Anaerobic Digestion for Developing Countries with Cold Climates

Utilizing solar heat to address technical challenges and facilitating dissemination through the use of carbon finance

On track towards a sustainable future (FAO 1987)

By

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Supervisor: Dr.ir. Grietje Zeeman

Master Thesis

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Faculty of Environmental Sciences

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Foreword

This thesis is the consolidation of years of study. It is almost incomprehensible to the casual observer but also for me, that I started off to become a psychologist. I must admit that it was not until I went to Cambodia in 2006 to work for GERES that for the first time I learned what really mattered to me.

In Cambodia I conducted a small survey for the Winrock Foundation on Solar Home Systems (SHS). One time, I was sitting in a house of a SHS owner, it was really hot and I was sweating heavily. The owner of the SHS saw me sweating and emphatically turned on the fan. That struck me…the same source which is making me sweat, is now used to run a fan which is directly cooling me!!! A similar moment happened during another study when I visited a household with biogas for the CDM baseline study for the National Biodigester Program Cambodia. To demonstrate the virtues of biogas, the owner lighted a biogas lamp in the living room with a candle and turned on a biogas stove. At that time I did not know so much about biogas and I was really impressed. The 'shitty' smelly waste of pigs is converted into something so useful, so clean, so handy…..

For this thesis I have had the wonderful opportunity to combine solar energy with biomass energy, by utilizing solar energy to overcome the impact of the cold on anaerobic digestion for rural development. Carbon trading is studied to cut down costs of a solar assisted biogas plant. The mechanism of carbon trading allows us to share some of our affluence with the neediest by reducing greenhouse gas emissions and by fostering sustainable development.

'*'Every moment, the sunlight is totally empty and totally full"*

Rumi

Summary

A large proportion of the rural poor in developing countries have no access to a secure source of energy. The rural poor in developing countries rely primarily on traditional biomasses, such as wood and charcoal. The reliance on traditional biomasses and solid fuels result in substantial human, social and environmental cost. To tackle these costs a switch to a clean fuel is required. One of the solutions is anaerobic digestion (AD) of manure or other biodegradable matter to produce a clean fuel: biogas.

The principle of AD has been known for 3-4 centuries and in 1920 the first digester was designed for house on site biogas production. A digester is a technology which converts the commonly found wastes in rural areas, manures, in a controlled anaerobic environment to biogas and an excellent fertilizer. Biogas is a clean, convenient, versatile and environmentally benign fuel which does not pollute the indoor air. Furthermore, a biogas plant has several additional benefits, such as replacing bought or collected wood (time or revenue savings), provision of light by biogas lamps, empowerment of women by relieving them of the drudgeries of traditional fuel gathering. A toilet is in most cases attached to a digester which improves sanitation, a significant virtue since the majority of the poor lack access to sanitation. The effluent from the digester, digestate, has a high fertilizer value comparable to chemical fertilizers. Digestate is also an excellent fish feed and can enhance fish yields. The adoption of biogas digesters has considerable spillovers to the local, national and even to a global level. For instance, at local level, employment opportunities, skills development and reduced pressure on the forest. At a national level, it leads to less health costs, more employment, and potential foreign exchange earnings and at a global level: greenhouse gas emission mitigation. Consequently, the cumulative effects of these benefits alleviate poverty and contribute to achieve the Millennium Development Goals.

However, the dissemination and adoption of biogas technology in developing countries with cold climates is limited. The cold temperature retard the growth rate of the microbes responsible for AD; this translates to a drop in biogas production during cold periods. Two strategies are possible to counteract the impact of low temperatures; either the digester volume and the sludge retention time has to increase to accommodate for the slower microbial growth rate or the temperature of the digester content has to increase. Both options however, add additional cost to the relatively expensive digester as perceived by the resource poor and this is another reason for the limited adoption of the technology.

To tackle these higher investment costs to counteract the cold, smart and robust low-tech solutions are required. Commonplace and relatively inexpensive alterations are the construction of a greenhouse canopy around the digester to capture solar heat, hot charging (heating the feedstock before feeding), additional insulation and increasing the retention time. Most of these solutions however do not provide sufficient heat which limits the temperature increase to 10°C while increasing the retention time is costly. Another solution is indirect heating using solar collectors whereby solar heat is captured and transported to the digester content via a heat exchanger. Few studies have studied solar assistance in detail. Most attempts have left out the heat enforcement on the soil with depth, even though it is an important parameter. Therefore, in this study comprehensive modeling was conducted on an underground built digester, based on the Indian Janata model, whereby for each digester component the heat transfer was analyzed by modeling the occurring temperature with depth. The objective is to avoid a digester cooling

down to less than 15°C during the worst case climatic conditions in terms of temperature and insolation by using solar heat from collectors. The modeling was conducted for specific locations in the Georgia, Romania, Kyrgyzstan and Bolivia. In addition, a sensitivity analysis was conducted to assess the impact of insulation and thermal diffusivity of the soil. The analysis showed that most heat is lost through the walls but with increasing insulation efforts directed at the walls, an increasing amount of heat is lost via the other digester parts with the exception of the dome. The heat transfer via the dome (the gasholder above the slurry) remained insignificant. Biogas is a good insulator if the circulation in the gasholder is negligible, which was demonstrated in the analysis.

The analysis showed that in Romania, even with a well insulated digester, a relative large collector area of 5,5 m^2 is required, while for other countries this is just 1,3 m^2, caused by the substantial higher insolation and higher temperatures. Furthermore, hot charging is only feasible if the digester is well insulated, which might prove costly. With less insulation efforts, hot charging is only feasible in Georgia.

Solar collectors and additional insulation both increase the capital costs, but cost reductions are possible by utilizing local materials with the additional benefit that it yields employment opportunities for local artisans.

Another approach to tackle these higher investment costs is the clean development mechanism or the voluntary offset market to obtain carbon financing. This approach has gained considerable momentum and is applicable to biogas projects. A biogas digester mitigates GHG emission by displacing fossil or non renewable biomass (NRB) for biogas, by avoiding methane emissions from manure management and by the displacement of chemical fertilizers.

All the CDM certified and biogas projects under validation are studied to determine the claimed carbon reduction per digester to estimate carbon income. On average around 4,01 tCO_{2eq} per year per digester is claimed, higher if methane from manure management is included and less without. Actual emission reductions however, depend on the local specific situation, the share of NRB and the manure handling system. However, with this average figure around €41-78/year per digester can be obtained during the crediting period of 10 years. The revenues originating from the carbon offsets can to a great extent cover the biogas program, service and maintenance related costs. In India the revenues are mostly used to facilitate access to affordable credit and loans.

The combination of increasing the temperature of digestion in harsh conditions by utilizing solar heat combined with insulation efforts is a feasible solution to promote biogas digesters, provided there is sufficient insolation. Investment cost mitigation is possible by combining carbon finance, local skills and local materials for solar collector construction and by diverting some of the social collateral benefits to subsidize biogas plants. The latter is justifiable since the internal rate of return is in most cases higher for the economy than for the direct beneficiary and the investor of the biogas plant.

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Chapter 1

INTRODUCTION

1.1 ENERGY POVERTY IN THE DEVELOPING WORLD

This thesis is about promoting energy security in rural areas of developing countries. The importance of energy security is stressed by the UN as a prerequisite for social and economic development; for sustainable development a switch to clean household energy has to be realized (Modi 2006).

Most of the poor rely on traditional biomasses, such as dung, fuel wood and agricultural waste for their energy provision. Although these biomasses meet the most immediate energy needs, they also cause substantial human, social and environmental costs (Sagar and Kartha 2007). To avoid these detrimental consequences caused by traditional fuels a switch to a more sustainable and clean energy resource is required (Singh & Sooch). Furthermore, for a secure and affordable energy provision, the poor should not rely on the volatile pricing of market fuels, especially in today's context[1] where the prices of food, fuel and feed have risen dramatically (IFPRI, 2007).

A solution for famers with sufficient biodegradable waste is anaerobic digestion to produce biogas (Yadvika et al, 2003). Biogas is a clean and versatile renewable energy source which can be utilized to meet several energy services, such as a fuel for cooking, electricity generation, lighting and space heating (GTZ 1999). Anaerobic digestion is a technology which not only benefits the poor but also improves the environment, a win-win situation. Consequently, there is no trade-off between environmental protection and economical development goals, they are compatible. This is in the spirit of the first summit on sustainable development in Rio the Janeiro in 1992, where trade-off discussions were for the first time supplemented with the identification of win-win situations (Martinussen 1997).

Anaerobic digestion (AD) of biomass in (bio) digesters to produce biogas is a proven technology and applied in developing world for over a century (Kashyap, Dadhich et al. 2003; Sagar and Kartha 2007). In many developing countries the dissemination of biodigesters is actively promoted during the last decades. For instance SNV, a Dutch development agency, promotes the dissemination of biogas digesters in Vietnam, Laos, Cambodia, Nepal and since recently also in Tanzania and other countries in Africa (van Nes 2008). Most *domestic* biogas digesters are situated in tropical countries; the occurring temperatures allow for a relative high rate of digestion and hence a relatively small and simple digester suffices.

[1] September 2008, before the financial crunch.

1.2 PROBLEM DESCRIPTION & OBJECTIVES

PROBLEM DESCRIPTION

Adoption of domestic biogas plants is generally limited to developing countries with a suitable climate, whereby the average daily temperature does not fall beneath 15-20°C during the winter months. Since most house on site digesters are designed for these temperatures, a lower temperature will affect biogas production negatively. For instance, in a part of China where the ambient temperatures drops to 6-10 degrees, biogas production decreases considerably and is insufficient to meet the households' energy needs (Daxiong, Shuhua et al. 1990). Similar obstacles are reported in Nepal and India (Yadvika, Santosh et al. 2004; Gautam, Baral et al. 2009). Consequently, people continue to rely on traditional or fossil fuels for their energy provision with associated monetary expenditures, time investment and other detrimental consequences.

To overcome the low biogas production rate, either the temperature of the digester or the retention time has to increase (Safley and Westerman 1990). Both solutions require an additional capital investment which decreases the affordability of a digester. This directly limits the opportunities to adopt domestic biogas plants by the rural poor to secure their energy needs (Yadvika, Santosh et al. 2004). To tackle these higher capital investments, this study assesses two practical solutions.

1. **Solar assistance**

   The sun is a 'free' renewable energy source and the heat can be captured by solar collectors for digester heating. A solar collector increases the overall expenditures but offsets are possible by using local skills and materials to design and to construct a solar collector. Furthermore, since energy security is maintained throughout the year more fuel is substituted by biogas and this has a time or revenue saving component. This solution is connected with modifying the digester to retain more heat, more insulation.

2. **Carbon revenues**

   A biogas installation results in greenhouse gas (GHG) abatement. This abatement is denoted as 'carbon offsets' and have a value under the clean development mechanism (CDM) or the voluntary carbon market. These offsets can be sold as carbon credits and utilized for policies to stimulate biodigester adoption, by, for instance, providing subsidies or soft loans. Consequently, these carbon revenues can cover a part of the required capital investments to tackle the impact of the low ambient temperature on biogas production.

RESEARCH OBJECTIVES

The objective of this research is to tackle the detrimental impact of low temperatures on biogas production by both increasing the insulation and by utilizing solar for digester heating. Since this thesis aims at developing countries, a prerequisite is that the solutions are both affordable and possible to construct with local skills and materials. The latter generates employment opportunities and hence contributes to economic development.

Furthermore, this thesis examines how digestion at lower temperatures affects the commonly reported benefits of biogas technology in developing countries. For instance, the survival rate of pathogens in digesters is higher at lower temperatures; hence, psychrophilic (low temperature) digestion might impede the benefit 'improvement of sanitation'.

A biogas system has several benefits at private, local and global level, how this fits into the framework of the millennium development goals is as well studied.

Finally, the carbon offsets resulting from the adoption of biogas technology are studied in detail. As aforementioned these offsets in the shape of carbon credits generate revenues, which can be employed for policies to stimulate the dissemination and adoption of domestic biogas plants.

1.3 INFORMATION SOURCES

This thesis is compiled using information from the following sources:

1. Scientific literature & syllabi of courses on technology, biogas and development studies of the University of Wageningen, Technical University of Eindhoven and the University of Utrecht.
2. Reports of NGOs such as SNV, GTZ and the UN.
3. Internet for general information to message boards on solving differential equations.
4. Interview with Wim van Nes, practice leader on biogas and renewable energy for SNV, a Dutch developmental organization which supports biogas programs in a great number of developing countries.
5. Psychrophilic anaerobic digestion batch experiments using cow manure as substrate, to assay the required sludge retention time at three selected temperatures.

1.4 SCOPE AND SETUP OF THIS THESIS

This thesis encompasses domestic biogas plants in rural areas of developing countries. It specifically aims at farmers with sufficient livestock and subsequently manure to displace cooking fuels by biogas. The more affluent farmers who are able to invest in a larger digester, could next to displacing cooking fuels, use biogas for other energy services, such as electricity generation provided they have sufficient digester feedstock

Note that in many developing countries a biogas plant itself is already too expensive for most farmers; in addition, a considerable proportion of the farmers might have insufficient digester feedstock. A study conducted in Cambodia revealed that in the six provinces around Phnom Penh only around 50% of the farmers had enough manure to displace their cooking fuels (Buysman and Mansvelt, 1996) and even less of them were able to invest in a biogas digester without additional financial support.

Community biogas plants are predominantly built in India serving a community or village. This study does not focus on community plants per se; however, scale augmentation to retain more heat could be a viable solution to overcome the cold. Conversely, a community biogas plant poses many difficulties, in particular at organizational level. Details on community biogas plants are out of scope of this thesis, for more information I refer to an interesting article about community biogas plants in India: Family and Community Biogas plants in Rural India (Roy 1981).

SETUP OF THIS THESIS

The setup of this thesis is as follows: First, biogas plants are described from a system perspective; this entails the whole process from manure production to biogas and slurry storage. Moreover a detailed assessment of the energy services which biogas can provide is given. Chapter three will focus on the benefits which results from the adoption of domestic biogas plants, not only from a private perspective but also at local, national and even global scale. The benefits beyond the household are the result of spillovers of the private benefits, the externalities. How these cumulative benefits connect with the framework of the MDGs is described thereafter. Chapter 4 will focus on the impact of psychrophilic temperatures on the physical-chemical processes as occurring during AD, the thermodynamics and on solutions applied in developing countries to overcome the low biogas production in the cold periods. Chapter 5 explores solar heat, a detailed analysis on how solar heat can increase the temperature of digestion is provided for four countries, Romania, Georgia, Bolivia and Kyrgyzstan. The potential of carbon revenues is assessed in chapter 6 to offset a part of the financial barriers. A short discussion is provided in chapter 7, which connects the previous chapters and is followed by a general conclusion.

Chapter 2

ANAEROBIC DIGESTION AND BIOGAS SYSTEMS

This chapter introduces anaerobic digestion from an historical perspective; from observation of the 'foolish dancing flames', the ephemeral flames as occurring in swamps, to the discovery of the microbes responsible for anaerobic digestion and biogas production. Furthermore, the history is sketched of domestic biogas utilization in the most important developing countries where the majority of biogas development and implementation occurred; India and China.

Thereafter, the actual process of substrate conversion in an anaerobic environment to biogas is discussed. A system perspective is taken to describe the whole biogas system. A biogas system consists of several connected compartments, manure collection, the respective digester designs, the gas and slurry storage to the gas handling and the utilization of the end-products (biogas and digestate). Finally, the last section assesses the energy services of biogas and relates energy demand with biogas production.

2.1 HISTORY OF BIOGAS

The first time mankind deliberately utilized biogas is covered in obscurity. Most early descriptions of biogas utilization are of mythical proportions. Spectacular is for example the first alleged use of biogas to heat bath water in Assyria, over 3000 years ago (Residua nd). Similar anecdotic recordings are found in ancient Chinese literature of 2000-3000 years ago; the description of covered sewage tanks, probably for biogas generation or waste treatment. These tanks have also been mentioned by Marco Polo. Later in the 16th century biogas is reported to heat bath houses in Persia (Residua).

The natural occurrence of biogas from swamps was already known by the Romans. They described the existence of mysterious dancing flames, '*ignuus fatuus*', which stand for 'foolish fires'; the English named it *will-o-wisps* and the Dutch '*dwaallichten*'. In fact, these ephemeral flames are the result of the combustion of inflammable gas from decaying organic matter, marsh gas. Some authors suggest that this occurrence gave rise to the myth of dragons (Gunnerson and Stuckey 1986).

In 1630 van Helmont, a Belgian, discovered that the emanation from decaying matter is different from air, it is another gas. He named it *'spiritis sylvestre'*, odd spirit (Helmont). That odd spirit was subsequently studied by Shirley in 1667, but it was Volta who introduced biogas in a scientific setting. In 1776 he concluded, that the amount of gas released is a function of the amount of decaying vegetation and that by mixing it with a certain proportion of air it becomes explosive (Gunnerson and Stuckey 1986). After Volta, Dalton described methane as mayor the proportion of biogas and Henry confirmed that town gas was similar to the gas which Volta studied. A student of Pasteur, Beschamp, discovered that biogas production was connected with microbial activity; in 1886 he discovered methanogens (Gunnerson and Stuckey 1986)

In the same century the first digesters are said to be built. The first digester has probably been built in a leper colony in India in 1859, but it was not until 1895 in England that for the first time methane (from biogas) was recognized as having a practical and commercial value (Harris 2008). The first studies dedicated to AD started in the late 1920, when Buswell studied the influence of nitrogen on AD, the stoichiometry of AD and biogas production. Not long thereafter, it was Barker who studied AD biochemically and he isolated for the first time methanogenic bacteria, the *Methanosarcina Bakeri* (Marchaim 1992). Baker's studies have contributed significantly to the development and understanding of AD and much of his work is still relevant, even in today's context (Gunnerson and Stuckey 1986).

ANAEROBIC DIGESTION IN THE DEVELOPING WORLD

AD for *domestic* biogas generation can be traced back to the beginning of the 20th century in the developing world, predominantly in China and India. The first pioneering studies were executed in China by Luo Guorui and in India by S.V. Desai (Agromisa 1984; Nianguo 1984).

THE CHINESE EXPERIENCE

Particularly in China, the utilization of biogas at household scale took off in the 20th century. In 1920 Luo Guorui, the father of the renowned Chinese dome digester, constructed the first digester in eastern Guangdong province (Nianguo 1984). Later on, the use of biogas was with great enthusiasm promoted by Mao Zedong in 1958 as part of the great leap forward campaign (Agromisa 1984). However, this mammoth campaign on digester dissemination focused too much on quantity which impaired quality. As a result, many of the built digester were soon damaged or did not function at all (Agromisa 1984; Daxiong, Shuhua et al. 1990). From 1979, after the gang of four[2] had been arrested, it became clear that most digesters were not working.

Not long after that time a new upsurge in biogas interest started to combat fuel shortages and this led to a professionalization of biogas project management (Agromisa 1984). However, the failures of many digesters, during the great leap forward, left a lasting impression on the farmers' mind, who lost their faith in the technology (Daxiong, Shuhua et al. 1990). Nevertheless, in 2004 around 15,4 million household digesters are in operation .

THE INDIAN EXPERIENCE

The pioneer of anaerobic digestion in India is S.V. Desai, for his first experiments on biogas production in 1939. This led to the development of the first Indian biogas plant in 1951, the Gramalaxi plant of the Khadi and Village Industries Commission (KVIC), better known as the KVIC digester (Agromisa 1984). KVIC was the first to introduce biogas plants amongst the famers in rural India. In 1962 their design became standardized and are still built nowadays (Singh and Sooch 2004). Two other models which became popular, are the Janata biogas plant introduced in 1978 and its successor, the Deenbandhu digester, developed by Action for Food Production (AFPRO) in 1984 (Singh and Sooch 2004). The name Deenbandhu and to a lesser extent Janata are quite pregnant, it means respectively in Hindi: *'friend of the poor'* and *'of the people'*. In 2003 around 3,8 million plants are in operation, (Khoiyangbam, Kumar et al. 2004) , and the target of the Indian government is 12 million by 2010 (Pathak, Jain et al. 2008). .

AD IN OTHER COUNTRIES

In other developing countries the adoption and development of biogas digesters for households was at a much smaller scale in the 20th century (Agromisa 1984). Noteworthy are the efforts in Taiwan, which resulted in the development of the plastic bag digester in 1960, the Taiwanese digester (FAO/CMS 1996).

Nowadays there is a renewed interest in AD in many developing countries, for reasons of energy security, combating deforestation, improvement of sanitation and so on. SNV for instance, a Dutch development organization is doing a great effort to disseminate biogas technology in many developing countries such as Vietnam, Cambodia, Laos and Nepal. In 2007 over 220.000 households (± 1,35 million persons) benefit from the efforts of SNV, their target is to bring biogas to 20 million persons in various developing countries (SNV).

[2] The gang of four took control of the Communist Part of China during the latter stages of the Cultural Revolution. After the revolution, they were effectively blamed for the malpractices and treasonous crimes that happened during that period

2.2 ANAEROBIC DIGESTION AND BIOGAS PROPERTIES

The bio-degradation of (complex) biomass under anaerobic conditions is denominated as anaerobic digestion (AD) and is made possible by an interacting group of anaerobic consortia (Cantrell, Ducey et al. 2008). An end product of AD is biogas, a mixture of predominantly methane and carbon dioxide and some small amount of other gasses, such as hydrogen sulfide and ammonia (GTZ 1999), see table 1.

TABLE 1: TYPICAL BIOGAS COMPONENTS (GTZ 1999 & META-ALVAREZ, 2003)

Gas	Formula	Unit	Prevalence *(%)
Methane	CH_4	%	50–70
Carbon dioxide	CO_2	%	30–40
Hydrogen sulfide	H_2S	mg/m^3	0-5000
Ammonia	NH_3	%	0-0,05
Humidity	H_2O	%	2% (20°C)-7% (40°C)

H_2S is a potential dangerous gas, but easily detected by its strong smell; however in high concentrations the olfactory system becomes paralyzed and could lead to death, see table 2.

TABLE 2: EFFECT OF H_2S ON HUMAN HEALTH (ADAPTED FROM EDER & SCHUTZ, 2006)

H_2S concentration in air (PPM*)	Effect
0,03-0,15	Odor of rotten eggs
15-75	Irritation of respiratory passages, nausea, vomiting, headache
100-330	Paralysis of olfactory system
>375	Death through intoxication (after several hours)
>750	Death after 30-40 minutes due to unconsciousness and halt in breathing
>1000	Rapid death due to respiratory paralysis

*(1 PPM is approximately 0,0001% of air mass)

When being near biogas installations and eye irritation or coughing are experienced one should leave immediately and look for fresh air. If one does not seek fresh air, the person may lose the ability to apprehend the hazard, since at concentrations around 100 ppm the olfactory systems is paralyzed after 2-15 minutes, continued exposure for several hours could then results in death (Trasher).

The main physical characteristics of biogas are depicted in the next table.

TABLE 3: CHARACTERISTICS OF BIOGAS (DEUBLEIN, 2008)

Characteristic of biogas:	Value
Energy content	20-25 MJ/m^3
Ignition temperature	650-750 °C
Density	1,2 kg/m^3
Critical pressure	75-89 bar
Critical temperature	190,65 Kelvin (-82,5°C)

Four separate reaction steps can be distinguished during the biodegradation of complex substrates during anaerobic digestion: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Yadvika, Santosh et al. 2004):

1. **Hydrolysis**
   Hydrolytic bacteria break down complex polymers and higher molecular mass compounds into soluble organic products (simple sugars) with the help of exo-enzymes
2. **Acididogenesis**
   The acidogenic (fermetative) bacteria degrade the hydrolyzed soluble substrate to volatile fatty acids (VFA), such as butyric, propionic and acetic acid while also carbon dioxide and hydrogen are formed.
3. **Acetogenesis**
   The acetogenic bacteria convert the higher VFAs to acetic acid.
4. **Methanogenesis**
   Finally, acetoclastic methanogenic bacteria reduce the acetic acid to methane and another strain of bacteria, hydrogenotrophic methanogens reduce CO_2 and H_2 to methane (Denac, Miguel et al. 1988). At psychrophilic temperatures, the most important pathway is acetoclasic methanogenesis (Kotsyurbenko 2005). Methanogens are *obligate anaerobic*, they cannot function in an aerobic environment (Fulford 1988).

The whole chain of steps is outlined in the next figure. Of this chain of steps, hydrolysis is in general considered to be the rate limiting step (Veeken and Hamelers 1999).

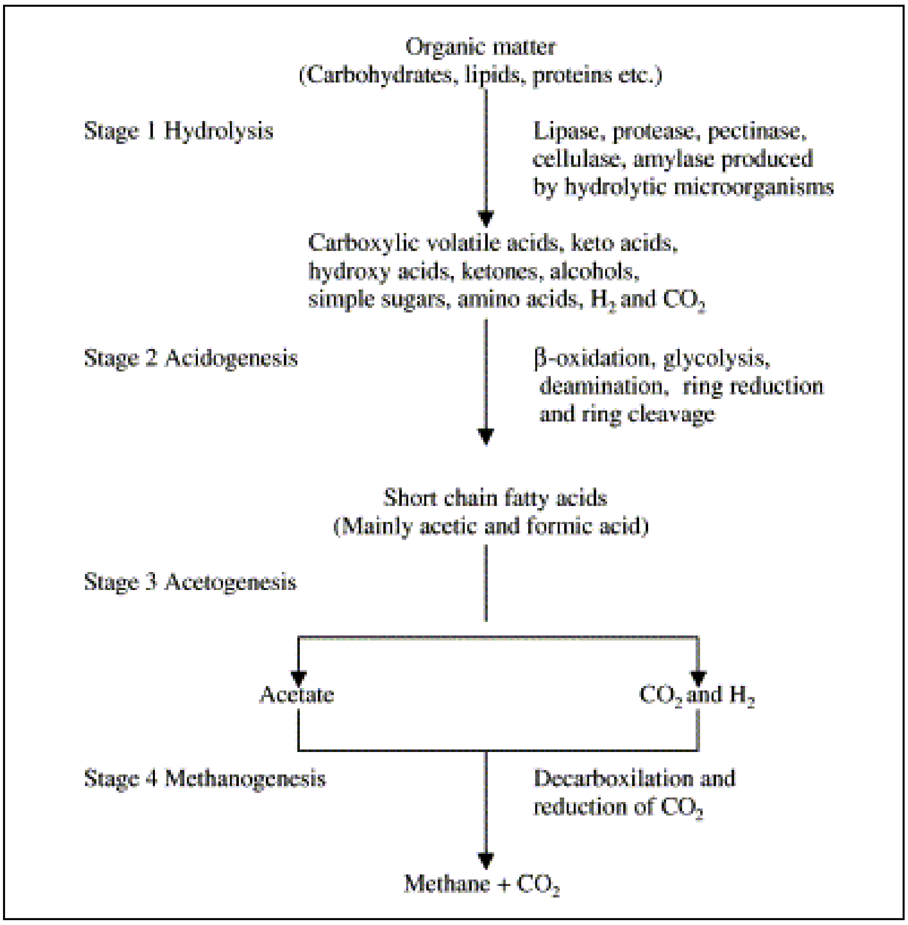


FIGURE 1: PATHWAYS OF ANAEROBIC DIGESTION (KASHYAP, DADHICH ET AL. 2003)

The consortia bacteria responsible for AD are classified according to different temperature classes, thermophilic AD occurs at proximately 45-60°C, mesophilic AD around 20-45°C and psychrophilic digestion at temperatures lower than 20°C (Kashyap, Dadhich et al. 2003).

Relative growth rates are proportionally related to the temperature of digestion, hence psychrophilic digestion has, as a result of the low temperatures, a lower rate of digestion compared to, say, mesophilic digestion (Lettinga, Rebac et al. 2001). As aforementioned, this is one of the obstacles to utilize AD for small scale application in countries with cold winters, the core subject of this thesis. The impact of temperatures is analyzed in detail in chapter 4.

2.3 BIOGAS SYSTEM

A biogas system comprises manure (substrate) collection, pre-storage of substrate, anaerobic digester, effluent storage, gas handling and final gas consumption (EPA 2007).

1. MANURE COLLECTION (ANIMAL WASTE MANAGEMENT SYSTEM)

Manure collection involves all the actions arising from the manure excretion to the moment of feeding it to the digester. The most common manure management practice in developing countries is to collect manure manually and feed it to the digester (GTZ 1999). Consequently, urine cannot be collected. Urine can be captured to some extent when animals are stabled on a concrete floor. This is most of the times not the case, with the exception of pigs rearing in some countries such as Cambodia (Buysman and Mansvelt 2006). If urine is not captured, a proportion of the nutrients are not recovered and some of the biogas potential is lost (GTZ 1999).

Feedstock

Any biodegradable substrate can serve as a digester feedstock. However, the conversion rate and efficiency differs substantially between substrates, where raw plant material containing a large number of lignin and cellulose are difficult to digest (Gunnerson and Stuckey 1986). In countries such as China, India and Cambodia the most common digester feedstock is cow dung (Agromisa 1984; Daxiong, Shuhua et al. 1990; GTZ 1999; Buysman and Mansvelt 2006). Other common feedstock's are buffalo and pig manure and to a lesser extent chicken droppings (Gunnerson and Stuckey 1986). Chicken dropping have a relatively high ammonia concentration and could therefore inhibit methanogenesis (Chen, Cheng et al. 2008). In countries such as Bolivia and Peru llama manure is available, which is just as digestible compared to cow manure, albeit with a lower methane yield (Alvarez, Villca et al. 2006).

Human Night Soil (HNS) is another good substrate for biogas production; however HNS as feedstock is in some countries loaded with taboos (GTZ 1999). Other types of manure from sheep's, goats, elephants and horses are much less frequently used, but can also serve as a feedstock. However, these manures pose some problems, pellets of sheep's and goats are difficult to collect, while the digestive tract of elephants and horses are less efficient in breaking down fibrous materials and hence contain a great deal of indigestible matter (Gunnerson and Stuckey 1986).

With any of the aforementioned substrates, straw, stalks and grass should be removed from the manure as these material tend to float on top of the slurry in the digester while the heavier parts, such as sand settle and accumulate at the bottom of the digester which effectively decreases the digester volume (GTZ 1999). This problem can be reduced by mixing or by avoiding a high dilution of the substrate; in these cases separation of the digester content does not occur.

Feedstock properties

Important parameters of feedstock are the C:N ratio, the total solids (TS) and the volatile solids (VS) of the substrate. The C:N is an important parameter as bacteria generally utilize carbon and nitrogen in a certain ratio (Gunnerson and Stuckley 1986). Ideally this is around 20-30:1 for biomass growth (Yadvika, Santosh et al. 2004; Ward, Hobbs et al. 2008). A lower ratio can depending on the pH either result in an increase of ammonia (NH_3) or ammonium concentration (NH_4^+), in an acid environment (pH<8) ammonia converts to ammonium (NH_4^+) which is highly soluble. In general the pH in a digester has to be between 6,5 to 7,5, which is the optimum pH for AD (Heldman 2003).

TS content is important for two practical reasons for domestic digesters, TS content should not be too high, otherwise substrate would not slide easily through the inlet of the digester and if toxins are present, such as ammonium in high concentrations, a high TS is likely to affect bacteria more than when the substrate is diluted. Alternatively, TS content should not be too low, otherwise the feedstock is very dilute, and a large digester volume is required. Gunnerson et al (1986) advices a maximum TS of around 12%, GTZ about the same, 10% both for semi-continuously fed small scale digesters. Batch digestion allows for a higher TS concentration, 16-22% (Nallathambi Gunaseelan 1997), provided there is no inhibition resulting from the high concentration of substances (Nallathambi, Gunaseelan, 1997).

The VS content is the total amount of organic matter and an important indicator for the potential biogas production. A rule of the thumb is to relate VS and COD (Chemical Oxygen Demand) on mass basis with 1:1,4 (Zeeman 2008).

Manure production and proporties

It is common to report manure and urine production as a percentage of life weight of animals to predict the manure production without extensive measurements. The next table shows the properties of some main digestion substrates found in the rural areas of developing countries.

TABLE 4: BASIC FEEDSTOCK PROPORTIES OF COMMON DIGESTION SUBSTRATES

Animal	**Daily waste as % of life weight**		**C:N** (manure)	**TS** (fresh manure)	**VS** (fresh manure)
	Manure	Urine			
Cattle	5	4-5	20-30	16-20%	13%
Buffalo	5	4-5	20-30	14%	12%
Pig	2	3	14	25%	12%
Poultry	4.5	1-1,5	8	25%	17%
HNS	1	-	6-10	15-20%	15%
Human urine	-	2	0,8	4-6%	2,9-4,3%

Values from Gunnerson and Stuckley (1986), GTZ (1989) and House (1981)

The table shows that especially poultry and HNS have an unfavorable C:N ratio. Furthermore, the TS content of the substrates is higher than the 12% as advised for continuously fed domestic digesters by Gunnerson et al (1986). A mitigation strategy to overcome the high TS content is dilution; the C:N ratio can be increased by, for instance, adding a substantial amount of cow or buffalo manure.

Collection efficiency

The animals are not always stabled near the digester which could make manure collection as digester feed impracticable. In Cambodia for example, pigs are held in shed near their houses while cows and buffalos are most of the times only stabled during the night, moreover, these differences are augmented due to seasonal differences (Buysman and Mansvelt 2006). In the wet season cattle are longer stabled than in the dry season, hence the amount of manure that can be collected is higher in the wet season; collection efficiency was found to be 57% in the dry season against 67% in the wet season. Another study found an average collection efficiency of around 75% in India (Tyner and Adams 1977). *Collectable manure* is the main variable to determine the available digester feedstock, and *not* the total amount of manure excreted per animal (Buysman and Mansvelt 2006). However, collection practices and energy utilization are likely to be intertwined, consequently the collection efficiency might increase if not all energy needs are met or decrease if there is abundant biogas production.

Pre-storage: Substrate might not be fed directly into the digester and is consequently stored for a limited period. When substrate is stored, drying should be prevented. Dry manure is hydrophobic and therefore very hard to mix with water (GTZ 1999).

2. ANAEROBIC DIGESTER – SYSTEMS, TYPES AND COMMON DESIGNS

The collected substrate is digested in a digester, sometimes referred to as a reactor and with the inclusion of the inlet and outlet it is referred to as a biodigester or biogas system/generator. The main function of a digester is both to retain the substrate for a sufficient period to allow the microbes to degrade the organic material and to provide optimal conditions for the microbes, i.e. an environment without oxygen. A digester can either run batch or in a (semi) continuous mode (Figure 2).

Batch system

Substrate is added to a batch digester at once and with proper inoculation after some time biogas is produced. The production will steadily rise and then fall off, since at first the easily digestible, biodegradable COD is converted and later the slower biodegradable COD (Gunnerson and Stuckey 1986). Batch systems can operate with a relative high amount of solids, 16-22% (Nallathambi, Gunaseelan, 1997). A mayor disadvantage is that the gas production is not steady and hence it is impossible to align gas production with gas demand at household level. However, when 2 or more fed batch systems are sequenced the systems can be aligned for a more reliable biogas output over time

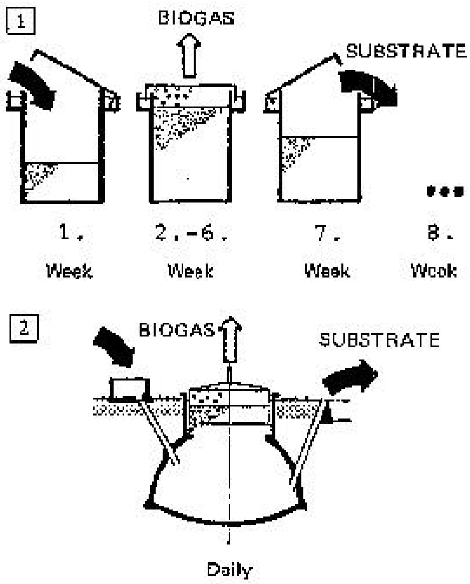


FIGURE 2: PRINCIPLES OF FED BATCH AND CONTINUES DIGESTER (GTZ 1989)

Fed Batch System

A fed batch system differs from a batch system in one respect; manure is added over a period of time until the system is full. The advantage of a fed batch system is that the system is both slurry storage and a biogas production unit.

Continuous system

A continuous system is fed (semi) continuously; this turns out to be daily or twice daily basis for house on site biogas plants in developing countries (GTZ 1999). Two types or continuous fed bioreactors are available, a mixed reactor and a plug flow reactor (Stalin and Prabhu 2007). A mixed flow reactor is in an ideal situation perfectly mixed due to stirring or agitation. In that case, the effluent concentration is the same as the concentration in the reactor and the sludge retention time (SRT) equal to the hydraulic retention time (HRT). A plug flow reactor has general a high length to diameter ratio and since there is no mixing a concentration profile can be observed; the biodegradable content decreases with the length of the reactor (Stalin and Prabhu 2007).

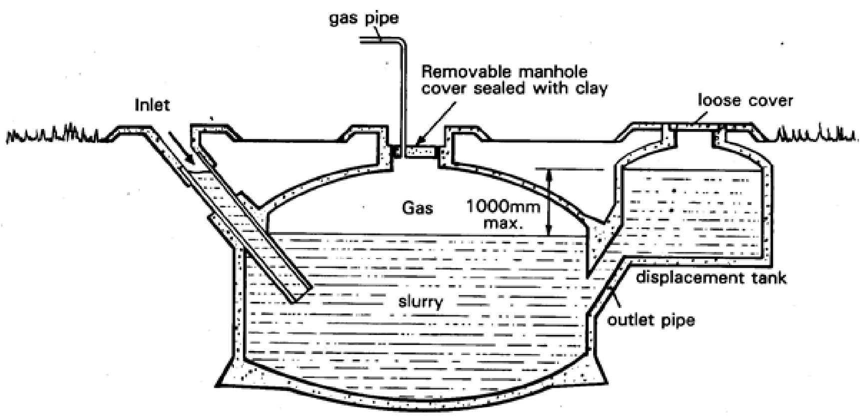
Domestic anaerobic digesters designs in the developing world

In developing countries primarily continuous designs are developed for house on site operation. The most archetypical for all developed house on site digesters are:

1. The Chinese dome digester
2. The Indian floating dome digester (KVIC digester)
3. The Taiwanese bag digester

1. The Chinese dome digester

The archetype of all the Chinese dome digesters is the water pressure digester of Luo developed in the 1920th (Nianguo 1984). The Chinese dome digester is by far the most popular in terms of numbers in the developing world (Fulford 1988; GTZ 1999). A Chinese dome digester is built underground; the top of the digester is a dome (hemispherical shaped cover) and is supported by straight walls residing on the base (Agromisa 1984). The upper part of the digester is the gasholder where gas is accumulated before use.



From left to right on the picture: through the inlet substrate flows to the reactor. Above the slurry is the gasholder, the manhole is at the top, which can opened to remove scum or to remove the contents for cleaning. Substrate is pushed to the displacement tank due to gravity of the substrates added and due to the amount of gas accumulated.

PICTURE 1: CHINESE DOME DIGESTER (SOURCE: (FAO 1986)

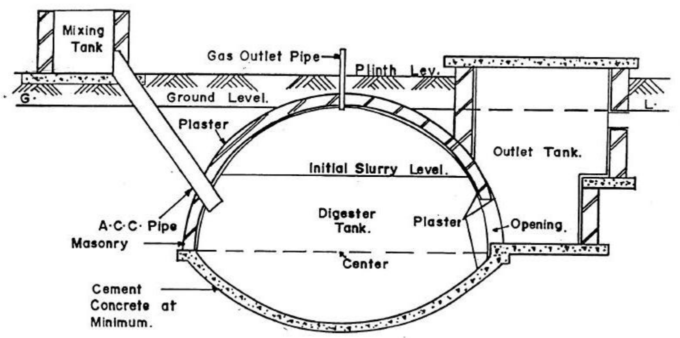
The pressure of gas is maintained through the weight of the slurry in displacement chamber (tank) resulting from gravitational forces. The amount of slurry in the displacement tanks varies depending on the amount of gas in the gasholder and feeding (Gunnerson and Stuckey 1986). The gas pressure is between 0 and 90 cm water column (Khoiyangbam, Kumar et al. 2004).

This design is vulnerable for gas leakages resulting from both the relative high gas pressure and the high structural forces on the hemispherical gasholder. To prevent leakages, the gasholder has to be plastered delicately with several layers of different materials, which require skilled and experienced masons (Daxiong, Shuhua et al. 1990). A weak ring, a flexible joint between the slurry part of the digester and the gasholder, also protects the gas holder from cracks occurring in the lower parts of the digester (GTZ 1999).

The Chinese digester is a prototype for many others digesters, for instance,

1. Janata (or Janta) model and its successor the Deenbandhu digester in India
2. Camartec design in Tanzania (Mwakaje 2008)

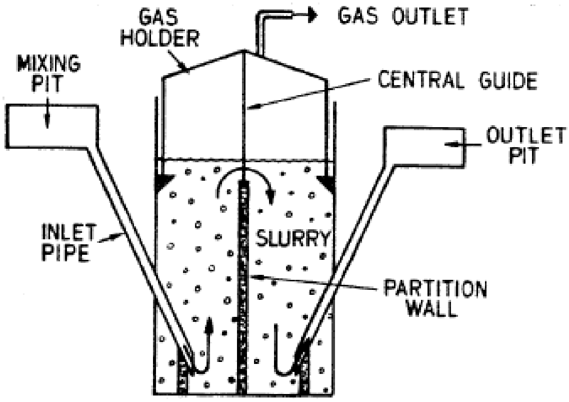
Beneath the Deenbandhu digester is shown. The Deenbandhu digester is reported to be superior compared the Chine Dome digester. The digester is more resistant to leaks since both the gasholder and the digester base are dome shaped (CEM 2005). A dome like structure can handle higher structural forces since the force is spread out over a large surface.



PICTURE 2: DEENBANDHU DIGESTER (CEM 2005)

Floating dome digester

A pregnant characteristic of the floating dome digester is the inverted movable (floating) drum, the gasholder, which sticks out of the digester. The floating dome digester was developed by the Khadi & Village Industry Commision (KVIC) and later nicknamed the KVIC digester (Singh and Sooch 2004). The floating dome digester is fed semi continuously and has a relative high depth to width ratio. Therefore a wall is placed in the middle of the digester to prevent short-circuiting (direct substrate flow from the inlet to the outlet) (Gunnerson and Stuckey 1986). Gas is captured in a movable



PICTURE 3: KVIC DIGESTER (FAO 1986)

inverted steel drum on top of the digester (GTZ 1999).

A drawback of this digester is the costly steel drum and therefore Indian scientists put forth other designs such as the Janata and its successor the Deenbandhu digester based on the Chinese dome digester. The Deenbandhu digester was found in an economic assessment to be the cheapest model compared to the Janata and the KVIC in terms of installation, operational costs and payback period (Singh and Sooch 2004).

Taiwanese bag digester

The Taiwanese bag digester was developed in the 1960s and is a plug flow digester. It is a flexible bag made of plastic, for instance red mud plastic (RMP) or PVC. It is a popular model in especially Central and South America (Gunnerson and Stuckey 1986; Herrero 2008)

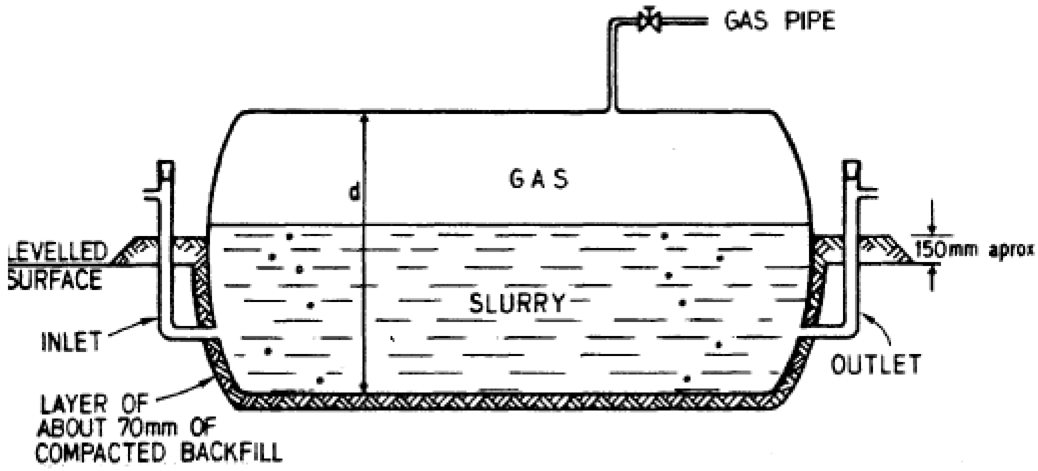


FIGURE 3: TAIWANESE FLEXIBLE BAG DIGESTER (FAO 1986; GUNNERSON AND STUCKEY 1986)

The digester is a long cylindrical bag (tube) supported by a hardened layer of masonry, concrete, compacted sand or mud trench (Gunnerson and Stuckey 1986). The digester is fed semi-continuously, 1-2 times per day. In south China some popularity is achieved with a tube like bag digester made of RMP (Daxiong, Shuhua et al. 1990). Daxiong et al (1990) claims that resulting from the thin covering of the digester, solar heat is absorbed better relative to a dome digester and hence a higher temperature of digestion is achieved. However, heat losses could be equally high due to the thin materials with a high thermal conductivity.

A great advantage of the bag digester is the simple design and low material costs, however the materials are not always available locally and for isolated areas costs are higher due to transportation costs (GTZ 1999). Furthermore, the effective life span of a bag digester is less than other digesters; GTZ claims it is only 2-3 years (1999) while others claim it is up to 10 years (Gunnerson and Stuckey 1986). Gunnerson et al (1986) assert that it is better to spend more on a design with a longer life span than one which is cheaper but with a shorter lifespan.

In India another variant is available, a balloon rubber plant reinforced with nylon. Evaluation of this model showed a lower performance compared to the Deenbandhu digester

during the winter and to a lesser extent during the summer (Singh, Vatsa et al. 1997). This contrasts the claim of Daxiong (1990) that the summertime performance should be better compared to a fixed dome underground digester.
For more information about these specific digester designs, the report of Balasubramaniyam et al (2008) list the main types of digesters and compares them in detail, or for a more extensive review of digester designs, digester sizes and experiences: Gunnerson et al (1986)

Contemporary developments
Current developments in China, Turkey and probably also India focus on decreasing the material costs of the digesters. Material costs of digester can fluctuate considerably, for instance in Cambodia, the digester costs increased in 2007 and the beginning of 2008 sharply due to the high oil prices making bricks very expensive (author's observation).

To reduce the dependency on expensive bricks but also on the extensive labor required for digester construction glass fiber prefabricated digester models are developed in China, Turkey and Georgia. The glass fiber digester design basically consists of two parts, a hemispherical base and a dome with attached in and outlets. The two shapes fit together, effectively reducing transportation volume (and thus costs) and hence a large number can be transported at once. In Georgia, people even claim it is possible to transport the digester on top of your car!

PICTURE 4: THE COMPONENTS OF A GLASS FIBER LIGHT WEIGHT DIGESTER (WECF 2008)

Picture 4 shows a light weight glass fiber digester constructed in Georgia using raw materials from Turkey. This model is developed by LDT (Global Energy) and SEMA in Georgia (WECF 2008). Similar digesters are constructed in China (van NES 2008). A factory in Chengdu (Chendu Hongqi Industry and Commerce Sharc.,Co.,Ltd) manufactures since 2002 biogas domes and entire biogas plants. A hybrid plant, combining a concrete base and walls with a glass fiber dome, costs more than a conventional digester, $293 against $253 in China (van Nes 2008). However, the main advantage of the glass fiber dome is the gas tightness which overcomes the weakest point of the concrete Chinese dome digester; so far they have sold over 80.000 pieces and received only 100 complaints (van Nes 2008), a high success rate.

These are interesting developments, which either reduce digester costs or improve performance and reliability. A disadvantage of these completely prefabricated digesters is the reduced amount of workers required for construction, which decreases employment opportunities. A hybrid version however still requires skilled masons for a large part of the digester construction, primarily masonry work for the base and the walls. Hence, a hybrid digester combines the best of both worlds; employment opportunities with an improved prefabricated absolute gastight dome in the opinion of the author.

3. EFFLUENT STORAGE

If the effluent is to be applied to the fields as fertilizer, slurry is stored until crop and land conditions allow spreading (Marchaim 1992). A contaminant advantage of storage is the continued degradation of the slurry and the removal of pathogens. If the slurry is used for fish feed, the slurry can be fed continuously and thus a short storage facility suffices. The BSP (Biogas support program) Nepal constructs biogas plants with a separate compost pit whereto the slurry from the outlet flows. There the slurry remains and is left to decompose until it is used (Mendis and Nes 1999).

4. GAS HANDLING

Gas is temporarily stored in the gasholder of the digester or in a plastic bag outside of the digester. The storage volume is directly related to the pattern of biogas consumption of the households, for instance when a family dines early in the evening the gas holder needs to be larger compared to families who have dinner late in the evening (GTZ 1999).

Biogas is a mixture of gasses, predominantly methane, carbon dioxide and some traces of hydrogen sulfide. Depending on the final use of biogas, it may be required or useful to shrub carbon dioxide, hydrogen sulfide and to remove condense water from biogas.

1. Hydrogen sulfide scrubbing from biogas

Biogas contains normally only a minor amount of hydrogen sulfide (H_2S), around 0,1% (GTZ 1999), but concentration varies with feedstock (Kapdi, Vijay et al. 2005). The main reason to shrub H_2S is to protect engines, gas storage tanks, refrigerators and compressors from corrosion (GTZ 1999; Kapdi, Vijay et al. 2005). When H_2S is combusted the following reactions occur (House 1981):

When air is added in the correct stochiometric amount for H_2S combustion, H_2S is converted to water and solid sulfur (1):

$$H_2S + O_2 \rightarrow 2H_2O + 2S \qquad (1)$$

However, the air flow in biogas stoves and other applications for biogas combustion is regulated for optimal burning of methane (House 1981), and not H_2S. The stochiometry of methane combustion (2):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad (2)$$

Consequently, the amount of oxygen is delivered is twice the optimum for the combustion of H_2S compared to methane. With an abundance of oxygen some of the H_2S is converted to sulfur dioxide and subsequently when sulfur dioxide meets the ubiquitous available water, it is oxidized to sulfurous acid and with more oxygen to sulfuric acid (3).

$$
\begin{aligned}
2\,H_2S + 3O_2 &\rightarrow 2H_2O + 2SO_2 \\
H_2O + 2SO_2 &\rightarrow H_2SO_3 \qquad (3) \\
H_2SO_3 + O2 &\rightarrow 2H_2SO_4
\end{aligned}
$$

These acids can damage biogas appliances and therefore it may be necessary to remove H_2S. Removing H_2S is examined for three approaches (Kapdi, Vijay et al. 2005).

1. Removal in the digester by adding oxygen

The removal of H_2S is possible by adding a small amount of oxygen (2-6%) in the digester. Consequently H_2S is oxidized into sulfur and water, a reduction of around 95%, 50 ppm is achievable (see equation 1). However, mixing air with biogas posses a potential hazard, biogas with 6-12% air is explosive (House 1981). If it possible to administer oxygen in the required small amounts this is a viable option. Although oxygen is poisonous to methanogens, the gas diffusion rate into the slurry is too low to affect them significantly (Kapdi, Vijay et al. 2005).

2 Removal in the digester: Liquid phase oxidation

The most (economic) feasible method according to Kapdi et al (2005) in the India context is liquid phase oxidation. By adding iron salt solutions (i.e. $FeCl_3$) directly to the digester slurry insoluble particles are formed, resulting in a very low remaining H_2S concentration, about 10 ppm in biogas.

3 Removal from biogas: Dry box method

In Cambodia and in other countries H_2S is scrubbed with rust in an enclosed container through where biogas flows. Rust, in the shape of iron hydrate or iron oxide react with H_2S resulting in a de-sulferization of biogas, the so-called dry box method (Dudley, Guentzel et al. 1980; House 1981; GTZ 1999; Kapdi, Vijay et al. 2005). By exposing the reactants to the air, the granular purifying mass (the iron oxides) can be regenerated; however, a great deal of heat is dissipated by this reaction. According to Kadpi et al (2005) the process is susceptible to high water concentrations in biogas. GTZ (1999) on the other hand, finds it a very practical and cost-effective solution, especially considering the fact that many types of tropical soils are ferriferous by nature and can be used as purifying mass.

It depends on the preferred practice if one applies iron salt to the digester slurry or uses the dry box method; both yield good results and are cost-effective. Adding oxygen to the digester is feasible but only with strict care since the oxygen concentration has to be monitored to avoid danger of explosion; the feasibility of that method for house on site digester is therefore limited.

2. Carbon dioxide scrubbing from biogas

CO_2 scrubbing is only required if it is necessary to upgrade biogas for more power output or to reduce storage requirements. Decreasing the CO_2 content of biogas increases the energy density and hence the volumetric efficiency of engines (power output per cylinder volume) (House 1981). The most feasible method at small scale is chemical absorption of CO_2. Good results are obtained by bubbling biogas through solutions of alkaline salts or solutions of amines. For instance, bubbling CO_2 through 10% aqueous solution of mono-ethanolamine (MEA) decreases the volumetric CO_2 content to around 0,5-1% (Kapdi, Vijay et al. 2005). The solution can be completely regenerated by boiling it for 5 minutes. Other possibilities are a solution of alkalines (NaOH, KOH & $Ca(OH)_2$) which react with CO_2 and forms H_2CO_3 (House 1981; Kapdi, Vijay et al. 2005).

3. Water removal

Biogas is saturated with water and this will condense when the temperature decreases. Excess water is easy to remove. Ideally pipes are laid to allow condense water to flow back into the digester (GTZ 1999). Otherwise a water trap is necessary to remove the condense water (Gunnerson and Stuckey 1986). The picture on the left shows an example of a water trap. From both sides the condense water flows to the lowest point where the trap is located. Water is then pressed out by the gas pressure itself. The height of the water column is equal to the maximum gas pressure + a safety margin to prevent gas release (GTZ 1999).

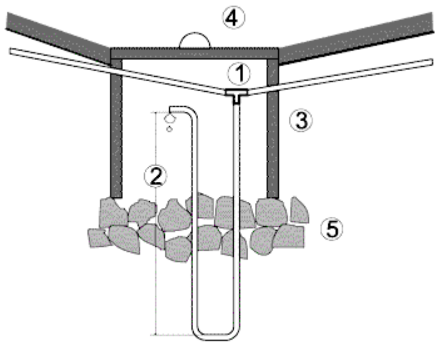


FIGURE 4: AUTOMATIC WATER TRAP, T-JOINT (1), WATER COLUMN (2), CASING (3), COVER (4) AND DRAINAGE (5) (GTZ 1999)

2.4 ENERGY SERVICES FROM BIOGAS

This section is about the energy services which can be derived from biogas. The energy content of biogas is predominantly determined by the methane content. By converting methane, biogas can be utilized for several energy services.

2.41 BIOGAS AND ENERGY

The energy yield (E) for any type of conversion from biogas can be determined with the next equation:

$$E = E_{CH_4} \times Fr_{CH_4} \times \eta_{con} \times \rho_{CH_4}$$ (adapted from (Cuéllar and Webber 2008)

Where $\boldsymbol{E}$ is the energy yield (J/ m^3 biogas) for any kind of conversion (i.e. combustion), $\boldsymbol{E_{CH_4}}$ the energy density of methane (J/kg) and Fr the fraction of methane in biogas and η_{con} the conversion efficiency and finally ρ_{CH_4} the density of methane (0,67 kg/m^3). The density of methane is temperature dependent and can be adjusted with the perfect gas equation of state.

The energy density of methane is respectively 50,1 MJ/kg lower heating value (LHV) and 55,5 MJ/kg higher heating value (HHV) (Hamelers, Jeremiasses et al. 2008). The difference between LHV and HHV is that HHV assumes that a specific quantity of the materials combusted return to the temperature of the reference state, which is defined at 25°C (Hamelers, Jeremiasses et al. 2008). Hence, the latent heat of vaporization of the water vapor is accounted for; this is only true when condensation occurs. In the case of LHV that is not considered and consequently LHV expresses the energy yield without condensation of water. In developing countries only LHV energy content is utilized for most energy services.

One 1 m^3 biogas containing 65% methane has a primary energy content of 21,82 MJ LHV, calculated with the above equation with η is 100%.

Energy availability & energy losses

The second law of thermodynamics denotes that with any energy conversion energy devaluates; the amount of work that can be done decreases. The maximum amount of work is also referred to as the exergy of a system. The efficiency of energy utilization is thus limited by the exergy resulting from the conversion. The overall efficiency of a biogas system, from manure collection to energy utilization is the product of:

1. Collection efficiency of the substrate
2. Methane recovery efficiency of the digester
3. Transportation efficiency of biogas from the digester to the biogas appliance
4. Conversion efficiency of the biogas appliance

The collection efficiency is the ratio manure collected and manure produced, methane recovery is a function of the microbial activity and retention time (see the next chapter), the transportation efficiency denotes leakage losses of methane (biogas) and finally the energy conversion depends on the specific energy conversion appliance.

Different kinds of substrates produce a different amount of biogas and methane. In literature a linear relation is obtained between the biodegradability and the lignin content of substrate (Haug 1993),

$$B = 0,83 - 0,028x \qquad \textbf{(1)}$$

Where, B is the biodegradable fraction (%VS) and x the lignin content (% of VS). Using that formula and with the ideal gas law, and an average conversion of 1,4 kg COD/kg VS (Zeeman 2008) and a 65% methane content of biogas, the ultimate methane recovery from selected wastes is calculated and compared with the values of GTZ (1989) of a dome digester with a retention time of 25 days at a temperature of 30°C.

TABLE 5: CALCULATED BIODEGRADABIITY AND METHANE YIELDS OF *FRESH* MANURE

Fresh manure source	**VS** (%)	**Lignin** (% VS)	**Biodegradable fraction** (% of VS	**Maximum methane production** ($l\ CH_4/kg$)	**Calculated *Methane* yields (GTZ 1989)** (l/kg VS)	(l/kg)
Cow & buffalo	13	7,9	61%	319	98-228	13-30
Pig	12	2,2	77%	402	221-358	27-43
Poultry	17	3,4	73%	384	202-403	34-69

* GTZ (1999) VS values and (l/kg VS) from GTZ 1989, lignin from Haug (1993). Methane yields are calculated with the assumption of 65% methane from the biogas values of GTZ. All values are averages and differ in practice depending on, for instance, diet, type of animal, animal stock.

The table shows that practical methane yields are lower than the maximum methane yield, depending on the feedstock. The ultimate methane recovery is in anaerobic digester not achieved, due to several limiting factors such as a *finite* retention time and suboptimal conditions. Optimal conditions would be, the right temperature, amount of mixing, the right amount of nutrients, the right C:N ration and pH for the microbes and a sufficient long HRT and SRT (FAO/CMS 1997). In less optimal conditions, the gas production is less.

Furthermore, cow manure is one of the worst feedstock in terms of biogas production. However, manure production of cows is much higher and hence fewer animals are required compared to pigs and chickens, see the next table and for an estimation of manure production per kg of life weight, see table 2.

TABLE 6: AVERAGE MANURE PRODUCTION PER ANIMAL IN DEVELOPING COUNTRIES

Manure source	**Manure production**** **(kg/day)**	**Author's value***** **(kg/day)**
Cattle	10	8,3
Buffalo	15	12,4
Pig dung	2.3	1,5
HNS	0.4	-
Poultry	-	-

** (GTZ 1999). Note that these numbers are guide numbers ***Average *collectable manure* in Cambodia (Buysman and Mansvelt 2006)

2.42 ENERGY SERVICES FROM BIOGAS

Biogas is a versatile fuel which can meet several services at household scale (Figure 5)

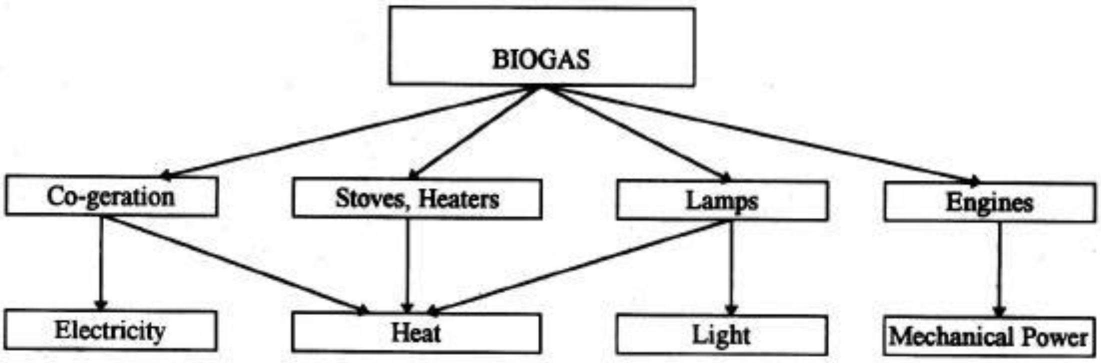


FIGURE 5: BIOGAS UTILIZATION AS AN ENERGY SOURCE (FAO/CMS 1996)

Each of these services is elaborated in this section shortly after an introduction on primary and secondary energy from biogas and amount of manure necessary to meet various energy needs.

The next table tabulates the energy conversion of biogas for cooking, lighting and electricity. The last row shows the amount of manure that has to be digested to obtain sufficient biogas for the aforementioned purposes. Biogas yields from manure are based on GTZ (1999)

TABLE 7: EXAMPLE CALCULATIONS FOR BIOGAS CONVERSION FOR THREE ENERGY SERVICES & REQUIRED MANURE INPUT

	Unit	Cooking	Lighting	electricity
Requirements	per day	5 persons 2/3 meals	3 hours	1 kWh
Conversion efficiency (η)	%	55%*	3%	25%*
Daily need	per day	1,5 m^3 biogas	150 liter/hour	4 kWh
Biogas requirement	m^3/day	1,5	0,45	0,66
Primary energy				
Total energy	MJ/day	32,8	9,8	14,4
Manure requirements				
Cow manure**	kg/day	33-75	10 – 22.5	14-33
-> η collection = 0,75	kg/day	44-100	13 – 30	19-44
Cows	heads	5-10	2-3	2-5

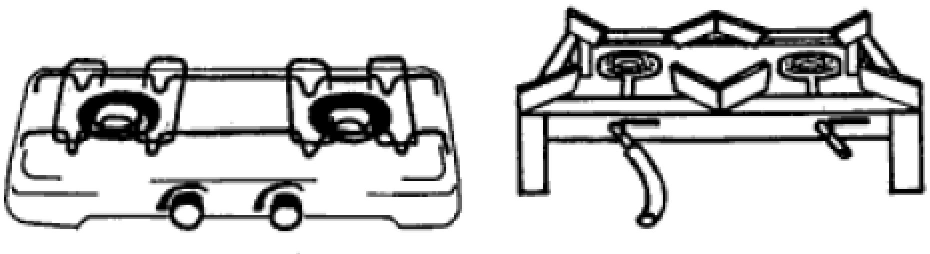
* (GTZ 1999) and explained in the next section **other types of manure yield different amounts of biogas and hence a different number of animals. 10 kg manure per day per cow is assumed

The table shows that a digester at household scale needs at least 5 cows for cooking and in total at least 8 for cooking, lighting and electricity at a collection efficiency of 75%. In Cambodia, it was found that an average family of 6,1 persons consumes 6,34 kg wood and their average stoves efficiency was 12%, this equals 1,14 m^3 biogas equivalents (Buysman and Mansvelt 2006). GTZ (1999) reports that 1 kg of dried cow dung corresponds to 100 liter of biogas, 1 kg charcoal to 0,5 m^3 biogas and 1 kg wood to 200 liter biogas, however, the efficiency is not denoted in the report of GTZ. In a similar fashion, LPG can be converted to biogas, 0,4 kg/m^3 biogas at an LPG stove efficiency of 60% (Buysman and Mansvelt 2006) and 12,3 kilo of dung cakes are equivalent to 1 m^3 of biogas (Muthupandi 2007). When one knows the baseline fuel consumption, prospect biogas consumption can be determined with these values.

1. BIOGAS AS ENERGY SOURCE FOR COOKING

The most important use of biogas is cooking (FAO/CMS 1996). The efficiency of biogas stoves is relatively high, 55-60% (GTZ 1999). Total biogas consumption for cooking is highly dependent on cooking and eating habits. In countries with a sophisticated cuisine or with the habit of three hot meals a day, gas consumption will be high, as it is also the case of well-to-do families (GTZ 1999). In practice, gas consumption for cooking varies between 300 and 900 liters per day per person, however, there will be some scale effects and children eat less; hence 5 persons don't consume 5 times that amount (GTZ 1999). In the Indian and Nepalese context, a 6 person family consumes around 1,5 – 2 m^3 (FAO/CMS 1996).

Biogas stoves are not very different from butane of propane stoves, although some adjustments have to be made since biogas comes normally at a relatively low pressure, 1-8 cm water column and combusting biogas requires less air compared to propane or butane (FAO 1986; GTZ 1999)



PICTURE 5: TWO TYPES OF 2-FLAME BIOGAS STOVES (GTZ 1999)

Picture 5 shows two 2-flame stoves. Depending on the requirements of the end-user smaller and bigger stoves are available. GTZ (1999) emphasizes the importance of an attractive appearance:

"A cooker is more than just a burner. It must satisfy certain aesthetic and utility requirements …"

Stoves are available with different capacities, designed to meet all meal requirements, for instance in India and Nepal two kinds generally used, one of 0,33 m^3 and one of 0,44m^3 biogas per hour.

2. BIOGAS AS LIGHTING FUEL

In a biogas lamp, biogas is combusted at a high temperature resulting in high incandescence. The high incandescence is the result of the high heat induced luminosity of rare earth materials present in the lamp (GTZ 1999). In terms of illumination, a 40W conventional light bulb compares to a biogas light using 90 liters/hour while 60W compares to 180 l/h (Fulford 1988).

A biogas lamp is interesting if no electricity is available and if there is excess gas. A drawback is the low efficiency of 3%, thus only 3% of the energy is converted into light. This amount is even lower than conventional light bulbs and certainly much lower than fluorescent tubes or low-energy light bulbs (compact fluorescent lamp). Kerosene lights compare favorably to biogas lights, with a twice as high efficiency (GTZ 1999). Additionally, since 97% is lost as heat, the lamp gets very hot and poses a potential fire hazard. The excess heat is however appreciated when the room temperature is low. Even with these drawbacks, a biogas lamp is feasible if there is excess biogas, since it has no opportunity costs and is therefore very interesting from a user perspective

PICTURE 6: A BIOGAS LAMP (AUHTOR'S PICTURE)

1. BIOGAS FOR MECHANICAL SHAFT POWER

Biogas is a high-grade fuel to use in an engine, since it burns at a high temperature (Fulford 1988). By combusting biogas in an engine, mechanical shaft power can be obtained for various purposes, such as food processing (hulling rice or grinding wheat or millet to flour), expelling seeds (for instance, the extracting oil from Jatropha seeds, a promising biofuel), driving a generator for electricity generation and water pumping (FAO 1986; Fulford 1988; GTZ 1999). For any of these purposes, a biogas plant should produce a considerable amount of biogas, GTZ (1999) even advices at least 10 m^3/day.

In theory biogas can also be deployed as motive power in tractors or automobiles. However, for these mobile vehicles, compression has to be applied to increase the energy density and to make it a practical fuel. Compression of biogas is tough, as a result of the low critical temperature and pressure, -82,5°C and 47,5 bar respectively (Gunnerson and Stuckey 1986; Kapdi, Vijay et al. 2005). An interesting project on biogas compression was conducted by students of the University of Michican, who designed a low-cost compressor for biogas (Figure 6). Their design is easy to implement and construct and has a large lever arm which is human powered. In 10 minutes the design was able to reduce the biogas volume with a factor 3 and store it in a compression tank (Baron, Leginski et al. 2008).

FIGURE 6: PROTOTYPE BIOGAS COMPRESSOR
(TO THE RIGHT THE LEVER ARM AND BOTTOM RIGHT THE COMPRSSION TANK)

The NGO ARTI from India is developing a compressor using recycled refrigerator parts. By using the compressor of a refrigerator, they claim to have reached a compression of 40 atmosphere; a 40-fold decrease in volume[3].

If biogas is stored for future use or as motive fuel, carbon dioxide should be removed to amplify the energy density and to reduce the storage volume. When carbon dioxide is removed and a compression of around 3 bar is applied using the compressor of Baron et al (2008), then an overall volume reduction of 4,6 times is possible (100% removal of CO_2 assumed and a CO_2 content 35%). The energy density increases accordingly.

Using the energy density of 50,1 MJ/m^3 methane and stored under 3 bar in a vessel of 0,25 m^3, the total energy content is around 37,6 MJ. A two wheeled tractor of 5 kW (6,7 HP,) with an efficiency of 25% can run for around half an hour with that energy (36MJ/5kW*25% = 1800 sec). In practice this might be around an hour since it is unlikely that the engine has a constant load factor of 100%. The picture beneath is an example of an engine with approximate similar power output. It is not hard to imagine that compressing biogas is more practical.

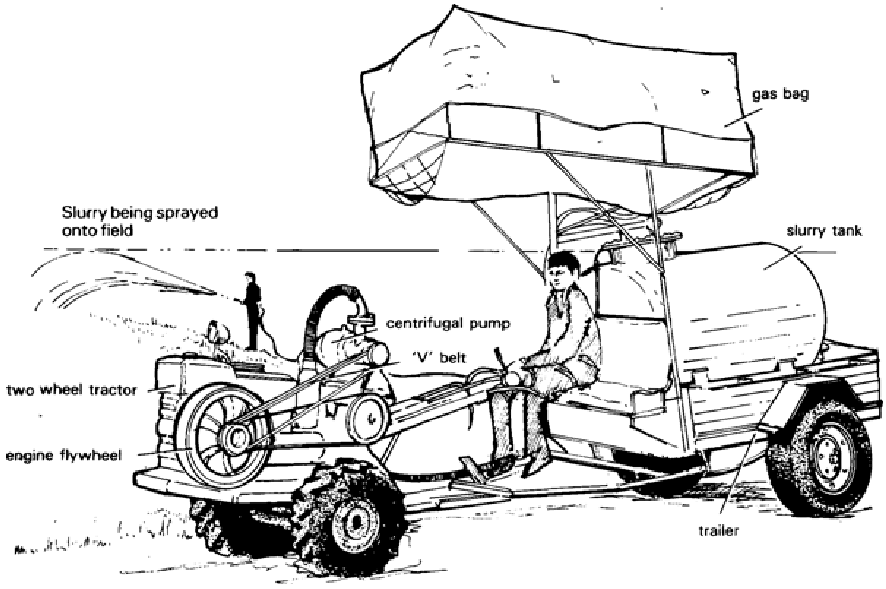


FIGURE 7: EXAMPLE OF A SMALL TWO-WHEEL TRACTOR IN CHINA (FAO 1986)

Biogas engines: There are two types of internal combustion (IC) engines (Fulford 1988; GTZ 1999):

1. Spark-ignition (SI) engines, 'otto engines'
2. Compression-ignition (CI)engines , 'diesel engines'

1. CI-engines

CI engines normally run on diesel (petroleum or petrodiesel). Diesel auto-ignites at a compression ratio of around 17:1 (GTZ 1999). A CI engine cannot run solely on biogas, since biogas does not auto-ignite resulting from its high auto ignition temperature. (Tippayawong, Promwungkwa et al. 2007). However, a CI engine can be converted to operate in a dual fuel mode; diesel and biogas. Diesel ignites biogas and for this only a small amo unt of diesel is

[3] (author's discussion with the founding member of and current president of ARTI India, dr. Arnand Karve during the COP-14 2008 in Poznan)

required. This practice is adopted widely in the developing world (Tippayawong, Promwungkwa et al. 2007).

Diesel has a heating value 43 MJ/kg and contains 370 ppm sulpher, while biogas has respectively 24,5 MJ/kg and around 1200 ppm sulpher (Tippayawong, Promwungkwa et al. 2007). The higher sulpher content in the form of H_2S is a treat to engine performance, which forms sulphuric acid when combusted and leads to corrosion. Another treat is the higher combustion temperature of methane compared to diesel which hampers lubrication of the engine (GTZ 1999; Hamelers, Jeremiasses et al. 2008).

Long term performance of dual-fuel CI engines is rarely studied and therefore Tippayawong et al (2007) studied long term performance (2000 hour) using a 5 kW Mitsubishi DI-800 from 1995 with as fuel 10% diesel and 90% biogas. During their first trail they encountered problems associated with insufficient lubrication and the high moisture content of the biogas after just 200 hours. By adding a condensation trap and special lubrication designed for gas engines, the engine operated satisfactorily for 2000 hours with an average efficiency of 22%. They concluded that duel fuel engines are a promising technique for on farm electricity generation. Similar results are obtained another study by Duc et al (2007), however they concluded that lubricant oil consumption was unacceptably high. Therefore they suggest a higher ratio of diesel to biogas, to avoid overheating of the engine and to reduce lubricant oil consumption (Duc and Wattanavichien 2007).

CI engines can in principle run on biogas alone when a spark igniter is added to the engine. In that case the compression ratio of diesel engines should be adjusted to avoid knocking (Kapadia 2006). These changes to the engine are significant and expensive; therefore only pre-converted CI engines are recommended by GTZ (GTZ 1999)

2. **SI engines**

SI engines can be converted to run on biogas by replacing the gas carburetor with a mixing valve while the speed of the engine should be limited to 3000 rpm (GTZ 1999). The purpose of the mixing device is for air-fuel control and spark timing to account for the slow combustion of biogas (Kapadia 2006). A major drawback is the decrease in efficiency, up to 30%, which can only be compensated by increasing the compression ratio. SI engines are not promoted to run on biogas by GTZ due to the decrease in efficiency (GTZ 1999).

3. ELECTRICITY GENERATION WITH BIOGAS ENGINES

By driving a generator connected to an IC-engine electricity is obtained. This is only interesting if no grid connection is exists or if the grid connection is either expensive or unreliable. The efficiency depends on the size of the engine and generator (gen-set), the larger the rated power output of a gen-set the higher the efficiency, from approximately 25% small scale to 40% in large scale systems (Cuéllar and Webber 2008). Excess heat from the gen-set could be utilized for digester heating via a heat exchanger absorbing the exhaust heat or using the gen-set cooling water to heat up the digester (Gunnerson and Stuckey 1986). Consequently, the *overall* efficiency of the biogas conversion is much higher as it comprises the efficiency of heat and electricity generation.

In practice the electrical efficiency may turn out to be much lower, especially if the gen-set is not dimensioned to the energy demand; when the load factor is very low the efficiency will be accordingly low. In 2006 the author studied electricity generation using biogas from a digester in Kandal (Cambodia) over a two week period and found an average energy yield of just 0,42 kWh electricity per m^3 biogas, an efficiency of 7% (unpublished). The engine would consume 2,39 m^3 biogas to produce 1 kWh, while if in small scale situations with an efficiency of 25% this is 0,66 m^3. The low efficiency is likely the result of a very low load factor, just 0,7 kWh while the maximum power output of the gen-set is 5 kWh. Efficiency improvements are possible by aligning demand with 60-80% of the maximum power output of the gen-set.

Normal practice in a developing country such as rural Cambodia, is run the gen-set only during the evening and in small rural village's electricity (if available) is supplied to the richer households during the evening using a small diesel generator. Electricity consumption is typically around 300-500 watt/day, either from the generator or from car batteries (author's observations). In other countries such as India and China and probably many more, the electricity demand is similar and hence a gen-set with a low capacity is necessary if used for one household. However, most research is biased towards large scale diesel gen-set to run on biogas, while there is a need for a low capacity gen-set of around 1 kW (Kapadia 2006).

The next table shows how biogas can meet the direct energy needs of a rural household in off-grid areas by running a gen-set for four hours in the evening. For this simulation a typical Cambodian rural household energy pattern is taken, however, the figure is also applicable to other countries, i.e. most Asian countries (see Annex 2)

TABLE 8: CALCULATION OF THE ELECTRICITY CONSUMPTION OF A HOUSEHOLD WITH THREE MAIN APPLIANCES

Appliance	Rated power (Wh)	Hours/day	Daily energy (Wh)
TV	50	4	200
Lights	15 (energy saving)	12 (3 lights)	180
Radio	20	2	40
		Total	420
		Primary energy (η =25%)	1680

The 1680 Wh primary energy demand as shown in Table 8 equals 6 MJ primary energy and that equals 0,27 m^3 biogas. With an assumed efficiency of 10% (a low load factor is assumed), a household needs in *total* around 2,18 m^3 biogas; 1,5 m^3 biogas for cooking and 0,675 m^3 for electricity generation, equivalent to 54-94 kg/day of manure (cow manure). In contrast to the advice of GTZ that 10 m^3 biogas per day for electricity generation is required; electricity generation for household consumption is quite feasible, even with an efficiency of 10%. What could be an obstacle is the operation and maintenance a gen-set requires next to the necessary capital investment, otherwise there are no good arguments against electricity generation from biogas.

5. OTHER USES OF BIOGAS

The next table shows some basic characteristics of other biogas appliances not mentioned before.

TABLE 9: OTHER APPLIANCE RUNNING ON BIOGAS (FAO/CMS 1996)

Appliance	Details	Biogas consumption (m^3/hour)
Heater	12" diameter	0,17
Incubator	18x18x18"	0,06
Refrigerator	18x18x18"	0,07

Radiant heater & Incubator

An infrared radiant heater can be used in agriculture to maintain the right temperature for raising young stock in a confined space. A radiant heater burns with a red flame of around 600-800 °C with an efficiency of around 95% (GTZ 1989). Commercially available radiant heaters run on butane, propane or natural gas and operate at a higher pressure, 30-80 mbar. Therefore the heaters need to be adjusted by replacing the injector. GTZ (1999) asserts in many cases it does not work satisfactory. There is little literature available of using these heaters running on biogas for household heating. Probably a common gas heater could be adjusted to run on biogas.

Another interesting use is to heat up an incubator for egg hatching. By heating water with biogas and allowing the water to flow through the incubator via a thermosyphon system the right temperature for egg hatching can be realized (GTZ 1989).

Refrigeration

All absorption type refrigerators running on ammonia and if equipped with a thermosyphon system can be converted to run on biogas (GTZ 1989). The main modification is the replacement of the burner. Remote ignition is possible which this eases operation (GTZ 1989). A refrigerator running on biogas consumes around 0,3-0,8 liter biogas per liter of useful volume per hour with an overall efficiency of 1,5-4% (GTZ 1996). For a 100 liter volume this accounts to around 0,72-1,92 m^3/day depending on the ambient temperature, however, GTZ assumes at least 2 m^3 /day is necessary.

An electricity fueled refrigerator of the same size consumes, depending on its efficiency class (A++ to B), respectively 84 to 210 kWh per year in the Netherlands (Milieucentraal), which is around 230 Wh to 570 Wh per day. When this amount is expressed in primary biogas equivalents using an gen-set efficiency of 25%, the daily biogas consumption is respectively (0,23 kWh *3,6kWh/MJ)/25%*21,8 MJ/m^3 biogas) 0,15 m^3 and 0,37 m^3 biogas equivalents, which is much lower than directly running on biogas. Even in countries where the ambient temperature is higher than in the Netherlands, using a gen-set to provide electricity for refrigeration is *much more* efficient compared to biogas fueled refrigerators However, a gen-set might not run all day. Therefore the fridge has to bridge a period without active cooling. A possible solution could be to use a battery for the period without electricity.

Proposal for a gen-set system with 24h electricity

A gen-set produces only electricity when the system is running and as argued above, the highest efficiency is reached when the load reaches the maximum capacity of the gen-set, say 80%. A high load is realized during peak demand which is in many cases during the evening. However, during the off-hours, electricity demand is very low and using an engine for a small load is not feasible.

To overcome these issues, a battery backup gen-set for 24 hours electricity generation could be interesting. With such a system there is electricity availability during off-hours for lighting and for instance for late-night toilet visits, radio or other small appliances. The battery would be charged when the generator runs, effectively increasing the load and therefore the efficiency, provided the generator can handle the additional load. With smart electronics, such as automatic charge control, deep discharge prevention and by sizing the time of charge and battery capacity with the hours without gen-set electricity a simple 24 hour electricity system can be designed (author's proposal).

Chapter 3

ANAEROBIC DIGESTION AND SUSTAINABLE DEVELOPMENT

In Chapter 2 it became clear under what conditions biogas can be generated and for which energy services it can be employed. This chapter will focus on the benefits of a domestic biogas plant and how it contributes to sustainable development.

The benefits of domestic AD are discussed at three different scales; the direct beneficiaries (the household members), the local benefits and the benefits at national and global scale. Moreover, I will argue that these benefits are crucial for poverty alleviation and sustainable development.

Finally, all these benefits are vital to reach the goals of a much grander framework, the Millennium Development Goals (MDG), which will be described in the last section of this chapter. According to the United Nations energy security is a prerequisite to achieve the MDGs and biogas is one of the means to obtain energy security and thus an important step for sustainable development and to combat poverty.

3.1 DOMESTIC BIOGAS PLANTS FOR SUSTAINABLE LIVELIHOODS

The utilization of biogas and digestate has several benefits, which are not confined to private benefits but have significant spillovers to a local and global scale and as such, it contributes to sustainable development and sustainable rural livelihoods. The key to these advantages is the altered utilization of biodegradable wastes and the efforts to make that happen (explained later). The benefits from domestic AD have an impact on different levels, see figure 8.

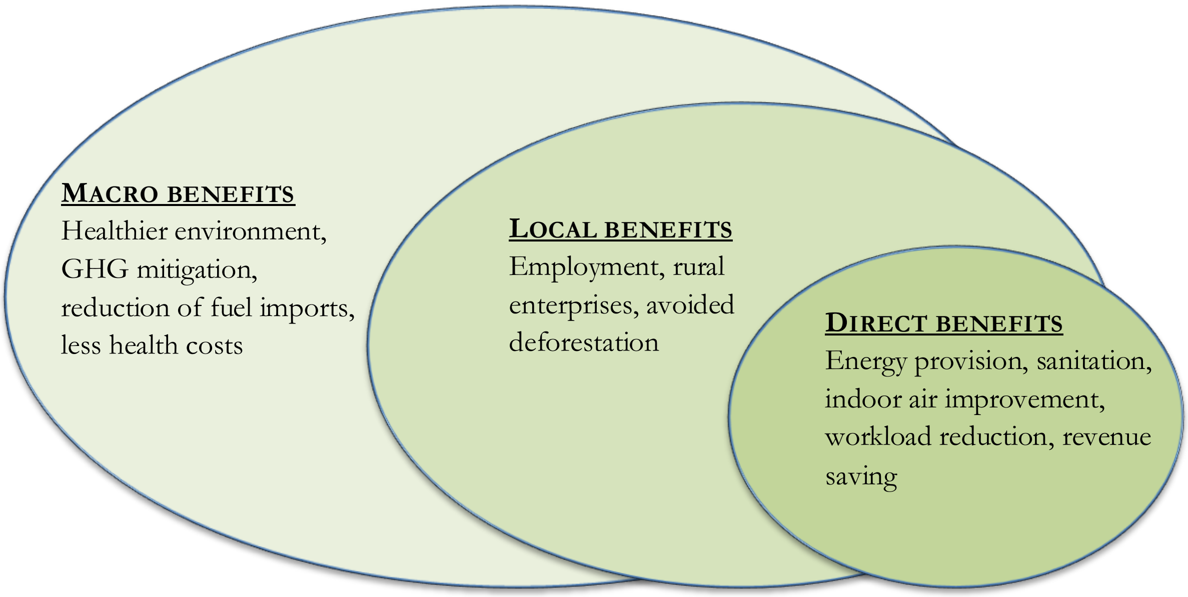


FIGURE 8: DIRECT, LOCAL AND MACRO BENEFITS OF AD (ADAPTED FROM (SRINIVASAN 2008)

The three types of benefits; the direct benefits at household scale, the benefits on a local scale and on a macro scale (national and global) are outlined in the next sections. Afterwards, reflection is given on the benefits and a rationale for policies is provided to stimulate biogas plant adoption and dissemination.

3.11 DIRECT BENEFITS

Direct benefits refer to all the advantages of domestic AD directly affecting the household members. Five direct benefits are considered:

1. On-site farm energy generation and women empowerment
2. Indoor air improvement
3. Sanitation improvement & pathogen removal and hazards
4. Chemical fertilizer displacement & nutrient recovery
5. Financial benefits

This is followed by a discussion and conclusion.

1. ON SITE FARM ENERGY GENERATION & TIME SAVINGS

Biogas utilization has become a symbol for access to modern energy services in rural areas (Srinivasan 2008). One of the most noticeable benefit is the provision of a clean and convenient cooking fuel; biogas. Biogas stoves are similar to LPG stoves and thus no special equipment is required to utilize biogas for cooking. A biogas stove has an efficiency of around 55-60% (GTZ 1999). See picture 7 of a biogas stove; notice the blue flame which indicates a good combustion of biogas.

By utilizing biogas for cooking purposes other fuels are displaced, this could be either traditional biomasses (dung, wood, charcoal) or fossil fuels (Sagar and Kartha 2007).

In the case of traditional biomasses, biogas displaces woody fuels and that has a time or revenue saving component. Time expenditure and the drudgery of wood gathering is avoided or revenues are saved if wood was bought otherwise for cooking (Srinivasan 2008).

PICTURE 7: EXAMPLE OF A BIOGAS STOVE (AUTHORS PICTURE)

Women empowerment

Time savings primarily affect women, in many developing countries their efforts contribute from 10 to 80% of the total energy supply and they are in general primarily responsible for cooking and to obtain cooking fuel. Women collect cooking fuels (biomass, dung, fuelwood) but they also produce charcoal, briquettes and dung cakes (Parikh 1995). The World Bank asserts that daily time expenditure on fuel collection by women is in India on average around 40 minutes (ESMAP 2004), but other source state it is around 2 hours (Dutta, Rehman et al. 1997) or even 3 hours in Nepal on daily basis (Gautam, Baral et al. 2009). Time is also saved on activities such as cleaning of cooking utensils and on cooking time in general, since biogas as a fuel is more convenient, does not cause soothing and provides more instant heat (GTZ 1999).

Some of the saved time is offset by the operation of the biogas plants. For instance, additional time is spent on water collection to dilute the manure before feeding it to the digester, on manure collection and on the effort of feeding the digester. According to van Nes (2008) these additional activities are hardly time consuming as they are an extension of normal activities, such as cleaning the stables and hence easy to incorporate in the daily routine. A comparative study on the impact of the Nepalese biogas program showed that total daily time savings including the additional time spent on digester operation were around 3 hours for women (Mendis and Nes 1999). In conclusion, the overall time savings are significant and are of such a scope that it opens new opportunities for women to develop themselves or to commit themselves to economic activities.

The role of women, as the prime users of cooking fuels, are in energy policy planning and also in biogas digester adoption programs most of the times insufficiently addressed (Parikh 1995). This sharply contrasts the fact that biogas utilization especially relieves women from the drudgery[4] of fuel collection with the numerous associated benefits. (Balakrishnan 1996; Biswas,

[4] Hard and monotonous work

Bryce et al. 2001). It allows women to fulfill their potential and as such it contributes to the empowerment of women (Srinivasan 2008).

Fossil fuel displacement

Biogas can also displace fossil fuels. In China for example where about 80-90% of the rural households use solid fuels, 45% of them use coal (Mestl, Aunan et al. 2007). In other countries, such as many EECA (Eastern Europe and Central Asia) countries, many household use bottled LPG (WECF 2008).

In the case fossil fuels are substituted by biogas, it saves primarily revenues saving and in the case of solid fossil fuels an improvement of the indoor air quality (Srinivasan 2008). In addition, switching fossil fuel to biogas reduces greenhouse gas (GHG) emission, more on GHG mitigation in the section about the macro benefits.

Biogas can also be used for lighting which is a considerable improvement over the hazardous open fire lighting from kerosene lanterns or candles (GTZ 1999). The superior illumination of biogas lanterns could result in longer study hours for children, more activities in the evening which both have a positive return and improves the quality of life (Srinivasan 2008). If households already have electricity, biogas lighting or biogas conversion to electricity is only revenue saving since the quality of lighting remains the same.

2. HEALTH BENEFITS

One of the most ubiquitous benefits from better health is less sick people, which results in less time investment on taking care of the sick, a higher productivity and less expenditures for medicines and health care. The time saved allows for other productive activities such as income generating activities or educational activities (Srinivasan 2008). Beneath three health improvements are discussed; indoor air improvement, sanitation improvement and hygiene and proper waste management.

Indoor air improvement

The displacement of solid fuels by a cleaner fuel, biogas, results in a considerable improvement of the indoor air quality with the concomitant advantage that soothing in the kitchen and cleaning efforts on pots is reduced to nearly zero (Rehfuess, Mehta et al. 2006; Srinivasan 2008). Indoor air pollution resulting from traditional biomasses is an immense health hazard in many developing countries, many houses are poorly ventilated and thus high levels of pollution can develop, a prime cause of premature deaths (Mestl, Aunan et al. 2007). The picture at the right shows a typical poorly ventilated kitchen[5]. Worldwide around 1,6 million deaths are attributed to indoor air

PICTURE 8: EXAMPLE OF A POORLY VENTILATED KITCHEN IN CAMBODIA (AUTHORS PICTURE)

[5] In rural Cambodia around 70% of the kitchens in rural areas are poorly ventilated (Buysman & Mansvelt 2006)

pollution resulting from solid fuel (Smith, Mehta et al. 2004). Furthermore, around 11% of the households worldwide depend primarily on traditional biomasses and the absolute amount of households relying on these biomasses has increased with 80% from 1971 to 2004 (Sagar and Kartha 2007).

Hazardous emission from solid fuels

The main hazardous emissions from solid fuels are small particles (PM10), carbon monoxide, nitrous oxides, formaldehyde and carcinogens (Smith and Mehta 2003; Smith, Mehta et al. 2004). These pollutants can cause inflammation of the lungs, in particular small particles which penetrate deep into the lungs while carbon monoxide reduces the oxygen caring capacity of blood (Rehfuess, Mehta et al. 2006). Women who cook on biogas are 3,2 times *less* likely to develop COPD (Chronic Obstructive Pulmonary Disease), such as bronchitis and emphysema compared to cooking on solid fuels. A study performed in India showed that women cooking with traditional biomasses are exposed to a daily benzopyrene (a carcinogenic aromatic hydrocarbon) equivalent of 400 cigarettes (Balakrishnan 1996). It is reasonable to assume that in other countries the exposure levels with similar stoves are the same. There is also some evidence which suggests that household coal combustion is associated with lung cancer (Mestl, Aunan et al. 2007). Indoor air pollution particularly impacts the health of women and children; children are in general close to their mother. The higher impact on women and children is the result of both more exposure to the pollutant and a longer duration compared to men (Smith, Apte et al. 1994). Furthermore, this is even more pregnant for children since they are the most vulnerable due to their undeveloped immune system (Rehfuess, Mehta et al. 2006).

Improved cook stoves versus biogas for cooking

Nowadays, considerable efforts are done to disseminate improved cook stoves (ICS) running on firewood or charcoal to reduce expenditure on cooking fuels, to curb deforestation and to improve indoor air quality. In China alone around 100 million improved cook stoves are disseminated (Smith, Shuhua et al. 1993) and the Ashdan awarded Cambodian Fuelwood Saving Program (CFSP) introduced over 300.000 ICSs in Cambodia (author's observation). These improved stoves are generally more efficient and sometimes more durable (Mestl, Aunan et al. 2007). However, even ICSs exceed the indoor air quality as set by national guidelines of specific countries (Rehfuess, Mehta et al. 2006) and thus the procurement of biogas as a cooking fuel is still a considerable health amelioration even compared to ICSs.

Disadvantages of biogas as a cooking fuel

Although the smokeless combustion of biogas has great merit, it also has some disadvantages, the smoke of traditional stoves keeps mosquito's away (Bajgain, Shakya et al. 2005) Therefore, installing biogas plants could increase the prevalence of diseases such as malaria or dengue fever. These issues need attention whenever a biogas dissemination program is set up. Additionally, the smoke is sometimes appreciated as increasing the taste of food.

The combustion of biogas results in the emission of SO_2. Exposure to SO_2 result in irritation of the nose, throat and eyes and chronic exposure may result in bronchitis and bronchial allergies (Gezondsheidsraad 2003). To mitigate that risk, a chimney is a simple measure to remove most of the SO_2. The produced SO_2 gas has a high temperature and therefore the gas will ascend quickly to the chimney and is removed from the kitchen.

3. SANITATION IMPROVEMENT & PATHOGEN REMOVAL AND HAZARDS

In many cases a toilet is attached to a digester and consequently access to clean and safe sanitation is obtained. This is a very important feature as many households in developing countries have no adequate access to sanitation. An estimated number of 2,6 billion are forced to defecate outside or use toilet systems without adequate waste disposal (Lancet 2007). Unsafe water and sanitation ranks number 6 just after alcohol, tobacco, blood pressure, unsafe sex and underweight in the top 10 disease risk factors of the WHO 2001 and 2002 (Smith and Mehta 2003). It is the most important environmental factor leading to premature death, with about twice the number of death and around five times the DAlYs (Disability Adjusted Life Years) compared to indoor air pollution (WHO 2002).

An intervention study conducted in Brazil examined the effect before and after access to sanitation and the intervention resulted in a considerable reduction of 43% in the high incidence areas of diarrhea, a sounds example of how access to sanitation is intermingled with health (Barreto 2004). However, the provision of sanitation is much more than an improvement of health; another important aspect of sanitation improvement is having a toilet which provides both safety and privacy (Dutta 1997). In a digester substrate is treated anaerobic and results in an almost complete removal of pathogens, see the next paragraph. Consequently, the health hazard of human excreta is reduced, provided that control measures are in place when the effluent is applied to the field (Pathak 2004).

Pathogens in waste and slurry

The digester feedstock, human and animals excrement contains pathogens, parasite eggs and viruses (Sahlström 2003). Consequently, substrate posses a potential health risk and since bacteria are very persistent they can survive for a prolonged period in an anaerobic environment (Sahlström 2003). Therefore, the digester effluent can contain pathogens such as, *Listeria*, *Escherichia coli*, *Campylobacter*, *Mycobacteria*, *Clostridia*, and *Yersinia*, a potential health hazard (Dudley, Guentzel et al. 1980).

A ubiquitous pathogen is *Salmonella*, which is potentially pathogenic to both humans and animals (Jones 1980). A study performed in India showed after a retention time of 10 days in an anaerobic digester almost all the Salmonella were inactivated at 37°C (Gadre, Ranade et al. 1986). Kumar et al. (1999) demonstrated in a laboratory experiment using artificial added strain of *Salmonella Typhi*, that it was removed after 15 and 25 days at respectively 35°C and at room temperature. Furthermore they observed that the survival *Escherichia Coli* (an indicator species for pathogens) depends on the temperature in a digester, 99,6% died at 35°C after 5 days compared to only 6,9% at room temperature. The longest surviving bacteria were *Streptococcus Faecalis* (40 days), the bacteria is therefore suggested as an indicator species for degree of decontamination of slurry (Bendixen 1994; Kumar, Gupta et al. 1999).

Parameters influencing pathogen survival in anaerobic digesters

According to (Côté, Massé et al. 2006) temperature and retention time are decisive factor for the survival of pathogens, pathogens are more likely to survive at low temperatures and short retention times. Consequently a tradeoff between a lower temperature and a longer retention time is possible. Temperature and the decimation time are for most pathogens hours in thermophilic-, days in mesophilic- and months in psychrophilic range (Sahlström 2003). Côté et al. (2006) asserts that there is minimal information available on the pathogens removal efficiency at low temperatures (15-20°C). Therefore they studied the removal rate of indigenous populations of *Cryptosporidium* and *Giardia* and *E-coli* in anaerobic bath digestion experiments at low temperature using swine slurries from different sources. After twenty days *Cryptosporidium* and *Giardia* populations were beneath detectable levels and *E.coli* was reduced by 98%. This experiment was conducted at higher psychrophilic temperatures, at 20°C.

Other parameters besides temperature and retention time influencing the pathogen survival/removal in digesters are pH, VFA, batch or continuous operation, bacterial species and the nutrients availability (Sahlström 2003). An increase in VFA inhibits survival of enteric organisms, such as E-coli (Abdul and Lloyd 1985). Kearney et al. (1993) found that a decline of the viable numbers of *Salmonella spp.* corresponds to an increase in VFA concentration and a decline of the pH, although that relation was not found at a short HRT. However, a high VFA concentration is not only toxic to pathogens but also to methanogens (Fullford 1988).

Digesters can be run either batch wise or continuously. Pathogen decline of *E. coli*, *S. typhimurium*, *L. monocytogenes*, and *Y. enterocolitica* were found higher for a batch system running for 1 month compared to continuous mode of operation with a feeding rate of 1-2 days in a laboratory experiment at mesophilic temperatures (Sahlström 2003). Details on mixing and SRT and HRT are not provided by Sahlström (2003). Furthermore, the literature on pathogen removal of batch versus continuous mode is very limited. Further study is necessary to confirm these differences.

Among pathogens there is variation in the persistence to conditions in anaerobic digesters. For instance, *Camplylobacter* causes most of the gastro-enteritis cases in humans; however the bacteria is very sensitive to AD and is therefore not found in digested sludge.

From the literature review above it is not possible to reliably predict pathogens decline during AD, another complicating factor is that the survival is interdependent on the characteristics of other pathogens (Kearney, Larkin et al. 1993; Theresa E. Kearney 1993). This might the result of competition for nutrients between pathogens. It is however clear that domestic AD is not a sterilizing treatment of the substrate, some pathogens will remain and therefore proper waste management in necessary to avoid pathogen contamination.

Proper Waste Management

Since most studies dedicated at low temperature digestion are performed at upper psychrophilic range these results are not completely translatable to, say, digestion at 15°C. However, all studies showed that pathogen survival increases with decreasing temperature while a longer retention time decreases pathogen survival. A total risk free environment can never be obtained for domestic AD, but with proper waste management most risks can be mitigated. A biogas system condenses the pathogens risk to one point in geographical sense, the digester (influent, effluent and storage). This yields opportunities to manage the risk.

To estimate the magnitude of the risk to get ill, the health hazard, the model of Covello and Merkhofer (1993) provides some valuable insights:

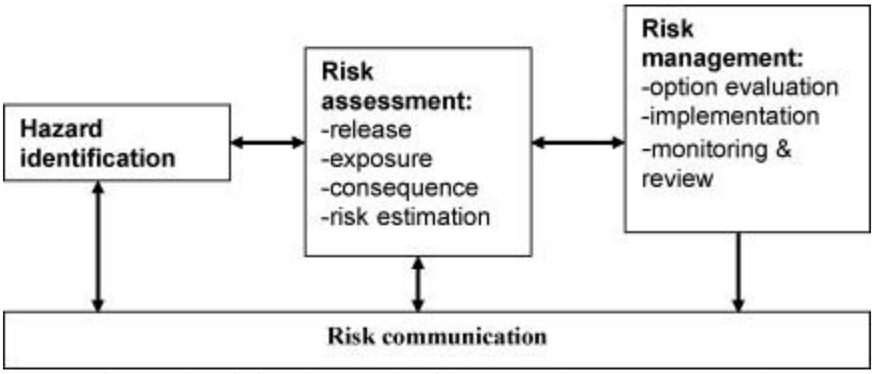


FIGURE 9: RISK ANALYSIS MODEL OF CORVELLO AND MERKHOFER (1993)

The hazard identification is the first step of the risk analysis (Peeler, Murray et al. 2007). To estimate the health hazard, the identification of indicator species is helpful. These indicator species, which are preferable not pathogenic and available in large numbers, are used to detect possible prevalence of disease causing pathogens. By doing so, indicator species indicate the hygienic treatment of substrate by AD (Sahlström 2003). Bacteria from the genus Enterococci (Faecal streptococci), *Enterococcus faecalis*, *Enterococcus faecium*,*Enterococcus avium*, and *Enterococcus galinarium* are suggested to be the best indicator species at low temperature digestion (Sahlström 2003), the so-called FS-method.

Subsequently, the health risk can be assessed; this depends on the method of release, the pathways for the introduction of the hazard (slurry, slurry spread, manure, slurry storage, digester contact etc.). The exposure differs among family members, children play around the house and can come into contact with slurry and water, but also the operation of the digester, feeding and spreading the effluent is another important pathway of exposure and animals might also be at risk. Animals should be part of the health assessment; they represent the wealth and capital of the poor rural family. The consequences are also necessary to take into account, for example sickness can cause economic losses, children dropping out of school, adverse effects on the environment. Risk estimation is the following product: *release x exposure x consequences*.

Risk management

Risk management is necessary to control the risk. Controlling the risk is possible by taking preventive measures, for instance avoidance of slurry application on fields where vegetables are grown which are eaten fresh/raw, while it can be applied to fields where crops are grown which are cooked or processed before consumption. Another suggestion, which is practiced in southern Europe, is to leave the sludge on the land for 3 weeks before planting crops to reduce the pathogens number and thus the health hazard (Wolters 2005). Additionally, as common in India and also in Nepal is to compost the slurry aerobically with other biodegradable wastes before applying it to the fields, which eliminates the remaining pathogens (Mendis and Nes 1999). GTZ (1999) has a similar advice; mixing slurry with organic wastes, such as crop residues, to reduce nitrogen loss and to remove the remaining pathogens. By doing so, a good compost is generated which is enriched with phosphorus and plant nutrients.

Some diseases are vector-borne and are spread via for instance flies. A health assessment should be carried out if vector borne diseases could proliferate if slurry is applied to the field in a particular region.

Finally, the findings have to be communicated to the end-users, whereby it is crucial to consider the needs, habits and attitudes of the end-user. The latter is of prime importance, since many development projects have failed in the past because of ineffective communication (Barnett 1990). The potential end-users of the technology, the biogas system, should be participant and not just a recipient of the outcome of a risk analysis. Without proper understanding of the socio-economical reality of the users, their culture, habits and needs, it is questionable if risk communication would lead to the desired results.

Hygiene and good manure management

A biogas system is a manure management tool. This means that manure is handled differently than without a digester. A benefit of AD is that the manure is collected and disposed, fed, to the digester which improves hygiene since it reduces the amount of flies and the risk of contamination with pathogens. Since manure is collected and most of the VS are converted to biogas foul odors are reduced. Although foul odor reduction is not directly a health benefit, it is a nuisance to the ones directly involved but also for the neighbors.

In Nepal, where around 9% of the biogas potential is realized, many users complained about an increase in the number of mosquitoes after the biogas plant was realized (Gautam, Baral et al. 2009). This is in contrast with hygiene improvement and is a potential health hazard; flies are transmitters of diseases such as malaria and dengue fever. The exact circumstances which causes an increase in mosquitoes is not mentioned or studied by Guatam and Baral et al (2009).

4. CHEMICAL FERTILIZER SUBSTITUTION

Digestate could displace expenditure on chemical fertilizer.. This is only true if digestate has similar advantages compared to chemical fertilizers, this will be assessed in this section. Other uses of digestate, such as, as feed in fishpond is also described. A simplified nutrient cycle of a biogas system is shown in the next figure.

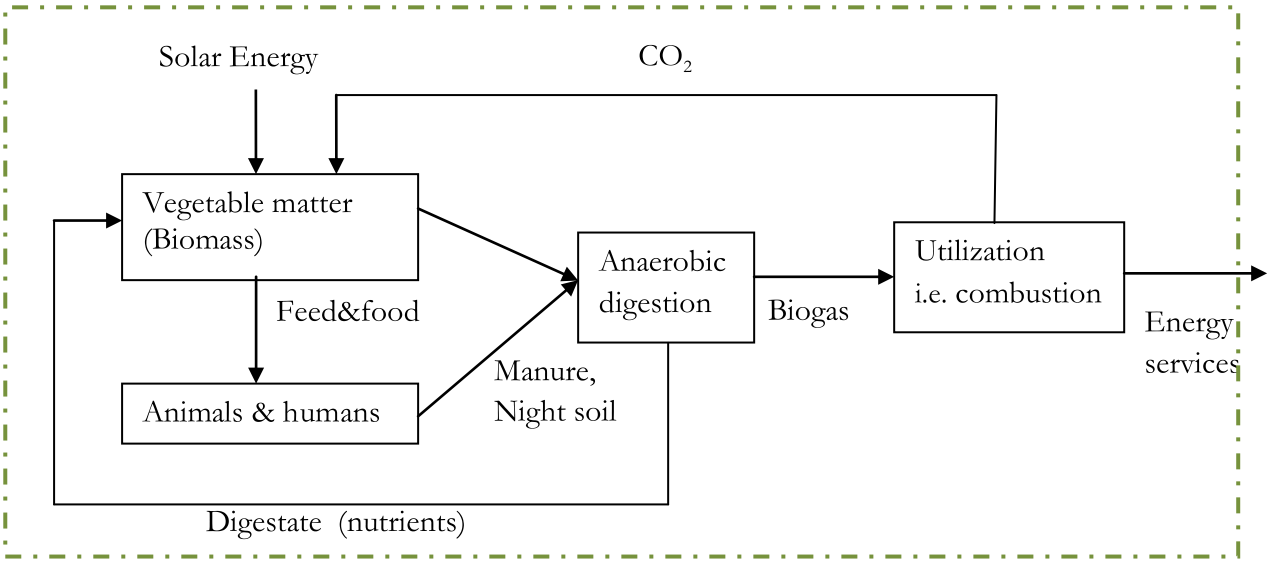


FIGURE 10: ENERGY TRANSFORMATIONS AND NUTRIENT CYCLE OF A BIOGAS SYSTEM (ADAPTED FROM (BARNETT, PYLE ET AL. 1978)

Consequently, when nutrient loops are linked, nutrients are recovered. From the farmer's perspective however, nutrient recovery alone is not decisive; it is the quality of the nutrients that matters, i.e. the availability of the nutrients for the crops. To put it differently, the *fertilizer value* of digestate has to be considered and this is elaborated next.

Fertilizer value of digestate

The composition and amount of nutrients in manure depends on the type of diet and the kind of species (Kirchmann and Witter 1992) and is an important variable for nutrient recovery. Total phosphorous and nitrogen amount are conserved during AD (Massé, Croteau et al. 2007). During AD carbon is lost as CO_2 and CH_4 and therefore the C/N ration decreases (Massé, Croteau et al. 2007), which results in an increase of N mobilization (mineralization to Ammonium N) and an a higher availability to the crops after application . A study in Costa Rica using Taiwanese style plastic bag digesters clearly showed this; NH_4-N increased with 78,3% due to a decrease of organic nitrogen compared to the feedstock (Lansing, Botero et al. 2008). Resulting from the high uptake by crops of NH_4^+, nitrogen leaching and ammonia emissions decreases compared to manure (Börjesson and Berglund 2007). There is some controversy over nitrogen volatilization after land application from digestate compared to raw manure; most studies seem to indicate that the volatilization amounts are similar (Massé, Croteau et al. 2007). This is the result from the lower viscosity of digestate, which enhances soil infiltration.

Phosphorus undergoes as similar process as nitrogen during AD, P is also mineralized and more readily available as a nutrient (Massé, Croteau et al. 2007).

Concerning other nutrients and micro nutrients no extensive studies are conducted, there are however some indications that although micronutrients are recovered during AD, the extractable fraction of P, Ca and Mg decreases due to sorption on small particles surfaces (Massé, Croteau et al. 2007).

Concluding the fertilizer value, most studies indicate AD treatment of manure conserves the nutrients and makes it more readily available to crops and it therefore mimics chemical fertilizers (GTZ 1999). Consequently, digestate is a good substitute for chemical fertilizers and a superior fertilizer compared to manure (Srinivasan 2008). However, drying of the digestate should be avoided as it results in an almost complete loss of inorganic nitrogen and hence reduces the fertilizer value considerably (GTZ 1999). Better is it to compost the digestate with biowaste residues for nutrient conservation.

Separation of the slurry or digestate to match nutrient requirements of the crops

Separation of the supernatant and the settled fraction of the digestate or slurry could be used to match nutrient requirements of the crops. This was studied with a psychrophilic AD sequencing batch reactor (PASBR), which was fed with swine manure for 2 weeks feedings and 2 weeks for reaction at 17°C, separation of the slurry occurred. Most of the ammonium and Na remained in the supernatant whilst the settled fraction contained most of the P, Ca, Mg, Al an Cu, S remained in both fraction equally (Massé, Croteau et al. 2007). Hence, if a PASBR reactor is installed instead of continuous mixed system the separation of nutrients could be used to match nutrient requirements of the crops (Massé, Croteau et al. 2007). For a CSTR this is possible if solid separation is applied on the effluent, however, for small scale installations this is unlikely to be feasible.

Revenue savings by the displacement of chemical fertilizers

Every kilo of displaced chemical fertilizer by digestate results in saved revenues and therefore frees up resources for other activities. In Nepal it is estimated that around 4329 tons nitrogen, 2109 tons phosphorous and 4329 kg potassium are saved annually because of the installation of biogas plants (Gautam, Baral et al. 2009), with an annual saving of $300.000. The GDP is around $237 and hence around 1266 yearly incomes are saved. Note that Nepal is a poor country and that chemical fertilizers are imported and used in relatively small quantities compared to developed countries.

Dung cakes and digestate for organic produce

In India, around 53% of the dung is dried for cooking purposes (Vergé, De Kimpe et al. 2007). In that case the provision of biogas is replacing dung as cooking fuel has an additional advantage. The nutrients in dung are not lost anymore as a result of combustion and thus the nutrients are conserved and recovered when the digestate is applied to the fields. This both reduces the need for chemical fertilizers and prevents soil depletion. In addition, if digestate is used as a fertilizer the harvest could be labeled organic. The market for organic products is growing rapidly and so is the awareness that sustainable agriculture is best for people and nature (Srinivasan 2008). Organic products are more valued and could therefore increase the farmers' income.

Digestate in pond cultures

Another use of digestate is as feedstock for fish poly culture to enhance fish yields and to displace bought feed (Srinivasan 2008). The potential of an integrated approach; excreta collection, digestion, biogas production and disposal in a fish pond is demonstrated with success in China (Edwards 1980). Most nutrients, 72-79% of N, 61-87% of P, and 82-92% of K are recovered by fish farming in shallow warm ponds (Edwards 1980). Not many studies have focused so far on the use of digester effluent as a substitution for chemical fertilizers as fish feed, rather surprisingly since around 2/3 of the world's production of farmed fish are fed by animal or humans wastes (El-Shafai, Gijzen et al. 2004), a common practice.

In one study conducted in India, the fish production was compared under three conditions: one control pond (no additives), one with chemical fertilizer (Urea 18:8:4, N:P:K) and one with biodigester effluent. (Balasubramanian and Kasturi Bai 1994). The ponds were otherwise identical. After 1 year the pond with digester effluent had a fish yield of 18,32±1,32 $kg.ha^{-1}.day^{-1}$, a 3,6 and a 10 fold higher fish production compared to respectively the pond with urea and the control pond. Thus, if digester effluent is added, fish yields will increase and expenditures on chemical fertilizers (urea) are avoided

In another series of experiments conducted in Israel, cow manure digestate was tested by replacing all the fish feed (15% fish meal, 16% soybean, 69% sorghum) or partly (Barash and Schroeder 1984). Fish yields were lower when only digestate was fed but remained the same when 50% was replaced. However, this difference was only observed for the common carp while tilapia fish yields were much less affected. Moreover, in smaller ponds, 400 m^2 instead of 1000 m^2 these difference were not observed, probably due to the higher edge ratio and the less depth. The results are a bit obscured by the fact that in all cases inorganic supplements were added.

Another study conducted in Thailand, digester effluent from HNS and water hyacinth was added to 200 m^2 ponds in various concentrations. At the highest organic loading rate, 100 kg COD/ha/day, a fish yield of 10 kg/day/ha was obtained, which was according to the authors impressive. According to them it is a solution to the protein-energy malnutrition as occurring in many developing countries (Edwards, Polprasert et al. 1988). Similar findings were found in a study in India. Adding the digester effluent (52 liters/ha/day) to a fish pond stimulated the growth of zooplankton and total fish significantly compared to a control pond with untreated manure as feedstock (Sehgal, Kaur et al. 1992). Yields were even higher with the supplemental addition of rice bran and oil cake (3:1 dry weigh basis) at a rate of 2% of fish biomass as daily feed, the growth of fish and zooplankton increased even further.

Pathogen risk

The picture on the right shows a fish pond and a toilet where the fish are fed by human excreta. This practice could increase the risk of pathogen contamination, since the fish from the pond are consumed by humans (El-Shafai, Gijzen et al. 2004). As aforementioned, digester effluent contains significantly reduced amounts of pathogens; consequently the pathogens risk when fish are fed with digestate is much less while a toilet attached to the digester allows for more privacy. In China, normal practice is to compost the digester effluent, and mix it with plant materials and soft mud for 10 days before feeding it to the pond (Edwards 1980). Another approach is to post treating the digester effluent to achieve an effective health risk mitigation (El-Shafai, Gijzen et al. 2004). That is possible by, for instance, adding a pond with plants growing on digester effluent (or directly on excreta) which are the feedstock for the fish in the next pond.

PICTURE 9: FISH POND WITH TOILET IN CAMBODIA (AUTHORS PICTURE)

Sludge-Pond cultures using water hyacinth

Sludge hydroponics is a type of agriculture where plants grow directly on the nutrients, for instance on the effluent of a digester. Plants like water hyacinth are well suited for hydroponically environments and this plant is a good livestock feed (Fry, no date).

Sludge-Pond cultures using duckweed

Some experiments are conducted using domestic waste water with an UASB tank as pre-treatment and three connected duckweed pond as post treatment (El-Shafai, Gijzen et al. 2004). Their experiments showed a high fecal coliform removal of 99,7% in the winter (12,5-20°C) and even higher in the summer. Nitrogen recovery was high as well, 80,5% in the duckweed, 5% was accumulated in the sediment and 15% denitrified. The effluent of the third duckweed pond can be utilized for agricultural irrigation. In another experiment they used duckweed directly from an UASB-duckweed pond system fed with domestic sewage for Tilapia rearing. The fish was safe for consumption, but when settled sewage was added, pathogen count in the fish’s tissue increased considerably, likely caused by the higher ammonia and nitrite in the water which affects the immune system of the fish negatively (El-Shafai, Gijzen et al. 2004).

In summary, digester effluent is a good fish feed, however for optimal fish yield some additives might be necessary. Post treating the digester effluent is advised to remove most of the potential health risks.

5. FINANCIAL BENEFITS

This section is an introduction to the main issues concerning financing and the investment barrier of a biogas plant. All the aforementioned private benefits, on-site farm energy generation, health benefits and chemical fertilizer displacement save revenues and time. Some of these benefits can be enumerated to direct monetary benefits while others only indirectly contribute to cost saving, such as avoided health costs. Saved time could also results in revenue generation if it leads to economic activities. However, if for instance collecting wood poses no *opportunity costs*, the saved time has no value in economic terms (Thirlwall 2006).

The monetary benefits of a biogas plant need to outweigh the capital investments costs within a foreseeable period. This is an obstacle for biogas dissemination since a biogas plant is a considerable investment and might therefore only reach the relative affluent farmers in developing countries (Buysman and Mansvelt 2006). If the investment costs are covered within a foreseeable period, a biogas plant directly contributes to poverty alleviation by reaching the poorer farmers with sufficient livestock (Mwakaje 2008).

From a private perspective it is important to determine the profitability of an investment in relation to the investment (Blok, 2007). A rule of thumb method is the payback period (PBP).

$$PBP = \frac{I}{B - C} \qquad (2)$$

$$C = iI + OM + F$$

Where, I is the initial investment, B the annual benefits (in this case avoided costs on fuel and fertilizers) and C the annual costs. The annual costs is the product of the interest rate (i), costs for operation and maintenance (OM) and the fuel costs (F), the PBP generally ignores time preference or the discounting of money (Blok 2007). For a proper analysis, time preference should be included, but the PBP formula here is used to address some mayor obstacles from a financial perspective. OM is, besides the time investment for running the plant, the insurance or services that the constructer of the plant provides. In general F has no costs and costs on OM are marginal compared to the total investment.

A major obstacle in many developing countries is the high interest rates together with a short payback period that financial institutions set. In Georgia for instance, interest rates on micro credits are around 25-38% and a PBP of 2-3 years is required on agricultural investments (WECF 2008). This is doable if seeds are bought and hence the returns follow directly after the selling of the harvest. A biogas plant however, is a long term investment and in countries like Georgia financial institutions have little knowledge and understanding of the impact and benefits of a biogas plant. This is likely to be the same in other developing countries. Hence, interest rates are high as a result of the high risk perception by banks and this supplemented with the financial crisis of 2008-2009 which leads to even higher interest rates.

The financial benefits and hence the PBP differs per country substantially. If fuel for cooking is scarce and has high prices, the PBP is likely to be relatively short. In developing countries with cold climates the investment costs of a digester will be higher due to modifications to combat the impact of low temperatures on biogas production or the returns are lower when during the winter time there is insufficient gas, as happens, for instance in the cold parts of China (Daxiong, Shuhua et al. 1990). A longer PBP will directly have an adverse effect on biogas adoption rates.

Biogas adoption and PBP in Tanzania and India

In South West Tanzania a study was conducted on the profitability of biogas plants (Mwakaje 2008). A biogas plant costs around $435-527 with an average PBP of 5-11 months. Remarked should be that the costs of savings on fuels, wood, charcoal and kerosene are $191/year and with that value the PBP would be 2,3 years for the cheapest digester (author's calculations). Hence, additional activities, such as cow milk selling and chemical fertilizer displacement contributed significantly to the short PBP. Even though the PBP period is relatively short, only the medium income farmers were able to invest in a biogas plant.

Most farmers were very interested in the technology, but 65% of the population found the investment the mayor constraint. These findings show that a short PBP period is not always sufficient to increase biogas adoption. A partial explanation might be that farmers in developing countries tend to be risk adverse; they actively seek for risk mitigating solutions which is a understandable strategy since acute poverty is never far away (Martinussen 1997).

A comparative study in India showed a strong relationship between digester size, type and PBP (Singh and Sooch 2004), see the next figure.

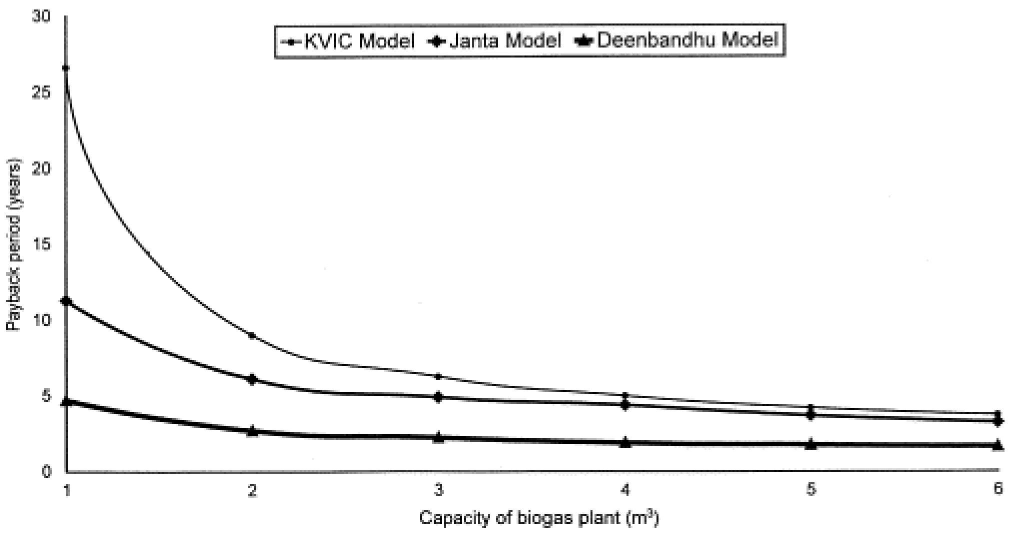


FIGURE 11: DIGESTER SIZE AGAINST PBP IN INDIA (SING AND SOOCH 2004)

The figure shows some digester models are inherently cheaper and hence the PBP is shorter. Since most families require 1-2 m^3 biogas/day, larger volumes only yield advantages when it displaces other fuels, i.e. when gas is also used to displace fuel for room heating or mechanical power. Furthermore, the figure suggests that a larger biogas plant requires a relatively lower investment and thus PBP. The PBP in India is longer than in Tanzania, 2-3 years for the Deenbandhu digester of 2 m^3 compared to 5-11 months in Tanzania.

The Deenbandhu, Chinese dome, Janata and KVIC floating dome digester have life spans of at least 15-20 years (GTZ 1999), the CAMARTEC digester as used in Tanzania is a derivative of the Chinese dome (Mwakaje 2008) and lasts probably also that long. Consequently, comparing the PBP with the lifespan of a digester, it is possible conclude that a digester is profitable for the most part of its lifespan.

In summary, obstacles for biogas plant dissemination are the relatively high investment costs and interest rates, while on the other hand the PBP period is much shorter than the life span of the digester. When means are found to invest in a biogas digester, a digester leads to avoided costs and alleviates poverty during the majority of its lifespan. Srinivasan (2008) argues that the spillover effects of a biogas plants which leads to a great number of benefits on local and global scale provide a sound rationale for subsidies. By allocating resources from societal collateral goals (and benefits) and revenues from CDM could provide means for subsidies. The rationale for subsidies is outlined in the section after the national and global benefits.

6. DISCUSSION & CONCLUSION

In conclusion, the direct private benefits of biogas utilization are the provision of a clean fuel which has obvious socio-economical benefits. It saves revenues or time which would otherwise be spent on obtaining fuels, in addition, biogas utilization improves the indoor air quality, sanitation, and the nutrients are remained in the slurry which on its turn displaces chemical fertilizers. Hence it will result avoided health costs which on its own alleviates poverty, as the WHO (2002) puts it for a lack of sanitation, '*enemies for health, allies for poverty* , alternatively, the procurement of biogas plants would then be *'allies for health, enemies for poverty'*.

The provision of clean on farm energy in a sustainable manner displaces traditional fuels, and therefore the families involved climb up the energy ladder. This also protects them against the volatile prices of primary energy sources (Modi 2006). An interesting article about the energy ladder and energy is the one of Smith & Apte et al. The conceptual framework of the energy ladder shows that when people have the possibility they will move up the ladder. Moving up the ladder means that, the cleanliness, efficiency and the convenience of the energy sources increases (Smith, Apte et al. 1994). Furthermore, Smith & Apte et al (1994) argued that in prehistory mankind depended on wood for their energy demand. In later times, when wood became scarce people had to turn to inferior fuels, such as crop residues or dung. The latter happened in India where many rural poor use dried dung as a cooking fuel (Sagar and Kartha 2007). In the developed world on the other hand, people have moved up the energy ladder and use primarily gas and electricity.

Biogas and the energy ladder

In respect to the energy ladder, a biogas digester uses the most inferior energy source, dung, and converts it into one of the most clean and efficient fuel, biogas, or with a gen-set electricity, high up the energy ladder (Figure 12).

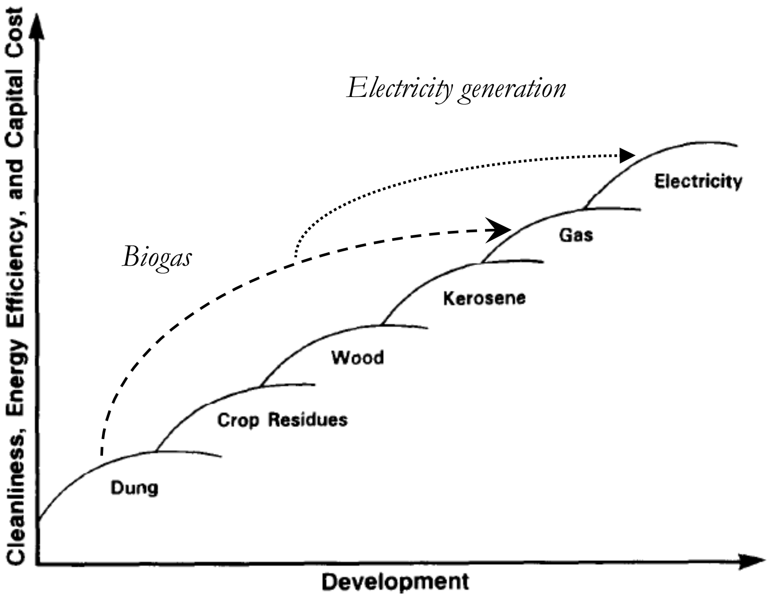


FIGURE 12: THE ENERGY LADDER (ADAPTED FROM SMITH & APTE ET AL. (1994)

The sum of the benefits as described result in the improvement in the quality of life and poverty alleviation. And this is especially true for women as they are traditionally responsible for the '*procurement, processing and use of cooking fuel for their families'* (Dutta, Rehman et al. 1997). Hence, biogas dissemination is a mean to combat energy poverty and poverty in general. In the next section we shall see that benefits are not confined to the direct beneficiaries, but has spillovers at different scales, so called positive externalities.

3.12 LOCAL BENEFITS

The main local benefits are spillovers from private benefits; the positive externalities which occur at local scale. The dissemination of biogas technology creates job opportunities in the rural areas, for instance the construction of digesters requires construction workers (both skilled and unskilled), technicians and employment in the financial sector (Srinivasan 2008). However, if skills are not available and training is provided by the biogas digester implementing or dissemination agency, as is common in India, Nepal, Cambodia, skills are created (Dutta, Rehman et al. 1997). This leads to skilled workers with spillovers to other sectors, see the story to the right from the Indian NGO experience. In Nepal around 11.000 people are employed in the biogas sector, but with a spin-off to employment provision of around 65.000 people nationwide (Gautam, Baral et al. 2009)! With this in mind, around 110.000 domestic biogas plants are built (as of 2005), hence around 1 job per 1,7 digesters!

> Mr Babubhai was barely able to make a living with farming for his family in a village in India. He attended a masonry training program for the biogas plant construction and started working as a biogas mason. As a result his annual income almost doubled. During the lean season he used his newly acquired skills to work on other projects, such as house construction. Over the years he acquired a house and commodities such as a television and a bicycle. Now he is living comfortably with his family.
>
> *Copied and adapted from Dutta, Rehman et al (1997)*

Skill creation

Job opportunities are as a result not confined to the biogas sector alone; the newly acquired skills are usable in many other sectors of the rural economy. More opportunities for income generation in rural areas might also lessen the lure for work in urban areas. It removes one of the main push factors, limited rural employment opportunities, while the main pull factor for urban migration, the higher wage, is abated by higher earnings resulting from the new skills (Thirwall 2006).

Impact on local forests

The displacement of traditional fuels avoids logging for fuel wood which relieves the pressure on the forests. Some authors estimate it saves around 2 ton of wood per household (Srinivasan 2008). A case study in a village in India showed that after 115 out of 130 households adopted biogas plants, the yearly demand for wood decreased from 300 cartloads of wood to a mere 15-20 (Dutta 1997). In Nepal around 2 ton per household of firewood is saved after the installation of a biogas plant, around 200.000 ton annually (Guatam, Baral et al, 2009).

In the case of Cambodia, in the six provinces around Phnom Penh, a household consumes around 2,3 ton per annum of which 77% is non-renewable biomass (NRB) (Buysman and Mansvelt 2006). In this context NRB means that the logging activities outpace the natural re-growth of the forests. If the pressure on the forest lessens, it could free up the recourse for other forest derived products, if done in a sustainable manner. In many developing countries forests provide multiple goods and services, such as spiritual and religious outputs, fodder, timber, medicines and non timber forest products (fish, game, rattan, bird's nest) (Godoy 1992; Cubbage, Harou et al. 2007).

Furthermore, the conservation of the forests benefits the people living downstream by on site erosion control and watershed protection and forest provide habitat to animals and thus supply biodiversity (Godoy 1992). In addition, forests provide other non extractive goods and services, such as recreational sites and (eco) tourism opportunities (Cubbage, Harou et al. 2007). Tourism provides additional employment opportunities and foreign exchange contribution. Moreover, less logging for fuel wood could also benefit the poor without a digester, especially if the natural re-growth equals the fuel wood gathering. In that case the time expenditure on fuel wood collection remains the same and does not increase as it would with a decreasing forest.

In conclusion, biodigester dissemination for the rural poor has multiple benefits at local scale, ranging from employment opportunities in rural areas to conservation of the forests with all aforementioned associated benefits. However, we should realize that these benefits do not occur automatically or do not happen at all if just a few digesters are installed.

3.13 MACRO BENEFITS

Three main impacts at macro (national or global) scale are considered, foreign exchange earnings, GHG abatement and avoided health expenditures (Srinivasan 2008).

Foreign exchange earnings

As discussed in the previous chapter, tourism results in foreign exchange earnings. Foreign exchange provides access to good which cannot be produced domestically (i.e. obtaining technology for industrialization). As argued in the Prebisch-Singer thesis, a switch from primary commodity producer to manufactured goods is necessary to overcome the tendency of falling primary good prices relative to manufactured goods prices. Consequently, a focus on manufactured export goods would improve the barter terms of trade (Thirwall 2006), which is important for development. However, it should not lead to neglecting the rural economy and agricultural development. Agricultural development should go alongside the development of other sectors to create surpluses and foreign exchange (Thirwall 2006). Organic produce have a higher added value than (bulk) primary agricultural commodities and this could also be a source for foreign exchange earnings (Srinivasan 2008).

Greenhouse gas abatement

A biogas digester reduces greenhouse gas (GHG) emission (Srinivasan 2008). This is an important feature, especially since it contributes to the efforts to mitigate GHG emission, which has obvious benefits. The UN for instance is deeply concerned about the current trends showing the rapid increase in temperature worldwide as presented its 4th climate assessment report in 2007 (Buysman 2007). Global warming, as the name suggests, is an issue on global scale. A biogas digester mitigates GHG emission through the following mechanisms (Clemens, Trimborn et al. 2006):

1. A change in manure management system, a biogas system captures methane and thereby prevents the release to the atmosphere
2. Biogas utilization for energy services displaces fossil fuels or NRB resulting in GHG abatement.
3. Chemical fertilizer displacement, the production and utilization of chemical fertilizers results in considerable GHG emission

More details on GHG abatement is discussed in chapter 6.

Avoided health expenditures

The improved sanitation and health benefits of a biogas digester have important spillovers for both the local and national economy. The expenditure on health at all levels; private, local and national is reduced. This frees up resources, which could, in the case of the national government, be used for economic development (Srinivasan 2008). Additionally, a healthier population is more productive.

3.14 REFLECTION ON THE BENEFITS & RATIONALE FOR SUBSIDIES

It is easy to sketch the multiple benefits resulting from the adoption biogas digesters. However, it is not always true that these benefits are realized after the installation of a biogas digester as a result from all sorts of cultural, social and practical reasons (Barnett 1990). For instance, the smoke of wood stoves keeps flies away, an appreciated feature of woodstoves, which relieves families of the nuisance and the danger of getting diseased (i.e. malaria or dengue fever) and therefore in addition to biogas wood stoves might still be used. In addition, the flavor of cooking on wood might be appreciated, for instance in Cambodia eggplants or fish are fried above wood fire and according to the locals preparing food that way is much more tasty (personal observation).

In general people welcome biogas plants (van Nes 2008). The Indian NGO experience also shows that the users of biogas installations appreciate the benefits, they report that users found better yields, less weeds when using digestate instead of fresh manure as fertilizer (Dutta 1997). Also the indoor air quality and cooking fuels displacement were much appreciated. Biogas adoption is however not always happening due to the high costs. However, since the benefits are so ubiquitous and not confined to the direct beneficiaries, there are good grounds to justify subsidies.

Rationale for subsidies

In the previous chapter benefits on all scales are outlined but even though a digester results in poverty alleviation and avoided costs after the PBP, the initial investment remains a large financial obstacle. Srinivasan (2008) asserts that focusing on the private benefits alone for justification of investments is narrowly defined; sometimes the overall benefits are even higher for the society than the owner of the biogas plant. Hence, Srinivasan (2008) argues that costs and surpluses should be relocated, which should free up resources for sustainable financing mechanisms such as micro-financing.

To some extent this is realized in India, digesters are (or were) partly subsidized in some states (Dutta, Rehman et al. 1997). In Tanzania it was found more appropriate to increase the availability of building material and the provision of cash would be a better solution (Mwakaje 2008). CDM is a mechanism based the principle of relocating costs and surplus. The developing country, the host, assists the developed country in achieving their Kyoto targets, by investing or disseminating low carbon technology such as a biogas plant (van der Gaast, Begg et al. 2009). The saved GHG emission has a value and could free up resources to propagate biogas technology by for instance training of producers, subsidizing digesters or for low interest loans. Chapter 6 will focus on the CDM mechanism.

The rationale for subsidies can be justified when the rate of return is higher for the national economy than for the biogas plant owner. Some of the generated advantages, the societal collateral benefits could in that case be used to subsidize biogas plants. To understand when there is a rational for subsidies, the IRR (initial rate of return), the NPV (net present value) and an economic CBA (cost benefit analysis) have to be determined. The NPV is the sum of the discounted annual net non-financial cash inflows during the lifetime of the project, the IRR the rate of return when the NPV is set at zero (Romijn & Biemond, 2005). The IRR should be higher than the interest rate of the market, otherwise the cost of financing are higher than the project would yield.

From a private (financial) perspective, the NPV needs to be higher or equal to 0, in that case the project is estimated to give a higher or the same yield than the prevailing market interest rate. If the NPV is lower, the investment would yield less than the market interest rate (i) (Romijn & Biemond, 2005) similarly if the IRR is lower than the prevailing interest rate. The private IRR is sometimes denoted as the financial rate of return (FRR) or financial CBA.

From an economic perspective, the rate of return is calculated by doing an economic CBA. The outcome is an economic rate of return (ERR), this is for instance executed by SNV for each biogas program (van Nes 2008). If the ERR larger than the IRR there is a justification for subsidies. The next table shows the situation for which subsidies can be justified from an economic perspective.

TABLE 10: RATIONALE FOR POLICIES TO ENCOURAGE BIOGAS ADOPTION (COPIED AND MODIFIED FROM ROMIJN & BIEMOND 2005)

	Economic CBA	
Financial CBA	*Econ. NPV ≤ 0* *Econ. ERR ≤ i*	*Econ. NPV > 0* *Econ. ERR > i*
Fin. NPV ≤ 0 *Fin. IRR ≤ i*	Abandon project. Yields are negative	Policies required to encourage biogas adoption
Fin. NPV > 0 *Fin. IRR > i*	Good private yields, but negative impact economy	No support required, sufficient private yields

<u>The Gray cell</u>

Biogas project which fall in right upper grey highlighted cell 'policies required to encourage biogas adoption', are not feasible from a private perspective, the IRR is beneath the interest rate and the NPV is negative, but it does generate positive externalities for the total economy which justifies subsidies.

<u>The Black cell</u>

Many project probably fall into the right down black shaded cell judging from the short PBP of biogas plants, see the section on financial benefits. However as argued, the farmers have limited funds and probably no access to credit with affordable interest rates. Also the PBP period increases if commercial loans are used, as a result of the high interest rates as is generally the rule developing countries. In developed countries project are generally only undertaken if the PBP is 2-3 years (Blok 2007), hence for farmers with limited funds it is even harder to invest in project with PBP of a similar or longer period. But, if projects fall in that cell, there are good grounds to develop policies to encourage biogas adoption since the ERR and the economic NPV is positive.

White cells

Project fallings in the white shaded cells need to be abandoned. The upper left cell, both harms the economy and the financial position of the investor; however this is unlikely to occur for biogas projects. The cell, lower left, shows that the private individual benefits but it harms the economy. A project should not be undertaken in that case, unless there is some other justification for it from another perspective (social or environmental).

In conclusion, for projects falling in the cells on the right, there are good grounds for policies promoting biogas adoption. This can be justified by the positive effects generated by the biogas plants on the whole economy. Even for the black cell, this can be justified, if farmers do not have access to credit or to credit with affordable interest rates.

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3.2 BIOGAS WITHIN THE FRAMEWORK OF THE MILLENNIUM DEVELOPMENT GOALS

In 2000, during the millennium summit of the United Nations, the international development goals were formulated, the millennium development goals (MDG). After ratification of these goals by the 189-member states, eight goals and 21 targets were promoted. The principal aim of these goals is to *"usher 21st Century progress and to accelerate development for all people"*, and targets have been set to be reached before 2015 (Excellence 2007). The MDG recognizes the human right for development and are an international commitment to combat poverty, hunger, ill-health, gender inequality, lack of education, access to clean water and environmental degradation.

The UN states that access to energy services are crucial to meet the millennium development goals (Modi 2006). To achieve the MDGs, a shift is necessary from the traditional biomasses to modern energy sources in the developing world (Sagar and Kartha 2007). Sustainable energy services allow for an escape from the vicious cycle of poverty, since it does so without harming the environment. Conversely, a multiplier effect can be identified on *health, education, transport, telecommunications, safe water, and sanitation services and on investments in and the productivity of income-generating activities in agriculture, industry, and tertiary sector* (Modi 2006), when a shift from traditional biomasses to modern energy sources such as biogas occurs.

The following eight MDG and their specific targets are developed (Thirlwall 2006):

1. **Eradicate extreme poverty and hunger**
   - Halve, between 1990 and 2015, the proportion of people whose income is less than $1 a day.
   - Achieve full and productive employment and decent work for all, including women and young people.
   - Halve, between 1990 and 2015, the proportion of people who suffer from hunger.

2. **Achieve universal primary education**
   - Ensure that, by 2015, children everywhere, boys and girls alike, will be able to complete a full course of primary schooling.

3. **Promote gender equality and empower women**
   - Eliminate gender disparity in primary and secondary education, preferably by 2005, and in all levels of education no later than 2015.

4. **Reduce child mortality**
   - Reduce by two thirds, between 1990 and 2015, the under-five mortality rate.

5. **Improve maternal health**
   - Reduce by three quarters the maternal mortality ratio.
   - Achieve universal access to reproductive health.

6. **Combat HIV/Aids, malaria and other diseases**
   - Have halted by 2015 and begun to reverse the spread of HIV/AIDS.
   - Achieve, by 2010, universal access to treatment for HIV/AIDS for all those who need it.
   - Have halted by 2015 and begun to reverse the incidence of malaria and other major diseases.

7. **Ensure environmental sustainability**
   - Integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources.
   - Reduce biodiversity loss, achieving, by 2010, a significant reduction in the rate of loss
   - Halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation.
   - By 2020, to have achieved a significant improvement in the lives of at least 100 million slum dwellers.

8. **Develop a partnership for development**
   - Address the special needs of least developed countries, landlocked countries and small island developing states.
   - Develop further an open, rule-based, predictable, non-discriminatory trading and financial system.
   - Deal comprehensively with developing countries' debt.
   - In cooperation with pharmaceutical companies, provide access to affordable essential drugs in developing countries.
   - In cooperation with the private sector, make available benefits of new technologies, especially information and communications.

Elaboration of these MDGs and their targets can be found on the website of the UN: www.un.org/millenniumgoals/poverty.shtml.

The table on the next page shows how the procurement of biogas plants affects these targets.

TABLE 11: PROCUREMENT OF BIOGAS AND THE MDG GOALS (SEIFERT, SUHARTA ET AL. 2006)

MDG LOGO	Impact by biogas digester dissemination
1 ERADICATE EXTREME POVERTY AND HUNGER	• Avoided expenditure on fuels (Srinivasan 2008) • Improvement of health and increasing productivity • Access to affordable and clean and secure energy source for cooking, lighting and other energy services (Sagar and Kartha 2007) • Availability of high quality fertilizer (digester effluent) • Employment opportunities resulting from biogas plant construction
2 Achieve universal primary education	• Time spend on attending school instead of firewood collection • Revenues availability for schools because of the decreased energy burden on the households' income (see MDG 1)
3 PROMOTE GENDER EQUALITY AND EMPOWER WOMEN	• Empowering women by time savings and removal of arduous work (Biswas, Bryce et al. 2001) • Using the potential of women's managerial skills and entrepreneurial skills to develop (made possible by the time savings) • Transfer of know-how (biogas training programs)
4 REDUCE CHILD MORTALITY	• Indoor air quality improvement, reduction of hazardous particles (Mestl, Aunan et al. 2007) • Avoiding of accidents resulting from traditional cooking (open fire) • Provision of potable water (sterilize by cooking) • Sanitation improvement, especially if a toilet is attached
5 Improve maternal health	• Improvement of living conditions (Mestl, Aunan et al. 2007) • Sterile water availability • Improvement of indoor air quality, hygiene and sanitation
6 Combat HIV/Aids, malaria and other diseases	• Biogas digesters dissemination could incorporate awareness campaigns • Water sterilization made possible by the provision of biogas for cooking • Sanitation and hygiene improvement • Less risk of pathogen transmission
7 ENSURE ENVIRONMENTAL SUSTAINABILITY	• GHG reduction • Chemical fertilizer displacement • Avoidance of unsustainable logging; keeping the forest service's intact (watershed, erosion provision, NTFP gathering, livelihoods, biodiversity) • Avoidance of dependency on fossil fuels
8 GLOBAL PARTNERSHIP FOR DEVELOPMENT	• Part of the framework on GHG mitigation, CDM and supporting the MDG goals 1-7.

Chapter 4

INFLUENCE OF TEMPERATURE ON DIGESTER PERFORMANCE

In this chapter the influence of temperature on digester performance is studied. The chapter begins with a theoretical perspective, where the impact on the speed of digestion is assessed by studying the kinetic parameters and next a thermodynamic perspective is taken to assess the influence of temperature on the amount of Gibbs energy available for substrate conversion. Based on the kinetics and the Arrhenius equation to forecast the performance of AD a model is described to relate the loading rate with temperature of a digester. With that model it is possible to predict how the loading rate can be adjusted to account for the lower temperature of digestion, subsequently this can be translated to measures to overcome a lower rate of digestion at lower temperatures such as increasing the retention time.

Secondly, an AD manure batch experiment is executed at 7, 8,5 and 16 degrees and based on that experiment a minimum substrate retention time is calculated at different temperatures, the full report of the experiment is pasted in annex 6.

Finally, the literature is studied to assess the efforts applied in developing countries to overcome the impact of cold temperatures on biogas production. For instance the extensive work executed in India to overcome the low ambient winter temperature as experienced in the Himalayan states of North India.

4.1 KINETIC CONSIDERATIONS

A digester for domestic purposes should be aligned to meet the energy demands of a household, a prerequisite to exploit all the benefits of a biogas system. An important parameter is the volumetric gas production of the digester which needs to be in accordance with the daily gas demand of a household. The volumetric methane yield, B (m^3 CH_4/m^3 digester volume/day), depends on (Gunnerson and Stuckey 1986):

1. B_0, the maximum biodegradability at infinite retention (m^3 CH_4/kg VS).
2. Q, the organic loading rate (kg VS/m^3 digester volume.day^{-1}).
3. Θ, the retention time of the solids (HRT).
4. K, maximum utilization coefficient, the mass of substrate consumed per time per mass of microbes (dimensionless).
5. μ_m, the maximum growth rate of microbes (day^{-1}).

The next kinetic model shows the relation between these parameters (Safley and Westerman 1990), the model is modified by the addition of Q to obtain the methane yield per unit of digester volume.

$$B = Q * B_o\left(1 - \frac{K}{(\mu_m \Theta) - 1 + K}\right) \qquad (3)$$

Equation 3 shows that at an infinite long retention time, the gas production equals the Q* B_o. The parameter B_0 depends on the chemical structure and composition of the substrate. In chapter 2.41 a relationship is derived between the biodegradable fraction and the lignin content. B_0 is temperature independent at sufficient long retention time (Safley and Westerman 1990).

The maximum utilization coefficient depends on the influent concentration but can be considered constant for psychrophilic anaerobic digestion (Safley and Westerman 1990). Hence, B_0 and K are constant for a specific substrate, but μ_m is temperature dependent while Q is a function of the added VS per day (Safley and Westerman 1990). The latter two variables can be manipulated to adjust for low temperature digestion by increasing the temperature of digestion or by decreasing the loading rate.

RETENTION TIME AND MICROBIAL GROWTH RATE

Substrate utilization of complex substrates in AD follows four consequent steps, hydrolysis, acidogenesis, acetogenesis and methanogenesis (see chapter 2.2). The retention time is the time microbes have to degrade substrate. When the retention time is sufficiently large, all the microbes have sufficient time to degrade the substrate and to have a net growth rate.

At insufficient long retention time, the system becomes increasingly acidified because the conversion rate of VFA to methane by the methanogens is slower than the production of VFA. Consequently the VFA concentration builds up, which results in a negative feedback, inhibition of methanogenesis, because methanogens are the most sensitive of all microbes in AD to a decrease in the pH (lower pH) (Gunnerson and Stuckey 1986; Kotsyurbenko 2005). In addition, under psychrophilic conditions the type VFA present in the system at short retention times changes in favor of higher molecular VFAs (Kashyap, Dadhich et al. 2003). For instance, several researchers found that with a HRT of 20 days at 20 °C, the propionate concentration to be three times higher than the acetate concentration; a built up of propionate VFA is toxic to methanogens (Zeeman, Sutter et al. 1988; Kashyap, Dadhich et al. 2003). Additionally, if the SRT (sludge retention time) is very short, methanogens will wash out of the system (digester), resulting in a dramatic decrease in biogas production. This happens when the net growth rate (growth - death) of the methanogens is lower than the net removal rate out of the system.

To conclude, to allow for an optimal digestion, the loading rate needs to be smaller or equal to the substrate utilization of the respective microbes, consequently the SRT has to be adjusted to reflect sufficient time for microbial substrate utilization and microbial growth.

LOADING RATE IN RELATION THE GROWTH RATE AND THE TEMPERATURE

The growth rate of microbes is temperature dependent and decreases at lower temperatures (van Lier, Rebac et al. 1997). In general the growth rate of microbes under psychrophilic conditions is below their optimum and in that case the decay (death) rate can be considered insignificant (Grotenhuis, Hamelers et al. 2008).

The next figure shows that the three temperature classes of methanogenic microbes each have an optimum growth rate; the dotted line shows an approximate exponential increase in metabolic activity at increasing temperature.

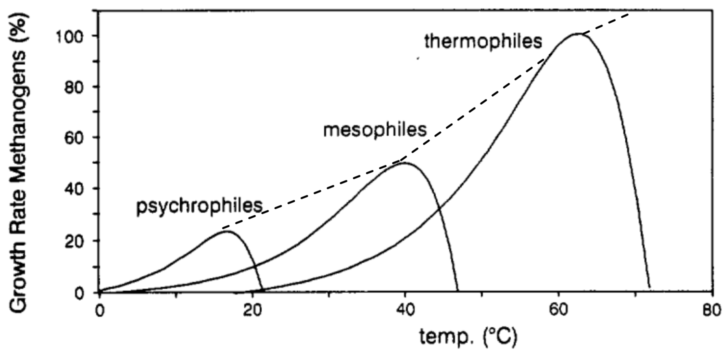


FIGURE 13: RELATIVE GROWTH RATE OF PSYCHROPILES, MESOPHILES AND THERMOPHILES (VAN LIER, REBAC ET AL. 1997)

The dotted line connecting the optimum growth yields of the microbes is added because in reality, for example, the growth rate of mesophilic microbes is higher at 25°C than psychrophilic microbes at 18°C. The growth rate of microbes can be described with the Arrhenius equation (Grotenhuis, Hamelers. et al 2008).

$$V = A.e^{-Ea/RT} \quad (4)$$

Where V is the process rate (t^{-1}), A the frequency factor (t^{-1}), Ea the apparent activation energy (J/mol), R the gas contant (8,31447 J/mol.K) and T the absolute temperature. Note that the decay rate is omitted since this is very low at psychrophilic temperatures.

For a specific microorganism the growth rate follows the Arrhenius equation until the optimum growth rate is reached, after that moment the decay rate affects the growth rate disproportionally causing a decline in the net growth rate. See for instance the figure above, where for the depicted mesophilic microbial community the optimum temperature is around 37°C, at a higher temperature the decay rate increases causing a decline in the net growth rate.

In general the rate limiting step of anaerobic digestion is hydrolysis (Gunnerson and Stuckey 1986; Chen, Cheng et al. 2008). Hydrolytic activity also follows the Arrhenius equation provided exo-enzymes from acidogenic bacteria are not rate limiting. The rate of hydrolysis is therefore a very important determinant for digester design. If for instance the hydrolysis rate is too low, the whole chain of AD is affected, methanogenesis, being the last step, is disproportionally affected. That might result in the wash out of methanogens and a decrease in biogas production due to the insufficient retention time.

Hence, the rate of hydrolysis is of crucial importance which is governed by the hydrolysis constant k_h (day^{-1}). The hydrolysis constant can for each substrate be determined by conducting batch experiments. With the obtained hydrolysis constant the minimum SRT can be calculated and if necessary the k_h can be adjusted for a different temperature using the Arrhenius equation. Details on how to obtain the k_h and to calculate the SRT on basis of the k_h is described in annex 6.

From the kinetics, we can extract three recommendations to overcome a lower gas yield at lower temperatures:

1. At lower temperatures the loading rate needs to be adjusted (downward) to account for the lower microbial activity, consequently the SRT increases.
2. To maintain the biogas output at a lower temperature, the volume of the digester has to increase with the same proportion as the SRT to accommodate for the slow microbial growth rate whilst the total feedstock amount does not change. The result is a larger digester at lower temperatures with a longer SRT but with a similar biogas output compared with a higher temperature with the same total amount of feedstock.
3. When the hydrolysis constant is known, the effect of temperature on reactor design can be studied using the Arrhenius equation. With that information it is possible to calculate the SRT at lower temperatures and to translate that into design implications.

FORECASTING DIGESTER PERFORMANCE AT LOWER TEMPERATURES

Safley and Westerman (1991) combined the van 't Hoff-Arrhenius equation of biological reaction performance with the substrate removal rate as a function of the temperature:

$$\frac{Q_1}{Q_2} = e^{p(T_2 - T_1)}$$

EQUATION 5: LOADING RATE IN RELATION TO THE TEMPERATURE (SAFLEY AND WESTERMAN 1990)

Where Q_1 is the loading rate at the reference temperature T_1 and Q_2 the adjusted loading rate at temperature T_2, p the rate constant (1/°C) which was found to be 0,1 for the temperature range 10-30 °C. This equation is true for long retention time, ≥ 20 days and a low influent concentration; cow manure ≤ 100 kgVS/m^3/day and 62 kgVS/m^3/day for swine manure (Safley and Westerman 1990). Safley and Westerman (1990) showed in their article that the model both fits their comprehensive literature overview on psychrophilic anaerobic digestion (PAD) and their experiments on PAD at various temperatures in the range 14-23°C. The equation of Safley and Westerman (1990) avoids the hassle of determining the hydrolysis constant for a specific substrate at various temperatures and provides a quick and uncomplicated method to calculate the required SRT at any temperature, provided reliable values of another digester are obtained.

With their model a suitable loading rate of a given digester operating at given temperature can be determined based on data of a digester operating at a different temperature with a known loading rate. Plotted in a graph, the ratio f (Q_1/Q_2) with a reference temperature of 25 °C has an exponential shape (Figure 14).

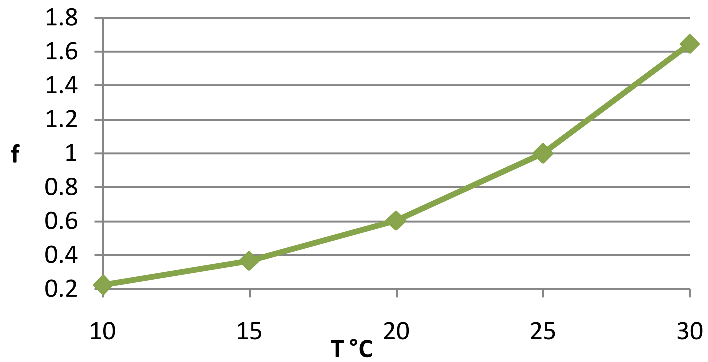


FIGURE 14: THE .LOADING RATE RATIO F (Q_1/Q_2) IN RELATION TO THE TEMPERATURE

Consequently, an increase in temperature allow for an exponential higher loading rate and a decrease in SRT. To modify a digester to a colder temperature regime without impairing the biogas production, the SRT and the digester volume has to be increased, while the loading rate per unit of digester volume has to reduce accordingly. This can be calculated as follows: $SRT_t = SRT_{25°C} * 1/f$, where SRT_T is the retention time at a different temperature regime (T) compared to the reference digester at 25°C with a known loading rate. With the obtained SRT a digester can be designed for a different temperature regime and for a desired overall gas production.

4.2 PHYSICAL CHEMICAL ASPECTS

Digestion at lower temperature affects the thermodynamics of the reaction; in general less Gibbs free energy is available for reaction.

<u>THERMODYNAMICALLY ASPECTS</u>

The Gibbs free energy of reaction is dependent on the temperature. Temperature affects the energy of the reaction in two ways; it impacts the Gibbs free energy of reaction and the standard Gibbs free energy. The next equation shows the Gibbs free energy of reaction.

$$\Delta G = \Delta G° + RTLnQ$$

EQUATION 6: GIBBS FREE ENERGY OF REACTION

Where ΔG is the Gibbs free energy of reaction, $\Delta G°$ the standard Gibbs free energy at STP (standard test conditions), R the gas constant, T the temperature and Q the reaction quotient. If Q is larger than 1, the Gibbs free energy for the reaction becomes more positive and hence the energy yield of the reaction decreases compared to the standard Gibbs free energy.

The standard Gibbs free energy of reaction is the sum of the standard enthalpy of reaction minus the absolute temperature times the entropy (Equation 7)

$$\Delta G° = \Delta H - T\Delta S°$$

EQUATION 7: STANDARD GIBBS FREE ENERGY OF REACTION

Hence, the standard Gibbs free energy of reaction increases with decreasing temperature. A reaction is only thermodynamically feasible when a reaction yields a negative Gibbs free energy; $\Delta G \leq 0$. However, microbes consume some of the energy to maintain themselves, for their growth. Biomass formation has a positive Gibbs free energy and consequently this anabolic reaction is coupled with a catabolic reaction by substrate degradation (von Stockar, Maskow et al. 2006). The Gibbs free energy for anabolism is at least -20 kJ/mol but actual values depend on the specific characteristics of the microbe (Grotenhuis, Hamelers et al. 2008).

Methane production occurs at temperatures near zero (Zeeman, Sutter et al 1988), therefore even at this temperatures microbes can gain sufficient energy, but growth rate and methane recovery is very slow. At lower temperatures the predominant substrate for methanogenesis is acetate (Hattori 2008). The activity of hydrogenotrophic methanogens is very low at psychrophilic temperatures as the Gibbs free energy gain is lower compared to acetoclastic methanogenesis (Kotsyurbenko 2005).

4.3 EXPERIMENTAL RESULTS

PAD (psychrophilic anaerobic digestion) batch experiments are conducted for 174 days to determine the impact of temperature on substrate conversion to biogas. The research paper on these experiments can be found in Annex 6. To minimize heating requirement for digestion, the parameter SRT is assessed by calculating the hydrolysis constant at low temperature digestion. With that knowledge the impact of temperature on digester design to generate sufficient biogas for one household is determined. If the SRT becomes too large, the digester volume will be accordingly large and the digester will be expensive. In that case additional insulation or adding heat might prove to be more feasible to increase the temperature and to decrease the required SRT.

In the research paper the first order hydrolysis constant at various temperatures is obtained. With the obtained hydrolysis constant the retention time for a CSTR can be calculated. This is possible by:

$$\frac{P_o - P}{P} = k_h . SRT \qquad (8)$$

Where P_0 is the influent concentration (biodegradable COD/kg manure) and P the effluent concentration at t=x. The SRT is equal to the HRT in a completely mixed reactor.

The obtained k_h for respectively 7,5 and 15°C are 0,0269 and 0,071 day^{-1}. The value at 15°C is obtained by adjusting the k_h at 7,5°C using the Arrhenius relation, see annex 6. These values are used to plot the recovered methane as COD against time using formula 8, see the next figure.

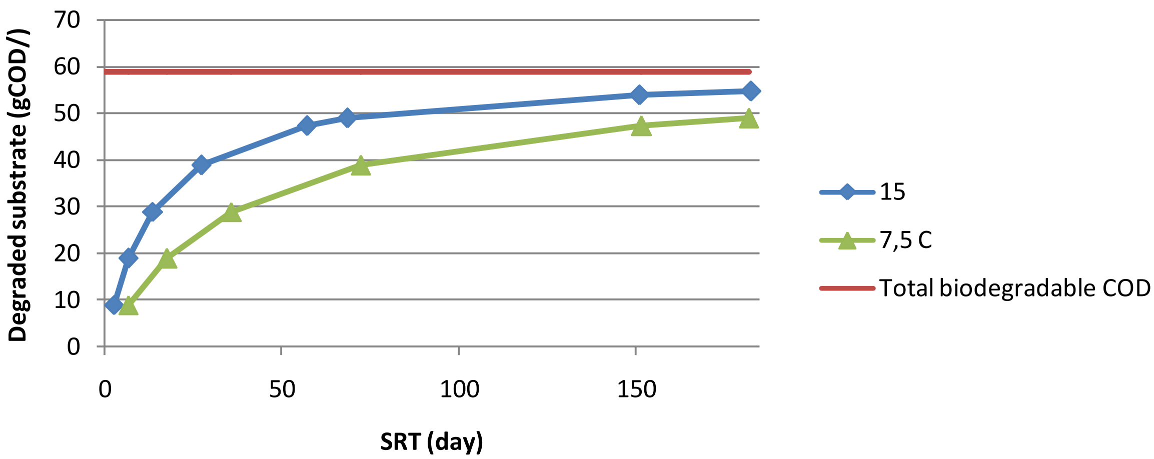


FIGURE 15: RECOVERED COD AS FUNCTION OF TIME FOR TWO TEMPERATURES

At 7,5°C less methane is recovered for the same retention time compared to 15°C. The figure clearly shows that either the SRT has to increase or the temperature to increase the biogas production. Furthermore, an optimal SRT has to be determined for which methanogens are not washed out or that their growth is inhibited by high VFA concentrations or other inhibition causing substances.

In retrospect, in chapter 5 a digester is designed. Originally the digester would be designed based on the results of the manure batch experiment. However, the obtained results were not available at the time of writing. Therefore, the obtained values from the experiment are compared with the used values in chapter 5. The digester in chapter 5 is a Janata digester operating at 15 °C with a retention time of 55 days, see the next chapter.

The methane production at time t=x can be obtained using formula 8 of the previous page. At an SRT of 55 days at 15°C 21,62 liter methane per kg manure is produced. If a methane concentration of 65% is assumed, the total amount of biogas production is 33,26 liter/kg influent. These values are very close to the values assumed in chapter 5 for the digester; these are 35 liter/kg. GTZ reports that for digesters in the field around 25-40 liter biogas per kg manure is produced.

Note that the influent material of the batch experiments was manure diluted 1:1 with water on mass basis. The digester in chapter 5 however operates with a TS content of 10,6% while the influent of the batch experiments is 9,0%, therefore the methane and biogas production of the experiment will be around 18% higher at a TS of 10,6% resulting from the higher concentration of biodegradable COD. Nevertheless, the methane and biogas production are comparable per kg TS.

It is interesting to compare if the difference in activity as obtained from the PAD experiments follows the relation found by Safley and Westerman (1991). A realistic value of 55 days for the SRT is taken for digestion at 15°C, a common value of digesters operating in the colder areas in India (see chapter 5). The SRT is adjusted using the formula of Safley and Westerman (1991) and subsequently compared to the values found in the experiment. The biogas production at an SRT of 55 days is used from the experiment to determine the required SRT at 7,5°C for the same biogas production.

TABLE 12: SRT AT DIFFERENT TEMPERATURES TO YIELD THE SAME AMOUNT OF GAS PER KG OF SUBSTRATE

Temperature	**SRT to produce 21,62 liter CH_4/kg**	
	Batch experiment	Safley and Westerman (1991)
7,5°C	173	116
15°C	55	55

Results from the PAD experiments show that at 7,5 degrees the same gas production is obtained after 173 days compared to 55 days at 15°C. The values of Safley and Westerman are obtained by using the quotient F of Safley and Westerman, which depicts the factor for which the loading rate expressed in kg/day has to decrease at a lower temperature, see equation 5. If the loading rate is decreases at the same influent concentration, the SRT (and reactor volume) will increase with the same factor as the loading rate decreases. The quotient is 2,1 in this case and hence the SRT is 116 days at 7,5°C. The experimental values however showed a quotient of 3,1, a higher temperature dependency.

It would be interesting to repeat the manure batch experiment and to calculate the hydrolysis constant at 15°C and compare if it fits the model of Safley and Westerman. Based on the obtained data from this experiment, the relationship between adjusting the SRT at different temperature is stronger than predicted by the equation of Safley and Westerman. The rate constant p in their equation is 0,1 but using the values of the PAD experiment a value of 0,15 is obtained, reflecting a higher microbial activity response to temperature changes. This could reflect the fact that the equation of Safley and Westerman is only valid for the temperature range of 10°C-30°C.

It is however, both from the experiment and the equation of Safley and Westerman (1991), safe to conclude that the SRT is exponentially related to the temperature and has to be increased at a decrease in temperature.

4.4 SOLUTIONS TO OVERCOME THE COLD – LITERATURE OVERVIEW

In most developing countries climate conditions are ideal for AD, the high ambient temperature, in the order of 20-25°C, allow for a relative small digester size and for a balanced gas production throughout the year. However, large areas in these countries are highlands or have a continental climate with warm summers but with cold winters, the lower temperatures of these areas impede biogas production (Nazir 1991). In North India for instance, the average ambient air temperatures falls beneath 15°C during the winter. Most researchers assert that beneath 15°C the biogas production is insignificant of conventional digesters (Sodha, Ram et al. 1987; Gupta, Rai et al. 1988; GTZ 1999). When using the equation of Westerman and Safley (1991), a digester operating at 15 °C requires a large volume, the digester volume relative to 25 °C needs to be 2,7 times larger and at 10 °C even 5,7 times to obtain the same biogas production. Taking financial costs into consideration, Anand and Singh (1993) even claim that the temperature of digestion should be 20°C.

As aforementioned in chapter 4.1, a digester can be modified to operate at any chosen temperature (0-97°C), provided the SRT is sufficiently long. The feasibility to operate a digester at a certain temperature regime is a matter of economic considerations underlying to opt for a long retention time, to add heat or to retain the heat better by applying additional insulation.

To address the issue of the decreased biogas production in winter time, scientist have suggested the following measures to increase the temperature of digestion for simple underground built domestic digesters (Hills and Stephens 1980; Anand and Singh 1993)

1. **The use of acclimatized inoculum**

2. **Digester design**
    a. Digester design aspects
    b. Increasing the digester volume to allow for a longer SRT
    c. Maintenance
    d. Insulation
    e. Solid state digestion

3. **Digester heating**
    a. Hot charging; adding (solar) heated water to the substrate
    b. Covering the digester with a greenhouse
    c. Solar assistance
    d. Heap composting

4. **Active heating**
    a. Utilizing heat from engine exhaust
    b. Electrical heating

1. THE USE OF ACCLIMATIZED INOCULUM

By acclimatizing inoculum to psychrophilic temperatures researchers hope to increase the biogas production. In one study digestate of a mesophilic digester was allowed to acclimatize for 1,5 year at 6 °C and thereafter used as inoculum (35%) for a manure batch experiment at 6 °C and compared to a sample under similar conditions but without an acclimatized inoculum (Nozhevnikova, Kotsyurbenko et al. 1999). Their results show a much higher methanogenic activity compared to the non-acclimatized inoculum condition (Figure 16).

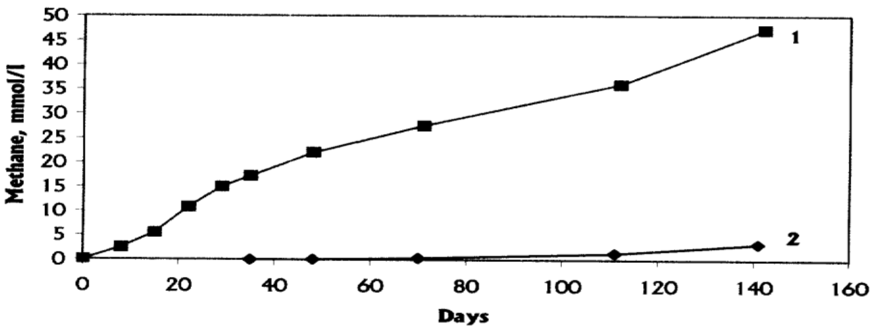


FIGURE 16: METHANOGENIC ACTIVITY OF (1) WITH ACCLIMATIZED INOCULUM AND (2) WITHOU ACLIMATIMZED INOCULUM (NOZHEVNIKOVA, KOTSYURBENKO ET AL. 1999)

A pitfall of adapted inoculum could be the increased sensitivity to temperature changes as a result of selection (Nozhevnikova, Kotsyurbenko et al. 1999). If digesters operate at 12 °C in the winter but at 30°C in the summer the adapted inoculum might not survive or show a decreased performance. Further study is necessary to examine to what extent it could offset a low digester performance in the colder months. Note that this strategy focuses on the acclimatization of methanogens, while hydrolysis is rate limiting.

In summary, adapting inoculum to the temperature of digestion could be a partial answer to increase biogas production. However, if digesters work at low temperatures for a prolonged period, the microbes should adapt due to natural selection to the occurring conditions and hence show a faster growth rate. Therefore, using adapted inoculum could especially benefit newly built digesters provided the adapted inoculum can handle seasonal temperature fluctuations.

2. DIGESTER MODIFICATIONS TO ADAPT TO COLDER TEMPERATURES

- Digester design aspects

Most domestic biogas plants are built underground and are thus not directly exposed to low ambient temperatures. The temperature of the soil is higher than the ambient temperature and reaches the average annual temperature at a depth of 2-4 meter. More about temperature and depth, see chapter 5.

Some digester designs are less resistant to low temperatures, for instance the floating dome digester has a mild steel drum which conducts heat much better than the masonry or concrete structure of a fixed dome plant. However, the floating dome digester has a higher depth to diameter ration and hence benefits more from the higher temperatures with depth. However, during the last decade of the 20th century only fixed dome digesters and since 1993 also rubber balloon (Taiwanese) plants are subsidized by the government of India in the colder hilly regions

(Kanwar, Gupta et al. 1994) and not the KVIC digester, probably because that model requires too much excavation of the rocky soil. The Deenbandhu digester is the successor of the Janata digester and designed to cut down investment costs by minimizing surface area without sacrificing the functional efficiency (Singh and Sooch 2004). Hence, as a result of its minimized surface area, the surface volume ratio is reduced resulting in less heat loss to the surroundings. Continued efforts were made to use best of these both models for optimal performance in the hilly region, which led to the introduction of the Himshakti plant (Khoiyangbam, Kumar et al. 2004). There is little literature available on the performance of the Himshakti plant, only that the diameter to depth ratio is increased to reduce soil excavations, however, a reduced digester depth might increase the exposure to low ambient temperatures. Probably other considerations are behind the Himshakti plant than to operate in a cold climate, the less depth to diameter ratio might reflect efforts to avoid cumbersome excavation of the rocky mountainous soils.

A one year comparison between a KVIC floating dome digester and a Janata digester in the hilly regions showed that the KVIC performed slightly better (Kalia and Kanwar 1989), despite the steel drum which has a high heat conductivity. However, they did find that the gas temperature in the gasholder of the KVIC digester fluctuated much more, which is probably the result of the high thermal transivity of the steel drum. Furthermore, the temperature of the KVIC remained around 15°C, 1-2 °C warmer than the Janata, while the average ambient temperature was around 10°C. This is caused by the high depth to diameter ratio of the KVIC, causing the model to benefit more from the higher temperatures as occurring deeper in the soil (Kalia and Kanwar 1989). In chapter 5, it will be shown that the gas in the digester acts as an insulator and since only gas is in contact with the steel drum of the KVIC digester the heat losses are limited and this is in additional explanation of the relative good performance of the KVIC compared to the Janata.

A Taiwanese bag digester, a rubber balloon type, was compared to a Deenbandhu digester the hilly regions of India during a 1 year study period. The Deenbandhu digester produced on average around 43% more gas and the gas reduction in the winter time was only 16% compared to 77% of the rubber balloon (Kanwar and Guleri 1994). Average ambient temperatures varied from around 10 to 25 °C. The temperature of the rubber balloon plant was around 2-3°C higher in the summer and 2-3°C lower during the winter compared to the Deenbandhu, clearly the plastic plant reacts faster to temperature fluctuations. In tropical regions without cold periods the rubber balloon plant is feasible but not in the hilly regions of India resulting from the higher heat losses (Kanwar and Guleri 1994). A plastic bag digester can be modified to retain more heat either by applying insulation or covering it with a greenhouse, more on this in the section about covering the digester with a greenhouse.

- **Increasing the digester volume to allow for a longer SRT**

The simplest modification is the enlargement of the reactor to accommodate for a longer SRT. For instance in India typical retention times of the KVIC floating dome digesters are in the tropical south 30 days and in the north 50-55 days (Tiwari and Chandra 1986). Using Equation 5 of Safley and Westerman (1991) a retention time increase from 30 to 50 days translates to a 5°C decrease in temperature which the modified digester can handle with a similar gas production and feeding. The Deenbandhu digester design in India is available for 40 and 55 HRT for various capacities using cow dung (Raheman 2002).

A 1 m^3 biogas production/day (volume is 2,65 m^3) rated modified Deenbandhu digester performance was evaluated under hilly conditions in north India; the modification of the original AFPRO design specification consisted of a slightly elevated HRT, 55 days instead of 50 days, the gasholder was reduced from 64% to 43% and the base diameter to the rise of the arch was 5,9:1 instead of 7:1 (Kanwar, Gupta et al. 1994). The average ambient temperature varied from 11,6 to 23,4 °C and the average digester temperature varied from 15,4 to 24,8 °C during the 1 year study period. A gas yield of 0,705 m^3/day during the coldest months was measured compared to 0.870 m^3 /day during the hottest months (Kanwar, Gupta et al. 1994). Since the digester remained above 15°C and only 20% less gas produced in the coldest months, the authors concluded that this is a very useful design for small or marginal farmers in the hilly regions.

- **Maintenance**

Heavy solids tend to settle in domestic digesters and hence the SRT and HRT slowly decline over time. Hence, the retention time needs to be maintained by regular cleaning as the next longitudinal study will illustrate.

Most studied are conducted within a relative short time span, however, digesters are designed to operate for a much longer period. Therefore, a longitudinal study of 10 year was set up to assess the impact on temperature on the biogas production of a Janata fixed dome in the hilly regions of India (Kalia and Kanwar 1998). They found a decrease in gas production in the winter when ambient and digester temperatures averaged respectively 11-12 °C and 13-14 °C compared to 25-26 °C and 22-23 °C in the summer. Hence, the digester canceled out the extreme temperature fluctuations. More interestingly though, they found a steadily decreasing gas production over the years, in five years time a 34% decrease during the summer and 13% during the winter. This was the result of the settling of solids in the digesters, which decreased the *effective* digester volume and hence the SRT and HRT. After cleaning the digester the gas production returned to the highest production as obtained during the first years of the study (Kalia and Kanwar 1998). Hence, digesters should be cleaned with regular interval to maintain the retention time and to keep the digester at maximum. Note that this strategy is generic and applies to all situations and temperatures.

- **Insulation**

Heating requirements or heat losses can be minimized by using insulation. Insulation is very straightforward; it comes down to the selection of construction material with a low heat transfer coefficient which is both affordable and available to retain more heat. For instance, the wall, the inlet and outlet and the floor of high altitude biogas reactor (HABR) in Nepal has a double stone wall with 4" thermal insulation resulting in a 55% heat loss reduction (SNV and BSP 2003).

- **Solid state digestion**

Solid state digestion refers to limiting the dilution of the substrate. The less the substrate is diluted the smaller volume is required for the same retention time. Some experiments on this are conducted in India. Singh and Anand (1994) showed that the Deenbandhu digester, with some minor modifications such as changing the inlet to avoid clogging, can handle a much higher TS content of the substrate. However, the TS should be lower than 18%, otherwise water has to be added. A rule of the thumb is to make a round ball of manure of 12,5 cm, and if the ball does not retain its spherical shape no water has to be added (Shyam 2001). Table 2 in chapter 2.2 list the

TS content of various substrates, where cattle dung has a TS of 16-20%, buffalo 14%, pig dung and poultry 25% and HNS 15-25%. Consequently, depending on the substrate some dilution might be necessary, to avoid clogging in the inlet but also to make the substrate better available for the microbes. This strategy is optimized by mixing to allow good contact between the microbes and the substrate.

3. ADDING HEAT TO THE DIGESTER

- Hot charging

Hot charging is not very practical at a long retention time of, say, 60 days. Simply because the influent needs to be 60 degrees higher to counteract 1 degree heat loss of the digester per day. If the influent is mixed with 1:1 with water, the temperature of the water needs to be almost 100 °C to heat up the influent to 60 °C (assuming the substrate is 20°C). Such a high temperature would affect the microbial consortia which are acclimatized to the psychrophilic temperatures in the digester negatively. However, if the digester is very well insulated, hot charging might be feasible to overcome a smaller heat loss per day (Anand and Singh 1993).

- Covering the digester with a greenhouse (solar canopy)

An 85 m^3 KVIC community biogas plant and an 8 m^3 domestic plant were covered with a greenhouse made of PVC and supported by a bamboo frame to retain and to capture solar heat (Figure 17). The experimental site was not located in a cold regions but near New Delhi during the winter. They obtained however, significant results, a temperature increase from 22°C to 32 °C (Sodha, Ram et al. 1987). The villagers noted a 100% increase of gas production during the winter when ambient temperatures were around 18 °C average.

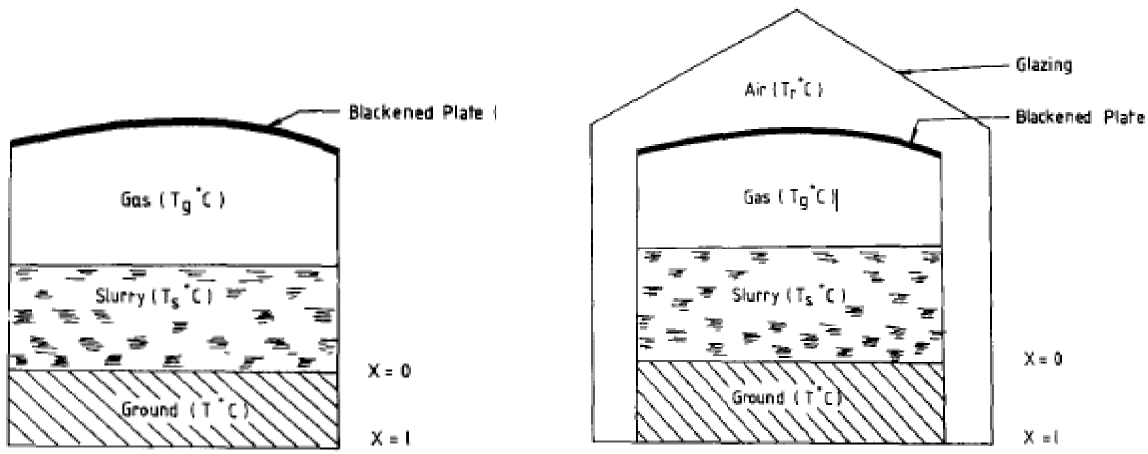


FIGURE 17: A CONVENTIONAL KVIC DIGESTER AND WITH GREENHOUSE (SODHA, RAM ET AL. 1987)

Heat losses during the night can be reduced by adding a movable insulation on top of the greenhouse at night (Tiwari 1986).

Varieties of the Taiwanese bag digester are employed nowadays in the cold hilly regions of countries such as India and Bolivia (Herrero 2008; Vinoth Kumar and Kasturi Bai 2008). The key to the success of these digesters at low temperatures lies in the combination of both a low cost system and the combination of a solar canopy to retain and capture heat. A field study in India showed that such a combination outperforms a conventional Deenbandhu digester with similar capacity, with 11,5% more gas production and an average slurry temperature of 26,3 against 22,4 °C of the Deenbandhu at an average ambient temperature of 17°C (Vinoth Kumar and Kasturi Bai 2008). Despite the better performance of the bag digester during the winter (10-12°C), gas production was insufficient for cooking and only used for lighting with the appreciated benefit that the heat of the light increased the room temperature. A bag digester allowed for 28 minutes lighting compared to 18 minutes of the Deenbandhu. A follow-up study should examine these findings in more details; it is difficult to generalize the findings of Vinoth et al (2008) since only two digesters were involved.

In Bolivia tubular biogas plants based on the Taiwanese bag digester, are being popularized in the Altiplano, a plateau at an altitude of 4000 meter. The combination of a solar canopy, hot charging and the thin plastic digester increases the digester temperature to 10 °C compared to 0°C ambient (Herrero 2008).

FIGURE 18: TUBULAR PLASTIC BIOGDIGESTER COVERRED WITH A PLASTIC SOLAR CANOPY IN BOLVIA (HERRERO 2008)

These digesters have a HRT of 60 days which seems relatively low considering the fact that Indian digesters typically operate with a HRT of 55 days at 15°C ambient. According to Herrero these digester produce around 0,75 m^3 gas at a retention time of 60 days. However, he aims at a HRT of 75 days, with a loading of 20 kg of manure (Herrero 2008) to produce around 0,75 m^3/day (Herrero 2008). Note that the density of biogas is lower at these high altitudes and hence the volumetric biogas demand per household is higher compared to lower altitudes. Furthermore, Herrero added that the temperature during the night is maintained by sand walls with high inertia; a high thermal mass, which avoids an excessive cooling down of the digester during the night.

The integrated approach of Herrero (2008), hot charging, solar greenhouse and sand walls with high inertia is very interesting. However, the actual performances of these digesters need to be studied further. It is however promising that such a low cost plastic digester seems to operate well under these extreme conditions of both altitude and temperature.

- **Solar Assistance**

Utilizing solar heat to increase the digester temperature is sometimes denoted as solar assistance. It is possible to distinguish between direct assistance and indirect assistance. In the latter case, solar heat is captured and transported via a medium to the digester. Direct assistance is for instance the heating of the digester or the soil around the digester by the sun. With indirect assistance a medium is required to transport the heat to the desired place.

Direct utilization of solar heat

The KVIC digester is easily modified to utilize solar heat. Tiwari and Chandra (1985) suggested integrating a shallow solar pond (SSP) to a traditional KVIC floating dome digester. By painting the floating mild steel drum, the gasholder, which sticks out of the ground, black, and by constructing on top of the holder a SSP and by covering the whole with a plastic sheet to prevent heat losses, solar heat is effectively captured. According to Sam et al (1985) (cited in Tiwari and Chandra 1986), these measures increase the slurry temperature with 7°C. The system can be improved by adding a movable insulation during the night over the system to prevent nighttime heat loss. That resulted in a temperature fluctuation reduction of 50% and the SSP averaged 30-35°C instead of 21°C without the movable insulation (Tiwari 1986; Tiwari and Chandra 1986).

In a similar experiment the gasholder of KVIC plant was covered with a transparent cover (size of the drum) and at night covered with movable insulation. That resulted in a 4 °C increase of slurry temperature and reduced temperature fluctuations, a low costs but less efficient alternative compared to the greenhouse covering (Tiwari, Rawat et al. 1988).

A simple but less effective solution is to glaze the floating dome of KVIC plant to increase the absorption of the solar heat flux in order to increase the digester temperature (Usmani, Tiwari et al. 1996).

Another simple and cost-effective option is to coat the ground around the digester with charcoal. Around three 2,5 m^3 KVIC digester a 1 meter strip of ground was coated with charcoal mixed with digester effluent and compared to three similar digesters without coating (Anand and Singh 1993). The simple act of coating yielded a biogas increase of 10-15%, an increase of 1-1,5°C digester temperature and a 3°C increase of soil temperature at 1-2 meter depth is realized. However, the black coating is quickly washed away by rains but otherwise lasts for 1,5 months. Considering the limited lifespan of the solution, it has limited practical feasibility, but it shows the potency of using the sun as energy source for digester heating.

Nowadays the KVIC floating dome digester has lost some of its benevolence as a result of the expensive mild steel drum (GTZ 1999). Other designs, such as the Chinese Dome and the Deenbandhu operate well at lower investments costs (CEM 2005).

With all the above mentioned options, a maximum temperature increase of the slurry is around 10-15°C (Tiwari, Chandra et al. 1989), so called low temperature heating. Hence, when ambient temperatures are really low, near zero degrees, alternative approaches are necessary. One of these approaches is solar assistances using a heat exchanger to transport the heat where needed, directly to the digester.

Indirectly utilization of solar heat

Indirect solar heat in this thesis refers to the use of a medium to transport the heat to the desired location. Water, or another fluid, is heated by a solar collector to a desired temperature and the fluid subsequently flows to the reactor where it transmits its heat via a heat exchanger to the digester content. The next figure shows a proposed solar assisted Janata digester in India.

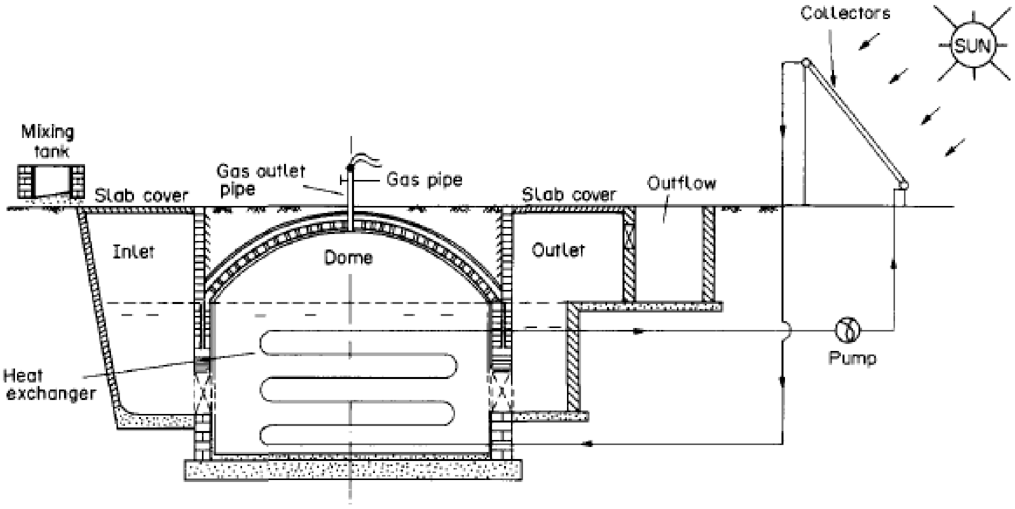


FIGURE 19: JANATA FIXED DOME PLANT WITH SOLAR ASSISTANCE (GUPTA, RAI ET AL. 1988)

The aforementioned Janata biogas plant was analyzed for its performance mathematically using the insolation (solar radiation on a given surface over a given time) and temperature of a common winter day near Dehli (Gupta, Rai et al. 1988). Compared to the average ambient temperature of about 16°C, the slurry temperature increased with 1 flat plate collector (1,5m^2) to 19°C at night to 26°C during the day at peak insolation. Furthermore, they showed that the effect of insulation is even larger than increasing the number of collectors. For instance, increasing the insulation from an overall heat transfer coefficient[6] (k_b) of 10,57 to 2,86 W/m^2.K increases the temperature of digestion during the night and day respectively from 16 to 20 °C to 21 to 27 °C (Figure 20), while increasing the number of collectors from 1 to 5 at a overall k_b of 10,57 W/m^2.K, a mere 2 °C during the night and 4 °C increase was obtained during peak insolation. Hence, efforts aimed at digester insulation in combination with a limited amount of collectors will increase the temperature of digestion considerably in India.

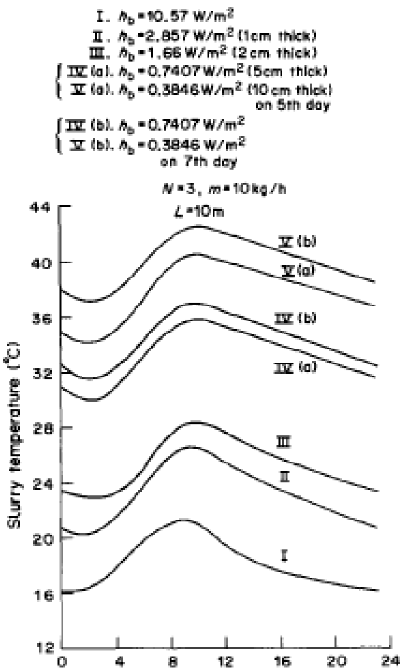


FIGURE 20: HOURLY VARIATION OF SURRY TEMPERATURE WITH DEGREE OF INSULATION (GUPTA, RAI ET AL. 1988)[6]

[6] in this thesis the heat transfer coefficient is denoted a k in line with Blok (2007), in the figure 20 it is denoted as h_b

A similar study was conducted for the KVIC floating dome digester (Tiwari, Chandra et al. 1989). An inherent disadvantage of this design is the very high heat transmission coefficient of the steel drum, 17 W/m^2.K in their study, compared to k_w of the walls of 0,78 W/m^2.K (Tiwari, Chandra et al. 1989). Their study showed, not surprisingly, that the decreasing the heat capacity of the slurry (decreasing the volume) and that the amount of solar collectors resulted in an increased temperature of digestion. The effect was smaller than the aforementioned study of Gupta and Rai et al (1988), probably due to the higher heat losses. As stated earlier, the Indian government does not subsidize KVIC plants in the hilly regions of India as a result of the low performance and the high depth to with ratio which require extensive excavation of the rocky mountainous soil.

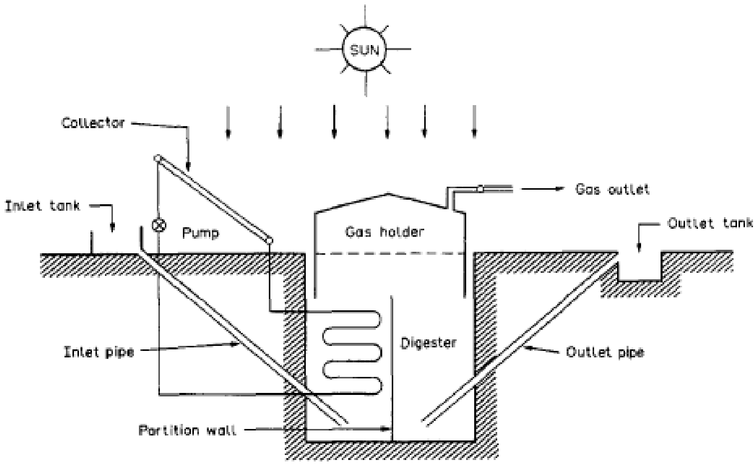


FIGURE 21: KVIC DIGESTER WITH ATTACHED FLAT PLANE SOLAR COLLECTOR (TIWARI, CHANDRA ET AL. 1989)

The experiences of indirect solar heating or integrating solar collectors with digester design are limited worldwide. The above mentioned examples were never actually implemented. Likely there are obstacles blocking the utilization of solar assistance using flat plate collectors in a financial sense, in addition, it increases the complexity of the system and consequently it is less failure proof (van Nes 2008).

Outside India, a study in Jordan showed that solar assistance is viable for digester heating, but ambient conditions are in Jordan very different, they do not experience cold winters (Alkhamis, El-khazali et al. 2000). Likewise, experiments are conducted in Egypt to utilize solar heat to heat up a small scale digester of 10m^3 to thermophilic temperatures (50°C) (El-Mashad, van Loon et al. 2004). They used some interesting approaches, such as using the heat of the effluent to heat the influent via a heat recovery system and integrating the solar collector as part of the digester roof (Figure 22), in addition their reactors was extremely well insulated, an average k_v of 0,33 W/m^2.°C.

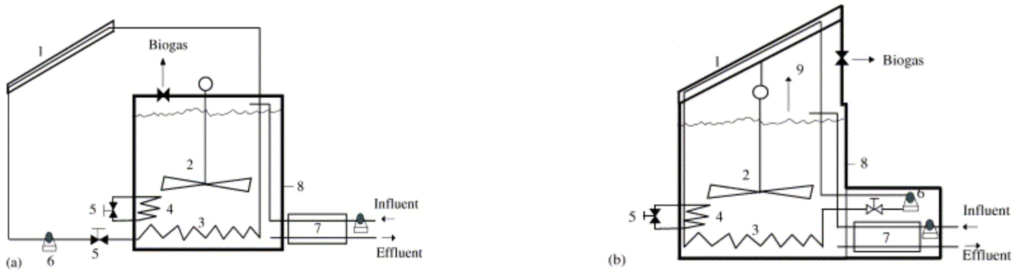


FIGURE 22: DIGESTER WITH SEPARATE SOLAR COLLECTER (A) INTEGRATED SYSTEM (B)

The next figure shows the differences between the integrated system and a similar system with a separate solar collector. Of the two designs, the integrated system performs during the colder months and is therefore recommended by El-Mashad and van Loon et al (2004), moreover, the temperatures fluctuations are both smaller and have a lower temperature fluctuation amplitude. Interesting about their study is that they showed that with ample insulation, the temperature fluctuations are less than 1 °C over a day and less than 5 °C annual (El-Mashad, van Loon et al. 2004). Evidently, this applies to Egyptian conditions, note however that the ambient temperature varied considerably; from 18°C minimum to 46°C maximum.

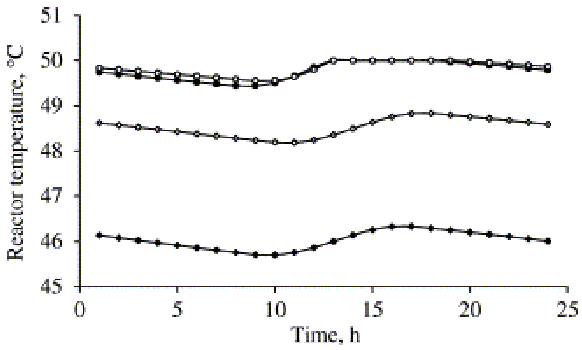


FIGURE 23: DAILY PROFILE OF THE REACTOR TEMPERATURE:
•, loose components system in June; ♦, loose components system in December; ○, integrated system in June; ◊, integrated system in December (El-Mashad, van Loon et al. 2004)

Another, possibly cheaper option is to use solar heat by storing the heat in a solar pond and then transporting it to the digester (Subramanyam 1989). If convection is prevent a temperature profile in the pond is created and consequently heat is stored (Sukhatme 1997). Convection can be prevented by adding salt to the ponds, a so called salt-gradient solar pond. This option is not studied in detail, but it could be a low-cost option in some cases.

- Heap composing

Aerobic composting of biowaste results in a considerable heat production. With this concept BSP (Biogas Support Programme) Nepal is extending biogas dissemination in Nepal to the mountainous areas. According to Prakash Lamichhane, senior officer of BSP Nepal, it is possible to use this concept in areas up to 3850 meter with an ambient temperature of -3/-4 °C while the temperature of the digester remains at 8-11°C. At these temperatures the digester continued to produce sufficient biogas. A drawback is the requirement of biodegradable material for composting. A publication about heap composting is expected during the end of 2008 or the beginning of 2009.

4. ACTIVE HEATING

Active heating is possible by utilizing engine exhaust (Gunnerson and Stuckey 1986) or electrical current to heat the digester. These options are generally not practiced and feasible at household scale in developing countries. Heat from engines is only feasible if engines are run on a daily basis and in the case of electricity only if it is available, reliable and affordable.

CONCLUSION

It became clear that common approaches such as a greenhouse for heating, hot charging and insulation a temperature increase of maximum 10-15°C is generally possible. When the ambient temperature is beneath 5°C and especially when the temperature is lower than 0°C other approaches are necessary such as active heating or solar assistance using solar collectors. The next chapter will study how this can be done by using solar collectors.

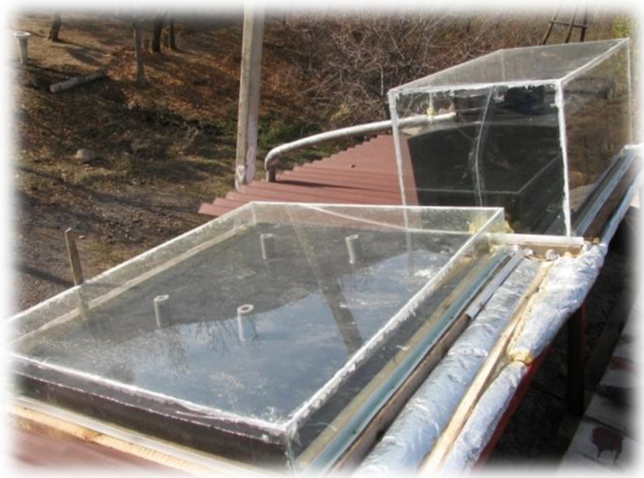
Chapter 5

SOLAR ENERGY FOR DIGESTER HEATING

In the previous chapter it became clear that for countries with cold periods below 5°C most simple solutions proved to be insufficient. Argued is that for those low temperatures active or passive heating is necessary. This chapter will focus on utilizing solar heat for heating using solar collectors.

An extensive analysis is provided for a digester operating in four different countries, Georgia, Romania, Kyrgyzstan and Bolivia. The goal is to assess the heating requirements using solar collectors of a digester operating at a minimum temperature of 15°C during the worst period of the year, in terms of insolation and temperature.

A sensitivity analysis is used to study the influence of insulation and the thermal diffusivity of the soil on digester performance.



PICTURE 10: EXAMPLE OF A LOCALLY CONSTRUCTED SOLAR COLLECTOR IN GEORGIA FOR WATER HEATING OF A SANITATION BLOCK OF A SCHOOL (AUHTOR'S PICTURE)

5.1 INTRODUCTION TO SOLAR ENERGY

Solar energy is virtually an inexhaustible source of energy and the tiny share of its output which reaches the earth is still thousands of times greater than our energy consumption (Sukhatme 1997). According to Sukhatme (1997) solar energy has two mayor advantages:

1. It is an environmentally benign source of fuel
2. Free and available in adequate quantities in most regions of the world

Hence, solar energy is an interesting energy source for digester heating. However, the source has two main disadvantages; solar energy is a dilute form of energy, the energy outside the atmosphere accounts to 1353 kW/m^2 (the solar constant) but at ground level even in the hottest regions only around 1 kW/m^2 remains to a maximum of 7 kWh/m^2.day (Sukhatme 1997; Van Helden 2007). Another disadvantage is the availability of solar energy, which varies greatly with time, in the sense that it is subject to the day-night cycle, weather patterns and seasonal changes due to the ellipsoidal orbit of the earth around the sun (Van Helden 2007).

Incoming solar radiation

Of the incoming radiation a part is reflected, absorbed and diffracted depending on the wavelength (Van Helden 2007), see the picture on the right. Furthermore at latitudes further away from the equator the radiation has to pass through more air mass depending on the season. For instance in the Netherlands, the radiation passes through 1,5 air masses compared to the situation when the sun is at the zenith and consequently more radiation is absorbed and reflected and as a result less radiation reaches the surface. A thicker air mass and the presence of clouds lead to a stronger diffraction of the radiation and consequently the ratio diffuse/direct radiation increases. In the Netherlands diffusion amounts to 50-60% of the incoming radiation; this is much lower in arid and desert like climates (Van Helden 2007).

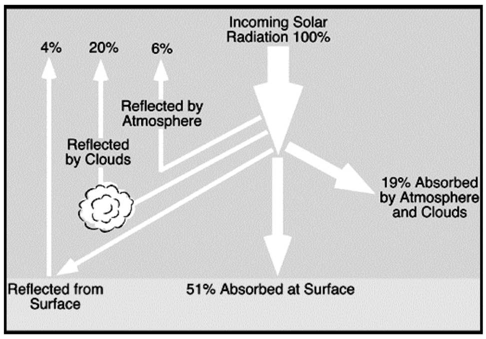


FIGURE 24: INCOMING RADIATION AND DIFFRACTION (MONSOON 2003)

Solar collection devices – flat-plate collector

A solar collection is a device which absorbs solar heat by exposing a dark surface to the sun (Sukhatme 1997). The dark surface is labeled an absorber, the primary side of the collector. A solar collector acts as a heat exchanger; heat from the absorber is transferred to the secondary side and then to a medium (liquid), for instance water (Van Helden 2007). When ambient temperatures fall below zero, other fluids should be used such as ethylene glycol to avoid freezing (Sukhatme 1997). When the incoming radiation is not concentrated the device which absorbs solar heat is labeled a flat-plate collector (Sukhatme 1997).

A flat-plate collector is simple in design, requires little maintenance and has no moving parts and therefore one of the most used and important type of solar collector (Sukhatme 1997). Additionally, a flat-plate collector can be constructed using local materials and skills, see the next box.

Box 2: Example of a simple collector compared to a flat-plate collector

The knowledge centre for small-scale applications of sustainable energy for developing countries of the University of Twente developed a zig-zag solar collector (WOT and BACIBO 2004). The collector can be constructed locally using local skills and materials. This type of collector differs from ordinary flat plate collector; the absorbed is constructed of one flow tube which is zigzagged over the absorber plate instead of multiple straight pipes (Figure 25). The zig-zag collector with attached storage tank and piping has an estimated cost of $450 (WOT and BACIBO 2004). For digester heating, only the collector is necessary (the digester could be considered the storage tank of solar heat) and thus the investment costs will be lower. A drawback is that the zigzag collector has a slightly reduced efficiency, however, the lower expenditure likely off-sets this disadvantage making the collector more cost-effective per kW solar heat absorbed (Monsoon 2003). Additionally, it generates employment opportunities at local level.

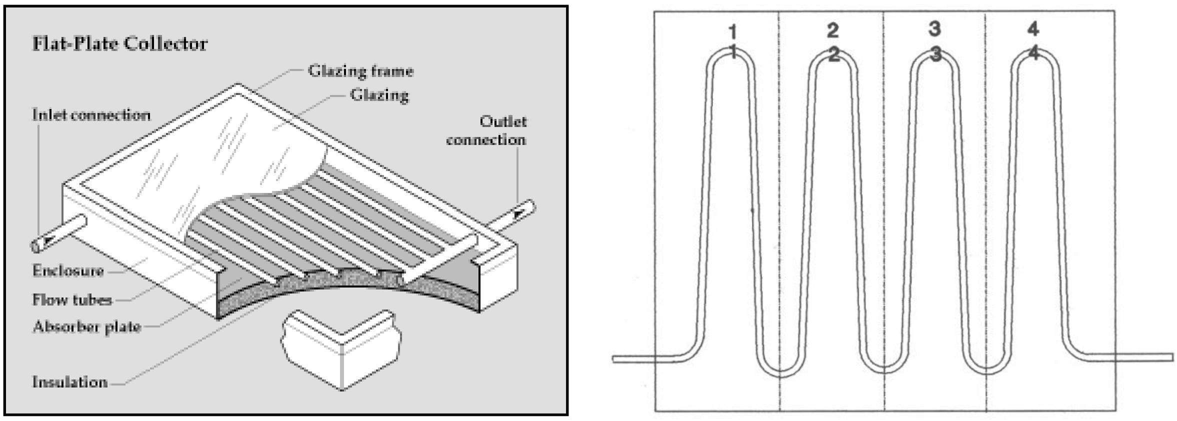


FIGURE 25: ORDINARY (ARUSHA TYPE) FLATE PLATE COLLECTER (LEFT) AND THE ABSORBER OF A ZIGZAG COLLECTOR (RIGHT) (WOT AND BACIBO 2004)

A manual is available on the website of WOT including the design of necessary tools to construct a zigzag collector at location[7]

For the reasons, simple technology, popularity and the relatively low price, solar assistance to heat up a digester using flat-plate collectors is considered. Figure 19 of the previous chapter shows how a flat-plate collector could be attached to a digester. The main component of a solar collector (as illustrated in the figure above) and its function are depicted in the next table (copied and adapted from Van Helden 2007).

TABLE 13: PROPORTIES OF A FLATE PLATE SOLAR COLLECTOR AND ITS FUNCTION

Component	Function
Transparent cover	Reduce convective heat losses Pass through of solar irradiation Reflect infrared emission of the absorber to the absorber Protection of the absorber
Absorber	Conversion of solar heat into sensible heat Transfer of heat to the absorber fluid
Insulation	Reduction of heat losses to the ambient
Enclosure	Provides rigidity

[7] see www.wot.utwente.nl/publications/zigzag.pdf

Efficiency and parameters of a flat plate collector

The instantaneous efficiency of a solar collector is defined as the ratio energy absorbed of the incoming radiation (Van Helden 2007). The efficiency is influenced by the transmission of the glass plate (τ), the part absorbed by the absorber (α); the product of τ and α is termed the transivity-absorptivity product. The solar flux absorbed (S, kWh/m^2) is therefore (Sukhatme 1997),

$$S = I_b r_b (\alpha\tau)_b + \{I_d r_d + (I_b + I_d) r_r\}(\alpha\tau)_d \quad (9)$$

Where, I_b and I_d are respectively the beam radiation and diffuse radiation (kWh/m^2), r the ratio of radiation falling on a tilted surface compared to a horizontal surface, the suffixes, b and d, respectively for beam radiation and diffuse radiation and r_r the reflected radiation by the glass plate in respect to a certain tilt factor.

The system efficiency can be determined as the ratio heat absorbed by the slurry in the digester and the incoming radiation. In section 5.3 that ratio is calculated. The next section will first focus on the setting of employing solar heat for digester heating.

5.2 METHODOLOGY AND APPROACH TO SOLAR HEAT UTILIZATION

The calculations and approach to utilize solar heating differs from the aforementioned research in India (see chapter 4.4). In this study the soil temperature is not omitted and regarded as the average annual temperature. Furthermore this study distinguished itself by an extensive modeling of the heat transfer of each digester part in relation to the ambient soil temperature at various depths. Moreover it will be shown that temperature fluctuations does not dampen out in the first few centimeters as assumed by Gupta and Rai et al (1989).

The approach followed for solar assistance is done for the worst case situation in terms of average ambient temperature. That situation is determined by modeling the annual temperature variation and by setting the 1st of January as the lowest average temperature (by calculation). Four locations are selected for local specific calculations on the utilization of solar heat.

COUNTRY SELECTION

Modeling of solar assistances is conducted for four countries; Georgia, Bolivia, Kyrgyzstan and Romania. These countries are selected by the request of WECF. WECF is a network of women's and environmental organizations which strives for a healthy environment for all. Their main focus is on women as they have been identified as the mayor group for sustainable development during the world summit in Rio de Janeiro in 1992 (WECF 2008). This thesis is an elaboration and extension of previous work of the author in collaboration with other students for WECF (Balasubramaniyam, Zisengwe et al. 2008). This thesis is connected to the work of WECF by one of their programs to improve sanitation of the citizens of the respective countries. A biogas plant is one of the approaches to improve sanitation, especially when a toilet is attached to the digester (see chapter 3.21).

The selected countries have in common that they all experience cold winters. As argued before, these cold winters impede biogas production and hence biogas adoption is limited in these countries. The next table shows the altitude, winter temperature, climate (according to Köpper-Geiger classification), the human development index (HDI) of the selected countries and a small list of countries with similar conditions.

TABLE 14: BASIC CHARACTERISTICS OF THE SELECTED COUNTRIES

Country	Romania	Kyrgyzstan	Bolivia	Georgia
Location	Arad	Bishkek	Altiplano	Tbilisi
Altitude (m)	80	800	4000	494
Winter temperature*	-1.5°C	-3°C	5°C	3°C
Climate	DFb	DWk	BSk	DFa
classification characteristics**	Cold, warm summer, no dry season	Arid, desert, cold	Arid, steppe, cold	Cold, hot summer, no dry season
HDI	69	110	114	97
Archetypical to:	Bulgaria, Moldavia, Uzbekistan, Belarus	Mongolia, west-China, Tajikistan	Peruvian highlands, parts of Iran, inner Turkey	Armenia, part of Russia,

*1st of January average temperature from BBC weather ** (Peel, Finlayson et al. 2007)

The items in the table are elaborated next.

Location & Temperature

In many cases the temperature differences within countries are greater than the differences between countries. Bolivia is clear example, the countries not only harbors extreme highlands with plateaus of around 4000 meters high, but has also tropical lowlands in the eastern part of the country. Therefore, the table above is only applicable to certain regions within the countries. These regions are as follows; at the extreme side there is the altiplano of Bolivia, a barren highland above the 3000 meters in the Andes. Tbilisi and Arad on the other hand are situated in low to hilly lands while Bishkek is located in mountainous lands. Arad is chosen as it is a city in the middle of a vast agricultural region in Romania.

Human Development Index (HDI)

The selected countries all belong to the middle developed countries. The HDI index gives a good indication of the state of development of a country, this in contrast to the per capita income (PCY) index of countries which is an aggregative average and does not reveal the nature and characteristics of development (Thirlwall 2006). The human development index is used by the UNDP to rank countries based on three variables, life expectancy at birth, educational attainment and standard of living. The standard of living is obtained by converting the PCY to the purchasing power parity (PPP), the later adjusts for price differences of commodities between countries (Thirlwall 2006). The PPP indicates the relative per capita income in terms of the affordability of certain primary goods and indicates the different levels of wealth between countries.

Assumed is that the low HDI rank is correlated to the benefits biogas will yield for the beneficiaries, such as revenue saving, fuel switch, indoor air and sanitation improvement.

Inhabitants of higher middle or high income countries might choose for others fuels or for larger scale biogas installations. Additionally, their energy provision is likely to be secure and well-developed.

Climate classification
The respective climates were categorizes according to the Köpper-Geiger climate classification, the most widespread and common used model in science (Peel, Finlayson et al. 2007).

Similar countries
The countries similar to the four archetypical countries are determined by using the Köpper-Geiger climate classification. Again, differences within countries are vast; therefore similarities are confined to specific areas within the countries.

DIGESTER DESIGN
Model calculations are performed for a standardized digester in each of the four countries. The standardized digester has to meet the following requirements and has to be adapted to the following framework of prevailing conditions (GTZ 1999).

1. 1.5 m^3 daily biogas yield for the immediate energy requirement of a 5-6 headed family (cooking and lighting)
2. Able to produce biogas during the coldest months
3. Digester model based on a successful well disseminated digester

With these requirements a digester is designed to withstand the coldest period, the 1st of January. The design must have a size which allows sufficient retention for microbes to degrade substrate at a temperature of 15°C. Additionally, 15°C is taken as the lower boundary limit temperature of digestion, meaning that in the worst case situation the temperature can fall to 15°C without impairing biogas production. In chapter 4.4 it was explained that 15°C is by most authors considered as the lower boundary limit for anaerobic digestion at household scale.

Digester model
The digester model selected is based on the assessment of digester designs in chapter 2.3. A Janata digester model is selected by means of simplification over a Deenbandhu digester. The main difference is the optimization of volume to surface area ratio, which in the case of the Deenbandhu digester results in less heat loss. The Janata digester is a well disseminated digester in India and in India's hilly regions and has proved to perform reliably over a great number of years (Kalia and Kanwar 1998; GTZ 1999). The Janata digester is a semi mixed reactor and is fed on daily basis. Assumed is that the HRT equals the SRT.

Digester design
The digester volume and the loading rate determine the HRT of the substrate. The SRT needs to be related to the rate of digestion (the growth rate of the microbes), which is related to the prevailing temperatures. The lower temperature limit is set at 15 °C which is only reached at dawn during the coldest time of the day just before solar energy is transported to the digester.

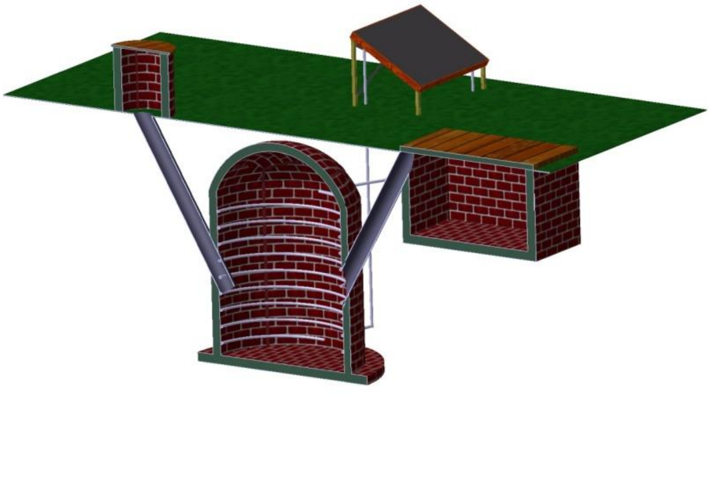
Typical retention time in the hilly regions of India with an average ambient air of 15°C during the winter is 55 days for the Janata digester (Kanwar, Gupta et al. 1994; Singh, Ghuman et al. 1998). This HRT/SRT is used and should provide ample time for the microbes to digest the substrate at the lowest temperature of digestion, 15°C. The net digester volume is calculated using:

$$V_{digester} = Q \times HRT \qquad \textbf{(10)}$$

Where Q is digester feed quantity in m^3/day, Q is the enumeration of both the substrate and water for mixing to lower the viscosity and the solid content of the substrate. Common practice is to dilute to a 1:1 volume base, however as aforementioned, solid state digestion is a viable option to decrease the digester volume. In this case a semi solid state digestion is assumed of 2:1 (manure : water). TS content would then be around 10,6% for freshly collected cow manure without urine. Non diluted fresh manure has a TS content of around 16% (GTZ 1989). In addition, assumed is that 1 kg of cow manure results in 35 liter biogas. Consequently for a 1,5 m^3 biogas yield, 42,8 kg manure is necessary which results in a Q of 64,3 kg/day. The net digester volume is in that case (55*64,3) 3,5 m^3. Note that the Janata digester is a semi-mixed digester and for that reason the SRT is equal to the HRT.

The gasholder is incorporated in the digester. The gasholder has to be designed to meet the gas requirements of the family, which depends on cultural practices and on when and how many times people cook their food (GTZ 1999). Assumed is that three times a day gas is consumed for mainly cooking and that between dinner and breakfast 40% of the daily biogas yield is produced and during the day 60%. The production rate during the day is higher resulting from a higher temperature of digestion. The gasholder in this case is around 40% of the daily gas demand and thus 0,6 m^3. This is not unreasonable, in Cambodia the gasholder of the disseminated digester model is around 33% of the daily biogas consumption (author's observations). Note that the actual capacity of the gasholder is the product of the (elevated) gas pressure and the volume.

The gross digester volume is sum of the net digester volume and the gasholder, which is 0,6 m^3 + 3,5 m^3 = 4,1 m^3.



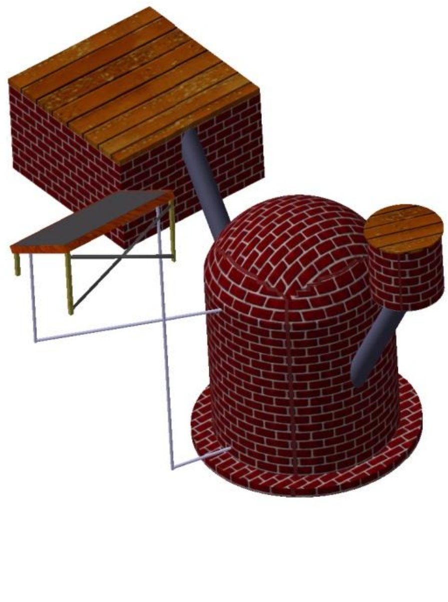


FIGURE 26: ISOMETRIC VIEW OF THE DIGESTER (SCALED DOWN)

The figure on the previous page shows an isometric CATIA presentation in scale of the digester. At the left there is a cylindrical mixing pit, the inlet which is connected by the inlet pipe to the digester. The digester itself is cylindrical shaped with a hemispherical dome; the latter is the gas holder. The spiral running through the digester is the heat exchanger, a pipe through where the hot water from the collector runs. The outlet pipe is connected to a small overflow tank; when the digester is begin filled slurry is pushed out of the system and ends up there. The solar collector at the back is connected with pipes to the heat exchanger in the digester. The next figure shows a front view of the digester.

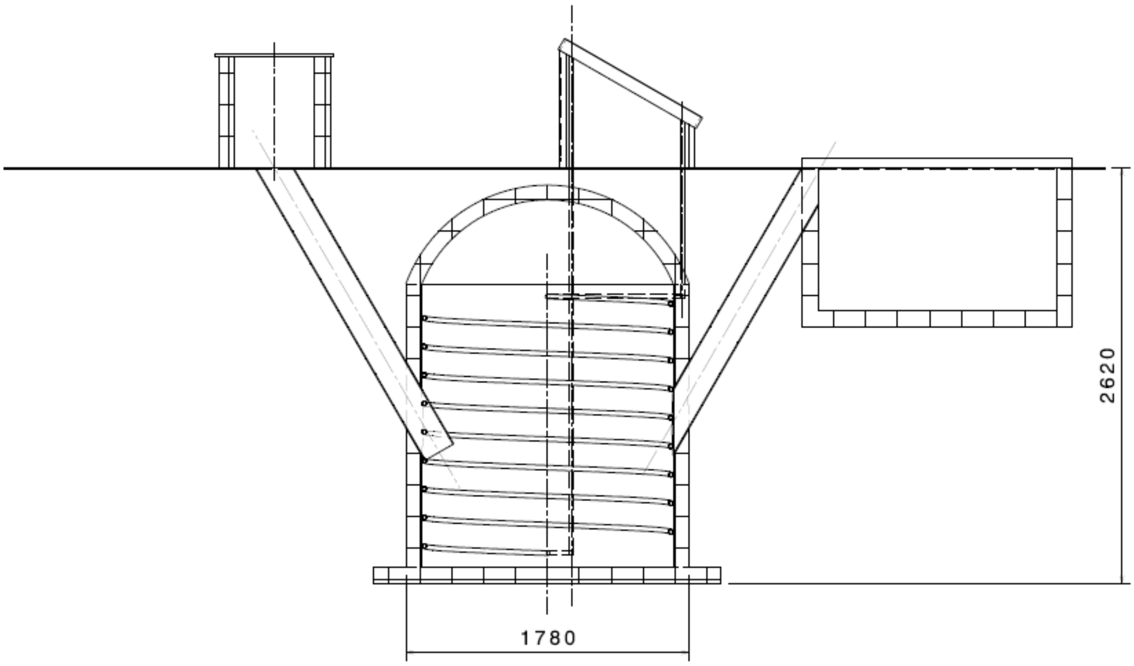


FIGURE 27: FRONT VIEW OF THE SOLAR ASSISTED DIGESTER

The displacement tank is situated 20 cm beneath the ground level, and hence the slurry level of the inlet and outlet are filled up to 20 cm depth at maximum, at any level higher slurry is discharged to the overflow tank. For both the inlet and the outlet the average slurry volume is calculated, the slurry level is on average 20 centimeter depth as set by the overflow. The angle of inclination is of both the inlet and outlet is 30° with respect to the digester walls, see the next table.

TABLE 15: DIMENSIONS OF THE DIGESTER PARTS

Part	Depth (m)	Height (m)	Internal Diameter (m)	Surface area (m^2)	Volume (m^3)
Dome*	(0,1-0,2) - 0,73	0,53	1,58	2,84	0,6
Walls	0,73 - 2,52	1,79	1,58	8,89	3,5
Base*	2,52 - 2,62	-	1,58	1,96	-
Inlet	0,2 - (1,23-1,73)	-	0,20	1,136	0,071
Outlet	0,2 - (1,23-1,73)	-	0,20	1,136	0,071

* the range given is the result of the thickness of the wall, which is 10 cm

Building material

The type of building material greatly influences the thermal resistance of the design. Most models in India and probably also in China, are constructed by masonry work using bricks, cement, sand and brick blast. The use of material determines the overall thermal resistance. The thermal resistance is varied by changing the materials in a sensitivity analysis in chapter 5.4. For this analysis it is assumed that the digester is constructed using bricks (10 cm) and the inlet and outlet are considered to be PVC pipes of 0.5 cm thickness. This is a simplification, mortar is omitted and the plastering for gas tightness of the dome.

As aforementioned, in most countries the ambient temperature falls beneath the desired temperature of digestion. Hence, a certain amount of solar heat needs to be captured to increase the temperature. In the next section the heating requirement is calculated.

5.3 ASSESSMENT OF SOLAR UTILIZATION

To determine the overall heating requirement for which solar collectors are deployed a thermal analysis is conducted. The amount of heat that is necessary to remain the digestion at a certain temperature is described with the next equation.

$$Q_{solar} = Q_{losses} \tag{11}$$

During the night there is continuous heat loss to the ambient, while during the day solar heat is added but also heat is lost to the ambient. Hence the length of both occurrences is important. When the daylight time (t_{day}) and the nighttime (t_{night}) are known, the losses per period of the day can be determined with the next heat balance equation.

$$(Q_{solar} - Q_{losses,day}).t_{day} = Q_{losses,night}.t_{night} \tag{12}$$

In this section first the nighttime is determined. When the length of the night is known, the temperature at the beginning of the night can be calculated from which the system cools down to the minimum value of 15 °C. The temperature at the end of the day (start of the night) is reached by adding solar heat during the day, the heating period. The amount of heat added during the day is the net solar heat input minus the losses during the day. The gross amount of solar energy input is the net solar input and the losses occurring between the collector and the slurry. When the gross solar energy amount is known, the necessary amount of solar panels expressed in square meters can be calculated. This is all elaborated in the next paragraphs.

The approach used could be labeled: *inverse solar heat requirement assessment* (ISHRA).

1. Day and night time

The hours of sunshine on a horizontal plane are determined in two steps: First the angle of declination (δ) of the apparent solar orbit relative to the equator has to be calculated for a specific latitude (φ) for the 1st of January and secondly the hours of sunshine (S_{max}) can be determined (Sukhatme 1997).

$$\delta = 23{,}45° \sin\left[\frac{360°}{365} \times (284 + n)\right] \quad (13)$$

$$S_{max} = \frac{2}{15}\cos^{-1}(-tan\varphi \times tan\delta) \quad (14)$$

Where:

δ	=	Angle of declination (angle the sun's and the earth's centre make when projected on the equatorial plane)
n	=	day of the year, where n=0 is 1st of January
φ	=	Location angle made by the radial line from the centre of the earth and the location with projection on the equatorial plane
S_{max}	=	Hours of sunshine at day n and at azimuth angle γ is 0°

The number 23,45° as depicted in equation 13 is the maximum declination angle of the sun, which happens in the middle of the summer, the sinusoid is then +1, in the middle of the winter the sinusoid is -1 and the angle of declination is -23,45°. Note that the middle of the winter is 21 December and not the 1st of January. The worst case insolation and temperature are thus not at the same date. The deviation is considered to be insignificant.

The multiplier of the cosine function, equation 12, 2/15, indicate the following: 15 is the hour angle, 1 hour represents 15° (15x24=360), and multiplied by 2 to yield a maximum of 24 hours (Sukhatme 1997).

Using the above equations, the day length and the cooling down period of the digester are depicted in the next table. The angle of declination at 1st of January is -23.08°. Meaning the zenith of the sun is 23.08° south of the equator. Bolivia is situated on the south hemisphere and hence the 1st of January is in the middle of the summer. Therefore, for Bolivia the values are taken of the 1st of July, the angle of declination is then 23.08° north of the equator. Results are depicted in the next table.

TABLE 16: DAY LENGTH AND COOLING DOWN PERIOD AT THE 1ST OF JANUARI

Country	City	Latitude (degrees)	Day length (hour)	Cooling down period (hour)
Romania	Arad	46.18°	8.5	15.5
Kyrgyzstan	Bishkek	42,88°	8.9	15.1
Bolivia*	El Alto	-16,5°	11	13
Georgia	Tbilisi	41,43°	9	15

* First of July as above mentioned

The table shows that the day length is the longest in Bolivia and the shortest in Romania.

2. Heating requirement

During the day the digester is heated by the use of solar collectors and during the night the digester slowly cools down to the set temperature of 15 °C. A sketch of the principal heat losses is shown hereunder.

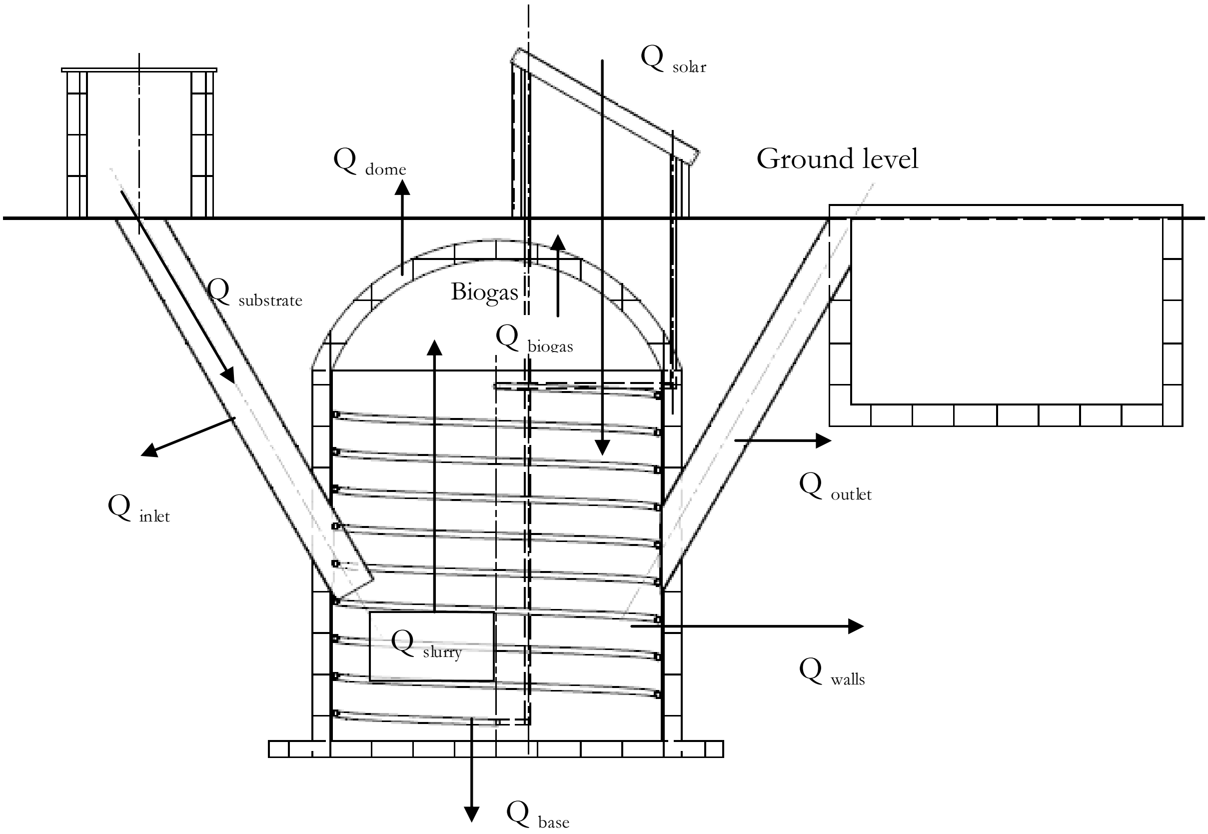


FIGURE 29: MAIN MODES OF HEAT TRANSFER MODES FROM THE BIOGAS PLANT TO THE AMBIENT

With the help of this sketch a heat balance for the cooling down period is constructed. For the heat balance it is assumed that the slurry and the gas are isothermal. Furthermore it is assumed that the biogas in the gasholder has the same temperature as the slurry. This is a reasonable assumption, since there is a continuous elevation of biogas bubbles from the slurry to the gasholder (Singh, Ghuman et al. 1998). The slurry in the inlet and outlet are considered isothermal with the slurry in the digester.

For the periods without heating, the slurry temperature follows the cooling law of Newton, the energy balance is then:

$$\boldsymbol{M_s . C_s \frac{dT}{dt} = -k_w . A_w(T_s - T_w) - k_b . A_b(T_s - T_b) - k_d . A_d(T_s - T_d) - k_i A_i(T_s - T_i) - k_o . A_o(T_s - T_o)} \quad \textbf{(15)}$$

Where, M_s is the slurry mass, C_s the slurry heat capacity, k the heat transmission coefficient, A the area, T_s the slurry temperature and suffixes w, b, d, ,i and o represent respectively, the wall, base, dome, inlet and outlet. The heat losses from the slurry to the biogas to the dome and the heat losses through the inlet and outlet are derived from other calculations, this is elaborated further on.

The unknowns in the balance are the ambient temperature of the soil (T_w, T_b, T_d, T_i and T_o) at different depths and the heat transfer coefficient of the digester parts (k_w, k_b, k_d, k_i and k_o), these unknowns are determined next. The area of the consecutive digesters parts (A_w, A_b, A_d, A_i, A_o) is determined in section 5.2 (see digester design)

Soil temperature at different depths

The digester will operate at a higher temperature compared to the surroundings; consequently heat is continuously transmitted to the surroundings. To calculate this heat loss, the soil temperature at different depths has to be determined. To do so, a sinusoid temperature distribution over the year is assumed, whereby the amplitude is half of the difference between the minimum and the maximum annual average diurnal temperature. Temperature changes over the day are considered to be insignificant compared to the temperature of digestion. This is a reasonable assumption since the heat capacity of a 2-3 ton slurry is very high and it was observed that at 2 meter depth there is no diurnal temperature cycle (Singh, Ghuman et al. 1998). Furthermore, studies in India showed that at 50 cm depth there is only a small fluctuation, even though the daily amplitude was 5°C (Chacko and Renuka 2002) In addition, a homogenous soil is assumed and treated as a semi infinite medium in terms of heat conductivity. For the harmonic analysis of ambient temperature enforcement on the soil (the heat flux) the following model is used (Heusinkveld, Jabobs et al. 2004).

$$\frac{\partial T}{\partial t} = \frac{D_h \partial^2 T}{\partial z^2} \qquad \textbf{(16)}$$

This model predicts with high accuracy the temperature distribution with depth and this is confirmed by conducting measurements in the field (Heusinkveld, Jacobs et al. 2004). Solving this differential equation yields the following relation between the temperature with time and depth (Hills 1982).

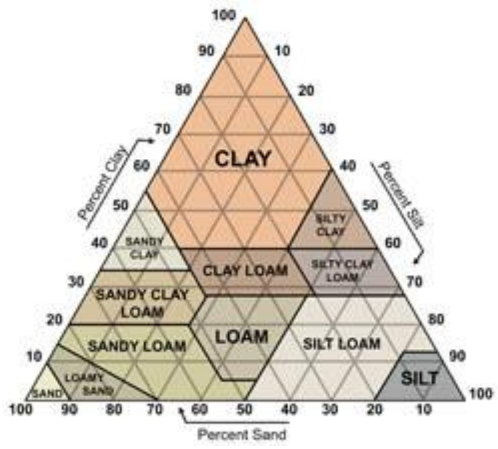
$$T(z,t) = T_a + A_0 e^{-Z/d} sin\left[\frac{2\pi(t-t_0)}{365} - \frac{Z}{d} - \frac{\pi}{2}\right] \qquad \textbf{(17)}$$

Where T(z,t) is the temperature at day t (day) and depth z (m), T_a is the average annual temperature, A_0 is the amplitude of the annual sinusoidal temperature variation, t_0 is the phase correction to adjust t to any other day, t is the 1st of January, d is the dampening depth.

The dampening depth is the product of the square root of the thermal diffusivity of the soil divided by the period; $d = (2D_h/\omega)^{1/2}$, where D_h is the thermal diffusivity and $\omega = 2\pi/365$ (rad/day). Finally, D_h can be calculated for any type of soil; $D_h = k/(\varrho * C_p)$, where k is the thermal conductivity (W/m.K), ϱ the density (kg/m^3) and C_p the specific heat capacity (J/kg.K) (Vermont 2003). Besides the ambient temperature fluctuation, the thermal diffusivity is *the* variable to predict heat enforcement on the soil with depth, and therefore elaborated next.

Thermal diffusivity of soil – soil type

Each type of soil has a different thermal diffusivity. In soil science five factors are distinguished which are responsible for the soil type; parent material, relief, climate, time, a biological factor, soil fauna and human influences (Locher and Bakker 1991). The triangle of Stiboka on the right classifies soil based on the percentages of clay, silt and sand content with the exception of peat or peaty material. In soil science the determination of soil based on Stiboka would be a technical single value classification; in reality soil is much more complex (Locher and Bakker 1991). In addition, the distribution of soil with depth is likely to differ; certain soils, for instance, show horizons and the organic matter is depth related, the topsoil contains more humus. The thermal diffusivity of some selected soils are depicted in the next table



PICTURE 11: TRIANGLE OF STIBOKA (SOURCE: SOILSENSOR.COM)

TABLE 17: THERMAL CONDUCTIVITY OF SELECTED SOILS

Soil	Condition	Thermal diffusivity ($m^2\ s^{-1}\ x10^{-6}$)
Sandy soil	Fresh	0.24
Clay soil	Dry	0.18
Peat soil	Dry	0.10
Rock	Solid	1.43

From Arya 2001 cited in (Vermont 2003)

As the table illustrates, thermal diffusivity varies with the type of soil. Thermal diffusivity is related to the type of material, the texture and water content. As the pyramid of Stiboka depicts, texture varies and hence the contact point between soil parts. If the space between soil parts is air, heat transmission only occurs through the contact point; air acts as an insulator. This situation changes drastically if the soil is wet, then the pockets of air are filled with water and since water is a relatively good conductor of heat the thermal diffusivity greatly increases (Loon 2008). Hence, it is complex to accurately predict the thermal diffusivity of soil without extensive measurements.

The soil of the selected countries fall into a certain group of main soil order, see the next table.

TABLE 18: GENERALISED MAIN SOIL ORDER AND TYPE

	Romania	Kyrgyzstan	Bolivia	Georgia
Order	Alfisols	Aridisols	Mountain soils	Mollisols
Characteristics	clayey	Silty/sandy	Rocky	Silty/sandy

From: (Jarvis 2000)

The main soil order depicted comprises a set of subcategories, at location the soil belongs to one of these subcategories. In practice though, soil varies greatly in countries and difference could be higher than between countries. Moreover, it is likely that people do not live on rocky soils but on soils with soft layer which allows farming. For reasons of uniformity and for a good comparison between the countries' conditions, the soil is considered to be clay in each country. A sensitivity analysis will in the next section determine the influence of a different soil on the digester temperature.

To calculate the temperature of the soil at the 1st of January, a sinusoid temperature distribution is assumed over the year whereby the average maximum temperature and the average minimum temperature of the year are the two extremes, the amplitude the height of both extremes in respect to average annual temperature.

TABLE 19: INPUT VARIABLES FOR TEMPERATURE DISTRIBUTION WITH DEPTH

Country	Unit	Romania	Kyrgyzstan	Bolivia	Georgia
Location	city	Arad	Bishkek	El Alto	Tbilisi
Average**	°C	10.92°C	11°C	7,6°C	13.95°C
Amplitude**	°C	11.5°C	14°C	2.25°C	11°C
Soil type		Clay soil	Clay soil	Clay soil	Clay soil
D_h*	$(m^2.d)$	0,015552	0,015552	0,015552	0,015552

*(Vermont 2003) **Calculated using the BBC weather average monthly temperatures.

Based on equation 6 the temperature distribution with depth is modeled. The next figure shows the temperature distribution in the soil of the selected countries.

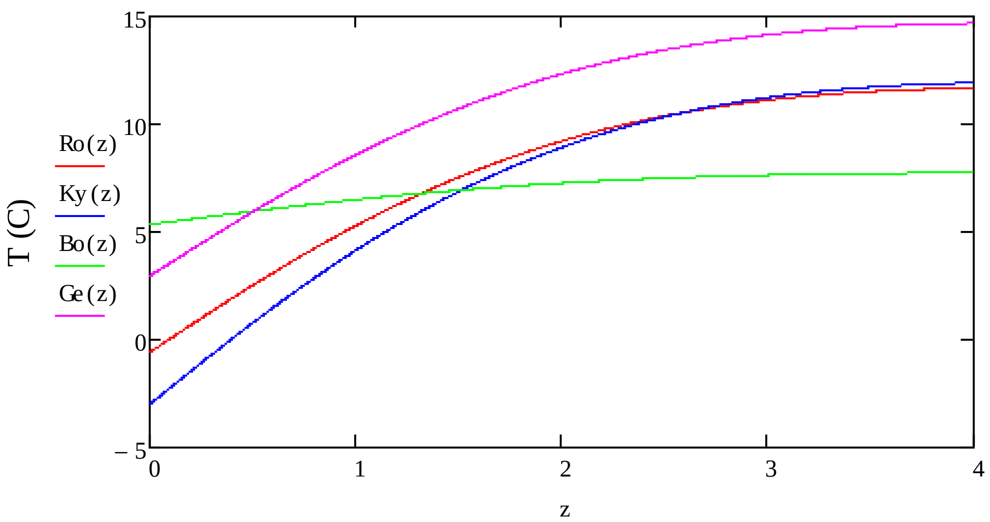


FIGURE 30: TEMPERATURE DISTRIBUTION WITH DEPTH (Z)
Ro(z) = Romania, Ky(z) = Kyrgyzstan, Bo(z) = Bolivia, Ge(z) = Georgia, depth z is in meters

Figure 30 shows that the soil in Bolivia has almost an uniform distribution of temperature with depth. This is caused by the small temperature fluctuations over the year; the amplitude is just 2.25°C. The other countries show more variation because of the higher temperature amplitude. In Kyrgyzstan and in Romania the upper soil is frozen on 1st of January. In Kyrgyzstan the soil is frozen to a depth of 39 centimeters and in Romania to a depth of 9 centimeter.

When the temperature of the soil is known, a heat analysis can be performed. To start with, it is necessary to specify the individual components of the digesters and value their heat conductivity.

The digester is for this analysis separated into five components, the dome, the side walls, the base (floor) and the inlet and outlet. The temperature distribution with depth especially affects the dome (Figure 30) followed by the walls, the inlet and outlet and the base.

The temperature distribution of the side walls, base and inlet and outlet are averaged over its depth. For the dome, the average height is taken as being representative for the average temperature, which is (0,6 m^3/2,84m^2) 21 cm, a point at 0,52 cm depth. That is however not entirely correct, but a good approximation of the overall temperature distribution. The average temperature experienced by the digester parts over the depth profiles is calculated by integrating equation 18 from depth z_1 to z_2:

$$T_{z_{1,2}} = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} f(z)dz \tag{18}$$

The next table shows the depth of each component and the average temperature, for the inlet and outlet average depths are used of the part which is filled with slurry, which is at a depth of 20 cm. This is a set value and determined by the overflow tank to where the slurry flows at any level lower than (less deep) 20 cm depth.

TABLE 20: SOIL TEMPERATURES EXPERIENCED BY THE DIGESTER PARTS IN THE SELECTED COUNTRIES

Digester part	Depth (z) (meter)	Romania (T, °C)	Kyrgyzstan (T, °C)	Bolivia (T, °C)	Georgia (T, °C)
Dome	0,2-0,73	2,65	0,93	5,98	6,05
Walls	0,73-2,52	7,72	7.10	6,97	10,90
Base	2,52	10,42	10,39	7,50	13,48
Inlet/outlet	0,2-1,48	4,33	2,98	6,30	7.67

Table 20 reveals the ambient soil temperature around the digester components. To assess the heat losses to the ambient, the type of heat transfer has to be determined.

Heat losses to the ambient

Heat transfer occurs via three basic mechanisms (Blok 2006).

1. Conduction: Thermal energy is transferred by the interaction between atoms
2. Convection: Heat is transport by the macro transport of the material
3. Ventilation: Exchange of air between the digester and the ambient.

Heat losses via ventilation

Ventilation is considered to be insignificant, ventilation only occurs when the covers of the inlet and outlet are opened. Furthermore, the thermal capacity of air exchanged is insignificant compared to the thermal capacity of the slurry which has a much higher density and heat capacity.

Convective heat losses

Convection could occur in the gasholder and or in the inlet/ outlet. The later is considering its size insignificant; however, in the gasholder biogas could circulate as a result of the temperature difference between the slurry and the upper part of the dome. To determine if the heat loss through natural convection can be considered insignificant, the ratio between the Grashof number (Gr) and the Reynold number (Re) has to be determined. The natural flow is insignificant when (Kays, Crawford et al. 2004):

$$\frac{Gr}{Re^2} \ll 1 \quad \textbf{(19)}$$

The Grashof number depicts the ratio between the buoyancy force and the vicious force (Kays, Crawford et al. 2004) and it calculated with the next equation.

$$Gr = \frac{g\beta\Delta T L^3}{v^2} \quad \textbf{(20)}$$

Where, g is the gravity (9,81 m/s), β the volume expansivity (K^{-1}), ΔT the temperature difference between the ambient and the slurry, L the characteristic length, the average height is taken of the dome for L and v the viscosity of biogas. β is for an ideal gas 1/T and for T 288,15 K is used, the temperature difference between the bulk fluid, the slurry, and the ambient is approximately (15-2,65°C) 12,35°C for Romania, L is 0,21 meter and the viscosity 0,0001027 poise for methane and 0,0001372 poise for CO_2, average dynamic viscosity (65% CH_4 and 35% CO_2) is $1{,}14x10^{-4}$ poise (g/cm/s), which is $1{,}14x10^{-5}$ Pa.s. The calculated Grashof number is in then: $29x10^{6}$.

The Reynold number is obtained with the following equation (Bruning 2007).

$$RE = \frac{\rho V D}{v} \quad \textbf{(21)}$$

Where, ρ is the density, V the velocity of the gas, D the diameter and v the dynamic viscosity. Of these parameters V is the unknown. The average density of methane and carbon dioxide at 15 °C is respectively 0.68 and 1,87 kg/m^3 (Liquide) and the average weighted density is 1,096 kg/m^3 (65% CH_4 & 35% CO_2). For D the average height of 21 centimeter of the gasholder is used and the dynamic viscosity is as calculated $1{,}14x10^{-5}$ Pa.s. The calculated Reynold number is $20x10^3$ V.

Solving equation (19) yields:

$Gr/RE^2 <<1$,

$Gr << Re^2$

$Gr^{1/2} << Re$.

Inserting the values gives:

$(29x10^6)^{0,5} = 20x10^3$ V

5385 << $20x10^3$ V

0,26 << V

V >> 0,26 m/s

Consequently V needs to be substantially larger than 0,26 m/s. A larger speed, in the range of 0,5 or 1 m/s, seems very fast to occur in the digester, therefore it is concluded that natural convection is insignificant.

In other countries, such as Kyrgyzstan ΔT of the slurry and the ambient is larger than in Romania, 18 °C, Gr is around (18/12,35) 1,5 times larger and root of Gr ($1{,}5^{\wedge 1/2}$) is 1,2 times larger. V needs in that case to be substantially larger than 0,31 m/s. This number does not differ considerably from the one of Georgia and therefore it is safe to conclude that even in Kyrgyzstan with the lowest winter temperatures heat losses through natural convection can be ignored.

Conductive heat losses

The main source of heat transfer is conduction between the digester content through the wall to the ambient (Blok 2007). Heat transmission (conduction) to the soil is a function of the area exposed and the type of material, the next table shows the thermal conductivities of selected materials.

TABLE 21: THERMAL CONDUCTIVITIES OF SELECTED MATERIALS AND GASSES (BLOK 2006)

Material	Thermal conductivity (λ) (W/m.K)
Concrete	1,3
Bricks	0,4-0,5
Plastic (PVC)	0,02
Methane(CH_4)	0,06362
Carbon dioxide(CO_2)	0,01465
Biogas	0,046,5*

* Assumed is biogas consists of 65% methane and 35% carbon dioxide, the average thermal conductivity is therefore 46,5 mW/m.K.

The heat transfer coefficient k of each component is determined by dividing the thermal conductivity λ by d, the thickness of the wall/component of the digester.

TABLE 22: INSULATION PROPORTIES OF SELECTED MATERIALS AND CALCULATED HEAT TRANSFER COEFFICIENT

Part	Insulation layer	Thermal conductivity (W/m.K)	Thickness (m)	k (W/m^2K)	A (m^2)
Dome	Bricks & Biogas	-	-	0,165*	-
Walls	Bricks	0.45	0,1	4.5	7,45
Base	Bricks	0.45	0,1	4,5	1,96
Inlet/outlet	PVC	0,20	0,05	-	1,14

* Since convective heat losses can be ignored, biogas is treated as an additional layer of insulation, see next paragraph

Note that this digester has no additional insulation against the cold, therefore it is hypothesized that the heating requirement is high and could be much lower with dedicated insulation. This is studies in the next section.

Heat transfer coefficient of the dome

The heat transfer coefficient k of the dome comprises the heat transfer from the slurry through both the biogas and the dome with each a different thermal resistance and thickness and surface area. The heat transmission is related to the thickness of the biogas layer. The average height of the dome is 21 cm (V_{dome}/A_{dome}) and this is taken as the average distance and hence the thickness of the biogas layer. The heat transmission is then (λ/d) 0,0465/0,21 = 0,22 W/m^2.K. The heat transfer coefficient through biogas and the dome can be calculated with (modified equation from Blok 2007):

$$k_{dome+biogas} = \frac{1}{\frac{1}{k_b} + \frac{A_b}{A_{d.}K_d}} \qquad (22)$$

Where k_b is the heat transfer coefficient of biogas (0,22W/m^2.K), A_b the area of the digester base, which is equal to the slurry area beneath the biogas, A_d the surface area of the dome (2,84 m^2) and k_d the heat transfer coefficient of the dome (10 cm bricks). The heat transfer of the dome (k_d, A_d) is expressed as if the area is equal to the digester base and hence the heat transmission is increased with a factor (A_d/A_b). By doing so, the overall heat transfer from the slurry to the soil via the biogas and the dome can be calculated. The calculated heat transfer coefficient of biogas and the dome is 0,165 W/m^2.K, which is lower than biogas alone, because both layers act as a heat resistor and hence the resistance increases.

Of the heat losses through the inlet and outlet only the losses through the PVC walls is considered. The thermal conductivity of air is very low and the inlet and the outlet is assumed to be well insulated by a cover.

3. Net solar power input

Solar irradiation per day

The amount of solar irradiation over a day can approximately be described with a sinusoid, whereby the period is equal to the hours of sunshine (S_{max}). The integration over the time of the sunrise (tr) and sunset (tr+S_{max}) yields the daily received irradiation. Next the equation of the solar flux (S, kW/m^2) over the day and the integration to obtain the diurnal incident irradiation (Ip, kWh/m^2/day) as determined by the author is shown.

$$S(t) = \frac{\pi Ip}{2.S_{max}} sin\left[\frac{\pi}{S_{max}}(t - t_r)\right] \qquad (23)$$

$$\int_{t_r}^{t_{s+S_{max}}} S\,(t) = Ip \qquad (24)$$

Diurnal irradiation values for an optimally tilted surface during the worst months of insolation are used for Ip. Insolation refers to the total amount of irradiation received by a surface area over a period of time. The 1st of January is taken as the worst day in the year when it comes to temperature, but the day length and the probably also the insolation are the worst on 21 December. This difference is considered minimal and therefore ignored. The next table shows the worst case insolation, the maximum solar flux and day length; in annex 6 the solar insolation map is shown which is used to obtain the insolation values.

TABLE 23: WORST CASE INSOLATION, SOLAR FLUX, DAY LENGTH AND TIME OF SUNRISE

Country	Insolation (kWh/m2.day)	Calculated maximum flux (W/m2)	Calculated day length (hour)	Sunrise* (hour)
Romania	2	370	8,5	8
Kyrgyzstan	4	706	8,9	7,8
Bolivia	4,5	643	11	6,75
Georgia	3	524	9	7,75

* All values are relative to the sunrise in Romania which is set at a *hypothetical* 8 AM.

The insolation values are plotted in the next figure.

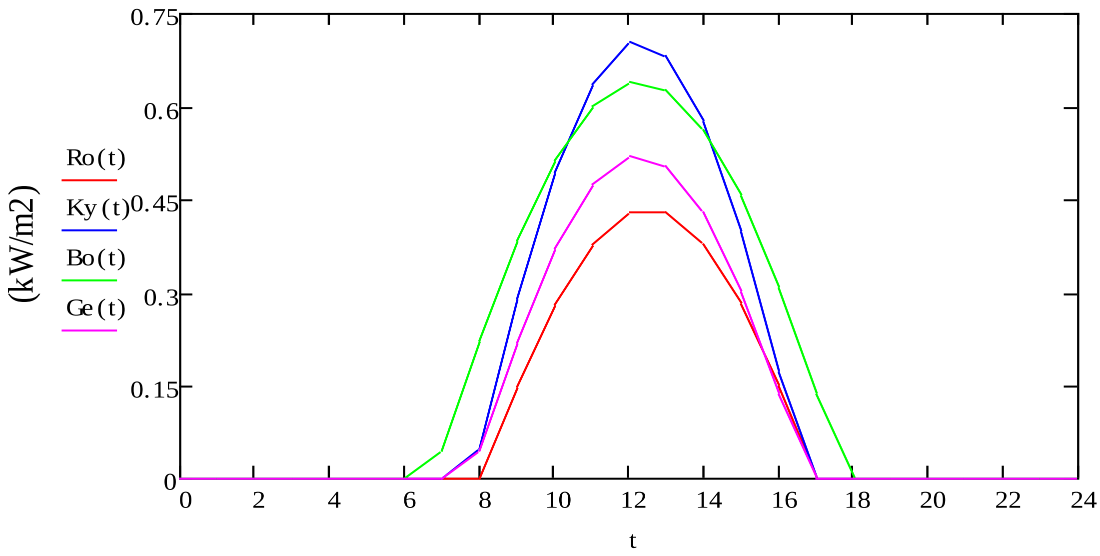


FIGURE 31: INSOLATION 1ST JANUARI ON AN OPTIMAL TILTED SURFACE AT t (hour)
Ro(t) = Romania, Ky(t) = Kyrgyzstan, Bo(t) = Bolivia, Ge(t) = Georgia

The figure shows that both the hours of sunshine and intensity varies considerably in the selected countries. This has implications for the amount of heat which can be extracted per surface area per moment of the day.

Collector efficiency

The next step is to determine the heat removal fraction by the heat collectors. By doing so, the net available heat to increase the digester temperature can be determined. For this, first the collector efficiency factor (F') has to be determined, which represents the amount of useful heat gain per unit of tube length which would occur if the absorber plate of the collector is at the inlet temperature (T_i) (Sukhatme 1997), see the next equation (25). That equation is based on the collector heat balance.

$$F' = \frac{1}{\left[W U_l \frac{1}{U_l}(W - D_o)\varphi + D_0\right] + \frac{\delta_a}{k_a D_0} + \frac{1}{\pi D_i h_f}} \quad (25)$$

Equation 26 is derived from the equation of the useful heat gain per tube over a infinite small length, the parameter ξ defines the ratio of heat conducted through the plate compared to a situation when the thermal conductivity of the plate was infinite (Sukhatme 1997).

$$\xi = \frac{\tanh\,[m(W - D_0)/2]}{[m(W - D_0)/2]} \tag{26}$$

$$m = \sqrt{\frac{U_l}{k_p \delta_p}} \tag{27}$$

Where:

Symbol	*Unit*	*Meaning*
W	m	Distance between two collector tubes
U_l	$w/m^2.K$	Overall loss coefficient of the collector
D_0	m	Tube outer diameter
ξ	%	Plate effectiveness
δ_a	m	Thickness of adhesive between the tube and the plate
k_a	w/m.K	Thermal conductivity of the adhesive
D_i	m	Inner diameter of the collector tube
h_f	W/m^2	heat transfer coefficient of the inside of the tube
m	m^{-1}	-
k_a	W/m.k	Thermal conductivity of adhesive
k_p	W/m.K	Thermal conductivity of the plate material
δ_p	m	Plate thickness

In the figure on the next page the parameters are plotted which are necessary to calculate the collector efficiency factor.

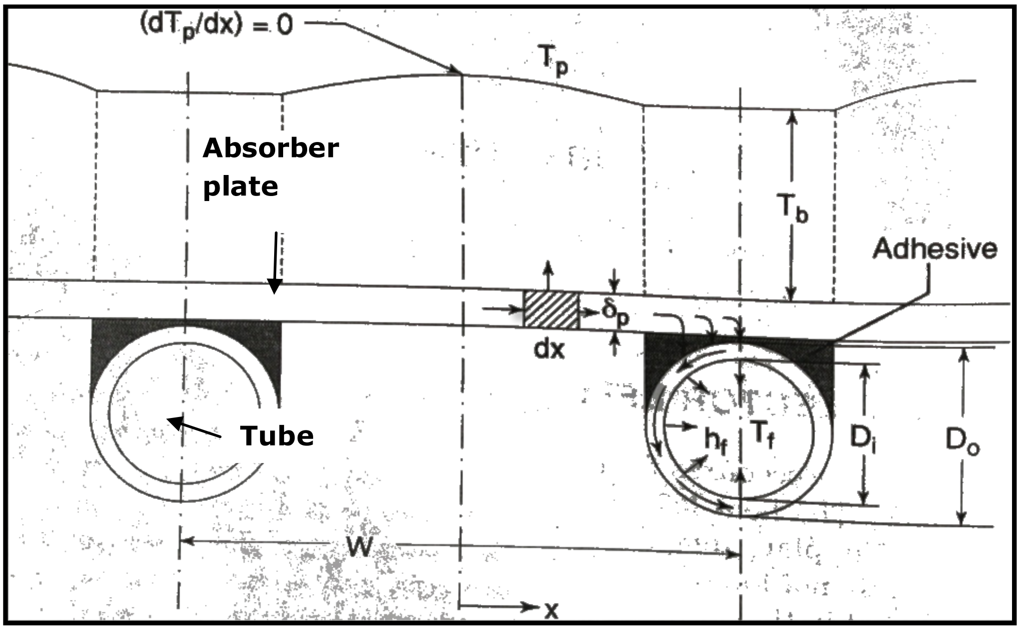


FIGURE 32: CROSSSECTION OF A FLAT PLATE COLLECTOR (SUKHATME, 1997)

COLLECTOR DESIGN

The outcome of the equation above depends on the type of collector. A wide range of collectors exist with different technical specifications. The specifications of the example collector of Sukhatme (1997) are used to obtain the collector efficiency factor. This approach is similar to Gupta et al (1986). Specifications of the collector plate of Suhatme are: W = 12 cm, U_l = 4 $W/m^2.K$, D_0 = 18 mm, D_i = 12 mm, h_f = 205 $W/m^2.K$, k_p = 35 $W/m^2.K$, δ_p = 1,3 mm. The effect of the adhesive on the collector efficiency is considered insignificant by Sukhatme (1997). Sukhatme (1997) obtained a collector efficiency of 0,895. In real life situations the F' can be calculated using the equations on the previous page. For the next calculations the value of 0,895 of Sukhatme is used for F'.

Sukhatme (1997) used for his calculations a collector with a double cover. However, nowadays the heat loss coefficient of a single plate can be lower than the heat loss coefficient used by Sukhatme for a double cover (Van Helden 2007). By applying spectral selective coatings the heat loss through the cover plate in the shape of radiative losses is greatly reduced. Very high quality spectral coatings achieve a coefficient of absorption of 0,96 and coefficient of emission 0,06. The coefficient of emission, the emissivity (ε), is the ratio between the radiated energy compared to that of a comparable black body (Van Helden 2007). A more mediocre collector based on less expensive coatings would have a coefficient of absorption of about 0,90 and a coefficient of transmission through the class plate of 0,90, hence the transmission adsorption product, $\tau\alpha$ is 0,81. Similar values are obtained by Gupta et al (1986). For this analysis it is impossible to determine the effect on $\tau\alpha$ on diffuse radiation and therefore for $\tau\alpha$ is 0,81 is used, similar to the other studies on solar assisted biogas plants.

Heat removal factor

The heat removal factor finally determines the amount of heat recovered from the solar flux by the flow of heated liquid in the collector tubes. The heat recovery factor depends on the mass flow rate of the liquid, if the flow rate is infinite, the heat removal factor is 1; 100% of the heat is removed (Van Helden 2007).

To heat up a digester the temperature of the liquid should not be higher than approximately 37 degrees, which is the upper limit of which mesophilic consortia can cope with. However, if the digester contains psychrophilic or psychrotropic organisms that temperature might be too high. Therefore, to avoid high temperatures, the temperature is set at 30 °C of the liquid. An important implication is that the flow rate has to be variable, since the solar flux is much higher during midday compared to the hours before and after midday. By increasing or decreasing the flow rate, the temperature of the liquid can be controlled and kept at the desired temperature. Hence the heat removal factor is variable since it directly depends on the flow rate. The next equation shows the heat removal factor.

$$Fr = \frac{\varphi C_w}{U_l A_p}\left[1 - e^{\left\{-\frac{F' U_l A_p}{\varphi C_w}\right\}}\right] \tag{28}$$

Where, φ is the mass flow rate of the liquid (kg/hour), C_w the specific heat of water (4,19 kJ/kg.K), U_l the overall loss coefficient of the collector (W/m^2.K), A_p the collector area (m^2), F' the collection efficiency factor (0,895).

Flow rate

Several methods consist to transport the heat with the liquid from the collector to the digester. A natural flow system (thermo siphon) is the most simple and in use in many Mediterranean countries for domestic water heaters (Van Helden 2007). The flow rate by this principle is governed by the buoyancy forces (natural convection) and the friction between the liquid and the pipes and the gravity. When the temperature difference between the inlet and outlet liquid of the collector rises, the buoyancy forces increases and thus the flow rate; the system is self-controlling (Van Helden 2007). By varying the pipe diameter the temperature of the water can be set, a pipe with a small diameter has more friction and thus a higher buoyancy force is required, hence the temperature of the water is higher than with a pipe with a larger diameter.

For this digester heat is required of around 30°C, subsequently the buoyancy forces will be relatively weak. A natural flow system poses some complications; the system is hard to model and to predict its performance (Parker 1991). Therefore this system is not applicable for a digester system whereby high temperatures of the heat exchanger need to be avoided and therefore control is necessary. For domestic solar heaters this is not a problem. Consequently, active controlling is required to control the natural flow. The flow rate can be controlled with a proportional flow regulator, which basically increases or decreases the flow rate according to a set value. In this case the set value will be 30°C. Any temperature lower will result in a decrease in flow rate and any higher in an increase. By doing so, the time that solar heat is transferred to the liquid is controlled by the flow rate resulting in a liquid temperature of around 30°C. At night when the temperature of the liquid is much lower than 30°C, the regulator would switch off the flow.

The flow rate (φ) is determined with the next equation (modified from Van Helden 2007)

$$\varphi = \frac{\frac{\pi Ip}{2.S_{max}} sin\left[\frac{\pi}{S_{max}}(t - t_r)\right]}{C_w(T_o - T_i)} \times A \times Fr(3600) \quad (29)$$

Where φ is the flow in kg/hour, C_w the heat capacity of water, T_o the outlet temperature of the collector (±30°C) and T_i the inlet temperature of the slurry, A the collector area and Fr the heat removal factor. The collector inlet temperature is the outlet temperature of the digester if no losses occur between the digester and the inlet. These losses are considered insignificant (collector is placed near the digester), and hence outlet temperature digester = inlet temperature collector. The outlet temperature of the digester is a function of the heat requirement to offset a cooling down beneath 15°C at the end of the night (the end of the cooling down period). The next figure depicts the required flow rate.

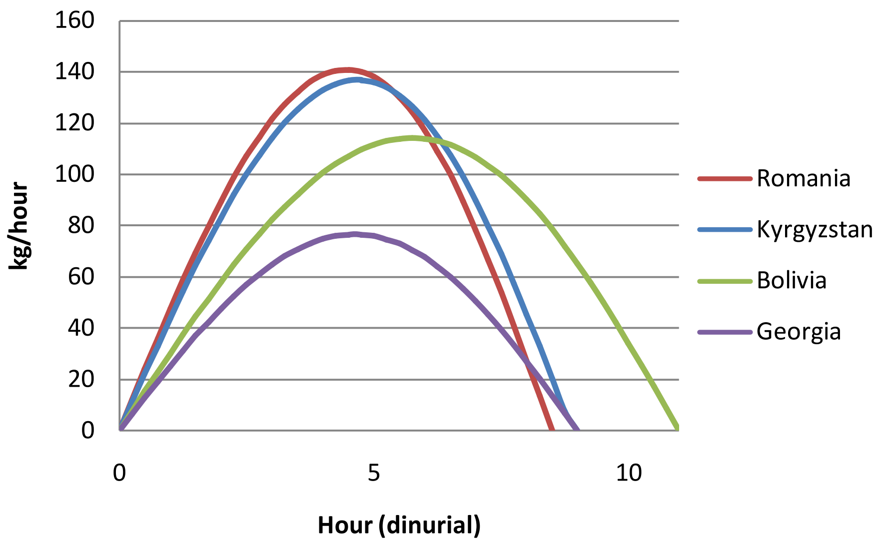


FIGURE 33: LIQUID FLOW DURING THE DAY

Omitted is the calculation of the required surface area and heat transfer coefficient of the heat exchanger, the piping, in the digester. This is however relatively straightforward. The pipe length with a known heat transfer should be dimensioned that even at the highest flow rates the liquid is cooled down to the digester temperature before the pipe leaves the digester.

Power for the pump and regulator

A pump with a proportional flow regulator consumes energy. The regulator itself consumes little power compared to the pump. A pump available at the largest electronic store Netherlands (Conrad) consumes around 1,5 ampere at 12 volts to pump 2,2 liter per minute, which is sufficient for this system. The pump costs around €22,49. At maximum speed the pump has a flow of 130 liters of water per hour ~ 130 kg/hour. This pump is used to estimate the total amount of electricity for a daily operation. Assumed is that the electricity consumed by the pump is proportional to the flow rate. Hence, 18 Watt hour (1,5*12) results in a debit of 130 liters, thus 1 Wh results in a debit of 7,3 liters, to be on the safe side a margin of 10% is added, 1Wh: = 6,6 liters. That margin also account for the power requirement of the regulator. Using these figures, the next table is depicted. In addition the days of operation using a 12 volt Lead-Acid (LA) battery is depicted with a depth of discharge (DOD) of 100% and 50%.

FIGURE 34: KAVAN PUMP CONRAD .NL

TABLE 24: SYSTEM AUTONOMY AND ELECTRICITY CONSUMPTION OF THE PUMP AND REGULATOR

Country	Daily flow	Electricity consumption	Calculated operation days (100 Ah battery)	
	(kg/day)	(Wh/d)	100% DOD	50% DOD
Romania	759,7	115,1	10,4	5,2
Kyrgyzstan	772,6	117,1	10,3	5,1
Bolivia	798,1	120,9	9,9	5,0
Georgia	438,0	66,4	18,1	9,0

The daily electricity consumption of the pump is not an enormous amount and as the table shows many days of operation are possible using a lead acid car battery for cases when grid electricity is not available or not reliable. The level of DOD is of importance since a logarithmic relation between the shallowness of DOD and cycle life exists, for instance a cycle life of 150-200 is to be expected at 100% DOD and 450-500 at 50% DOD (Buchmann 2005). Consequently, a shallower DOD results in a disproportional shorter cycle life span of the battery. In many developing countries batteries are used at household scale; Batteries are commonly used in rural areas for small scale applications such as lighting and television in the developing world and charged at local battery charging stations (BCS) (SGA 1999).

In areas with neither BCSs nor (reliable or affordable) grid electricity are available other solutions are necessary. Judging from the small amount of electricity the system consumes a small PV (Photo voltaic) panel might suffice. The flow rate is proportional with the insolation and hence the electricity demand. The electricity production of a PV is likewise proportional to the insolation and therefore the production of electricity is linearly related to demand of electricity. However, to be on the side the PV panel should be over dimensioned with, say, 10%.

A PV system for this purpose is relatively simple; the output of a 12 volt PV panel does not have to be inverted to another voltage. However, it might be necessary to control the voltage somehow since the voltage output of a 12 Volt panel, which can be up to 20 volts open circuit (Zolingen 2007). If that is necessary, a simple step down converter should be connected between the solar panel and the pump to alter the voltage to a stable 12 volt DC. For the PV assessment the following specification are used, Ip as given in table 16, efficiency losses due to low irradiation of 5% and 5% voltage alteration losses. The PV panel used is a commercially available multicrystalline silicone panel with an efficiency of 13% (Zolingen 2007). Hence the system efficiency is 13%* 90% = 11,7% and since the system has to be over dimensioned with 10% the PV area required is multiplied by 1,1. In the following table a PV-system to provide electricity for the pump is assessed.

TABLE 25: PV SYSTEM FOR PUMP POWER ASSESSMENT

Country	Peak solar flux in winter (W/m^2)	Peak water flow (kg/h)	Peak PV power (Wp)	Solar panel (m^2)
Romania	370	140,87	23,48	0,54
Kyrgystan	760	136,73	22,79	0,28
Bolivia	643	114,28	19,05	0,25
Georgia	524	76,53	12,76	0,21

* A common way to denote the power output of a solar module at STD (Standard test conditions)

The peak energy demand is calculated by dividing the peak water flow by 6,6 Watt/kg water to obtain the peak power input. This times 1,1 for system over dimensioning the peak power (Wp) of the solar panel is obtained. The solar area required is then the peak solar power output divided by peak solar flux times the solar system efficiency.

A PV panel is however relatively expensive, a 20 Watt model costs in the Netherlands around €189 and a 12,8 Watt probably around the €100 (www.zonne-energie.com). It does however render the biogas solar assisted system independent of other fuels.

Now the flow rate is determined, the total heat requirement can be determined.

Heating requirement and the hourly temperature change

To determine the daily temperature change in the digester, the next equation has to be solved.

$$T(t) = \begin{cases} T(t_{cooling\ down}) & t_r + S_{max} < t < t_r \\ T(t_{Heat-}t_{cooling\ down}) & t_r < t < t_r + S_{max} \end{cases} \qquad (30)$$

Whereby S_{max} is the maximum sunshine hours and t_r the hour of sunrise. The function for cooling down is depicted in the beginning of this section. The function for heating is the function of cooling and solar heat and substrate heating. Since the flow rate is 1:1 related to the insolation as set by the flow regulator, the heating of the system follows the sinusoidal rate (half period) of diurnal heating.

$$\boldsymbol{M_s . C_s \frac{dT}{dt} = + \frac{\pi Ip}{2.S_{max}} sin\left[\frac{\pi}{S_{max}}(t - t_r)\right] - k_w . A_w(T_s - T_w) - k_b . A_b(T_s - T_b) - k_d . A_d(T_s - T_d) - k_i A_i(T_s - T_i) - k_o . A_o(T_s - T_o) - M_{sub} C_{sub}(T_s - T_{sub})} \qquad (31)$$

Whereby M_{sub}, C_{sub} and T_{sub} are respectively, the mass (kg), the heat capacity (4,19 kJ/kg.K) and the temperature (°C) of the substrate. The temperature of the substrate is set at 5°C and for simplification a linear heating is assumed, whereby the temperature increases in 8 hours to the temperature of the digester.

The two equations (30) are solved numerically, whereby time steps are set at 15 minutes, a resolution of 96 steps per day. After the analysis the sum of the solar input is compared to the daily net solar input to check whether the numerically approach would lead to inaccuracies. The maximum deviation between the input of heat and the sum of the heat after analysis was 0,5%, hence the results are reasonably accurate.

The temperature distribution over the day is shown in the next figure.

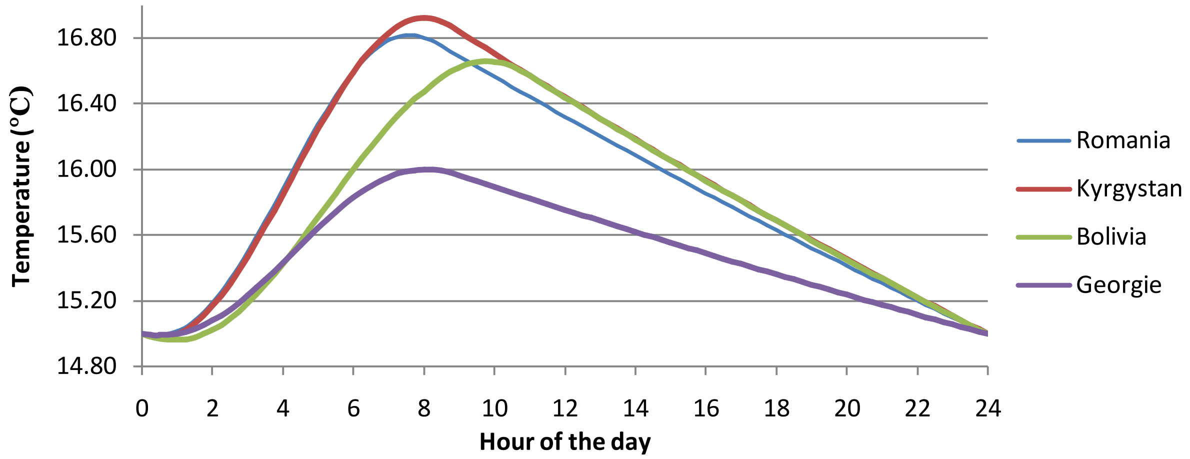


FIGURE 35: HOURLY DIGESTER TEMPERATURE DISRTRIBUTION

To calculate the amount of solar collector area, the heat removal factor (Fr) has to be determined. Since the flow in this system is adaptive to the fluid temperature, which has to be around 30°C, the flow rate is variable. Hence Fr is a function of the flow rate. The next table shows the hourly Fr during the period the sun shines.

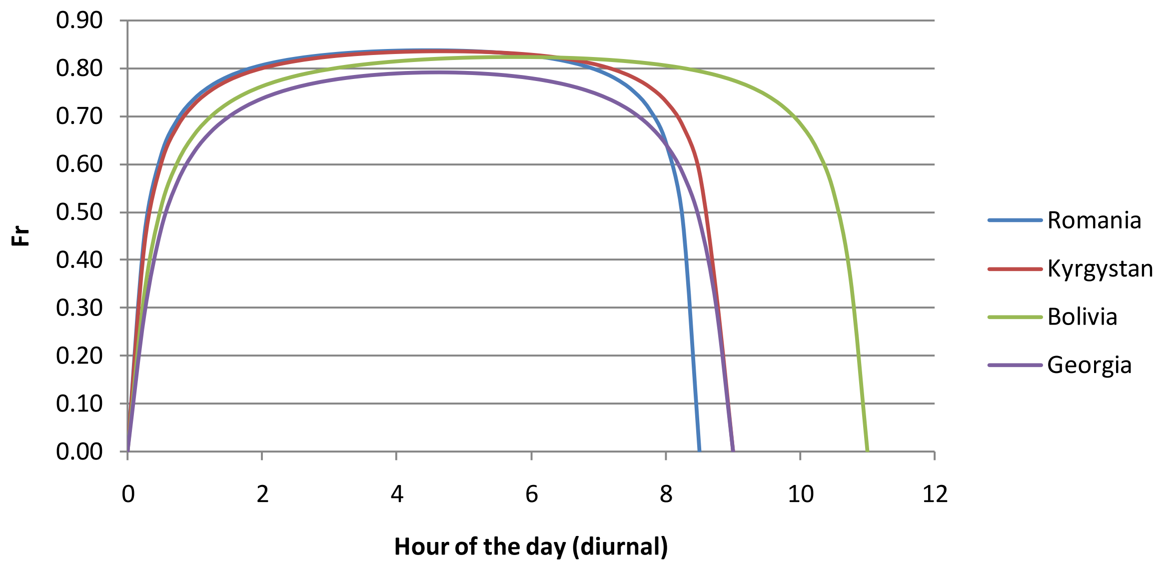


FIGURE 36: HOURLY HEAT REMOVAL FACTOR OF THE SOLAR COLLECTORS

In general the average value of Fr is taken (Van Helden 2007). Judging from the previous figure, the Fr is more or less constant over a large period during the day.

The next table shows the average heat removal factor, the average flow rate and the average digester temperature required to avoid a cooling down beneath 15°C.

TABLE 26: AVERAGE DIGESTER TEMPERATURE, FLOW RATE AND HEAT REMOVAL FACTOR

Country	Average temperature °C	Flow rate (kg/h)	Average heat removal
Romania	15,88	92,08	0,77
Kyrgyzstan	15,94	88,29	0,76
Bolivia	15,79	74,24	0,75
Georgia	15,48	50,06	0,70

When the average Fr is compared with the Fr as plotted in the previous figure, the average approximates most values in the graph with the exception of the hour after sunrise and before sunset. The flow rate is different in the countries; this is the result of the different heating requirement. Fr is the highest in the case with the highest flow rate as predicted.

4. COLLECTOR AREA REQUIREMENT

Taking the heat removal factor as an average, the area can be calculated by dividing the daily heat requirement by the daily irradiation (I_p) and the heat removal factor (adapted from Sukhatme 1997):

$$A = \frac{Q_{heating}}{I_a Fr - U_l(T_i - T_a)} \quad \textbf{(32)}$$

$$I_a = \frac{I_p}{\tau\alpha} \quad \textbf{(33)}$$

Where I_a is the amount of absorbed heat by the absorber of the solar collector, for the other values see equation 29. The effective collector area necessary for the digester are depicted in the next table per country. Since every collector has a frame around the cover plat which reduces the effective surface area and hence the total collector area is an estimated 5% larger.

TABLE 27: COLLECTOR AREA REQUIREMENT FOR DIGESTER HEATING

Country	Total heating (MJ)	Collector area ($\tau\alpha$=0,81) (m^2)	Collector area ($\tau\alpha$=0,92) (m^2)
Romania	44,6	12,69	11,16
Kyrgyzstan	45,2	5,74	5,04
Bolivia	47,3	5,50	4,83
Georgia	26,6	5,11	4,50

Table 27 shows that the collector area is much larger in Romania compared to the other countries, caused by the lower insolation and the lower temperatures. Kyrgyzstan with even lower temperatures during the winter has around half of the collector area requirement due to the much higher insolation. In Bolivia and Georgia the collector area requirements are around 5,5 m^2. The amount of heat gained is related to the collector area and the insolation, for that reason the heat gain between Romania and Kyrgyzstan does not differ substantially while the collector area does.

A very high quality spectral coating with $\tau\alpha$= 0,92 reduces the collector area required somewhat. However, the total effect is limited and probably the additional costs would not compensate for the reduction in collector area.

5.31 SYSTEM ASSESSMENT AND STABILITY

Of the system the following specifications are assessed, stagnation temperature, solar fraction and system efficiency. The stagnation temperature is the maximum temperature the solar collector can attain which happens when no heat is withdrawn, which results in an equilibrium temperature between the heat gain and the heat losses. This could happen when the flow is blocked or the pipes are clogged. The stagnation temperature is given by (Van Helden 2007):

$$T_{stag} = T_a + \frac{\alpha\tau I_a}{U_l} \quad (34)$$

The solar fraction is the amount of heat originating from the sun compared to the total amount of heat utilized for heating. The system efficiency is the ratio heat used for heating the digester and the incoming insolation.

TABLE 28: STAGNATION TEMPERATURE AND SYSTEM EFFICIENCY OF THE MODELLED SOLAR ASSISTED DIGESTER

	Romania	Kyrgyzstan	Bolivia	Georgia
Stagnation temperature*	74,8°C	140°C	135.6°C	109.1°C
Solar fraction	100%	100%	100%	100%
System Efficiency	48,8%	54,7%	53,1%	48,1%

* τα = 0,81, other values obtained from the beginning of this section

When no heat is withdrawn in all countries except Romania the absorber temperature reaches a temperature above 100°C, and probably also in Romania during the summer. Consequently safety values are needed to release steam in that situation. The solar fraction is 100% by design, since the sun is the only source of heat. The system efficiency varies between the countries, largely attributable to the amount of solar area required, the flow rate and the losses to the ambient of the system. The efficiency values are around 5-10% lower than reported values in the literature, see Parker (1991) and Sukhatme (1997). This is likely the result of the relative low flow rate and of the low τα product.

System stability

The system is designed to keep the temperature of the slurry at 15°C minimum. However, if the system fails and the worst case conditions in terms of temperature and insolation continue, the temperature might not recover to 15°C. A 10 days analysis is conducted whereby the digester is allowed to cool down for one day, this could happen if the regulator fails, if something is blocking the pipes, leakages and so on.

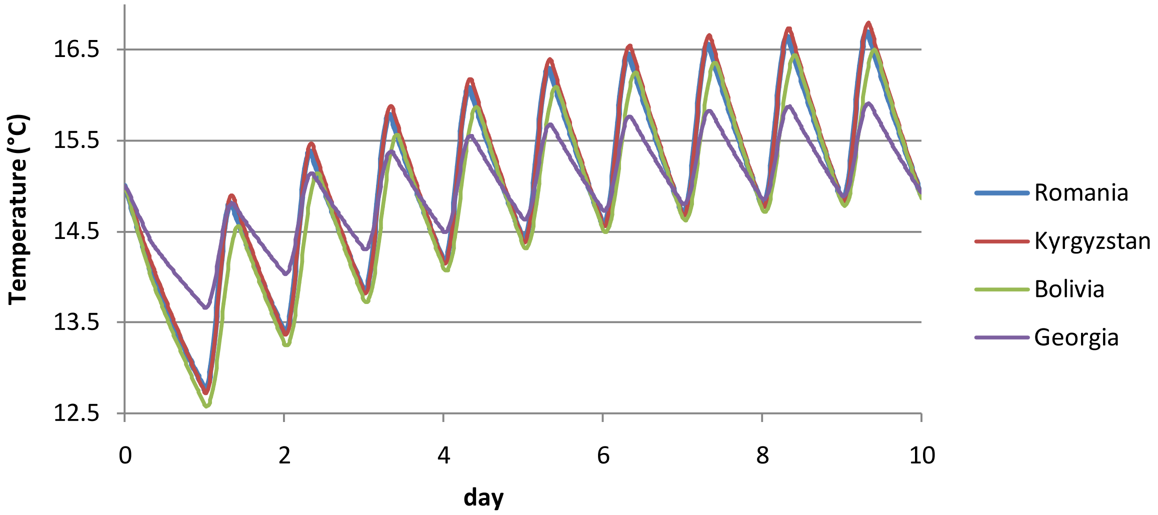


FIGURE 37: 10 DAY ANALYSIS OF DIGESTER TEMPERATURE WITH THE FIRST DAY WITHOUT HEATING

The analysis shows that within 10 days the digester recovers in most countries, in the case of Georgia the system recovers much faster resulting from the higher soil temperatures with depth. Since, the digester temperature is lower than for which it is designed, the households in the selected countries would for a certain amount of days have insufficient biogas to meet their energy requirements.

If the heating fails permanently, the stagnation temperature of cooling can be determined, which is the average temperature of the area around the digester.

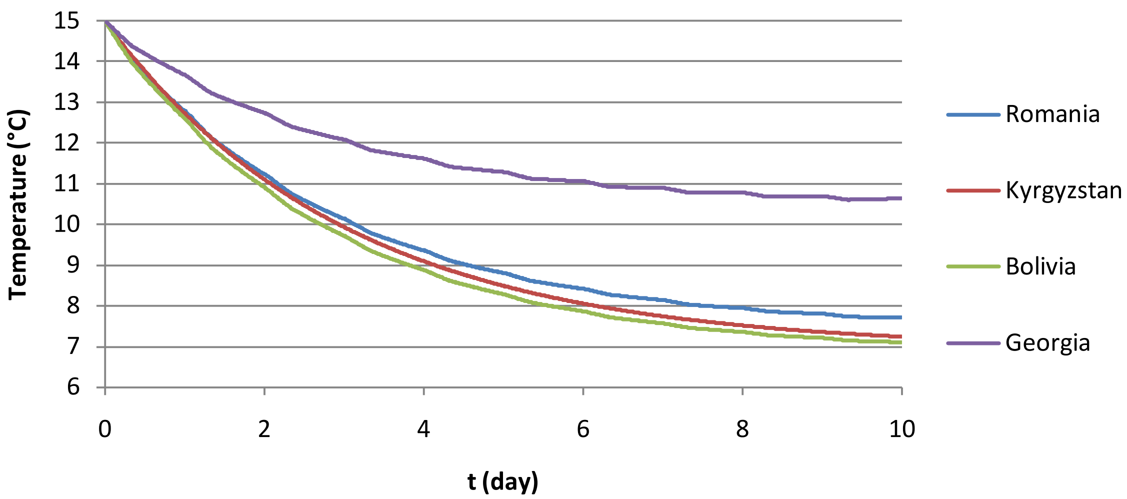


FIGURE 38: COOLING DOWN CURVE RESULTING FROM SOLAR SYSTEM FAILURE

The irregularities in the figure are caused by the daily substrate feeding which has an assumed temperature of 5°C. The figure shows that the digester temperature in Georgia remains much higher than the other countries. Furthermore, the figure shows that the overall heating requirement in Georgia is much less than the other countries.

Conclusion

The transient analysis showed that heating the digester to at least 15 °C is possible. However, the collector area required is large, especially in the case of Romania. This area can be reduced by several means, such as adding dedicated insulation and hot charging. A sensitivity analysis in the next section will study the influence of insulation and hot charging on the required number of solar collectors.

5.4 SENSITIVITY ANALYSIS

5.41 EFFECT OF INSULATION ON COLLECTOR AREA

From the analysis of section 5.3 the main heat losses of the digester components are depicted in the next table.

TABLE 29: RELATIVE HEAT LOSS OF EACH COMPONENT

Country	Dome	Walls	Base	Outlet	Inlet	Substrate
Romania	0,42%	63,22%	9,33%	10,16%	10,16%	6,84%
Kyrgyzstan	0,47%	67,51%	9,34%	11,25%	11,25%	6,75%
Bolivia	0,30%	64,49%	13,36%	7,88%	7,88%	6,18%
Georgia	0,51%	59,68%	5,75%	11,57%	11,57%	11,00%

The table shows that in every country most heat is lost through the walls, then the inlet and outlet, the base, heat required for substrate heating and finally the dome.

El-Mashad & van Loon et al (2004) performed a transient analysis on a solar assisted reactor in Egyptian conditions with a varying degree of insulation. The next table shows first the two materials used in the previous analysis and the other materials are used by their analysis.

TABLE 30: CALCULATED HEAT TRANSFER COEFFICIENTS OF SELECTED MATERIALS

Material	Calculated heat transfer coefficients (k) ($W/m^2.K$)
Bricks (10 cm)	4.5
10 cm bricks + 11 cm rock wool	0,33
40 cm straw loam	0,67
30 cm straw loam	1
40 cm bricks	1,7
9 straw loam	2.5

Source (Blok 2007 & El-Mashad, van Loon et al 2004)

The table shows that the insulation can be greatly improved of the modelled digester which had an overall k-value of 4,5 $W/m^2.K$ of the walls. The k-values of the better insulating materials have been used to assess the impact on the collector area to maintain a minimum of 15°C in the digester.

Experimental manipulation

The inlet and outlet, with a k-value of 4 $W/m^2.K$ are improved to 1,5 $W/m^2.K$ by applying a small layer of additional insulation. The k-value of the base remains the same (4,5 $W/m^2.K$) and the insulation of the wall is varied from 4,5 to 0,33 $W/m^2.K$.

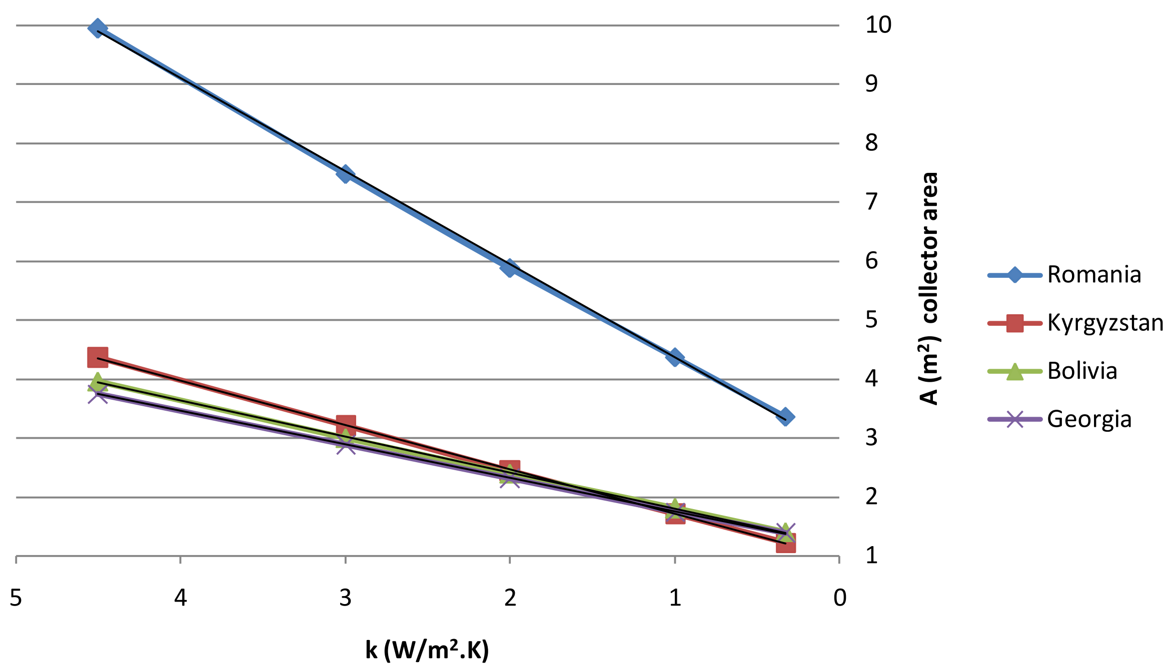


FIGURE 39: INSULATION OF THE WALLS AND THE REQUIRED COLLECTOR AREA TO HEAT THE DIGESTER TO AVOID A TEMPERATURE LESS THAN 15°C.

The figure shows a drastic linear reduction of collector area with increasing insulation. When 10 cm bricks and 10 cm rock wool are applied to the wall, (k=0,33 $W/m^2.k$), the collector area is beneath 1,5 m^2 for all countries except Romania. An economic analysis should determine trade-offs between better insulation and collector area. However, increasing the insulation will improve the system stability, since temperature fluctuations are less and in the case there is a day without heating the digester would cool down less and recover more quickly.

When the linear relation between k and A is known, one can use this for an economic analysis to determine tradeoffs. The next table shows this relationship.

TABLE 31: INSULATION VERSUS COLLECTOR AREA IN THE SELECTED COUNTRIES

Country	**Insolation (Wh/day)**	**function of k and A**	**A/k** ($m^2/W/m^2.K$)	R^2
Romania	2000	A = 1,58 k + 2,79	1,58	0,999
Kyrgyzstan	3500	A = 0,75 k + 0,96	0,75	0,999
Bolivia	4500	A = 0,61 k + 1,19	0,61	0,999
Georgia	3000	A = 0,57 k + 1,19	0,57	0,899

Insolation values as depicted in chapter 5.2

For every 1 W/m^2.K increase of the insulation of the base, the collector area required to maintain the digester at 15 °C decreases in the case of Romania with 1,58 m^2, in Kyrgyzstan 0,75 m^2 and in the other countries with around 0,57 m^2. Due to the higher insolation in Kyrgyzstan A/k is much lower compared to Romania, while temperatures and heat enforcement on the soil does not differ substantially.

Heat losses of individual components

When the walls are better insulated, the other digester parts will lose relatively more heat. This is analysed for Romania where the conditions are the most extreme compared to the other countries in terms of sunshine hours, insolation and the second worst in low soil temperature. In addition, increasing the insulation of the walls will greatly augment heat losses through the base. Therefore also the effect of base insulation is studied.

Hence there are three conditions, the original with improved insulation of the inlet and outlet (k= 1,5 W/m^2.K), manipulation 1: k-walls is 0,33 W/m^2.K without insulating the base, and manipulation 2: k-walls is 0,33 and k-base is 2 W/m^2.K. The insulation of the base is less because the base has to bear the weight of the digester and therefore strong solid materials are necessary making insulation with rock wool for instance not feasible.

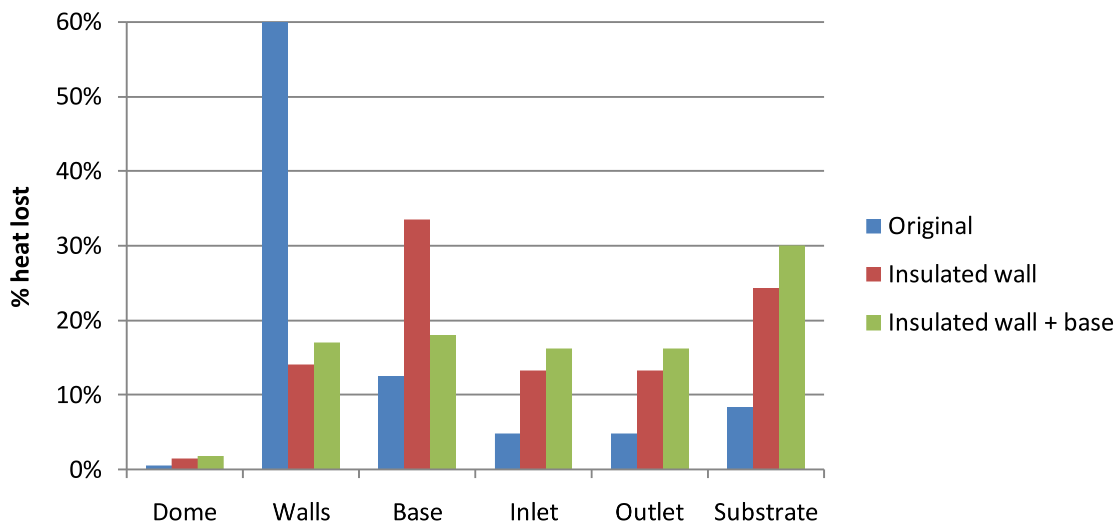


FIGURE 40: RELATIVE HEAT TRANSFER OR DIGESTER COMPONENTS IN ROMANIA

The figure shows that the dome does not need additional insulation even when the base and the walls are very well insulated. This contrasts the suggestion of Tiwari et al (1988) to focus insulation efforts to the dome. Furthermore, when the walls are well insulated, the base looses most of the heat. When increasing the insulation of the base to 2 W/m^2.K, all the digester parts with the exception of the dome loose approximately the same amount of heat. The figure also shows that with proper insulation the relative amount of heat used for substrate heating increases considerably. Hence, substrate heating might be interesting, so called hot charging. In the next section it is studied if hot-charging alone is sufficient in a very well insulated digester to keep the digester at 15°C minimum. If that would be the case, a considerable investment to obtain solar assistance is avoided.

5.42 HOT CHARGING

Hot charging is the act of heating the feedstock before feeding it to the digester. This is modelled for a feeding rate of once a day to heat up the digester in order to avoid a cooling down to a temperature less than 15°C. Hot charging is studied for three conditions. Condition 1, the original situation but with improved insulation of inlet and outlet of 1,5 $W/m^2.K$, base and wall have a k-value of 4,5 $W/m^2.K$. Manipulation 1 (M1), the base and the wall both have a k-value of 2 $W/m^2.K$, and manipulation 2, (M2), the walls and the base have respectively a k-value of 0,33 and 2 $W/m^2.K$.

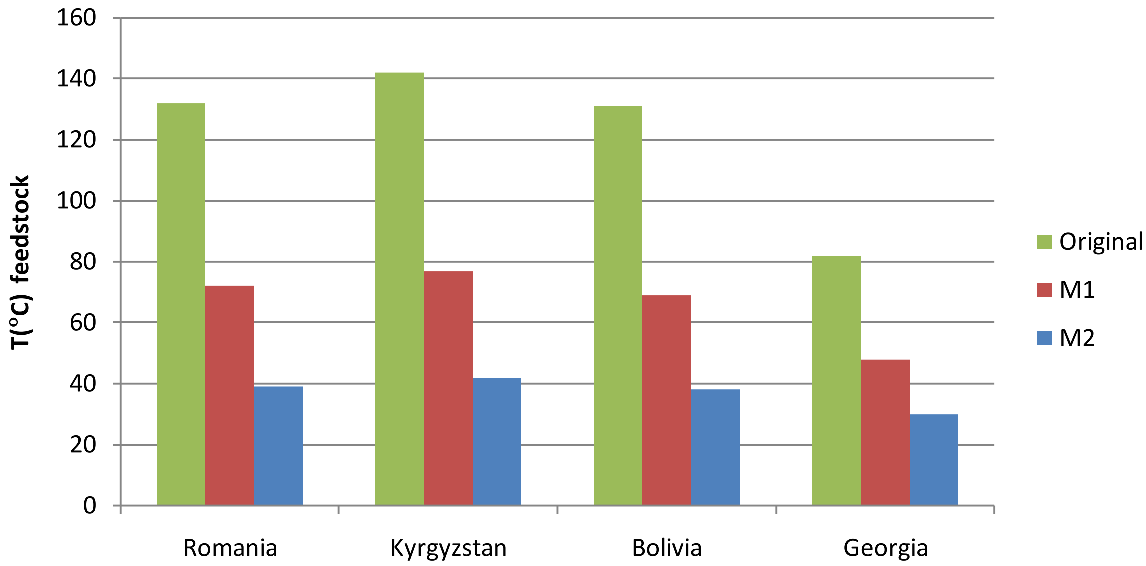


FIGURE 41: HOT CHARGING TO HEAT UP THE DIGESTER TO A SET MINIMUM TEMPERATURE OF 15 °C

The figure shows that hot charging is feasible when the digester is well insulated. Hot charging becomes complicated at M1, since the temperature has to be above 100°C if mixed with dung with a temperature of 5°C on a 1:2 volume basis (water : dung), it would only be possible in Georgia if water is used to heat up the substrate. In the control condition it is not possible in each case. What could be feasible in M1 is to mix water and dung and heat it together in for instance a solar cooker to the desired temperature.

The solar box on the right pictures is a simple box made of carton. The enclosure is double walled and insulated, the inner outside is painted black to retain the incoming heat, the glass cover allows radiation to pass but prevents the release of infrared radiation and the movable side plate is covered with an aluminium sheet to reflect the incoming beam to the glass cover.

PICTURE 12: SOLAR COOKER BOX
Source: http://modok.us/2007/02/

Experiments conducted in Cambodia whereby the authors was involved showed that it is possible to increase the temperature of a pot filled with water (5 litres) to a temperature of around 80-90°C within 2-3 hours with an approximate insolation of 4 $kWh/m^2.day$. Further study should determine if this is a viable option in the selected countries, since it could be a very low cost alternative compared to solar collectors provided the digester is well insulated.

The analysis of hot charging is not entirely correct due to the assumption made previously. Assumed is that the heat would be evenly dispersed of the system within a 7 hour period. However, more likely is that most heat is in the inlet and hence due to the high temperature difference more will get lost through the inlet. Additionally, the microbes can experience a heat shock since the feedstock is above their optimum temperature.

If hot charging is to be applied, some of the aforementioned issues can be overcome, by

1. Agitation. By agitating the slurry the heat is evenly spread and will cool more quickly and hence microbes are less affected by the high feedstock temperature. It is possible to add a mixer for agitation to a dome digester; such a mixer can be manually powered.
2. When the feedstock is fed to the inlet, the feedstock should be mixed well with the digester content by using a long pole to press the feedstock into the digesters. Subsequently, one should use the mixer for agitation for a couple of minutes to distribute the heat evenly in the digester.

5.43 INFLUENCE OF THE SOIL TYPE ON THE HEATING REQUIREMENT

Soil type and texture influences the thermal diffusivity as previously explained. In this section the influence of soil on the dampening depth is studied. Argued before is that water containing soil has a higher thermal diffusivity (van Loon 2008), see the next figure.

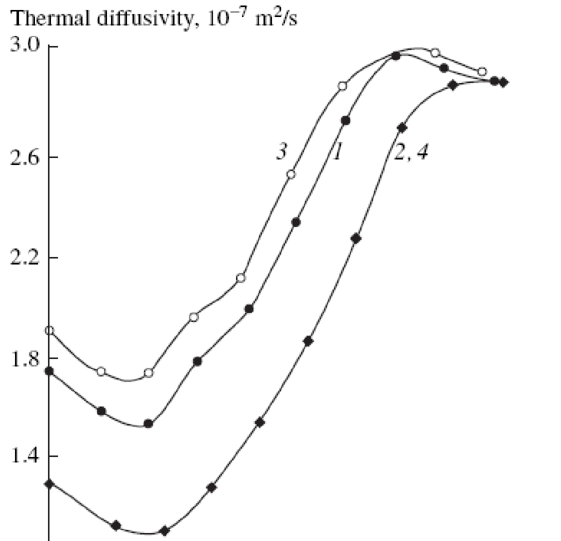


FIGURE 42: EXAMPLE GRAPH OF A VARYING THERMAL DIFFUSIVITY WITH WATER CONENT OF (1) NON SALINE SOILS (2) MEDIUM SALINE AND (3) STRONGLY SALINE LOAM SOILS (TIKHONRAVOVA 2005)

Hence, with increasing water content, the thermal diffusivity greatly increases, and the degree of salinity improves the diffusion. For the next analysis, clay loam soils of various water contents thermal diffusivities are compared.

TABLE 32: EFFECT OF THE THERMAL DIFFUSIVITY ON THE SOIL TEMPERATURE AROUND DIGESTER PARTS

Soil characteristic*	**Country**	**Dome** T (°C)	**Walls** T (°C)	**Base** T (°C)	**Inlet/outlet** T (°C)
dry	Romania	2,32	7,74	10,44	4,35
20%		1.71	6,42	9,16	3,39
38%		1.19	5.09	7,61	2.53
dry	Kyrgyzstan	0,93	7,10	10,40	2,98
20%		-0,21	5,52	8,86	1,48
38%		-0,85	3,90	6,97	0,79
dry	Bolivia	6,13	7,41	8,00	7,60
20%		5,80	6,72	7,26	6,13
38%		5,70	6,46	6,95	5,96
dry	Georgia	5.73	10,92	13,50	7,67
20%		5.15	9.66	12,28	6,76
38%		4.65	8,38	10,79	5.94

* All soils are clay loam with varying water content, dry, 20% and 38%. Thermal diffusivity respectively is $1{,}8*10^{-7}$ m^2/s, 20% : 2,3 10^{-7} m^2/s and 38% $4*10^{-7}$ m^2/s

As expected, the temperature decreases when the thermal diffusivity of the soul increases. The effect is considerable. Chapter 5.41 showed that the walls and then the base looses most of the heat; this effect will increase considerably judging from the lower average temperature at a thermal diffusivity of $3x10^{-7}$ m^2/s (water content of 38%), the average temperature of the walls and the base decreases with 2-3,5 degrees in most countries. How would this affect the heating requirement?

Heating requirement with various thermal diffusivities

The heating requirement is studied for a medium insulated with varying degree of soil thermal diffusivity. The insulation is in each case: k-value base and walls 2 ($W/m^2.K$) and the inlet/outlet 1,5 ($W/m^2.K$). The dome is similar as described in 5.2.

- Condition 1: Medium insulated and with a thermal diffusivity (D) of $1{,}8*10^{-7}$ m^2/s
- Condition 2: Medium insulated digester and a D of $2{,}3*10^{-7}$ m^2/s
- Condition 3: Medium insulated digester and D of $3*10^{-7}$ m^2/s

The results are displaced in the next figure.

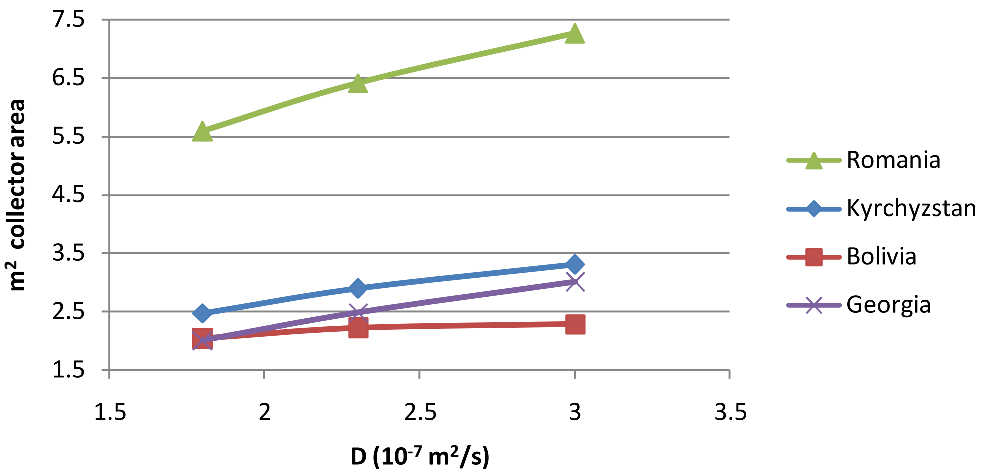


FIGURE 43: THERMAL DIFFUSIVITY OF THE SOIL VERSUS REQUIRED COLLECOR AREA TO MAINTAIN A MIMIMUM OF 15°C OF A MEDIUM INSULATED DIGESTER.

The heat enforcement on the soil is in particular strong in Romania. Comparing the situation of a D of 1,8*$10^{-7}m^2/s$ with 3* $10^{-7}m^2/s$ the collector area has to increase with 33% to supply sufficient heat to the digester to maintain the 15 °C. In other countries the heat enforcement on the soil is less resulting from the smaller temperature fluctuations and because of the higher insolation.

In Bolivia there is only a small effect on the collector area required when the thermal diffusivity of the soil increases, this is because the annual temperature fluctuations are the least, see chapter 5.2. To overcome, the increased heat loss caused by the increase of thermal diffusivity from 1,8- to 3* $10^{-7}m^2/s$; the collector area in respective Kyrgyzstan, Bolivia and Georgia has to increase with 25,2%, 10,9% and 23%.

Since the lines in the figure are approximate linear, a relationship between the thermal diffusivity and the required collector area is determined and depicted in the next table. The relationship is valid from a D of 1,8* $10^{-7}m^2/s$ to 3* $10^{-7}m^2/s$.

TABLE 33: RELATION BETWEEN COLLECTOR AREA (A) AND THERMAL DIFFUSIVITY (D) OF THE SOIL

Country	**Insolation (Wh/day)**	**A/D $m^2/(10^{-7}.m^2/s)$**	**R^2**
Romania	2000	1,74	0,99
Kyrgyzstan	3500	0,83	0,99
Bolivia	4500	0,69	0,99
Georgia	3000	0,20	0,89

Insolation values from chapter 5.2

The table shows that with an increase of thermal diffusivity of the soil with 1*$10^{-7}m^2/s$, the collector area has to increases with 1,74 m^2 in the case of Romania to overcome the higher heat losses and to maintain the digester temperature at 15°C minimum. These values are much lower in the other countries for two reasons: Firstly, the insolation in the other countries is much higher, hence per unit of area the collector absorbs more heat and secondly, the heat enforcement is less, which is especially true for Bolivia.

5.4 DISCUSSION AND CONCLUSION

Gupta et al (1998) pointed out that temperature fluctuations dampen out within the first centimetres of the soil and for their analysis they used an average ambient temperature for the soil independent of depth. Tiwari and Ghandra et al (1989) used in their analysis of a KVIC solar assisted biogas plant also the average temperature. However, in the previous section it became clear that their approach is not correct. For instance in Romania, the temperature around the dome is 2,65 °C and around the base 10,42 °C during the coldest period of the year. Additionally, when soil becomes wet it results in a lower temperature with depth. To conclude, the modelling in this chapter showed clearly and comprehensively that the heat enforcement on the soil does not dampen out within a few meters.

This analysis did confirm the viability of hot charging as suggested by authors like Kumar et al (1979) and Hills and Stephens (1980) cited in Kumar and Bai (2008). However, the applicability of hot charging is limited unless the digester is very well insulated and the temperature of the soil is relatively high. In all the selected countries hot charging was feasible when the digester is very well insulated (k-value walls 0,33 $W/m^2.K$ and the base 2 $W/m^2.K$), while in Georgia it might also be applicable for less insulated digesters. When the author visited Georgia for an energy training of WECF he witnessed various occasions where hot charging was put into practice for digester heating (WECF 2008). The main benefit of hot charging is that it displaces a relative expensive solar collector system, it is a straightforward approach for digester heating and since manure has to be mixed with water anyhow it only requires heating the water as additional workload.

A dramatic decrease of collector area for digester heating can be obtained by increasing the insulation. Reduction of collector area varied from 0,57-0,75 m^2 for most countries to even 1,58 m^2 in Romania for every +1 $W/m^2.K$ increase of wall insulation. Similar findings are found by Gupta et al (1998), however they did not determine the reduced collector area but showed how it increases the digester temperature.

In conclusion, a solar assisted digester should involve insulation efforts focussing on predominantly the walls and to a lesser extent the inlet, outlet and the base. An economic analysis has to be conducted to determine trade-offs between insulation and the collector area. Furthermore, in relative mild climates, such as some areas in Georgia, the temperature can be maintained by hot charging, for an insulated digester with a k-wall and base of 2 $W/m^2.K$ or less. In other countries this is only feasible for an very well insulated digester with k-wall of 0,33 $W/m^2.K$.

Further research should focus on scale effects; a larger digester has a relative smaller surface area and hence the exposure to the cold soil is less per unit of volume. A larger digester is very interesting for households in cold climates for more gas production; with the additional gas other services such as room heating are possible. Another approach would be to operate the digester at mesophilic temperatures or even higher as studied by Mashad et al (2004). A higher temperature results in higher microbial activity and thus both the retention time can decrease and the loading rate increase. By doing so, the digester remains relatively small but more biogas can be produced for services such as room heating provided sufficient biomass is available.

Chapter 6

CARBON FINANCE FOR BIOGAS PROJECTS

The clean development Mechanism (CDM) is a mechanism which allows for the transfer of low carbon-technology to developing countries in exchange for carbon credits. This chapter provides an overview of this mechanism and the opportunities and risks associated for the promotion of domestic biogas plants. Another approach to obtain carbon revenues is the voluntary market. Both markets have their disadvantages and advantages.

In addition, the biogas projects registered and under validation by the CDM executive board are studied to determine the amount of credits obtained and how these credits are spent.

FIGURE 44: THE ESSENCE OF EMISSION TRADING (HEEGDE, 2008)

6.1 INTRODUCTION

In 1992 the UNFCCC (United Nation Framework on Convention on Climate Change) was established as an outcome of the earth summit of the United Nations in Rio de Janeiro to address issues as sustainability and climate change. Subsequently, this was followed by the Kyoto protocol which was adopted to commit developed countries, Annex I countries, to mitigate their GHG emission (Heegde 2008). After ratification by Russia in 2006, the protocol came into force. Annex I countries have to reduce their GHG emission relative to 1990 in the period 2008-2012 by a certain defined amount, around 6-8%.

Three flexible mechanisms were introduced to curb GHG emission cost-effectively; one of them is the clean development mechanism (CDM). CDM allows Annex 1 countries to invest in carbon saving projects in developing countries in return for Certified Emission Reductions (CERs) (Anaya de La Rosa 2006). A CER equals 1 tCO_2 equivalent. The host party, the developing country, is assisted by this mechanism in achieving sustainable development, which is the second goal of the UNFCCC, next to GHG mitigation (Heegde, 2008). A domestic biogas plant contributes both to sustainable development and GHG mitigation as became clear in chapter 3. For this reason carbon finance is applicable for biogas projects as will be elaborated in this chapter.

THE CDM PROJECT CYCLE

The CDM procedure consists of two periods, the approval period and the crediting period. The basic typicality's of these periods are explained hereunder, see also the next figure.

1. The approval period

Project design: This stage includes developing a project concept, writing of a project identification note (PIN) and the development of a baseline and monitoring methodology and stakeholder consultations. The project owner overseeing this process is called the project proponent (PP).

***Project concept*:** the PP conducts a feasibility study to assess the technical feasibility, investment requirements, a risk assessment, administrative and project impact. This report is the foundation for a project concept.

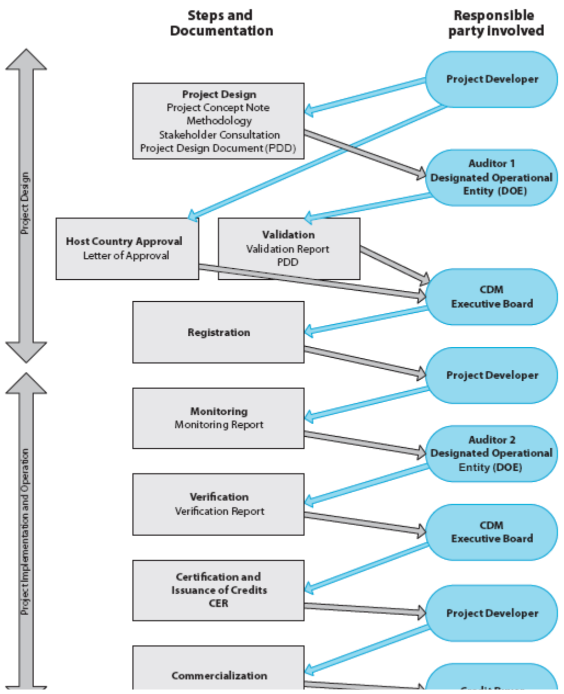


FIGURE 45: CDM PROJECT CYCLE (KOLLMUS, ZINK ET AL. 2008)

Methodology: A CDM methodology defines the rules that a project developer needs to follow to establish a project baseline and to determine project additionality to calculate emission reductions and to monitor the parameters used to estimate actual emission reductions (Kollmuss, Zink, & Polycarp, 2008). A baseline study assesses the baseline GHG emission in absence of the project and if required certain sustainability criteria are part of the study. Based on the study an *ex ante* estimation of the GHG emission reduction for prospective CERs is determined.

Stakeholder consultation: Under the CDM the PP has to prove that the project activities do not have an negative impact on the local population and other stakeholders. The PP has to ensure that all relevant stakeholders have had the opportunity to comment on the project.

PDD: based these activities a PDD (Project Design Document) is written. A PDD basically describes the CDM project activity in detail and is the basis for all future planning and administrative procedures (Kollmuss, Zink, & Polycarp, 2008).

Project validation: A designated national authority (DNA) has to inspect the project, the PIN or more often the PDD, on certain sustainability criteria and based on that, issues a letter of no objection (LONO) (Heegde, 2008). Subsequently the PDD with the LONO is submitted to a designated operational entity (DOE) for validation, auditor 1. A DOE has to perform a technical check to establish whether administrative and legal procedures are followed correctly, the correct methodologies are applied and if the targeted emission reduction is realistic (Heegde, 2008). The validated PDD is subsequently submitted to the executive board (EB) of the CDM for registration. From that moment the crediting period starts.

The main costs are apart from the time investment of the PP, the validation by the DOE. Ball-park estimations by Heegde (2008) are around €12.500 for validation (for small scale biogas projects), consultancy fees, if the baseline study or other parts are subcontracted, around $10.000-20.000 (Heegde, 2008). Additionally, a fee is levied on the amount of CERs generated, US$0,10/CER below 15.000 CERs/year and above US$ 0,20/CER to a maximum of US$350.000.

2. The crediting period

The crediting period does not immediately result in a carbon cash inflow. Firstly, the PP is responsible to monitor the project and has to assess if the carbon offsets are realized as predicted. On a defined interval the PP can sell the generated CERs, but to do so, the CERs have to be verified by a DOE. After the verification, the EB will certify the CERs to the project and only after that moment CERs can be sold. The total crediting period is either 10 years or 3 times 7 years, for the latter the whole process is repeated after 7 years.

The PP can sell CERs at an earlier stage to an interested buyer via emission reduction purchase agreement (ERPA). However, since there is more risk involved in this, the CERs are accordingly lower valued (Heegde 2008). However, ERPAs might be interesting for the PP since it offers upfront payment during an early stage of the project.

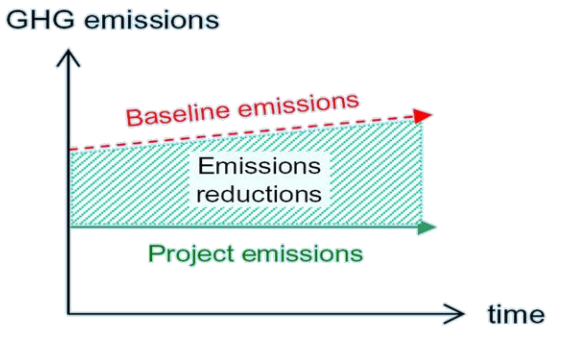


FIGURE 46: GHG EMISSION OF BASELINE THE PROJECT AND THE REDUCTIONS

The purpose of the whole CDM project cycle is to obtain CERs which are reliable and contribute to sustainable development. The generated CERs are the GHG mitigation of the baseline emissions in absence of the project minus the project emissions, see figure 47.

Eligibility for carbon finance – *additionality*
An important aspect of carbon finance is the concept of additionality. It has to be proved that the project is not economic or financially feasible or is not the most economic or financially attractive[8]. Otherwise, the CDM revenues have no additional value and are sponsoring financially attractive projects.

In the case of biogas projects, some examples are given of significant barriers for which additionality is safeguarded[9]:

1. Investment barrier: in the case the initial investment is too high for the households.
2. The costs for large scale dissemination of biogas plants, related maintenance and service are too high for the project coordinator or developer.
3. There is insufficient local knowledge available for an autonomous take-off of the technology.

Carbon markets
Global market exists on the virtue that neither GHG emission mitigation nor GHG emission has boundaries. CDM allows annex 1 countries to offset their emissions in non-annex 1 countries. There are two carbon markets (Heegde 2008):

1. The UNFCCC compliant market to trade CERs.
2. A parallel voluntary offset market, the non-compliant market where everyone can claim and sell carbon offsets. This market is outside the Kyoto Protocol.

The generated carbon offsets for the voluntary market are designated as voluntary emission reductions (VERs). One VER represents 1 tCO_{2eq}, similar to one CER. Procedures and rules are very different of both markets. The CER market is well documented and project eligibility are tightly controlled under the provisions of the Kyoto Protocol, while the VER market lacks these provisions and control (Eggertson 2008).

The VER market
The VER market is everything outside the CER market. Since VERs are obtained without the elaborated procedure of CDM and sometimes even without independent auditors, the quality is at stake. According to Eggertson (2008) there is a tendency towards higher VER standards, but at the moment basic CDM procedures such as additionality are not always scrutinized (Eggertson 2008).

The main standards to ensure a high quality VERs are: the Gold Standard (GS) for premium standard VERs and the Voluntary Carbon Standard (VCS) the minimum standard VERs. Other standards are somewhere in between, such as the VER+ standard, the CCB

[8] From the additionality tool of the EB, see
http://cdm.unfccc.int/methodologies/PAmethodologies/AdditionalityTools/Additionality_tool.pdf
[9] From the gold standard methodology, see
http://www.cdmgoldstandard.org/uploads/file/GS%20biodigester%20methodology%20301007%20Final.pdf

standard and the social carbon methodology (Kollmuss, Zink et al.2008). The mentioned standards have the same project cycle as the CDM project cycle.

The gold standard (GS) has the highest quality control and is endorsed by a great number of environmental groups, such as Greenpeace and WWF (Eggertson, 2008). The gold standard is also applicable to CDM, generating GS-CER, premium carbon credits. The standard rewards only energy efficiency and renewable energy projects, they promote '*emission reduction from the beginning*'[10] as stated on their website. Which means, they do not invest in projects which allows the continuation of current bad practices, such as investing in deforestation or afforestation (carbon sequestration projects) to compensate for fossil fuel emissions, but only in projects which involve *'behavior change'* , to lesson our dependency on fossil fuels[10].

The value of carbon credits

All carbon credits are equal, but some are valued more (Heegde 2008). However, the credits with the highest value are not always the most cost-effective way to obtain financing for a project. The transaction costs, verification, validation, monitoring and other costs are generally the highest for CERs, which can offset the higher value of CERs (Heegde 2008).

The next table shows an overview of the value of the credits from the different carbon standards. In addition, the requirements for the additionality and the co-benefit generation are shown relative to CDM procedures. Co-benefits are, for instance in case of a biogas installation, indoor air quality improvement, time saving, less cleaning efforts and sanitation improvement.

TABLE 34: VALUE OF CARBON CREDITS AND BASIC REQUIREMENTS RELATIVE TO CDM RULES AND REGULATIONS (KOLLMUSS, ZINK ET AL. 2008)*

Standard	Additionality rigidity	Co-benefits	Carbon unit (1 tCO_{2eq})	unit price
Clean Development Mechanism (CDM)	=	=	CER	€14-30
Gold Standard CER	=/+	+	GS-CER	>€10
Gold Standard VER	=/+	+	GS-VER	€10-20
Voluntary Carbon Standard (VCS)	=	-	VCU	€5-15
VER+	=	-	VER+	€5-15

* Symbols mean: = is equal to CDM procedures, - is less stringent and + is more stringent, according to the analysis of Kollmuss, Zink et al.2008)

Prices are expected to rise in the future, currently a CER is around €17(December 2008) while credits under the European trading scheme are around €22 (Tilche and Galatola 2008).

Contribution to sustainable development

Not all standards put sustainable development (the generation of co-benefits) as strict as CDM. This could result in projects which only consider emission reduction and ignore possible negative externalities, see the next box.

[10] from www.cdmgoldstandaard.org

Box 3: Inconsideration of externalities of a carbon project

An example of this is a recent practice of a carbon offset company, stichting (= NGO) Face which planted trees in Uganda on farmland for various energy companies, both from the Netherlands (Driehuis 2008). By planting trees the energy companies were able to avoid shutting down their polluting coal fired power plants and to deliver '*green*' gas to the Dutch consumers. Green gas is nothing more than natural gas whereby the GHG emission is offset by buying carbon credits. In their search for a cost-effective carbon credits, stichting Face planted trees in Uganda. The unfortunate outcome was that the land of which stichting Face had concessions of from the government, was populated for ages, but the government failed to recognize the rights of the people living there. The people inhabiting that area were subsequently chased away, and sadly, the concessions last for 99 years. Legally, the offset company in the Netherlands did nothing wrong, however, it did not involve stakeholders and did not assess the impact on the local population as required by some standards and CDM. According to the website of Stichting Face, the credits are according to the VCS standards. As shown in the previous table, the standard[1] is not stringent, and indeed, none of the money generated flows back to the local population.

This is a clear example of how projects can do more damage than good without strict procedures concerning stakeholder involvement and co-benefits. The implication of the negative attention resulting from these malpractices could be that the public looses interest in offsetting their carbon emissions.

Fortunately, as Eggertson (2008) also mentioned, there is a tendency to opt for higher quality standards. This is in line with the Rio declaration on sustainable development in 1992 and the spirit of second objective of CDM: *'contribute to sustainable development in the host country'* (Anaya de la Rosa 2006).

This chapter does not intend to provide a detailed analysis of the different carbon markets, but merely to introduce the main concepts and its applicability to biogas projects. The key to obtain carbon funding is emission reduction, how and how much is possible with domestic biogas plant is explained next.

6.2 PRINCIPAL PATHWAYS OF GHG EMISSION AND MITIGATION

Global warming potential

In this chapter three GHGs are mentioned, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), the main gasses of which the emissions are affected by a biogas plant (Bhattacharya, Thomas et al. 1997). These gasses differ in their impact on global warming both in time and in radiative efficiency (Forster, Ramaswamy et al. 2007). A simple and purely physical index, the global warming potential (GWP) was developed by the IPCC in 1990 to compare gasses based on a time-integrated global average radiative forcing of a pulse emission of a GHG relative to that of 1 kg CO_2. The obtained values are the global warming potential (GWP) of gasses which is also adopted by the Kyoto protocol, see the next table on GWP (Foster, Ramaswamy et al. 2007).

TABLE 35: GHG AND THEIR GLOBAL WARMING POTENTIAL

GHG (common name)	Chemical formula	GWP (time horizon = 100 years)	
		SAR[1]	TAR[2]
Carbon dioxide	CO_2	1	1
Methane	CH_4	21	25
Nitrous oxide	N_20	310	289

[1] Second Assessment Report and [2] Third Assessment Report of the IPCC. Values from Foster, Ramaswamy et al. (2007)

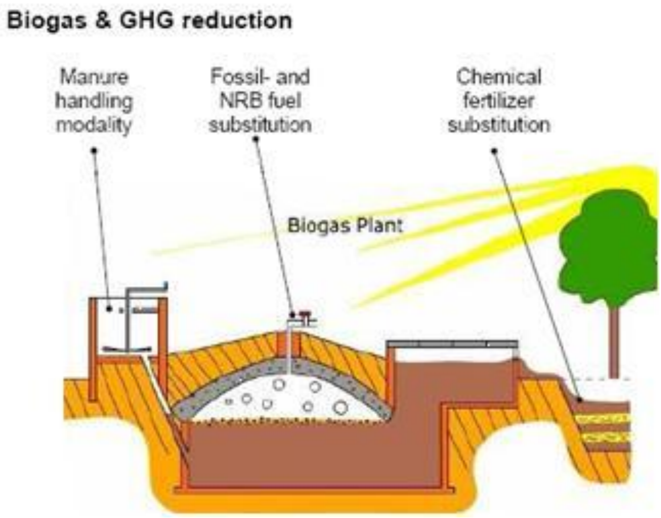
The difference between the GWP reported by the SAR and TAR is due to new scientific insight and understanding. By using the GWP, all gases can be converted into CO_2 equivalents, (CO_{2eq}), one ton of CO_{2eq} is denoted as tCO_{2eq}. Not all gasses are equal, and this is the key point why a biogas plant mitigates GHGs as later on will become clear.

Pathways of GHG emission affected by the adoption of biogas plants

A biogas plant mitigates GHG via the following main pathways (Pathak, Jain et al. 2008):

1. Fuel switch substituting fossil fuel or non renewable biomass
2. Chemical fertilizer substitution
3. Change in manure management modality (Heegde 2008)

Pathak, Jain et al (2008) also add to this list saved trees since trees absorb carbon from the atmosphere during the majority of their lifetime.



PICTURE 13: GHG REDUCTION OF A BIOGAS PLANT (HEEGDE 2008)

1. FUEL SWITCH TO DISPLACE FOSSIL OR NON RENEWABLE BIOMASS

The captured biogas from AD can be utilized for various energy services, and by doing so, it displaces other fuels. As aforementioned, the priority of most users is biogas for cooking and secondly for lighting. Depending on the local customs and availability of fuels, either fossil fuels or biomass is displaced.

Obviously, in the case of biomass, this only applies to non renewable biomass (NRB). Biomass is a carbon sink due to the uptake of CO_2 for photosynthesis and consequently carbon is sequestered in biomass. When biomass is utilized as a cooking fuel, the carbon is converted to CO_2 and released to the atmosphere. Only in the case when the uptake of carbon by photosynthetic plants equals or is higher than the emission of CO_2, biomass can be considered renewable (Sagar and Kartha 2007). In every other case, biomass is NRB in varying fractions for a *specific* source area of biomass. In the case of fossil fuels it is quite straightforward. Fossil fuels are sequestered carbon and hence when burned or combusted the stored carbon is released, leading to an increase of CO_2 in the atmosphere.

Furthermore, combustion of wood, crop residues, coal, kerosene, does not only result in CO_2 emission, but also small quantities of methane and N_2O are emitted (Zhang, Smith et al. 2000). Zhang, Smith et al. (2000) measured the emission of a stove running wood, which amounted 1,52 kg of CO_2, and 5,06 gram of methane. Consequently, combusting wood can result in a net-GHG emission due to the higher GWP of CH_4 even from a renewable source!

2. CHEMICAL FERTILIZER SUBSTITUTION

The fertilizer value of digestate has properties similar to chemical fertilizer and is superior compared to manure, see chapter 3.11. If digestate substitutes otherwise used chemical fertilizers, the following sources of GHG emission are avoided (Bhattacharya, Thomas et al. 1997).

- GHG emission caused by the transportation of chemical fertilizers from the place of production to the site of application.
- Avoided primary energy use for the production of chemical fertilizers and the associated GHG emission.
- Avoided N_2O and CO_2 emission resulting from the application of chemical fertilizer to the soil (Heegde 2008). The GHG emission from the application of fertilizers fall in the category agricultural soil emissions of the IPCC.

For instance, Urea ($CO(NH_2)_2$, an important N-releasing fertilizer, is converted to ammonium (NH_4^+), hydroxyl ion (OH^-) and bicarbonate (HCO_3^-), the latter evolves partly into CO_2 and water, hence carbon dioxide is released (Klein, Novoa et al. 2006). Commercially produced urea uses CO_2 from fossil fuels (Klein, Novoa et al. 2006).

An attempt to estimate the CO_2 emission from the production of chemical fertilizers resulted in the following relationship on mass basis (36) (Pathak, Jain et al. 2008):

$$Emission\ CO_2 = N\ content\ \times 1{,}3 + (Pcontent + K\ content) \times 0{,}2 \qquad \textbf{(35)}$$

N_2O is produced in the soil by bacteria under aerobic conditions via the processes of nitrification and denitrification. Whereby during nitrification ammonium is oxidized under anoxic conditions to nitrate and during denitrification nitrate is reduced to N_2. An intermediate is N_2O of the denitrification process and a by-product of nitrification. (Klein, Novoa et al. 2006). The emission factor for mineral fertilizers applied on managed soils, such as urea, is 0,01 kgN_2O-N per kg N according to the IPCC 2006 guidelines.

The emission factor of N_2O for cattle, poultry and pig manure is twice as high compared to chemical fertilizers containing N (Klein, Novoa et al. 2006). Hence, the use of digestate to displace manure as fertilizer also avoids N_2O emission (Klein, Novoa et al. 2006). N_2O emission for digestate is considered to be insignificant by Klein, Novoa et al (2006), but as Zeeman (2008) pointed out there is a great deal of uncertainty involved and it is not well studied by the scientific community (personal communication)

For this reason and others, these emissions are not covered by any accepted CDM or other carbon methodologies.

3. CHANGE IN MANURE MANAGEMENT MODALITY

The mitigation potential from the manure management modality depends entirely on manure management practices. For instance, if manure stored in a wet environment most of the manure will decompose anaerobic, hence methane is released to the atmosphere. If manure is however stored in a dry environment, it decomposes predominantly aerobically with minimal methane emission. This is clearly reflected in the next table, the dryer the manure is stored, the lower the methane conversion factor (MCF). The MCF represents the portion of the biochemical methane potential (BMP), which is converted into methane.

The figures in the next table, have an uncertainty of ±20%, this is the result of the complexity of the matter and the great number of parameters which affect methane production (Hongmin, Mangino et al. 2006).

TABLE 36: MCF AS FUNCTION OF TEMPERATURE AND MANURE HANDLING SYSTEM

Manure handling system		MCFs by average temperature (°C)		
		<10-14	15-25	26-28+
Pasture/range/paddock		1%	1,5%	2,0%
Daily spread		0,1%	0,5%	1,0%
Solid storage		2,0%	4,0%	5,0%
Dry lot		1,0%	1,5%	2,0%
Liquid/slurry (with natural crust cover)		10-15%	17-41%	44-50%
Liquid/slurry (without natural crust cover)		17-25%	27-65%	71-80%
Uncovered anaerobic lagoon		66-73%	74-79%	79-80%
Pit storage below animal confinement	< 1 month	3%	3%	30%
	> 1 month	17-35%	27-65%	71-80%

Copied and adapted from (Hongmin, Mangino et al. 2006). Definitions of each system can be found in annex 7

In an anaerobic digester methane is recovered and captured for energy services. Technically this is referred to as methane capture and destruction (Heegde 2008). When the methane content of biogas is combusted, the main GHG emission is carbon dioxide. While this is also a GHG, it can be considered renewable as the emission equals the absorption by the plants/crops for their photosynthesis. Consequently, the carbon cycle is closed; the emitted carbon dioxide belongs to the so called short cycle carbon emission (Jarvis 2000).

Leakage emission from biogas plants

Leakages are emission sources resulting from the implementation of a technology. The retention period of substrate in a digester is finite and thus the effluent contains biodegradable substrate to some extent which is under the right conditions converted to methane. Also the effluent chamber (the displacement tank), the influent chamber, the time between manure production and the digester feeding, the storage area of substrate, effluent storage and the application to the field, are all potential sources of methane emission (Khoiyangbam, Kumar et al. 2004). The next figure shows emission from the influent and effluent.

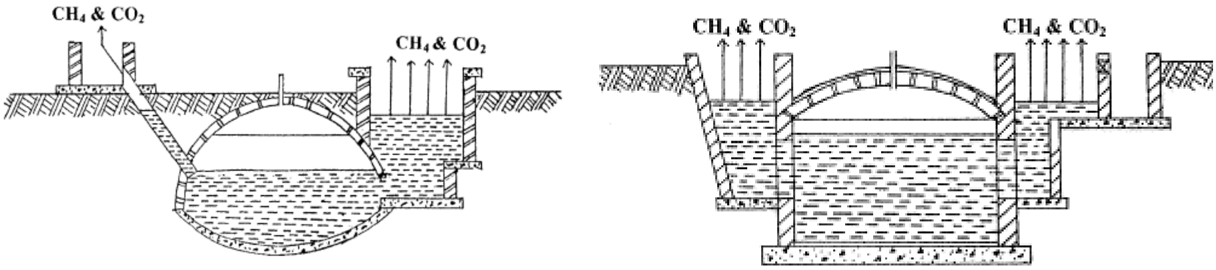


FIGURE 47: LEAKAGE EMISSION FROM A DEENBANDHU AND A JANATA BIOGAS PLANT (KHOIYANGBAM, KUMAR ET AL. 2004)

The IPCC estimates the leakage emission of biogas plants to 5-15% of the total methane production (Pathak, Jain et al. 2008). In many biogas programs a value in that range is taken depending on the local conditions. For instance the baseline study conducted for the National Biodigester Programme Cambodia took the average value of 10% of the total biogas production (Buysman and Mansvelt 2006) and the same by a macro study on GHG emission from biogas plants in India (Pathak, Jain et al. 2008). Taking the average value is a simplification, but to determine the average leakage emission of a great number of biogas plants is in most cases too cumbersome.

In the hilly regions of India a study was conducted to assess methane emission from the influent and effluent chamber (Khoiyangbam, Kumar et al.2004). They concluded that methane emission follows the temperature variation closely, both seasonally and diurnal, much alike the trend of the MCF values, see the previous table. The next figure shows their results.

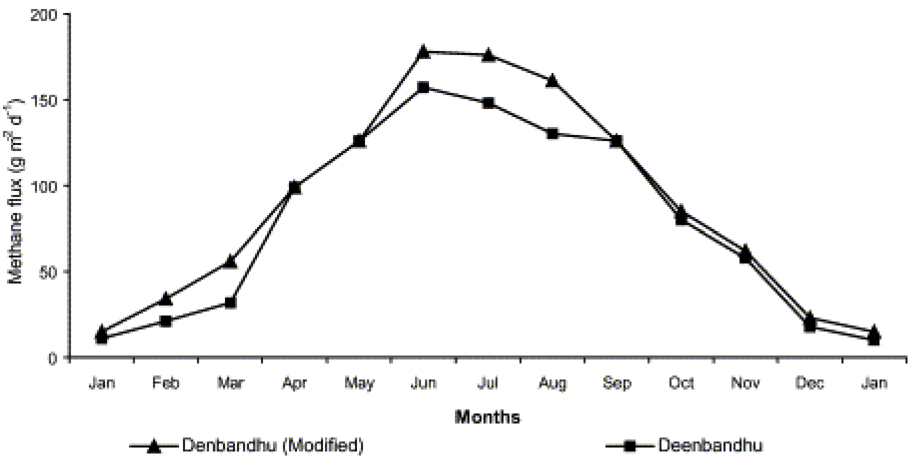


FIGURE 48: METHANE FLUX OF TWO 2 M³ FIXED DOME PLANTS (KHOIYANGBAM, KUMAR ET AL.2004).

Unfortunately, they did not study the percentage of methane lost compared to the total amount of methane emission. It does indicate however, that leakage emissions from biogas plants in countries with cold climates are likely to be lower than the average due to the low temperatures. However, the storage time before the effluent is applied to the fields is longer than in tropical countries with 2 or 3 growth seasons. Since the emission is a product of both time and temperature, the reduced emissions could be offset by the longer storage period.

N_2O emission reduction from AWMS

Another important gas which emission is affected by a change in manure management modality is N_2O. How N_2O is produced is explained in the previous paragraph. An important parameter for the N_2O emission is the storage period and the type of storage. From the moment manure is applied to the fields, the emissions are regarded as agricultural soil emission by the IPCC. In the paragraph chemical fertilizer substitution there is a short introduction on soil emissions. Because, soil emissions are not part of the manure management, daily spread for instance has no GHG emission resulting from the short period it is retained. Selected default emission factors are shown in the next table.

TABLE 37: EF OF N_2O EMISSION OF SELECTED MANURE SYSTEMS AND THE GWP

System	Definition	EF (kgN_2O-N/kg N content)	Adjusted by GWP (kgCO_2eq/kg N content)
Solid storage	Stored in piles or stacks for several months	0.005	1,445
Dry lot	Stored in open confined area and removed periodically	0.02	5,96
Liquid/slurry	Stored in tanks or ponds without the addition of water	0.005	1,445
Anaerobic digester	Closed environment for biogas capture and destruction	0	0

Source: IPCC 2006 guidelines

Previously, asserted was that digestate has similar proportions to chemical fertilizers and hence the presence of the ammonium ion could result in N_2O emission. The EF is however zero in the judgement of the IPCC expert group, for two reasons (Klein, Novoa et al. 2006):

1. The absence of an oxidized from of nitrogen
2. The low potential of nitrification and denitification in the slurry

As stated earlier, this judgement goes along with a considerable amount of uncertainties and therefore N_2O emission reductions are not accounted for by any methodology.

6.3 METHODOLOGIES TO APPRAISE CARBON MITIGATION

Not all the emission sources are approved by the EB as discussed in the previous chapter. Under CDM a number of methodologies are approved to determine the GHG emission. A PP can however, propose new methodologies to the EB. The approval of methodologies under CDM is the responsibility of the EB and the EB is acting under the authority and guidance of the meeting of the parties (COP/MOP) of the Kyoto protocol (Möllersten and Grönkvist 2007). Once approved, the methodologies apply to all coming projects.

SSC (small scale) CDM methodologies are only applicable to domestic biogas projects (Heegde 2007). The advantage is that these methodologies are simplified, have a shorter review period prior registration of the project activities and it is allowed for one DOE to validate, verify and certify emission reductions. SSC projects are limited to a certain size, depending on the project type, see the next table.

TABLE 38: PROJECTS TYPES AND SSC BOUNDARY SIZE

Type	Project activity	SSC boundary
I	RE (renewable energy) projects	< 15 MW electricity or 45 MW thermal
II	EE (emission efficiency) projects	< 60 GW hours per year
III	ER (emission reduction) projects	< 60 $ktCO_{2eq}$ /year

From the CDM rule book: www.cdmrulebook.org

In the case of domestic biogas installations for a fuel switch and AWMS, three SSC CDM methodologies are approved at the moment (30-12-2008), the following is sourced from the UNFCCC website.

TABLE 39: THE MAIN METHODOLOGIES APPLICABLE TO DOMESTIC BIOGAS PROJECTS

Reference	Type, number and SSC Methodology title
AMS-I.C	***I.C. Thermal energy for the user with or without electricity***
	Key points: This methodology entails all renewable energy technologies that displace fossil fuels for thermal energy (i.e. cooking and heating). For the GHG emission the IPCC default values may be used. The methodology does not apply to NRB. Leakage has to be considered if the energy generating equipment of the baseline is transferred to the project or another activity.
	History: 28 march 2008, version 13
AMS-I.E.	***I.E. Switch from Non-Renewable Biomass for Thermal Applications by the User***
	Key points: This methodology entails the displacement of NRB for small thermal appliances by renewable fuels, such as biogas. For the emission reduction the fraction of NRB has to be established using nationally approved methods, survey or governmental data. The definition of renewable biomass (RB) is found in Annex 18, EB 23. To determine NRB, a multiple indictor assessment is necessary to supply sufficient evidence, such as increasing time expenditure on wood gathering, increasing prices, trends in type of biomass used next to historical or remote sensing data. Leakage only has to be considered if NRB is substituted by RB.
	History: Initial adaption since 1st of February 2008
AMS-III.D	***III.R. Methane recovery in agricultural activities at household/small farm level***
	Key points: Applies to the recovery and destruction of methane which would in absence of the project lead to release of methane to the atmosphere. The methodology is limited to 5 tCO_{2eq}/year/household. Precautions must be in place to prevent emissions if applied to the fields, furthermore, the captured methane has to be destroyed, i.e. combusted for cooking needs. The IPCC tier 2 approach has to be followed for the baseline emissions.
	History: Initial adoption 19 October 2007

Source, the UNFCCC site: http://cdm.unfccc.int/methodologies/SSCmethodologies/approved.html

The above mentioned methodologies are subject to change, for instance, the precursor of AMS-I.D was on hold until March 2008. The above mentioned methodologies can be combined for one project activity. In case biogas is used for other activities, such as electricity generation, other methodologies apply.

Some of the methodologies also apply for the voluntary market while there are also dedicated methodologies developed, see the next table.

TABLE 40: VOLUNUTARTY MARKET METHODOLOGIES

VER standard	Approved methodologies	Remarks
Gold Standard (GS) (www.cdmgoldstandard.org)	For CER only CDM methodologies apply, for VER dedicated methodologies might be available. For biogas a small scale methodology is available: Small scale Biodigester Methodology 301007.	The biogas methodology incorporates the GHGs CO_2 and CH_4 for both the baseline and project activity.
Voluntary Carbon Standard (VCS) (www.v-c-s.org)	CDM methodologies and California Climate Action Registry (CCAR)	CCAR is only applicable to projects in California.
VER+	CDM methodologies	New standard

Sourced from the respective websites

None of the methodologies allow for N_2O emission reductions and hence the calculated GHG mitigation using the methodologies is a conservative approach. However, that approach does cover uncertainties and not recognized or considered leakages. To provide some insights, the baseline study for NBP Cambodia found, based on their survey among 300 households, an emission of 1,07 tCO_{2eq} - N_2O/year, around 33% of the total manure management related emissions based on the IPCC 1996 default guidelines (Buysman and Mansvelt 2006). Hence, a significant proportion of GHG abatement is not accounted for under CDM or any other scheme.

Recent developments in methodologies

Contemporary developments are the concept of satisfied and suppressed demand and program of activities or programmatic CDM.

- ***Suppressed and satisfied demand***

This concept assumes that in the baseline situation, households do not have access to the required domestic energy against the comparably better off household. They suffer from suppressed demand and therefore the satisfied demand situation can be taken as baseline. The main advantage is that this avoids the cumbersome establishment of a NRB fraction by using the baseline of a corresponding technology, i.e. LPG stoves. Furthermore, without this concept no reduction claims are possible if dung is dried and used as a cooking fuel, since dung is considered renewable. With this concept the full amount of energy consumption is applicable for the baseline emissions. This concept is at the moment only possible for the Gold Standard-biodigester methodology (Heegde 2008). In the future, it might however be approved by the EB as well.

- ***Program of Activities (PoA), programmatic CDM***

This allows adding a similar project, even from other countries, to a PoA, after the registration of a PoA, The new project only requires validation. This has several advantages, such as standardization of CDM administration and a better negotiation position in selling carbon credits due to the larger amount of credits available. However, the administrative requirements for the registration of a PoA are significant and a major drawback is that at the moment only one methodology can be used (Heegde 2008). If the latter changes in the future, it may be very interesting to combine biodigester projects within or between countries.

6.4 REDUCTION CLAIMS AND PROJECT FINANCING

Carbon revenues, CERs or VERs, are by definition 'helping' the project developer to promote low carbon technology or carbon saving technologies such as biogas plants resulting from the obligation of additionality. This section will consider what can be expected in terms of carbon offsets of a biogas plant and the related carbon revenue generation.

The CDM registry is studied on biogas projects which are certified or under validation to determine the amount of GHG emissions claimed per household digester (as of December 2008). The next table shows the small scale biogas projects which are in the CDM registry. Most of the projects are still in the phase of validation, but a PDD is drafted and available on the CDM site. Furthermore, the baseline fuel is shown to assess which fuels biogas will displace.

TABLE 41: GHG REDUCTION OF VARIOUS BIOGAS PROGRAMS

Title	Year (PDD)	Country	Methodology	Phase	Baseline fuel	Units (1000)	tCO_{2eq}/ yr.Unit
Bagepalli CDM Biogas Programme	2005	India	1 (V5)	reg.	NRB & kerosene	5,5	3,56
BSP activity 1	2005	Nepal	1 (V6)	reg.	Wood and kerosene	9,7	4,99*
BSP activity 2	2005	Nepal	1 (V6)	reg.	Wood + kerosene	9,7	4,99*
Vedaranniyam Biogas Project	2006	India	1 (V9)	val.	Kerosene	12	2,85
Kolar District biogas project	2006	India	1 (V9)	val.	Kerosene	12	2,85
Kolar Biogas project	2008	India	1 (V13),2,3	val.	Kerosene	10	6,19
Hassan Biogas project	2008	India	1 (V13),2,3	val.	NRB, kerosene	10	6,19
Hubei Eco-Farming Biogas Project Phase I	2007	China	1 (V12),3	val.	coal	33	1,76
Biogas CDM Project of Bagepalli Coolie Sangha	2008	India	1 (V13), 2	val.	Kerosene and NRB	18	3,94
SEDS biogas project	2008	India	1 (V13), 2,3	val.	NRB and kerosene	5	3,31
NBP Cambodia phase I	2008	Cambodia	1,2,3 (VER)	-	NRB	17,5	4,40

*capped to 4,99, the maximum GHG mitigation allowance for AMC-I.C.. 1= AMC-I.C, Vx = version of 1, 2 = AMS-I.E. 3 = AMS-III.D, reg.= registration, val. = under validation

Previous the approval of AMS-I.E, NRB was included in AMS-I.C, therefore the programs of Nepal for instance use only one methodology which covers both fossil and NRB fuels.

The average GHG reduction per biogas unit is 4,01 tCO_{2eq}/year with a standard deviation of 1,4 of all the projects, which is somewhat higher for the plants with AMS-III.D and lower without AMS-III.D, see table 41. SNV estimates a range of 1,7 to 5,9 tCO_{2eq} per domestic biogas plant per year, based on their assessments of the various biogas programs in which they are involved in (Heegde 2008). In a macro study on biogas in Nepal, the mitigation of a domestic biogas plant was calculated to 5 tCO_{2eq}/year, of which 6,6 tCO_{2eq} reduction because of the displacement of NRB fuels and (-) 1,6 tCO_{2eq} resulting from leakages (Pokharel 2007). Pathak et al (2008) calculated 9,7 tCO_{2eq}/year per domestic biogas plant in India, however they did not follow established approved methodologies. The saved GHG emission of chemical fertilizers substitution was included and their estimation of firewood consumption was very high, 15,1 kg/day per household, which is much higher than other studies, for instance in Cambodia 8,95 kg/day was found per household (Buysman and Mantsvelt, 2006). It does demonstrate however, that the obtained emission reduction figures using CDM methodologies are conservative and do not represent the total GHG reduction.

Obviously, the total amount of GHG mitigation depends on local situation, the size of the installation, the kind of fuels biogas substitutes and how the installation is operated and this is especially the case of methane emissions. For instance, SNV reports that in some countries in Africa animals are not kept near the houses/farms but are freely roaming around (Heegde 2008). Hence manure is excreted in the fields, sundried and decomposes primarily aerobic without releasing methane, hence a biogas installation would not incur GHG emission abatement resulting from AWMS.

The next table shows the average GHG mitigation which is claimed by the various biogas programs. Furthermore, the potential carbon revenues are calculated per domestic household sized digester, excluding costs for validation, registration and verification. The estimations of the report of Heegde (2008) from SNV are also used.

TABLE 42: ESTIMATED CARBON INCOME PER DOMESTIC DIGESTER AND CARBON STANDARD

Methodology	tCO_{2eq}/year mitigation	CER	GS-VER	VCS	Heegde
		€17	€15	€10	€8
AMS-I. C & AMS-I.E	3,78 (0,9)	64,3	56,8	37,8	30,3
+ AMS-III-D*	4,64 (2,1)	78,8	69,5	46,4	37,1
Average	4,01 (1,4)	69,6	61,4	40,9	32,7

* AMS –I.E & -I.C and AMS-III.D. Prices are averages from table 33 except the CER which is the value reported by Tiche and Glatola (2008), because the average price of CERs from table 33 is rather high in the opinion of the author. The SD is in parenthesis.

The table shows that between 38 and 79 euro per digester per year could possibly be obtained by selling VERs or CERs. Heegde (2008) used a conservative value but he/she also stated that the value was likely to be higher. Tiche and Glatola (2008) expect that the carbon value will increase with the coming years, which supports the view of Heegde (2008).

Peculiarities of the biogas programs

Note the difference in emission claims of the two biogas programs in Kolar, India. Presumable at the time, AMS-III.D was not approved or on hold and therefore the Kolar district program did not include that methodology. The other program in Kolar state in their PDD that manure and urine is stored in a deep pit, whereto also kitchen waste flows and the pit is flooded with water during the rainy season. Hence, contents in the pit is for some time of the year a lagoon and otherwise a slurry, both with a high MCF and thus there is a considerable methane emission of the animal waste management system.

The program in China, Hubei, has a relatively low GHG mitigation per unit per household, just 1,76 tCO_{2eq}/year. This is caused by the relative high coal consumption after the project implementation. This could reflect the fact that the average annual temperature is between 13,2-17,6°C, and hence, the winter temperature is much lower which might result in insufficient biogas production. During the winter, people might still rely on coal for their main cooking fuel or for space heating. However, judging from the size of the digesters, some mitigation measures to offset the low biogas production are taken. The biogas units in Hubei are large, between 8-15 m^3, much larger than the units in (tropical) India, which are around 2-3 m^3, for instance in Kolar.

Carbon revenues to promote biogas adoption – project implication

The obtained carbon revenues are additional and thus promote the biogas program/project sustainability. Hereunder, the impact on the biogas project financing is sketched using the information from the CDM registry.

TABLE 43: ADDITIONALITY AND USE OF CABON REVENUES

Title	Additionality proofing & impact on financing of the biogas plant
Bagepalli CDM Biogas Programme	Unclear how carbon revenues are used. They state that there is an investment barrier for biogas plants which can be tackled using the carbon income.
BSP activity 1	Additionality proofed by the subsidies needed for biogas plant adoption using an economic sensitivity analysis. Revenues for quality control of biogas plants for successful adoption
BSP activity 2	Same as activity 1
Vedaranniyam Biogas Project	CDM channeled towards mayor proportion of loan repayment. Loans provided by the PP, since famers have no access to credit from banks.
Kolar District biogas project	Same as the Vedarranniyam biogas project
Kolar Biogas project	Same as the Vedarranniyam biogas project
Hassan Biogas project	Applies to biogas systems which do not receive subsidies from the Indian government to overcome the investment barrier. Not clear to what extent and how carbon revenues are used to decrease financing costs
Hubei Eco-Farming Biogas Project Phase I	Financial barrier: CDM used for a loan guarantee mechanism to obtain credits (78%), 12% of revenues for technical service systems and training programs for the households
Biogas CDM Project of Bagepalli Coolie Sangha	No debt facilities available, carbon revenues presumably for loan provision. Not clear to what extent and how carbon revenues are used to decrease financing costs
SEDS biogas project	Similar as Bagepalli Coolie Sangha biogas CDM project
NBP Cambodia phase I	Similar as BSP Nepal

The main use for carbon credits is not directed to lower the costs of the biogas plant but to increase the accessibility to invest in a biogas plant by providing loans. In some case the credits are used for loan repayment, which lowers the total loan and thus the financing of the biogas plant. It is not clear under which conditions the loans are provided, the interest rate and the payback period.

Heegde (2008) performed for SNV an example calculation of the Pakistan National Biogas Program on domestic biogas plants. He/she used an conservative GHG reduction of 3,3 tCO_{2eq}/year/plant, broke down the expenses as €479 as the farmer's investment including financing costs, €226 for the support costs, program activities, assistance and carbon related expenses and an investment subsidy of €77. The value of the CERs/VERs is taken as €8 and the crediting period is 10 years with an assumed annual price increase of 2% and a discount rate of 10%. The next figure shows the results.

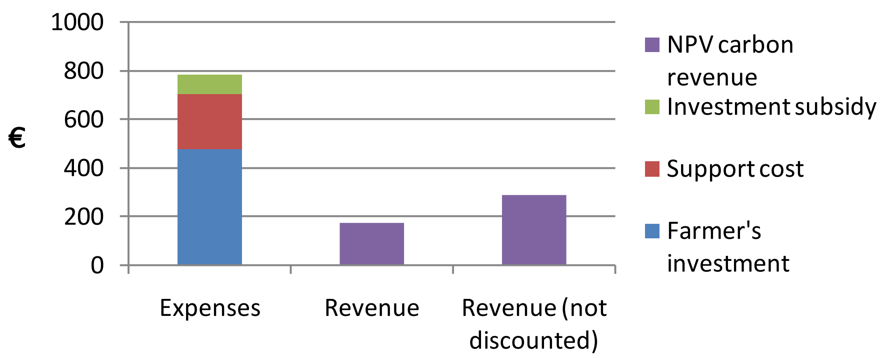


FIGURE 49: PROJECT EXPENSES AND REVENUES PER BIOGAS PLANT

Heegde (2008) concluded that carbon revenues can support to a large extent the support costs of a biogas program.

Pokharel (2007) claims that as a result of the carbon income, the domestic biogas sector became an economic self-sustaining sector in Nepal, even at a carbon price of €5/tCO_2eq. However, to reach the target set by BSP of 200.000 units from 2003 until the end of 2010, costs will increase since most accessible areas are already reached. Hence, the viability of the program cannot be maintained with carbon revenues alone in the near future and additional subsidies are required. Both examples show that the carbon income is very important for the e economic viability of biogas programs.

Opting for the right market, voluntary or the certified market

The calculated GHG mitigation expressed in carbon units can be sold either as VERs or CERs. Heegde (2008) provides some guidelines and these are hereunder described.

- CDM and Gold standard VER biodigester methodology are almost the same, but the post validation procedure (registration, verification and issuance) is likely to be shorter or simpler for the GS-biodigester methodology.
- CERs are more attractive than VERs and will hence have a higher value.
- The absorption capacity of the VER market could prove to be insufficient, which introduces a significant financial risk for projects that are dependent on carbon financing.
- In general, CDM methodologies and procedures are more complicated, lengthy and expensive compared to VER schemes.
- The value of CERs depends on the commitment period, the current period 2008-2012 has more or less set the CER value but beyond 2012 the value is uncertain. This especially impacts projects with upfront payment based on CERs after 2012, which might have a much lower value. VER value is less impacted by the commitment period.

According to Heegde (2008), programs with less than 10.000 units over a 3 year period should opt for the voluntary market, because of the limited economy of scale and therefore the costs for development, validation, registration and verification are disproportionally high. For larger scale programs, CDM and also the GS methodologies are more interesting as the higher costs are offset by the higher valued carbon credits.

6.5 DISCUSSION AND CONCLUSION

This chapter has focused on curbing GHG emission by capturing and destroying methane for energy services to displace fossil or NRB fuels. To obtain carbon revenues certain methodologies have to be followed to calculate the GHG abatement. Most biogas projects/programs use AMS-I.C and AMS-I.E while the more recent programs also include AMS-III.D. The saved GHG emissions can be sold either as VERs or CERs.

From the assessment of the various biodigester projects it became clear that around 4,01 tCO_2eq /year with a SD of 1,4 is on average claimed per domestic household sized digester. In practice the amount of GHG mitigated depends heavenly on the local situation, which is in particular affected by the type of animal waste management system.

Most of the mentioned biogas projects are not in cold climates, but the Hubei biogas project is and BSP Nepal are pushing the limits towards less accessible, colder and high mountainous areas (Gautam, Baral et al. 2009). In cold climates households need an additional energy service, room heating. If a biogas plant can provide biogas for heating, the displacement of NRB or fossil fuels for room heating occurs with the related GHG reduction component. In that case the carbon income would be higher. However, if during the summer there is no use for the additional biogas, there is a risk that biogas is released to the atmosphere which could offset the saved GHGs or even reduce it considering the GWP of methane. Biogas for heating is however very interesting, because it does result in air pollution when combusted and it displaces other fuels which has a time or revenue saving component. A follow up study should determine the feasibility of biogas for room heating without the summer time leakage or otherwise identify additional biogas uses during the summer.

Carbon revenues can to a great extent cover the biogas program costs and since the crediting period is either 10 years or 3 times 7, the maintenance, support and monitoring of the built plants is secure for a similar long period. The registered biogas programs revealed that carbon revenues to cover the program costs is only done for the programs in Nepal and China; in India on the other hand the revenues are mostly used to safeguard loan repayment or to facilitate access to affordable credit. The income from carbon revenues cannot cover most of the digester costs at current carbon prices.

For a solar assisted biogas plant, carbon revenues can be used to offset a part of the higher costs. That is however only possible if the scope of a biogas program is sufficiently large otherwise the transaction costs, for validation, verification and certification, are disproportionally high.

Chapter 7

DISCUSSION & CONCLUSION

Anaerobic digestion in cold climates for domestic, house on site, biogas generation is worldwide hardly practiced. The prime reasons for the limited adoption are the capital investments required to overcome the impact of the low temperatures on biogas production. Consequently, the focus of this thesis is to find innovative and affordable solutions to mitigate the impact of the low temperatures on biogas generation for the rural poor.

This study showed that in relatively mild climatic winters, with average ambient temperatures of 5-10°C, relative simple measures are adequate to avoid a decrease in biogas production. However, in countries with more severe winter, active heating is necessary. One of the possibilities studied is to capture solar for digester heating using solar collectors. In chapter 6 a detailed analysis was provided on the use of solar heat and insulation measures to increase the temperature of digestion.

The transient approach to utilizing solar differs from other studies, like Tiwari and Chandra (1989) and Gupta and Rai (1988). For instance, a detailed assessment was made on the influence of the heat enforcement on the soil with depth and the temperature was not considered to be the annual average. Furthermore, the digester was split up in components since all of them are in contact with soil of a different temperature and have therefore a different heat transmission to the ambient. Finally, the digester was controlled to avoid a heat shock of the microbes and the whole was modeled to resist the most extreme conditions in terms of insolation and temperature to keep the digester temperature at least at 15°C.

The digester model is based on existing well-performing digesters operating at 15°C in India, the digester is able to provide year-round 1,5 m^3 biogas per day. That amount of gas is sufficient to meet the most immediate energy needs of the people. It allows to cook 2/3 meals a day for 5 persons or 2 meals and 3 hours of light from a biogas lamp. The substrate requirement is in that case 43 kilo of fresh cow manure per day per family for the designed digester; consequently their energy supply for cooking is secure. The latter is stressed by the UN as a prerequisite to achieve the Millennium Development Goals. Whilst it also allows people to make a big leap on the energy ladder, from using wood, coal or agricultural residues to one of the most benign, versatile and clean fuels; biogas. Furthermore, it saves women from the drudgeries of wood collection, taking care of the fire and removing soot from the cooking pots. Obviously, if bought fuels are used, the use of biogas has other advantages, such as revenues saving. Added to that, if otherwise solid or traditional fuels are used, the indoor air quality is greatly improved by the use of biogas, which benefits all household members, but in particular women and children who are most often near the fire.

Access to sanitation can also be provided if a toilet is attached to the digester, which is a commonplace practice. However, there is always a health hazard since biogas is produced from waste which contains certain pathogens from zoological origin or and from anthropogenic origin if a toilet is attached. The health hazard is the product of the retention time of the pathogens in the digester and the temperature, the shorter the retention time is and the lower the temperature the higher the health hazard. Safley and Westerman (1990) developed a model whereby RT at a given temperature can be determined relative to a digester with a known RT and digester temperature. They showed that at lower temperatures the RT has to increase to accommodate for the lower growth rate of microbes. From the conducted manure batch experiments at psychrophilic temperatures a similar relation was observed albeit that the relation was stronger than Safley and Westerman observed.

Hence, there is a trade-off, at lower temperatures the health hazard increases, but since the retention time (RT) is longer, the hazard decreases but is not removed. Therefore, care has to be taken when handling digestate and it should not be added to fields with vegetables which are eaten raw for instance. With proper risk management, the risk of contamination can be controlled. Furthermore, the provision of a digester and of a toilet is in comparison to the situation without a digester a grand improvement of both sanitation and hygiene.

However, although a biogas installation has considerable benefits it remains an expensive technology even when carbon finance is utilized to the greatest extent. The poverty reduction potential is therefore limited for the poorest of the poor but the less poor will greatly benefit and will escape from the cycle of poverty. The poorest of the poor might however benefit indirectly considering the grand spillovers, such as employment opportunities.

All the mentioned benefits are not reached without a large scale biogas program and if biogas plant adoption rates are not sustained for a number of years. As Heegde (2008) also asserts, a small program is not attractive for carbon finance, he advises programs to be around 10.000 units for CDM.

The main conclusions of this report are:

Conclusions related to the benefits of biogas

1. The procurement of biogas for domestic purposes has considerable benefits which help to achieve the 8 millennium development goals (MDG).
2. Benefits from a biogas plant cause substantial spillovers to a local, national and global scale, such as employment generation and reduced pressure on the forest
3. The cumulative multiplier effect of the benefits is sustainable development and poverty eradication from the grassroots level. It enables rural areas to develop, to save revenues, to generate income, to promote employment which avoids the migration to the cities for a better life.

Biogas in cold climates

1. In countries with cold winters the retention time of the substrate and sludge has to increase or heating has to be applied. If winter temperatures drop beneath 5-10°C solar assistance is a viable solution for digester heating.
2. Solar heating should go together with improving the digester insulation both to avoid excessive heat loses and to limit the expenditure on solar collectors.
3. Of the selection countries, Romania, Kyrgyzstan, Bolivia and Georgia, hot charging is in particular interesting in Georgia provided the digester is well insulated.

4. The parameters heat enforcement on the soil, with depth and soil type, substantially influences the heat losses and the heating requirements of the digester and should therefore be included for similar studies.

Concerning financing & GHG abatement

1. The considerable spillovers make a sound rational for subsidies and policies to promote biogas adoption.
2. The cumulative GHG savings of a biogas plant can be used to obtain carbon finance to cover a large part of biogas program costs or on policies to stimulate biogas plant adoption, i.e. subsidies.
3. Carbon methodologies are conservative by nature; actual GHG emissions resulting from biogas plants are higher.

ANNEX 1: SULFUR OXIDE EMISSION

The stochiometry of sulfur combustion:

$$2\,H_2S + 3O_2 \rightarrow 2H_2O + 2SO_2$$

Suppose biogas contains 2% H_2S, the room temperature is 25 °C, then per cubic meter combusted biogas 0,807 mol SO_2 is emitted. A large stove consumes around 0,44 m^3 per hour and hence per hour 22,74 gram SO_2 is emitted (GTZ 1989).

Suppose the kitchen is 10 m^3 large, the concentration after 1 hour is 2,274 grams SO_2 per cubic meter. Beneath 2 mg/m^3 epidemiologic research shows there are no effects on the human body. Hence, the emitted SO_2 needs to be diluted with a factor 11370 (22,74/11370 = 2mg/m^3) within one hour.

ANNEX 2: WORLDWIDE ELECTRICITY CONSUMPTION

Country/association	Entails	Yearly consumption per capita (kWh)	Daily household consumption (n=5) (kWh/day)
LDC	Least developed countries	42	0,115
ASEAN	Association of Southeast Countries	211	0,578
SAARC	South Asian Association for regional cooperation	90	0,25
Central Asia	-	500	1,37
Africa	Continent	143	0,4
Latin America & Caribbean	Continent	411	1,13
Europe	Continent	1503	4,12
North America	Continent	4386	12

From: http://www.unescap.org/stat/data/syb2007/27-Energy-supply-and-use-syb2007.asp.

Note that the values are averages; the consumption is likely to be somewhat lower in rural areas compared to urban areas. Europe and North America are depicted as reference.

ANNEX 3: PROMOTION POSTER OF THE NATIONAL BIODIGESTER PROGRAM CAMBODIA

'Our family obtained a high living standard and better health after installing a biodigester'

ANNEX 4: MANURE BATCH DIGESTION AT PSYCHROPHILIC TEMPERATURES

A. INTRODUCTION

In this thesis anaerobic digestion (AD) is studied at low temperatures, psychrophilic anaerobic digestion (PAD). Most studies however, are conducted at mesophilic temperatures for apparent obvious reasons; higher temperatures allow a higher loading rate or a smaller digester volume (Safley and Westerman 1990).

During the past two decades PAD has gained more attention, notably by Zeeman and Sutter et al (1988), Safley and Westerman (1990) and the extensive research conducted in India's hilly regions on domestic biogas production at temperatures in the psychrophilic range (Kanwar, Gupta et al. 1994; Kalia and Kanwar 1998). These studies showed that biogas production decreases per unit of volume with decreasing temperature. The observed decrease in biogas production is the result of relative growth rate of microbes, which is proportional to the temperature; psychrophilic microbes have a lower relative growth rate compared to mesophilic or thermophilic microbes (van Lier, Rebac et al. 1997).

A decrease in biogas production during the winter hampers energy the security of the rural poor in developing countries. Several solutions are suggested to increase the digester temperature, for instance by utilizing solar heat, additional insulation or by increasing the sludge retention time (SRT) (Tiwari and Chandra 1986), more on this in chapter 4.4.

THE PAD EXPERIMENT

The experimental work consists of manure batch AD experiments at various psychrophilic temperatures. The outcome of the study would yield information on to which extent solar heat and insulation are necessary to increase the temperature of digestion in relation to the SRT and temperature. Based on that, a follow up study could appraise each of the solutions in an economic assessment whereby trade-offs are identified for the most cost-effective digester. The latter is of vital importance to reach the rural poor.

The PAD manure batch experiment consists of two manipulations and three temperature conditions. To ensure that hydrolysis is rate limiting, an abundance of (exo) enzymes for hydrolysis and inoculum for methanogenesis is added to the bottles (Veeken and Hamelers 1999). This is realized by adding two inoculates; digestate (for the enzymes) and granular sludge (for the methanogenesis) to the manure. In addition, the effect of dilution on biogas production is studied. Normal practice in developing countries is to dilute manure before feeding it to the digester. Less dilution results in a smaller required digester volume for the same biogas production and thus a lower investment, provided that dilution does not affect the substrate conversion (Singh and Anand 1994). The effect of dilution is studied for two manipulations, undiluted and diluted with 1:1 with water for each of the three temperature conditions, 7,5 °C, 8,5 °C and 16 °C.

B. METHODS & MATERIALS

B.1 MANURE PRE-TREATMENT

Manure of dairy cows was collected at the beginning of June 2008 at an organic dairy cattle farm in the city of Wageningen, the Netherlands. The collected manure was fresh and not mixed with urine. The collected manure was considered too solid for the digestion experiments and was therefore mixed with an equal amount of water. Additional pretreatment consisted of homogenizing the manure to smaller particles using a Waring commercial blender. The digestate originated from a manure digestion plant Nij Bosma in Zathe and the granular sludge originated from an anaerobic paper wastewater treatment plant in Eerbeek, both located in The Netherlands.

B.2 EXPERIMENTAL SET UP

In total 24 serum bottles of 500 or 1000 ml were filled with manure, digestate and granular sludge. For each temperature condition (n=3) 8 bottles were available, three for a triplicate filling of manure, digestate and granular sludge, three with similar triplicate filling but with an identical amount of water to obtain a 1:1 dilution with the treated manure and finally a duplicate filling with only digestate and granular sludge, the control bottles.

The inoculum ratio for filling was based on the specific methogenic activity as determined by Rebac and van Lier et al (1999) to achieve a 50% conversion within 5 days. They found a inoculum activity of respectively 0,1, 0,05 and 0,01 gram $COD\text{-}CH_4/grVS.day^{-1}$ at respectively 15°C, 10°C and 4°C[11] (Rebac, van Lier et al. 1999). The added digestate was based on the VS content of granular sludge, a VS ratio of 1:10 (digestate: granular sludge).

A typical bottle at 7,5°C consisted of 15 gram manure, 45 gram digestate and 135 gram granular sludge. A bottle at 8,5°C and at 16°C contained less digestate and granular sludge, respectively 9 and 4,5 gram digestate and 28 and 14 gram granular sludge.

Next to the serum bottles, sacrifice bottles of 150 ml were filled in a similar fashion to allow for the measurement of COD dissolved, VFA concentration and $N\text{-}NH_4^+$ during digestion. The next table shows the 3 temperature conditions, the two experimental manipulations (undiluted, diluted) and the control bottles.

Table 44: Number of serum and sacrifice bottles per condition and manipulation

Condition	A: 7,5°C		B: 8,5 °C		C : 17°C	
	Serum	Sacrifice	Serum	Sacrifice	serum	Sacrifice
Diluted	3	10	3	10	3	10
Undiluted	3	10	3	10	3	10
Control	2	-	2	-	2	-

The specific methanogenic and hydrolytic activity of the two inoculate were determined in another experiment. Four serum bottles of 500 ml were allocated per temperature condition. Two of those bottles were filled with granular sludge and acetic acid to determine the specific methanogenic activity (SMA) of the granular sludge and two bottles were filled with starch, digestate and granular sludge to determine the specific hydrolytic activity (SHA).

[11] However, the experiment was conducted at different temperatures due to the unavailability of fridges with the requested temperature

After the filling, the bottles were flushed with nitrogen, sealed off and placed in cold stores. The temperature of these cold stores was measured routinely. The temperature of coldest store turned out to be higher than expected, therefore the experiments conducted at 7,5°C have a relatively higher amount of digestate and granular sludge to manure ratio compared to the other two conditions.

B.3 PROPERTIES OF THE MANURE, DIGESTATE AND GRANULAR SLUDGE

Macro COD and total NH_4^+-N of the dairy manure was determined by the Sartorius laboratory, located at the University of Wageningen before the start of the experiment. VS, FS (ash) and TS content of the manure, digestate and inoculum were in duplicate determined conform the standard methods (APHA, 1998); a sample was taken of each substrate and air dried at 105°C for 2 days in a desiccator and thereafter placed in another desiccator operating at 550°C for 2 hours. Total solids were determined by the fraction of the weight remaining after drying at 105°C, VS was determined as the fraction lost at 550°C. Results are depicted in the next table.

TABLE 45: MANURE, DIGESTATE AND GRANULAR SLUDGE CHARACTERICTICS

Substrate	TS (g/kg)	FS (g/kg)	VS (g/kg)	COD (g/kg)	N total (g/kg)
Manure*	88,5	28	75,3	109	2,9
Digestate	55	19	36	NA	NA
Granular sludge	162	41	121	NA	NA

*of the treated manure which is 1:1 diluted with water.

B.4 BIOCHEMICAL METHANE POTENTIAL

The biochemical methane potential (BMP) was determined by measuring the biodegradability of the manure through the cumulative methane production over time (Nohra, Barrington et al. 2003). The pressure increase was measured using a GMH 3150 portable manometer every 2-3 days to once a week after 2 months. The measured pressure increase was corrected with the pressure increase of the control bottles and adjusted for the volumetric headspace differences between the bottles, in order to remove the endogenous biogas production resulting from the self-digestion of digestate and granular sludge. Gas samples of 100 μl were collected once every three to four weeks; the gas composition was determined with a Hewlett Packard 5890 gas chromatograph.

B.5 BIOCHEMICAL ANALYSIS

Every 3-4 weeks 6 sacrifice bottles (of every condition 1 diluted and 1 undiluted)) were sacrificed to analyze the pH, COD dissolved (COD_{dis}), NH_4^+-N and the VFA. The first bottle was opened at t=0 and the last, the 7th bottle[12], 174 days later. For the VFA analysis three 2 ml samples per bottle were centrifuged at 10000 rpm for 10 minutes in a Hermle Z300 centrifuge. The supernatant of the 3 samples were added in one vial and centrifuged again for 10 minutes at the same speed. Subsequently, 0,1 ml 15% formic acid was added to 1 ml supernatant and centrifuged under similar conditions to obtain a clear solution for the VFA analysis. Finally, the VFA was analyzed in a Hewlett Packard 5890A gas chromatography which was equipped with a glass column packed with Supelcoport and coated with 10% Fluorad FC431 (Veeken and Hamelers 1999).

[12] sacrifice bottle 8,9,10 were not analyzed due to time constrains.

For the COD_{dis} and NH_4^+-N analysis the samples were diluted around 20 times and filtered using a paper filter S&S 595½. Of the filtrate, a sample was centrifuged for 10 minutes at 10.000 rpm in the same centrifuge for the COD analysis. Of the supernatant 2 ml was added to a Dr Lange kit (100-2000 mg COD/l) according to standard methods (APHA, 1998). The remainder was used for the NH_4^+-N analysis (about 10 ml) and analyzed in a Skalar Auto-Analyzer type SAN^{plus}.

During the first analysis it proved very difficult to obtain a clear solution for the COD dissolved determination and therefore the supernatant was diluted 1,1 times with 15% HCl (aq) solution. Unfortunately, HCl (aq) destroyed some of the dissolved proteins which subsequently precipitated; therefore the results of the first measurement showed an underestimated COD dissolved concentration. In latter analysis this problem was avoided by applying more extensive centrifugation and dilution.

B.6 SPECIFIC METHANOGENIC ACTIVITY AND HYDROLYSIS RATE

To characterize the two inoculates (digestate and granular sludge) SMA and SHA tests were conducted, see B2 for the set up of the experiment. The activity measurement consisted of the pressure transducer technique, whereby on regular intervals the pressure increase was measured using a GMH 3150 portable manometer (Enright, McHugh et al. 2005). Since acetate is directly consumable by methanogens and the VS of granular sludge is known, the specific methanogenic activity can be determined and expressed as $gCOD\text{-}CH_4/gVS.day^{-1}$. The activity of hydrogenotrophic methanogens was not determined, however at PAD the most important pathway of methane production is acetoclastic methanogenesis and therefore this measurement yields a good estimation of the overall methanogenic activity (Kotsyurbenko 2005).

For the hydrolysis activity test, biogas production is rate limited by the degradation of starch by the hydrolytic bacteria. Inhibition by methanogenesis was avoided by adding granular sludge for methanogenesis in abundance with a similar inoculation ratio as the batch PAD test. Once starch is degraded in either acetic acid or CO_2 and H_2, methanogenic activity starts and biogas is produced. Since hydrolysis is rate limiting, the observed biogas production is directly related to the hydrolysis rate. The rate of hydrolysis is expressed as $gCOD\text{-}CH_4/gVS.day^{-1}$.

The specific activity of both tests is finally determined by the depletion rate of both substrates whereby the steepest part of pressure increase against time was used (Nohra, Barrington et al. 2003). Gas sampling was done in a similar fashion as described in section B.4.

B.7 CALCULATIONS

MAXIMUM BIODEGRADABILITY

The maximum biodegradability (BD) was determined at the end of the experiments with the next formula (El-Mashad 2003).

$$BD = \frac{(Accumulated\ CH_4\ as\ COD)}{Total\ COD\ in\ sample}100 \qquad \textbf{(36)}$$

METHANE RECOVERY, THE SMA AND HSA

The methane recovery is calculated and expressed as COD per kilo treated manure, see equation 38 (adapted from El-Mashad 2003). Also the formula for the specific methanogenic and hydrolysis activity is depicted (39)

$$M_{CH_4} = \frac{C \cdot P_{hc} \cdot V_h \cdot P_r}{R \cdot T \cdot M_a}$$ **(37) Methane recovery per kg treated manure**

$$Mac\ or\ Hac = \frac{C \cdot P_{hc} \cdot V_h \cdot P_r}{R \cdot T \cdot VS \cdot t}$$ **(38) Specific methanogenic/hydrolysis activity**

Where:

M_{CH_4}	=	Methane production (gCOD-CH_4/l)
C	=	COD equivalence of methane (64 gO_2/mol CH_4)
P_{hc}	=	Corrected pressure in the headspace (Pa) ($P_{hc} = P_{atm} + \Delta P - \Delta P_{en}$)
P_{atm}	=	Atmospheric pressure at t = 0 day
ΔP	=	Pressure increase in the bottle (Pa) since t=0
ΔP_{en}	=	Endogenous volumetrically corrected biogas production (Pa) $\Delta P_{blc} = \Delta P_{bc} *(V_{bl}/V_{bottle})$
ΔP_{blc}	=	Pressure increase in the control bottle since t=0 (Pa)
V_h	=	Headspace volume (m^3)
V_{bh}	=	Headspace volume control bottle (m^3)
P_r	=	Percentage of methane in the headspace (%)
R	=	Gas constant (8,31447 $J.mol^{-1}K^{-1}$)
T	=	Temperature (K)
M_a	=	Manure mass (kg)
Mac/Hac	=	Specific methanogenic or hydrolytic activity (CH_4-COD/VS.day^{-1})
VS	=	Volatile Solids (gram)
t	=	Time (days)

To calculate the volumetrically corrected pressure, the pressure increase from endogenous biogas production of the control bottles was adjusted to account for the different headspace volumes. This was done since each serum bottle has a different headspace volume and therefore it is impossible to simply subtract the pressure increase resulting from the endogenous pressure increase as measured by the control bottles. The corrected pressure of bottle x is: $\Delta P_x = \Delta P_{bc} *(V_{bl}/V_x)$.

HYDROLYSIS CONSTANT AND THE SRT

The most common mathematical description to determine the hydrolysis constant is the first order relation (Bruning 2007).

$$\frac{\delta P}{\delta t} = -k_h . P \qquad 39$$

Where P is the concentration of biodegradable constant (g COD/kg), t the time in days and k_h the hydrolysis constant (1/day). The equation is solved to:

$$Ln\left(\frac{P}{P_0}\right) = -k_h . t \qquad 40$$

The digester considered in chapter 5 for solar assistance is assumed to be completely mixed, a CSTR, hence the SRT=HRT. With the obtained hydrolysis constant the retention time can be determined for a given degradation in a CSTR (Grotenhuis, Hamelers et al. 2008):

$$\frac{P_0 - P_{t=x}}{P_{t=x}} = k_h . SRT \qquad 41$$

The maximum degradability (P_0) is calculated with the following:

$$P_0 = Influent\ COD - influent\ COD_{diss} - influent\ COD_{ss\ inert}$$

Where, influent COD is the macro COD, the influent COD dissolved the concentration at t=0 and the COD suspended inert, the amount of COD which is reluctant to AD. The suffixes diss and ss inert are an acronym of respectively dissolved and suspended inert.

$$Influent\ COD_{ss\ inert} = (influent\ COD - influentCOD_{diss}) - \{CH_4COD_{t=\infty} - (influentCOD_{diss} - effluentCOD_{diss\ t=\infty})\}$$

The effluent is the remaining COD concentration at t = ∞, in this case infinity is 174 days. Finally, the remaining biodegradable concentration P at t=x can be determined.

$$P_{t=x} = P_0 - CH_4COD_{t=x} - (COD_{diss\ t=x} - influent\ COD_{diss})$$

All formulas are from the course Water Treatment taught at the University of Wageningen by Zeeman, G (2008)

C. RESULTS & PRELIMINARY DISCUSSION

In most bottles biogas production started as soon as the bottles were filled independent of the temperature. After some time it appeared that some bottles were leaking and consequently there was no pressure built up. Fortunately, in all conditions at least one bottles did not shown signs of leakage, however, if only one bottle remains the accuracy of the results is threatened, causing the measurements to be more sensitive to measurement errors, see at the end of this report an overview of the 'bottle issues'. The next table provides a quick overview of the remaining bottles on which the analyses are based on.

TABLE 46: THE REMAINING SERUM AND SACRIFICE BOTTLES AT THE END OF THE EXPERIMENT

Condition	Undiluted bottles	Control bottles	Diluted bottles	SMA bottles	SHA bottles
A (7,5°C)	3	1	2	1	1
B (8,5°C)	2	2	2	2	1
C (16°C)	1	1	1	1	1

The experiment started with three diluted and three undiluted bottles, two control bottles and two bottles for SMA and SHA for each temperature condition. In the conditions with only one bottle left, the obtained results have an indication value only. Of the sacrifice bottles, 7 out of a total of 10 were analyzed per condition and manipulation due to time constraints and each time only bottles were taken which showed a pressure increase.

C.1 SPECIFIC METHANOGENIC AND HYDROLYTIC ACTIVITY

The SMA and SHA experiments showed a higher activity with a higher temperature (table 47).

TABLE 47: SPECIFIC METHANOGENIC AND HYDROLYTIC ACTIVITY

Condition	SMA	SHA
A (7,5°C)	3,56	-
B (8,5°C)	5,53 (0,4)	4,52
C (16°C)	21,92	11,92

Values are expressed as $mgCH_4$-COD/gVS.day, the standard deviation, if available, is in parenthesis.

The value of the SHA at 7,5°C is 1,07 $mgCH_4$-COD.gVS^{-1}.day, which is much lower than the bottle at 8,5°C. The value is not added to the table for two reasons: Firstly, the bottle at 7,5°C showed only a pressure increase during the first weeks, thereafter the bottle remaind at 107 kPa. Apprarently, the bottle is leaking when the pressure of 107 kPa is attained. Hence, the pressure would have been higher if the bottle did not leak at 107 kPa and this likely explains the low value. Secondly, since the bottle at 8,5°C showed a steady pressure increase over time, without any indications of leakage. A reliable SHA value at 7,5°C should be near the obtained value at 8,5°C considering the small temperature differences, since the value is not anywhere near, the value at 7,5°C is omitted.

The next figure presents the obtained values graphically.

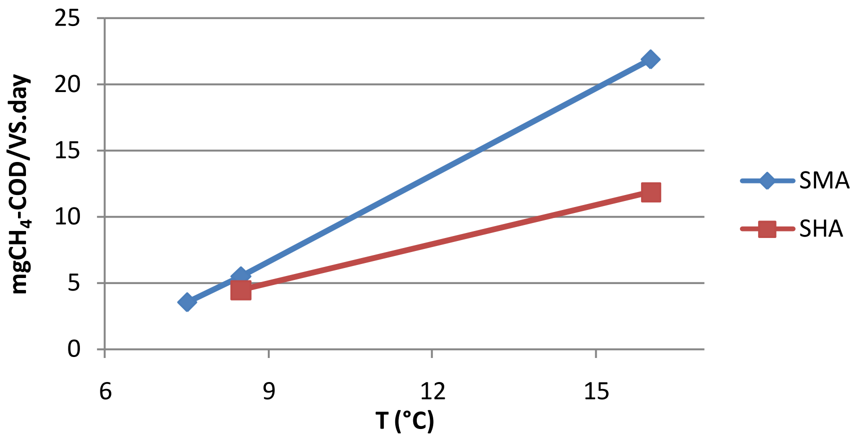


FIGURE 50: SMA AND SHA AS FUNCTION OF THE TEMPERATURE

The SHA and the SMA show a linear rate increase with temperature. This is unlike the prediction of both the Arrhenius equation and the study of Safley and Westerman (1990). However, since the two data points at 7,5 and 8,5 °C are very close to each other they are virtually one point and it is simple impossible to reliably draw an exponential curve based on two points. Further experimental work is required at different temperatures to draw a reliable activity curve with temperature.

The results from SMA test are of indicative value only since only the bottles at 8,5°C are in duplex and have some reliability while the other values are all of one bottle per temperature condition. From the specific activity tests it is therefore only possible to conclude there is positive relationship with temperature.

C.2 Bath test – parameters Temperature, pH, N-NH_4^+ and VFA

Temperature

The temperature of the coldest store was from the start of the experiment higher than expected, 7,5 °C instead of 4-5°C. From day 66 to day 74 the cold store malfunctioned and during that time the temperature was around 13,5°C. After and before the malfunction the temperature was close to steady 7,5°C ± 0,2°C. Condition B was conducted at 8,5°C instead of 10°C, the store remained throughout the experiment near 8,5°C. Condition C revealed a slight fluctuation temperature of 16°C ±0,7°C until day 74. From day 74 the temperature of the cold store was turned down to 6°C, beyond the control of the author. From day 84 the bottles were placed in an incubator which operated at 16°C.

pH of the liquid

The pH was measured of each sacrifice bottle. The pH varied of most conditions considerably, but showed a steady decline from around day 100. The diluted bottles have a lower pH compared to the undiluted in each condition after 110 days.

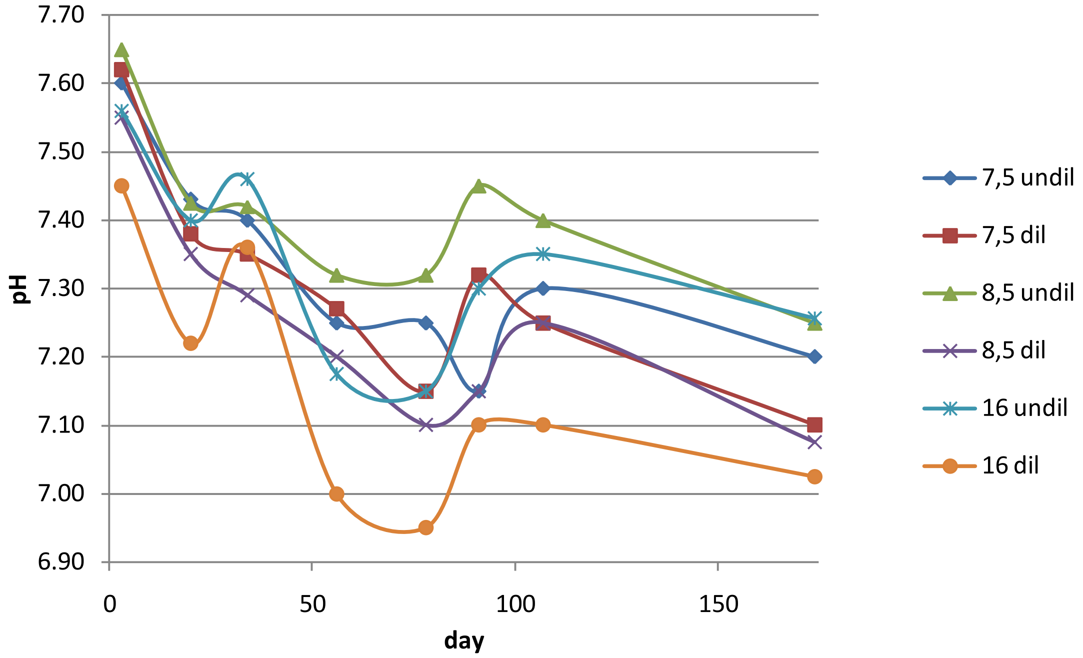


FIGURE 51: THE Ph OF THE LIQUID OF THE SACRIFICE BOTTLES AT DIFFERENT TEMPERATURES AND LEVELS OF DILUTION

<u>AMMONIUM</u>

The ammonium concentration increased of all conditions over time. The concentration in the undiluted bottle at 16°C remained after 10 days higher than the other bottles. The concentration in the other bottles stabilized after approximate 90 days. The ammonium concentration is higher in the undiluted bottles compared to the diluted bottles, see the next figure.

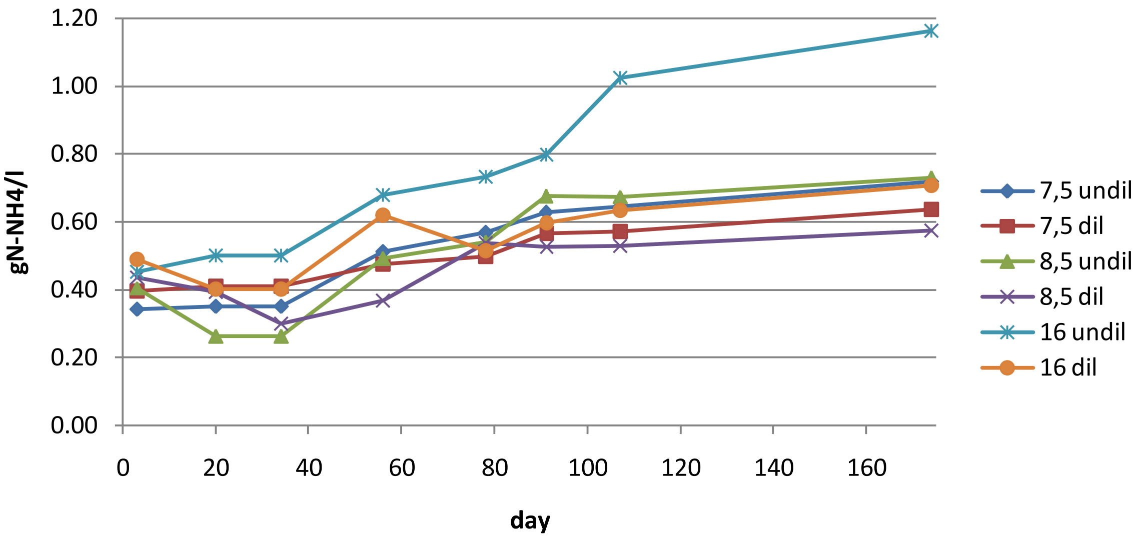


FIGURE 52: AMMONIUM CONCENTRATION OF THE LIQUID AGAINST TIME AT DIFFERENT TEMPERATURES AND DILUTIONS

<u>VFA-COD CONCENTRATION</u>

The VFA concentration expressed in COD equivalents reveal an initial high concentration which quickly decreases over time and appears to (dynamically) stabilize after 35 days, followed by the bottles at 8,5°C undiluted after 80 days. The stabilization occurs because the VFA-COD production equals the VFA-COD consumption of the methanogens.

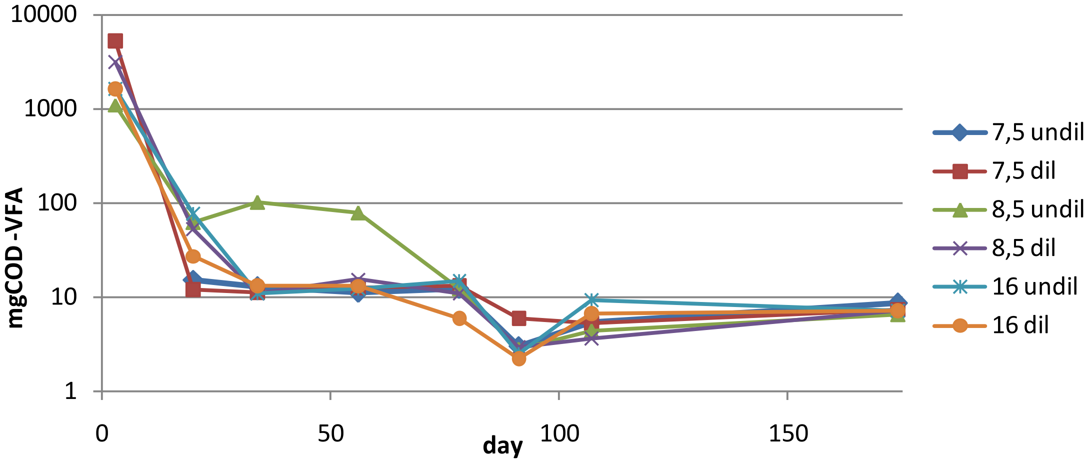


FIGURE 53: VFA-COD OF THE LIQUID AGAINST TIME AT DIFFERENT TEMPERATURES AND DILUTIONS

The interaction between the parameters VFA, pH and ammonium can lead to inhibition of methanogenesis (Chen et al 2008). At the start of the experiment, the total VFA concentration ranged from 0,3 to 5,2 gram/liter with a relative high pH (7,45-7,65). Methanogens are sensitive to a high pH, a high VFA and ammonium concentration (Chen et al 2008); however, since VFA concentration immediate decreased after day 1, there is no indication of inhibition or toxicity effects.

The undiluted bottle at 8,5°C however, displayed a different picture with an initially relative high VFA-COD concentration of 1100mg VFA-COD/liter and from day 20-70 a concentration of 100 mg VFA-COD/liter (mainly acetate and valeric acid). The undiluted bottle at 8,5°C has compared to the other bottles one of the highest pH-value, which is presumably caused by the relatively higher VFA concentration. From 70 days the VFA-COD concentration decreased similar as the other bottles.

DISSOLVED COD OF THE LIQUID

The amount of COD dissolved in the liquid indicates the availability of non-biodegradable COD and the biodegradable COD. The latter is feedstock for the VFA generation and subsequently methanogenesis. The results show no clear trends to around 110 days, from that moment concentrations slowly declines. In general the COD_{diss} concentration is higher in the undiluted bottles compared to the diluted bottles, see the next figure.

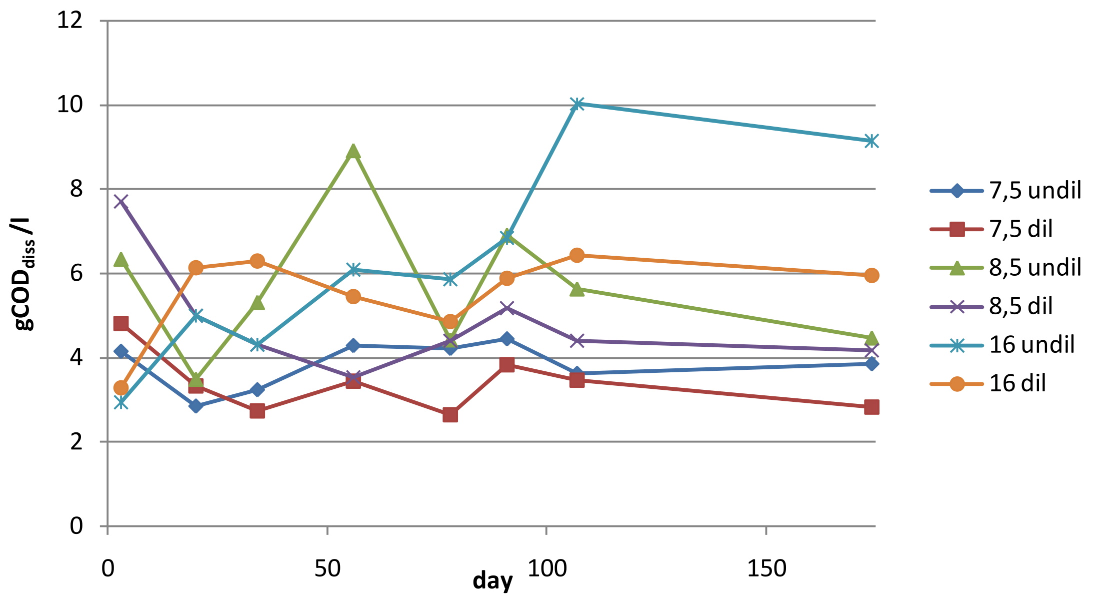


FIGURE 54: DISSOLVED COD CONCENTATION OF THE LIQUID AGAINST TIME

The COD_{diss} concentration increases for some bottles with time, apparently COD_{diss} is being produced and converted to inert COD_{diss}, COD which is refractory to AD. This is especially the case for the bottles at 16°C. Note that the figure shows the COD dissolved of the liquid and not of the manure. It was impossible to obtain the COD dissolved of the manure alone since no control sacrifice bottles were available to determine the COD dissolved concentration resulting from digestate and granular sludge.

CH_4-COD RECOVERY

Methane recovery expressed in COD equivalents per kilo of *treated manure* is depicted in the next figure. As aforementioned, treated manure was obtained by mixing fresh manure with 1:1 water on mass basis. The undiluted bottles at 7,5°C have the highest methane recovery followed by the diluted bottles at 16°C.

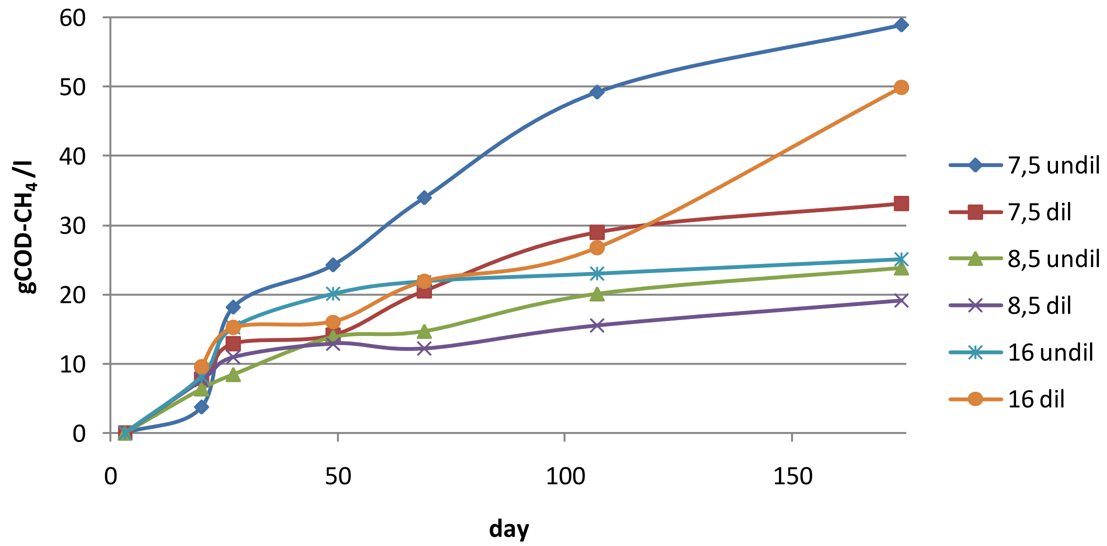


FIGURE 55: METHANE RECOVERY AS CH_4-COD OF THE TREATED MANURE

Strikingly, the bottles at the lowest temperatures perform better than the bottles at higher temperatures, with the exception of the diluted bottle at 16°C. This is opposite than expected, expected was that the bottles with the highest temperature would attain their BMP in less time followed by the other bottles in order with the height of temperature. A possible explanation is pressure induced leakages above a certain threshold of which many bottles seemed to suffer except the bottles at 7,5°C where only in the diluted condition 1 bottle was removed.

In conclusion, it appears that the relatively higher inoculation ratio of the bottles at 7,5°C resulted in a relative higher methane production compared to the other bottles despite the lower temperature.

C.4 BIOLOGICAL METHANE POTENTIAL

The BMP measurements reveals that the undiluted bottles at 7,5°C perform exceptionally compared to bottles at higher temperatures. The other bottles stabilize from around 100 days while the recovery of the diluted bottle at 16°C increases considerably after 110 days. The next graph looks very similar compared to the graph on the previous page, but shows something different, the recovered methane compared to the maximum recovery of methane.

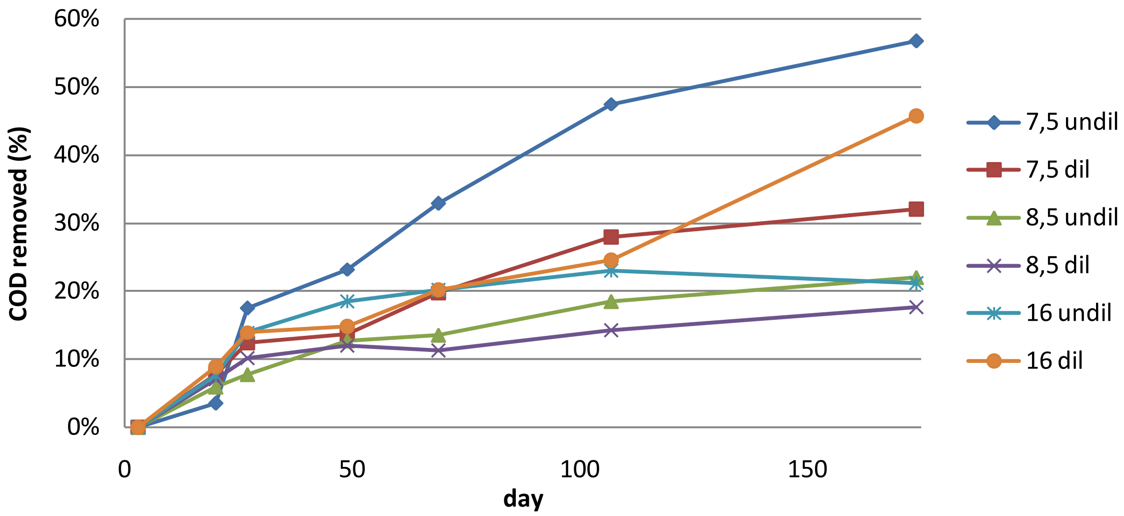


FIGURE 56: PERCENTAGE RECOVERED COD AS METHANE

The next table shows the biodegradability expressed as percentage of the total amount of available COD at 174 days.

TABLE 48: PERCENTAGE OF METHANE RECOVERED AT DIFFERENT TEMPERATURES AFTER 174 DAYS

Condition	A:7,5°C	B: 8,5°C	C: 16°C
Undiluted	57,7% (9%)	22,0% (6,7%)	23,0%
diluted	32,0% (6,7%)	17,6% (0,9%)	45,8%

Values are expressed as percentages recovered CH_4 as COD, SD if available in parentheses

Since the added manure should not substantially differ among bottles, only of the undiluted bottle at 7,5°C the methane recovery can be considered to be representative of the maximum methane recovery. The other bottles should in time reach the same value.

C.5 HYDROLYSIS CONSTANT AND SRT

The value for the influent biodegradable COD (P_0) is taken from the bottle with the highest value of all bottles. This is a reasonable since all the bottles contain the same substrate and therefore the highest value approaches the maximum biodegradation to the best extent. The bottle with the highest biodegradation was the bottle at 7,5°C undiluted: 58,91 gCOD/kg.

COD_{ss} inert was calculated based on the methane as COD recovered as CH_4 and the average COD_{diss}. This was done since there is no clear trend in the COD_{diss} concentration over time; the values are approximated by a straight line. P_o was determined in a similar fashion, and entails the original COD concentration minus COD_{ss} inert and the average COD_{diss} of the diluted bottle at 16°C (explained later). Since the COD_{diss} concentration of the two inoculates is not determined it is not possible to assay the amount originating from the manure. Therefore, the concentration COD_{diss} is used from the bottles which are the least mixed with two inoculates, which are the bottles at 16 °C. The COD_{diss} in these bottles yields the best approximation of the amount originating from manure. However, the bottle at 16°C undiluted showed an increase in COD_{diss} concentration over time, which is difficult to explain and in addition the bottle showed a decrease in pressure during the last months. Hence, values of the diluted bottle at 16°C are taken.

The hydrolysis constant is calculated by taken the slope of $Ln(P/P_0)$ against the time, the slope is in that case $-k_h$, see equation 41. Of the calculated hydrolysis constants only the values of the undiluted bottles at 7,5°C were considered reliable, because only these bottles were in triplicate whereas of the others either one bottle remained or the gas pressure showed fluctuations. The obtained k_h of the undiluted bottles at 7,5°C is 0,0269 (day^{-1}).

However, in chapter 5 a digester is designed to operate at 15°C, hence the k_h at 15°C has to be determined. As aforementioned, the results from bottles at higher temperatures were considered unreliable and therefore another approach was necessary to obtain the k_h at 15°C. By determining the activation energy (Ea) the hydrolysis constant at 15°C can be calculated. Ea is obtained by, $\ln k = \ln k_1 - Ea/RT$, where k is SHA (kgCH_4-COD/kgVS.day), R the gas constant, T the temperature (K) and k_1 the rate constant.

By plotting this formula in a graph, ln k against 1/T, Ea is obtained, since the slope is Ea/R, see the next graph. As aforementioned, only the values for the SHA value at 8,5 and 16°C were considered representative and therefore the line in the graph contains is composed of two points.

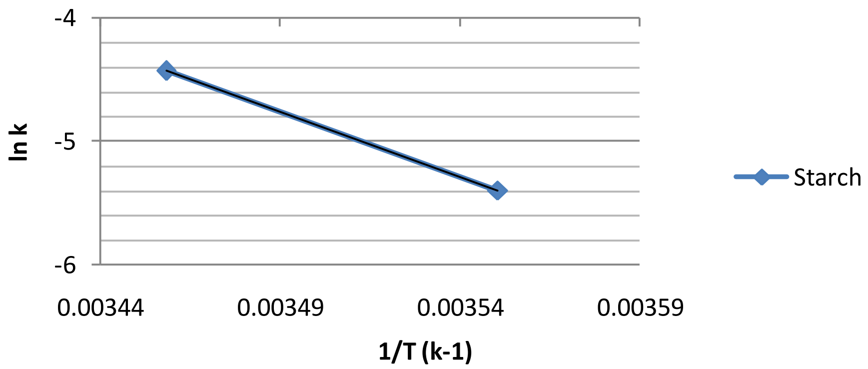


FIGURE 57: THE SPECIFIC HYDROLYTIC ACTIVITY VERSUS THE INVERSE OF THE TEMPERATURE

The obtained Ea is 87,5 kJ/mol, which is somewhat higher than in other studies. Typical values for the activation energy are normally around 64 kJ/mol for enzyme kinetics (Grotenhuis, Hamelers et al. 2008). It does however rule out that diffusion of hydrolytic enzymes to the particle surfaces is rate limiting, since the activation energy for diffusion is around 20 kJ/mol (Veeken, Hamelers 1999). Note that based on the two SHA values it is hard to determine if typical Arrhenius behavior is shown of biological reaction rates with temperature.

With the obtained Ea and the k_h at 7,5°C is know the k_h at 15°C can be calculated. To do so the next formula is used, $\ln k_h = \ln k - Ea/RT$, which yields a k_h of 0,0714 day^{-1}. Based on that the retention time can be calculated for a given degree of degradation, where 100% degradation is 100% removal of (biodegradable) P_0.

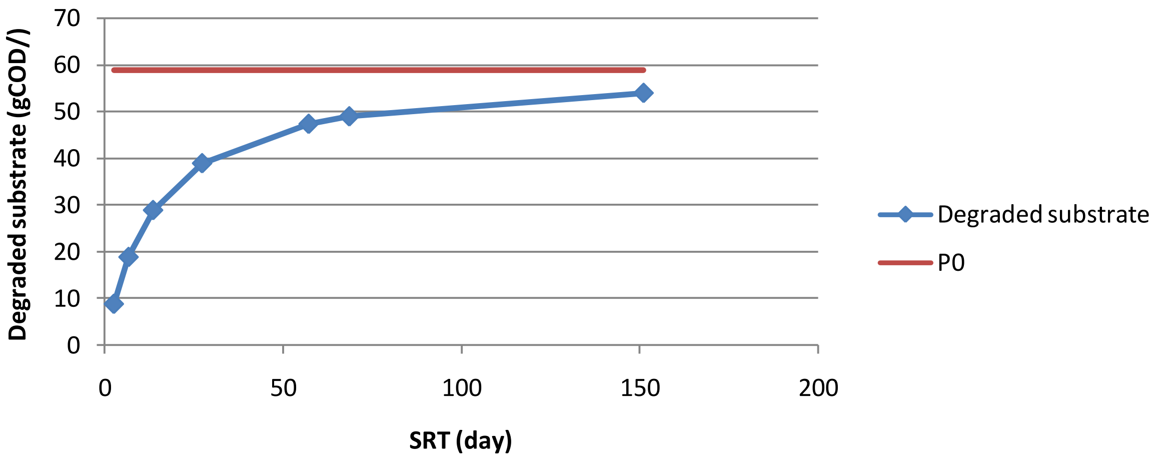


FIGURE 58: SUBSTRATE DEGRADATION RECOVERED AS METHANE COD AGAINST THE SRT FOR A TEMPERATURE OF 15°C

The red line in the figure shows the maximum degradation, the blue line shows the degradation at a given day. Since P_o is based on the recovery of methane, the recovered methane at a given SRT can easily be calculated based on the figure; this is done in chapter 4.3, next to a more extensive examination of the effect of temperature on biogas production. Zeeman (1991) conducted a manure batch experiment at 15°C inoculated with digested slurry. The results from that study showed a clear relationship for the COD reduction and with the retention time, similar to as depicted in figure 58. However, Zeeman (1991) found a much lower COD reduction rate with retention time. The main reason behind this is that Zeeman (1991) did not use an inoculate for methanogenesis, hence in her case AD was inhibited by the methanogens leading to acidification of the system and a long start up time. In the experiment of the author however, AD was not limited by the growth rate of the methanogens (and hydrolysis) and consequently a higher COD conversion rate was observed with a negligible start up time, see figure 58.

D. DISCUSSION & CONCLUSION

The SHA and SMA test showed as expected, an activity rate proportional with temperature. The results unfortunately have only an indicative value since most of them are from one sample. A more extensive study with other more durable sealing of bottles has to be conducted to confirm these results. From the results it is only possible to conclude that there is a clear trend.

Furthermore, the obtained hydrolysis constant of the manure batch test were only reliable for the undiluted bottles at 7,5°C. To be able to calculate a k_h at 15°C the activation energy is calculated based on the SHA test and used to convert the value at k_h at 7,5°C to the k_h at 15°C. By doing so a k_h is obtained of 0,071 day^{-1} and that value is used in chapter 4.3 to assess SRT on biogas production.

EFFECT OF DILUTION & TEMPERATURE ON METHANE RECOVERY

In almost all cases the bottles with additional dilution showed a lower pH, a lower $N\text{-}NH_4^+$ concentration and a lower COD_{diss} concentration. This is largely attributable to the effect of additional water which 'dilutes' the values and hence decreases concentrations. Consequently, in almost all cases this effect is the strongest for the bottles at the highest temperatures, since they have the lowest inoculation ratio and hence the added water (1:1 to manure) results relative to the other bottles, in lower values, because the other bottles contain much more inoculate.

The undiluted bottles a higher methane recovery, with the exception of the diluted bottle at 16°C after 110 days. No attempts have been made to reconcile the differences, simply because there is insufficient data available for an ANOVA test. Temperatures differences are also not compared statistically; the SD of 16°C is not obtained, rendering a least square statistical test impossible.

HYDROLYSIS CONSTANT

The high amount of leaking bottles and the non-decisive results are interfering with practical application to design a digester for solar assistance in chapter 5. Only the values at the lowest temperature were considered valid. See chapter 4.3.

METHANE RECOVERY AGAINST TEMPERATURE

The bottles at 7,5°C outperformed the other bottles with the exception of the diluted bottle of 16°C. This is contrary the prediction of the Arrhenius equation of biological reaction rates and growth models of microbes. Some possible explanations are listed:

1. Pressure induced leakages

A large number of bottles suffered from fluctuating gas pressures, possibility indicating a pressure induces gas leakages, whereby gas is only released at a certain threshold, i.e. at 120 kPa. This happened in the undiluted bottle of 16°C for instance to some extent.

2. Inhibition

Since the analysis revealed that VFA did not accumulate, there was no inhibition of methanogenesis. The COD_{diss} fluctuated during the first 100 days considerably, but it remained at the same level approximately. This indicated that the produced COD_{diss} is converted to VFA-COD which is directly converted to methane. Normally, the COD_{diss} would decrease over time to a certain value, the non-biodegradable fraction, which did not happen in all the bottles. A complicating factor is the fact that the results of the first analysis are skewed downwards and should have been higher. However, even with this unreliable first analysis it is impossible to explain the difference in methane recovery.

Another explanation could be inhibition of acidogenesis, resulting in a built up of higher VFAs. That did also not occur, only to some extent for the undiluted bottle at 8,5°C. In that bottle a relatively high presence of C5-VFA was present, between, 33-45 mg/liter until day 75. After day 75 the concentration decreased to the values of the other bottles. The other higher VFA, C3,C4 remained low during the whole experiment from day 17.

Based on this it is possible to conclude there was no built up of intermediate products during AD, hence acetogenesis and methanogenesis are not inhibited. Consequently, either acidogenesis or hydrolysis is inhibited.

Close examination of the added inoculate revealed that digestate was added ten times less compared to granular sludge on VS basis. While there are only ball-park estimates for the ratio VS digestate versus VS granular sludge, it could be that the ratio should be lower. If that is true, results could be obscured by the fact that hydrolysis was inhibited by the insufficient amount of exo-enzymes, since bottles were placed in a different temperature regime than on forehand considered and hence the bottles which are placed in a higher temperature regime are relatively less affected by the insufficient inoculation by the digestate. This is true for the bottles at 7,5°C, which are inoculated for a temperature of 4-5°C, while the bottles at 8,5°C were inoculated for 10°C and are therefore disproportionally more affected. The bottles at 16°C were inoculated for approximate that temperature.

In that case the rate of hydrolysis cannot be predicted by the Arrhenius equation for enzyme catalysis (Veeken and Hamelers 1999). Also hydrolysis cannot be described with the first order kinetics, since the hydrolytic enzymes did not occupy all the available biodegradable adsorption sites (Veeken and Hamelers 1999).

The results showed that the bottles at 7,5°C perform much better than the other and the bottles at 8,5°C performed the worst, as predicted by this explanation. We also see that the diluted bottle at 16°C suddenly started to perform much better after 100 days, this might indicate that an increased enzyme production for hydrolysis. Enzymes for hydrolysis are produced by the acidogenic bacteria (Grotenhuis, Hamelers et al. 2008). Consequently, the acidogenic bacteria produced insufficient enzymes for hydrolysis and was therefore the rate limiting step.

3. Coincidence

Finally, coincidental variation in manure feed. Although the manure was well mixed and blended to small particles, it could have happened that a large particle ended up in some bottles. Such a particle would be refractory to hydrolysis due to its relatively small surface and possibly high lignin content. If more bottles were available per condition the effect of a different feed would show up in a different amount of methane production and a higher inert COD content. Because of the large amount of bottle failures, it is impossible to determine the extent of coincidence, and this severely hampers the reliability of the obtained data. At 16°C only one bottle per condition remained, and hence it is almost impossible to compare the impact of temperature. Even if the other conditions at 7,5 and 8,5°C showed a temperature dependent increase in the rate of digestion, it would still be limited due to the closeness of the temperatures and hence impossible to extrapolate it to other temperatures.

A follow up study should replicate this study to confirm or to disprove the obtained results and the mentioned explanations. This study did however show a clear temperature related SHA and SMA. In addition, based on the obtained SHA values and the k_h at 8,5°C the hydrolysis constant at 15°C was obtained by applying the Arrhenius relation.. The outcome of this experiment is used to write chapter 4.3, to calculate the minimum SRT of a CSTR at 15°C and to calculate the related methane production.

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E. BOTTLES ISSUES

- Serum bottles

Bottles at 7,5°C

Condition A	Bottle identity	Used for analysis	Remarks
Triplicates undiluted	1	yes	None
	2	yes	None
	3	yes	None
Control	4	yes	None
	5	no	Leaking, follows the ambient pressure
Triplicates dilution	6	no	Continuing pressure decrease after day 41
	7	yes	None
	8	yes	None

Bottles at 8,5 °C

Condition B	Bottles identity	Used for analysis	Remarks
Triplicates undiluted	9	yes	None
	10	yes	None
	11	no	pressure decrease after 65 days
Control	12	yes	None
	13	yes	seems to follow ambient pressure
Triplicates dilution	14	yes	None
	15	no	Slight pressure decrease and methane content
	16	yes	None

Bottles at 16 °C

Condition C	Bottles identity	Used for analysis	Remarks
Triplicates undiluted	17	yes	None
	18	no	After 41 days flushed with nitrogen and resealed. Bottle 18 continues to leak, 19 not usable
	19	no	
Control	20	yes	None
	21	no	Follows the ambient pressure
Triplicates diluted	22	no	pressure decrease after 49 days
	23	yes	None
	24	no	varying pressure

ACTIVITY TEST BOTTLE ISSUES

Bottles at 7,5°C

Condition 7,5°C	Bottles identity	Used for analysis	Remarks
SMA duplicates	A	yes	None
	B	no	no pressure increase
SHA duplicates	C	no	no pressure increase
	D	no	varying pressure

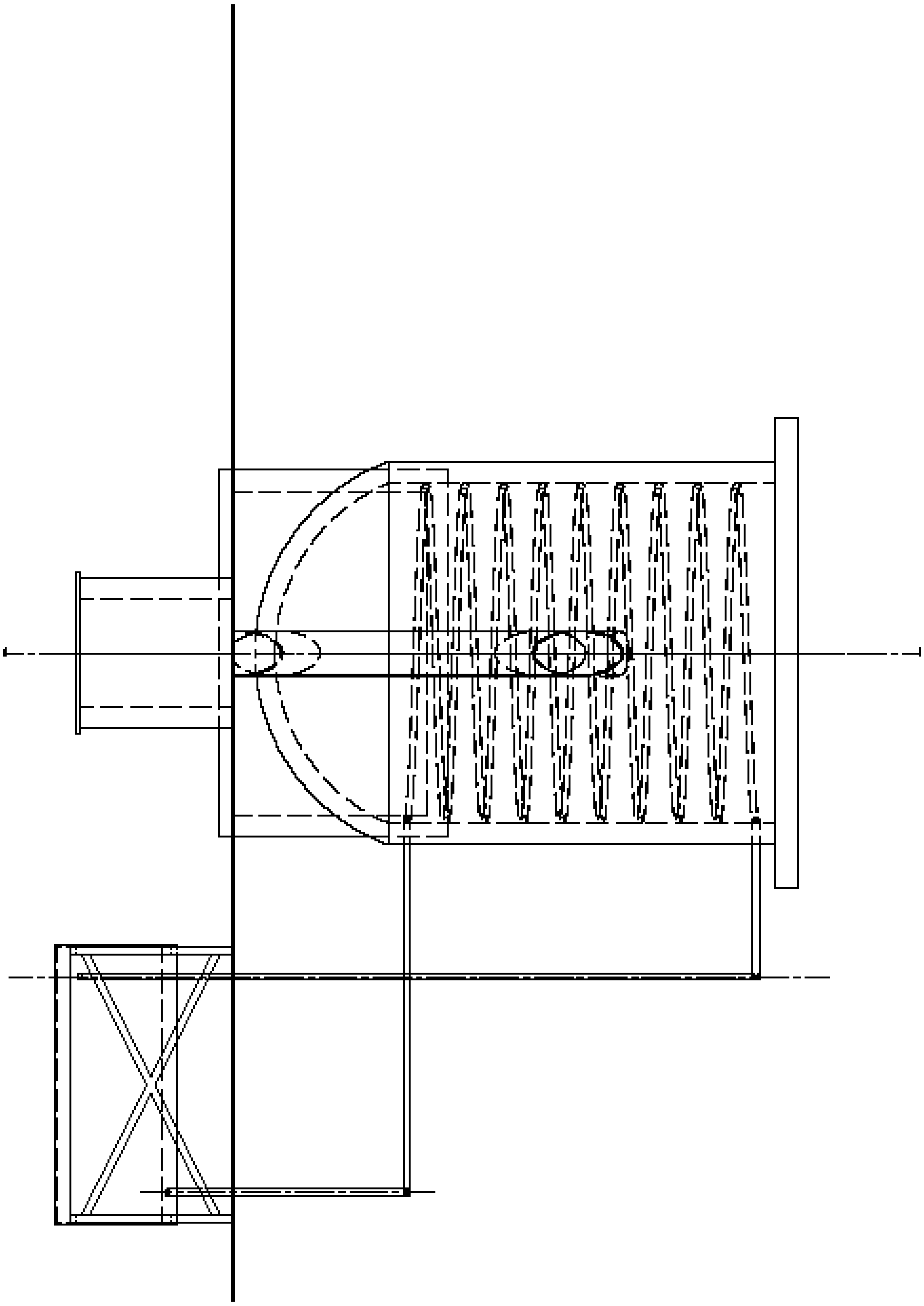
Bottles at 8,5°C

Condition 7,5°C	Bottles identity	Used for analysis	Remarks
SMA duplicates	E	yes	None
	F	yes	None
SHA duplicates	G	yes	Low SHA
	H	yes	None

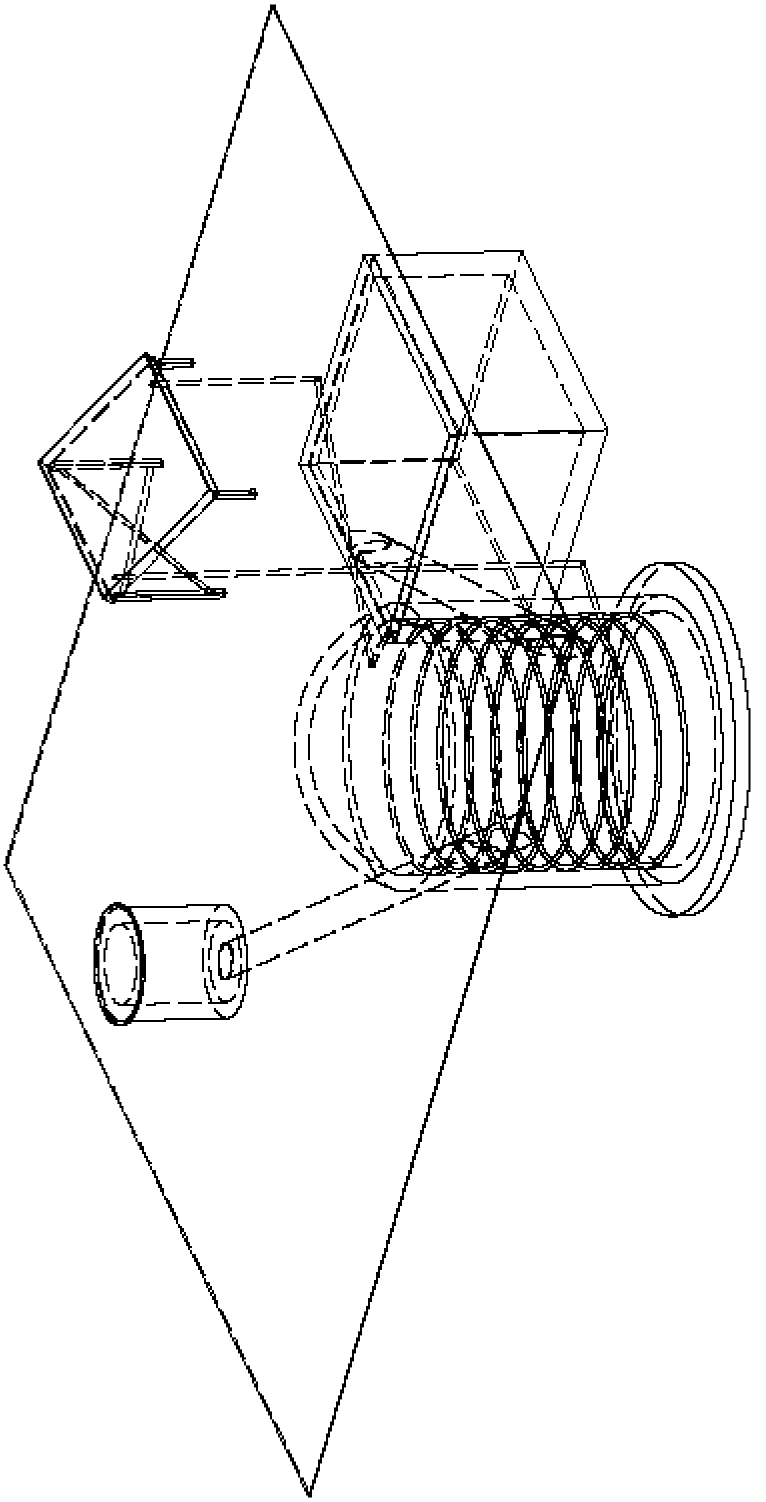
Bottles at 16 °C

Condition 7,5°C	Bottles identity	Used for analysis	Remarks
SMA duplicates	I	yes	None
	J	no	Follows ambient pressure
SHA duplicates	K	yes	None
	L	no	Follows ambient pressure,

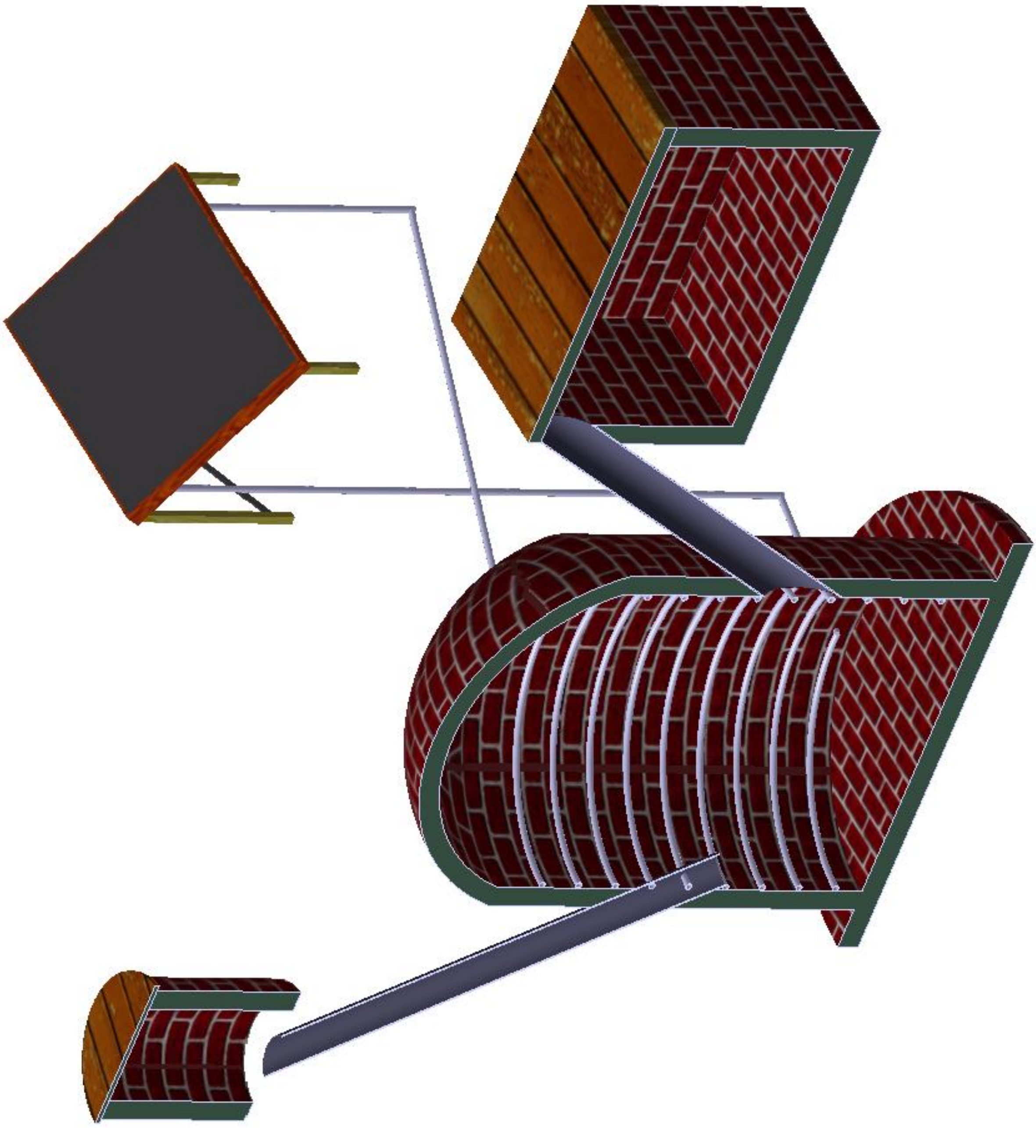
ANNEX 5: THE SOLAR ASSISTED DIGESTER, SCALED DOWN 1:25



Left view
Scale: 1:25

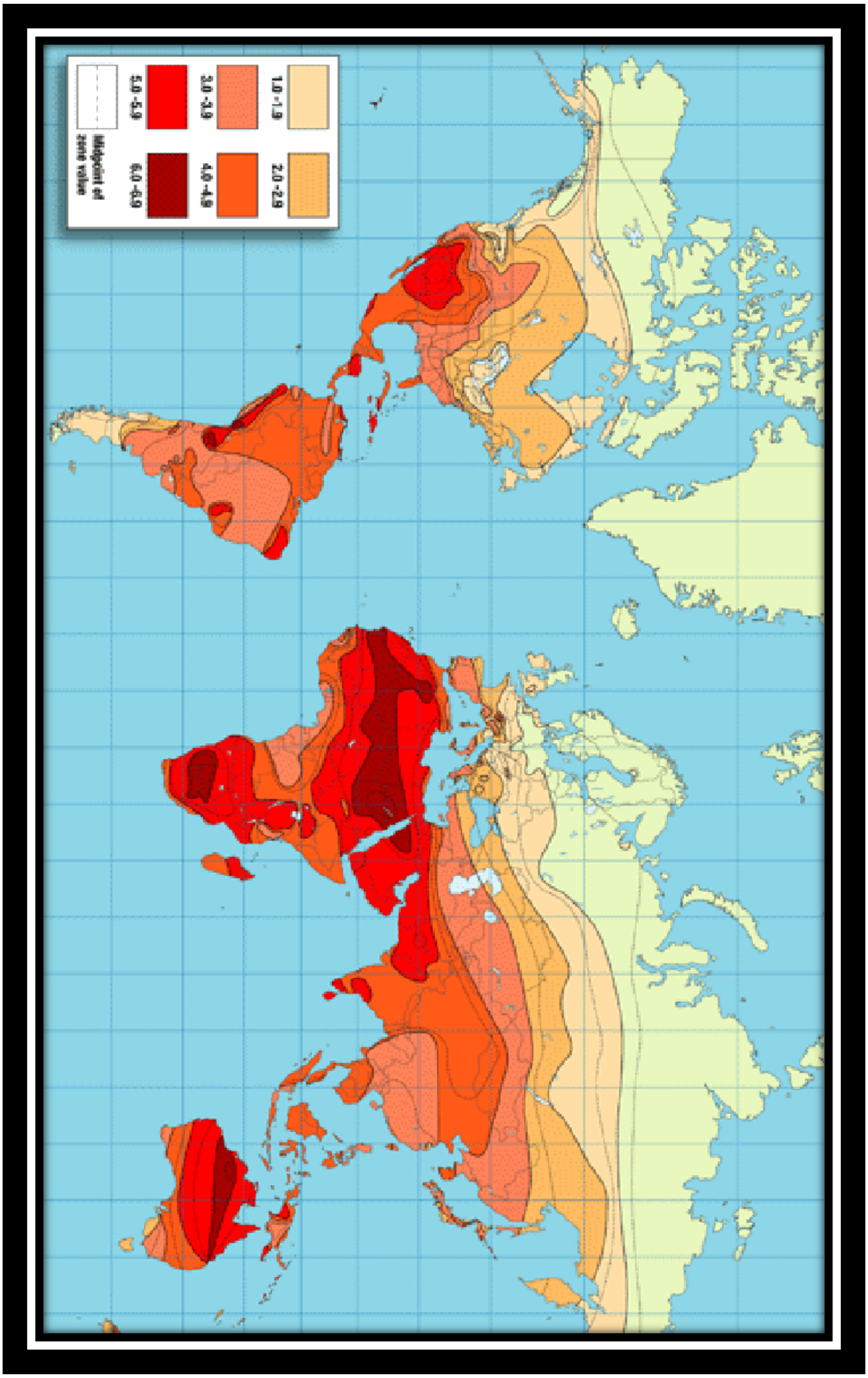


Isometric view
Scale: 1:35



ANNEX 6: WORST INSOLATION MAP

From http://www.oynot.com/solar-insolation-map.html, map is based on the worst case insolation on an optimally titles surface.



ANNEX 7: DEFINITIONS OF MANURE SYSTEM

TABLE 10.18
DEFINITIONS OF MANURE MANAGEMENT SYSTEMS

System	Definition
Pasture/Range/Paddock	The manure from pasture and range grazing animals is allowed to lie as deposited, and is not managed.
Daily spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion.
Solid storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Dry lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically.
Liquid/Slurry	Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the animal housing, usually for periods less than one year.
Uncovered anaerobic lagoon	A type of liquid storage system designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.
Pit storage below animal confinements	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility, usually for periods less than one year.
Anaerobic digester	Animal excreta with or without straw are collected and anaerobically digested in a large containment vessel or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4, which is captured and flared or used as a fuel.
Burned for fuel	The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.
Cattle and Swine deep bedding	As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system also is known as a bedded pack manure management system and may be combined with a dry lot or pasture.
Composting - in-vessel[a]	Composting, typically in an enclosed channel, with forced aeration and continuous mixing.
Composting - Static pile[a]	Composting in piles with forced aeration but no mixing.
Composting - Intensive windrow[a]	Composting in windrows with regular (at least daily) turning for mixing and aeration.
Composting - Passive windrow[a]	Composting in windrows with infrequent turning for mixing and aeration.
Poultry manure with litter	Similar to cattle and swine deep bedding except usually not combined with a dry lot or pasture. Typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl.
Poultry manure without litter	May be similar to open pits in enclosed animal confinement facilities or may be designed and operated to dry the manure as it accumulates. The latter is known as a high-rise manure management system and is a form of passive windrow composting when designed and operated properly.
Aerobic treatment	The biological oxidation of manure collected as a liquid with either forced or natural aeration. Natural aeration is limited to aerobic and facultative ponds and wetland systems and is due primarily to photosynthesis. Hence, these systems typically become anoxic during periods without sunlight.

[a] Composting is the biological oxidation of a solid waste including manure usually with bedding or another organic carbon source typically at thermophilic temperatures produced by microbial heat production.

From (Hongmin, Mangino et al. 2006)

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