In phase 4, the DM-content of the input was as planned by the planners; the input of water was reduced by nearly 90% and the DM-content of the input varied around 17.5%.

However, the loading rate of the plant remained extremely low, because there was no need for more biogas due to the fact that the construction of the lodgments for additional students was (and is) not completed yet. But it was decided not to increase the loading rate, because this would have increased also the greenhouse gas emissions by methane escaping via the over pressure device.

The undiluted manure showed a **DM**-content of **20.6%** (Std. dev. +/- 2.7%) at an **OM**-content of **73.0%** of the DM (+/- 2.7%). The biological degradation reduced the OM to **64.1%** (+/- 0.4%). This relatively low reduction is not surprising considering the fact that the manure has already passed the intestine of a ruminant, where the easily degradable compounds had been degraded; this digestion within the animal reduced the OM of the input to less than 75% (in undigested biomass, OM is in general far higher than 80% thus causing a significant higher gas yield).

Table 7 resumes some parameters of the phases 1, 2 and 4. In phases 2 and 4, the addition of liquid was reduced significantly. This caused an increase of the retention time (HRT) of the substrate within the digester. It was planned to run the plant with HRT's of 30 to 50 days. Because the loading rate was not increased in order to avoid a harmful over production, the HRT was in phases 2 and 4 extremely high, i.e. about six to nine times too long!

Phase	HRT	LR	Biogas production			Biogas need
	d	kg OM/ m^3*d	m^3/m^3 reactor*d	m^3/kg OM	m^3/d	m^3/d
1	100	0.51	0.140	0.252	13.66	10.63
2	217	0.38	0.106	0.289	11.69	11.43
4	274	0.37	0.107	0.301	11.83	10.45

Tab. 7: *Running parameters of the biogas plant (HRT: hydraulic retention time, LR: loading rate, OM: organic matter, d: day)* (S. Huber)

Because of the very long retention time and the low OM-content of manure, the loading rate was also extremely low: In this kind of biogas plant and at the in Tanzania prevailing climatic conditions, the LR may reach values of 3 - > 5 kg OM/m^3*d, producing ten to twenty times more biogas under the precondition of re-inoculation and adding also co-substrates with higher and better degradable OM-content, such as fruit, vegetable and kitchen wastes etc. The data suggest that significantly higher yields than 100 m^3/d or far more than 1 m^3 biogas per m^3 reactor and day should be achievable at DM-contents of around 16-18%. The yield per kg OM is very good – what is not surprising considering the very long HRT (In Europe, the yield of manure from cows not fed with concentrated feed is rather lower in completely mixed digesters, where some substrate is exported too quickly).

The increase of the DM-content of the feed did not have a negative effect on the biogas production; in contrary, the yield per OM showed even an increase.

The temperature of the digestate was around 30° C. The temperature was measured by inserting a thermometer through the opening at the outlet pit ~50 cm into the interior. There, the temperature varied +/- ~2° C, because the output warmed up with the sun. Deeper inside the digester the variations were probably much lower. The ambient temperature reached values up to 35° C. The membrane of the covering warmed up to more than 40° C at the sun. It was planned to protect the covering by constructing a shelter with a second hand camouflage net of the Swiss army (see picture on the front page). Currently there is a discussion about constructing a solid roof.

The pH did not vary and was slightly higher than 7.5. For further information see S. Huber (2014).

Jewell (1980) compared over several years a cheap, full scale plug-flow system constructed of low cost materials and with earth supported structure to a completely mixed reactor digesting identical diary manure in both systems (including straw in some experiments). There were different experimental periods varying the HRT at 35° C and also at 25° C (constant) digestion temperatures. Both reactor volumes were 34 m^3. The plants were run at maximum only 30 days HRT. Jewell stated in the summary of the study that *although this low cost plug-flow system outperformed the completely mixed unit throughout the study, perhaps the greatest advantage of this approach is ease of modification, operation and maintenance*. He obtained 10 to 20% more gas than in the completely mixed system and *the total volumetric biogas production rates varied from 1.3 to 2.5 volumes per volume of reactor per day for the plug-flow reactor*.

At the same time, Jewell stated *that serious problems with float formation occurred when the influent solids were diluted to 8 percent total dry solids*. AT higher DM-contents and also at lower temperatures than 35 C, the viscosity of the digestate was high enough to prevent the scum formation.

In Switzerland, Kompogas plants run at loading rates of up to over 12 kg OM/m^3*d at thermophilic temperature producing up to 7.5 m^3/m^3 reactor per day (Edelmann and Engeli, 2005 a).

If the Mivumoni plant is run at 40 d HRT adding 2.5 m^3 of substrate per day including some co-substrates, which have not passed yet through the intestine of an animal, a biogas production of about **150 m^3/d or 1.5 m^3/m^3 of reactor can be reached easily**. Even higher productions would be possible by increasing the amount of co-substrates. It may even be suggested that the Mivumoni plant, thanks to the possibility of re-inoculation, outperforms the plug-flow digester of Jewell (1980), who reached peaks of up to more than 4 m^3/m^3.

Summing up, it may be said that the digester and the whole installation work – with potential for some improvements - as planned. Unfortunately, this could not be fully proven with a high DM-content of the input, because in Mivumoni there is not yet enough need for biogas and because the stay of Sabrina Huber latest only five months: Thus, there was not enough time (~270 d; Tab. 7) to replace all the diluted material within the digester with “thicker” input.

A manual for the plant operation including explanations of the functioning of the different plant components can be found in Appendix 4. This manual was written in addition to an oral training of the local people. Regrettably, it is not translated yet into Kisuaheli.

Currently, a master project work is being done at the ETHZ on the theoretical maximal gas production and the mode of operation at full loading rate (Pezzati, 2015).

Conclusions

Advantages of the arbi plug-flow design

Aside from some minor problems, which can be improved when designing further plants, the arbi plug-flow digester works well. Unfortunately, it was not possible to reach the limits of its performance.

The digester has been designed for the digestion of (semi-)solid wastes with a dry matter content of > ~12%. However, the functioning of the plant at high DM-levels could not be fully proven, because on the one hand there was - regarding the very long HRT - not enough time during the timed bachelor thesis to increase the DM within the whole digester. On the other hand, it was not possible to reduce the HRT without causing a high overproduction of biogas, which is a dangerous greenhouse gas.

Nevertheless, long experiences with Kompogas plants as well as the vast experiences of W. Jewell argue for a very high probability that this "simplified Kompogas-fermenter" will work well also at high loading rates with high DM-contents.

Summing up, it may be stated that the arbi plug-flow design shows many **advantages** such as

- **No restriction in size**: it can be built from a few to up to several 100 m^3.
- **Low construction costs**: the surface of the walls is small – despite of the length of the way the digestate has to pass through – thanks to the "U"-shape, which can be achieved with a simple barrier.
- **Easy access into the interior** by taking away the plastic cover
- **Optimal degradation**: there are no shortcuts for the material passing through the reactor thanks to plug-flow design.
- **Optimal disinfection**: the vast majority of pathogens (harmful bacteria and viruses, pathogenic germs for humans, plants and animals as well as seeds of weeds) are killed, because of an assured minimal retention time within the reactor (Baier et al., 2010).
- **Easy re-inoculation**: at high LR and short HRT it is easily feasible to recirculate 10-15% of the digestate from the outlet pit into the inlet pit in order to prevent the washing out of methanogenic bacteria.
- **No restriction to digest liquid substrates**: because at DM-contents higher than 8-10% there is no separation into scum layer, liquid phase and sediment, it is possible to digest all kind of (semi-)solid wastes, which are dangerous for climate, soil and water if dumped.
- **Help for optimal gas evolution**: in the first half of the digester, where larger solid particles are not yet disintegrated, the escaping of the gas bubbles can be improved by an intermittent gentle moving of the stirring arms (e.g. 3 times 5 minutes per day).
- **Reduction of sediment input**: design of the input pit for keeping back - at least a part of - the heavy sediments, thus reducing the number of intervals of maintenance works.
- **Very low and constant gas pressure:** the fermenter and the gas lines can be operated at very low, constant gas pressures thanks to the sinter nozzles used for heat generation. This reduces significantly the biogas loss at leakages.

Comparing all the small household digesters in developing and emerging countries to the sophisticated plants, the **arbi plug-flow digester closes a gap**: It is inexpensive (see below), all the same not limited in size and will work with modest expenses for operation and maintenance for a long life span. It will allow digesting all kind of (semi-)solid wastes in addition to manure, which are abundant all over the world and which produce significantly more gas per kg OM than animal excrements, saving water at the same time.

Economic aspects

The construction costs of the biogas plant in Mivumoni are not representative at all for several reasons:

I) It is a pilot plant with a new design (developing and engineering) with additional features such as bull's-eye, gas meters, etc. causing additional non-recurring expenditure. *II)* The situation in Mivumoni is unusual, because the biogas plant and the biogas users are far away from each other, what increased the costs for placing long pipes, condensate traps etc. *III)* Additional features of the plant such as a large and masoned pit for the digestate, a fence around the installation, containers for collecting rain water from the roof, channel from stable to the plant, stoves, etc. increased the costs, *IV)* The components have been erected with Swiss quality standards, what also added some costs.

As mentioned above, future plants may be constructed saving quite a lot of money: In many – if not in most – of the cases, where the ground water level is not at or close to the surface, it will be possible to save costs for constructing walls and floor: Because in organic matter there are lignocellulose fibres, which are hardly degraded, they will quickly occlude fine pores in the ground, where the liquid of the digestate could escape (so-called biological self-sealing). If there is loam in the neighbourhood, it may be used for additional sealing. Masonry is only necessary for building the crown, the in- and outlet pits and the pit for the stirrer (Fig. 40). If the users or a co-generator are not too far away, feasible solutions can probably be found to use the digester covering for storing/buffering the gas production directly in the digester above the digestate.

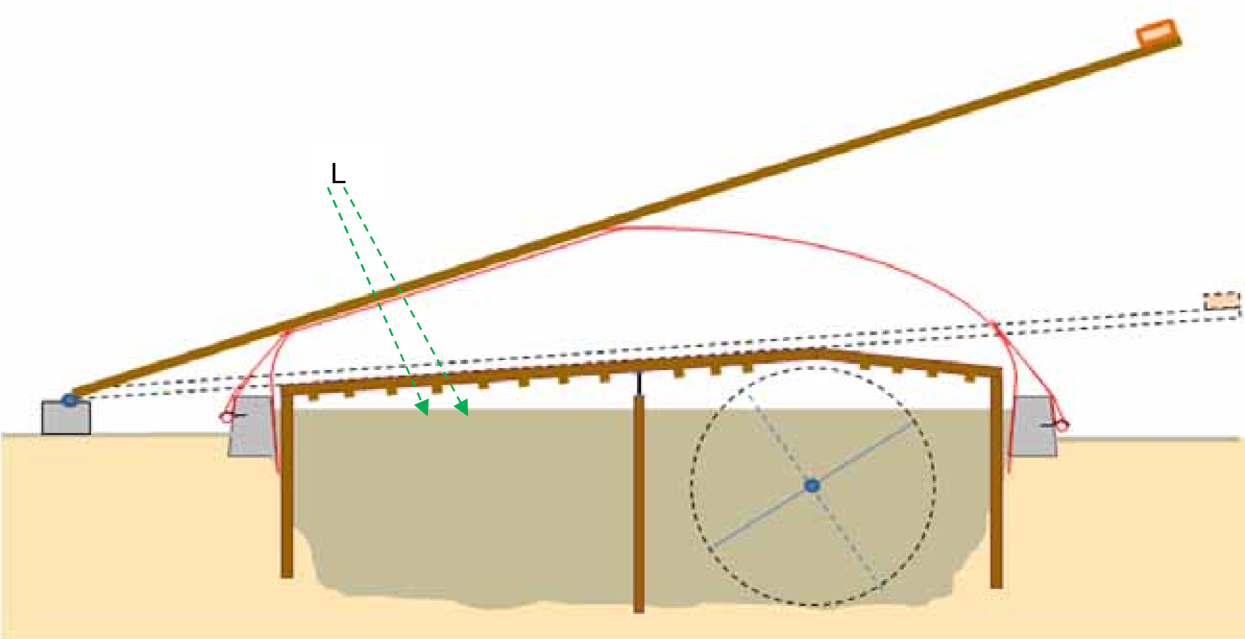


Fig. 40: *Impression, how a future arbi plug-flow digester perhaps could look like: The crown holding the cover is masoned. If the gas is used for running a motor, (thin) laths (L) are fixed under the construction built for hindering the balloon to dive into the digestate; these laths serve as surface for the growth of H_2S-oxidizing bacteria, if a (very) small amount of air is pumped constantly into the gasholder. The elementary sulphur produced by the bacteria falls from time to time into the digestate and will be brought out to the fields for fertilizing.*

However, a more comfortable technical solution for storing the gas above the digestate creating the desired gas pressure at the same time needs still some reflections. Alternatively, the local conditions have to be considered: If there is electricity (or just a solar panel plus a battery), the (low) gas pressure to run nozzles or a co-generator as well as the oxygen supply for sulphur oxidation can be generated by small blowers. In this case, the balloon may be operated at ambient pressure, i.e. without a construction for the weight, increasing the longevity of the balloon and reducing the construction costs furthermore.

Earnings of the plug-flow digester

Between April 2013 and October 2014, the digester produced (only) 8'438 m^3 biogas (Huber S., 2014). At a methane content 56% this corresponds to about 5.6 kWh/m^3, what comes up to a total production of about 47 MWh. Charcoal has a calorific value of +/- 8 kWh/kg. The biogas of about 19 months corresponded therefore to about 5'875 kg of charcoal – what is comparable to the amount of charcoal bought before the plant was constructed. A bag of charcoal of ~36 kg would have cost about 16'000 TSH what corresponds to a price of 0.25 US$/kg. Therefore the biogas plant generated **savings of around 925 US$ per year** at actual (very low) running conditions. (It might even be more, because the energy content of charcoal is not used completely: When the meal is cooked, the coal continues to glow; the gas can be stopped immediately…!)

But as mentioned above, a production of 1.5 m^3/m^3 reactor and day, that means about 12 times more gas than actually produced respectively, is most probably achievable while not yet reaching the limits of the plant at all. This will correspond to an annual production of about 55'000 m^3 of biogas or **over 300 MWh of energy per year** (assumption: 5.6 KWh/m^3), allowing the production about 110 MWh of electricity by cogeneration (efficiency ~35%). The tariff for general electricity usage in Tanzania (T1) is 221 TSH/kWh – besides of a service charge per month of 14'233 TSH (Tanesco, 2015). Thus, the **electricity,** that could be produced yearly, **has a value of about 13'000 US$** (exchange rate: 1US$ = 1'835 TSH). In addition, there would be the heat for warm water production for washing and drying of fruits etc. By substituting **charcoal** only, about **11'000 US$** could be saved per year (assumption: charcoal used 100%, see above).

The earnings depend very much on the cost structures of the country where it is built (price of the energy, subsidies, such as compensation for electricity fed into the grid etc.). But it may be stated that – depending on the local situation – **yearly earnings more than 10'000 US$ are possible** with a plant of 100 m^3. Using also the heat of cogeneration and/or or increasing the loading rate for higher gas productions than 1.5 m^3/m^3, earnings of up to 20'000 US$ will be achievable. Furthermore, the digestate is a very good organic fertilizer improving also the humus content of the soil and thus the yield of the field crops (Bafu, 2007).

Construction costs and return on investment

Regarding the investment costs, there may also be variations of labour costs and construction materials depending on the construction site. In Mivumoni the construction costs were – as mentioned previously already – for different reasons above the ordinary. The costs of plant construction are given in Appendix 3: The costs for the construction the plant's walls added up in Mivumoni to ~23'000 US$ plus ~4'800 US$ for the mixing device. The UV-resistant, polyester-tissue-reinforced membrane for covering the plant accounted for 2'200 US$ (1'940 €) and the gas storage balloon was 1'915 US$ (1'690 €) (excluding shipping to Tanzania). Thus, the biogas plant (excluding the extraordinary long pipework) amounted to about 30'000 US$.

However as mentioned above, the biogas plant can be constructed at significantly lower costs by saving engineering costs and much of the cement and steel applied in Mivumoni (cf. Appendix 3). Most probably, it will be possible to construct an improved plant of 100 m^3 at much less than 20'000 US$. Table 8 gives a very rough estimate of the costs for constructing a 100 m^3 plant producing daily 150 m^3 biogas (mainly manure). The investment data of Mivumoni base on the costs displayed in Appendix 3 and the (not realistic) assumption that all gas could substitute for charcoal. The estimations of the future plant base on the following assumptions:

- constructed in a more simple way using much less cement and steel,
- less sophisticated and at the same time more stable stirring device,
- using the gas for cogeneration in a 25 kW gas motor,
- a bit larger covering for the gas storage directly above the digestate (possibly even without weight for generating pressure using a small, solar/battery driven blower to generate the pressure necessary for the gas motor and for direct burning)
- H_2S reduction by blowing a small amount of oxygen into the gas room, where the sulphur oxidizing bacteria may grow on a wooden growth surface.

The plant operation costs are based on the assumptions that semi-skilled worker(s) are responsible for feeding the plant. When producing electricity, an additional skilled worker (who can also take care of the generator) is needed.

Component	Mivumoni	Future plant	Costs
	US$		US$
Masonry incl. earth works	19'800	pits; ground self-sealing/clay	8'000
Wood for supporting the cover	3'400	incl. laths (H_2S)	4'200
Stirring device	4'700	no movable connections	3'000
Covering membrane	2'200	incl. gas storage	3'500
Storage balloon incl. foundation/covering	4'000		- - -
Piping, gas meter, different costs	2'000	incl. shipping/installation motor	3'000
Nozzles for 8-10 stoves	200	co-generator 25-30 kW	8'000
Plant investment costs total	**36'300**		**29'700**
Annual earnings: substituting charcoal	11'000	Earnings: electricity	13'000
		Earning heat cogeneration	?
Annual running cost: Salaries, maintenance	2'000	incl. maintenance motor	4'000
Annual capital costs (10 years, 4%)	4'475		3'662
Total annual operating costs	6'475		7'662
Operating result: Income per year	**4'525**	(Heat not considered!)	**5'338**

Tab. 8: *Rough cost estimates for the actual Mivumoni plant (assuming that all the gas could be used for charcoal substitution) and for a possible future plant. (Assumptions: see text)*

The generator price bases on an internet research, where different products in the range of 25 to 30 kW were found on the Chinese and Indian market at less than 10'000 US$ (e.g. 25 kW generator set form Weifang Hualing Power Co., Ltd. for 6'899 US$).

It is evident that an arbi plug-flow digester can be operated at **economically very interesting conditions** – even if the costs should be higher than estimated (what is not probable at all). Without a gas motor a digester can be built for less than 200 US$/$m^3$ reactor volume. Here it is important that a cost estimation is made by local people with local prices for construction material, possibly also taking into account tasks done by the future operator himself. As mentioned above, the construction costs of Figure 8 base for Mivumoni on the costs shown in Appendix 3. For the future plant, costs basing on similar salaries were assumed.

Small fixed dome and floating drum digesters will cost more than 100 \$/m^3. (Small units had cost – without indication when and where - \$ 800 to \$ 1700; SSWM, 2015). But it has to be kept in mind that the small, conventional digesters will produce only 0.15 – maximal 0.4 m^3/m^3*d, because they have to be fed with highly diluted animal excrements. As mentioned above, the plug-flow design can yield – depending on the kind of feed – over 1.5 m^3/m^3*d multiplying the income per volume (and spoiling at the same time less water...)

When producing **electricity**, it is possible to **pay back the investments of a well-planned 100 m^3 plant** digesting mainly cow manure **within 5 - 6 years**, without taking into account a possible use of waste heat from co-generation as well as the benefits of producing an improved fertilizer and soil conditioner. (cf. Tab. 8, invest and operating result)

If all the gas is used only for heat production in order to substitute for charcoal, the investment of a future plant would decrease to US$ 17'900 (no gas motor and less expensive wooden construction) and the annual operating costs decrease (calculated with the same assumptions as in Tab. 8) to US$ 4'207. The operating result amounts to US$ 6'793; it would be even better than producing only electricity! However, besides of food processing industry there are hardly consumers with a corresponding high heat demand.

When producing **heat** substituting for charcoal, it is possible to **pay back the investments of a well-planned 100 m^3 plant** digesting mainly cow manure **within 4 - 5 years**, without taking into account the benefits of producing an improved fertilizer and soil conditioner.

The estimations of the operating results base on the assumption of a life span of 10 years at 4% interest. However, the plant will live a lot longer; maybe the balloons will have to be replaced once in the future. Thus, the **operating results could even be better**. Furthermore, there exists – depending on country – the possibility of subsidies.

Economy of the Mivumoni plant

If the plant in Mivumoni is fed at its full potential, it will be difficult to use all biogas for charcoal substitution even after completion of the site extension, however. Unpublished and still preliminary results of Pezzati (2015) basing on detailed data of a school in Dar es Salaam indicate that the daily heat need will be around 80 m^3 of biogas for the planned 500 people of the monastery complex (the need includes cooking, washing clothes and washing dishes). This would correspond to an annual saving of about 5’900 US$ by substituting for charcoal. (Comparatively: Our preliminary estimation was approximately 55 m^3/d; see page 24). The operating result would be around zero calculating with the actual (high) investments for this pilot plant shown in Appendix 3 (taking into account that the running costs are a bit lower, when less material is necessary to feed the plant). I.e., it will **not be possible to write the investments off over ten years**.

The annual operating result could be improved to a win of about 2’600 US$ by using daily ~70 m^3 of biogas for electricity production. Therefore, it is recommended to install a generator in addition to the gas use for cocking.

Economy of a future plant in an urban area

In an urban area there is a lot of organic waste rich in energy. This will allow increasing the loading rate with easily degradable organic matter such as food, kitchen and market wastes. A preliminary estimation of Pezzati (2015) basing on literature suggests that with this kind of waste biogas productions of up to 2.5 - 3 m^3/m^3*day can be achieved by adding daily 3.2 metric tons of a mixture of food and market wastes with 18% dry matter at an organic matter content of 90% (HRT = ~30 d, LR = 5.2 kg OM/m^3*d). This will allow producing yearly ~200 MWh of electricity representing a value of approximately 23’000 US$. Taking into account the slightly higher investment costs (larger motor) and operating costs (more labor), an annual operating result of about 15’000 US$ can be achieved.

When digesting energy-rich wastes is presumably possible to **pay back the investments of a well-planned 100 m^3 plant within less than 3 years**, without taking into account a possible use of waste heat from co-generation as well as the benefits of producing an improved fertilizer and soil conditioner.

Economy: conclusions

The data achieved so far show that it is possible to run simple medium-size plug-flow reactors at economically favourable conditions. The “U”-shaped plug-flow reactor is the simplest way constructing a biogas plant including all parts necessary for a good digestion. Regrettably, it was not yet possible to prove the technical performance of the Mivumoni plant at high loading rates. However, vast experiences achieved with sophisticated as well as simple straight designs of plug-flow reactors suggest a good functioning of the chosen solution.

It seems to be reasonable to build an improved reactor in a town in collaboration with a local technical university, where staff and students can supervise the operation and test different operating conditions. This will allow achieving more detailed data in order to determine more precisely the optimal operation conditions for different substrates and their economic implications.

Next steps

In Mivumoni

In a first step – which is actually on the way – the **DM content** of the plant has to be **increased**. The loading rate has to be adapted to the biogas need (as done actually).

In order to be able to increase the LR, It is important to **connect additional kitchens** to the gas grid. This needs some reflections because of the low gas pressure: It is reasonable to have gas storage balloons next to the users because of the pressure loss in long gas pipes. But it will be impossible to generate in all balloons the same pressure by putting exactly the right amount of bricks: the balloon with a little more weight on top will be filled last / emptied first. I.e. it will be necessary to find an easy way for the management of the future gas storage. This is been examined – between others – in a master study work at ETHZ (Pezzati, 2015).

In addition, it seems to be reasonable to consider the possibility of installing a "**biogas-bag filling station**" for the people of the village Mivumoni (c.f. Appendix 6): Carrying biogas by bags (Pütz K., 2015) to users outside the monastery complex is a good idea to substitute for more charcoal, thus improving the ecological and economic earnings (Fig. 41).

Fig. 41:

Left: Pipe smoking Ede carrying the biogas needed for the meals of one family on his back. The bag has been filled at the little hose in Figure 30. (Picture: Lattmann)

Biogas bag on the outside of a house in Africa
(Picture: Pütz / www.swr.de)

However, the **bags** actually sold in Africa **could probably be improved**: In Mivumoni the material has been attacked by rats. Therefore it could be advantageous to construct the bags with strong tissue reinforced PVC, which can be repaired easily. There are also socio-economic questions to be answered: How is the acceptance to cook with biogas of the future users? What are the optimal size, construction/form and operation of the bag? Do the users buy one bag, which is afterwards replaced by a full one at the gate or at the plant? What's the charge for a filling? For clearing such questions, discussions with the local people, the staff of the monastery and also with technicians of the balloon factory will be necessary.

Though, in order to increase the LR and also to improve the profitability of the Mivumoni plant, it seems to be reasonable to **install a gas motor for electricity production**. Actually, a robust and reliable, easy to repair Indian biogas power system - Pradash PNG-15-BG, natural aspiration, delivering maximally 15 KW_{el} - could be placed at the monastery sponsored by Ökozentrum Langenbruck (Fig. 42). There, the motor was evaluated 2007-2008 by M. Schmid. It consumes ~8 m^3 biogas/h. This would allow e.g. to pump ground water into the tower during some hours at night and to run some agricultural motors and/or (sponsored) washing machines during daytime in addition to covering all the heat needs directly by gas.

Currently, some batteries are charged by solar energy during daytime. This energy is used mainly for lighting and for two small refrigerators. For large motors, such as for the pump that exhausts the digestate storing pit, the electricity is produced by a diesel driven generator. Thus it is recommended to clear, whether and how this biogas motor could be integrated into the energy concept of Mivumoni.

Fig. 42:

Pradash biogas power system

In general, but especially when increasing the loading rate, it is most important to **translate** the (possibly adapted and extended) **manual** for the plant operation in Kiswahili by the local staff (cf. Appendix 4). For running the plant while feeding significantly more biogenic waste, it will be necessary to employ a person responsible for the plant operation. An additional training course for the staff involved seems to be necessary.

With the company producing the **nozzles** it should be clarified in which countries there exist (or will exist, respectively) agencies selling their products.

Regarding the arbi plug-flow digester technology

The **design and fixation of the membrane** covering the digester **has to be improved** in contact with the company that delivered the membranes. It has to be clarified, what some standard sizes of covers made out of high quality, UV-proof and easy repair material will cost incl. shipping (e.g. for 40, 80 and 120 m^3 digester size). At the same time it has to be cleared, how the crown of the digester has to be constructed so that it fits with the cover.

In order to achieve further knowledge and experience, it is recommended to **build a plant in an urban area** digesting wastes with a high DM and OM-content, such as organic household and market wastes (Fig. 43) and/or industrial wastes. As already mentioned above, this plant is built preferably in collaboration with a local university: This allows supervising the plant at different running conditions by students and staff of the university as well as exchanging and publishing the experiences made.

Respecting the experiences made, it is desirable to define some standard sizes of plants and to write **manuals for the plant construction and operation** including a list of construction elements (including alternatives, if components are no locally available). It has to be clarified, whether it is reasonable to produce and offer some parts, such as the overpressure device, at cost saving prices. One could even imagine offering a set including balloon, overpressure device and some small parts such as nozzles, water proof bush for the stirring axle, and a construction manual at an inexpensive price.

Fig. 43:

Right: view on a tiny part of the mountain of household wastes in Denpassar, Bali. A very large part of the daily delivered 800 m^3 is organic - polluting air, ground and water (Photo R. Warthmann, zhaw)

Left: market wastes of a market of Djakarta: it would be easily feasible to make two heaps: one organic and one inorganic.
(Photo: Edelmann)

In general

Today it seems to be crucial to make in developing countries a **step towards reliable, medium size biogas plants** (40 – >200 m^3), which produce enough gas to run a gas motor. The small, traditional plants work well in many cases. But their potential is very limited because they use normally highly diluted animal manure and there are a quite high percentage of plants that do not work properly or not at all any more. Depending on the local social preconditions, it should be examined, whether it is possible to build a somewhat larger plant instead of several small ones, digesting – besides of manure – organic solid wastes, which yield a lot more biogas. The results of this project suggest that in many cases the construction of an appropriate medium size plant could be more reliable and economically significantly more interesting than constructing several small plants.

Biogas production is a **multi-disciplinary task**: it concerns many fields, such as engineering and construction, microbiology and biotechnology, electrical and mechanical engineering and – last, but not least – agronomy. Not only in developed countries, but even more in developing countries inter-disciplinary collaboration is not widespread at all. It is a *most urgent* task to create inter-disciplinary biogas projects in developing countries, where different faculties work closely together.

In this context, zhaw and arbi propose to build up **competence centres for biogas research**, for the transfer of know-how and the joint development of appropriate solutions to digest solid wastes as well as industrial waste waters containing organic compounds. Together with Udayana University in Denpassar, Bali, a project proposal has been submitted to Repic. (Warthmann and Edelmann, 2014). Currently, the partners have to find additional funding as well as to establish in Bali an interdisciplinary network for the project at the university and also within the country.

The digestate, i.e. the **fertilizer and soil conditioner** produced is at least as important as the production of renewable energy. It shows very good properties for agricultural application (Bafu, 2007; regarding the advantages of the digestate for fertilizing see also Appendix 4, p. 66). For a sustainable survival of mankind it is extremely important to recycle to our soils the inorganic nutrients as well as humus forming compounds as much as possible. It is not by chance that FAO has declared the year 2015 to be the international "Year of Soils – healthy soils for healthy life" (FAO 2015). Unfortunately, in developing countries well-grounded know-how on the application of organic fertilizer is missing to a large extent. There are many open questions about how to store, transport und applicate organic fertilizers, especially digestate, and how to reduce with simple measures the ammonia losses while storing and bringing out the digestate. The main problem of the digestate is an increased ammonium concentration at an increased pH-value, what increases the danger of ammonia volatilization significantly (Edelmann et al., 2005 b). Here, there is still a large field for additional applied research and also for information of the operators of biogas plants.

At the same time, it seems to be most important to improve the contacts and the know-how exchange between governmental agencies, NGO's, plant constructors and operators: At the biogas seminar organized within the limits of this project in Tanga, Tanzania, (cf. list of participants, Appendix 5) it was evident, that some participants working on the same subject in the same country did even not know each other! Therefore, it is proposed to organize at regular intervals **meetings/seminars/congresses**, where representatives of biogas organizations from different countries as well as delegates of foreign aid organisations can exchange their experiences with biogas in emerging countries as well as develop strategies for the future development of bioenergy.

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Final remarks

a.) Congratulations that you reached until here reading this report ☺ !

b.) If you think it was interesting, please forward it to other people interested in biogas!

c.) If you should consider building a similar plant, feel free to contact us at info@arbi.ch ! We are happy to give you some news, support or advice – if we can…!

d.) If you have built a similar plant, we are very happy to receive some links, data and comments on your operating experiences!

We do wish you all the best in the field of "Applied Fartology"!

For the Mivumoni-Team: Werner "Ede" Edelmann

January, 2015

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Annexes

Appendix 1: Abstract of the Bachelor thesis of Michel Muther and Janick Stähli

Development and characterization of a biogas cooking place for developing countries

zhaw, 9.2012

Abstract

The silencers of the Porsilent company are already known from the pneumatic industry. In this paper these silencers are getting used and analyzed as burner. The scientific findings are the basis for the cooking zone which is powered by biogas. These robust and cheap jets permit operation at very low gas pressure. This saves investment costs in infrastructure and minimizes maintenance on the distribution network.

In Tanzania (Mivumoni) the biogas plant produces energy for cooking. A biogas-powered cooking zone with a capacity volume of 5 l, which is based on these silencers, should run faster than a conventional electric cooking zone. There is also a big cooking zone which should be powered by biogas or as an alternative with firewood. The aim of this topic is to figure out how many jets, which jet-types and in which arrangement the best results are achieved for both cooking zones. Based on these results a concept-plan for the big cooking zone will be elaborated.

The biogas plant in Hünenberg was the source for the experiments conducted with simulation cooking pots with different-sized silencers. In the first step the flow rate of the jets were determined. In a further stage, the nozzles were tested individually whilst the gas pressure and the distance to the cooking pot have been changed. These tests showed that the PSS 12 with a pressure of 1 mbar is the most efficient. With this scientific finding a circle with three and four PSS 12 jets had been created and tested. In this experiment the pressure and the diameter of the arrangement had been changed and analyzed to determine which setting is the most efficient.

The results of these experiments were that the small cooking zone should be run by a single PSS 14 jet. This type can be well regulated and shows the best efficiency. The big cooking zone is optimally heated with a tube construction of galvanized steel tubes and a ball valve. The choice of the jet is the PSS 11. This type works with a pressure between 1 to 3.5 mbar and an efficiency of 30 to 44% and boils 40l water with an operating pressure of 2 mbar in only 34.9 minutes. The cooking zone can also run with an arrangement of three PSS 12 jets. The efficiency is a bit more balanced but the construction is more expensive and the handling more complicated. Moreover, the efficiency at a low pressure is not as good as when it is heated by a single big PSS 11 jet.

Appendix 2: Abstract of the Bachelor thesis of Sabrina Huber

Measurements and experiences while operating a novel plug-flow Digester for developing countries in Mivumoni, Tanzania

zhaw, 10. 2014

Abstract

Not only in Europe has interest in biogas shown a significant increase in the last few years, but this form of renewable energy is also on the rise in developing countries. For example, in China some 40 million biogas plants were installed in 2011 thanks to national and international support programs (Vögeli, Lohri, Gallardo, Diener, & Zurbrügg, 2014).

The types of biogas plant used in developing countries have distinct differences in their dimensions, technical equipment and end use of the biogas compared to plant used in industrial countries. The three main plant types are the fixed-dome digester, the floating-drum digester and the tubular digester. All types have inherent advantages and disadvantages.

The situation in Tanzania is very similar to that in other developing countries. Currently, more than 75 % of the Tanzanian population lives in rural areas. Up to 94% of energy needs are currently met using organic mass, mainly firewood (biomass). It is the duty of the women and the children to collect the firewood, where need outweighs environmental considerations. The high consumption of firewood promotes deforestation and soil. Most families use either kerosene, firewood or charcoal for cooking. Tanzania, after Kenya, is one of the predominant African countries in the biogas sector. With the help of the national biogas program *Tanzanian Domestic Biogas Program* (TDBP), more than 10'000 biogas plants have been installed and commissioned.

In 2012, a new type of plug flow digester was installed in the compound of the Capuchin Sisters in Mivumoni, Tanzania by a Swiss planning team. It is a U-shaped structure with a reactor volume of 106.5 m^3 covered with a gas membrane. The substrate mainly used is the excrement of more than 180 cows from the farm run by the monastery. Some of the planners involved have previous experience with biogas plant in developing countries and have set clear goals that should be met by the new biogas plant in Mivumoni. After two years in operation, sufficient data was available to perform an analysis of the system.

Measurements of the weight and volume of the substrate used have been recorded along with other measurements in and around the plant. With the data, some common operational parameters were calculated which provided insight into the biochemical process and the mode of operation. In addition, issues involving structural components of the system were analysed and these were improved where possible.

Evaluations of the measurements show that the full potential of the plant is not being used. At the moment, the plant is operating under very low loading rate. The average daily production of biogas is 11.8 Nm^3. The hydraulic retention time is currently over eight months. The organic loading rate corresponds with 0.37 kg oTS/ (m^3*day) which is far less than the recommended rate of 2 to 5 kg oTS/ (m^3*day) (Schünemeyer, 2005). Only the specific gas production is within the scope of the characteristic values of 0.15 to 0.53 m^3 /kg oTS (Bayerisches Landesamt für Umwelt, 2007).

The capacity of the biogas plant is therefore not being fully utilised because presently the biogas yield only covers the self-consumption and there is currently no other way to use the gas in the compound. It is anticipated that once further opportunities for using the gas become available, increasing production at the plant with the available substrate should be quite feasible.

Appendix 3: Investment costs of the biogas plant

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FRANCISCAN SISTERS IN MIVOMONI, PANGANI, PO BOX 1680, MOSHI, TZ

INVOICE BIO GAS PLANT 10. 4. 2013

NO	ITEM DESCRIPTION	UNIT	QTY	RATE TSHS.	AMOUNT TSHS.	US$ (1= 1'800 TSH)
0	PRIME COSTS. MOBILIZATION	SHL			4'500'000	2'500
	SUBSTRUCTURE					
1	Site clearance					
	Remove 150mm thick top vegetable top soil	m²	120	3'500	420'000	233
2	Foundation					
2.1	* Excavation 240 cm deep	m³	225	15'500	3'487'500	1'938
2.2	* Excavation of pad foundation for columns 150 x 150 cm	m³	7	12'000	84'000	47
2.3	Moving the soil to Sister house	m3	160	8'500	1'360'000	756
2.4	Backfilling	m3	65	6'000	162'500	90
2.5	150mm thick compacted hardcore	m²	65	14'800	962'000	534
2.6	Formwork for a strip footing column base and ground beam	m²	9	37'500	337'500	188
2.7	Reinforcement for columns and ground beam 16mm dia High tensile steel	Kgs	260	4'500	1'170'000	650
	12mm dia High tensile steel	Kgs	1300	4'500	5'850'000	3'250
2.8	Concrete					
	* Plan concrete grade 20 for strip footing	m³	3	325'000	975'000	542
	* Reinforced concrete grade 25 for column base, ground beam and concrete floor slab	m³	16	355'000	5'680'000	3'156
	SUPERSTRUCTURE					
1	Block work					
	* 230mm thick solid block laying with cement mortar (1:4)	m²	96	38'000	3'648'000	2'027
	* 150mm thick solid blocklaying with cement mortar (1:4)	m²	10	35'000	350'000	194
2	Formwork					
	Formwork for columns, upper beam	m²	40	37'500	1'500'000	833
3	tensile steel	Kgs				
	12mm dia high tensile steel	Kgs	480	4'500	2'160'000	1'200
4	Concrete					
	Cast reinforced concrete grade 25 for upperbeams and columns	m³	3	355'000	1'065'000	592
5	Roof Structure					
	51 x 150mm Rafters, struts, tie beam & wall plate	m	350	17'500	6'125'000	3'403
12	Finishes					
	Wall					
	* 15mm thick material plastering with Cement mortar (1:4)	m²	195	8'500	1'657'500	921
	40mm thick cement sand screed floor finish	m²	65	8'000	520'000	289
13	PRELIMINARIES 10%	SHL			4'200'000	2'333
	TOTAL				**41'714'000**	**23'174**

INVOICE BIO GAS PLANT / FENCE / MIXER

NO	ITEM DESCRIPTION	UNIT	QTY	RATE TSHS.	AMOUNT TSHS.	US$ (1= 1'800)
	SUBSTRUCTURE					
1	**Site clearance**					
	Leveling site	shl			150000	83
2	**Foundation**					
2.1	* Excavation					
	60 cm deep for posts	no	31	10'000	310000	172
2.8	**Concrete**					0
	* Plan concrete grade 20 for foundation	m^3	3	325'000	975000	542
3	Steel post 50mm	no	31	55'000	1705000	947
4	Chain link wire 180cm h	m	93	14'500	1348500	749
5	Steelwire 3 line	m	300	3'000	900000	500
6	gate 350 cm x 180 cm	no	1		800000	444
7	Spannset	no	12	25'000	300000	167
8	gate 150 cm x 180 cm	no	1		250000	139
	Total Fence				**6738500**	**3744**
9	**MIXER**	$				**4770**

INVOICE BIO GAS PLANT / STORAGE DIGESTATE

NO	ITEM DESCRIPTION	UNIT	QTY	RATE TSHS.	AMOUNT TSHS.	US$ (1 = 1'800)
	SUBSTRUCTURE					
1	**Site clearance**					
	Remove 150mm thick top vegetable top soil	m^2	100.00	3'500	350'000	194
2	**Foundation**					
2.1	* Excavation					
	160 cm deep	m^3	200.00	15'500	3'100'000	1'722
	* Excavation of pad foundation for columns					
	150 x 150 cm	m^3	7.00	12'000	84'000	47
	Moving the soil to Sister house	m3	100.00	8'500	850'000	472
	Backfilling	m3	65.00	6'000	162'500	90
2.4	150mm thick compacted hardcore	m^2	95	14'800	1'406'000	781
2.6	Formwork for a strip footing column base and					
	ground beam.	m^2	9.00	37'500	337'500	188
2.7	Reinforcement for columns and ground beam					
	16mm dia High tensile steel	Kgs	260.00	4'500	1'170'000	650
	12mm dia High tensile steel	Kgs	1100.00	4'500	4'950'000	2'750
2.8	**Concrete**					
	* Plan concrete grade 20 for strip footing	m^3	3.00	325'000	975'000	542
	* Reinforced concrete grade 25 for column					
	base, ground beam and concrete floor slab	m^3	16.00	355'000	5'680'000	3'156
	SUPERSTRUCTURE					
1	**Block work**					
	* 230mm thick solid block laying with cement					
	mortar (1:4)	m^2	50.00	38'000	1'900'000	1'056
	* 150mm thick solid blocklaying with cement					
	mortar (1:4)	m^2	10.00	35'000	350'000	194
3	Re-bar work for columns and upper beam					
	12mm dia high tensile steel	Kgs	320.00	4'500	1'440'000	800
4	**Concrete**					
	Cast reinforced concrete grade 25 for upper					
	beams and columns	m^3	3.00	355'000	1'065'000	592
12	**Finishes**					
	Wall					
	* 15mm thick material plastering with					
	Cement mortar (1:4)	m^2	125.00	8'500	1'062'500	590
	Floor					
	40mm thick cement sand screed floor finish	m^2	95.00	8'000	760'000	422
13	**PRELIMINARIES 10%**	SHL			2'700'000	1'500
	TOTAL				**29'467'500**	**16'371**

Appendix 4: Manual for the plant operation

Manual for the operation of the biogas plant

General safety remarks:

- Biogas is a mixture of Methane and Carbon Dioxide (CO_2) of about 2:1. **Methane burns** and may form an **explosive mixture** when mixed with enough air. Therefore **do not smoke or use fire in the neighbourhood of the plant or of gas pipes** etc., because there might be a gas leakage (what we naturally do not hope…..!).

- In addition, there are some gases such as water vapour and **Hydrogensulfide** (H_2S) in the biogas. Hydrogensulfide stinks like rotten eggs and is poisonous, if biogas escapes into enclosed rooms (e.g. into the kitchen, while the windows and the doors are closed). Therefore: if biogas has escaped (e.g. because a valve has not been closed well in the kitchen), **aerate the room immediately and do not smoke or light a fire**!

- Inside the biogas plant there are **anaerobic conditions**, i.e. there is no oxygen at all in the biogas. Therefore it is dangerous to go for a revision inside the plant, even if the content has been pumped out to a large extent! Be sure, that the gas is really exchanged by air – or better: **remove the membrane of the digester**!

Feeding of the plant:

- **All organic materials** – such as animal manure, kitchen wastes, harvesting residues, grass, straw, waste plant oil etc. – **produce biogas**, **with the exception of wood**, which is practically not digestible. Therefore it makes no sense to introduce wood into the plant (it just takes room which is better used for digestible matter).

- Some water is needed for the survival of the bacteria, but **water does not produce any biogas**! (i.e. it just takes away volume necessary for the organic matter to be digested.) This biogas plant should be able to handle quite “thick” substrates. So do **add as few water as possible** when feeding the plant!

- Remember, it is the same with cows or men: “**well chewing is half of the digestion**”! If the raw material is chopped into small pieces, the bacteria have more surface, where they can attack the organic matter (the enzymes of the bacteria degrade always just organic compounds at the surface of the organic particles). Therefore: **The smaller the pieces fed - the better!,** i.e. the quicker and more complete is the digestion (e.g. do not throw whole pineapples into the inlet pit, but chop them first into pieces!)

- Mineral matter, such as **stones or sand**, sinks to the ground inside the plant. This sediment also takes unnecessarily volume away, which is better used for digestion! It will make it necessary to open the plant after a certain time in order to remove these sediments out of the plant (what’s time consuming and hard work!). Therefore: **Take care to import as few stones and sand as possible** into the plant together with manure or other substrates in order to reduce the risk of unwanted maintenance works.

- The lower part of the **inlet pit** (Fig. 2; further down) is separated by a little wall from the inside of the digester (40 cm high; Fig. 1). Hopefully heavy stones and sand – which never can be eliminated totally - sink down to the ground of the inlet pit and **do not enter** into the digester! For this reason it is very important to **mix well the material, which you feed** inside the inlet pit with the mixing tool, in order to **let sink down these heavy mineral components** (and also for turning the input more homogeneous and better mixed with bacteria – see further down: re-inoculation).

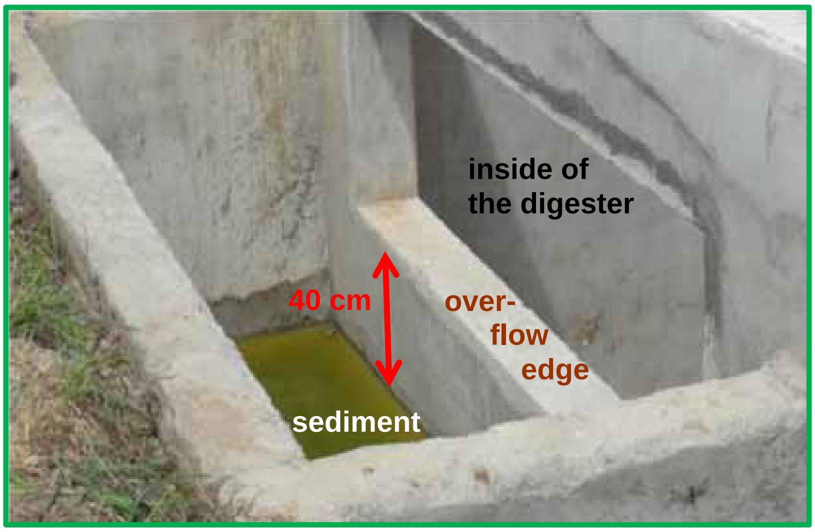

Fig 1: *View of the inlet pit with its lower part, where most sediment will accumulate (hopefully..!). The part, were sediment may accumulate is 40 cm deep from the overflow edge to the bottom.* (Lattmann)

- Check regularly, whether **sediments have accumulated on the bottom of the inlet pit**! Check with the mixing device, where the overflow edge is and check subsequently the height of stones and sand at the bottom of the pit. If sediment has accumulated: **grab it out**, at the very latest before it reaches the height of the overflow edge at the entrance into the digester (Fig. 1)! (You may shovel the sediment on the mixing platform and wash the organic parts away before dumping it somewhere.)

- When **organic matter** is in contact with air, it **starts to decompose** and in addition manure of ruminants contains already many anaerobic bacteria. This degradation (fouling) reduces the biogas potential! Therefore **take care to use organic waste as quickly as possible** for biogas production!

- A biogas plant is an organism with similar needs as those of us! **Do not feed one day a huge amount and next day nothing**! Feed rather **three times a day** (or at least **twice**)! Feed **every day about the same amount**! (Maximum: about 3-4 m^3/day)

- The bacteria **do not like quick changes**, because they have to adapt their set of enzymes to the new diet. Therefore **do not change abruptly the diet**! (e.g. give cow manure every day and add first just a smaller part of the heap of rotting fruits instead of feeding one day cow manure and next day all of a sudden only oranges…!).

- Like us, the biogas plant likes a diet which is composed of different "dishes": Cow manure is ***not*** a good substrate for biogas production, because a cow is "a walking biogas plant", which has already degraded all the easily degradable matter. It is **very favourable to add so-called co-substrates**, such as kitchen wastes, wastes from harvesting or rotten fruits etc. etc. **All co-substrates produce more gas than manure**, because they have not already passed through stomachs and intestines!

- **"Solid" manure** can be dropped directly into the inlet pit. **Liquid manure** enters via the channel and the mixing platform. The **liquid manure may be used to humidify solid co-substrates**, which are chopped on the mixing platform. But take care that the input remains "thick" like a pudding.

Feeding procedure

Throw the solid manure directly into the inlet pit. Grind large particles of co-substrates on the mixing platform and humidify the pieces with liquid manure (if available/necessary). Throw the co-substrates into the inlet pit. Add now about 10 - 15% of material from the outlet pit into the inlet pit for re-inoculation (why: see further down!) and humidification: The "pudding" of the outlet pit will be usually more liquid than the raw material in the inlet pit. Therefore it will add – besides bacteria – some additional water to the inlet for humidification.

Then **mix well the mixture inside the inlet pit** using the metal bar with cross. The inlet pit is the place, where the material is mixed! (The stirring device inside the digester has another main purpose; see further down!) **Only if the "pudding" in the inlet pit is really too thick for moving the mixing device, add some buckets of urine or fresh water from the tank**!

Operation of the installation:

The following figure 2 shows a birds view of the digester covered gastight by a green PVC-membrane (green colour in Fig. 2): The raw material enters or via the channel and the **mixing platform** or by dropping it directly into the **inlet pit**, from where it is moved into the digester when feeding next time.

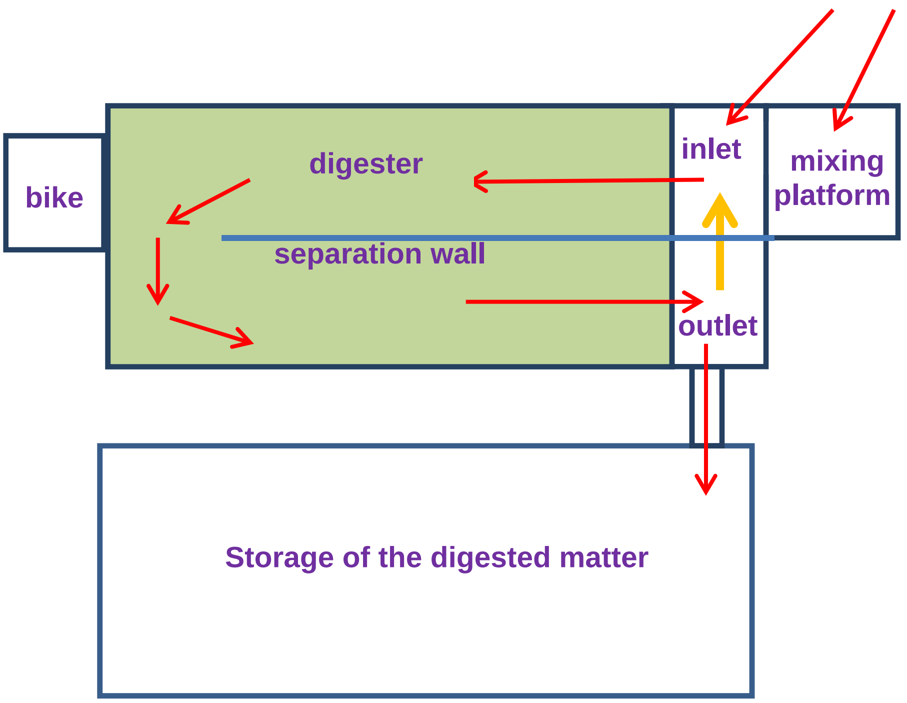

***Fig. 2**: Birds view of the biogas plant*

The **digester** is a so-called **plug flow digester**, i.e. the material enters through the opening at the inlet pit and **has** to flow all way around the separation wall to the opening at the outlet pit. This has the big advantage that it is impossible, that some fresh material is already exported the same day when it was fed. (This happens in all other, more or less completely mixed digesters!) Therefore, all material stays for about the same time inside the digester. This guarantees that **no biogas potential is lost** and at the same time that practically **all pathogen germs** (unwanted bacteria such as *Salmonella*, germs of weeds, viruses, phytopathogen germs, eggs of *Ascaris* etc.) **are killed** and that the output is free of contaminants causing diseases!

Inside the digester, there are **three groups of anaerobic bacteria** – i.e. bacteria living without oxygen - which work together and depend on each other:

- First, the **hydrolytic bacteria** “chop” the very large macro-molecules into small pieces.
- Then the **acidifying bacteria** produce out of those pieces small organic fatty acids, i.e. mainly acetic acid.
- At the end the **methanogenic bacteria** convert acetic acid, hydrogen and CO_2 into biogas.

Re-inoculation:

The methanogenic bacteria are located mainly towards the outlet side and they grow very slowly (duplication time: more than one week!). **Especially when feeding much** (i.e. when the retention time of the material is less than ~30 days in the digester) it exists therefore the danger to export too many methanogenic bacteria with the output (they cannot duplicate any more quickly enough) and the digester runs sour! **Therefore it is reasonable to re-inoculate the input at high loading rates by adding ~15% of digested output material to the raw input material**, in order to **increase the bacterial number** within the input and thus within the plant (yellow arrow in Fig. 2). **More bacteria make the same job faster**, i.e. they degrade better the substrates and produce more gas! For this reason, this plant design has especially been developed to have input and output pit side by side for easy re-inoculation.

The about 15% material for re-inoculation has the advantage to **add additional liquid** into the fresh material: There is a liquefaction of the raw material during digestion, because the degradable solids are converted into biogas. (However, the mineral compounds important for plant growth remain dissolved in the water of the output, as explained further down in the chapter on fertilizing with digested slurry!)

“Stirring”, i.e. gently moving respectively:

On the inlet side the particles are not degraded into tiny pieces yet. As the bacteria produce gas, solid particles may move upwards with tiny gas bubbles attached at their surface and form a **solid sum layer at the surface, if too much water is added to the input**. This scum layer may become very solid and thick, hindering digestion. With little water, there is no danger of a scum layer, but the bubbles have more difficulty to rise up to the surface. Therefore the content has to be moved gently from time to time. This is not mixing in terms of shaking a drink, but just a **<u>very</u> gentle opening of some ways for the escaping of gas** by freeing the little gas bubbles.

The mixing is done by using the bicycle: There is an **axis with some mixing arms on the inlet side** of the digester. These arms are turning **all slowly** (pole pole!) rectangular to the flow direction inside the “pudding”, i.e. there is no mixture forwards and backwards hindering the function of the plug flow design. At the same time, gradients of chemical compounds within the slurry (such as fatty acid concentrations etc.) will be equalized. On the outlet-side, the material is already a lot more homogeneous and more liquid due to the hydrolysis happening mainly on the inlet side. There, it seems not to be necessary to break a scum layer and therefore no mixing device is installed inside the outlet half of the digester.

It is proposed to start “biking” with **3 times five minutes per day** and to increase the frequency, if one realizes that the resistance of the pedals increases every day. If there is little resistance, the frequency may be lowered to 2 times per day. There is a **bull’s eye** within the gas holder at the end of the inlet side, where – preferably at night using a lamp – it should be possible to **watch the state of the slurry** as well as the functioning of the stirrer arms. Not all materials behave the same way; the formation of a scum layer is only probable when adding too much water, facilitating the separation of sediment and a scum layer with a watery phase in between.

Fertilizing with digested matter:

All the material of the outlet pit, which is not used for re-inoculation, flows over the edge of the outlet pit into the storage tank (see Fig. 2; **storage of the digested matter**), from where it may be brought out to the fields and used for fertilizing purposes.

The digested matter ("digestate") shows **many advantages**:

- It contains still **all the mineral nutrients important for plant growth**, such as Ammonia, Phosphate and other ions. (Only C, H, O and eventually some Sulfur will escape with the gas).
- Due to the mineralization process by bacterial degradation, **more nutrients** are transformed into a mineral form and consequently dissolved in the liquid. Therefore, they are **available immediately for the roots** of the plants on the field. (Therefore: Bring the digestate out, when the plants start to grow, i.e. not too early, because of possible loss by washing them out into the ground water with heavy rain fall).
- The small and the easily degradable organic compounds have been digested. Therefore the digester **output does not stink anymore**!
- The organic acids have been digested. Therefore the output **does not "burn" anymore** when brought out – what is good for the organisms living in the soil!
- The **refractory organic compounds** (compounds difficult to be broken down by anaerobic bacteria, such as humic acids) are important for the formation of humus and thus for the vitality of the soil. They **remain in the outpu**t and increase the fertility of the soil!
- In contrast to undigested organic matter, **the output is hygienically safe!**
- Due to the degradation of the solid particles, the output shows better flow characteristics, i.e. it **infiltrates better and quicker the soil** than untreated manure, what reduces the loss of nutrients, such as – to some extent - ammonia evaporating at the air.

The digestate shows one *disadvantage* in comparison with undigested organic matter: During decomposition, Ammonium (NH_4^+) is liberated. **Ammonium** is in a chemical equilibrium with volatile Ammonia (NH_3). Higher pH-values favour the volatile Ammonia in relation to the non-volatile **Ammonium**. On the one hand, digestion raises the pH-value and on the other one the Ammonium concentration increases. Thus, there may be up to ten times more Ammonia present in the digestate than in undigested organic matter. This **causes significant nitrogen losses by Ammonia volatilization** without additional measures (These losses are reduced just partially by the quicker infiltration of the digestate into the soil, as mentioned above).

Ammonia is harmful for the environment. In order to keep Ammonia losses as small as possible, it is very important to **bring out the digestate whenever possible at times with low temperatures** (i.e. not at noon, but in the early morning or at night) and preferably on humid (not wet) grounds, where infiltration is favoured. It is also advantageous not to spray the digestate with high power for hindering the Ammonia losses. It is better to **discharge it by pouring it gently on the ground**. Ammoinia losses may be reduced by covering the storage pit (e.g. with a plastic foil) hindering the intense contact of the stored digestate with the open air.

Because the output of anaerobic digestion shows these very positive properties mentioned above, it is **highly recommended to stop the composting** of organic matter: **All** biomass can be digested with the exception of wood: Woody material may be used as mulch or fire wood, if it is not composted.

The gas distribution and utilization system:

There are some components of the gas distribution which need an explanation:

- First, the biogas is led via a flexible tube to a **first gas meter** (gas meter 1) attached on the wall of the bike shelter (Fig. 2): this meter measures **all biogas produced**. There are two closing valves on both sides of the gas meter for closing the gas lines for short revisions (see further down). However, the handles are *not* mounted: if one of these valves remains closed, the gas cannot escape, thus increasing the pressure in the digester and damaging the digester membrane.

- Unfortunately, there **condensation water accumulates in the gas meter**. However, it has been mounted a little tap for **regular draining** of the water (Fig. 3)!


Fig. 3: *Gas meter near the biogas plant with a little tap for dumping the condensate (R. Lattmann).*

- The gas meter is followed by an **overpressure protection**: If the gas cannot escape towards the gas users (e.g. when the storage balloon is already full) it must be possible that the additional gas, which is formed continuously, can escape somewhere else, i.e. through the overpressure protection tube. In order to avoid that gas can escape under normal conditions the **water level must always be around the middle between the min and the max sign!!!** The overpressure protection is **very important** to protect the membrane of the digester as well as the gas storage balloon near the kitchen. Too much water may also damage the balloons! Therefore control regularly and drain some water with the tap, if condensate has accumulated in the bucket!

- **Under normal conditions, the pressure in the gas system is low**: Only about 2 mbar, what corresponds to **2 cm of height difference** between the water level on the right and left hand side of the u-shaped tube, respectively. The pressure is generated by putting weight on the gas balloon near the kitchen. Low pressures show the advantage of less gas losses, if there is eventually a small gas leak somewhere in the piping.

- The **pressure needed for opening the overpressure device is about 5 - max. 8 mbar**. At normal conditions the water inside of the bucket in the middle between the "min" and the "max" sign. If at normal running conditions, i.e. gas storage balloon I not completely full, the water level is higher than the middle, let some **water flow out at the tap**! If the level shod go once towards "min", add some water. If the gas storage balloon is 100% full, the gas bubbles through the water and may escape through the pipe towards the flare.

- If the overpressure device is working, the gas will escape through a **sinter blast valve** on top of the fence, which serves as a **flare** (Fig. 4). So, if someone realizes that the storage balloon at the kitchen is full in the evening and nobody will use gas until the early morning, it is highly **recommended to light the gas** escaping through the sinter valve by using matches or a lighter. **Biogas is a greenhouse gas more than twentyfold stronger than CO_2 and very harmful for the climate, if it is not burnt!**

Fig. 4: *Sr. Agricola with an employee of Harald Frey looking at the flare (R. Lattmann)*

- After the overpressure branch there is a big red **closing valve** in the tube that leads to the storage balloon and the kitchens. This valve **may be closed, whenever somewhere the gas system has to be opened** (e.g. if the digester has to be opened for maintenance, i.e. for excavation of the sediments. So the gas within the balloon can still be used for cocking). In addition, there is also a small tap for taking biogas samples (normally closed).

- The long gas line towards the storage and the users is underground. The tubing shows slight declines towards the 4 **condensation traps**, which are located inside pits along the way. The traps consist of a hose coming out of the gas line at its deepest point and entering in a bucket filled with water. If water condensates in the line, it will flow through this hose into the bucket, which will overflow. However, it **has to be made sure regularly, that the buckets are full** (evaporation!); if there is no or just few water in one bucket, the whole biogas will escape there! Take care that the pits are not filled with water in the rainy season!

- The **gas storage balloon** stocks the gas production during periods, when there is no demand for biogas. The covering platform (metal frame) of the balloon guarantees **the gas pressure within the whole system**. There may be put some bricks on the edge of the covering on its side towards the building in order to increase the gas pressure, if a higher pressure is needed (see Fig. 5). Here it may need some experience to find out the best conditions: The actual value of the gas pressure can be seen at the “u”-shaped hose in the kitchen.

- From the balloon, the gas is led to the washing house and the kitchens. Before the line goes into the washing house, there is a **second gas meter** (gas meter 2). In the contrary to gas meter 1, this one measures only the gas, which is really used by the kitchens and the washing house. (The gas meter 1 measures the total, i.e. the gas used plus the gas escaping via the flare). The **values of the gas meters have to be filled daily into a protocol sheet**, in order to get more information on the functioning of the biogas plant.

Fig. 5: *The gas balloon is covered by a platform. Bricks may be added on its upper side (towards the building), if the gas pressure has to be increased. (Edelmann)*

- At the gas users, the gas is burnt with **sinter blast valves**, named “burners” from now on. If you need heat, open the closing valve ahead of the burner, light the gas escaping at the burner with a match or a lighter and put the burner under the pot that has to be heated. **Regulate the gas flow** by closing the gas valve partially and **regulate the heat around the pot by closing more or less the valve in the exhaust gas tube** of the stove! (Only possible with the big stoves; small burners are just placed underneath the pot to be heated). If the valve of the exhaust pipe is fully open, more air is sucked through the space around the pot and the efficiency of the heating is lower, because too much air cools the temperature! So, find out the optimal conditions for heating the pots!

- When the cocking is over, **be sure to close the closing valve tightly!!!** (See general remarks!). The big stoves can be fired also by wood, if necessary (gas balloon empty, maintenance works etc.).

- Last, but not least: **Enjoy your meal !!!** It is cooked with organic waste and its cooking has **no negative effect on the environment**!

Maintenance:

The following Table 1 shows the works and the interval of the works that have to be done. The list is not complete, however: In addition it is necessary that those, who are responsible for the plant, keep their eyes always open, when they are near the plant! (Are the doors of the fence closed, that no cow may enter and damage the digester membrane? Is there some unexpected observation that should be written into the protocol? etc.)

Action:	**When:**
Collect the raw material, chop ev. co-substrates and feed all into the inlet pit of the digester	2-3 times per day
Add 15% of digested material to the input	When feeding much
Mix **well** the material inside the inlet pit (sedimentation!)	When feeding
Operate the bike for 5 minutes	3 times per day (ev. + or -)
Check the amount of water in the overpressure device	daily
Check the system gas pressure in the kitchen	daily
Check whether all closing valves are in the correct position	daily
Read the gas meters 1 and 2 (note date and time)	daily
Estimate and protocol the amount of materials fed per day	daily
Empty the condensate within the 1. gas meter	Daily (if necessary)
Refill all buckets of the condensation traps with water	weekly (ev. more often)
Clean the bull's eye with water	weekly (ev. more seldom)
Control the level of sediments in the inlet pit	weekly
Watch the mixing device through the bull's eye	When information on the interior of the plant is needed
Burn the gas escaping at the flare	When necessary (balloon full)
Take the sediment out from the inlet pit	When necessary
Take the sediment out of the digester (i.e. opening and taking all material out)	When necessary (see trouble shooting)

Tab. 1: *Works and intervals of works to do at the biogas plant*

Trouble shooting:

No gas in the storage balloon:

- Check at the bike, whether **the gas meter 1 is turning**, i.e. whether there is gas production within the digester.
- **If the meter 1 is *not* turning**: check, whether somebody has closed one of the closing valves immediately before and after the gas meter. If closed: **open it/them immediately**! (These valves may be closed for a quick revision of the gas meter only! Therefore the handles are not mounted.)
- If the valves at the meter are open and there is no gas: see further down “no gas in the digester membrane” or “poor gas quality”.
- **If the meter 1 is turning**: Wait eventually an hour and watch, whether the storage balloon is growing again (Perhaps it was just down because of high gas demand).
- Check whether there is enough water in the overpressure device; refill if necessary!
- Check, whether a bucket in one of the condensation traps is not filled well with water, allowing gas to escape in the condensation trap!
- Check, whether all closing valves at the users (kitchens, washing house etc.) are closed!
- If all these points are OK, check whether there is somewhere a leakage in the gas line or in the storage gas balloon (try to smell the odour of biogas!).
- If necessary, contact Rolf Lattmann (address at the end).

No gas in the digester membrane:

- Check, whether the gas tube between the membrane and gas meter 1 is fixed well.
- Check (with eyes and nose…), whether there is a leakage in the gas membrane. If yes: mend it with a piece of membrane and PVC-glue according to the manual of the glue.

Poor gas quality:

It is a sign of poor gas quality, i.e. low methane content, if the flame shows a more red/yellowish colour with few bluish components: Methane burns with a light blue flame, which can be well seen in the dark; at daylight it is nearly invisible. The gas quality depends on the one hand on the raw material fed: the higher the percentage of fats and oils, the better the gas. On the other hand, bad gas quality may be a sign of overloading the digester and of wash out of the methanogenic bacteria (much CO_2 in the gas).

- If possible: measure the pH-value of the material in the outlet pit. If it is <7, there is the **danger that the digester runs sour**! **Stop all feeding immediately** (like us, when we have stomach problems…!). Wait until the gas is good again and the pH-value has risen to 7-8. This may need some days! Then re-start to feed **raising slowly the diet and increase the re-inoculation rate**.
- If gas production stops and does not recover any more, the digester has run sour. Then you must pump out all material and restart the process with fresh cow manure. (This happens *very* rarely and only when not observing the points named above, however.)

Contacts in case of trouble:

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We wish you a lot of pleasure with your renewable energy!

The arbi - team

Appendix 5: The Biogas Seminar in Tanga, Tanzania

On August 19 - 21, 2013, a biogas seminar financed by this project was organized in the Nyinda Classic Hotel in Tanga with participants mainly from Kenya and Tanzania (see list of participants). In the seminar room all participants presented their works (ppt's available) and discussed different topics. One day was used for an excursion to different small fixed dome digesters, to the Mivumoni biogas plant as well as to the industrial Katani plant near Muheza, where a part of the waste originating from treating sisal fibers is digested in a completely mixed digester for electricity production.

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List of participants of the biogas seminar in Tanga, Tanzania, on August 19 - 21, 2013.

Demonstrating the functioning of the "Testorit"-instrument at the field excursion: a cheap device for measuring the CO_2-content of the biogas.

Appendix 6: Pictures of Mivumoni (Nivumomingi) (© Google Earth 2015)

Above: The small village of Mivumoni (V) and the monastery area (M) at the dirt road connecting Muheza and Pangani

Below: The area of the monastery: stable (S), digester (D), storing balloon (B), guest house (G), new lodging of the boarding school (L)