Biogas from Solid Waste

Conception and Construction of a Dry Fermentation Pilot Plant
for Developing Countries

Master Thesis by

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Abstract

In most parts of the world, the population living in cities is growing. Urbanisation leads to major waste management and energy supply problems. Dry anaerobic digestion is a technology that can help to improve both the waste and the energy situation. In the investigated, discontinuous dry digestion process organic solid waste is filled batch-wise into garage-like digesters without mixing it with water or reducing its size. In Europe, such systems have been developed and implemented successfully. However they are generally costly and complex. To investigate the suitability of the technology in developing countries a pilot plant is constructed and tested in Kumasi, Ghana, in collaboration with the Kwame Nkrumah University of Science and Technology.

The pilot plant proves that the technical construction is possible at a low price with local material. On the basis of a shipping container a dry fermentation plant is built and tested. The major challenge is the construction of an opening, which allows easy loading and seals airtight when the digester is closed to provide anaerobic conditions that are crucial for the biological process. A detailed analysis of the performance is subject to subsequent research. The investment costs of the pilot plant are similar to the cheapest wet fermentation alternatives. In a financial assessment a hypothetical full scale plant, consisting of five parallel batch digesters and a grid connected electricity generator is analysed. Different scenarios are developed based on present and possible future conditions. Only the scenario which assumes a very high feed-in tariff for electricity of 35 ¢/kWh, includes usage of the generator's excess heat and considers revenues from compost sales is economically viable. For a wider dissemination, the main stumbling block is the lacking policy support in Ghana that would create an environment that favours investments in renewable energy technologies and alternative waste treatment options.

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Abbreviations

AD	Anaerobic Digestion
BTWA	Biogas Technologies West Africa
CDM	Clean Development Mechanism
CH4	Methane
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
EAWAG	Eidg. Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz
EEG	Erneuerbare Energien Gesetz
ETH	Eidgenössische Technische Hochschule Zürich
GHG	Greenhouse Gas Emissions
H2S	Hydrogen Sulfide
HD-PE	High Density Polyethylen
IBC	Intermediate Bulk Container
IWWA	Integrated Waste Management in West Africa
KITE	Kumasi Institute of Technology, energy and Environment
KMA	Kumasi Metropolitan Assembly
KNUST	Kwame Nkrumah University of Science and Technology
kVA	Kilo Volt-Ampère
kW	Kilo Watt
kWh	Kilo Watt Hours
LEC	Levelised Electrity Cost
mbar	Millibar
MSW	Municipal Solid Waste
NPV	Net Present Value
O&M	Operation and Maintenance
O_2	Oxygen
ppm	Parts Per Million
PVC	Polyvinylchloride
SANDEC	Sanitation in Developping Countries
SNEP	Strategic National Energy Plan
SWM	Solid Waste Management
t	Tonne
TPES	Total PrimaryEenergy Supply
TS	Total Solids
WTC	Waste Treatment Cost

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Introduction

As in most parts of the World, Ghana's cities grow at a rapid pace. Between 1984 and 2002, the share of people living in cities has increased from 32.0% to 43.8% (NESSAP 2010). The densely populated urban areas face the challenge of treating growing waste volumes as well as meeting an increased demand for energy.
Both the waste and the energy sector of Ghana are confronted with major problems. In 2009, nearly 60% of Ghana's primary energy demand is provided by firewood and charcoal, which is associated with deforestation and indoor air pollution. (Yankey 2009) Moreover, only 15 % of the waste in Ghana is treated in an adequate manner (KMA 2000). A large share of the waste is dumped in small, unsanitary landfills, burnt or dumped illegally. This leads to a range of adverse effects on the environment including pollution of soil, surface- and groundwater through leachate and uncontrolled methane production due to anaerobic conditions in the landfill (Rothenberger et al. 2006).
As municipal solid waste (MSW) in Ghana consists of up to 60% of organic material (NESSAP 2010), there is an enormous potential for the production of biogas that could be used for cooking, lighting or electricity generation. Furthermore, the digestate can be composted to obtain a nutrient rich fertilizer for agriculture.
While biogas has proven its viability as an energy technology in rural areas of Asia and partly in Africa in the form of small-scale wet fermentation plants, its application to treat MSW is negligible (Bensah 2009). Using MSW as a substrate can lead to operating problems during wet fermentation due to the structure or impurities. These problems do not arise if treated in a batch wise operated dry fermentation plant. (Lutz 2010) Experts report that this type of dry fermentation process has a high potential in developing countries. (Fei-Baffoe 2006; Darkwah 2011). It has already been successfully implemented for in recent years in Europe (Lutz 2010; Bioferm 2011). Advantages of dry fermentation include simple design, low water consumption and low process energy consumption (little pumping, no mixing, or stirring needed). Substrate with high

dry matter can be used as an input and digested material can easily be post-composted (Lutz 2010; Khalid et al. 2011).
However, up to date, there is no experience with this technology in developing countries. To proof the suitability of this type of technology in low and middle-income countries, it is indispensable to run a pilot plant under real conditions. Since the systems implemented in Europe are too expensive and too complex for operation in developing countries, it is necessary to develop and design a dry fermentation digester, which is adapted to the conditions in developing countries.

1.1 Project Objective

The main objective is to develop, build and operate a dry fermentation digester which is appropriate for developing countries. Within the scope of this project, a biogas demonstration plant for organic household waste shall be constructed with locally available material in Kumasi, Ghana. The project shall explore and advance dry fermentation technology and thereby contribute towards improving solid waste management (SWM), clean energy production and overall sustainable development.

1.2 Hypothesis

Dry fermentation is a viable technology to improve municipal solid waste treatment in developing countries like Ghana. It can be built and operated economically, reliably and safe. It will give organic waste a new value utilizing it as a basis to harness renewable energy and to produce organic fertilizer.

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Background

2.1 Project Location

The research project is carried out in Ghana, a West African country at the Gulf of Guinea (see Figure 1). It shares borders with the Republic of Togo in the east, Burkina Faso in the north and Côte d'Ivoire in the west (see Figure 2). Ghana has a tropical climate. Its coastline is dry and warm. Towards the centre the climate changes to hot and humid with over 2,000 mm rainfall per year. Further north the climate changes to hot and dry. (MCI 2008; Cia-Factbook 2011)

Figure 1: *Map of Africa (Cia-Factbook 2011)*

Figure 2: *Map of Ghana(Cia-Factbook 2011)*

In 1957, Ghana was the first country in Colonial Africa to gain its independence (Yankey 2009). Being a former colony of Great Britain, it kept English as official language that is widely spoken throughout the country. Apart from English there is a multitude of local languages, with languages of the Akan family being spoken by about half of the population (MCI 2008). After the colonial era, Ghana went through a time of political instability due to many coups. In 1981 Jerry Rawlings took over power and political parties where banned. Only in 1992, after the approval of a new constitution, multiparty politics was reintroduced. Rawlings was re-elected in 1996. In 2000 he was constitutionally prevented from running for a third term and John Kufuor overtook the presidency. Since 2009 Atta Mills is in office. (Cia-Factbook 2011)

Ghana has a population of 24.3 million in the year 2010 (BBC 2011). It increased by 30% (18.8 million) since the year 2000 and roughly doubled since 1984 (KITE 2008). The economy of Ghana is dominated by small scale agriculture and trading. Half of the working population is employed in the agricultural sector (Arthur et al. 2009). Besides farming and trading, Ghana is very rich in natural resources, especially gold. Gold and cocoa beans are the most valuable export goods (Cia-Factbook 2011). In December 2007 offshore oil production started and is expected to boost Ghana's economy (BBC 2011).

The research project is carried out in Kumasi, the second largest city in Ghana. It lies in the centre of the country, 240 kilometres northwest from Accra, the biggest city and capital of Ghana. Its population is estimated to be 1.7 Million (Kumasi Guide 2008). Its location makes it one of the most important traffic hubs of Ghana. Since historic times Kumasi is a focal point for traders and businessmen. It hosts the biggest market in West Africa (Kejetia Central Market). The central location and the important markets in Kumasi attract a large number of people. During daytime the population can almost double due to commuters. (Drechsel et al. 2004)

The project is carried out at KNUST at the department of agricultural engineering, in the form of a master thesis at the Swiss Federal Institute of Technology in Zürich (ETH). It is a project of Sandec, the Department of Water and Sanitation in Developing Countries at the Swiss Federal Institute of Aquatic Science and Technology (Eawag). The construction site for the digester is the sewage treatment plant of KNUST. This facility is placed a little off the residential and faculty areas in the south of the campus.

Figure 3: Map with the location of Kumasi (NO 2011)

Figure 4: *Project site at the KNUST sewage treatment site*

2.2 Solid Waste Management in Ghana

This chapter explores the solid waste situation in Ghana with a special focus on Kumasi. Firstly, the current state on a national level is outlined. In a second part, the case of Kumasi is studied in detail. Kumasi's solid waste management is a case in point for the visible and immediate issues the waste burden poses for growing cities in developing countries. The failure to provide adequate waste treatment facilities results in unsanitary conditions and environmental pollution (Drechsel et al. 2004). In chapter 2.2.2, Kumasi's major waste sources are identified and current waste management practices are analysed. Furthermore a short outline of the political framework conditions is drawn.

While MSW is generally seen as the last stage of consumption it can be the initial substrate source for biogas production. This chapter provides the reader an idea how much and where this potentially valuable feedstock is produced and how it is currently used.

2.2.1 Overview

In Ghana poor solid waste management (SWM) remains a great issue. Adequate waste disposal and treatment facilities are not in place (NESSAP 2010).

According to the 2000 Housing and Population Census, only 5% of the waste in Ghana is collected directly at household level. 57 % of it is hauled from public transfer stations and collection sites. 26% is dumped at unspecified locations such as vacant lots or water bodies. The remaining 12% of the waste is burnt or buried. (KMA 2000; NESSAP 2010) The waste situation in Ghana has been gradually improving. Recent numbers show, that the share of collected waste in the major cities has clearly risen since 2000. The share within the five major cities is roughly 80% in 2010 (KMA 2010; NESSAP 2010). Nevertheless, poor disposal of refuse and its management at final disposal sites remains a serious problem. Dumping in open spaces is still in practice and where controlled-dumping is practiced, environmental impact, immediate or long-term, is ignored (NESSAP 2010). As the share of collected waste increases, another immediate problem arises. The major landfills in urban areas are almost full. The landfills in Accra are expected to be full within 6 month. As land is scarce in urban areas, it is difficult and expensive to find space to open new landfills. This leaves two options: Either the waste is transported over long distances to dumpsites away from the city centres or alternatives that reduce the burden of solid waste are implemented. (IWWA 2011)

The Government of Ghana addresses the problems in the National Environmental Sanitation Strategy and Action Plan (NESSAP), published in 2010. It is based on the Environmental Sanitation Policy (EC 2010). The NESSAP "is a response to the need to refocus attention on environmental sanitation in Ghana and provide clear strategies and action plans that will guide implementation by Metropolitan, Municipal and District Assemblies (MMDAs). "The law enforcement, compelling standards and regulations are to be introduced from governmental level, whilst the planning and implementation shall take place in a decentralized way", the MMDAs being the highest authority. (NESSAP 2010) The underlying philosophy of the NESSAP is to see waste as “material in transition” and to create “awareness for change of attitude towards the handling and disposal of all types of waste by demonstrating that there is value in all the components of wastes.” This philosophy namely also includes the recycling of the organic fraction. (NESSAP 2010)

Another approach from Ghana’s Government to address the SWM problem is from a renewable energy perspective. In a bioenergy policy draft by the Energy Commission of the government of Ghana, one main goal is to introduce “ policy responses to Biomass Waste issues include facilitation of collection, incentives for use of industrial and agricultural and other waste, synchronisation of sewerage systems and legislation and incentives for channelling municipal waste for energy purposes”. In case of MSW the policy strategies are namely to **“**legislate against unplanned disposal of industrial and municipal waste “ and to ”develop feed-in-tariffs favourable for electricity generated from waste “. (EC 2010)

Also the private sector is showing initiative to improve the sanitation situation. Zoomlion, the leading waste company, is planning a large centralized composting plant in Accra (Zoomlion 2006). Moreover, feasibility studies on further composting and biogas plants are being conducted (Mensah 2011; Ofori 2011).

The efforts of the Government and of private companies aim in the right direction to improve the SWM situation. However, the issues are immediate and no effective policies are in place up to date. All the efforts are at a planning stage. To turn the ambitious goals into effective measures, several challenges need to be addressed. There are already laws in place for a better SWM. For instance, unplanned disposal of waste is prohibited. However the problem is a lack of effective enforcement of the legislation (Drechsel et al. 2004). The decentralised organisation structures combined with no clear definition of roles and responsibilities between agencies lead to a lack of coordination and create inefficiencies (IWWA 2011). Another concern is missing public awareness in respect to sanitary issues. There is no tradition of bringing waste to a dumping station but dumping individually in the back yard and burning waste is common and socially accepted. A feeling for the health hazards and threats has yet to be created. Finally the lack of financial means limit the regional authorities to implement action plans.

2.2.2 Kumasi

Kumasi is the second largest city in Ghana and the city where the dry fermentation pilot plant shall be constructed. Reducing the scope to a single city makes it possible to take a closer look at solid waste issues in more detail.

In a first step the current waste management system is explained. In a second step, the waste sources and waste streams are identified. On this basis, conclusions can be drawn with respect to the amount of waste that would theoretically be available for biogas production.

In Kumasi the collection of solid waste is organised by the Waste Management Department (WMD), which is part of the Kumasi Metropolitan Assembly (KMA). The Kumasi WMD operates 124 transfer stations. These stations are usually equipped with containers and dustbins where individuals bring their waste for collection and haulage to the landfill. Although, such transfer stations can be found throughout the city they do not cover the area sufficiently. Thus illegal dumping into open spaces and water drains remains an issue. House to house collection was introduced in 2002 (Bantama district) and is planned to be expanded. Up to date it only covers a minor part of the total waste collected (2% to 5 %, according to KMA 2010). Haulage is done both by the WMD and private waste management companies. Apart from Zoomlion, which handles roughly 25% of the waste, the private contractors are small companies which operating only a few trucks. The waste is deposited in two main landfills. One is an engineered landfill (Dompoase) owned by the KMA (Drechsel et al. 2004). This landfill was opened in 2003 with an expected lifetime of 15 years (Wikner 2009). The other landfill (Amanfrom) is owned and operated by Zoomlion. This dumpsite is not an engineered, sanitary landfill as the KMA owned Dompoase landfill.

***Figure 5:** Zoomlion owned dumpsite (Amanfrom)*

***Figure 6:** Dumping of refuse in open space*

Up to date, the KMA subsidizes the waste collection and dumping. If citizens bring their waste to one of the waste transfer stations, or if house-to-house collection is offered, they only pay a small share of the actual cost. For example the haulage of a collection container to the dumpsite, including the cost for landfill management costs 10 US$/ton However, only 1.5 US$ are charged to the individual waste producer. The rest is paid by the government to the private waste companies in the form of subsidies. Those subsidies are planned to be stopped by 2012 and the full cost shall be charged to the waste producer. This would mean a substantial increase in cost for individuals (Arthur et al. 2011). Furthermore it would minimise the problem of ir-regular payment to the waste contractor by the deeply indebted KMA (KITE 2011).

According to the most recent numbers available from the Kumasi Metropolitan Assembly, 1,200 tons of waste is produced in Kumasi daily (Ofori 2011). In Table 1, a summary of the key figures, characterising the waste situation in Kumasi can be found.

Table 1: *Key figures for the characterization of the waste situation in Kumasi*
Data sources: (KMA 2010; Ofori 2011)

Parameter		**Unit**
Population Kumasi	1.6	million
MSW generated	0.75	kg/(capita·day)
MSW generated	1200	tons/day
MSW collected	81	%
MSW collected	972	tons/day
Collection cost	6	US$/Ton
Disposal Cost	4	US$/Ton
Total cost	**10**	**US$/Ton**

Table 2 shows the waste composition in Kumasi in the year 2010. The share of organic material (40.2%) is low when compared to the national average of over 60% (NESSAP 2010). The second largest share is inert material. Plastics and bottles which make up 20.1% of the total are partly recycled on a informal basis by human scavengers (Wikner 2009).

Table 2: *Waste characterization of MSW in Kumasi made by Ofori (2011)*

Material Type	**Tonnes**	**Share**
Organic Material	482	40.2%
Inert (Sand, ash, fine organics, demolition waste)	250	20.8%
Plastics	238	19.9%
Paper and Cardboard	84	7.0%
Textiles	83	6.9%
Metals	27	2.2%
Wood	20	1.7%
Glass / bottles	14	1.3%
Total	**1,200**	**100.0%**

A study on the organic waste flows has been carried out by Drechsel et al. (2004). The availability of organic waste is segmented into the major sources of waste. Furthermore the availability of the waste recycling and compost production is considered. In this context, it is assumed that the same numbers hold true for biogas production. Available means, it is not already used for other purposes like animal feed and it is collected and can be transported. Manure, dung and liquid waste (mainly night soil) is not considered as it is not appropriate to be treated in a dry main sources: household, markets and industry. A part of the waste stated in Table 3 is reflected as MSW in Table 1.

The households generate up to 260’000 tons of waste per year. This equals a per capita production of about 0.6 kg per person and day. Around 20% of this waste is used as animal feed. Another 24% is dumped in water bodies or informal dumpsites. The remaining 56% is collected and land filled. The estimated fraction of organic waste which is land filled is only 44% due to its usage as animal feed. Nonetheless, this equals about 64,000 tons per year of organic waste available for biogas production. (Drechsel et al. 2004)

The four biggest markets in Kumasi account for an estimated 90,000 tons of waste per year. Around 90% percent of this waste is collected while the remaining part is used as animal feed. With an estimated share of 75% organic material, around 60,000 tons organic market waste is available. (Drechsel et al. 2004)

Kumasi is a major timber-processing city. In over 60 sawmills, a yearly 230,000 to 290,000 tons waste is generated. This is partly used as straw on poultry farms or by informal carpeting activities to produce low quality products such as fuel wood. The remaining 105,000 to 120,000 tons go to landfills or are dumped into the river and could be used for energy production. (Drechsel et al. 2004)

Kumasi has three breweries which produce 11,000 to 12,000 tons of waste of high nutrient quality. The solid refuse however is mainly sold or given away as livestock feed to farmers (Drechsel et al. 2004). The Guinness brewery uses a modern wet digester to treat liquid waste. Therefore the brewery waste is not to be considered as available for dry fermentation

Five abattoirs operating in Kumasi produce around 2,400 tons of waste per year. One of those abattoirs used to have a wet fermentation biogas plant, which ceased operation. (Wikner 2009) No information about what exact type, the use of the gas and the reason why it is not working anymore is available. Thus the total 2,400 tons would be available for biogas production.

The above stated numbers show that about 228,800 to 248,800 tons of organic waste is available for biogas production in Kumasi every year. In Table 3 the availability of organic waste for biogas production is summarized.

Table 3: *Waste sources in Kumasi and availability for biogas, based on Drechsel et al. (2004)*

Waste Type	Total waste [t/y]	Available for biogas production [t/y]
Household waste	260,000	64,000
Market waste	90,000	60,000
Sawdust	230,000-290,000	105,000-121,000
Brewery waste	11,000-12,000	0
Abattoir waste	2,400	2,400
Total	**593,400-654,400**	**231,400-247,400**

2.2.3 Summary and Conclusion

There is an abundance of organic waste in Kumasi. As a large share of the waste is produced in certain, concentrated areas such as markets, sawmills or abattoirs, separation and collection could be done relatively easy. Furthermore there is an abundance of organic waste in other major cities of Ghana (Drechsel et al. 2004). Therefore the potential for dry fermentation is very high. The mere amount of input material is not a limiting factor. The framework conditions seem to be changing into a direction that makes it more appealing to invest in alternative waste treatment technologies. The problems with overfilled dumpsites will further push rethinking current waste management practices. However, regarding the recycling of organic waste, there are still high barriers and constraints concerning mainly the financing of separation or the introduction of source separation. The barriers are lower if the focus is put on industries producing organic waste. If a plant is placed near such an industry, transport ways and costs arising from sorting can be avoided. In the best case the produced heat, electricity and fertilizer can directly be used by the industry.

2.3 The Energy Situation in Ghana

This chapter provides a short overview of the energy situation in Ghana. The first part outlines the current pattern of energy production and use. Part two looks in detail at the status of biogas technology dissemination in Ghana.

2.3.1 Overview

As typical for low and middle-income countries, Ghana has a low total primary energy supply (TPES) per capita. Ghanaians use 4.7 MWh per capita and year. This is low compared to a developed country like Switzerland (40 MWh) or the United states (87 MWh). But the values are comparable to other West African countries like Côte d' Ivoire (5.8 MWh) or Nigeria (8.5 MWh). (IEA 2008)

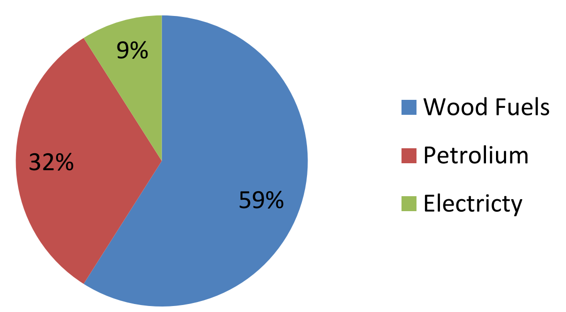

***Figure** 7: Energy consumption in Ghana in 2007 (Yankey 2009)*

Ghana's energy market is dominated by traditional wood-fuels. They are used for cooking and water heating in both the residential and commercial sector. Wood fuels comprise mainly of firewood (76%) and charcoal (Arthur et al. 2011). They represent 59% of the total energy consumption (Yankey 2009). Around 90 percent of the wood fuel comes from the natural forest, the remaining parts are residues from the wood processing industry (KITE 2008).While the wood fuel sector creates many jobs, the negative impacts are alarming. The wood fuel resources are dwindling at a rate of 3 percent per year. Since the beginning of the 20th Century, Ghana has lost about three-quarters of its forest (Arthur et al. 2009). At the same time the demand for wood fuels is continuously increasing (KITE 2008). Moreover, the indoor usage of wood fuel is associated a range of adverse health effects (Bruce et al. 2000).

The second biggest source of energy is petroleum products that account for 32% of the overall energy consumption in Ghana. Of the total, one third is used in the form of gasoline, one third as gas oil and another 18% as residual fuel oil. Among the remaining part, 4% is used in the form of liquefied petroleum gas (LPG) (Yankey 2009). Additionally, Ghana has discovered major offshore oil reserves in 2007 and started to produce at the end of 2010 (BBC 2011). The impact of the oil discovery on the energy market remains uncertain at the moment.

Electricity represents the remaining 9% of energy consumption (Yankey 2009). Currently, 55 % of the population have access to grid-based electricity. The penetration of electricity into rural areas is limited to 15%. Furthermore, the grid connected areas suffer from voltage fluctuations and power blackouts on a regularly basis. With a per capita electricity consumption of only 301 kWh in the year 2007 the electricity consumption is low even among low and middle income countries. As the country develops and population grows, the consumption is projected to grow significantly (Yankey 2009; ME 2009a) .Today, the largest share of the electricity is produced by the two hydro plants Akosombo and Kpong, which are located at lake Volta, the world's largest artificial lake. They have an overall generation capacity of 1'180 MW (Yankey 2009). The share of hydroelectricity has declined from 92% in 2000 to 77% in 2009. One reason for the lower share is the increase in production capacity from thermal power plants that has tripled in the respective period (Addo et al. 2009). The strategic national energy plan (SNEP), of Ghana's Energy Commission projects a share of thermal power plants in 2020 between 43 and 59% (ME 2009a). Hence it can be argued, that renewable energy sources introduced, mainly replace the installation of thermal generation capacity.

Statistically, Ghana uses a large share of renewables. However, if traditional biomass use (fuel wood and charcoal) and large hydro plants are excluded, the share of renewables is negligible. There are a few projects such as solar torches in rural areas, biodiesel production from Jatropha or photovoltaic installations at schools and hospitals. These projects are generally commissioned by the public hand and financed by donor money and play a marginal role in Ghana's energy market. (Yankey 2009)

2.3.2 History and Current Status of Biogas

Before 1980, there were only few biogas dissemination programs. They mainly focused on biogas for domestic cooking. Most of these installations broke down and have been abandoned after a short period due to poor technology and lacking policy support (Bensah and Brew-Hammond 2010). In the 1980s several demonstration plants for cattle owning farmers have been built (KITE 2008). In 1992 the Ministry of Energy commissioned the first large scale biogas plant which powered a 12.5 kVA electrical generator. Unfortunately the plant suffered several setbacks and has not marked a turning point (Bensah and Brew-Hammond 2010).

Up to today barriers such as unfavourable policies, non-availability of appropriate feed materials, poor financing arrangements, problems with social acceptance, absence of an appropriate market, and lack of information are prevailing and have kept biogas low (Bensah and Brew-Hammond 2010). However, there has been a significant increase of biogas installations over the past decade (Bensah and Brew-Hammond 2010). This increase is mainly ascribed to the private company Biogas Technology West Africa (BTWA) and further entrepreneurs, which have successfully merged into biogas business (KITE 2008; Bensah and Brew-Hammond 2010).

Today around 100 biogas plants are installed in Ghana (KITE 2008). Out of this total, 50 plants have been characterized and examined by Bensah and Brew-Hammond (2010). The review showed that the plants are generally in a very poor state; only 22 (44%) were functioning satisfactory. The others were partially working (20%), not working at all (28%), abandoned (4%) or under construction (4%) (Bensah and Brew-Hammond 2010).

The largest share of the plants are built to improve the sanitary situation (72%) and not to harness energy (28%). The main reason is that biogas is an efficient and cost effective way to treat night soil and thereby replacing a septic tank (Bensah and Brew-Hammond 2010). These bio sanitation plants are predominantly located at educational and health institutions in urban areas (KITE 2008). For private persons, such as small scale farmers, the high investment cost are the main inhibitive factor to use biogas technologies (KITE 2008). The focus on sanitation is also visible in the pattern of gas and effluent usage. Of the functioning plants surveyed by Bensah and Brew-Hammond (2010), the gas was leaking and not used in 50% of the cases. Only 34% of the plants used the gas for cooking. Also, over 90% of the functioning plants discharged the effluent into public drains or bushes. The effluent usage as a fertilizer is insignificant (Bensah and Brew-Hammond 2010).

The most common plant types in Ghana are fixed dome digesters. In the review of Bensah and Brew-Hammond (2010), 80% of the plants were fixed drum digesters, 10% floating dome digesters and 10% other types. The reason is that the fixed dome design is cheaper and needs less maintenance than the floating drum design (Bensah 2009).

2.3.3 Summary and Conclusion

Biogas plants represent a very marginal part of Ghana's energy market. Ghana has very few running biogas plants (about 100) when compared to other African countries such as Kenya (about 2000) or Tanzania (between 4000 and 5000) (Bensah 2009).

A comprehensive study by the Kumasi Institute of Technology (KITE 2008) has concluded that on the household level biogas has no great prospect and is not competitive despite a large technical potential. The investment costs are generally higher than the willingness and ability to pay by the customers. The currently installed plants are mainly institutional and aim to improve sanitation. The state of the plants is generally poor, gas is often leaking and the effluent discharged into drains

A reason for this is that biogas has received inadequate attention from public institutions. Presently there is no clear strategy to promote biogas in Ghana. The needed policy support to overcome financial barriers is lacking and there is no national body mandated to advance biogas. The government's National Energy Plan (SNEP) states modest goals in regard to disseminate the biogas technology. (Bensah 2009; Arthur et al. 2011)

As of early 2011, a renewable energy act is waiting for approval by the parliament. It aims at promoting renewable energy sources for electricity generation (ME 2009b). Biogas is among the supported technologies. Notably Biomass from waste is specifically mentioned in the draft. The act includes a broad spectrum of proposed policy tools including feed in tariffs, renewable purchase obligations and fiscal reduction to support the renewable energy technologies (ME 2009a). Up to date, those policy plans remain without tangible commitments.

Despite the unfavourable policy framework, more and more entrepreneurs have successfully taken up the biogas business in the past decade (KITE 2008). With more incentives from the public sector, this market-based approach is very promising to start harnessing Ghana's huge technical potential for biogas production.

2.4 Dry Fermentation Technology

In this chapter, the principles of dry fermentation are outlined. The differences to wet fermentation are explained. Furthermore an overview on the various types of dry fermentation plants is given.

The formation of biogas through dry fermentation takes place according to the principle of anaerobic digestion (AD). In the absence of oxygen, microbiological processes decompose organic matter into Methane and Carbon-Dioxide. However, the term "dry fermentation" can be misleading however. As in every biological process, water plays a crucial role. On the one hand, anaerobic digestion only takes place in a wet environment as the bacteria are only active in the liquid phase of the substrate, which is mostly water. On the other hand water allows movement of solved parts and bacteria. The water thus helps to disperse bacteria evenly in the system. (House 2010) Hence the distinction of wet and dry fermentation is only an indication in terms of the content of water. Generally the content of water is expressed indirectly as the percentage of total solids (TS) of the total mass in the digester, meaning that the rest is in a liquid form. Pumping and stirring becomes more and more difficult above 6 to 10 % of TS. Below that value, the process is called wet fermentation. Above it is generally called dry fermentation. The German policy for renewable energies (EEG) defines dry fermentation as substrates with dry matter content above 30% that are stackable and added to the digester without any additional water (FNR 2006). However, water is usually added to the dry fermentation process in form of a recycled inoculation liquid called percolate.

When treating municipal solid waste (MSW) in a wet fermentation plant the substrate has to be shredded into small pieces and mixed with water. With the technique of dry fermentation one can avoid additional equipment and uses less process energy as the substrate can be filled in without reducing its size or mixing it with water. Thus dry fermentation is highly suitable for the treatment of MSW (Fei-Baffoe 2006). The biological process that takes place in dry fermentation is analogous to the process in wet fermentation. This process is generally referred to as anaerobic digestion. That process can be split up in three major steps (simplified).

1. Hydrolysis stage: The organic matter is split up into shorter proteins, fatty acids and sugar.

2. Acetogenic stage: The bacteria in this stage decompose the products form stage one into acetic acid hydrogen and carbon dioxide.

3. Methanogenic process: This process finalizes the process and turns the acetic acid into methane, carbon dioxide and water

The acidifying bacteria in step two and the methane forming bacteria in step three build a close symbiosis. If these two stages are not in equilibrium, the process can break down quickly. If the methane forming bacteria cannot metabolise all the produced acids, the pH will drop. As the methane forming bacteria are sensitive to a pH drop. This will further reduce their activity. Consequently the pH drops even more. This means a system that starts to be unbalanced is difficult to bring back to equilibrium (FAL 2007). To prevent acidification dry fermentation digesters are generally inoculated with a population of methane forming bacteria at the beginning. Suitable inoculation material is fresh cow dung or dung from any other ruminant animal, which contains the needed bacteria population. Effluent or digestate from an already running plant can also be used as inoculation material. Batch digesters need to be inoculated at every startup event. This can be done by keeping part of the digested material and mix it with fresh substrate.

Dry fermentation plants can be divided into two major categories: Continuously fed and batch-wise fed digesters. Both can be operated either in one stage, in which all biological processes take place in the same digester room, or in two stages, in which case the hydrolysis takes place in a separate digester (FNR 2006). Two stage digesters allow a better control of the process but make the installation more complex. In continuous as well as batch wise operated digesters, the plant comprises of an airtight digester, which provides the anaerobic environment. Continuously operated plants need mechanical equipment to load the biomass and transport it within the digester. As the dry matter content is very high, such equipment must be robust with strong engines. These complex installations consume additional energy and increase investment and operation costs. (FAL 2007)

The big benefit of a continuously run plant is that it only has to be shut down for maintenance purposes. During normal operation it has a stable culture of bacteria that is continuously fed with fresh substrate and produces a continuous stable gas output.

However, as the focus of this research project lies on finding an option for developing countries the spotlight is put on batch dry fermentation plants, which have the simplest and cheapest design (Khalid et al. 2011). There are no moveable parts such as stirring devices or plug flow coils and the substrate does not need elaborate processing (Lutz 2010).

There are three main types of batch plants that have proven functionality in Europe. The most popular batch digester is the percolation digester. It consists of several garage-like digester rooms. Each garage has a door that closes airtight. At the roof inside the digester room a sprinkling system is installed to wet and to inoculate the substrate. The running plants in Europe have a heated digester room (House 2010; Lutz 2010). Under tropical conditions like in Ghana, it is assumed that insulation and heating is not needed. Three companies are producing this technology commercially in Europe: Bekon Energy Technologies GmbH & Co, Bioferm GmbH and Helector Germany GmbH (Look-TNS process).

The second technology used, is the heap procedure usually consisting of a large polybag into which the biomass is piled, similar as in maize or grass silage. No percolation takes place. The Bag Budissa Agrosevice GmbH is producing polybags for this technology in Germany.

The third option is the retain procedure. Instead of sprinkling the loaded digester, the whole digester is flooded with percolate periodically. The company Chiemgauer builds plants based on this principle (Liesch and Müller 2007).

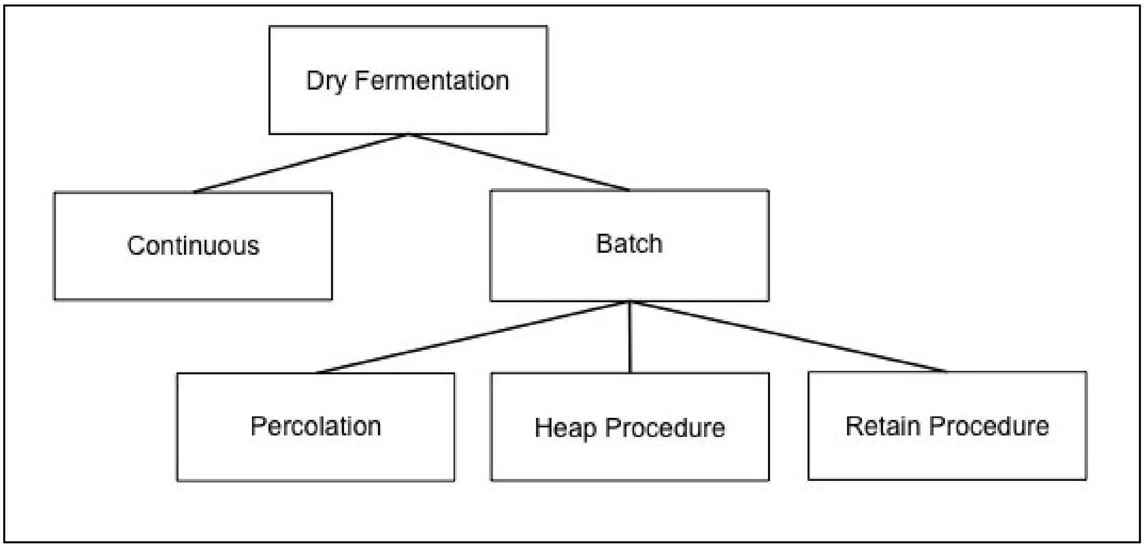

Figure 8: *Graphical distinction of the different dry fermentation principles*

A major advantage of the dry fermentation technology is the handling of the digestate. It is relatively dry and can easily be treated by post-composting to produce an organic fertilizer (Lutz 2010).

One important aspect when operating batch plants is the potential risk of explosive gas mixtures. As the digester room is opened to unload the digestate and load fresh material, the oxygen in the ambient air and the methane inside the digester mix and can form an explosive combination. Operating plants avoid this security issue by flushing the digester room with fresh air (Gronauer and Aschmann 2003; Bioferm 2011) or with exhaust gas from the CHP, consisting mainly of CO_2 before opening the digester door (Bütikofer 2011).

3

Construction

3.1 Method

The construction process starts with an analysis of the functional principle of dry fermentation plants in Europe. Through a literature study, a visit of a Bekon dry fermentation plant in Switzerland and expert interviews, core parts that comprise a dry fermentation plant are identified. These parts shall be constructed with the same functionality but in a manner, which is suitable for developing countries. The suitability of available material and design options is evaluated based on the criteria listed in Table 4.

***Table 4**: Criteria to assess suitable materials to built the digester*

Material aspect	Criterion
Economics	Low Material cost High income generation for local enterprises and individuals
Availability	Available within Ghana, preferably Kumasi Little time needed to obtain items
Durability	Not subject to corrosion Withstand weather and other external influences
Security	Suitable for inflammable gas
Ease of Handling	Low degree of needed expert knowledge or specialized tools needed
Form	Suitable for easy loading and unloading Airtight opening can be built easily

In a first step, materials to build a small and a medium scale digester are evaluated based on the aforementioned criteria. In a preliminary study, a small-scale digester is built to test technical solutions. On the small scale, less material is needed and it can be built and tested easier and faster. The findings from the small-scale digester help to choose suitable material and equipment for the construction of a medium scale digester. Each criterion of each option is rated on an ordinal scale between 1 and 5. The overall score gives an indication on which option is the best.

As a second step the technical performance of the chosen material and design is assessed. The first tests on the technical performance are made before loading the substrate. The digester is tested for its air tightness. To this end, air is pumped into the digester room with a compressor. Firstly, all outlets are closed and the pressure build up is measured to find out whether the container starts leaking at a certain pressure. Secondly, the gas exit is opened and equipped with a gas meter to compare the amount of air pumped in with the amount that exits. This difference is considered as leakage.

Figure 9: *Pressure meter test to find the maximum pressure build up.*

Figure 10: *Gas meter test to estimate amount of leakage*

Subsequently, the ease of handling during loading is evaluated. During and after the batch test, the technical solutions that are installed are assessed and tested. The findings are described qualitatively.

3.2 Results

3.2.1 Material and Design Assessment

The batch dry fermentation plant is built after the principle of a garage-like air tight digester. This is the same principle as Bekon and Bioferm use to build their plants. Its functionality can be described by four core parts. These parts are:

- Air tight shell
- Opening
- Percolation system
- Gas tapping system

Figure 11 depicts the functional principle of the considered dry fermentation batch technique.

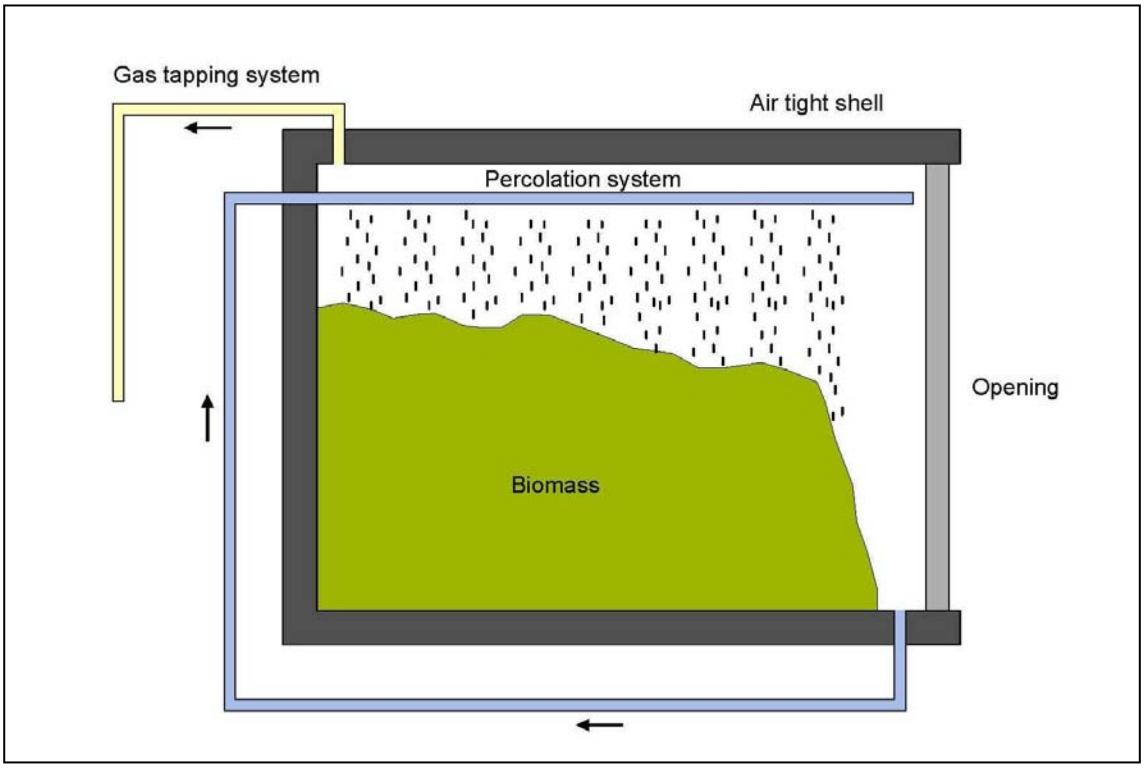

Figure 11: *Schematical representation of the used garage dry digestion plant*

In Table 5, the above mentioned core parts are listed and their respective functionality is described.

Table 5*: Core parts that have been identified as crucial for the construction of a dry fermentation plant*

Airtight shell	The airtight digester room is the core piece of a dry fermentation plant. It provides the anaerobic environment which is needed for the biological processes of biogas formation.
Opening	The digester needs an opening which enables easy loading of the feedstock and easy unloading of the digestate. This opening is a major challenge. The door needs to seal the digester airtight but also has to be constructed in a way that allows easy opening after each cycle. When closed again, the door should seal the container airtight without any replacements of sealings or repairs.
Percolation System	In addition to anaerobic conditions, methane forming bacteria require a wet environment. Furthermore, they should be dispersed to all parts of the substrate. These two critical aspects can be realized with a percolation system that circulates a liquid with a population of methane forming bacteria (percolate). A shower-like installation at the roof of the digester sprinkles the percolate evenly over the biomass. The percolate trickles down, exits at the bottom and can be collected in an external storage tank. The percolate is re-circulated to sprinkle the biomass on a regular basis. An appropriate filter at the percolate outlet hinders coarse particles from entering and blocking the circulation system.
Gas Tapping	The gas tapping takes place at a hole at the highest part of the digester. The produced gas is captured and channelled through a pipe to the outside of the digester. Commonly the gas tapping pipe is equipped with a flash back arrestor and a dewatering unit. The flashback arrestor stops sparks and flames from entering the container and igniting a possibly explosive gas mixture. The dewatering unit extracts condensation water from the out-flowing gas. The tapped gas can then be passed through gas analysis equipment, a gas meter or gas cleaning and compression processes before being directed to its end use.

Contrasting to plants operating in Europe, no heating system is installed. Because of the tropical climate it is assumed that the process runs without additional heat and a sophisticated heating system can be omitted.

The gas storage and usage as well as the post-composting of the digested material are further important steps of the process. These aspects are not within the scope of this study and will be investigated in subsequent research.

3.2.2 Preliminary study on a small-scale

Within the preliminary study, different construction materials were assessed. For the small-scale digester, potential materials included a standardized IBC container, a flexible IBC bag, a digester made from concrete and bricks as well as a polyethylene tank. For each of these material limiting problems were identified, mainly concerning the airtight opening and the security. The final choice to build the small scale digester is a High Density Poly Ethylene barrel with a capacity of 300 litres.

Following the technical solutions for the identified core parts are presented and discussed in detail. Those technical solutions are built in consideration of their suitability for the medium scale plant.

Airtight shell
A second hand high density polyethylene (HD-PE) barrel is used (see Figure 12). It has a volume of 300 litres. The HD-PE barrel has a high resistivity against corrosive influences. It can also withstand UV- radiation, temperature changes and mechanical influences.

It is not suitable for scaling up. Only a limited choice of sizes is available, 300 litres being the biggest.

Opening
The barrel has a 50 cm opening at the top (see Figure 12) through which loading and unloading can take place easily. For unloading the barrel has to be tilted.

An opening on the top is only suitable on the small scale as a small barrel can be tilted when unloading. For a medium scale plant, the top loading/unloading process would be cumbersome.

Percolation system
At the bottom and on the top of the barrel, a hole is cut and equipped with a PVC fitting for 1 inch (the unit "inch" is from here on abbreviated with a double prime) PVC pipes (see Figure 13). These two fittings are the entry and exit point of the percolate.

Suitable to be applied on a medium scale.

At the bottom hole the percolation liquid, which has flown through the column of biomass, exits the container. A perforated 3 pipe (connected at the inside of the barrel to the PVC fitting) serves as a filter, which keeps back the biomass while the percolate can exit freely (see Figure 14).

Suitable to be applied on a medium scale.

Figure 12: *300 litre HD-PE barrel*

Figure 13*: 1'' PVC pipe fitting. Allows to connect pipes to the barrel*

Figure 14*: 3'' PVC filtre pipe. Prevents coarse particles from getting into the external part of the percolation system.*

The percolate is collected outside the barrel in a 25 litre HD-PE container. This container is then lifted manually to the top and connected with 1’’ PVC pipes to the top hole of the barrel (see Figure 15).

The PVC piping proved to be viable for scaling up. On the medium scale, an electric pump is needed to elevate the percolate.

The percolation liquid flows through the top hole into the sprinkling system at the inside. This sprinkling system consists of a perforated 1’’ pipe (see Figure 16)

Suitable to be applied on a medium scale.

Gas Tapping
The gas is tapped at the top through the PVC fitting with a 1” PVC pipe. With the used configuration, gas tapping and percolating takes place through the same pipe. Therefore a valve that allows closing the digester for pipe change from percolation to gas measurement is installed. Subsequently the dewatering unit used can be seen. This traps condensing water in the gas way and can be emptied on a regular basis. For security reasons an overpressure seal is installed. This consists of a foot valve that only allows gas flow in one direction and only opens above a pressure of 20 mbar (see Figure 17).

The gas tapping with the used PVC pipes proved suitability to be scaled up. Also the dewatering unit principle as well as the overpressure seal can be used. On the medium scale the percolation system and the gas tapping will be installed independently from each other.

Figure 15: *Percolation system made from a 25 litre HD-PE container and 1" PVC pipes, connected to the top hole of the digester*

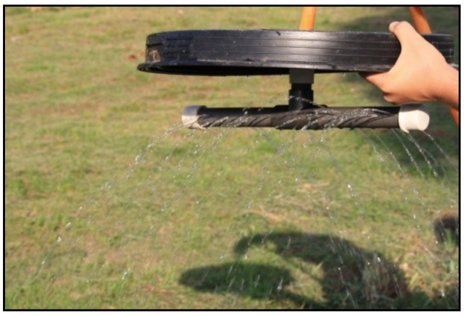

Figure 16: *Percolation system connected to the top hole in the lid of the digester*

Figure 17: *Gas tapping connected to the top hole. Included is the overpressure seal, a PVC valve and the dewatering unit*

Lessons learned from the preliminary study:

- All the piping and connections are made with 1'' PVC plumbing material. Such material is widely available in Ghana. Virtually all the water piping in houses is made with PVC pipes. Those are produced locally and are available in all different sizes at very low cost. A vast variety of connection parts and valves can be found. No special tool is needed for construction. Additionally they are resistant to corrosion or to environmental influences such as UV radiation. PVC pipes proved very suitable in the preliminary study and will be used for the medium scale plant.

- Air tightness of the digester is very hard to achieve. The opening is a major concern as it has to be opened after each cycle but needs to seal air tight during operation. Silicon sealant is good to support air tightness but is not a very durable solution.

- Connections and fittings have to be installed very carefully with appropriate sealing material such as Teflon tape as gas leaks occur very easily.

- A filter at the bottom of the container made form a 3'' PVC pipe with 4 mm holes works very good as a filter. The hole size is good to prevent coarse particles from getting into the percolation circuit but not getting blocked due to congestion and settlement.

- A perforated 1'' PVC pipe works very well to sprinkle the biomass (percolation system). By adjusting the size and the amount of holes the sprinkling properties can easily be changed.

- A closed circuit for the percolation system is favourable. Handling the liquid in a container and changing connections from gas tapping to percolation is unhandy. Overall a closed percolation system is favourable as the percolation liquid can contain pathogens, has a very strong smell and biogas produced from the bacteria in the percolate is kept within the closed system. In such a system, the anaerobic bacteria are never exposed to oxygen.

3.2.3 Medium scale digester

For the building of the medium scale digester three potential materials were taken into account for further investigation.

One possibility is to use polyfoil to build the airtight digester room. Polyfoil is very cheap and widely available. One option would be to operate the plant after the principle of grass or maize silage. Using this technology, the biomass is loaded mechanically into a polyfoil tube. After each cycle the tube is cut open for unloading and disposed off, see Figure 18. Another option is to build a digester room similar to a wet fermentation bag digester as depicted in Figure 19. Such a polyfoil digester is scalable to virtually any size desired. Furthermore the polyfoil can serve as a gas holder. However, there is a big drawback. The foil is susceptible to mechanical damage. It is very likely that the foil will be damaged on a regular basis while handling the substrate or by environmental factors such as animals or rough weather. Another challenge is the technical knowledge that is required to weld the foils to bags and to repair holes and cuts. This knowledge is not available everywhere and limits the construction of the digester. These disadvantages lead to the decision not to choose this option.

Figure 18: *Polyfoil digester in Germany. Being cut open to remove the digestate (LfULG 2002)***.**

Figure 19*: Polyfoil wet digester in Costa Rica. Gas storage directly in the poly bag (RCR 2006)***.**

The second option that was taken into account is a digester made from bricks and concrete. For this particular research project, the option is rated unsuitable mainly due to the fact, that it is a fixed, non movable installation, which needs considerable time for a building permit and its construction. Moreover, the airtight door would need to be a tailored construction likely made of metal and a custom rubber tube sealing. The door needs specialised work and is likely to be expensive. An additional challenge is to obtain gas tight quality concrete which can withstand the gas pressures without stress cracks.

In Figure 20 and Figure 21 a digester made from bricks and concrete can be seen. On the right hand side of the garage digester, a wheel loader that is filling such a garage is being displayed.

Figure 20: *German garage digester built from bricks and concrete with a custom made air tight door (Gronauer and Aschmann 2003)****.***

Figure 21*: Wheel loader filling a dry digestion garage digester (Stiller 2010)****.***

The third option is a shipping container (see Figure 22). It is prefabricated and ISO standardized. There are two common sizes available; 20 feet (the unit “feet” is from now on abbreviated with single prime) (33 m^3 internal volume) and 40’ (66 m^3 internal volume). As Ghana has access to the sea, second hand shipping containers in a good shape can be bought easily at a reasonable price. Shipping containers are already airtight to a certain degree as they should be water proof for shipping. The focus while buying a second hand shipping container should be put on the shape of the door’s rubber sealings as they can be in very different conditions. For a summary of the three considered options see Table 6. Following Table 6, the results of the option rating is displayed in Table 7. Of the three options the shipping container reaches the best overall score.

Table 6: Summary of positive and negative aspects of the different design options considered

Option	Positive aspects	Negative aspects
Polybag	- Cheap - Easy and quick to build the digester - Easy to remove after research project - Lightweight makes it easy to transport - Digester room can serve as gas storage if dimensioned properly - Easily scalable to needed size - Resistive against corrosive influences	- Low resistance against mechanical damage - Loading unloading difficulties - Technical equipment and knowledge needed for plastic welding and gluing. - Possible electrical discharges and sparks from polyfoil can lead to ignition of burnable gas mixtures
Concrete structure	- Scalable to the desired size - Different shapes possible - Different qualities of concrete and bricks available - Needed construction knowledge available - Durable material	- Not movable - Air tightness problems and pressure cracks can arise from bad quality work or material - Air tight door needs to be custom made - Corrosion damages can occur - Building of the digester needs time and adds uncertainties
Shipping container	- No time needed to build the digester - High resistance against mechanical damage - Big opening for loading and unloading - Very commonly used throughout the world, standardised - Equipped for easy transportation	- Standard two wing door can lead to air leakages - Big quality differences amongst second hand containers - Corrosion if not maintained properly

***Table 7:** Ordinal score (one to five) of each option with respect to the criteria listed in Table 4.*

	Polyfoil	**Concrete**	**Shipping container**
Economics	4	3	3
Availability	4	3	4
Durability	1	3	3
Security	3	4	4
Ease of Handling	3	3	5
Form	4	4	4
Sum	**19**	**20**	**23**

The final choice is to build the medium scale digester with a 20' shipping container. Table 8 specifies how the chosen shipping container performs in respect to the criteria listed in chapter 3.1.

Table 8: *Decision taking criteria for the final choice of the medium scale digester construction*

Criterion	**Description with respect to chosen option (shipping container)**
Availability	Ghana has major harbour cities, Tema and Takoradi. Second hand shipping containers are abundant. Shipping containers only have a limited lifetime in which they get a certificate for over sea shipping. After this time they are still in good shape for reuse. In the harbour areas a large quantity of used containers can be bought right from the spot. The transport within Ghana can easily be arranged through shipping companies or private truck owners.
Economics	The price for second hand shipping containers can vary considerably. It ranges from 800 US$ to around 4000 US$ and is highly dependent on the quality of the container. The shipping container used for the prototype was purchased at a price of 1200 US$.
Durability	A shipping container is made from steel. It is painted with a long lasting bitumen paint to withstand rough conditions while shipping. However, cracks in the paint are susceptible to corrosion. Therefore it needs to be well maintained and repainted from time to time. The floor is made of wood panes, which are joined together with silicon sealing. This grants for air tightness. However, the wood panes and the sealing can be degraded over time and have to be replaced on a regular basis.
Security	There is no risk of sparks due to electrical discharges as when handling polybags. However sparks can occur while opening and closing doors as metal parts are being moved. If the outlets are blocked, high overpressure could result in ruptures or cracks. Furthermore the shell can lead to a severe accident in case of an explosion.
Ease of Handling	A shipping container can be modified with ordinary metal works tools. Welding machines and electrical grinders including skilled workers can be found in every bigger city in Ghana Substrate loading and unloading can easily be carried out through the big steel doors. A shipping container biogas plant can easily be built at a location with good access to skilled workers and machines and then be transported to the operation site.
Suitable Form	Shipping containers are mainly available in two sizes. Either 20' or 40' are used. Additionally there is a vast quantity of smaller containers (e.g. 4', 6' or 10'). As it has a big door, loading and unloading can easily be done. One drawback is that the opening is a two wing door. The connection point of those two doors in the middle causes air tightness problem (see description later on).

In the following part, the crucial elements for a dry fermentation plant are listed according to the assessment in chapter 3.2.1. Each core part is followed by a detailed description on how the requirements are met. To start, a side view of the shipping container on which those parts can be seen (see Figure 22) as well as a schematic representation (see Figure 23) are presented.

Airtight shell

The airtight shell is provided by a standard 20‘ shipping container. However, there are some parts that have to be modified to guarantee air tightness. Usually such a container comes with four ventilation holes to prevent condensation and mould growth while transporting goods. Those can easily be closed by welding iron plates over the holes.

Another issue is the floor, which is made from wooden plates. The gaps at the edges of the plates are sealed with silicon sealing. This sealing usually has to be replaced if one uses a second hand container, because it gets cracks over time.

Figure 22: *Side view of the shipping container*

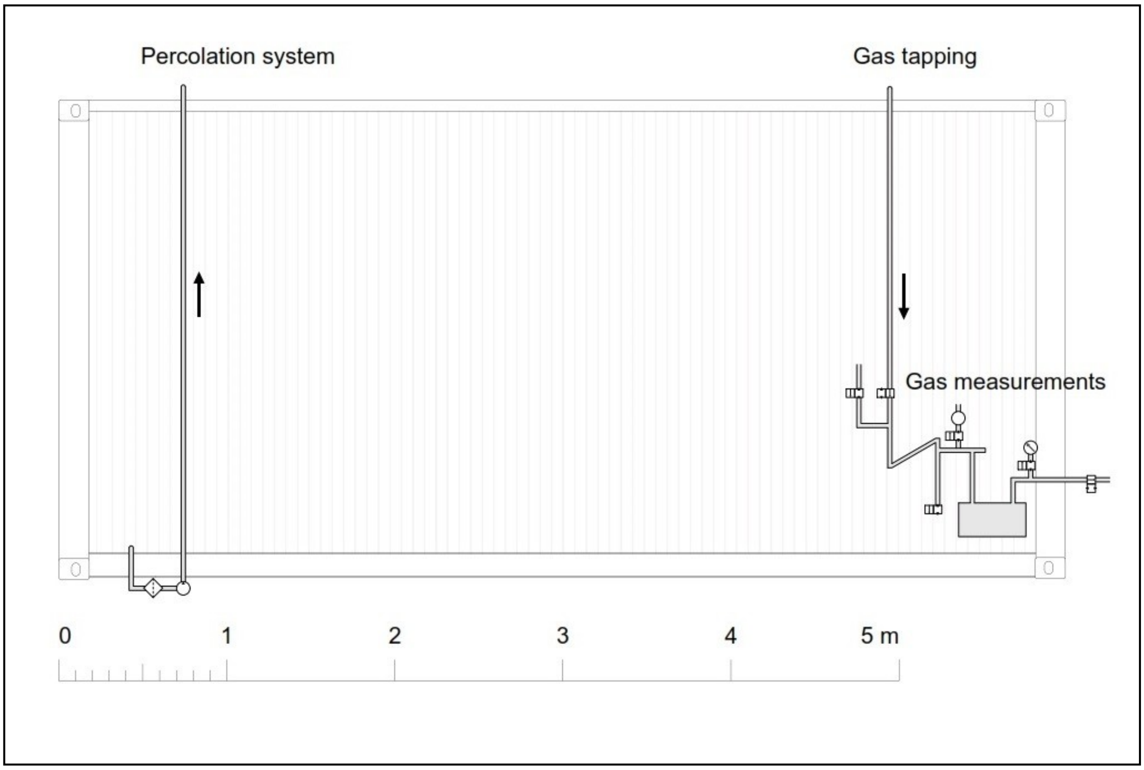

Figure 23: *Schematic representation of the side view of the shipping container*

Opening

The most challenging part to grant air tightness is to seal the door. A standard shipping container door has two wings. Each wing is equipped with rubber sealings. Those prevent water from entering the container during transport. However, those rubbers do not seal completely airtight and need to be modified. Technically it is difficult to make a two wing door airtight. Hence one of the two doors is closed and sealed permanently with silicon sealant. The other door is left with the standard rubber sealing. However, leakage tests showed that this rubber sealing is not sufficient. Therefore, a series of four butyl rubber bicycle tubes are joined together and placed around the rubber of the door. If the door is shut, the bicycle tube can be inflated to fill the gaps where air could possibly be leaking (see Figure 25). In the first test it turned out, that the bicycle tubes that have been joined with vulcanizing glue were losing air and had to be re-pumped at least once a day. Therefore, as a solution to assist the leaking tube, silicon sealant was applied when closing the door for the first test run (see Figure 26 and Figure 27). Loading and unloading is easy. Although one door is closed permanently, the second door is still big enough to access the container with a wheelbarrow. As loading and unloading is done manually, the one door solution is sufficient (see Figure 24).

Figure 24: *The shipping container while loading. With one door permanently closed*

Figure 25: *Inflated bicycle tube*

Figure 26: *Adding silicon sealant before closing the door*

Figure 27: *Silicon sealant applied to the rubber sealing of the door*

Percolation system

To install the percolation system, holes are cut into the container with an electrical welding machine. Then PVC fittings with rubber sealing rings can be attached to the container (see Figure 28 and Figure 29).

The sprinkling system is built with 1'' PVC pipes. Such pipes are very cheap and can be joined together to the desired length. The percolation system consists of two pipes that have 2 mm holes drilled on either side of the pipe (see Figure 30). The pipes are held by six metal rings which are welded to the roof (see Figure 32) . At one bottom side of the container, the percolation system has an exiting hole. At the inside of this hole, a filter to keep coarse particles in the container is installed. This filter consists of a 3'' pipe. This PVC pipe has a length of 2.2 metre and is perforated with 6 millimetre holes. (see Figure 31)

The percolate flows through this filter, exits the shipping container and is stored in a 300 litre Polytank. This Polytank is placed in a hole below the level of liquid in the container. Thus the percolate can flow into the storage tank by gravity if the outlet valve of the shipping container is opened (see Figure 33).

From there it is pumped through a filter into the percolation piping system at the container ceiling. The pumping is done by a 0.5 hp vortex water pump (manufactured by Shimge, China).

Figure 28: *PVC fitting for 1'' pipe connection*

Figure 29: *PVC pipe connected at container top*

Figure 30: *Principle of the percolation system*

Figure 31: *Filter tube*

Figure 32: *Running percolation system*

Figure 33: *Percolate storage tank*

Gas tapping

The gas tapping requires another hole to be welded into the container at one top corner. Again a PVC fitting is installed to attach a 1'' pipe, which leads to the bench at the side of the container with the measuring device and subsequently to the gas exit. Prior to the measuring devices, a flash-back arrestor is installed in which the gas bubbles through a column of water. It has a valve above to refill the flash-back arrestor with water to keep a constant level. This device prevents sparks occurring during handling of the gas meter or the gas analyser from entering the container (see Figure 34 and Figure 35). After the flash-back arrestor a condensation trap is installed. This prevents water from entering the gas meter. This unit can be emptied with a valve at the end of the hose. Afterwards the gas meter is connected. This is put into a plastic housing to protect it from rain and other environmental influences. Subsequently the exiting pipe could be connected to a consumer or a gas storage device. At this stage of the project, this link is not yet realised and thus the gas exit is open.

Figure 34: *Gas measurement bench*

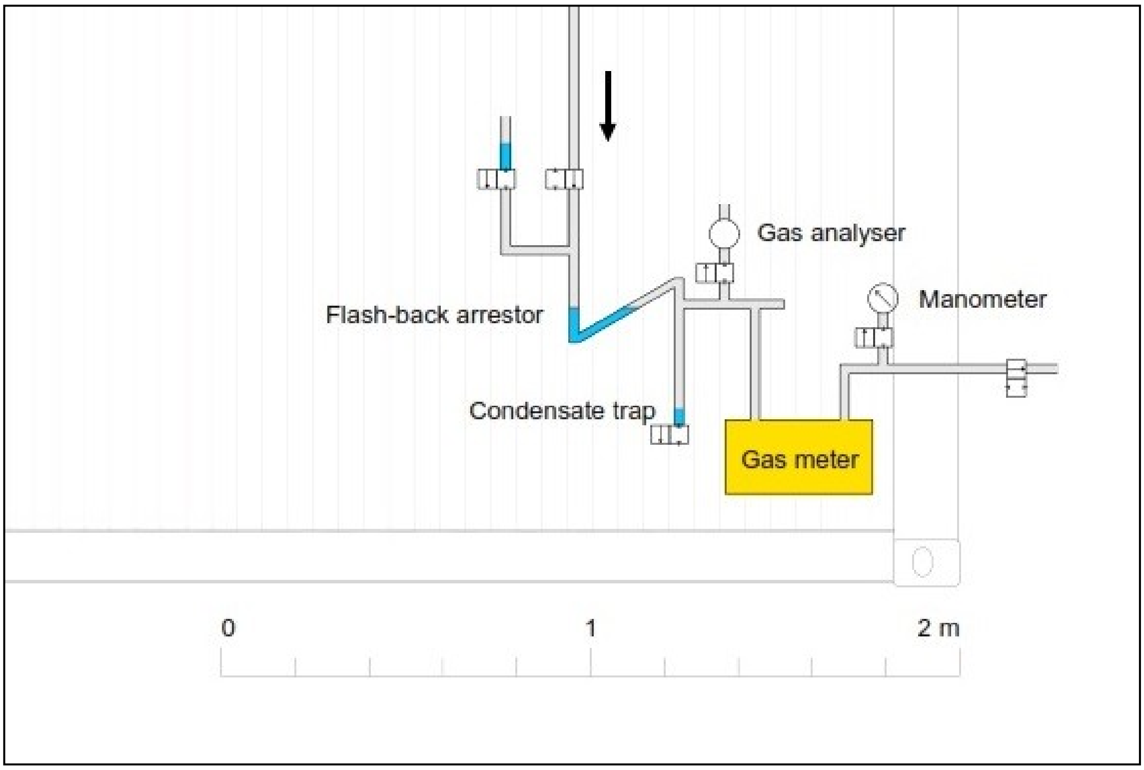

Figure 35: *Schematic representation of the gas measurements*

3.2.4 Technical Performance

The performance tests show, that an overpressure of 5 mbar can be reached. A higher pressure can not be reached, even if air is pumped in for additional 15 minutes. Test with the gas meter showed that 87% of air pumped into the container by a compressor exits through the gas meter. No pressure build-up was discovered during measuring with the gas meter. This indicates that the remaining 13% are leaking out of the container at other points of the digester.

The percolation system caused a problem, when the pump is connected to the storage tank. While pumping, foam is being built in the impeller room of the pump. This leads to a pumping failure. The foam and air in the pump has to be removed and the pumping system needs to be restarted. During the test run this problem arose two to three times per percolation cycle. This means, the pump had to be restarted roughly every 100 litres of pumping. If the pump is connected directly to the shipping container this problem does not occur.

Another issue discovered while operating the percolation system is the blockage of sprinkling holes. Some of the sprinkling holes in the pipes at the ceiling of the container were congested. Consequently, the liquid was sprinkled through only a few holes at a high pressure. Therefore the water was sprinkled unevenly over the biomass.

3.3 Discussion

The small scale digester proved to be very helpful to test technical solutions. Different design options can be tested easily and at low costs. However no suitable material for the digester room was found that can be scaled up.

The medium scale design assessment led to three options that all have advantages and drawbacks. The decision in favour of the shipping container considered on the one hand that the shipping container ranked highest based the criteria defined in chapter 3.1. On the other hand, the limited time strongly favoured to choose a shipping container, because it is a prefabricated digester room. Nevertheless, the other two options could also be viable options to build a dry digester. Especially the fact, that those two options could be scaled to the desired size is an advantage over the shipping container.

The subsequent discussion of the medium scale digester concerning the chosen shipping container option is divided into the same core parts as outlined in the methods chapter.

Air tight shell

In general, the shipping container turned out to be a good solution to construct an airtight shell. Except for the problems with the door, that is hard to seal air tight (see following section "opening"), all other expected difficulties could be overcome.

- The ventilation holes could easily be closed by welding a plate over them.
- The wooden floor plates could be sealed tight with silicon sealant.

On the long run, the air tightness of the shell could rise problems due to corrosion. If the container is not well maintained and painted every now and then, small holes and damages can develop quickly due to the humid climate with a lot of rainfall. Additionally the biogas and the moisture at the inside also develop a very corrosion friendly climate.

- Those corrosion problems can be prevented by painting it with bitumen paint on a regular basis.

The durability of the wooden floor is uncertain. On the short run it seals very good as describe above. On the long run, decomposition of the wood could be a serious problem.

- The degradation problem of the wooden plates can be prevented by painting the panes or by applying a long lasting lacquer. The wood could also be replaced with steel plates, welded to the steel container walls.

Opening

The opening has to fulfil two main tasks. One is to enable easy loading and unloading, the other is to seal the container air tight, once the door is closed.

The first task is met very well. The door can be opened completely and the open door wing is not constraining loading and unloading.

The second task still raises problems. The rubber sealing around the door is not sufficient to seal air tight.

- One door can be permanently closed with silicon sealant as only one door is needed for loading and unloading. Nevertheless it is yet to be proven how durable this solution is. During the first test run very small leaks still occurred.

- For the second wing of the door, several approaches have been tried. A sealing can be made from bicycle tubes strapped around the door which are inflated once the door is closed. The tubes improved the air tightness and prevented percolate to leak out at the bottom of the door. However the bicycle tubes lost air and had to be re-inflated frequently. Thus, the solution with the bicycle tubes needs further research to find a more durable solution.

- Another solution could be to replace the rubber sealings of the door. Those rubbers are clinched to the door edge of the door with an aluminium bar. Those rubbers should be available as spare parts. Possibly new rubbers already provide the needed air tightness.

- As a temporary solution, the door can be sealed with silicone sealant for the first test run. This rises minor problems for closing and opening. Before closure the silicon has to be applied. Before the next batch run, the old sealant has to be removed so that the sealant can be applied for the next run.

- A tailored door after the principle of a fridge or butchers door can solve the problem as they are designed to seal airtight.

- It is also possible to purchase special cold storage or controlled atmosphere containers. Such containers have improved door sealings that assist air tightness but are more expensive

Percolation system

The percolation system showed a good performance during initial testing. However those tests were carried out with pure water and not with the actual percolation liquid. During operation, some of the sprinkling holes in the percolation pipe got blocked. This led to high liquid pressure and to uneven sprinkling.

- One solution could be to drill bigger holes into the pipes and thus avoid congestion. Possibly the amount of sprinkling holes would need to be reduced to grant a sufficient liquid pressure until the very end of the pipe.

- Another solution could be to use a different technique to sprinkle the water. One possible option would be the principle of a fire sprinkler where water is piped on a deflector plate.

An issue discovered while operating the percolation system is a problem with the centrifugal pump. The pump tends to build foam in the impeller room and consequently stops working. This foam building is likely o be caused by gas (mainly CO_2) that bubbles out of the liquid due to an under pressure that is formed while drawing liquid from the percolation tank.

- This problem can be solved by placing the pump below the liquid level of the storage tank. As the storage tank is buried, this is unhandy. The pump can be connected to the shipping container directly. This makes the system simpler because the storage tank is not required. This solution has been successfully tested. The principle is shown in the two pictures below

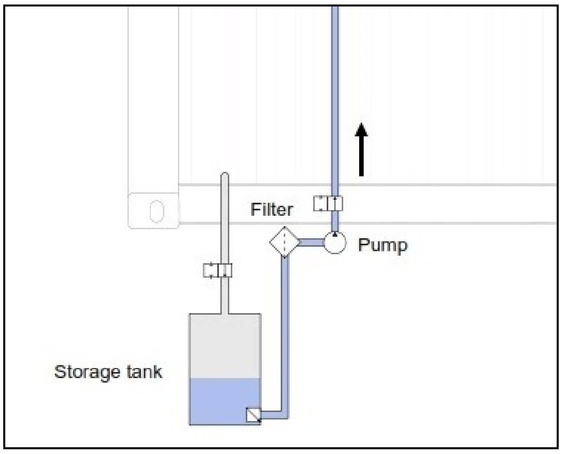

Figure 36: *Schematic representation of the percolation system with storage tank*

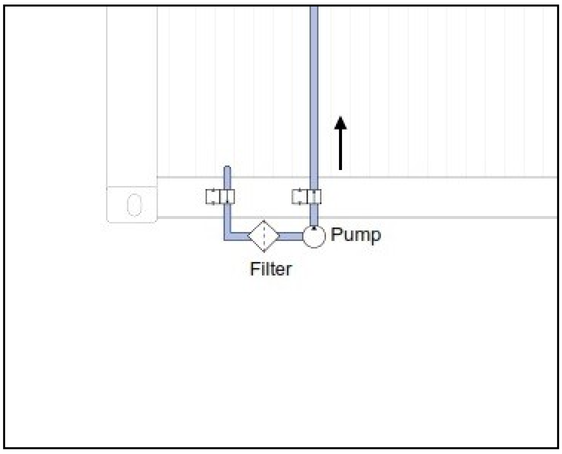

Figure 37:*Schematic representation of the percolation system with direct connection*

- Another solution could be a pump that can be submersed into the storage tank. This would also prevent under pressure generation in the pipe before the pump as the liquid is pushes into the pipes from the beginning.

Gas tapping

The gas tapping worked very well. However one concern is the open gas exit. This is a problem as air enters the container when the inside of the container cools down and an under-pressure is formed.

- One solution is a one way the exit to prevent air from entering the gas way.
- The installation of a gas storage would also minimise the problem. In that case only biogas can be drawn in and not ambient air.

3.3.1 Summary

Positive aspects

- The purchased second hand shipping container is cheap
- Shipping containers are ISO standardised abundant in harbour areas
- The shipping container needs only few modifications to be converted to a dry fermentation plant
- Regular welding equipment is sufficient to make modifications.
- The construction time is short
- The shell and the floor can be sealed air tight easily
- The percolate filter performed well
- The gas tapping with the measuring installation works well
- All material is locally available
- PVC piping and connections are easily available and cheap

Negative aspects

Table 9: *Problems and proposed solutions for the construction*

Problem	**Proposed Solution**
Air leaks at the door	Replace the rubber sealing with a new robust inflatable tube around the door or use a cold store container
Pump malfunctioning due to foam building	Connect the pump directly to the percolation outlet or use a pump submersed into the storage tank
Air intake	Install a one way valve at the gas exit or connect to a gas storage
Blockage of the percolate system	Use less but bigger holes or install a system based on fire sprinkler principle with a pipe and a deflector

4

Performance

4.1 Method

After the construction of the medium scale plant, it is taken into operation. The operational performance during the first test run is measured by the development of the gas composition, the pH value of the percolate and the gas volume that is produced daily. The gas composition is measured with a gas analyzer Dräger X-am 7000 at the gas exit before the gas meter. The percolate pH and temperature is measured with a Hach HQ D40 pH measuring sensor. Those measurements are made at the percolate outlet of the shipping container. The amount of percolate that is re-circulated is estimated from level markers on the storage tank. To measure the volume of gas produced, a gas meter is installed. A Gas meter from Erdgas ZH, Switzerland (type G4ZR W C-0) with a minimal gas flow of 0.04 m3 per hour is used. Ambient temperature and pressure are not compensated. The used measurement protocol can be found in appendix A.2

Table 10 lists the parameters, which are measured and the respective measuring technique. The specified parameters are all measured daily (one measurement at a specified point in time) and then transferred to Microsoft Excel and Matlab for further evaluation. The complete measurement data can be found in appendix A.1

Table 10: *Measured parameter and technique used for the gas analyses*

	Parameters measured	Measurement technique
Gas composition	CH_4 [%vol]	Infra red sensor (IR)
	CO_2 [%vol]	IR
	O_2 [%vol]	Electro chemical sensor (EC)
	NH_3 [ppm]	EC
	H_2S [ppm]	EC
Percolate	pH	Glass electrode sensor
	Temperature [°C]	PT100
	Quantity recirculated [m^3/day]	Readings of fill level markers
	Fresh water added [m^3]	Readings of fill level markers
Gas quantity	Biogas [m^3/day]	Gas flow meter

4.2 Results

4.2.1 Test run specification

In the first test run the plant is operate for 23 days. The feedstock is the organic fraction of MSW from the dumpsite in Amanfrom. The waste is separated on the dumpsite and delivered with a truck by Zoomlion (see Figure 38). It is very rich in structural material such as cuttings of bamboo and sugar cane. It has a large quantity of coconut shells, straw parts and banana leaves. The content of fruit residues and food leftovers is low. (See Figure 39) A detailed feedstock analysis has not been carried out. The density of the feedstock is 500 kg/m^3 and a total of 8 tons is loaded into the shipping container. To inoculate the substrate layers of cow and sheep dung are mixed in. A total of 1.5 tons is added (30% cow dung, 70% sheep dung). Moreover, additional inoculant-liquid (water, which is mixed with fresh cow dung and left to soak for 24 hours) is percolated. A total of 750 litres distributed over six days is pumped in. Table 11 lists specifications of the operation.

Figure 38: *Delivery of the organic waste at the plant site*

Figure 39*: Substrate material, rich in structural material*

Table 11: *Test Run Specifications*

Parameter	Specification
Test Site	KNUST sewage plant
Substrate Material	Organic fraction of MSW from Amanfrom dumpsite (8 tonnes)
Inoculant Material	Sheep dung from Animal science KNUST (450 kg)
	Cow Dung from cattle research KNUST (1.05 t)
	Fresh sewage sludge (200 kg)
Percolation liquid added	Fresh water (pH 6.5, 1100 l)
	Cow dung liquid (pH 6.3, 750 l)
Percolation Cycle	250 to 500 litres daily
Retention time	23 days
Temperature	No heating, ambient temperature between 25 and 38°C

4.2.2 Gas analysis and percolate pH

Throughout the test run, the gas composition and the produced volume are measured. The three graphs in Figure 40 display the results from the gas analysis. The produced gas volume rose constantly to a total of 15 m^3.

The gas composition analysis shows a carbon dioxide content of nearly 40% within a few days after starting up. At the same time the oxygen content dropped to less than 2%. However the oxygen is not consumed completely but the content kept fluctuating around 2%. The methane content rose constantly at a rate of about 1% per day. It reached a maximum of 21% after 23 days. At two occasions it can be seen, that the oxygen content rises notably. At these two points, the methane as well as the carbon dioxide content drops. At the same points, the gas meter counted backwards. The content of Hydrogen Sulphide (H_2S) varies considerably. It reached maximum values of around 300 ppm. However, other measurements only recorded a concentration of a few ppm. The gaps in the three series are days where no measurements were taken.

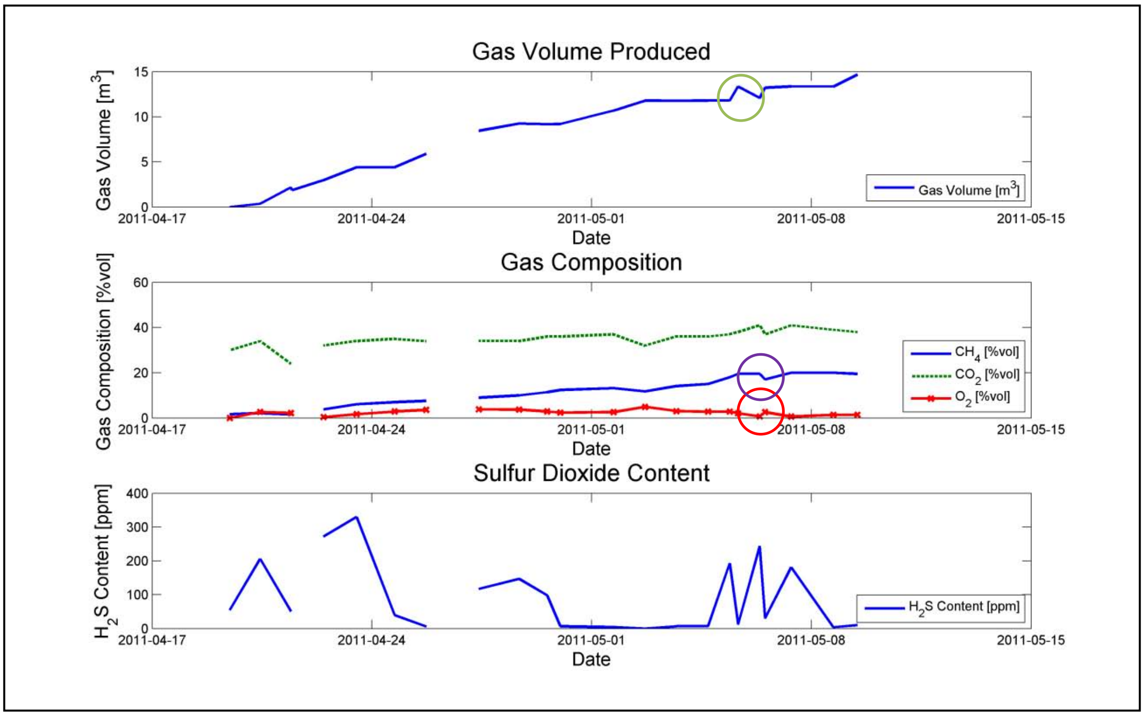

Figure 40: *Gas measurements*

The initially added fresh water and cow dung percolate had an average pH of 6.8. However the pH dropped to pH 5.6 within one day and stayed almost constant. After 5 days, the pH of percolate in the outside tank was corrected with ash and with soda (NaOH) to a pH of 7.5. This correction was repeated the two following percolation cycles. Each time 250 litres were pumped in, summing up to a total of 750 litres of corrected pH percolate. These corrections did not change the pH of the exiting percolate.

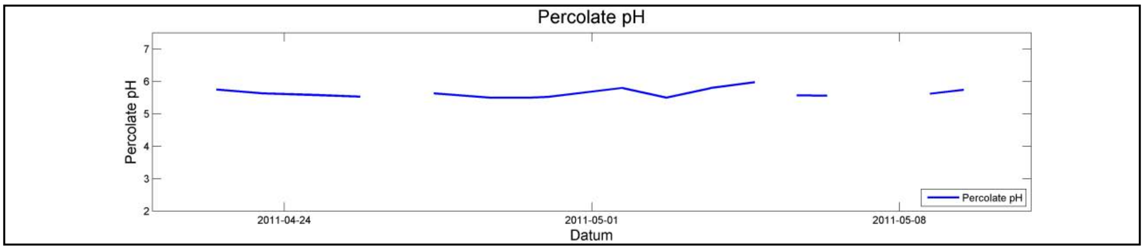

Figure 41: *pH of the exiting percolation liquid*

4.3 Discussion

After closing the plant, the container contained ambient air. The quick rise of the CO_2 content after start up is due to aerobic decomposition of the substrate. During this period, the oxygen of the container is consumed. In an ideal case, all oxygen should be used up. The reason why oxygen remained at 2 % could be connected to the daily temperature variations. The change in ambient temperature and in radiative heating between day and night led to the expansion and contraction of the gas within the container. At night the gas in the container is contracted. A temperature reduction of 10°C (which equals a relative decrease of about 3% on the absolute temperature scale) causes a relative pressure decrease of roughly 30 mbar compared to daytime conditions. Consequently air can be drawn into the digester through leakages and through the open gas exit. This reasoning suggests that early in the morning (after the digester drew in ambient air during the night) the oxygen content should be higher than in the evening. Moreover, in case the digester drew in the air through the gas exit, the gas meter should count backwards. To test this hypothesis, for two days measurements were taken twice daily (early morning, evening). The results are marked with a circle in Figure 40 strongly support the hypothesis. In the morning, the oxygen is higher (red circle), while the Gas meter counted backwards (green circle). At this event the methane content slightly decreased (blue circle).

The methane content rose constantly but only reached 21% at the end of the test run. This is a content at which the biogas cannot be ignited easily. In a good system, the methane content reaches up to 60% within the first days (Gronauer and Aschmann 2003).

There are different possible reasons that explain the low methane content: The oxygen that is always present in the container is toxic to the methanogenic bacteria and could inhibit their production. However, an oxygen content of 2-3% is not a critical factor for methane production. Furthermore it only affects the methanogenesis if it is dissolved in the liquid phase and penetrates the substrate heap (Baier 2011). Another reason is the start up process. To obtain a stable process an appropriate inoculation is crucial. In normal operation, depending on the substrate composition up to 70% of the digested material is mixed with fresh substrate to inoculate the process with methanogene bacteria (FNR 2006). In the case of the first batch test, this inoculation would need to be made with external material such as cow dung or effluent from an existing biogas plant. In our case, supply difficulties led to an inappropriate amount of inoculant material. Furthermore, some of the material was of low quality as the cow dung was already a few days old and mixed with straw.

The fact that the pH of the percolate dropped to 5.5 in the first day further supports the thesis of a slow process start up. The acidifying bacteria produced acids at a much higher rate, than the methane forming bacteria were able to cope with.

Another reason could be that the substrate material is decomposed to easily and therefore very susceptible to acidification. This is rather unlikely as the substrate was very diverse and contained a high share of structural material (see Figure 39).

The fact remains that a pH of 5.5 is too low for a regular operation of a dry fermentation plant. It can be assumed that methane forming bacteria stop their metabolism if exposed to a pH that low (House 2010). That the methane content rose nonetheless constantly indicates that certain areas, possibly where a lot of inoculant material was present, worked at a higher pH and produced gas while other areas did not produce gas (Baier 2011).

A second issue which made the pilot plant more susceptible to acidification is that no cross percolation is possible. In case of a full scale plant with several parallel running digesters, the percolate of a stable running digester is used to wet and inoculate a newly started digester. The more acidic percolate from the new digester is respectively pumped into the running digester with a stable methane forming bacteria population (Bütikofer 2011).

After 5 days of operation, alkaline materials were added to the percolate in the storage tank to increase the pH value. Firstly, ash was added. Ash helped to increase the pH slightly but some problems with sedimentation of ash particles in the percolate tank arose. The soda added increased the pH to 7.5. Although this was done 3 times for the full percolate tank, no effect on the exiting percolate was noticed. As no effect was observed and the effect of large amounts of soda on the microbiological life was hard to estimate, the addition of soda was stopped. Overall the effect of the regular percolation remains unclear. It is likely that the daily percolation with a percolate pH of 5.5 had a negative impact on the process.

Unfortunately the test had to be stopped after 23 days for post-composting due to the limited time of the research project. It is unclear whether the digester would have reached a stable process if left to start up for a longer time. Future studies should make sure the process is inoculated with an adequate amount of material. For example cow paunch could be obtained from abattoirs. If the percolate turns acidic, it could help the process to discharge the percolate and add fresh water instead of re-circulating the percolate. The optimal amount and pattern of percolation should be investigated by trials. Generally, the amount of percolate increases over time as the moisture remains trapped in the container and additional water from the substrate is available.

The low level of gas volume indicates that either the biological process worked at a very low rate or that there was significant leakage. The total of 15 m^3 over 23 days is very low. A regular plant should produce around 9 m^3 per day (Gronauer and Aschmann 2003).

4.3.1 Summary

Positive aspects:

- Measurement setup functioned well
- The oxygen content decreases very fast as expected
- Correspondingly the carbon dioxide content rises up to 40% very quickly
- The methane content rises constantly, although very slow
- The hydrogen sulphide content is generally low. At some points in time, high concentration can be measured, but not over longer periods of time.

Negative Aspects:

Table 12: *Problems and proposed solutions for the operation*

Problem	Proposed Solution
Slow increase in CH_4	Better inoculation from the beginning
Oxygen in the digester	Close leaks, install one way valve or gas storage at gas outlet.
Low pH of the percolate	Better inoculation from the beginning

5

Financial Assessment

5.1 Method

In the first part of the financial assessment a cost-benefit analysis is carried out. To account for the time value of money, the obtained values are used to calculate the net present value (NPV) and the levelised cost of electricity (LEC) of a plant with a life span of twenty years. Throughout the financial assessment only the medium scale digester is considered. For the built medium scale prototype (a single batch digester) only a cost assessment is made, as it is not sensible to operate it as a standalone plant with a generator or a gas cleaning and compression unit to bottle the gas. This is due to the facts that one single batch digester has gas supply interruptions of a few days after each cycle and that the equipment (generator or compressor) is too expensive for a single digester. The revenues and further financial indicators are only calculated for a hypothetical full-scale plant, which consists of five parallel digesters and an electricity generator. The full-scale plant is based on the built prototype.

The financial analysis depends on different assumptions that greatly influence the economic performance. Factors such as the electricity tariff, the availability of substrate material and its transport distance or the market value of compost can vary greatly. Therefore different scenarios are developed to account for possible variance. Moreover, all assumptions are listed and all sources are enclosed.

5.1.1 Costs & Benefit Analysis:

In this study, the considered costs include investment costs (which occur only once upon construction) as well as operation and maintenance cost (which occur while running the plant). If available, the actual costs from the construction of the prototype are used. Not included are costs for planning and developing the plant, insurance and tax cost, the land costs and costs for permits or licenses.

The maintenance costs also include the replacements of plant parts. Based on an assumed lifetime of each part (T_{part_n}), the respective replacement costs (C_{part}) are evenly distributed over the plants life span (T_{plant}) according to the following formula which yield the yearly replacement cost (R_{yearly}). The yearly replacement cost is the sum of the replacement cost of every part n:

$$R_{yearly}[\$] = \frac{\sum_{n=0}^{N}((\frac{T_{plant}[a]}{T_{part\_n}[a]} - 1) \cdot C_{part}[\$])}{T_{plant}[a]} \quad (1.1)$$

The considered revenues are sales from electricity, fertilizer, heat, climate certificates and avoided landfill costs. Other revenues or environmental benefits are not included. The energy and fertilizer revenues are based on the output of the plant and their respective market value. As only one short test run of the digester has been carried out, the energy and fertilizer output are calculated with values found in literature. The gas output for one batch is calculated in multiple steps.

First the digester capacity per batch is calculated. The digester capacity (C_{batch}) is considerably smaller than the total volume ($V_{digester}$). On the one hand the digester cannot be loaded to the very top, Therefore a certain share remains empty (x_{loaded}). On the other hand, a specific share of the fermented substrate from the prior batch is kept inside the digester to inoculate the fresh substrate (x_{fresh}). Taking into account the density of the fresh substrate ($\rho_{substrate}$), the digester capacity can be calculated:

$$C_{batch}[kg] = V_{digester}[m^3] * x_{loaded} * x_{fresh} * \rho_{substrate}[\frac{kg}{m^3}] \quad (1.2)$$

Based on the digester capacity (C_{batch}) and a theoretical value for the specific gas output per tonne of substrate ($v_{specific}$), within the considered retention time (t_r) the gas output per batch (V_{batch}) is calculated:

$$V_{batch}[m^3] = C_{batch}[kg] * v_{specific}[\frac{m^3}{kg}] \quad (1.3)$$

To obtain the yearly digester capacity (C_{yearly}) and the yearly gas output (V_{yearly}), the retention time of the substrate in the digester (t_r) and the yearly load factor (F_{load}) of the plant are considered. Values for the retention time and the load factor are estimations based on the literature review and expert interviews (Lutz 2010; Bütikofer 2011).

$$F_{load} = \frac{t_{operational}[h]}{8760[h]} \tag{1.4}$$

$$C_{yearly}[kg] = \frac{365[d]}{t_r[d]} \cdot F_{load} \cdot C_{batch}[kg] \tag{1.5}$$

$$V_{yearly}[m^3] = \frac{365[d]}{t_r[d]} \cdot F_{load} \cdot V_{batch}[m^3] \tag{1.6}$$

Based on the yearly gas output (V_{yearly}), the amount of electricity (E_{el}) and heat (E_{th}) that is generated is calculated, considering the lower heating value of methane (LHV), the share of methane in the produced biogas ($x_{methane}$) and the respective efficiency of the generator (η_{el} and η_{th}).

$$E_{el}[kWh] = V_{yearly}[m^3] \cdot LHV[\frac{kWh}{m^3}] \cdot x_{methane} \cdot \eta_{el} \tag{1.7}$$

$$E_{th}[kWh] = V_{yearly}[m^3] \cdot LHV[\frac{kWh}{m^3}] \cdot x_{methane} \cdot \eta_{th} \tag{1.8}$$

For composting, it is assumed that from one ton of waste that is loaded in to the digester, half a ton of compost can be produced (Schleiss 2010). This reduction on weight is due to loss of moisture, carbon and nitrogen (Bachert et al. 2008).

To obtain the revenues, the final product (electricity, industrial heat, fertilizer) and its respective market price are considered.

The avoided landfill costs are based on expert interviews. The climate certificates revenues are calculated according to methodology AMS III-F of the United Nations Framework Convention on Climate Change (UNFCC 2010). The greenhouse gas reductions caused by diverting organic waste from landfills are calculated with the excel tool myclimate calculator v03 (myclimate 2010). The reductions are then multiplied with an assumed market price for climate certificates.

5.1.2 Financial Measures

In a second step, the values of the cost-benefit analysis are integrated in an economic model to account for depreciation and time value of money. The financial measures used in this analysis are the NPV and LEC.

The NPV calculation considers both the initial investment (R_0) and all future net cash flows (R_n) over the plants lifetime (N).To obtain the NPV, the future net cash flow of each operational year (R_n) is discounted to its respective present value by the discount rate *i* (Yescombe 2002).

$$NPV = -R_0 + \sum_{n=1}^{N} \frac{R_n}{(1+i)^n} \qquad (1.9)$$

The LEC is the average electricity generation cost over the whole lifetime. For every operational year (n) of the plants lifetime (N), both the costs (C_n) and the electricity production (E_n) are discounted. By dividing the levelised cost by the levelised electricity production, the levelised cost of electricity is obtained.

$$LEC = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+i)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+i)^n}} \qquad (1.10)$$

The same rational is used to calculate the cost for treating one tonne of waste (WTC). Dividing the NP by the discounted waste volume of every year n yields the average cost for treating one tonne of waste (WTC).

$$WTC = \frac{NPV}{\sum_{n=0}^{N} \frac{W_n}{(1+i)^n}} \qquad (1.11)$$

5.2 Results

To start, Table 13 gives an overview of the most important characteristics of the studied biogas plants. The hypothetical full-scale plant is based on the built prototype. It is assumed that the gas is used to power a biogas electricity generator, which feeds in the grid. The plant is operated with the organic fraction of municipal waste. The substrate is fermented for 28 days (Lutz 2010) and then post-composted for 6 weeks (Bütikofer 2011) to obtain organic fertilizer (compost).

Table 13: *Plant specifications*

	Prototype	**Full Scale Plant**
Digester size	$33m^3$ total volume $23m^3$ load volume	165m2(5 * 33m2) total volume $115m^3$ load volume
Generator	none	10 kW el, biogas generator
Capacity (Fresh Substrate)	6 tonnes per batch 0.25 tonnes per day[1]	6 tonnes per batch 1.25 tonnes per day[1]
Substrate	MSW (organic)	MSW (organic)
Retention time	28 days, 6 week post composting	28 days, 6 week post composting
Life time		20 years

5.2.1 Costs

All values for the calculation of the investment costs are listed in Table 14. When possible, the actual costs from the construction of the prototype are used. Otherwise sources of the literature values are enclosed. For the full-scale plant, the costs are generally multiplied by the number of additional digesters, assuming that there is no price reduction due to bulk purchases or more effective construction work. The costs for the additional parts are added.

[1] The capacity per day is based on values from Table 16. The calculations are based on formula 1.5.

Table 14: *Investment costs*

Material	Prototype [US$]	Full Scale [US$]	Source	Lifespan [a]
Shipping Container	1,200	6,000	Prototype	20
Percolate Tank	50	250	Prototype	10
Pipes and Connections	120	600	Prototype	5
Tools	150	750	Prototype	5
Pump	100	500	Prototype	4
Filter	20	100	Prototype	1
Door Sealing	200	1,000	Assumption	5
Floor Sealing	50	250	Prototype	4
Generator(inclusive Grid Connection)		20,000	Arthur 2009	10
Workers Office		2,000	Assumption	20
Water Connection		300	Assumption	20
Electricity Connection		300	Assumption	20
Roofing for waste separation and composting		1,000	Rothenberger et al (2006)	20
Contingencies (+10%)		3,305	Yescombe (2002)	
Total Material Cost	**1,890**	**36,355**		
Construction work				
Manager wage	750	3,750	Arthur 2009	
Worker wage	300	1,500	Arthur 2009	
Transport	500	1,500	Prototype	
Welding	200	1,000	Prototype	
Generator & Grid Connection		1,000	Assumption	
Site preparation		1,000	Assumption	
Other (+10%)	175	975	Assumption	
Total Work Cost	**1,925**	**10,725**		
Total Cost	**3,815**	**47,080**		

The largest cost components are the generator and the grid connection. The next major investment is the digester, which is a second hand shipping container. The work cost amounts to one quarter of the total investment cost of the full-scale plant. The total investment costs of the full-scale plant sum up to 47,080 US$.

The column “life span” lists the expected life time of each part. Some parts such as the percolate filter will need regular replacement. These lifetime values are used to calculate the yearly replacement cost according to formula 1.1 in chapter 5.1.1.

The operation and maintenance costs are further dependent on the price of the substrate material and the required labour. The substrate price reflects the collection, transport and fuel costs and is assumed at 17 US$ per tonne. For the operation it is assumed that the prototype needs one part time manager (20% work load, 20US$ daily wage) and one full time worker (10 US$ daily wage). The full-scale plant needs one manager, five workers and one part time specialist mechanic (20% work load, 25 US$ daily wage) to maintain the generator. The workers duties include separation of the waste, loading and unloading of the feedstock, managing the percolation system, post-composting of the digested material and maintaining the plant. The costs are assessed for one operational year.

Table 15 *Operation and maintenance costs*

	Prototype [US$ per Year]	**Full Scale [US$ per Year]**	**Source**
Substrate Cost	1,000	5,000	Prototype
Electricity, water and consumables	50	350	Prototype
Plant worker wages	3,650	18,250	Arthur 2009
Manager wage	-	7,300	Arthur 2009
Technician wage	-	1,825	Arthur 2009
Replacement	92	1,460	Prototype
Total	**4,792**	**34,185**	

The operation and maintenance costs are 4,792 US$ for the prototype and 34,185 US$ for the full scale plant. Apart from the difference in scale, the variation is due to the fact that a generator is maintenance intensive and is assumed to be replaced every 10 years (Gronauer and Aschmann 2003). The separation of waste, the loading/unloading of the substrate and the composting of the effluent are labour intensive.

5.2.2 Benefits

The benefits are calculated via the gas output as described in chapter 5.1.1 using the values listed in Table 16. It is assumed that half of the fermented substrate is kept in the digester to inoculate the new process (see share fresh feedstock). The retention time is taken from running plants in Europe (Gronauer and Aschmann 2003; Lutz 2010). Considering the feedstock and the retention time, a theoretical specific gas output of 100 m^3 per ton of feedstock is assumed. This value is rather conservative but agrees with literature (FNR 2006).

In a first step, the amount of fresh feedstock is calculated. The five parallel digesters have a capacity of 0.83 tonnes per day and 301 tonnes per year. The calculated gas output is 83 m^3 per day and 30,112 m^3 per year. Multiplied with the LHV of methane (10kWh/m^3) and using efficiencies for a small scale combined heat and power plant (CHP), (here assumed to be 35% for electricity, 40% for heat) a total 62.9 MWh electricity and 71.8 MWh heat is produced. (Moran and Shapiro 2006). The underlying assumptions and the results obtained are presented in Table 16.

***Table 16** Assumptions and Results for the Energy output calculations.*

Parameter	Unit		Source
Feedstock Density	tonne/m^3	0.5	Prototype
Digester Volume	m^3	165(5*33m3)	Prototype
Share Loaded Digester Volume	-	0.7	Prototype
Share new Feedstock	-	0.5	FNR 2006
Retention Time	days	28	Lutz 2010
Yearly Load Factor Plant	-	0.8	Hoffstede (2004)
Gas output per ton	m^3/tonne	100	Liesch and Müller (2007)
Methane content	-	0.6	House (2010)
Lower heating value	kWh/m^3	9.9	Moran and Shapiro (2006)
Input/Output Ratio Compost	Kg /Kg	0.5	Schleiss (2010)
Efficiency Generator (Electricity)	-	0.35	Assumption
Efficiency Generator (Heat)	-	0.40	Assumption
Fresh Feedstock	tonne/day	0.8	Calculation
Fresh Feedstock	tonne/year	301	Calculation
Gas Output	m^3/day	83	Calculation
Gas Output	m^3/year	30,112	Calculation
Heat Generation	kWh/year	71,836	Calculation
Electricity Generation	kWh/year	62,856	Calculation
Capacity CHP	kW	9	Calculation
Output Compost	tonnes	150	Calculation

The benefits are calculated by considering the market value of the different products (electricity, heat and fertilizer). In a scenario approach, different assumptions are used:

A “baseline” scenario assumes a modest feed in tariff of 12 cents/kWh (Blaser 2011) for electricity, no heat usage, modest avoided landfill costs (4 US$/tonne, this equals the amount the government pays to manage waste at a landfill, (Ofori 2011) and a very low market value for compost (10 US$/tonne) (Nketja 2011).

In a “low-revenue” scenario, it is assumed that the electricity is sold at the current market price of 8 Cents/kWh (Blaser 2011), avoided landfill costs are zero, process heat cannot be utilized and compost has no market value.

In a “high-revenue” scenario, a feed-in tariff of 23 Cents/kWh (Darkwah 2011) for electricity is assumed, avoided landfill cost are high (8 US$/tonne, this assumes that the government subsides organic waste recycling), process heat can be used partly (15 Cents/kWh) and compost sales at 40 US$ per ton roughly covers the costs of post-composting (Lang 2011). The “CDM” scenario keeps all the assumption from the baseline scenario but includes revenues from climate certificates. The revenues are assumed to be 10 US$/t CO_2 eq (Arthur 2009).

The “Composting” scenario assumes that the plant is installed at an existing composting plant. The cost of the substrate and the sale of the compost are not included as it is assumed that these costs are attributed to the compost plant. Moreover, the office buildings, water and electricity supply are assumed to be existing. Also, the cost for work is lower due to efficiency gains. The other assumptions are as in the baseline case. Therefore, the investment cost only amounts to 43,480 US$ operation and maintenance cost amounts to 16,410 US$.

In all scenarios it is assumed that the biogas is used to generate electricity and not for cooking. This is due to the fact that several sources state that there is no demand or ready market to sell biogas for cooking (KITE 2008; Darkwah 2011).

Table 17: *Specific market value and revenues for the assumed scenarios:*

		Base Line	**Low**	**High**	**CDM**	**Composting**
Electricity Price	US¢/kWh	12	8	35	12	12
Heat Price	US¢/kWh	0	0	15	0	0
Compost Price	US$/ton	10	0	40	10	0
Avoided Landfill Cost	US$/ton	4	0	8	4	0
Climate Certificate (CO_2-eq)	US$/ton	-	-	-	10	-
Electricity Revenues/year	US$	7,543	5,029	22,000	7,543	7,543
Heat Revenues/year	US$	0	0	17,959	0	0
Compost Revenues/year	US$	1,506	0	6,023	1,506	0
Avoided Landfill Cost/year	US$	1,205	0	2,409	1,205	0
Climate Certificate revenue	US$	0	0	0	15,056	0
Total Revenue per Year	**US$**	**10,253**	**5,029**	**48,390**	**25,309**	**7,543**

The results show a large spread. In the “high” scenario the revenues are 48,390 US$, almost five times higher than in the “base line” scenario with 10,253 US$ and almost ten times higher than the revenues of 5,029 US$ in the “low” scenario. The revenues for the “CDM” and the “Composting” scenario lie in between.

5.2.3 Financial Measures

In this section, the NPV and the LCE are presented for each scenario. For the calculations an discount rate of 27% is assumed (Arthur 2009).

Table 19 summarizes the results of the financial analysis. Only the "High" scenario has a positive NPV. The "Baseline" scenario has a negative NPV of -134,973 US$. The CDM Revenue is calculated to be 20,280 US$ per year (based on a green house gas emission reduction of 2 t CO_2eq per tonne of waste diverted from the landfill. The additional CDM revenue is not sufficient to generate a positive NPV with the baseline assumptions. The LCE is 75 Cents/kWh for all scenarios, except the "composting" scenario. The LCE of the composting scenario is 45 Cents/kWh, which is lower as the costs are partly allocated to the composting plant. The waste treatment cost range from negative 4 US$/tonne of waste (which means the treatment of waste is profitable) to a price of 110 US$/tonne.

Table 19: *Summary of financial indicators (NPV and LCE)*

	Baseline	Low	High	CDM	Composting
Invest Cost [US$]	47,080	47,080	47,080	47,080	43,480
O&M Cost [US$/year]	34,185	34,185	34,185	34,185	16,410
Revenue [US$/year]	10,253	5,029	48,390	25,309	7,543
NPV [US$]	-134,973	-154,161	5,091	-79,677	-76,046
LCE [US cents /year]	75	75	75	75	45
WTC [US$/ton]	96	110	-4	57	54

5.3 Discussion

Generally, there is a large spread between the different scenarios. The profitability of a biogas project depends on many factors, which can vary greatly depending on the circumstances. For example, the future feed in tariff for electricity can vary between the current tariff of 8 cents/kWh up to a preferential feed in tariff of 35 cents/kWh(Blaser 2011; Darkwah 2011).

Additional to the uncertainty in cost and revenues, a new technology involves many operational uncertainties. Throughout the calculations it is assumed that gas is produced without major technological failures.

The goal of the financial analysis is therefore not to give any definite numbers, but provide an idea how the financial analysis of such a project can vary and to give an idea which factors are important for profitable operation.

5.3.1 Costs

The investment costs for a full scale plant (165 m^3 total volume) were estimated to be 47,080 US$. When compared to wet fermentation plants, this cost can be considered competitive. In a survey by Bensah (2009), Ghanaian biogas companies stated the investment cost of 10 m3 Puxin digester between 1,700 and 3,500 US$ (170 to 350 US$/$m^3$). Actually built plants in the same survey show higher costs: A 80m^3 biogas plant at Eastern Regional hospital in Ghana (comprising of two 40m^3 digester, a balloon gasholder and a biogas stove) cost 40,000 US$(500$/m^3). Another example is a 40 m^3 biogas plant with a biogas stove at Pope Johns seminary in Kofordua that cost 40,000 Us$ (1000$/$m^3$) in 2007. A feasibility study for a wet fermentation plant with electricity feed in at the very same site at KNUST sewage plant was projected to cost 286,600 US$ for a 800 m^3 plant (358 US$/$m^3$)

Therefore, investment cost for a wet digester observed in Ghana are assumed to range between 170 US$/$m^3$ and 1000 US$/$m^3$. The planned dry digestion plant account for 285 US$/$m^3$. However, a more powerful indicator would be to compare the cost per gas output. These numbers are not available.

The operation and maintenance costs are mainly caused by the waste separation, replacements and labour. Again, costs can vary: If source separation of waste would be introduced or the plant is placed close to a food or fruit processing industry, organic waste does not need to be separated. This would reduce the separation cost and work load significantly. If unsorted MSW from a dumpsite is used as feedstock, the separation costs are high.

5.3.2 Benefits

The revenues are based on an estimated gas yield of 83 m3 per day. This equals 13 days of cooking on a gas stove, or it should be sufficient to supply 40 families of 5 to 6 people with daily cooking gas (Lohri 2009). The gas could also be used to power roughly 200 40W light bulbs continuously.

The most important factor influencing the revenues is the feed-in tariff as electricity is the major product of the plant. Presently there is no official feed in tariff in Ghana. Feed-in tariffs for renewables are negotiated individually between the national grid company and the plant owner (Darkwah 2011). This adds uncertainty and operational risk . The possible range of feed-in tariff has a strong impact on the financial viability, it is considered in the different scenarios.

The second important revenue stream is heat. Heat is only considered in the “High” scenario as it is only used certain specific industrial processes, such as drying fruits or to provide hot water in an abattoir or to treat hazardous waste (e.g. sterilize hospital waste with steam) (Aklaku 2011). These applications have to be considered as niches. Nonetheless if the heat can be used and thus replace fossil fuels, it can become a very important revenue factor.

A third possible income stream is compost. The digestate of a dry fermentation plant can be post-composted to produce a nutrient rich organic fertilizer. Depending on the soil conditions, the price of competitors (such as chemical fertilizer or chicken manure) and the location of the plant, the post composting process can be a profitable revenue stream or merely additional cost. Ghana is a case in point for this: In Kumasi, organic fertilizer on compost basis has virtually no market value. One reason is that the soils are in a good condition and chicken manure from industrial chicken husbandry is available free or at very low cost. In Tamale the situation is different. Soil condition is poorer than in Kumasi and the addition of a fertiliser can increase harvest (Fosu 2011). Thus farmers are more willing to pay for compost. Even within a city, the location is important. If the composting is done centrally on a big dumpsite, it is not likely that customers are within close transportation distance. On the other hand if the compost is produced within the premises of a fruit processing industry where plantations are close, the compost can directly be used on the fields and add value (Aklaku 2011).

The amount of generated climate certificates can vary greatly depending on the baseline assumptions. The condition at the dumpsite (type of dumpsite, water content of the waste, climate conditions, fraction of organic material) can vary greatly. Depending of the assumptions the GHG reduction can vary between 1 tonne of CO_2 equivalents per ton of waste and 6 tonne of CO_2 equivalents per tonne of waste. Climate certificate revenues are on the one hand an attractive additional revenue stream. On the other hand, the administrative work to get a project registered and its associated transaction costs can be considerable and poses an important barrier (Rogger et al. 2010). These costs are not considered in the CDM scenario. Up to date no CDM project is in place in Ghana.

5.3.3 Financial Measures

Only the “High” scenario has a positive NPV. This scenario assumes substantial policy support for biogas and a very favourable environment. If the present conditions remain, a dry fermentation plant can hardly be operated with a profit. From an energy point of view, the scenario (except “composting”) the LEC is 75 cents/kWh. This means with a feed in tariff of 75 cents per kWh, all cost could be covered by the electricity sales. Such a high feed in tariff is beyond all expert statements and highly unrealistic. Therefore, it is important that a dry fermentation plant is constructed where heat and compost are further revenue streams. Looking at the “composting” scenario, in which compost is assumed to have a value which covers the composting cost (including work and facilities), the LEC is 45 cents/kWh. That value is still high, but a lot closer to a realistic scenario if optimal conditions are assumed.

The waste treatments costs show a large spread. In the best case, the treatment of waste by anaerobic digestion is profitable through the sales of the products. In the worst case, the cost amount to 110 US$/tonne. In Europe these are average to low costs to treat biowaste (Hogg 2002). For a developing country, this waste treatment costs are very likely beyond the budget of the municipality.

5.3.4 Summary

- The simple design of the dry fermentation plant leads to low investment cost. The high cost for the generator and grid connection are the same for any biogas technology.
- In regard to investment cost per cubic meter digester room, dry fermentation is comparable to wet fermentation.
- The choice of the site is critical. On the one hand the substrate costs are directly dependent on the site. They could be high in the case the waste needs to be transported over long distances and separated. They could even be negative, if the plant recycles the waste e.g. of a fruit factory which would otherwise have to pay a waste collection fee. On the other hand, the revenues are again dependent on the site and on the local policies. The site determines which of the products can be used and in what way (heat, fertilizer, or electricity). The policy framework determines the market value to some extent.
- The overall viability is dependent on those revenue parameters as shown by the NPV results. A general conclusion whether dry fermentation is a financially viable technology is not possible. The technology can only be profitable within very favourable circumstances.
- Biogas from solid waste has a broad range of benefits from climate impacts to sanitation improvement and from renewable energy to agriculture. This makes the technology undisputedly attractive for a clean and sustainable development. On the downside, it makes the allocation of revenues and costs more difficult. This has in turn implication in regard to policy support, as it makes it unclear which ministry (energy, sanitation or agriculture) should be mandated to support the dissemination

6

Conclusion

Positive Aspects

Batch dry fermentation plants have a simple design and low water and process energy consumption. They can use bulky solid waste as a substrate with a high dry matter content and the digestate can be easily post-composted. The construction of the pilot plant proved that the construction is possible to be realised in Ghana. It can be built at a low price with local material. On the basis of a shipping container a dry fermentation plant can be built without high-tech parts or specialized tools.

Negative Aspects

The pilot plant revealed some drawbacks of the technology: The airtight sealing remains a major challenge. Particularly the sealing of the door needs further investigation to find a permanent solution. The security risk of potentially explosive air/methane mixture is an important factor to consider. Methane is a burnable gas and explosive mixtures and sparks have to be avoided by all means. Operation is considerably safe if precautions are followed. In case of faulty handling however, severe accidents can occur. As the technology is not very mature yet, the security issue need further research, which includes the development of a digester room flushing system (see chapter 2.4). Further research also needs to be directed on the durability of parts like the PVC piping or the sealed wooden floor. Although the plant construction is made with simple technology it needs to be operated and taken care of by trained personnel. If handled wrongly the delicate parts such as the sealings or the PVC pipe connections can be damaged easily. Because of the percolation system that has to be operated frequently, the operation of the plant needs regular attention and requires water and electricity.

Technology comparison to wet digestion

Comparing dry fermentation to simple wet fermentation technologies (such as Chinese fixed dome digester or Puxin digesters) fewer arguments remain in favour of dry digestion. Wet digesters can also have a very simple design. No mixing or stirring device is involved, hence no electricity connection is needed. Performance and suitability is proven in a vast number of plants throughout Asia and Africa. The performance of the pilot dry fermentation plant however is yet to be proven. Nevertheless, the performance of dry fermentation plants in Europe show a competitive performance. Albeit there is a degree of uncertainty to the cost assessment, the economics show that the prices per digester volume are similar.

A striking advantages compared to wet fermentation is the suitability to ferment stackable substrate with high dry matter content and the handling of the digestate. This fact makes it a very suitable option to improve SWM as stated earlier on. In a wet digestion process, municipal waste input has to be cut into small pieces by a shredder and is mixed with water. The subsequent digestate is liquid and cumbersome to handle. Currently over 90% of the biogas plants in Ghana discharge the effluent in public drains or bushes. This is associated with health concerns and environmental pollution. The effluent can contain pathogens and introduces large quantities of nutrients into water bodies (Bensah 2009). With dry fermentation the digestate is solid. It can be unloaded with shovels and forks. It can be easily piled up and post-composted. A simple shelter is sufficient to prevent leakage during heavy rains. Composting produces organic fertilizer and kills pathogens. This organic fertilizer can be transported with common trucks and applied to fields without specialized tools. If there is no demand for organic fertilizer, the compost can be dumped on the dumpsite without further treatment or health concerns.

Technology comparison to composting

Looking at dry fermentation mainly as a technology to treat organic waste, composting is another alternative. The technological advantages of dry fermentation are clear: The biogas production adds a valuable product while the post-composting of the digestate maintains all the advantages of only composting. Two main aspects have to be considered for the comparison of composting and dry fermentation. Firstly: It can be that biogas technology is too complex for developing countries. Secondly it might be too costly and a plant cannot be operated economically. Whether the technology is appropriate in respect of the ease of operation is too early to say. Many characteristics are very promising. With the current circumstances (energy prices, waste handling fees), dry fermentation is not financially viable. However, the financial problems are also true for any other biogas technology and hold true to some extent for composting, as the policies are unfavourable. The fact that not a single biogas plant exists, that treats MSW underlines these issues.

Framework Conditions

Ghana has no tradition in producing biogas. It only has about 100 biogas plants of which roughly half in operation. Biogas plays a very marginal role in the energy sector. Other African countries have significantly wider dissemination of biogas plants, for instance Kenya about 2000 Tanzania between 4000 and 5000 (Bensah 2009).

SWOT Analysis

As a general overview on the project, the conclusions of this study are summarized in a SWOT analysis (Strengths-Weaknesses-Opportunities-Threats) (Frischknecht and Schmied 2009).

Table 20: *A SWOT analysis as a general overview on the project*

	Strengths	***Weaknesses***
Internal	- Low tech construction - Low investment cost - Easy handling of substrate and diges-tate - Low process energy needed	- Immature technology - Performance uncertainties due to lacking test - Durability uncertain - Technical problems unsolved (air tightness) - Security issues - Low market value of gas and compost
	Opportunities	***Threats***
External	- Improves SWM - Reduces GHG emissions - Closes nutrient cycles by producing fertilizer - Creates jobs - Reduces dependency on fossil fuels, wood fuels and energy imports - Renewable energy policies are being drafted	- Current, unfavourable conditions could persist - Impact of discovered oil reserves on renewable energies is uncertain - Trained personnel is rare - Acceptance of new technology is uncertain - Financial risks due to high dis-count rates

Conclusion with respect to the hypothesis

Solid waste management and energy supply are two of the biggest issues of growing cities in developing countries. Urbanisation leads to an intensification of such problems. Therefore solutions to reduce the growing waste burden are crucial. Furthermore new energy sources need to be made accessible to meet the increasing demand. Dry fermentation technique is a promising technology to help to solve these problems. It can reduce the burden of waste and generate renewable energy. If the operators are well trained and work with care, the operation is safe and the plant is durable. The built prototype indicates that it is an appropriate technology for developing countries. However, due to the limited time and scope of this study, subsequent research is needed to provide further evidence and to improve the technical performance of the plant. The most important factor determining future success or failure, the economic viability, remains uncertain. Currently, dry fermentation is financially not viable. But the policies are changing towards promoting biogas and sustainable SWM.

The hypothesis can thus only be partly answered with yes. Nevertheless, it is highly promising to make further research to develop a marketable low-tech dry fermentation plant.

A

Appendix

A.1 Measurement Data

date and time	Fresh water added	cow dung liquid	Percolate [l]	Gasmeter [m3]	percolate pH out	percolate pH in	percolate Temp. [°C]	CH4 [%]	CO2 [%]	O2 [%]	H2S [ppm]	Remarks
19.04.2011 11:20	100		100	0.0		6.8	-	1.7	30	0	55	Container closed without sealing the door the day before.
20.04.2011 10:30	0		0	0.4				2.2	34	2.7	206	Container reopened again and faecal sluge added
21.04.2011 10:00	0		0	2.2		5.96	35.5	1.6	24	2.2	51	
21.04.2011 11:00	400		400	1.9		-	-	-	-	-	-	Fresh water added
22.04.2011 11:00	200		600	3.0	5.75	5.98	-	3.8	32	0.4	272	100 liter of fresh water added, 100 l of water with ash added
23.04.2011 12:15	0		450	4.4	5.63	5.57	34.2	6.1	34	1.7	330	percolate left out before gas measurement
24.04.2011 17:20	0		0	4.4	5.58		29.5	7	35	2.9	40	Pump error
25.04.2011 17:30	100	100	200	5.9	5.53	6.6	31.4	7.6	34	3.6	6	Pump error
26.04.2011 00:00	Dräger Error, Pump failed											
27.04.2011 09:40	0	0	0	8.5	5.63	7.5	29	9	34	3.8	117	3.5 dl NaOH (granulat) added, pH cow dung 6.14
28.04.2011 16:30	300	100	600	9.3	5.5	8.36	30	10	34	3.7	147	3.5 dl NaOH (granulat) added
29.04.2011 14:00	0	100	300	9.2	5.5	8.5		11.4	36	2.9	98	8 l NaOh pH 11.8; Percolate outlet leaks with 1 dl per minute
30.04.2011 00:00	0	100	250	9.2	5.52	6.67		12.4	36	2.4	7	
01.05.2011 16:45	0	150	250	10.7	5.8	5.5		13.2	37	2.6	4	
02.05.2011 16:45	0	200	250	11.8	5.5	5.66		11.8	32	4.9	0	Pump was blocked, had to be unblocked manually.
03.05.2011 16:45	0	0	250	11.8	5.79	5.57		14.1	36	3	7	Valve after gas meter was closed over night.
04.05.2011 17:00	0	0	250	11.8	5.97	5.48		15	36	2.8	7	percolation filter cleaned
05.05.2011 09:30	0	0	0	11.8				18	37	2.8	193	pH not measured, no percolation
05.05.2011 16:00	0	0	450	13.4	5.57	5.57	34	19.5	38	2.1	12	
06.05.2011 08:30	0	0	0	12.1	5.56	5.56		19.5	41	0.7	244	
06.05.2011 12:30	0	0	450	13.2				17	37	2.6	30	
07.05.2011 08:30	0	0	0	13.4				20	41	0.6	181	
08.05.2011 16:45	0	0	450	13.4	5.62		29.5	20	39	1.4	4	Gas valve after gasmeter was closed
09.05.2011 11:10	0	0	300	14.7	5.74		28.6	19.5	38	1.4	10	
10.05.2011 00:00	No Measurements available											
11.05.2011 08:30	0	0	0	15.3	5.83			21	38	0.7	65	

A.2 Measurement Protocol

Name:
Date:
Time:

	Measurement 1	
Gas meter	m3	
Dräger:		
CH4	%	%
CO2	%	%
O2	%	%
NH3	ppm	ppm
H2S	ppm	ppm
Pump time:	min	min
Pressure	mbar	
pH	in	out
Temp.	°C	
Percolated	l	
Water added		l
Cowdung liquid added		l
NaOH added		g

Remarks:

Checklist

1 Water level Flashback arrestor sufficient
2 Gas meter readings
3 Close valve 8 + 9
4 Attach Dräger
5 Dräger leakage check.
Display shows 'pump flow error' if OK
6 Open valve 7
7 Measure until stable (ca. 5 min)
8 Copy readings to protocol
9 Close valve 7
10 Disconnect Dräger, let it run for 10 min to clean
11 Open valve 1
12 Take percolate pH sample and measure
13 Let Polytank fill with percolate -> check level!
14 Close valve 1
15 Turn on pump
16 Open valve 3
17 Make sure it starts to pump water
18 -> if not open air screw and add water.
19 Maybe repeat water adding
20 When Polytank is almost empty close valve 3
21 Turn off pump immediately
22 Probably repeat steps 11 to 18
23 Probably repeat steps 1 to 10
24 VALVE CHECK!
25 Closed valves 1, 2, 3, 4, 6, 7, 8

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