- **MASTERS DISSERTATION** -

POTENTIAL FOR DOMESTIC BIOGAS AS HOUSEHOLD ENERGY SUPPLY IN SOUTH AFRICA

By

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Potential for domestic biogas as household energy supply in South Africa

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SYNOPSIS

Domestic biogas technology is a clean, renewable form of energy that is accessible to low-income households through anaerobic digestion of readily available organic waste. The objective of this desktop study was to determine the amount of biogas required for substitution of conventional domestic fuels (fuelwood, paraffin and coal), to quantify the health benefits from reduced indoor air pollution due to such a substitution and to evaluate the availability of feedstock for adoption of domestic biogas technology in South Africa.

The energy demand by low-income South African households for cooking with fuelwood was calculated to be 27 MJ/day and the total energy demand to be 68 MJ/day. Approximately 80% of the total energy is used for cooking, water heating and space heating and approximately 20% is used for lighting. To meet the energy demand for cooking (27 MJ/day) with fuelwood with a thermal efficiency of 13%, it was calculated that 2 500 L/day/household of biogas is required which is in line with studies conducted in India and China. In order to meet the total energy demand of 68 MJ/day by low-income South African households, it was calculated that biogas of

approximately 6 250 L/day/household is required of which 5 000 L/day/household is used for cooking, water heating and space heating and also 1 250 L/day/household for lighting. A photovoltaic (PV) solar home system is recommended for lighting in rural households instead of using the inefficient biogas lamps which often pose a safety risk to the household members.

Complete substitution of fuelwood used for cooking with 2 500 L of biogas per day results in cost savings of R904 per household per annum which is 4.3% savings of the average household income and translates to a gross national annual cost savings of approximately R 1.5 billion. Complete substitution of fuelwood as a source of energy results in cost savings of R1 808 per household per annum which is 8.6% of the household income and translates to a gross national annual cost savings of R4 - 5 billion.

In terms of burden of disease and mortalities, it was determined that fuelwood use in South African households results in 702 790 and 22 365 attributable disability-adjusted life years (DALYs) lost and mortalities respectively. It was also determined that 50% of the attributable DALYs lost and mortalities from solid fuel use can be avoided by substitution of fuelwood used for cooking with 2 500 L of biogas per day per household whereas complete substitution of fuelwood with biogas can result in the avoidance of approximately 85.4% of total DALYs lost and mortalities from solid fuel use.

It terms of feedstock availability, it was determined that there is potential for domestic biogas technology utilising cattle and pigs waste as feedstock. Due to access to sufficient cattle dung, it was determined that approximately 613 662 households can potentially benefit from 2 500 L/day capacity biogas digester installations fed with cattle dung. Approximately 131 392 households can potentially benefit from 5 000 or 6 250 L/day capacity biogas digester installations fed with cattle dung. The number of households that have access to sufficient pigs waste to benefit from installations of 2 500 or 5 000 or 6 250 L/day capacity biogas digesters fed with pig waste are 12 089. Due to the number of chickens required and the average number of chickens kept by South African households, it can be deduced that it is not feasible to operate a biogas digester fed solely with chicken waste. It was also determined that South African households do not generate sufficient human excreta and food waste to feed a biogas digester of a sufficiently large size. It is therefore recommended that community digesters in peri-urban areas/informal settlements be co-fed with 1:1 mixture of sewage and food waste. It is also recommended that the households interchangeably utilize the biogas from the community digester for cooking purposes.

Non-sewered households with access to on-site water supply generate sufficient greywater for feeding a domestic biogas digester. This is therefore recommended over drinking water. Non-sewered households with access to off-site water supply generate insufficient greywater for feeding biogas digesters of 5 000 L/day and 6 250 L/day capacity. It is therefore recommended that in non-sewered households with access to off-site water supply greywater be augmented with harvested storm water or water from nearby rivers, dams and streams.

Since the present work is a desktop study, it is recommended that a pilot scale study be launched to confirm the findings of this study regarding the quantity of biogas required to substitute conventional domestic fuels as well as the feasibility of domestic biogas technology in low-income South African households or at community level.

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Abbreviations

AD	Anaerobic Digestion
BOD	Biochemical Oxygen Demand
C: N	Carbon to Nitrogen
COD	Chemical Oxygen Demand
CPI	Consumer Price Index
DM	Dry Matter
FBW	Free Basic Water
GHG	Greenhouse Gas
GWh	Giga Watt Hour
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
IAP	Indoor Air Pollution
LPG	Liquefied Petroleum Gas
m.a.s.l	Meters Above Sea Level
NERSA	National Energy Regulator of South Africa
OLR	Organic Loading Rate
ppm	Parts Per Million
PV	Photovoltaic

PVC	Polyvinyl Chloride
TS	Total Solids
UNEP	United Nations Environment Programme
US$	United States Dollar
v/v	volume by volume
VS	Volatile Solids
WHO	World Health Organization

Nomenclature List

C	Carbon
$C_6H_{12}O_6$	Glucose
$CH_3(CH_2)_2COOH$	Butyric acid
$CH_3(CH_2)COOH$	Propionic acid
CH_3CH_2OH	Ethanol
CH_3COOH	Acetic acid
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
H	Hydrogen
H_2	Hydrogen gas
H_2O	Water
H_2S	Hydrogen Sulphide
K_2O	Potassium Oxide
N_2	Nitrogen gas
NH_3	Ammonia
NO_x	Oxides of Nitrogen
O	Oxygen
O_2	Oxygen gas

P_2O_5	Phosphorus Pentoxide
PM	Particulate Matter
PM_{10}	Particulate matter having an aerodynamic diameter less than 10 µm
$PM_{2.5}$	Particulate matter having an aerodynamic diameter less than 2.5 µm
Q	Heat
SO_2	Sulphur Dioxide
η	Thermal Efficiency

CHAPTER 1: Introduction

1.1. Energy Crisis in Africa

Energy plays a vital role in the socio-economic development of a region. Africa is not only the poorest continent in the world but it was the only major developing region with negative growth in income per capita during 1980–2000. Biomass in the form of mainly fuelwood and charcoal is the dominant energy source used in Sub-Saharan Africa (SSA), accounting for about 74% of total energy consumption, as compared to 37% in Asia and 25% in Latin America (Parawira, 2009; Amigun *et al*, 2012). People living in SSA lack access to clean, affordable, reliable, safe, and environmentally-safe energy and rely on solid biomass to meet their basic needs for cooking (Brown, 2006). This is a major contributor to poverty and a hindrance to development.

Africa is a net energy exporter, but the majority of its population lacks access to clean energy, and many African countries rely on imported energy. Half a billion people living in SSA do not have access to electricity in their homes and rely on solid forms of biomass (fuelwood, agricultural residues, animal wastes, etc.) to meet basic energy needs for cooking, heating and lighting. The disadvantages of these traditional fuels are many: (1) they are inefficient energy carriers and their heat release is difficult to control, (2) they release harmful gases, and (3) their current rate of extraction is unsustainable (Parawira, 2009; Amigun *et al*, 2012).

1.2. Energy Utilization in South African Households

South Africa is an industrialised and energy intensive country and the 12th largest emitter of CO_2 in the world (UNEP, 2004 as cited in Hemraj, 2010). The country is heavily reliant on coal for the production of electricity and has a 1.6% share of the world's carbon emissions (UNEP, 2004 as cited in Hemraj, 2010). In a South African study on attitudes and perceptions about energy, 85% of households indicated that they have access to electricity. Fuelwood was the most dominant solid fuel used in South African households with 10% of households with access to electricity and 54% of households without access to electricity relying on fuelwood as an energy source for cooking. Apart from cooking, another energy-intensive thermal application is domestic space heating. Though in households with access to electricity only 7% still used fuelwood for space heating, in households without access to electricity 29% used fuelwood. It is important to note that more than 53% of households without access to electricity do not make use of any energy source to stay warm, thus rather using blankets and warm clothing. In terms of water heating, approximately 46% of households without access to electricity used fuelwood (Department of Energy, 2013). It can be deduced that in South African context, fuelwood is the major solid fuel of concern for replacement with renewable sources of energy such as biogas.

In terms of lighting, 97% of households with access to electricity use it for lighting and approximately 1% relying on candles. There are 59% of households without access to electricity that rely on candles for lighting, with 36% relying on paraffin. Other energy sources such as photovoltaic (PV) solar systems hardly feature and account for less than 2% (Department of Energy, 2013). The marginal use of PV solar systems can be attributed to the Government's off-grid electricity supply initiative in 1999 to install solar home systems (SHS) to 300 000 rural households. By 2004, it was estimated that only 20 000 – 30 000 SHSs had been installed instead of the 300 000 originally envisaged (Prasad, 2007).

South African proportion of households that rely on coal as the main source of energy for cooking and space heating has diminished from 3% to 0.8% and 5% to 1.8% respectively from 2002 to 2012. Mpumalanga province remains the main user of coal with 5.7% and 10.5% of households still relying on coal for cooking and space heating respectively (Statistics South Africa, 2013b). The use of coal is more prevalent in urban areas and peri-urban/informal settlements of Mpumalanga province (without access to electricity) which do not keep livestock therefore substitution of coal with biogas is less important in the context of this study.

1.3. Biogas as renewable energy source

Biogas is a renewable form of energy which is currently employed in the developing world especially Asia to combat the environmental and health effect of fossil fuel combustion. Biogas is a low cost technology which is used to meet the energy demands of low income households. Poverty-struck Asian, South American and African countries can make use of this form of energy to reduce domestic consumption of fossil fuels which have both environmental and health effects.

Research on domestic biogas technology has been conducted in Asian countries especially China and India, both of which have seen growth in the installation of domestic biogas digesters in these countries. In 2007 it was reported that around 4 and 27 million biogas digesters had been installed in India and China respectively (Bond & Templeton, 2011). Such growth has been influenced by extensive research in these countries thus encouraging governmental and private sector participation through subsidies and credit offerings.

Unlike other renewable energy production systems such as biodiesel and bioethanol technologies, biogas production derived from agricultural residues, industrial and municipal wastewater does not compete with food production systems (Parawira, 2009), therefore making such technology suitable for the developing world especially Africa which is faced with food shortages. The use of energy crops (i.e. maize, wheat and oats grain) for the production of biogas as practiced in developed countries such Germany, United States and New Zealand can compete with food production systems (Heiermann *et al*, 2009). In developing countries, there is a serious shortage of food therefore food production is much more important and should take precedence over the production of energy crops for biofuels (Parawira, 2009).

Biogas is produced through anaerobic digestion of organic waste therefore making the technology ideal for African countries that have poor waste handling systems and sanitation facilities. South Africa is one of the African countries that has seen poor growth in terms of domestic biogas digester installations hence the inception of this study.

1.4. Problem Statement

The problems arising from non-sustainable use of fossil fuels and traditional biomass fuels have led to increased awareness and widespread research on the accessibility of new and renewable energy resources, such as biogas, biofuels, and biodiesel. Past research on biogas technology in Africa has focused more on the prospects, constraints and how biogas technology has failed in Africa. Hennekens (2012) conducted a study which was aimed at gaining a sociological understanding of the potentials of biogas practices to address the problem of domestic energy in low income households, in both rural and peri-urban areas in South Africa. The study identified the various stakeholders in the biogas sector, extensively explored the potentials and barriers of biogas technology in South Africa and presented case studies on the currently installed biogas digesters. The present study continues from the work done by Hennekens (2012) by investigating the extent to which biogas derived from organic waste could alleviate the problem of rural and peri-urban household's access to clean energy in South Africa, the health co-benefits of the substitution of presently used solid fuels and the constraints to adoption of domestic biogas technology. The following research objectives have been formulated to address problem statement.

1.5. Research objectives and scope

This study was aimed at achieving the following research objectives:

i. Evaluate the energy demand by a low-income South African household.
ii. Evaluate the amount of biogas required for substitution of fuelwood used for cooking and the amount of biogas required for complete substitution of conventional domestic fuels.
iii. Quantify fuelwood and cost savings from substitution with biogas.
iv. Quantify the reduction in the burden of diseases from installation and operation of a domestic biogas digester.
v. Evaluate the availability of feedstocks for domestic biogas digester implementation in low-income South African households.
vi. Estimate the number of households in South Africa that can potentially benefit from domestic biogas technology due to availability of feedstocks.
vii. Evaluate the demand and availability of water required for operating a domestic biogas digester.

The initial scope of work was to address the substitution of all conventional domestic fuels (coal included). However, due to the limited coal use in rural areas where biogas technology is more feasible due to the availability of feedstock, coal substitution was disregarded in the study.

1.6. Methods

To achieve the research objectives listed in Section 1.5 above, the primary research method used is to calculate the required parameters based on values obtained from a literature study. The literature study was also used to identify the gaps in terms of biogas technology adoption and dissemination in South Africa thereby formulating the research questions to address those gaps. Literature study conducted includes analyzing the text in scientific articles, policy documents, census reports, research reports and websites.

1.7. Report Outline

The research on the potential of biogas as household energy in South Africa commences in Chapter 2 with the literature survey. Chapter 2 describes biogas characteristics as an energy source, biochemical processes involved in the production of biogas, the status of biogas technology in the developing world, and the benefits of adopting biogas as household energy and the constraints in the dissemination of biogas technology.

Chapter 3 defines the research methodology followed to address the research questions. Chapter 4 outlines the results of the calculations conducted in Appendix A as well as the results obtained from literature. The results are also discussed in Chapter 4 where the calculated results are compared to the results obtained from literature. The conclusions and recommendations are provided in Chapter 5 and 6 respectively where the feasibility of using biogas as household energy and the suitable practice in South Africa is explored. Lastly, the dissertation concludes with a case study regarding local power supply from a biogas socket which is currently piloted in Bangladesh, Rwanda and Tanzania.

CHAPTER 2: Literature Review

2.1. Introduction

This chapter reviews the energy demand by low-income households in South Africa using conventional domestic fuels. Biogas is explored as a potential energy substitute of conventional domestic fuels. Biochemical processes involved in biogas production are reviewed and the factors that affect these biochemical processes are explored. The status of domestic biogas technology in the developing world is also reviewed and the challenges faced are presented. This chapter concludes with the review of the benefits of domestic biogas technology and the current South African policies that govern the use of biogas are presented.

2.2. Energy demand in low-income South African households

The majority of non-electrified households in South Africa rely on biomass as a main source of energy used for cooking, space heating and water heating. Households without access to electricity are mainly located in rural areas of KwaZulu Natal, Eastern Cape and Limpopo and informal settlements of Gauteng (DoE, 2013). According to the Energy Research Centre (ERC) at the University of Cape Town (2004) as cited in Damm & Triebel (2008), approximately 64% of the households that depend on fuelwood for cooking purposes are in the lowest income brackets, where household income ranges from R0 to R9 600 per annum. A survey of 348 rural households in the Eastern Cape conducted by Prasad (2007) found that the poorest households with an average monthly income of R819 (R9 828 per annum) were without any supply of electricity. The Government of South Africa (2000) as cited in Damm & Triebel (2008) also reported that 70% of rural households are poor. It can therefore be deduced that mainly low-income households without access to electricity residing in rural areas and peri-urban/informal settlements of South Africa rely on biomass (fuelwood predominantly) as a main source of energy for cooking, space heating and water heating.

The total annual fuelwood consumption in South African households was estimated at 11.2 million tons which is equivalent to 190 400 TJ or 52 889 GWh (DME, 2006 as cited in Damm & Triebel, 2008). This represents approximately 40% of the total energy consumption in South

African households. The high proportion of fuelwood is attributed to its low efficiency in inefficient cooking and heating methods used by rural households. The total number of households that depend on fuelwood for cooking and heating purposes is generally estimated at around 2.3 – 2.8 million (Census, 2001; DWAF, 2004 as cited in Damm & Triebel, 2008). It is thus concluded that a good estimate for the average annual household fuelwood consumption is 4.5 tons per annum per household (≈ 12 kg/day/household) (Damm & Triebel, 2008).

2.2.1. Energy efficiencies of domestic fuels

There has been a variety of fuelwood efficiencies reported in literature which is mainly attributed to the types of cooking stoves and the testing method used. In the rural areas of the developing countries, the use of traditional or conventional cooking stoves and three stone fires (TSF) or open fires is still prevalent. Pathak *et al* (2009) reported a 40% burning efficiency of fuelwood used in conventional cooking stoves in rural India whereas Yu et al (2008) reported a 24% fuelwood efficiency used in traditional cooking stoves in China. These high efficiencies are attributed to the nature of the cooking stove used as well as its ability to retain or transmit heat. According to Xiaohua (1996), the thermal efficiency of the stoves in China was only 5-20%, while the average was about 10-11%. The improvement in efficiencies can be attributed to implementation of more improved and efficient cooking stoves in China over the years.

According to Muye (2015), cooking on TSF or open fires is still a norm in Africa. In South African rural households, open fires are still the most prevalent cooking method. Open fires for cooking have a low efficiency in the range of 3–8%, which means that about 92–97% of the energy is lost to the surroundings (Muye, 2015). According to Ballard-Tremeer (1997), the low efficiency of open fires is attributed to the low heat transfer efficiency due to high losses to the ground. Several studies have been conducted by researchers worldwide to determine the fuelwood efficiency of various cooking stoves including TSF using a Water Boiling Test (WBT). The WBT is a simplified simulation of the cooking process. The WBT involves operating the stove under conditions of heating up and simmering, using water to simulate food. Water is brought to boil as rapidly as possible during the heating-up phase (commonly called the 'high-power phase') and is then maintained within 5°C of boiling for 30 minutes during the simmering phase (called the 'low-power phase') (Ballard-Tremeer, 1997). Table 2-1 shows the reported fuelwood thermal efficiencies for open fires measured using the WBT:

Table 2-1: Thermal efficiencies of fuelwood in open fires measured using WBT

Thermal Efficiency (%)	**Source**
13	Boy *et al* (2000)
14	Ballard-Tremeer (1997)
16	Umogbai (2011)
18	TERI (1987) as cited Smith *et al* (2000)
18	Venkataraman *et al* (2010)
23	CES (2001) as cited in Rajendran *et al* (2012)

One of the limitations of the WBT is that it is a controlled test therefore it is less representative of the actual cooking. Ballard-Tremeer (1997) stressed that during the WBT, their open fires were sensibly controlled therefore considerably lower efficiencies would have been achieved by building larger fires. One of the major contributors to lower thermal efficiency is the moisture content of the fuelwood. The moisture in fuelwood (or any fuel) acts as a heat sink thus lowering the combustion efficiency (Ballard-Tremeer, 1997). The WBT takes into consideration the moisture content by measuring it and incorporating in the thermal efficiency calculation. The thermal efficiency obtained from a WBT is an overestimate of the actual thermal efficiency therefore it is logical that the lowest thermal efficiency (13%) from Table 2-1 be used in the calculation as it is the figure that is closest to the actual thermal efficiency.

The thermal efficiency for the biogas stoves varied between 50 and 60% (CES, 2001 as cited in Rajendran *et al*, 2012; Itodo *et al*, 2007; RCSD, 2008; Fulford, 1988:161). Khadi and Village Industries Commission (KVIC) and Bureau of Indian Standards (BIS) recommend that the efficiency of domestic burners should not be less than 55% (Smith *et al*, 2000). It can be deduced that using a biogas efficiency of 55% as reported in Smith *et al* (2000) for calculations in this present study is reasonable.

Another application for biogas besides cooking is lighting. In remote rural areas where there is no access to electricity, farmers use biogas for lighting too (Ghimire, 2013). Biogas used for lighting can be used in Liquefied Petroleum Gas (LPG) lamps or biogas lamps. Due to the inefficiency of biogas lamps, it is not recommended to use biogas for lighting and it should only be used where there is an excess of biogas (Everson & Smith, 2015). According to Thom (1994) as cited in Everson & Smith (2015), the efficiency of biogas lamps is approximately 5%. Al Seadi (2008) as cited in Smith & Everson (2016) reported a slightly lower efficiency of 3%. The use of biogas for lighting is often discouraged due its complexity from a technical and safety perspective (Everson & Smith, 2015).

The energy demand by a household is also dependent on the heating value or calorific value of the fuel used. The calorific value of any fuel is the energy released per unit mass or per unit volume of the fuel when the fuel is burnt completely. Table 2-2 shows reported calorific values of the various domestic fuels. Fuelwood has the lowest calorific value which is attributed to its moisture content. According to Ballard-Tremeer (1997), the calorific value of Saligna which is hardwood that is grown extensively in South Africa on a commercial basis was 19.76 MJ/kg and the calorific value of Pine (softwood) was 20.42 MJ/kg. Considering the poor quality of fuelwood that is now available to rural areas due to deforestation, a slightly lower calorific value of fuelwood of 17 MJ/kg used in the present study is reasonable. Due to the marginal differences in the calorific values of biogas reported by the sources in Table 2-2, an average calorific value of 20 MJ/m^3 will be used in the calculations of the present study.

Table 2-2: Calorific values of domestic fuels

Fuel	**Calorific Value**	**Units**	**Source**
Paraffin	35	MJ/L	(Pathak *et al*, 2009)
	38	MJ/L	(Fulford, 1988: 161)
Fuelwood	16	MJ/kg	(Pathak *et al*, 2009)
	18	MJ/kg	(Fulford, 1988: 161)
Biogas	20	MJ/m^3	(Pathak *et al*, 2009)

Fuel	Calorific Value	Units	Source
	19	MJ/m^3	(Fulford, 1988: 161)
	21	MJ/m^3	(Surendra *et al*, 2014)
	22	MJ/m^3	(CES, 2001; Itodo, 2007)

2.2.2. Economic value of fuelwood

There are two main value components of fuelwood which are (i) direct value where a market exists and fuelwood is traded, and (ii) opportunity cost which is related to the time spent collecting the resource (Damm & Triebel, 2008). The gross direct use value of fuelwood to rural households ranged from R600 to over R4 400 per year, with a mean of approximately R2 000 (Damm & Triebel, 2008). Census 2001 showed that 2.3–2.8 million of households rely on fuelwood which translated to a total gross direct use value of fuelwood in the region of R4.5 – R5.5 billion (Damm & Triebel, 2008).

Approximately 1-5 hours are spent on a given day to collect fuelwood by mainly women and girls (Damm & Triebel, 2008). On a monthly basis, the time spent can range from a few hours to over 80 hours per month, depending on the frequency of collection and the proximity of the fuelwood resource (Damm & Triebel, 2008). Taking an average of 40 hours per month at R12 per day, the opportunity cost would be of the order of R720 per annum, or 36% of the gross value of fuelwood to rural households (Damm & Triebel, 2008). Deducting this from the gross value means that the net direct-use value of fuelwood is of the order of R1 250 per household per annum, or R3–3.5 billion per annum in total (Damm & Triebel, 2008).

2.2.3. Burden of disease attributed to indoor smoke from fuelwood use

Although air pollutant emissions are dominated by outdoor sources, human exposures are a function of the level of pollution in places where people spend most of their time. Human exposure to air pollution is thus dominated by the indoor environment. Cooking and heating with solid fuels such as animal dung, wood, agricultural residues or coal is likely to be the largest source of indoor air pollution globally. When used in simple cooking stoves, these fuels emit substantial amounts of pollutants, including respirable particles, carbon monoxide, nitrogen and sulphur oxides, and benzene. Limited ventilation is common in many developing countries and increases exposure, particularly for women and young children who spend much of their time indoors (WHO, 2002).

Studies have shown reasonably consistent and strong relationships between the indoor use of solid fuels and a number of diseases. These analyses estimate that indoor smoke from solid fuels causes about 35.7% of acute lower respiratory infections (ALRI), 22.0% of chronic obstructive pulmonary disease (COPD) and 1.5% of trachea, bronchus and lung cancer. Indoor air pollution may also be associated with tuberculosis (TB), cataracts and asthma. The most important interventions to reduce this impact are better ventilation, more efficient vented stoves, and cleaner fuels (WHO, 2002).

Various estimators of the health impact of air pollution have been employed in recent health impact assessments. Some assessments have used indices such as the attributable risk (AR), or measures derived from it, such as the number of attributable cases, to quantify the burden of disease or death in a given population. The impact of increases in the mortality rate due to air pollution has also been quantified in terms of the average reduction of lifespan produced in a given population, using estimators such as years-of-life-lost (YLL). Still other assessments combine impacts on morbidity and mortality, using estimators such as disability- or quality-adjusted life-years (DALYs or QALYS, respectively) (WHO, 2001). DALY combines in a single metric, the time lived with a disability and the time lost due to premature death (DALY = YLL + YLD). YLL is the years of life lost due to premature death and YLD is the years lived with a disability (Prüss-Üstün *et al*, 2003). One DALY is equal to the loss of one healthy life year (WHO, 2002). According to Prüss-Üstün *et al* (2003) the DALY is the widely-used estimator of burden of disease and can be applied across cultures, therefore it is principal estimator used in this present study. Biogas reduces the burden of diseases associated with solid fuel use in rural low-income households by providing a cleaner cooking fuel as a substitute to solid fuels which is extensively discussed subsequently.

2.3. What is biogas?

Biogas is a mixture of gases produced by anaerobic digestion (AD) of biological matter. Various biological matters (substrates) can be used as feedstock in a domestic anaerobic digester such as kitchen waste, animal and human excreta due to their availability on a domestic level. The use of human excreta for biogas production and using bio-slurry that results from it has been dismissed in other countries as it was perceived socially and culturally unacceptable (Amigun et al, 2012; Van Nes & Nhete, 2007).

Biogas consists of 50-70% methane, 30-40% carbon dioxide and traces of other gases such as hydrogen sulphide, ammonia and hydrogen (Ghimire, 2013; Surendra et al, 2014). Biogas is an odourless and colourless gas that burns with clear blue flame (soot–free) similar to LPG gas (Ghimire, 2013). Typical compositions of raw biogas and the properties of the components are summarised in Table 2-3 below (Surendra et al, 2014):

Table 2-3: Chemical composition of biogas and properties of components

Components	**Concentration (v/v)**	**Properties**
CH_4	50 - 75%	Energy carrier.
CO_2	25 - 50%	Decreases heating value. Corrosive, especially in the presence of moisture.
H_2S	0 - 5 000 ppm	Corrosive and toxic. Sulphur dioxide emission during combustion.
NH_3	0 - 500 ppm	NO_x – Emissions during combustion.
N_2	0 - 5%	Decreases heating value
Water vapour	1 - 5%	Facilitates corrosion in the presence of CO_2 and sulphur dioxide (SO_2).

Normal combustion of biogas with excess air is expressed by reaction (1) below:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{Heat} \quad (1)$$

Biogas has a calorific value of approximately 21 – 24MJ/m^3 (Bond & Templeton, 2011). Bio-slurry, which is rich in nutrients is produced as a bi-product in the biogas production process which can be used as a potent organic fertilizer for crop production. Bio-slurry unlike synthetic fertilizer imparts no detrimental effect on soil or on the environment.

Biogas is a clean and renewable form of energy that could be a substitute (especially in the rural sector) for conventional sources of energy such fuelwood, coal and paraffin which are causing ecological–environmental problems and at the same time depleting at a faster rate (Gautam, Baral & Herat, 2009).

2.3.1. Biochemical processes involved in biogas production

Anaerobic digestion of biological matter to produce biogas is achieved by a series of biochemical reactions which are made possible by the existence of specific micro-organisms (bacteria). The biochemical processes involved in the production of biogas can be divided into three stages (see Figure 2-1 below) namely hydrolysis, acidogenesis (acid-formation) and methanogenesis (methane-formation).

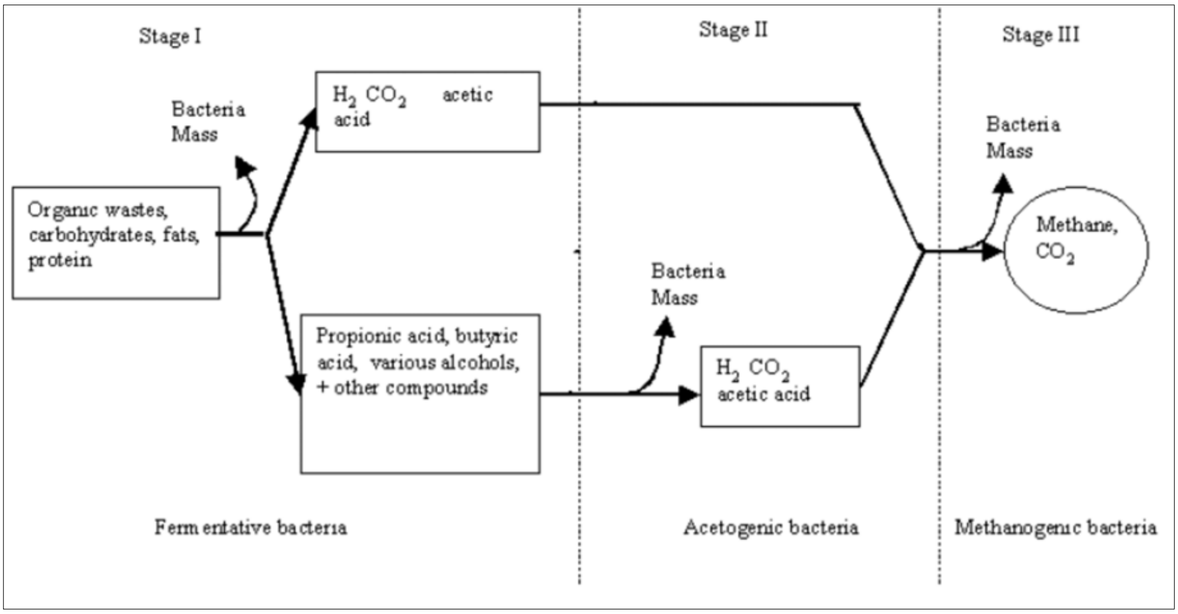

Figure 2-1: The three-stage anaerobic fermentation of biomass (Source: Thomas *et al*, 1999)

2.3.1.1. Hydrolysis

Hydrolysis involves the breakdown of long chain organic molecules such as carbohydrates, cellulose, proteins, lipids and fats into simpler shorter molecules such as monosaccharides and amino acids by extra-cellular enzymes of facultative (such as *Streptococci)* and obligatorily anaerobic bacteria (such as *Bactericides* and *Clostridia)* (Yadvika *et al*, 2004). Hydrolysis can be represented by reaction (2) below:

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow n(C_6H_{12}O_6) \qquad (2)$$

The hydrolysis of carbohydrates takes place within a few hours, the hydrolysis of proteins and lipids within few days. Lignocellulose and lignin are degraded only slowly and incompletely. The facultative anaerobic bacteria make use of the dissolved oxygen in the water and thus cause the reducing conditions necessary for obligatory anaerobic microorganisms (Deublein & Steinhauser, 2008: 94).

2.3.1.2. Acidogenesis

The second stage involves the conversion of the fermented intermediate materials into short-chain organic acids, C1-C5 molecules (e.g. butyric acid, propionic acid, acetate and acetic acid), alcohols such as ethanol, hydrogen and carbon dioxide by the action of acidogenic bacteria (Deublein & Steinhauser, 2008). This stage can be illustrated by the following reaction:

$$n(C_6H_{12}O_6) \rightarrow 3nCH_3COOH_2 \qquad (3)$$

Products of the acidogens such as butyric acid and propionic acid are further degraded by acetogenic microorganisms into acetic acid as shown by reaction (4) and (5) below (Deublein & Steinhauser, 2008: 96; Yadvika et al, 2004):

$$CH_3(CH_2)COOH + 2H_2O \rightarrow 2CH_3COOH + CO_2 + 3H_2 \qquad (4)$$

$$CH_3(CH_2)_2COO^- + 2H_2O \rightarrow 2CH_3COO^- + H^+ + 2H_2 \qquad (5)$$

Acetogenic bacteria are obligatory hydrogen producers and acetic acid is further produced through the reduction of the hydrogen and carbon dioxide as shown by reaction (6) below (Deublein & Steinhauser, 2008: 96):

$$2CO_2 + 4H_2 \leftrightarrow CH_3COOH + 2H_2O \tag{6}$$

The acetate formation by reaction (3) runs automatically and is thus thermodynamically possible only with very low hydrogen partial pressure. Acetogenic bacteria can get the energy necessary for their survival and growth, therefore, only at very low hydrogen concentration. On the other hand, methanogenic bacteria can survive only with higher hydrogen partial pressure. They constantly remove the products of metabolism of the acetogenic bacteria from the substrate and so keep the hydrogen partial pressure at a low level suitable for the acetogenic bacteria. Therefore acetogenic and methanogenic microorganisms must live in symbiosis (Deublein & Steinhauser, 2008: 97; Dioha *et al*, 2012). According to Dioha *et al* (2012), this cooperation between methanogenic bacteria and acetogenic bacteria is called syntrophic acetate oxidation (SAO).

When the hydrogen partial pressure is low, H_2, CO_2 and acetate are predominately formed by the acetogenic bacteria (Deublein & Steinhauser, 2008: 97; Dioha *et al*, 2012). When the hydrogen partial pressure is higher, predominately butyric acid, propionic acid and ethanol are formed. From these products, the methanogenic products can process only acetate, H_2 and CO_2 (Deublein & Steinhauser, 2008: 97).

About 30% of the entire CH_4 production in the anaerobic sludge can be attributed to the reduction of CO_2 by H_2 (70% from acetate), but only 5-6% of the entire methane formation can be attributed to the dissolved hydrogen (Fulford, 1988: 31; Deublein & Steinhauser, 2008: 97; Dioha *et al*, 2012). The bacteria (acidogens and acetogens) use up all the oxygen present creating an anaerobic environment for the methane-producing micro-organisms to react afterwards (Yadvika *et al*, 2004).

2.3.1.3. Methanogenesis

Methanogenesis is the final stage of the biogas production process. In this stage, methane and carbon dioxide (biogas) are formed by various obligatory methane-producing microorganisms called methanogens as shown by reactions (7), (8) and (9) below (Deublein & Steinhauser, 2008: 98). These methanogens include acetotrophic species (acetate utilizers) such as *Methanosaeta*, *Methanosarcina* spp. and *Methanothrix* spp and also hydrogenotrophs (hydrogen utilizing species) such as *Methanobacterium*, *Methanococcus*, etc. (Yadvika *et al*, 2004; Dioha *et al*, 2012).

Reduction of CO_2 *by* H_2: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ (7)

Oxidation of acetate: $CH_3COO^- + H_2O \rightarrow CH_4 + HCO_3^-$ (8)

Oxidation of ethanol: $2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$ (9)

When the methane formation works, the acetogenic phase also works without problems (Deublein & Steinhauser, 2008: 99). When the methane formation is disturbed, over-acidification due to accumulation of organic acids from the acidogenesis step occurs (Deublein & Steinhauser, 2008: 99). According to Dioha *et al* (2012), methanogens are easily affected by various disturbances such pH changes or the presence of toxic compounds such as heavy metals or organic pollutants.

2.3.2. Biogas digester technology

Biogas digester technology can be utilised industrially and domestically. Industrial biogas digesters are mainly used in developed countries for anaerobic digestion of municipal solid waste to release the pressure from landfill sites (Libsu, Chavan & Wonde, 2011). The biogas thus generated is mainly used for power production. In recent years, considerable attention has been paid towards the development of industrial reactors for anaerobic treatment of high strength organic effluents leading to the conversion of organic molecules into biogas. These reactors, known as second generation reactors or high rate digesters have been developed in industries such as distillery, pulp and paper, dairy and slaughterhouse, and can handle wastes at a high organic loading rate of 24 kg COD/m^3 day and high upflow velocity of 2-3 m/h at a low hydraulic retention time. These reactors can be classified as follows (Rajeshwari *et al*, 2000):

i. Fixed film reactors
ii. Upflow anaerobic sludge blanket reactor (UASB)
iii. Anaerobic fluidized bed reactor.

Domestic biogas digesters are most popular among the developing countries due to their ability to produce biogas on a small scale at household level. The biogas produced is used as fuel to minimise the use of biomass as fuel. This study focuses on domestic biogas digesters which are most popular among the developing countries including South Africa. Table 2-4 below shows the amount of biogas, digester size and cattle numbers required based on the household size.

Table 2-4: Requirements of digester volumes (Dioha *et al*, 2012)

Number of persons in the family	**Requirements of Biogas for cooking and lighting (m^3) per day**	**Volume of digester required (m^3)**	**Number of cattle needed**
Up to 4 persons	1	4	2 – 4
5 – 6	1.5	6	4 – 5
7 – 9	2	8	5 – 7
10 – 13	2.5	10	7 – 9
14 – 18	3.75	15	9 – 12
19 – 25	5	20	13 – 15

There are three domestic biogas digester types that are popular in developing countries namely:

2.3.2.1. Chinese fixed dome digester

The Chinese fixed dome digester (see Figure 2-2 below) consists of a cylindrical chamber with a feedstock inlet and a bio-slurry outlet, which also serves as an overflow tank (Pérez *et al*, 2014). Biogas is stored in the upper part of the chamber called the dome. When biogas production starts, the slurry is displaced into the overflow tank by the pressure of the gas in the dome. The volume of the overflow tank is equal to the volume of the biogas storage. Gas pressure increases with the volume of biogas stored resulting in the difference in slurry levels between the inside of the digester and the overflow tank. It is constructed underground to facilitate loading and to make use of the insulating properties of the soil, thus maintaining favourable temperature inside the digester (Pérez *et al*, 2014). It is constructed with locally available materials such as bricks, concrete and stones (Surendra *et al*, 2014). Construction material contributes significantly in the capital costs of the digester. An inventory analysis of household biogas digesters at high altitude conducted by Pérez *et al* (2014) showed that bricks and cement accounted for 60% of the total cost in the fixed dome digester construction.

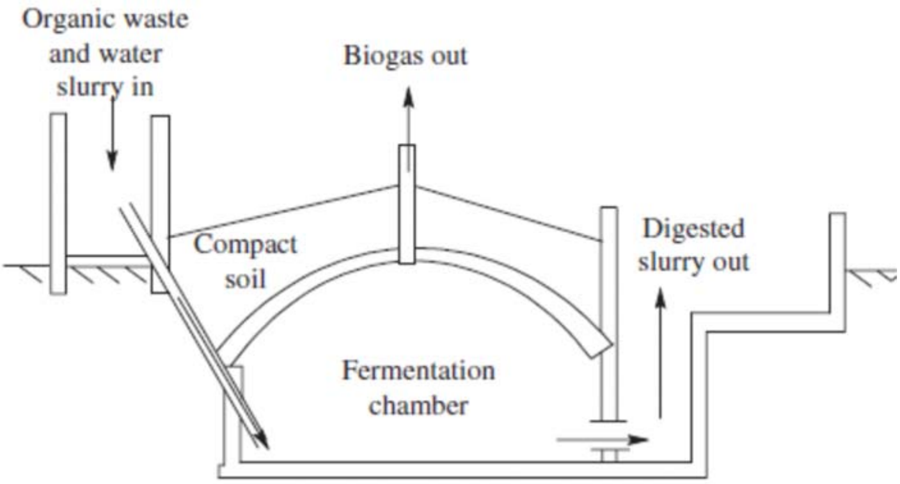

Figure 2-2: Schematic diagram of a Chinese fixed dome digester (Source: Gautam *et al*, 2009)

Sizing of a biogas digester depends on the location (urban or rural), number of households (single or multiple household), and feedstock availability (Rajendran *et al*, 2012). For instance, the size of these digesters can typically vary between 4 and 20 m^3 in Nepal (Gautam, 2009; Ghimire, 2013), between 6 and 10 m^3 in China (Daxion, 1990 as cited in Rajendran *et al*, 2012), between 1 and 150 m^3 in India (Tomar, 1994 as cited in Rajendran *et al*, 2012) and in Nigeria it is around 6 m^3 for a family of 9 members (Adeoti *et al*, 1990 as cited in Rajendran *et al*, 2012). Instead of having a single household biogas digester, a large volume digester is used to produce biogas for 10–20 homes, and is called community type biogas digester (Rajendran *et al*, 2012). In countries where houses are clustered as in Nigeria or the informal settlements in South Africa, these types of biogas digesters are more feasible (Akinbami *et al*, 2001 as cited in Rajendran *et al*, 2012).

2.3.2.2. Indian floating drum digester

The Indian floating drum type digester (see Figure 2-3 below) consists of two tanks (the upper tank and the lower tank) where the slurry is contained in the lower tank; with the upper tank (inverted tank) serving as a cap which is lifted by the biogas as it is generated (Dana, 2010). As the gas is being consumed, the gas pressure drops therefore the upper tank sinks back down. In general, plastic tanks are preferable to steel tanks for both slurry container and gas storage tanks as both the slurry and biogas can corrode steel tanks rapidly (Dana, 2010). In contrast, according to Bond & Templeton (2011) and Surendra *et al* (2014); a floating drum type digester is often constructed with concrete and steel. Unlike the fixed dome type digester, only the inverted tank is above the ground (Surendra *et al*, 2014).

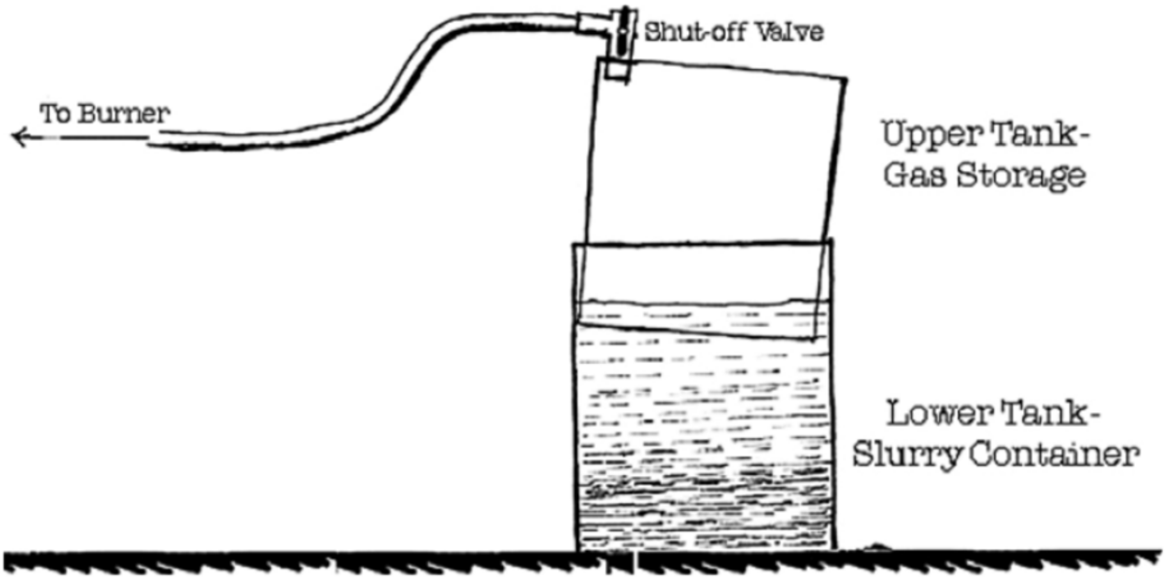

Figure 2-3: Schematic diagram of an Indian floating drum digester (Source: Dana, 2010)

The average size of these kinds of digesters is around 1.2 m^3 (Gosling, 1982 as cited in Rajendran *et al*, 2012). For a small-medium size farm the size varies from around 5–15 m^3 (Werner *et al*, 1989 as cited in Rajendran *et al*, 2012). Singh and Gupta (1990) compared 14 different community biogas plants with a floating drum model. The size of each digester was about 85 m^3.

2.3.2.3. Taiwanese plastic tubular digester

The Taiwanese plastic tubular digester (see Figure 2-4 below) operates in plug-flow mode. The size of such digesters varies from 2.4 –7.5 m^3 (Rajendran *et al*, 2012). Feedstock flows through a tubular plastic (polyethylene or PVC) bag from the inlet to the outlet, while biogas is collected by means of a gas pipe connected to a burner or a reservoir (for storage) (Garfí *et al*, 2012). In order to maintain higher process temperatures and reduce overnight temperature fluctuations, the digester is buried in a trench and/or covered by a greenhouse (Ferrer *et al*, 2011; Garfí *et al*, 2012; Pérez *et al*, 2014; Surendra *et al*, 2014). Taiwanese plastic tubular digesters are said to be the simplest (in terms of implementation and handling) and most inexpensive design but are susceptible to mechanical damage and have a short operational life of only 2-10 years (Surendra *et al*, 2014). Pérez *et al* (2014) gives a more conservative operational life for the plastic tubular digester of less than 5 years.

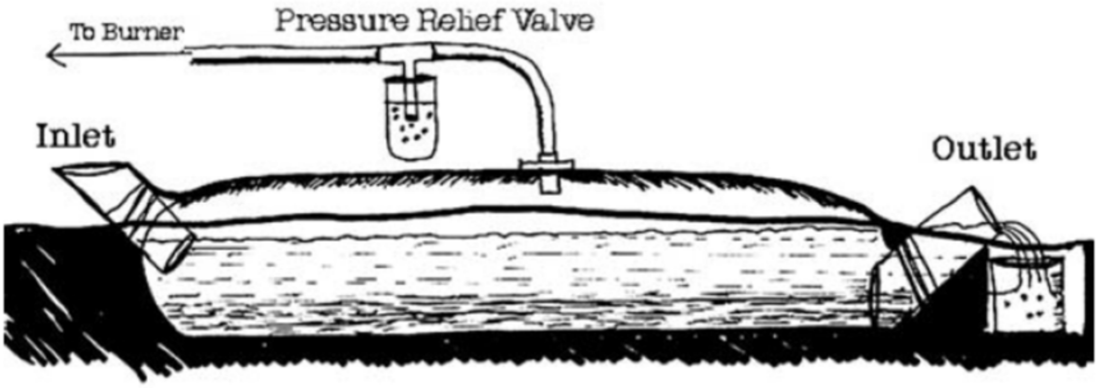

Figure 2-4: Schematic diagram of a Taiwanese plastic tubular digester (Source: Dana, 2010)

The Chinese fixed dome digester is the design of choice because of its reliability, low maintenance requirement and long lifetime (Parawira, 2009). According to Ghimire (2013), a 4 m^3 sized digester can produce 800 – 1 600 L/day of biogas that can fulfil energy demand for cooking for a 4-5 member family. According to Bond and Templeton (2011), 1 500 – 2 400 L of biogas is sufficient to supply cooking requirements for a family of five.

2.3.3. Kinetics of anaerobic digestion

Several kinetic models have been developed to describe the anaerobic digestion of biological material. The Monod model can be used to determine the rate of substrate utilisation (r_s) by Equation 1 below:

$$r_s = \frac{Q_{max} S}{K + S} \qquad \text{Equation 1}$$

Where S is the limiting substrate concentration, K is half velocity concentration, and Q_{max} is maximum substrate utilization rate. The above equation is applicable for a low substrate concentration. However, for high substrate concentration ($S >> K$), the equation is re-written as:

$$r_s = Q_{max} \qquad \text{Equation 2}$$

According to Mittal (1996), the Monod model suffers from the drawback that one set of kinetic parameters are not sufficient to describe the biological process for both for short- and long-retention times, and that kinetic parameters cannot be obtained for some complex substrates. To alleviate limitations of the Monod model while retaining its advantages, Chen & Hashimoto (1978) developed an alternative equation which attempts to describe kinetics of methane fermentation in terms of several parameters. According to Equation 3, given below, for a given loading rate (S_0/q) daily volume of methane per volume of digester is depended on the biodegradability of the material (B_0) and kinetic parameters μ_m and K (Chen & Hashimoto, 1978).

$$r_v = \frac{B_0 S_0}{q}\left(1 - \frac{K}{q\mu_{max} - 1 + K}\right) \qquad \text{Equation 3}$$

Where,

r_v = volumetric methane production in cubic meter methane gas per cubic meter digester per day.

S_0 = Influent volatile solids concentration in kg VS per cubic meter digester

B_0 = Ultimate methane yield in cubic meters methane per kg VS

q = Hydraulic retention time (HRT) in days

μ_m = Maximum specific growth of the microorganism in per day.

K = Dimensionless kinetic parameter, for cattle dung, $K = 0.8 + 0.0016e^{0.06S_0}$

For predicting the daily gas production in a semi-continuous biogas digester fed with cattle dung, Equation 4 below can be used (Fulford, 1988: 152). The reaction is derived from the first order kinetics model.

$$g = C.V.S_o \frac{k}{1 + k.R} \qquad \text{Equation 4}$$

Where,

g = daily gas production in cubic meter per day

C = Yield constant for the substrate

V = volume of the reactor in cubic meters

S_0 = Initial substrate concentration

k = First order rate constant in per day

R = Hydraulic retention time in days

Typical values for yield and rate constants for cattle dung in semi-continuous digesters are given in Table 2-5 below.

Table 2-5: Kinetic constants for cattle dung in semi-continuous digesters (Fulford, 1988: 152)

Temp (°C)	Yield Constant: C (L/kg)		Rate Constant: k (1/d)	
	Volatile Solids	COD	Volatile Solids	COD
33.5	402	347	0.083	0.081
30.1	450	-	0.052	-
27.5	310	-	0.044	-
25	289	237	0.069	0.078
24.4	250	-	0.036	-
20.3	310	-	0.022	-
16	178	164	0.033	0.026

2.3.4. Characteristics of feedstocks

In general, all types of biomass can be used as feedstock as long as they contain carbohydrates, proteins, fats, cellulose, and hemicellulose as main components (Deublein & Steinhauser, 2008: 57; Bond & Templeton, 2011). However, the biodegradability of the feedstock depends on its physical and chemical form (Fulford, 1988: 33). Typical feedstocks used for biogas production are as follows:

i. Animal waste
ii. Kitchen/food waste
iii. Human excreta/sewage
iv. Co-digestion

Raw plant material is bound up in plant cells, usually strengthened with cellulose and lignin, which are difficult to digest. In order to let the bacteria reach the more digestible foods the plant material must be broken down (Fulford, 1988: 34). Cattle dung is a suitable feedstock due to the presence of methanogens in the stomachs of ruminants (Bond & Templeton, 2011) and because it has been ground up by the animal's teeth and has also been broken down chemically by acids and enzymes in the animal's gut (Fulford, 1988: 34).

"It is believed that fresh human excreta are suitable for biogas production, whereas sludge collected from septic tanks, pit latrines, etc. is not. This is most likely because both aerobic and anaerobic digestion contribute to the decomposition of biodegradable waste in pit latrines, leaving a residual of biologically-inert solids after a certain residence time" (Bond & Templeton, 2011).

There are several measurements that can be made to define the characteristics of the feedstock or slurry (Fulford, 1988: 34):

i. Total solids (TS) is a measure of the dry matter (DM) left after the moisture has been removed (by heating 105 °C).
ii. Volatile solids (VS) is a measure of the organic solids lost when the dry matter is burnt (at 500 °C or 600 °C)
iii. Chemical oxygen demand (COD) is a measure of the pollution strength of the slurry. It is determined by chemically oxidising the sample
iv. Biochemical oxygen demand (BOD) is an attempt to measure the pollution more realistically. Aerobic bacteria are used to digest the sample and the oxygen is measured.
v. Carbon to Nitrogen ratio (C: N) is an important parameter as anaerobic bacteria need nitrogen compounds to grow and multiply. Too much nitrogen however can inhibit methanogenic activity.

Typical values for some of the aforementioned parameters are given in Table 2-6 below and Table 2-7.

Table 2-6: Properties of typical feedstock (Fulford, 1988: 35)

Feedstock	%VS	C:N Ratio
Pig Manure	80	14
Cow Manure	77	20-30
Chicken Manure	77	8
Human excreta	15-20	6-10

VS is not an ideal measure of the digestibility of a feedstock. Lignin and other indigestible solids will burn at 500 °C, while some digestible solids, such as sugars, leave a carbon deposit when heated. COD and BOD are also not ideal ways to predict what proportion of the feedstock will be digested in an anaerobic digester, as they were designed as measures of the aerobic digestibility of materials (Fulford, 1988: 35). COD is useful in that it is possible to define a value for methane. Using this figure, a digester should produce 350 litres of methane per kg of COD digested (Fulford, 1988: 36).

The best way to determine the anaerobic digestibility of a feedstock is to digest it in small laboratory digesters (2 litres) in controlled temperature baths. The values of total carbon during measurement can be misleading, as some of the carbon is bound up in indigestible lignin (Fulford, 1988: 35).

Table 2-7 below shows typical biogas yields per kg of dry matter of selected feedstock used for domestic anaerobic digesters.

Table 2-7: Biogas production from selected feedstock

Feedstock	**Daily production (kg/animal)**	**%DM**	**Biogas yield (m^3/kg DM)**	**Biogas yield (m^3/animal/day)**	**Source**
Pig Manure	2	17	0.25-0.5	0.128	Surendra *et al* (2014)
Cow Manure	8	16	0.2-0.3	0.32	(Bond & Templeton, 2011)
Chicken Manure	0.08	25	0.35-0.8	0.01	
Human excrement/sewage	0.5	20	0.35-0.5	0.04	
Vegetable Waste	-	5-20	0.4	-	(Deublein & Steinhauser, 2008: 59-61)
Bio waste from households	-	40-75	0.3-1.0	-	

2.3.4.1. Animal Waste

The specific characteristics of animal manure (as a feedstock for AD) vary with species and geography, but in general, animal manure has a high moisture content (75–92%) and volatile solids (VS) ranging from 72 – 93% of total solids (TS), as well as a good buffering capacity which makes it an ideal substrate for AD (Surendra *et al*, 2014). According to Garfí *et al* (2012), the digestibility and net energy content of animal excreta is greatly influenced by type of species, age and type of feeding. Furthermore, animal manure contains large and diverse microbial communities; hence anaerobic digesters receiving animal manure as a feedstock can be initiated without the addition of any external inoculums (Surendra *et al*, 2014). However, because of a relatively low readily degradable organic content, animal manure has low biochemical methane potentials (BMP) and digestion can be slow (Surendra *et al*, 2014). In addition, depending on manure type and freshness, a high concentration of NH_3, generated during digestion, creates unfavourable environment for methanogens (Surendra *et al*, 2014).

The liquid manure from all animal species may contain foreign matter from animal feed. Unwanted foreign matter that impairs the fermentation of liquid animal manure includes (Deublein & Steinhauser, 2008: 62):

i. Sand from material present in feed of pigs and poultry
ii. Sawdust from scattering
iii. Soil from roughage
iv. Soil which is carried from meadows
v. Skin and tail hair, bristles and feathers
vi. Cords, wires, plastic, stones and others.

The presence of foreign matter leads to an increased complexity in the operations and increases the operating expenditure of the plant. Such operational complexities and operating expenditure includes continuous stirring of the digester, desludging of the digester and scum removal. For an example, during the process of fermentation of liquid manure from pigs and cattle the formation of scum caused by feed residues and straw and/or muck is expected. Pig liquid manure rather causes aggregates at the bottom as the feed contains a certain proportion of sand and consists of undigested parts of corn and grain. Likewise chicken manure leads to a similar phenomenon due to a high content of lime and sand (Deublein & Steinhauser, 2008: 64).

In general, organic acids, antibiotics, chemotherapeutic agents, and disinfectants found in liquid manure can impair or even disrupt the fermentation process in biogas digesters (Deublein & Steinhauser, 2008: 64). This is in accordance with Dioha *et al* (2011) regarding the sensitivity of methanogens to toxic compounds such as heavy metals and organic pollutants. In the liquid manure of pigs, the high content of heavy metals such as copper and zinc derived from additives in the feed can be the limiting factor (Deublein & Steinhauser, 2008: 64).

The degree to which the organic substance in the biomass is decomposed in the digester depends on the origin of the liquid manure. The organic content in liquid manure derived from cattle is only 30% decomposed because of the high raw fibres in the feed, while about 50% of pig manure and more than 65% of chicken manure is broken down (Deublein & Steinhauser, 2008: 64).

2.3.4.2. Kitchen/food Waste

Kitchen/food waste is bio-waste generated by households. Kitchen wastes include peels of vegetables, peels of fruits, waste milk and milk products, stale cooked and uncooked food, and spent tea (Munda *et al*, 2012). Kitchen wastes and crop residues are some underexploited substrates for the domestic biogas production (Rajendran, Aslanzadeh & Taherzadeh, 2012). Kitchen wastes contain a high amount of fat in the form of animal fat from meat and cooking oil (Rajendran *et al*, 2012). According to Bond & Templeton (2011), this high-fat content can enhance the biogas production.

Food and food-processing waste are arguably the best resource for bio-methane production because of their high moisture (> 80%) and VS (95% of TS) contents (Surendra *et al*, 2014). With the exception of meat waste, most food processing waste is poor in nitrogen content; but is rich in readily fermentable organic matter (Surendra *et al*, 2014). Scano *et al* (2014) attributes this to the high simple sugars content often found in vegetable and fruit waste which is easily fermentable to organic acids thus promoting acidification with a resulting inhibition of methanogenic bacteria activity. Co-digestion of food waste with cattle dung is therefore recommended due to the readily available methanogens in the stomachs of cattle.

Raw vegetable matter usually needs to be treated before it can be used. It can be physically chopped up or minced, or it can be treated chemically (Fulford, 1988: 34). The methane potential of organic substrates increases with reduced particle size because of increased surface area thus enhancing microbial activity. The presence of lignin in peels makes food waste harder to hydrolyse therefore pre-processing food waste enhances gas production (Munda *et al*, 2012). One good method seems to be to compost vegetable matter for five days before feeding it to the digester, as aerobic bacteria are better at breaking down cellulose (Fulford, 1988: 35).

In urban areas bio waste is poor in structure and quite pasty. This waste includes leftovers, spoiled food, market waste, and different industrial waste (e.g. mash, waste liquor, waste from the food industry and the industry of luxury articles). In the outskirts of a town or in rural settlement the bio waste is fairly rich in structure and fibrous, and hence is well suitable for composting (Deublein & Steinhauser, 2008: 66).

Methane percentage in biogas from agro-feed digesters is higher than in animal waste feed digesters, so the agricultural waste will be good alternative source for biogas. Leaves, grasses, and other garden waste are a good alternative feed for biogas. High carbohydrate content in agricultural species results in higher biogas output, but due to low nitrogen content the bacterial growth is low. So, co-feeding a mixture of animal waste and agricultural species can result in both higher rate and ultimate yield of biogas production (Munda *et al*, 2012).

2.3.4.3. Human Excreta/Sewage

Anaerobic digestion of human waste provides sanitation by reducing the pathogenic content of substrate materials. Hence biogas installation can dramatically improve the health of users. This is particularly the case where biogas plants are linked to public toilets and/or where waste is no longer stored openly. Rapid public health improvements following biogas implementation have been observed in rural China, with reductions in schistosomiasis and tapeworm of 90–99% and 13% respectively (Bond & Templeton, 2011).

Solid retention times of 3 weeks at mesophilic conditions are enough to kill pathogens leading to typhoid, cholera, dysentery, schistosomiasis and hookworm. However, for eliminating other pathogens mesophilic anaerobic processes are rather ineffective, with typically 50% inactivation of helminth eggs and modest reductions of tapeworm, roundworm, E. coli and Enterococci. Thus, the World Health Organisation (WHO) suggests pathogen reduction by mesophilic AD is insufficient to allow subsequent use of human excreta as fertiliser (Bond & Templeton, 2011).

Some potential users are reluctant to try the biogas digesters out of concern about sanitation. Use of human wastes for biogas production and the subsequent digested sludge, for example in schools, as a source of fertiliser faces cultural and health resistance. Even though the AD process naturally reduces the pathogen load, handling biogas feedstock particularly human excreta and using biogas slurry as fertiliser does pose some risk of infection (Parawira, 2009).

Human, pig and chicken manure are also good feedstocks, but need a ‘starter’, such as slurry from a working digester, if they are used to start a biogas plant, because these animals do not have all the right bacteria in their gut (Fulford, 1988: 34).

2.3.4.4. Co-digestion

Several studies have found that the use of multiple substrates often has synergistic effects in that biogas production is higher than would be expected on the basis on methane potential of feedstocks components (Shah, 1997). Surendra *et al* (2014) recommends co-digestion of different organic substrates, not only to improve biogas production but to cope with feedstock scarcity. Co-digestion can improve the nutrient balance; maintain the pH, and results in positive synergism (Rajendran *et al*, 2012). This is illustrated by data showing biogas yields for cattle manure, sewage and a 50:50 mix of cattle manure and sewage to be 0.380, 0.265 and 0.407m^3/kg DM respectively after 40 days' digestion (Shah, 1997). Consequently, co-digestion is often beneficial and the focus of much recent research activity, often with combinations of sewage, municipal waste and industrial waste (Bond & Templeton, 2011).

As previously mentioned animal waste is rich in nitrogen and microbial activity therefore co-digesting with feedstocks rich in carbohydrates but poor in nitrogen can significantly enhance biogas production. Feedstocks such as food waste which are rich in fermentable organic matter can enhance system stability and overall biogas production. The results of work that was conducted by Munda *et al* (2012) in co-digestion of cow dung with kitchen and agricultural waste is shown in Table 2-8 below.

Table 2-8: Comparison of cumulative biogas production (cm^3/kg solid feed) from pure cow dung and other co-digested feed (Munda *et al*, 2012).

No. of days	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
Pure Cow dung	400	988	2 454	4 657	11 607	19 237	26 324	27 858
Cow dung & corn waste	390	1 061	2 252	3 402	6 627	10 855	13 394	14 203
Cow dung & kitchen waste	848	1 590	2 882	4 330	6 411	9 727	13 319	14 819
Cow dung & spent tea waste	2 429	3 009	3 659	3 977	4 318	7 314	9 688	10 450

Comparing biogas production from all feedstocks to pure cow dung, it was found that after 25–30 days average gas production is less, which shows that the effect of other feedstocks (spent tea waste, corn waste, kitchen waste) had ended after 25–30 days. The results obtained from cow dung mixed with spent tea waste showed that initially gas production is high. This may be due to the mixture of sugar in spent tea waste. The simple organic compounds like glucose are easily converted to acid and then methane, and because of this the gas production is high initially (Munda *et al*, 2012).

2.3.5. Factors affecting biogas digester operation

Biogas digestion is a microbial process, and for that reason requires the maintenance of suitable growth conditions for biogas producing bacteria (Yadvika *et al*, 2004). The common factors that affect biogas production include:

2.3.5.1. Temperature

Temperature inside the digester has a major effect on the biogas production as it impacts the growth of the methane producing bacteria (Yadvika *et al*, 2004). There are temperature ranges during which anaerobic fermentation can be carried out: psychrophilic (<30 °C), mesophilic (30 – 40 °C) and thermophilic (50 – 60 °C) (Yadvika *et al*, 2004). El-Mashad *et al* (2004) as cited in Alvarez & Lidén (2008) classified the three temperature ranges for the AD process as <20 °C for psychrophilic, 20 – 40 °C for mesophilic and >40 °C for thermophilic. However, anaerobes are more active in the mesophilic and thermophilic temperature ranges (Yadvika *et al*, 2004). Oxygen is less soluble in the thermophilic temperature range, so that the optimal anaerobic operating conditions are reached more quickly (Deublein & Steinhauser, 2008: 113).

While anaerobic digestion is more efficient in the thermophilic region than in the mesophilic region, rural biogas digesters operate in the mesophilic range because higher temperatures are difficult to maintain. The Chinese fixed dome digester is an underground design, which utilises the earth’s insulating properties to maintain healthy process temperatures. The gas production rate roughly doubles for every 10 °C rise in temperature between 15 °C and 35 °C (Fulford, 1988: 33). Alvarez & Lidén (2008) conducted a study on a bench-scale digester fed with a mixture of llama-cow-sheep manure which showed that a temperature reduction from 35 °C to 25 °C resulted in a reduction of 30% biogas production rate, whereas temperature reduction from 25 °C to 18 °C caused biogas production rate reduction of 51%. A study conducted by Pérez *et al* (2014) showed that in the plastic tubular model (without greenhouse), the biogas production rate dropped by 70% during winter months as compared to summer months; while in the fixed dome model the biogas production rate dropped by only 15%. This is attributed to the lack of insulation for the plastic tubular model therefore exposed to temperature fluctuations as compared to the fixed dome model which is constructed underground therefore making use of the earth's insulating properties. The gas production efficiency (the gas produced per kilogram of feedstock) also increases with temperature. According to Cha *et al* (1997) as cited in Alvarez & Lidén (2008), the activity of acidogenic bacteria is suppressed at temperature below 20°C. A mesophilic digester works best at 35 °C (Fulford, 1988: 33).

Methanogenic bacteria are sensitive to drastic temperature changes (Fulford, 1988: 33; Yadvika *et al*, 2004). Even small variations in temperature can cause a substantial decrease in activity, resulting in a build-up of undigested volatile acids causing acidic conditions (Deublein & Steinhauser, 2008: 113). Therefore, the temperature should be kept exactly within a range of ± 2 °C (Deublein & Steinhauser, 2008: 113). A sudden change of more than 5 °C in a day can cause a temporary inactivity of the methanogenic bacteria (Fulford, 1988: 33). The optimum temperature is achieved when the methanogenic bacteria consume all the acids at approximately the same rate that they are being produced by acidogenic bacteria (Dioha *et al*, 2012).

2.3.5.2. pH

An appropriate pH level is very important for effective performance of the methanogenic bacteria (Yadvika *et al*, 2004). When a biogas digester is newly started, the acidogens become active first, increasing the acid content thus reducing the pH to below 7. The methanogens then start consuming these acids, increasing the pH back to neutral (Fulford, 1988: 114). The ideal pH value for methane formation lies between 6.5 and 7.5 (Yadvika *et al*, 2004; Fulford, 1988: 114).

A working biogas plant is naturally buffered therefore the acid level is controlled by the process itself (Fulford, 1988: 32). A drop in the pH-value and a rise of the CO_2 in the biogas is an indication of a disturbance of the fermentation process (particularly the methanogenesis step) (Deublein & Steinhauser, 2008: 115). Some of the CO_2 produced by the bacteria dissolves in the water to form bicarbonate ions (HCO_3^-) which results in a mildly alkaline solution (Fulford, 1988: 32). For normal anaerobic fermentation, concentration of the volatile fatty acids, acetic acid in particular, should be below 2 000 ppm; too high a concentration will greatly inhibit the activity of methanogenic bacteria (Van Buren, 1979: 24; Yadvika *et al*, 2004).

2.3.5.3. Carbon to Nitrogen ratio

For optimum growth and activity of bacteria and production of biogas, it is desired that the feed contains adequate nutrients. While carbon supplies energy, nitrogen is needed for cell growth (Munda *et al*, 2012). It is generally found that during AD, microorganisms utilize carbon 25–30 times faster than nitrogen. Thus to meet this requirement, microbes need a 20-30:1 ratio of C to N with the largest percentage of the carbon being readily degradable (Yadvika *et al*, 2004). A wider range of C: N ratio is given in Deublein & Steinhauser (2008: 115) as 16-25:1. Table 2-6 shows the C: N ratio for some of the typical feedstocks.

A low C: N ratio basically means that the substrate is rich in nitrogen and vice versa. Substrates with a too low C: N ratio lead to increased ammonia production and inhibition of methane production (Deublein & Steinhauser, 2008: 116). For an example, if chicken manure is used as feedstock, the addition of carbon such as chopped grass or water hyacinth can reduce the possibility of toxicity from too much nitrogen affecting the bacteria (Fulford, 1988: 36).

If the C: N ratio is too high, then gas production can be enhanced by adding nitrogen in the form of cattle urine or urea, or by connecting a toilet to the digester (Fulford, 1988: 36). Co-digestion is beneficial in improving the C: N ratio. Use of urine soaked waste materials is particularly advantageous during winter months when gas production is otherwise low (Yadvika *et al*, 2004).

2.3.5.4. Nutrients availability

Feedstock to the digester must contain enough nutrients to enhance the growth of microorganisms. The need for other nutrients besides carbon and nitrogen is very low due to the fact that with anaerobic process not much biomass is developed, so that for methane formation even a nutrient ratio C: N: P: S of 500: 20: 5: 3 and/or an organic matter ratio of COD: N: P: S = 800: 5: 1: 0.5 is sufficient (Deublein & Steinhauser, 2008: 116).

2.3.5.5. Solids concentration

Solids concentration is the amount of fermentable material of feed in a unit volume of slurry (Yadvika *et al*, 2004). Ordinarily 7–9% solids concentration is best-suited for optimum AD

(Yadvika *et al*, 2004). A wider range for optimum solids concentration in low-rate biogas digesters is given by Bond & Templeton (2011) and Rajendran *et al* (2012) as 5-10%. Some literature recommends solid concentration for feedstock to be between 8% and 12% (Fulford, 1988: 35). The water content should normally be around 90% of the weight of the total contents (Van Buren, 1979: 23). Therefore feedstock such as cow dung must be diluted with water prior to being fed into the biogas digester (Fulford, 1988: 35). Typical values of the solids concentrations (as %TS) for various feedstocks are given in Table 2-6.

A low solids concentration means that the digester volume is used inefficiently. It can also lead to a separation of the slurry, the heavier solids sinking to the bottom to form a sludge layer and the lighter solids floating to form a scum layer on top of the liquid (supernatant). The scum layer can dry out to form a solid mat, preventing gas release from the liquid and blocking pipes which will result in operational complexities and increase the operating expenditure of the digester. This should not happen if the solids concentration is kept above 6% (Fulford, 1988: 35).

A feedstock with a high solids concentration (greater than 12%) does not easily flow through the inlet pipes (Fulford, 1988: 35). If toxins are present, such as a high nitrogen concentration, bacteria are more likely to be affected in the thick slurry (Fulford, 1988: 35). However slurries of up to 30% total solids can be digested in a dry fermenter (Fulford, 1988: 35). If the water content is too low, acetic acids will accumulate, inhibiting the fermentation process and hence production; also a rather thick scum will form on the surface (Van Buren, 1979: 23).

2.3.5.6. Organic loading rate (OLR)

Organic loading rate is the amount of volatile solids fed per unit volume of digester capacity per day. Gas production rate is highly dependent on loading rate. Methane yield was found to increase with reduction in loading rate. There is an optimum feed rate for a particular size of plant, which will produce maximum gas and beyond which further increase in the quantity of substrate will not proportionately produce more gas (Yadvika *et al*, 2004). The normal OLR of a digester operating in mesophilic condition is 2-3 kg VS/m^3.day (Rajendran *et al*, 2012).

If the digester is underfed (loading rate is too low), the bacteria will exhibit a lower metabolic activity and very small quantities of biogas will be produced, although perhaps with an efficient solids breakdown (Stafford, Hawkes & Horton, 1980: 83). If the digester is overfed (loading rate is too high), an overload situation will be produced in which volatile fatty acids (VFA) builds up, inhibiting methane production, and the proportion of carbon dioxide rises (Stafford, Hawkes & Horton, 1980: 83).

2.3.5.7. Hydraulic retention time (HRT)

HRT is the ratio of the volume of the digester to the daily feed rate. HRT is the average time spent by the input slurry inside the digester before it exits (Yadvika *et al*, 2004). At higher temperatures (beyond 35 °C), the HRT is reduced due to enhanced microbial activity inside the biogas digester. It is possible to carry out methanogenic fermentation at low HRT’s without stressing the fermentation process at mesophilic and thermophilic temperature ranges (Yadvika et al, 2004).

In tropical countries like India, HRT varies from 30–50 days while in countries with colder climate it varies from 60-90 (Pérez et al, 2014) or may go up to 100 days (Yadvika *et al*, 2004). Shorter retention time is likely to face the risk of washout of active bacterial population because they do not have sufficient time to grow at the same rate as the material is being pumped in and out of the digester (Yadvika *et al*, 2004; Dioha *et al*, 2012). Longer retention time requires a large volume of the digester and hence more capital cost. Hence there is a need to reduce HRT for domestic biogas plants based on solid substrates (Yadvika *et al*, 2004).

2.4. Biogas as a renewable energy source in the developing world

2.4.1. Domestic biogas technology status in Asia

In Asia, countries such as China and India have seen massive campaigns to popularise the technology. Widespread dissemination of biogas digesters in developing countries stems from the 1970s and there are now around 4 and 27 million biogas plants in India and China respectively (Bond & Templeton, 2011). The rapid development of biogas through these countries is linked to accumulated technical knowledge, the availability of fermentation materials, and strong state support, including financial.

Similar encouraging signs of growth have been received from other Asian countries such as Nepal, Vietnam and Bangladesh which have reported 205 762, 75 820 and 10 019 of biogas digesters installed respectively up to 2009 (see Table 2-9 below). The 299 908 biogas plants installed in 14 countries till the end of 2009 under the framework of SNV national biogas programme in Asia and Africa produce more than 600 million liters of biogas per day which is equivalent to 3 000 tons of fuelwood or 360 Kiloliters of paraffin or 240 Ton of LPG or 900 Megawatt-hour of electricity (Ghimire, 2013). Table 2-9 below shows the growth in the number of domestic biogas digesters installed in selected Asian countries.

Table 2-9: Number of biogas plants installed in Asia

Country	**Year of programme initiation**	**Cumulative number of biogas plants installed up to 2009 (Ghimire, 2013).**	**Cumulative number of biogas plants installed up to 2012 (Surendra *et al*, 2014).**
China	1974	27 000 000	35 000 000
India	1970s	4 000 000	4 500 000
Nepal	1992	205 762	268 464
Vietnam	2003	75 820	152 349
Bangladesh	2006	10 019	26 311
Cambodia	2006	6 402	19 173
Lao PDR	2006	1 020	2 888
Indonesia	2009	50	7 835
Pakistan	2009	100	2 324
Bhutan	2011	-	265
Total		**31 299 173**	**39 979 675**

2.4.2. Domestic biogas technology status in South America

In Latin American countries i.e. the rural areas of tropical countries like Colombia and Costa Rica and the hilly regions of Peru and Bolivia, the implementation of biogas plants is growing dating back to the 1980s (Pérez *et al*, 2014). The simple constructions are similar to those in Asia, with a digester volume of 2-10m^3 with a growing interest in the Taiwanese plastic tubular digester design by the Andean communities in the past decade. Taiwanese plastic tubular digesters are known for their low cost, and ease of implementation and handling (Garfí *et al*, 2011; Pérez *et al*, 2014).

Andean communities reside on the highest mountain peaks in the world with highest altitude of 6 960 meters above sea level (m.a.s.l.) thereby making it one of the coldest regions in the world. The Peruvian Andes is characterized by two seasons, a dry sunny season with an average of 13 °C and a wet cloudy season with an average temperature of 9 °C (Garfí *et al*, 2011). Low temperatures (psychrophilic conditions) due to high altitude played a major role in the poor performance of the digesters in the Andean countries therefore requiring insulation increasing capital cost (Pérez *et al*, 2014).

2.4.3. Domestic biogas technology status in Africa

Unlike Asia, domestic biogas technology in Africa is still embryonic although the potential is there. Taking into consideration multiple assumptions, Africa is estimated to have to have some 168 million head of domestic cattle thereby the technical potential market for domestic biogas in Africa is estimated at 18.5 million households (Van Nes & Nhete, 2007; Ghimire, 2014). This is considering only animal excreta as feed.

In most cases, biogas was introduced free of cost through a pilot or demonstration project. Such projects were often implemented through government structures with intent to motivate people to adopt the technology automatically (Van Nes & Nhete, 2007). However, this approach has not led to widespread dissemination and market development of the technology (Van Nes & Nhete, 2007). There are project initiatives that are currently running in Africa such as SNV supported national biogas programmes which are active in nine African countries

(Ghimire, 2013). Through such programmes, Africa has seen a 44% rise in the number of biogas digesters installed from 2011 to 2012. An analysis conducted by Van Nes & Nhete (2007) revealed that the exact number of plants installed in Africa was not known but the most units were installed in Tanzania (more than 4000), Kenya and Ethiopia with hundreds to only a few in other countries (see Table 2-10 below). This lack of information regarding the number of biogas digester installed is attributed to the fact that in most African countries, the biogas programme was initiated post 2007. Unfortunately, an estimated 60% of these plants failed to stay in operation (Van Nes & Nhete, 2007). The same failure rate was reported for the 27 million biogas digesters installed in China (Surendra *et al*, 2014).

An African biogas initiative was launched in May 2007 in Nairobi which aimed at installing two million biogas plants by 2020 with half of the digesters connected to toilets. The initiative also aimed at job creation, reducing health costs, saving wood and reduction of greenhouse gas emissions etc. (Van Nes & Nhete, 2007).

Table 2-10: Number of biogas plants installed in selected African countries

Country	**Year of programme initiation**	**Cumulative number of biogas plants installed up to 2009 (Ghimire, 2013).**	**Cumulative number of biogas plants installed up to 2012 (Surendra *et al*, 2014).**
Rwanda	2007	434	2 619
Ethiopia	2008	128	5 011
Tanzania	2008	3	4 980
Kenya	2009	106	6 749
Uganda	2009	40	3 083
Burkina Faso	2009	1	2 013
Cameroon	2009	23	159
Benin	2010	-	42
Senegal	2010	-	334
Total		**735**	**24 990**

2.4.4. Domestic biogas technology status in South Africa

Some of the first biogas digesters were set up in Africa in the 1950s in South Africa but similarly to its African counterparts, growth of domestic biogas technology in South Africa is at its infant stage (Amigun *et al*, 2012). Compared to Asian countries, biogas development in Africa has been pretty modest so far because of various challenges, especially, the high investment costs, limited access to credit facilities, insufficient awareness raising activities and significantly lower purchasing power of potential households (Parawira, 2009).

A total of 38 biogas production operations have been registered by National Energy Regulator of South Africa (NERSA) to date. The majority of these biogas digesters are of fixed dome type fed with cow dung, pig manure, kitchen waste and agricultural residue (De Bruyn, 2013).This is in line with the Gas Act of 2001 which stipulates that small biogas projects in rural communities not connected to the national gas pipeline grid are exempted from obligation to apply or hold a license but have to be registered with NERSA.

Most of the biogas operations in South Africa are in the rural areas of Limpopo and KwaZulu Natal and of the fixed–dome design (De Bruyn, 2013). It has been estimated that more than 300 000 rural South African households could benefit from the waste-to-energy production to meet their cooking needs, thus eliminating long travels to collect five wood used for cooking (Greben & Oelofse, 2009) which this study aims to evaluate.

2.4.5. Challenges for the dissemination of domestic biogas technology

Developing countries have faced several challenges in the biogas sector which have constrained the dissemination of domestic biogas digesters. These are listed as follows:

2.4.5.1. Lack of a renewable energy policy

An existing renewable energy policy can assist in breaking the barriers for the wide scale dissemination of biogas technology. Policy should guide the stakeholders and suppliers to maintain quality of product and services. Renewable energy needs to come into a government's main streaming agenda as evident from the success of biogas programmes in China and India.

Government should provide active promotion and facilities such as tax and custom exemption, laws and other supports to promote biogas technology (Ghimire, 2013). In countries like China, India and Nepal, biogas programmes developed quickly due to the financial injection and the technical support by the government (Surendra *et al*, 2014).

It is essential to establish a separate autonomous renewable energy apex organization at national level to coordinate and facilitate the stakeholders (Ghimire, 2013). In absence of such an organization, renewable energy including biogas cannot take place as a national programme (Ghimire, 2013). In South African context, Hennekens (2012) identified the stakeholders involved in domestic biogas technology such as Agama Biogas, Nova Institute, Trade plus Aid, CSIR etc.

2.4.5.2. Climate too cold or too dry

Areas where the temperature sometimes goes below 10 °C (such as the hilly areas of Nepal and rural communities of Peruvian Andes) are not suitable for biogas production unless the digester is protected against temperature extremes (Gautam *et al*, 2009). Due to this, the biogas technology has been found to be less feasible in high-altitude areas. Therefore more research needs to be done in increasing the efficiency of biogas production in colder regions (Gautam *et al*, 2009). Research on biogas technology at high altitudes of rural Andean communities has been conducted by Alvarez & Lidén (2008), Ferrer *et al* (2011), Garfí *et al* (2011), Garfí *et al* (2012) and Pérez *et al* (2014).

From 2006 to 2011 more than 30 digesters were implemented in rural Andean communities of Peru by means of pilot research and development cooperation projects (Ferrer *et al*, 2011). Most of them were located at altitudes of between 3 000 and 4 000 m.a.s.l, where average annual temperatures are 10 °C and irradiation as high as 6.0 – 6.5 kWh/m^2.day (Ferrer *et al*, 2011). As previously mentioned, in such conditions the use of greenhouses and burying the tubular digester inside a trench is important in increasing process temperatures (to around 20 ˚C) and reduce overnight temperature fluctuations (Ferrer *et al*, 2011; Garfí *et al*, 2012; Pérez *et al*, 2014).

Developing countries in Africa, South America and Asia occupy regions where the climate is warm most of the time. The high ambient temperatures (15 – 40 °C) permit the utilization of anaerobic reactors without heating, if they are designed and operated at convenient organic loading rates. Arid areas are not conducive for biogas production since biogas operation requires the use of water (Parawira, 2009).

2.4.5.3. Lack of private sector participation

The private sector has a key role in promoting renewable energy and making the biogas sector commercially sustainable and market oriented. The national policy should be developed in such a way that it attracts more private companies to participate in the biogas sector (Ghimire, 2013). In 2009 there were more than 30 private companies in Nepal that were involved with the biogas sector. However, only eight of these companies were capable of installing more than 500 biogas plants per year because they were weak financially (Gautam *et al*, 2009).

2.4.5.4. Low income of the target group

One of the major barriers for the widespread dissemination of domestic biogas technology is the high installation, operating and maintenance cost which puts it out of financial reach of many rural households (Surendra *et al*, 2014). Access to micro credit makes biogas technology more affordable for the poor (Ghimire, 2013). In Nepal, over 260 micro-finance institutions are providing credits for households which are unable to pay for the upfront cost of biogas digester (Surendra *et al*, 2014). Another challenge is reducing the existing high costs of installation of robust fixed-dome biogas designs without compromising on quality and performance and making it affordable to the people (Ghimire, 2013).

Biogas technology in the developing world has the potential of reducing greenhouse gas (GHG) emissions thereby generating carbon revenues (Ghimire, 2013; Surendra *et al*, 2014). Nepal and Cambodia have already started obtaining carbon revenues from their biogas programmes and other countries like Bangladesh, Vietnam and Rwanda are in process of obtaining it. Carbon credits can be a viable and sustainable source of funds to continue the programme in the longer term, and therefore needs attention right from the beginning (Ghimire, 2013). According to

Surendra *et al* (2014), carbon revenues could be deployed for research and development (R&D) and dissemination of biogas technology locally.

2.4.5.5. Lack of technical knowledge

Lack of knowledge about the construction, operation and maintenance of biogas systems is often cited as a reason for non-adoption of biogas in some countries in Africa (Parawira, 2009; Amigun *et al*, 2012; Surendra *et al*, 2014). Where people have installed biogas reactors, problems arising from the bad quality of the installed units and the poor operations and maintenance capacity of users have led to poor performance and even abandonment of biogas digesters. In some instance, the demonstration effect has been one of failure and has served to deter rather than enhance biogas adoption (Parawira, 2009; Amigun *et al*, 2012). According to Parawira (2009):

> *It is also important to realise that lack of information on improved technologies such as biogas technology at all levels, government, energy institutions, and consumers, poses a very serious problem for technology penetration. Poor infrastructure prevents access to the vast information available in the public domain about biogas technology and its application. Generating interest among the various stakeholders and setting up information systems using relatively cheap devices now available can assist greatly. Setting up or strengthening existing information systems is very important for the use of renewable energy technologies such as biogas. These systems should be capable of coordinating energy and energy-related information activities with appropriate means for collection, filtering, storage, retrieval and dissemination.*

In order to promote the implementation and proper use of anaerobic digestion technology, it is important to initiate long-term anaerobic digestion and other renewable energy training and capacity-building programmes, and to perform scientific work in this field (through appropriate research) (Parawira, 2009). Biogas technology and its implementation can be included in the curriculum of most engineering and technical courses offered in educational and private institutions. It is important to establish contact between research and university groups and experienced contractors, and to initiate collaboration with polluting industries, i.e., to interest them in the system, either for use as an environmental protection method or for energy production. In addition, experts should provide reliable and pertinent information about the biogas technology and its potential to local authorities, politicians, and the public in general (Parawira, 2009; Amigun *et al*, 2012).

2.4.5.6. Limited water availability

The site-specific issues that have limited the scope of biogas technology in sub-Saharan Africa include the availability of water and organic materials for effective bio-digester operation (Parawira, 2009; Amigun *et al*, 2012; Surendra *et al*, 2014). Inadequate water supply for operating biogas plants in other areas is a significant hindrance for the widespread adoption of biogas technology; particularly if the water source is distant from individual households and/or is limited during changing seasons (Surendra et al, 2014). It also poses a constraint for biogas installation and operation in some countries because biogas plants typically require water and substrates such as manure to be mixed in an equal ratio (Parawira, 2009; Amigun *et al*, 2012; Surendra *et al*, 2014). At least 60 L of water is required for a cow per day as well as an additional 60 L/day to feed into the digester (Surendra et al, 2014).

Only a small percentage of the population in mountainous and African regions has consistent access to sufficient water (Surendra *et al*, 2014). Sub-Saharan countries such as Tanzania and Botswana are classified as dry countries due to their arid climate therefore unsuitable domestic biogas technology. Many parts of these countries are characterised by long periods of drought between rainy seasons. According to the Department of Waters Affairs and Forestry (1997), South Africa is classified as an arid country with rainfall less than the world average and very unevenly distributed across the country

In 2001, the South African Government approved the free basic water (FBW) policy to provide 6 000 L of safe water per household per month (200 L per household per day) for a household of 8 people (Department of Waters and Forestry, 2007). Since the inception of the FBW policy, the percentage of households with access to piped water or tap water in their dwellings, off-site (communal taps) or on-site improved from 85% in 2002 to 90% in 2013 (Statistics South Africa, 2013b). Although generally households' access to water is improving, 4.2% of households still had to fetch water from rivers, streams, stagnant water pools and dams, wells and springs in 2013 (Statistics South Africa, 2013b).

Greywater is often preferred over drinking water for mixing with organic waste even though it is of inferior quality. According to Rodda *et al* (2010), greywater is untreated household effluent from baths, showers, kitchen, hand wash basins and laundry (i.e. all non-toilet uses). Approximately 50 – 80% of indoor household water use is normally used for these purposes. According to Carden *et al* (2007), the approximate volume of greywater produced per household is 75% of the household water consumption. Carden *et al* (2007) assumed that 25% of the non-sewered households in South African have access to onsite water supply and that they consume approximately twice the average amount of water than those that use off-site water (i.e. 200 L/household/day). Based on the number of non-sewered households of 5 237 000 in 2004 and a 75% return factor (as greywater), it was estimated that over 500 000 m^3 of greywater is generated daily in non-sewered areas in South Africa. This amounts to 185 million m^3 per annum (Carden *et al*, 2007). Statistics South Africa (2013a) reported 6 216 000 non-sewered households in South Africa which translates to over 600 000 m^3/day of greywater generated in 2013. The increase of greywater generated from 2004 to 2013 can be attributed to the increase in the number of households in South Africa from 11 425 000 and 15 107 000 respectively (Statistics South Africa, 2013a).

In China, biogas technology is used for the treatment or sanitization of greywater. In 1995, biogas digesters in China cities handled 100 million m^3 of greywater per year (Mengjie, 2002). Josefsson (2009) and Ng'wandu *et al* (2009) have recommended the use of greywater in domestic biogas digesters. Greywater contains nitrogen and phosphorus which can aid in microbial growth in the biogas digester. The use of greywater from the kitchen is often discouraged due to high levels of micro-organisms, COD, oil, grease and detergents (Rodda *et al*, 2010). The feeding of greywater contaminated with detergents or chemical cleaning products will inhibit the microbiological processes of the biogas digester (Josefsson, 2009 & Ng'wandu *et a*l, 2009). Persistent chemical products (PCPs) used for cleaning purposes can also contaminate the bio-slurry, rendering it inappropriate as fertilizer (Josefsson, 2009). It is therefore recommended that kitchen greywater be separated from the greywater that is fed into the domestic biogas digester or alternately biodegradable or environmental friendly cleaning products be used in the kitchen.

2.5. Benefits of biogas technology

Beyond producing free, clean and renewable energy for developing countries through anaerobic digestion of readily available biomass at household level such as kitchen waste, animal waste and human waste, biogas technology offers the subsequent benefits.

2.5.1. Health benefits

Burning of solid fuels such as fuelwood, animal dung, agricultural residues and coal releases smoke which contains toxic pollutants such as carbon monoxide, hydrocarbons and particulate matter (Smith *et al*, 2005 as cited in Amigun *et al*, 2012; Surendra *et al*, 2014). Cooking is usually performed indoors without proper ventilation thus resulting in severe health effects associated with indoor smoke (Surendra *et al*, 2014). Evidence on solid fuel use and the burden of diseases such as acute lower respiratory infections (ALRI) or pneumonia for children younger than 5 years, chronic obstructive pulmonary disease (COPD), and lung cancer has been reported in several developing countries (Desai *et al*, 2004; Surendra *et al*, 2014). Moreover, studies have linked indoor air pollution (IAP) exposure to a variety of other health effects; such as asthma, cataracts, tuberculosis and hypertension among others (Desai et al, 2004; Surendra et al, 2014). Biogas improves health of the rural low-income households by providing a cleaner cooking fuel thus avoiding these health problems (Amigun *et al*, 2012). Women spend a lot of time in the kitchen with children cradled on their backs therefore they are at high risk of these health problems (Libsu *et al*, 2011).

Indoor air pollution from solid fuels accounted for 3.5 million (2.6 million to 4.4 million) deaths and 4.3% (3.4–5.3) of global DALYs in 2010 (Lim *et al*, 2012). In 2012, the number of deaths attributed to IAP had increased to 4.3 million globally, almost all in low and middle income (LMI) countries. The South East Asian and Western Pacific regions bear most of the burden with

1.69 and 1.62 million deaths, respectively. Almost 600 000 deaths occur in Africa, 200 000 in the Eastern Mediterranean region, 99 000 in Europe and 81 000 in the Americas. The remaining 19 000 deaths occur in high income countries (WHO, 2012). Importantly, women and children suffer the most from IAP because they are traditionally responsible for cooking and other household chores which involve spending hours by the cooking fire, and prolonged exposure to smoke (WHO, 2006).

In rural areas, infants are generally cradled in the back of their mothers who are doing the daily gathering of fuel and cooking with exposes them to these harmful products. These pollutants are the major causes of chronic bronchitis and lung diseases. A further concern related to IAP is the level of toxic carbon monoxide released during combustion of biomass (Libsu *et al*, 2011). Carbon monoxide combines with haemoglobin to form carboxyhaemoglobin (COHb) which reduces the oxygen-carrying capacity of blood. COHb has more severe effect on pregnant women resulting in either foetal damage or low birth weight of infant (Libsu *et al*, 2011).

Often, the rural population are also faced with the lack of sanitation, resulting in water borne diseases such diarrhoea, typhoid and cholera affecting mainly women and children. Rural households which currently do have sanitation generally, use pit-latrines, which have a serious impact on groundwater pollution (Cawood & Simelane, 2004). Sanitation problems can be solved by connecting toilets to biogas digesters thus using human excreta/sewage as feedstock.

The other health benefit is associated with the relief in abdominal pains attributed to reduced workload on the women and children which are involved in the collecting and carrying of fuelwood over long distances for cooking purposes (Amigun *et al*, 2012).

2.5.2. Biogas slurry as an organic fertilizer

In addition to fuel in form of biogas, anaerobic digestion (AD) produces an organic fertilizer in the form of bio-slurry or digestate as a by-product which rich in nitrogen, potassium and phosphorus. The spent digested slurry (digestate) exiting the biogas digester enhances physical, chemical, and biological attributes of the soil as well as increases crop productivity when applied to the land. Due to improved flow properties, the digestate can penetrate into the soil faster which reduces the risk for nitrogen losses in the form of ammonia (Surendra *et al*, 2014). The digestate is also known to suppress soil borne pathogens by stimulating soil actinomycetes which produce antibiotics (Surendra *et al*, 2014).

Fulford (1988: 29) reported that the chemical composition of bio-slurry consists of 1.41%, 1.18% and 1.48% of nitrogen, phosphorus and potassium respectively. In general bio-slurry contains N_2 (1.8%), P_2O_5 (1.0%), K_2O (0.9%), Mn (188 ppm), Fe (3 550 ppm), Zn (144 ppm) and Cu (28 ppm) (Surendra *et al*, 2014). A summary of the nutrient contents of the digestate compared against other organic manure is included in Table 2-11 below.

Table 2-11: Nutrient content of important organic manure (Surendra *et al*, 2014)

Organic Manure	**Organic Matter (%)**	**C:N**	**N_2 (%)**	**P_2O_5 (%)**	**K_2O (%)**
Farm yard manure	25-55	15-20	0.40-0.80	0.60-0.82	0.50-0.65
Biogas slurry	60-73	17-23	1.50-2.25	0.90-1.20	0.80-1.20
Vermicompost	9.80-13.40	-	0.51-1.61	0.19-1.02	0.15-0.73

Human excreta contains higher amounts of plant nutrients than cow dung, therefore the incorporation of human excreta as a feedstock can improve the overall nutrient qualities of the slurry, and if treated properly, the slurry can be utilized in agriculture as a complete fertilizer (Surendra *et al*, 2014). AD also results in a significant reduction of odours (up to 80%) of the crude feedstock (Surendra *et al*, 2014) resulting in an odourless bio-slurry that does not attract flies (Fulford, 1988:40).

However, spent slurries' derivation (in part) from animal and/or human excreta maybe of concern particularly when dealing with the large-scale loading, transportation, and distribution of the slurry in remote, underprivileged regions. Pathogenic micro-organisms (e.g. *Salmonella*, *Listeria*, *Escherichia coli*, *Campylobacter*, *Mycobacteria*, *Clostridia*, *and Yersinia*) are known to be naturally present in raw feedstock (Surendra *et al*, 2014). Although AD can significantly reduce the aforementioned microbial pathogens, the digestate may still not be completely safe to use as fertilizer; especially at short solids retention time under mesophilic temperatures (Parawira, 2009; Bond & Templeton, 2011; Surendra *et al*, 2014). Therefore, to prevent public health risks, proper post-treatment of bio-slurry is required prior to application as a soil amendment (Surendra *et al*, 2014).

2.5.3. Economic benefits

Economic benefits from biogas are the creation of jobs in the biogas sector and the funds that can made through carbon credits. In Nepal, approximately 11 000 people are employed in the biogas sector. Due to the installation of biogas digesters, the use of imported paraffin has been reduced by 7.7 million liters per annum in Nepal thus resulting in savings of approximately US$2.1 million per annum (Gautam *et al*, 2009).

As previously mentioned, along with the methane gas, biogas digester produces organic fertilizer that is high in nitrogen, potassium and phosphorus contents (Gautam *et al*, 2009; Surendra *et al*, 2014). This organic form of fertilizer can be used in farmlands as an alternative to chemical fertilizers. Chemical fertilizers are usually imported in Nepal (Gautam *et al*, 2009). It has been estimated that there is an annual saving of 4 329 tons nitrogen, 2 109 tons phosphorous and 4 329 kg potassium due to the installation of biogas digesters in Nepal (Gautam *et al*, 2009). This translates into an annual saving of almost US$ 300 000 (Gautam *et al*, 2009). Garfí et al (2012) reported approximately 1.5% savings of household annual income from substituting compost with bio-slurry as fertilizer in rural Andean communities.

An article in the Nepal Times pointed out that the Nepal’s successful biogas program brought farmers a clean fuel, conserved forests and provided high quality fertilizer for crops. Moreover, Nepal also benefits in terms of hard cash (in the form of carbon revenues) received from the industrialized nations for the burning of biomass to release greenhouse gas emissions into the atmosphere (Libsu *et al*, 2011).

2.5.4. Social development

Social development is closely related to the reduced workload from the women and children and also the availability of clean energy in a household. In the majority of developing countries, women and children are responsible for fuelwood and dung collection which are both time consuming and exhausting tasks. For example, women and children in some places travel more than 5 km and spend nearly 6 hours a day gathering biomass and cooking food (Surendra *et al*, 2014). The time spent collecting solid fuels imposes opportunity costs that constrain socio-economic development (Garfí *et al*, 2012). According to Garfí *et al*, biogas digester installations in rural Andean communities reduced the time spent for collecting solid fuels by 50% and envisaged that 80 - 90% time spent collecting solid fuels can be reduced in regions where digesters are operated in mesophilic conditions. A survey reported by Surendra *et al* (2014) showed that a third of the time spent collecting solid fuels is saved through biogas installation. In addition to IAP, the labour is hard and can lead to back-and neck-pain as well as other physical ailments (Surendra *et al*, 2014).

Due to the significant demands on time and labour, women and children are deprived of opportunities for education, recreational activities and other income-generating activities (Garfí *et al*, 2012; Surendra *et al*, 2014). In rural areas where there is no electricity supply, the use of biogas as a source of light has enabled women to engage in evening study, has made easier literacy classes and other home and community activities (Libsu *et al*, 2011). Thus the installation of biogas plants at the household level can directly provide increased and better opportunities for gender equality in rural areas of developing nations; the long-term social benefits of which may be significant (Surendra *et al*, 2014).

2.5.5. Greenhouse gas emissions reduction

Domestic use of conventional fossil fuels such as wood, coal, and paraffin in inefficient stoves to meet energy demands contribute towards greenhouse gas emissions. Biogas helps to reduce greenhouse gas emissions by displacing the consumption of fuelwood and paraffin (Dioha *et al*, 2012; Garfí *et al*, 2012). The biogas is assumed to be produced on a sustainable basis, and therefore CO_2 associated with biogas combustion is reabsorbed in the process of the growth of the fodder and foodstuffs (Dioha *et al*, 2012).

Uncontrolled decomposition of each metric tonne of solid waste could potentially release 50-110 m^3 CO_2 and 90-40 m^3 CH_4 into the atmosphere, contributing to global warming (Parawira, 2009). According to Bond and Templeton (2011), biogas technology could potentially reduce global anthropogenic methane emissions by around 4%. Burning of biogas does produce a greenhouse gas in the form of CO_2 which has a global warming potential (GWP) that is over 20 times less than that of CH_4.

Biogas technology does not only contribute to controlling environmental pollution and recycling of nutrients but alleviates dependence on imported fossil fuels. In the South African context, utilization of biogas to meet energy demands of low income households can assist in reducing pressure to the national power grid.

2.5.6. Reduced deforestation

The most significant implication of high dependency on fuelwood for fuel especially in developing countries is its association to deforestation. Fuelwood accounts for 54% of forest loss in developing countries (Amigun *et al*, 2012; Garfí *et al*, 2012; Surendra *et al*, 2014). Global deforestation is responsible for 17–25% of all anthropogenic GHG emissions, making it one of the leading causes of increased GHG emissions (Surendra *et al*, 2014). In Nepal, the installation of biogas plants has helped protect the forest (Gautam *et al*, 2009). For instance, there is an annual saving of 2 tons of fuelwood per household that has installed a biogas plant (Gautam *et al*, 2009). Garfí *et al* (2012) reported 50% higher annual fuelwood savings in Nepal of 3 tons per household. This means that there is a nationwide saving of more than 200 000 tons of fuelwood per annum (Gautam *et al*, 2009).

Deforestation is a contributor to soil erosion resulting in vulnerability to the effects of droughts and floods. As the degree of deforestation increases, so does the amount of time spent searching for fuelwood due to its scarcity. Therefore the use of biogas reduces the dependency of rural communities on fuelwood thereby reducing deforestation, soil erosion and burden to women and children.

2.6. Renewable Energy Policy in South Africa: the biogas technology context

In 2000, the estimated energy contribution from renewable energy sources was 115 278 GWh/annum (mainly from fuelwood and waste) which had come about largely as a result of poverty (e.g. fuelwood and animal waste used for cooking and heating) (Department of Minerals and Energy, 2003).

According to the White Paper on Renewable Energy of 2003, the Government set a medium-term (10-year) target of 10 000 GWh renewable energy contribution to final energy consumption by 2013 (i.e. a 1 000 GWh/annum increase), to be produced mainly from biomass, wind, solar and small-scale hydro (Department of Minerals and Energy, 2003). The renewable energy is to be utilised for power generation and non-electric technologies such as solar water heating and bio-fuels (Department of Minerals and Energy, 2003). This is approximately 3% (1 141 MW) of the projected electricity demand for 2013 (41 539 MW) which is almost equivalent to replacing two (2 x 600 MW) units of Eskom's combined coal fired power stations (Department of Minerals and Energy, 2003).

In 2010, the total South African generating capacity was estimated at 46 993 MW with 17% contributed by renewable energy sources (hydro, wind and solar) and the envisaged energy generating capacity by 2030 is 89 532 MW with 30% from renewable energy. According to the White Paper on Renewable Energy of 2003, a potential exists to utilise manure from cattle, pig and poultry farms. The potential energy that can be harvested from animal manure in South African farms is shown in Table 2-12 below:

Table 2-12: Potential energy from livestock manure and litter (Department of Minerals and Energy, 2003)

Type	Energy Production (GWh/year)
Cattle	3 889
Pigs	306
Poultry	1 417

2.7. Conclusion

In terms of achieving the research objectives, it can be concluded that the literature review partially answers the question on the availability of animal waste. Literature only specifies the amount of power that can be produced by taking advantage of the available animal waste (cattle, pigs and poultry) not for feeding a domestic biogas digester. This confirms the findings by Hennekens (2012) that in South Africa energy equals electricity.

The availability of organic waste (animal, human and food) in South African households for feeding a domestic biogas digester is not explored in the literature review which is addressed in this study. The literature reviewed does not quantify the number of households that can benefit from biogas digester installations fed with animal, human and food waste which is addressed in this study.

One of the remaining gaps from literature that is addressed by this present study, is the energy requirements by an average sized household in South Africa and hence biogas requirements to substitute the conventional domestic fuels. Literature reviewed only specifies biogas requirements as per application of biogas technology in China and India. In the literature, the reduction in the burden of diseases and mortalities due to the substitution of conventional domestic fuels with biogas is not specified but addressed in the study.

CHAPTER 3: Methodology

The methodology discussed in this chapter was followed in order to answer the following research questions:

(i). What is the energy demand for cooking derived from fuelwood by low-income South African households?

(ii). What is the total energy demand by low-income South African households for all household applications such as cooking, water heating, space heating and lighting?

(iii). What is the equivalent biogas requirement for meeting the energy demand for cooking and the total energy demand for all household applications?

(iv). Is 800 – 1 600 or 1 500 – 2 400 L/day of biogas reported by Ghimire (2013) and Bond and Templeton (2011) respectively sufficient to meet the energy demand for cooking for an average sized South African household of 4-5 members?

(v). What are the energy and costs savings that can be incurred by low-income South African households from installations of domestic biogas digesters.

(vi). What are the health benefits (improvements in burden of disease) due to reduced indoor smoke from solid fuels?

(vii). Is a South African household producing sufficient organic waste (kitchen/food waste, animal waste and human excreta) to be used as feedstock to the biogas digester for daily biogas production? What is the corresponding water demand for each feedstock?

(viii). How many households in South Africa that can potentially benefit from domestic biogas digester installations fed with animal waste (cattle, pigs and chickens)?

(ix). Is it feasible to operate a domestic biogas digester fed with food waste and human waste? Are South African households producing sufficient food waste for feeding a biogas digester? Is the average household size in South Africa sufficient to produce the required human waste?

(x). Is it feasible to operate a biogas digester co-fed with a 1:1 mixture of cattle dung and human excreta and a 1:1 mixture of kitchen/food waste and human excreta?

(xi). Do South African households have access to sufficient water supply for daily feeding of domestic biogas digesters?

3.1. Research design

3.1.1. Energy demand by low-income households

The energy demand of an average sized family in South Africa was calculated using daily fuelwood consumption by a South African household which was obtained from Damm & Triebel (2008). The energy demand was calculated using Equation 5 below. The efficiency and calorific value of fuelwood used in the calculations were 13% and 17 MJ/kg respectively.

3.1.2. Biogas requirements for substitution of fuelwood used for cooking

The energy demand calculated in Section 3.1.1 above was used to calculate the biogas requirements for replacing fuelwood used for cooking using Equation 5. The biogas requirement was compared against the 800 - 1 600 and 1 500 – 2 400 L of biogas per day per household required for cooking reported by Ghimire (2013) and Bond and Templeton (2011) respectively. The efficiency and calorific value of biogas used in the calculations were 55% and 20 MJ/m^3 respectively.

$$Q = m \times C_v \times \eta \qquad \text{Equation 5}$$

Where,

Q = Energy demand (MJ/day),

m = Fuel demand (kg/day or L/day)

C_v = Calorific value of fuel (MJ/kg or MJ/m^3), and

η = Fuel thermal efficiency.

3.1.3. Biogas requirements for complete substitution of conventional domestic fuels

The amount of biogas required for complete substitution of the conventional domestic fuels was also calculated using Equation 5 based on the calculated total energy demand by low-income households in South Africa obtained from Damm & Triebel (2008). The efficiency and calorific value of biogas used in the calculations were also 55% and 20 MJ/m^3 respectively.

3.1.4. Energy and costs savings

The percentage fuelwood savings is the amount of fuelwood saved due to the installation of domestic biogas digesters to produce sufficient biogas for cooking and for complete substitution of conventional fuels. The cost savings incurred by households from using biogas were calculated using the net direct cost of the fuelwood reported by Damm & Triebel (2008) and the percentage fuelwood savings. The percentage of the income saved was calculated based on the cost savings from firewood substitution and the upper band of the income range for low income households. The income bracket of R 0 – R9 600 reported in ERC (2004) as cited in Damm & Triebel (2008) is based on Census 2001. The net direct cost of fuelwood and the upper band of the income bracket was inflated to current times using equation 6 below:

$$\frac{Price_2}{Price_1} = \frac{CPI_2}{CPI_1} \qquad \text{Equation 6}$$

Where $Price_2$ is the current item price, $Price_1$ is the base price, CPI_2 is the current consumer price index and CPI_1 base year consumer price index.

3.1.5. Reduction in burden of diseases

The attributable DALYs lost and mortalities avoided due the substitution of fuelwood use with biogas were calculated based on the attributable DALYs lost and mortalities from indoor smoke due to solid fuel use in Africa obtained from WHO (2002). The solid fuel mix used in South Africa was obtained from Statistics SA (2013b) to calculate the attributable DALYs lost and mortalities avoided from indoor smoke from fuelwood use.

3.1.6. Feedstock availability for feeding a domestic biogas digester

The properties of the various feedstocks for biogas digesters accessible to South African households were evaluated from different literature sources and tabulated in Table 2-6. The number of animals and the amount of animal waste required for feeding the digester to produce enough biogas for partial and complete substitution of conventional domestic fuels were calculated using Equation 7 and Equation 8 below respectively. The same methodology was followed when calculating the number of people and human waste required for feeding an average sized domestic biogas digester. The availability of animal waste in South Africa was evaluated based on the number of livestock kept in South African households reported by Statistics SA (2011). The availability of human waste was evaluated based on the average size of a South African household as reported in Statistic SA (2013b). The evaluation of food waste availability was based on the average food waste generated by South African households as reported by the Department of Environmental Affairs (2012).

$$Number\ of\ animals = \frac{Biogas\ Requirement\ (m^3/day)}{Biogas\ Yield\ (m^3/animal.day)} \qquad \text{Equation 7}$$

$$Waste\ Requirement = Daily\ Production\ (kg/animal) \times Number\ of\ animals \qquad \text{Equation 8}$$

The amount of water required for mixing with waste was calculated using Equation 9 below. The % DM for the various feedstocks used in calculations were obtained from Table 2-6 and % $DM_{(new)}$ is the optimum percentage dry matter of 8% for feeding a digester as recommended by Yadvika *et al* (2004). Feed is the waste requirement calculated using Equation 8.

$$Water\ added = \frac{\%DM_{old} \times (Feed)}{\%DM_{new}} - Feed \qquad \text{Equation 9}$$

3.1.7. Number of households that can potentially benefit from digester installations

The number of households that can potentially benefit from domestic biogas digester installations were evaluated based on the calculated number of animals required compared to the available number of animals in low-income households. For human waste, the feasibility of domestic biogas technology was evaluated by comparing the calculated number of people required against the average size of a South African household. The feasibility of operating a biogas digester fed solely with food waste was evaluated by comparing the calculated food waste required against the average food waste generated by a South African household. The feasibility of the options of co-digesting a 1:1 mixture of cattle dung and sewage and a 1:1 mixture of human waste and food waste were also explored using the above mentioned principles.

3.1.8. Water availability for feeding a domestic biogas digester

The availability of water at household level for feeding a domestic biogas digester was evaluated by comparing water consumption by non-sewered South African households with access to water supply on-site or off-site and greywater generated by these households against the water requirements of the various feedstocks.

3.2. Data collection

In order to achieve the research objectives, the following data were collected from various literature sources:

i. Thermal efficiencies (%) and calorific values (MJ/kg or MJ/m^3) for conventional domestic fuels and biogas were obtained from different literature sources as discussed in Section 2.2.1.
ii. Fuelwood consumption in (tons/annum/household) by low-income households was obtained from Damm & Triebel (2008).
iii. The energy mix in low income South African households was obtained from Statistics SA (2013b).
iv. The economic value of firewood in (R/household/annum) was obtained from Damm & Triebel (2008).
v. The number of attributable DALYs and mortalities due to indoor smoke from solid fuels were obtained from WHO (2002).
vi. The properties of the various feedstocks such as biogas yields and % DM were obtained from Bond & Templeton (2011) and Fulford (1988:35)
vii. The South African population numbers and the average size of a South African household were obtained from Statistics SA (2013b).

viii. Household livestock numbers and the number of households involved in livestock production from Statistics SA (2011).

ix. Available water resource in the form of free basic water supply and greywater generated by low-income households were obtained from Department of Waters and Forestry (2007) and Rodda *et al* (2010) respectively.

3.3. Data analysis

A comparative study of the following was conducted:

i. The calculated biogas requirement by low-income households for cooking against the 800 – 1 600 and 1 500 – 2400 L/day/household that were reported by Ghimire (2013) and Bond and Templeton (2011) respectively.

ii. The calculated fuelwood savings from substituting conventional domestic fuels with biogas in low-income South African households against the 74% and 84% reported by Bond & Templeton (2011) for China and the Southern province of Sri Lanka respectively.

iii. The calculated number of animals (cattle, pigs and chickens) required per household against the number of animals per agricultural household.

iv. The calculated number of people to produce enough human waste against the average number of people per household in South Africa as reported by Statistic SA (2013b). The calculated number of people is then used to deduce the number of households required for feeding a community digester. This was also conducted for the co-digestion of 1:1 mixture of cattle dung with human waste.

v. The calculated amount of food waste required against the amount of food waste generated by a low-income South African household as reported by the Department of Environmental Affairs (2012). This was also conducted for the co-digestion of 1:1 mixture of human waste with kitchen waste.

vi. The calculated water demand for each feedstock against each other and against the water supply in form of FBW and greywater generated by households.

CHAPTER 4: Results and Discussion

4.1. Energy demand by low-income households

Based on the average annual household fuelwood consumption of 4.5 tons per annum discussed in Section 2.2, the energy demand from fuelwood and the total energy demand for an average sized family (5-6 members) were calculated as shown in Appendix A.1.1 to be approximately 27 MJ and 68 MJ per day per household. The calculations were based on fuelwood efficiency and a calorific value of 13% for open fires and 17 MJ/kg respectively as discussed in Section 2.2.1.

4.2. Biogas requirements for substitution of firewood used for cooking

The amount of biogas required for the substitution of fuelwood used for cooking was calculated as shown in Appendix A.1.2 to be approximately 2 500 L/day/household. This is in line with the biogas requirement for cooking of 1 500 – 2 400 L of biogas per day per household as reported by Bond and Templeton (2011). The calculations were based on biogas efficiency and calorific value of 55% and 20 MJ/m^3 respectively. Based on these calculations it can be deduced that 800 – 1 600 L/day produced from a 4 m^3 biogas digester reported by Ghimire (2013) is insufficient to meet the energy demand for cooking in an average sized low-income household in South African context. The following linear relationship between the biogas requirement for cooking and the efficiency of fuelwood being replaced has been developed and represented by Equation 10 below:

$$B_c = 19\,054 \times \eta \qquad \text{Equation 10}$$

Where, B_c (L/day/household) is the biogas requirement for cooking and η (%) is the efficiency of the fuelwood being replaced.

4.3. Biogas requirements for substitution of conventional domestic fuels

Based on the assumption made by Pathak *et al* (2009) and Surendra *et al* (2014) that 80% of the produced biogas would be used for replacement of fuelwood and the remaining 20% for replacement of paraffin used in households for cooking and lighting respectively, the same assumption is made in this study. Table 4-1 shows energy consumption by activity in 2004 for 11 425 000 households (Statistics SA, 2013b), which was estimated on the basis of the total energy demand and the relative percentages as estimated for 2000 in South Africa (Damm & Triebel, 2008). For households that utilise fuelwood for cooking (39.9%), space heating (12.4%) and water heating (31.9%) as shown in Table 4-1, an assumption of 80% fuelwood replacement is reasonable.

Table 4-1: Estimated residential energy consumption by activity (Damm & Triebel, 2008).

Activity	**TJ**	**in %**
Cooking	193 791	39.9
Lighting	26 227	5.4
Space heating	60 226	12.4
Water Heating	154 935	31.9
Other	50 512	10.4
Total	**485 691**	**100**

In South African context, it was calculated as shown in Appendix A.1.3 that 5 000 L per day per household is required for the replacement of fuelwood used for cooking, space heating and water heating. The daily biogas required for replacement of paraffin for lighting was calculated in Appendix A.1.3 to be approximately 1 250 L per day per household. Due to inefficiency of biogas lamps (3 -5%) and the safety concerns associated with using biogas for lighting, it is recommendable that alternative lighting technologies such PV solar home systems be implemented. PV solar home systems comprises of a solar panel, battery, LED lights and a cellphone charging device.

The total daily biogas requirement for complete substitution of conventional domestic fuels is therefore estimated at 6 250 L/day/household. The following linear relationship between the biogas requirement for complete substitution of conventional domestic fuels and fuelwood efficiency has been developed and represented by Equation 11 below:

$$B_T = 47\,634 \times \eta \qquad \text{Equation 11}$$

Where, B_T (L/day/household) is the total biogas requirement for substitution of conventional domestic fuels and η (%) is the efficiency of the fuelwood. It is worth noting that Equation 10 and 11 are only applicable to the conditions set out in this study and were formulated to accommodate the variation in fuelwood efficiency from different cooking stoves.

4.4. Energy savings from biogas substitution of conventional domestic fuels

Installation of a 2 500 L/day capacity biogas digester per household will result in 50% reduction in the total household fuelwood use (100% fuelwood used for cooking) whereas a 5 000 L/day capacity digester would result in 100% reduction in the total household fuelwood use. This is comparable to the 74% reduction in household usage of fuelwood in China (Remais *et al*, 2009 as cited in Bond & Templeton, 2011). It is also in line with a survey conducted by de Alwis (2002) as cited in Bond & Templeton (2011) in the Southern province of Sri Lanka which found that the introduction of biogas for cooking resulted in an 84% reduction in fuelwood consumption.

4.5. Cost savings from biogas substitution of conventional domestic fuels

As previously mentioned, the net direct-use value of fuelwood is R1 250 per household per annum as reported by Damm and Triebel (2008). The adjusted net direct-use value of fuelwood due to inflation was calculated in Appendix A.1.4 to be R1 808 using the yearly average CPI for 2008 and 2015 of 79.3 and 114.7 respectively as reported in Statistics South Africa (2016). Therefore, the estimated cost savings based on the 50% reduction of the total fuelwood use from installing a 2 500 L/day capacity biogas digester per household was calculated to be R904 per household per annum. The upper band in the income range for low-income households was R9 600 per annum according to Census 2001 as reported by Damm and Triebel (2008). The adjusted income due to inflation is calculated in Appendix A.1.4 to be R21 013 per annum using the yearly average CPI for 2001 and 2015 of 52.4 and 114.7 respectively as reported in Statistics South Africa (2016). It can therefore be deduced that 4.3% of income in low-income households can be saved by substituting fuelwood used for cooking with biogas. Complete substitution of fuelwood as an energy source would result in 8.6% savings of household income. According to Statistics South Africa (2013a), the number of households that still relied on fuelwood as the main source of energy for cooking was approximately 1.581 million (10.5% of the total number of households) in 2013. Therefore the estimated gross national cost savings was calculated to be close to R1.5 billion per annum. As previously mentioned there are 2.3 -2.8 million households that still rely on fuelwood as the main source of energy, therefore complete substitution of fuelwood with biogas can result in cost savings of R4 – 5 billion per annum.

4.6. Reduction in burden of diseases

The estimated DALYs lost and mortalities in South Africa due to indoor smoke from solid fuels in 2001 were calculated as shown in Appendix A.1.5 to be 822 940 and 26 189 respectively (WHO, 2002). According to Desai, Mehta and Smith (2004), the burden of disease from solid fuel use (SFU) in India was 11 million DALYs lost and 360 000 deaths. The difference between these two developing countries is attributed to the greater number of households in India of 152 million with 81% relying on solid fuels whereas 23% of the 11 million households in South Africa relied on solid fuels in 2002 (Desai *et al*, 2004). Based on the estimate by WHO (2002) that indoor smoke from solid fuels causes about 35.7% of ALRI, 22.0% of COPD and 1.5% of trachea, bronchus and lung cancer, the DALYs lost and mortalities per cause are shown in Table 4-2 below:

Table 4-2: Attributable DALYs lost and mortalities per cause

	ALRI	**COPD**	**Trachea, bronchus and lung cancer**	**TB, cataracts and asthma etc.**	**Total**
DALYs	293 790	181 047	12 344	335 760	822 940
Mortalities	9 349	5 761	393	10 685	26 189

According to Statistics South Africa (2013b), solid fuel use (SFU) for cooking in South African households in 2002 comprised of 1.3%, 13.3% and 85.4% of animal dung, coal and fuelwood respectively. Table 4-3 shows the attributable DALYs lost and mortalities per cause or exposure outcome due to indoor smoke from fuelwood use:

Table 4-3: Attributable DALYs and mortalities per cause due to fuelwood use

	ALRI	**COPD**	**Trachea, bronchus and lung cancer**	**TB, cataracts and asthma etc.**	**Total**
DALYs	250 897	154 614	10 542	286 739	702 792
Mortalities	7 984	4 920	336	9 125	22 365

Due to the increased numbers of households with access to electricity in South Arica, the percentage of solid fuel use for cooking dropped from 22.6% in 2002 to 12.6% in 2012 (Statistics South Africa, 2013). Though SFU[*] has dropped by more than 44%, the solid fuel mix in South African households is still dominated by fuelwood (92% in 2012). Substitution of 50% of total fuelwood use (100% of fuelwood used for cooking) by 2 500 L of biogas per day per household will result in attributable DALYs lost and mortalities avoided as shown in Table 4-4 below:

Table 4-4 Attributable DALYs and mortalities avoided per cause due to fuelwood substitution

	ALRI	**COPD**	**Trachea, bronchus and lung cancer**	**TB, cataracts and asthma etc.**	**Total**
DALYs	125 449	77 307	5 271	143 370	351 397
Mortalities	3 992	2 460	168	4 563	11 183

It can therefore be deduced that 50% fuelwood substitution with biogas will result in 43% of total attributable DALYs lost and mortalities from indoor smoke due to SFU avoided. Complete

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[*] In this work SFU is defined as: household combustion of solid fuels such as animal dung, coal and fuelwood

substitution of fuelwood with biogas will result in 85.4% of total attributable DALYs lost and mortalities from indoor smoke due to SFU avoided.

4.7. Availability of feedstocks

4.6.1. Animal and human waste

The calculated amount of waste and water (as shown in Appendix A.1.6) required for feeding a 2 500, 5 000 and 6 250 L/day capacity biogas digester are shown in Figure 4-1 below. The ratio of cow dung to water required for daily feeding of a domestic biogas digester was calculated to be 1:1 which concurs with Bond & Templeton (2011) and Smith (2011) regarding equal amount of water to be added simultaneously if cow dung is used as feedstock to a digester. Food waste gave the least waste to water ratio of 0.31:1 which is attributed to the higher %DM of 48% thus requiring more water for dilution to 8% DM.

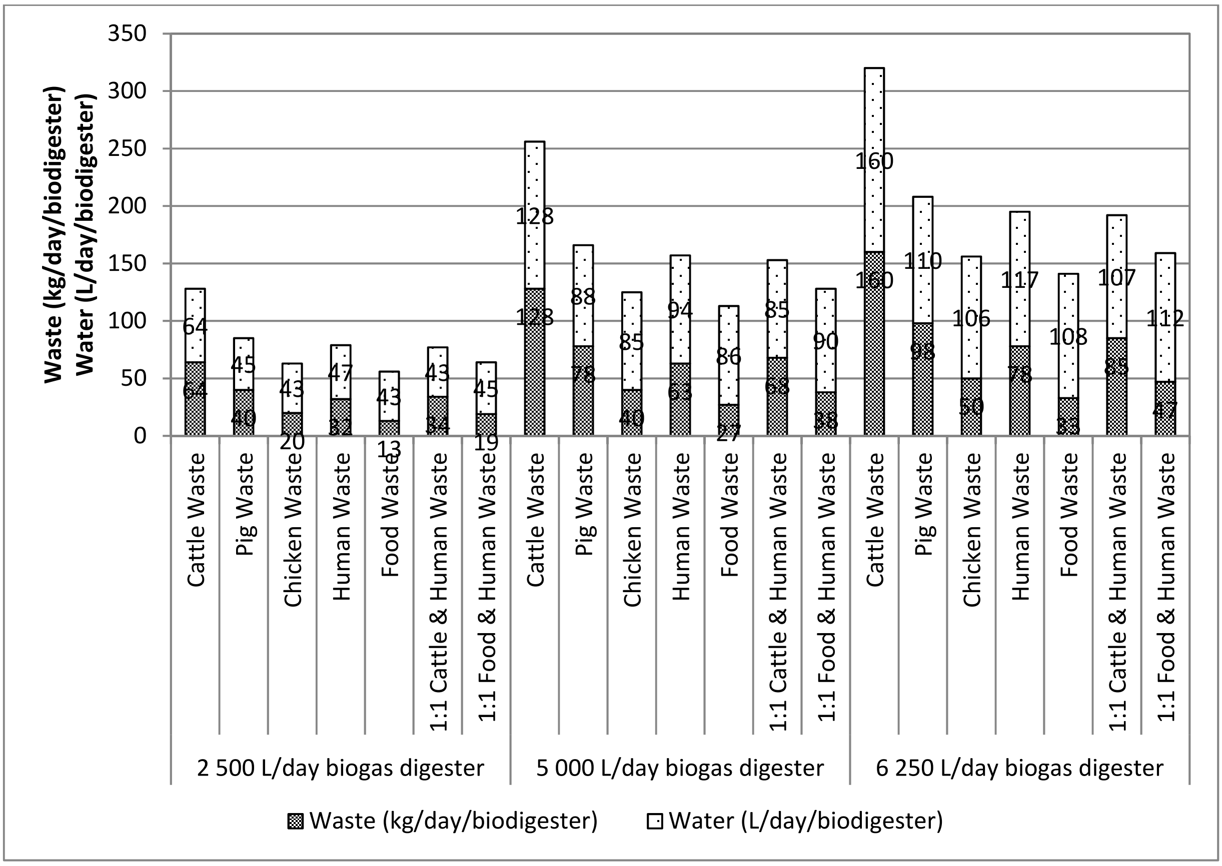

Figure 4-1: Quantification of feedstocks

The number of animals (cattle, pigs and chickens) and people required per household to produce enough waste for feeding a 2 500, 5 000 and 6 250 L/day capacity biogas digester were calculated in Appendix A.1.6 and are shown in Figure 4-2 below. According to Bembridge & Tapson (1993) cited in Gaudex (2014), in Southern Africa, 68% of communal farmers own fewer than ten cattle, with an average of six cattle per household. According to Table 4-5, 78% of agricultural households own ten or fewer cattle. According to Figure 4-2 below, 8, 15 and 20 cows are required for feeding a 2 500, 5 000 and 6 250 L/day capacity biogas digester respectively. The number of cows (8) required for feeding a 2 500 L/day capacity biogas digester is double the number reported by Hennekens (2012) of a minimum of 4 cows to feed a domestic biogas digester, in order to provide enough biogas for a family to cook on. Thus using Table 4-5, it can be deduced that approximately 613 662 South African households can potentially benefit from 2 500 L/day capacity biogas digesters installations fed with cattle dung. Using Table 4-5, the number of households that can potentially benefit from installations of a 5 000 or a 6 250 L/day capacity biogas digesters fed with cattle waste can be estimated at 131 391 (117 934 + 13 457).

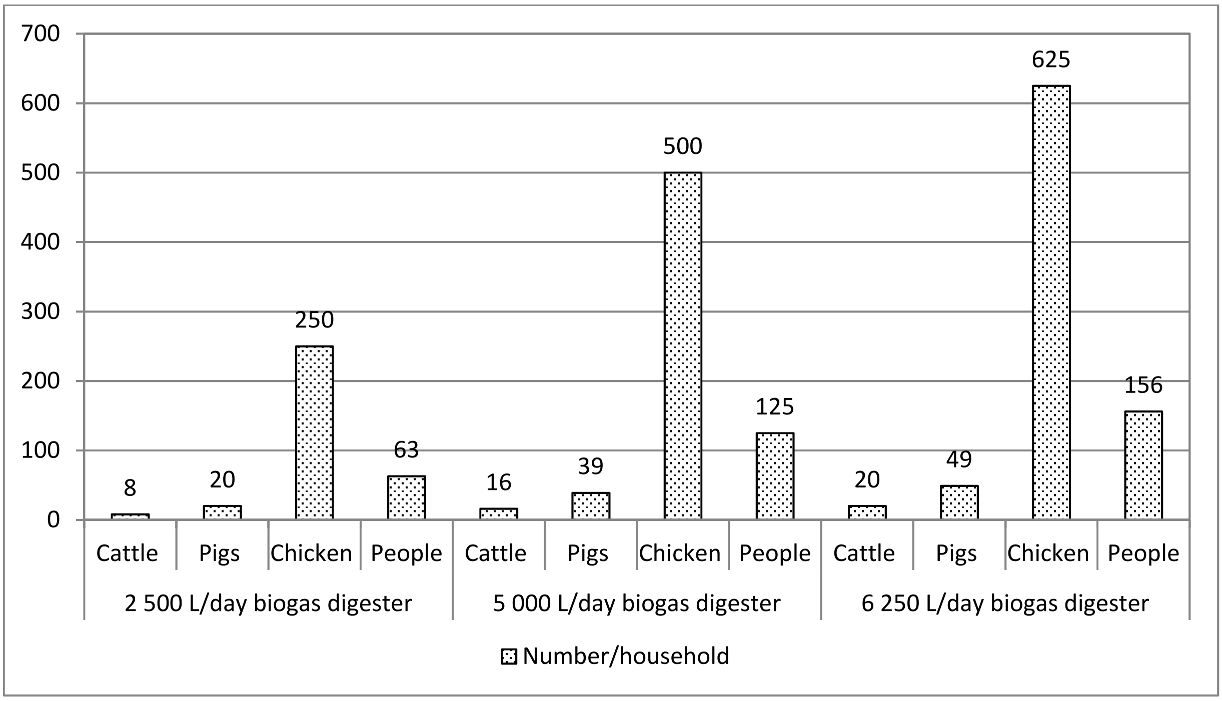

Figure 4-2: The number of animals and people required

The number of pigs required to produce enough waste to feed 2 500, 5 000 and 6 250 L/day capacity biogas digesters is 20, 39 and 49 respectively (see Figure 4-2 above). Thus from Table 4-5 it can be deduced that 89% (100 589/112 678) of the total number of households that own pigs cannot benefit from domestic biogas digesters fed with pig waste due to insufficient number of pigs. Only 12 089 households can potentially benefit from a 2 500 or a 5 000 or a 6 250 L/day capacity biogas digester fed with pigs waste.

Table 4-5: Number of households involved in livestock production (Statistics SA, 2011)

Livestock	**1-10**	**11-100**	**+100**	**Total**
Cattle	482 270	117 934	13 457	613 662
Pigs	100 589	9 716	2 373	112 678

The number of households involved in poultry production was estimated at 1.4 million as per report by Statistics South Africa (2011). The total number of chickens in South African households reported by Statistics South Africa (2010) was 22.8 million. Therefore the number of chickens per household (involved in poultry production) can be estimated at 16. Based on the number of chickens required (see Figure 4-2 above), it can be deduced that it is not feasible to operate a biogas digester fed with solely chicken waste at household level in South Africa. Therefore a chicken farm is recommended for such an application.

According to Statistics SA (2013a), the South African population was estimated at 53 million and the number of households at 15.1 million therefore it can be estimated that there are four people per household Based on the number of people required (see Figure 4-2 above), it can be deduced that the size of an average South African household is not sufficient to produce enough human excreta for feeding a 2 500, 5 000 and 6 250 L/day capacity biogas digester. Therefore a community digester used by 15, 30 and 39 households is recommended for feeding a 2 500, 5 000 and 6 250 L/day capacity biogas digesters respectively.

4.6.2. Kitchen/Food waste

The solids concentration (as % DM) and biogas yield (m^3 biogas/kg DM) for food waste was calculated in Appendix A.1.5.5 to be 34% and 0.55 m^3/kg DM. The calculated daily food waste requirements per household for feeding a 2 500, 5 000 and 6 250 L/day capacity biogas digester were calculated to be approximately 13 kg, 27 kg and 33 kg respectively (Figure 4-1 above).

The estimated quantities of household food waste generated in South Africa per income group are indicated in Table 4-6 below. The total food waste generated in South African households is estimated at 1.44 million tons per annum as shown in Table 4-6. The number of households in South Africa in 2012 was estimated at 14.6 million (Statistics South Africa, 2013a). Therefore the average food waste generated can be estimated at 270 g per day per household. Thus it can be deduced that a South African household does not generate enough food waste to feed a 2 500, 5 000 and 6 250 L/day capacity biogas digester. This is in agreement with one of Hennekens' (2012) interviewees who asserted that the amount of food waste generated by households is insufficient for feeding a domestic biogas digester.

Table 4-6: Quantities of household food waste generated annually in South Africa (Department of Environmental Affairs, 2012a).

Income Level	**Domestic waste (tonnes/annum)**	**Food waste (%)**	**Food waste (tonnes/annum)**
Low	5 600 116	18.08	1 012 688
Middle	2 929 639	10.98	321 577
High	1 093 352	9.56	104 713
Total	9 623 106		1 438 977

4.6.3. Co-digestion

Co-digestion of a 1:1 mixture of cattle dung and human waste is not feasible in South African context. The number of people required per household (see Figure 4-3 below) to produce enough waste is higher than the average size (4 members) of a South African household. The majority of households that own cattle are in rural areas (Statistics SA, 2011). Co-digestion of cattle dung and human waste in a community digester is also not feasible for either rural or peri-urban areas due to the unavailability of cattle dung in peri-urban areas and the segregated nature of rural households.

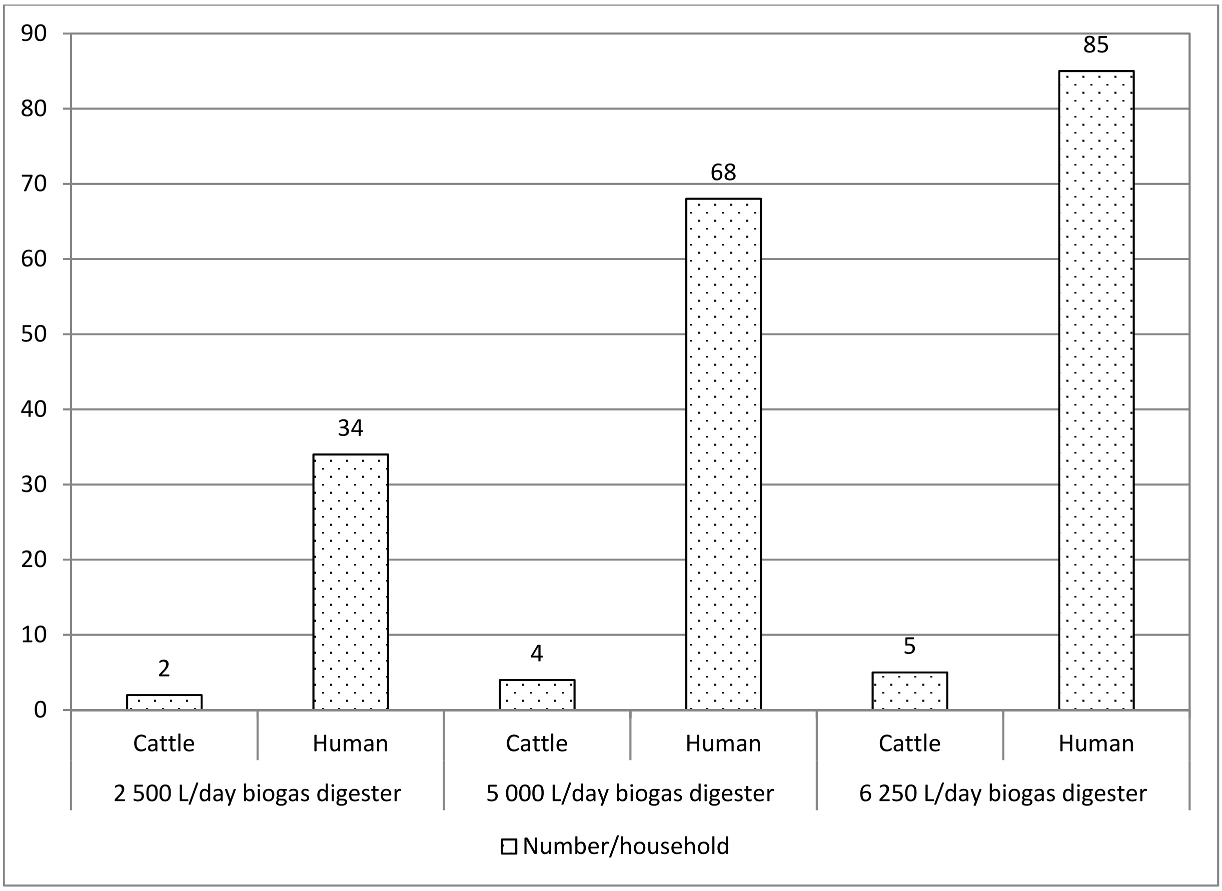

Figure 4-3: Co-digestion of a 1:1 mixture of cattle and human waste

Co-digestion of a 1:1 mixture of kitchen waste and human waste requires a household with at least 19, 38 and 47 people and food waste of 9.5, 19 and 23.5 kg/day (see Figure 4-1) for feeding a 2 500, 5 000 and 6 250 L/day capacity biogas digester respectively. Based on the average amount of food waste generated by a South African household of 270 g per day and the average size of 4 members, it can therefore be deduced that there is insufficient waste (kitchen waste and human excreta) for feeding the digesters at household level. A community digester in a peri-urban area or informal settlement is a feasible option due to the availability of both food and human waste.

4.6.4. Water Availability

The water requirement per feedstock as compared against the water consumption by non-sewered South African households with access to on-site and off-site water supply is shown in

Figure 4-4 and Figure 4-5 respectively. Cattle waste has the highest water demand of all the feedstocks and this attributed to the higher amount of cattle waste required compared to the other types of feedstocks.

It can be deduced that the installation of a 2 500, 5 000 and 6 250 L/day capacity domestic biogas digester in non-sewered households with access to on-site water supply will result in the consumption of approximately 24%, 47% and 60% respectively of the water consumption (equivalent to FBW) for feeding the digester. Alternatively, the installation of a 2 500, 5 000 and 6 250 L/day capacity domestic biogas digester in non-sewered households with access to on-site water supply will result the handling of approximately 31%, 62% and 78% of the total greywater generated by households respectively by feeding the digester.

In terms of non-sewered households with access to off-site water supply, the installation of a 2 500, 5 000 and 6 250 L/day capacity domestic biogas digester will result in consumption of 45%, 89% and 112% respectively of the total water consumption. Alternatively, the installation of a 2 500, 5 000 and 6 250 L/day capacity domestic biogas digester will result in the handling of 60%, 119% and 149% respectively of the total greywater generated by non-sewered households with access to off-site water supply.

It can be deduced that non-sewered households with access to on-site water supply generates sufficient greywater for feeding a domestic biogas digester therefore recommended over drinking water. Non-sewered households with access to off-site water supply generate insufficient greywater for feeding biogas digesters of 5 000 L/day and 6 250 L/day capacity. It is therefore recommended that in non-sewered households with access to off-site water supply greywater be augmented by harvested storm water or water from nearby rivers, dams and streams. This will ensure that drinking water is not used for feeding a biogas digester.

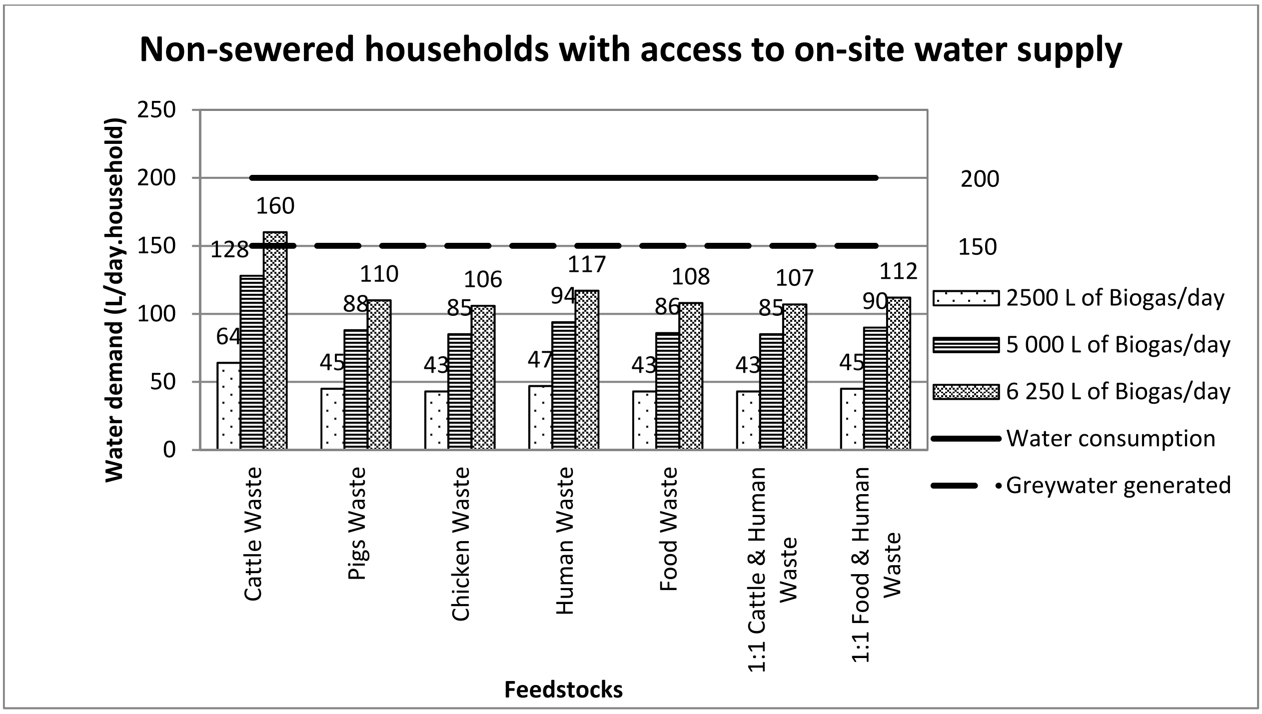

Figure 4-4: Water demand per feedstock for non-sewered households with access to on-site water supply

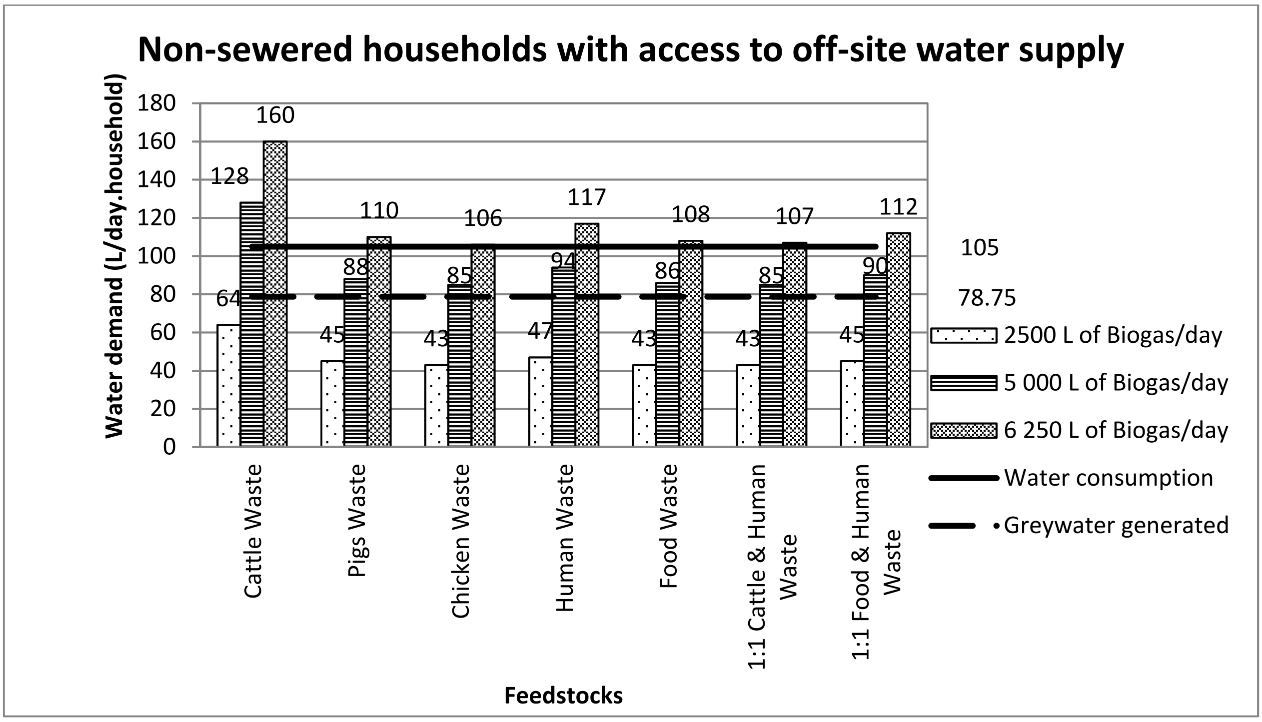

Figure 4-5: Water demand per feedstock for non-sewered households with access to off-site water supply

4.6.5. Biogas digester capacity

According to Table 2-4, the volume of digester required for the production of 2 500 L/day of biogas is 10 m^3 and 7 - 9 cattle are needed. Using the Excel model shown in Appendix A.1.7 it was determined that in order to use a 10 m^3 digester volume, more feedstock is required. Instead of feeding 128 L/day of a 1:1 mixture of cow dung and water as calculated in Appendix A.1.5.1 which require 8 cows, 145 L/day is required which translates to 9 cows needed. This means that the Excel model agrees with the contents of Table 2-4. According to Appendix A.1.7, the volume of digester required for the production of 2 500 L/day of biogas is 28 m^3 but when the feed rate is slightly increased a smaller digester volume is required. This is attributed to reduction in the organic loading rate (kg VS/m^3/day) by reducing the digester capacity of which according to Yadvika *et al* (2004) increases biogas yield.

Using the Excel model, for biogas production of 5 000 L/day; the calculated optimum digester volume is 20 m^3 fed with a 1:1 mixture of cow dung and water at a rate of 290 L/day (18 cattle needed) which is slightly higher than the calculated rate of 256 L/day (16 cattle needed). For biogas production of 6 250 L/day, the optimum digester volume is 25 m^3. The predicted feed rate is 363 L/day (22 cattle needed) which is slightly higher than the calculated rate of 320 L/day (20 cattle needed). A 20 m^3 digester volume can be used for biogas production 6 250 L/day but the predicted feed rate of a 1:1 mixture of cattle and water is 382 L/day which translates to 24 cattle required.

CHAPTER 5: Conclusions

The amount of biogas required to meet the energy demand for cooking by a South African household is approximately 2 500 L/day which is in line with the 1500 – 2 400 L/day reported by Bond and Templeton (2011). The amount of biogas required for complete substitution of fuelwood used for cooking, water heating and space heating is estimated at 5 000 L/day/household and 1 250 L/day/household of biogas is required for substituting paraffin used for lighting. The amount of biogas required for complete substitution of conventional domestic fuels is therefore estimated at 6 250 L/day/household.

It can be concluded that fuelwood use in South African households contributes 702 790 and 22 365 attributable DALYs lost and mortalities respectively. Substitution of fuelwood with 2 500 L of biogas per day per household will result in the avoidance of approximately 50% of the total attributable DALYs lost and mortalities from indoor smoke due to solid fuel use. Complete substitution of fuelwood with biogas will result in avoidance of 85.4% of attributable DALYs lost and mortalities due to solid fuel use.

It can be concluded that there is potential for domestic biogas technology utilising cattle and pig waste as feedstock. Due to access to cattle dung, approximately 613 662 households can potentially benefit from biogas digester installations fed with cattle dung for the production of 2 500 L of biogas per day per household. The number of households that can potentially benefit from the installation of a 5 000 or 6 250 L/day capacity biogas digester fed with cattle dung is 131 392. Due to access to pigs waste, the number of households that can potentially benefit from installations of 2 500 or 5 000 or 6 250 L/day capacity biogas digesters fed with pigs waste is 12 089. Due to the number of chickens required and the average number of chickens kept in South African households, it can deduced that it is not feasibly to operate a biogas digester fed solely with chicken waste.

Based on the average size of a South African household and the number of people required, it can be concluded that South Africa households do not produce enough human excreta to feed a digester for complete substitution of fuelwood used for cooking and for complete substitution of conventional domestic fuels. South African households generate less than 2% of the required food waste for feeding a family sized biogas digester therefore it can be concluded that food waste is not a potential digester feedstock in South African context.

A biogas digester fed with animal waste is more suitable for rural areas as most households own livestock. Biogas digesters fed with sewage are more suitable for peri-urban areas/informal settlements where a community digester can be connected to the water-borne sewage system. Informal settlements with centralized ablution facilities are ideal for connecting with a community biogas digester for the production of biogas.

Based on the water demand of biogas technology and the fact that South Africa is a water stressed country with limited water supply to low-income households, alternative water sources were assessed such as greywater for feeding a digester. It was determined that non-sewered households with access to on-site water supply generate sufficient and surplus greywater for feeding a domestic biogas digester. Non-sewered households with access to off-site water supply generate insufficient greywater for feeding biogas digesters of 5 000 L/day and 6 250 L/day capacity therefore requiring alternative water sources for augmentation. It is therefore recommended that in non-sewered households with access to off-site water supply greywater be augmented by harvested storm water or water from nearby rivers, dams and streams. This will ensure that drinking water is not used for feeding a biogas digester.

CHAPTER 6: Recommendations

It is recommended that a pilot scale study be launched to determine the actual replacement of fuelwood by biogas as well as the feasibility of domestic biogas technology in low-income South African households. Approximately 800 000 agricultural households in South Africa can gain access to 960 million liters/day of biogas for complete substitution of fuelwood used for cooking. Due to water scarcity and water supply in South Africa especially in low-income households, it is recommended that biogas digesters be connected to ablution facilities to make use of flushing water thus limiting the water demand.

It is also recommended that community biogas digesters fed with human waste be installed in peri-urban areas/informal settlements. The community biogas digesters must be connected to local ablution facilities. Food waste generated by the households can also be fed into the digester thus resulting in co-digestion of food and human waste. Approximately 15 households can generate enough human waste to feed a digester for daily biogas production of 2 500 L to be used by at least one household per day for cooking purposes. Therefore a few of these biogas digesters can be installed in a single community. In terms of biogas consumption, households can take turns in utilizing biogas for cooking.

Instead of using inefficient biogas lamps for lighting purpose which poses a risk to the safety of the household members, it is recommended that PV solar home systems be installed in rural households to provide electricity for lighting and charging of mobile devices. The significant amount of energy required for water heating in low-income South African households of approximately 32% can be met by the installation of a solar water heating system. This will reduce the size of the biogas digester required.

Non-sewered South African households with access to on-site water supply should make use of the generated greywater for feeding domestic biogas digester instead of drinking water supplied by the government in the form of FBW. Non-sewered South African households with access to off-site water supply should make use of the generated greywater and in cases where it is insufficient it must be augmented with harvested rainwater or water from nearby rivers or dams. Where it is envisaged that greywater won’t be sufficient for feeding a domestic biogas digester, it is recommended that a water supply technology such as rainwater harvesting be implemented simultaneously with domestic biogas technology.

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Appendix A

A.1. Sample Calculations

A.1.1. Energy requirements from fuelwood by an average sized family

$$Q = m \times C_v \times \eta$$

$$m = \left(4.5\ \text{tones/ annum.household}\right) \times \left(\frac{1000\ \text{kg}}{1\ \text{ton}}\right) \times \left(\frac{1\ \text{year}}{365\ \text{days}}\right) = 12\ \text{kg/day/household}$$

Fuelwood calorific value (C $_v$) = 17 MJ/kg

Fuelwood efficiency = 13%

$$Q = 12\text{kg/day/household} \times 17\text{MJ/kg} \times 0.13 = 27\ \text{MJ/day/household}$$

According to Damm & Triebel (2008), 27 MJ/day.household represents 40% of the total energy consumption in a South African household therefore the total energy is calculated as follows:

$$Q_T = \frac{Q}{0.4} = \frac{27\ \text{MJ/day.household}}{0.4} = 68\ \text{MJ/day.household}$$

A.1.2. Biogas required to substitute fuelwood as an energy source

$$Q = v \times C_v \times \eta$$

$$\text{Biogas calorific value } (C_v) = 20\ \text{MJ/m}^3$$

$$\eta = 0.55$$

$$v = \frac{Q}{C_v \times \eta}$$

$$= \frac{27\ \text{MJ/day.household}}{20\text{MJ/m}^3 \times 0.55}$$

$$= 2.4\ \ \text{m}^3 = 2\,500\ \text{L/day/household}$$

A.1.3. Complete energy substitution of conventional domestic fuels

Biogas required for fuelwood replacement (80% of total energy):

$$v = \frac{0.8\left(68\ MJ/day/household\right)}{20\ MJ/m^3 \times 0.55} = 4.9\ m^3 \approx 5\,000\ L/day/household$$

Biogas required for paraffin replacement (20% of total energy):

$$v = \frac{0.2\left(68\ MJ/day/household\right)}{20\ MJ/m^3 \times 0.55} = 1.24\ m^3 \approx 1\,250\ L/day/household$$

Total biogas requirement = 6 250 L/day/household

A.1.4. Cost savings from biogas substitution of conventional domestic fuels.

According to Damm and Triebel (2008), the net direct-use value of fuelwood was R1 250 and therefore the adjusted value due to inflation is calculated as follows:

$$\frac{Price_2}{Price_1} = \frac{CPI_2}{CPI_1}$$

$$\begin{aligned} Price_2 &= \frac{CPI_2}{CPI_1} \times Price_1 \\ &= \frac{114.7}{79.3} \times R1\,250 \\ &= R1\,808 \end{aligned}$$

According to Census 2001 reported by ERC 2004 as cited in Damm and Triebel (2008), the upper band in the income bracket for low-income households is R9 600 which can be inflated to current times as follows:

$$\begin{aligned} Price_2 &= \frac{CPI_2}{CPI_1} \times Price_1 \\ &= \frac{114.7}{52.4} \times R9\,600 \\ &= R21\,013 \end{aligned}$$

A.1.5. Burden of disease attributed to indoor smoke from solid fuels

According to WHO (2002), the attributable DALYs lost due to indoor smoke from solid fuels in Africa were 12 318 000 in 2000. Based on the African population of 655 476 000 and the South

African population of 43 791 000 in 2000, the DALYs lost in South Africa can be estimated as follows:

DALYs lost in South Africa = $12\ 318\ 000 \times \frac{43\ 791\ 000}{655\ 476\ 000} = 822\ 940$

According to WHO (2002), the attributable mortalities due to indoor smoke from solid fuels in Africa were 392 000 in 2000 therefore the number of deaths in South Africa can be estimated as follows:

Mortalities in South Africa = $392\ 000 \times \frac{43\ 791\ 000}{655\ 476\ 0\ 00} = 26\ 189$

A.1.6. Availability of feedstocks

The number of animals, waste produced and water required for the production of 2 500 L/day/household of biogas were calculated as follows:

A.1.5.1. Cow Dung

$$Number\ of\ cows = \frac{2.5\ m^3\ /day.household}{0.32\ m^3\ /cow.day} \approx 8\ cows/household$$

$$Waste\ produced\ = 8\ kg/cow.day\ \times 8\ cows\ = 64\ kg/day$$

The amount of water required to dilute 64 kg/day of cow dung with a % DM of 16% to an optimum % DM of 8% is calculated as follows:

$$Water\ demand = \frac{\%DM_{old} \times (Feed)}{\%DM_{new}} - Feed = \frac{0.16 \times 64\ kg/day}{0.08} - 64\ kg/day = 64\ L/day$$

A.1.5.2. Swine Waste

$$Number\ of\ pigs = \frac{2.5\ m^3\ /day.house\ hold}{0.128\ m^3\ /pig.day} \approx 20\ pigs/house\ hold$$

$$\text{Waste produced} = 2\ \text{kg/pig.day} \times 20\ \text{pigs} = 40\ \text{kg/day}$$

The amount of water required to dilute 40 kg/day of pig waste with a % DM of 17% to an optimum % DM of 8% is calculated as follows:

$$\text{Water demand} = \frac{\%DM_{old} \times (Feed)}{\%DM_{new}} - Feed = \frac{0.17 \times 40\ \text{kg/day}}{0.08} - 40\ \text{kg/day} = 45\ \text{L/day}$$

A.1.5.3. Poultry Waste

$$\text{Number of chickens} = \frac{2.5\ m^3\ \text{/day.household}}{0.01\ m^3\ \text{/chicken.day}} = 250\ \text{chickens/household}$$

$$\text{Waste produced} = 0.08\ \text{kg/chicken.day} \times 250\ \text{chickens} = 20\ \text{kg/day}$$

The amount of water required to dilute 20 kg/day of chicken waste with a % DM of 25% to an optimum % DM of 8% is calculated as follows:

$$\text{Water demand} = \frac{\%DM_{old} \times (Feed)}{\%DM_{new}} - Feed = \frac{0.25 \times 20\ \text{kg/day}}{0.08} - 20\ \text{kg/day} = 20\ \text{L/day}$$

A.1.5.4. Human Excreta

$$\text{Number of people} = \frac{2.5\ m^3\ \text{/day.household}}{0.04\ m^3\ \text{/person.day}} = 63\ \text{people/household}$$

$$\text{Waste produced} = 0.5\ \text{kg/person.day} \times 63\ \text{people} = 32\ \text{kg/day}$$

The amount of water required to dilute 32 kg/day of human excreta with a % DM of 20% to an optimum % DM of 8% is calculated as follows:

$$\text{Water demand} = \frac{\%DM_{old} \times (Feed)}{\%DM_{new}} - Feed = \frac{0.20 \times 32\ \text{kg/day}}{0.08} - 32\ \text{kg} = 47\ \text{L/day}$$

A.1.5.5. Kitchen/Food waste

The weightened average of % DM and biogas yield for food waste was calculated as follows based on data in Table A-0-1 below:

$$Weightened\ \ average\ \ of\ \ \%\ DM\ = \sum x_i \times \%\ DM_{\mathrm{i}}$$

Where, x_i is the % of total pre-consumer waste as shown in Table A-0-1.

$$\begin{aligned} Weightened\ \ average\ \ of\ \ \%\ DM\ &= (0.28 \times 0.88) + (0.08 \times 0.12) + (0.03 \times 0.92) + (0.48 \times 0.13) + \\ &\quad (0.1 \times 0.17) + (0.01 \times 0.08) \\ &= 0.34 \end{aligned}$$

$$\begin{aligned} Weightened\ \ average\ \ of\ \ biogas\ \ yield\ &= (0.28 \times 0.65) + (0.08 \times 0.65) + (0.03 \times 0.95) + (0.48 \times 0.4) + \\ &\quad (0.1 \times 1) + (0.01 \times 0.7) \\ &= 0.55\ m^3/kg\ DM \end{aligned}$$

Table A-0-1: Composition and properties of food waste

Commodity group	**Post-consumer food waste (1 000 tons)**	**% of total Post-consumer food waste**	**%DM**	**Biogas yield (m^3/kg DM)**
Cereals	142	28%	88%	0.65
Roots and Tubers	41	8%	12%	0.65
Oil seeds & Pulses	13	3%	92%	0.95
Fruits and Vegetables	241	48%	13%	0.4
Meat	52	10%	17%	1
Fish and Seafood	10	2%	-	-
Milk	3	1%	8%	0.7
Total per stage of the food supply chain	502	100%	34%	0.55

The amount of food waste required as feed to produce 2 500 L/day of biogas is calculated as follows:

$$\begin{aligned} Dry\ \ matter\ &= \frac{2.5\ m^3/day.house\ hold}{0.55\ m^3/kg\ Dry\ matter} \\ &= 4.55\ kg\ Dry\ matter/day.household \end{aligned}$$

$$\begin{aligned} Food\ waste &= \frac{4.55\ \ kg\ Dry\ matter/day.household}{0.34} \\ &= 13\ \ kg/day.household \end{aligned}$$

The amount of water required to dilute 13 kg per day per household of food waste with a % DM of 34% to an optimum %DM of 8% is calculated as follows:

$$Water\ demand\ = \frac{\%DM_{old} \times (Feed)}{\%DM_{new}} - Feed = \frac{0.34 \times 13\ kg/day}{0.08} - 13\ kg = 43\ L/day$$

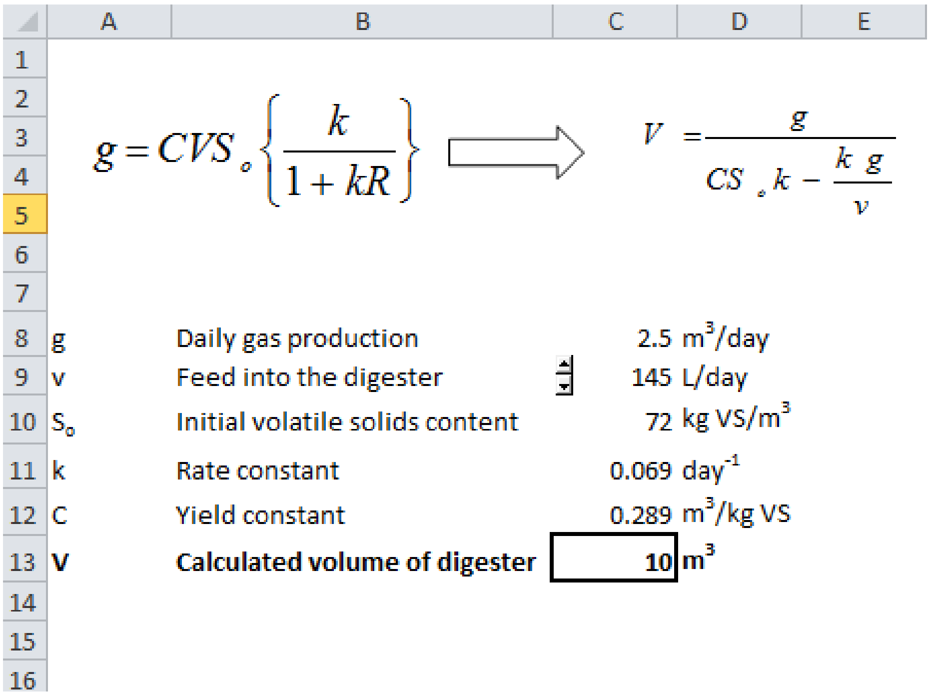
A.1.7. Prediction of digester volume

The volume of the digester required to produce 2 500 liters of biogas per day was predicted using the equation below which was derived from Equation 4. The feedstock requirements for the production of 2 500 L/day of biogas as calculated in Appendix A.1.5.1 is 128 L/day mixture of cattle dung and water at a ratio of 1:1. The total solids content of cattle dung mixed with water is 9% and the volatile solids content is approximately 80% of this, say 72 kg/m^3 (assuming the density of slurry is 1 000 kg/m^3). Assuming that the digester is operated at a temperature of 25 °C, from Table 2-5 the yield constant C and the rate constant k are 289 L/kg and 0.069 day^{-1} respectively.

$$V = \frac{g}{CS_o k - \frac{k\,g}{v}}$$

$$V = \frac{2.5\ m^3/day}{\left[(0.289\ m^3/kg) \times 72\ kg/m^3 \times 0.069\ day^{-1}\right] - \frac{0.069\ day^{-1} \times 2.5\ m^3/day}{0.128\ m^3/day}} \approx 28m^3$$

An excel model was created to estimate the optimum digester capacity (m^3) operated at 25°C fed with a 1:1 mixture of cattle dung and water for biogas production of 2 500, 5 000 and 6 250 L/day/household. For production of 2 500 L/day of biogas, the calculated optimum digester volume is 10 m^3 fed with a 1:1 mixture of cattle dung and water at a rate of 145 L/day as shown in Figure A-0-1.



$$g = CVS_o\left\{\frac{k}{1+kR}\right\} \Longrightarrow V = \frac{g}{CS_o k - \frac{k\,g}{v}}$$

A	B	C	D
g	Daily gas production	2.5	m^3/day
v	Feed into the digester	145	L/day
S_o	Initial volatile solids content	72	kg VS/m^3
k	Rate constant	0.069	day^{-1}
C	Yield constant	0.289	m^3/kg VS
V	**Calculated volume of digester**	**10**	**m^3**

Figure A-0-1: Excel model for the prediction of digester volume.

A.2. Case Study: Biogas socket: for local power supply

Users of biogas systems often live in off-grid areas, and have a strong need for electricity, especially due to the rise of the mobile phone (TNO, n.d.). Domestic biogas systems have the potential to be used for electricity generation, but up to now, electricity generation was not possible on small scale, household systems (TNO, n.d.). Dutch Development Organisation (SNV, TNO, BoPInc and SimGas) have joined forces to develop a low cost electricity generator that works on biogas: Biogas Socket (see Figure A-0-2 below).

Figure A-0-2: Biogas Socket (Source: TNO, n.d.)

The Biogas Socket works on the principle of thermo-electric generation, using a piece of semi-conductor material (a Peltier element) that transforms the heat from a small biogas flame into electricity, without any moving parts (TNO, n.d.). The excess heat generated is cooled away via a tank filled with about 5 liters of water (TNO, n.d.). The Biogas Socket can produce up to 3-5 watts of power that serves small-scale household power needs (Siddique, 2014). Mobile sets are charged through a USB port attached at the bottom of the structure (see Figure A-0-3 below) (Siddique, 2014). The Biogas Socket has been installed in 6 rural households in Bangladesh and currently being tested in Rwanda and Tanzania (Siddique, 2014). The cost of the Biogas Socket is estimated in the vicinity of 10 000 Bangladeshi Taka which is approximately 1 700 South African Rands.

Figure A-0-3: Biogas Socket charging mobile set (Source: Siddique, 2014)