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INVESTIGATING THE POTENTIAL OF DOMESTIC BIOGAS PRODUCTION TO ENHANCE ENERGY ACCESS IN UGANDA

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Declaration

I declare that the contents of this thesis report are my original work and are as a result of my personal research, except where otherwise indicated. This report has not been submitted anywhere else for any academic purposes or otherwise.

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Signature:

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GOD BLESS YOU ALL.

Dedication

I dedicate this report to my parents, Mr. Perez Nduhuura & Mrs. Jennifer Nduhuura, who have sacrificed beyond their abilities so that we, their children, can have the best of life.

Abstract

Access to energy is recognised globally as a key factor for the socio-economic transformation of every country. However, even with this knowledge, many people worldwide still lack access to modern energy services. As such the use of traditional fuels such as solid biomass, with its associated challenges, remains prevalent especially in developing countries. The use of biogas has been promoted as a suitable replacement for traditional biomass fuels in many developing countries. However, despite the introduction of biogas technologies in Uganda in 1950s, biogas use has remained low in the country.

The potential role that domestic biogas production can play in enhancing access to modern energy in Uganda remains largely unappreciated. This research was therefore carried out to investigate this role by assessing the biogas technical potential, identifying the most suitable biogas production technology and assessing the economic viability of biogas production at a domestic/household level in Uganda.

Biogas, which is majorly composed of methane and carbon dioxide, is produced through the anaerobic digestion process from various biodegradable materials including animal manure, agricultural wastes, energy crops, and MSW. The common technologies for domestic biogas production are fixed dome digester, floating drum digester and tubular digester.

To estimate the biogas technical potential at a household level in Uganda, data about the quantity, availability, composition and biogas yield of the available feedstock was used. The selection of the best biogas technology was achieved based on the assessments provided by biogas experts, masons and potential biogas technology users. The Priority Estimation Tool software, which is a multi-criteria decision making software employing the analytical hierarchy process method, was used to synthesize the obtained information and give meaningful results. The economic viability of biogas production in Uganda was assessed using the cost-benefit analysis approach by evaluating the costs and benefits of the selected biogas technology over its estimated lifespan.

For purposes of data collection, a case study of Wakiso district was chosen. Relevant data was obtained from potential biogas users, biogas experts and masons, and also from literature sources. Subsequent computations carried out using Microsoft Excel spreadsheets revealed that the biogas technical potential from livestock manure is 380.7 million m^3/year while that from municipal solid waste is 62.2 million m^3/year. The potential biogas users identified lifespan and capital cost as the most important technical and economic criteria respectively when selecting a suitable biogas production system. A fixed dome biogas system was subsequently selected as the most suitable domestic biogas production technology in Uganda. Domestic biogas production in Uganda was also found to be economically competitive with NPV of UGX 7,668,362; IRR of 37%; BCR of 2.2; and discounted payback period of 3.95 years.

The results obtained indicate that the potential for domestic biogas production to enhance energy access in Uganda is high. There is therefore a need to actively promote domestic biogas use in Uganda because of the huge potential that exists in the country. The positive economic returns associated with biogas use can be a major driver to biogas production if the indirect monetary benefits such as time savings, improved health, improved agricultural production and environmental protection are clearly explained to the people.

Key words: feedstock availability, technology selection, economic viability.

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List of abbreviations

AGECC	Advisory Group on Energy and Climate Change
AFR	Africa region
AHP	Analytical Hierarchy Process
ARTI	Appropriate Rural Technology Institute
BCR	Benefit-Cost Ratio
BSU	Biogas Solutions Uganda
Btu	British thermal unit
CAMARTEC	Centre for Agricultural Mechanization and Rural Technology
CDM	Clean Development Mechanism
CI	Consistency Index
EAP	East Asia and Pacific region
ECA	Europe and Central Asia region
EJ	Exa-joule
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
IEA	International Energy Agency
IRR	Internal Rate of Return
KWh	kilowatt hour
KVIC	Khadi and Village Industries Commission
LCR	Latin America and the Caribbean region
LUPO	Land-Use Planning Oromiya
MEMD	Ministry of Energy and Mineral Development
MENA	Middle East and North Africa region
MSW	Municipal Solid Waste
MW	Megawatt
NGOs	Non-Governmental Organisations
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OFMSW	Organic Fraction of Municipal Solid Waste
PJ	Peta Joule
RI	Random Index
SAR	South Asia region
SDGs	Sustainable Development Goals

SNV	Foundation of Netherlands Volunteers
SSA	sub-Sahara Africa
TED	Technology for Economic Development
TWh	Terawatt hour
UGX	Uganda Shillings
UN	United Nations
US/USA	United States of America
UV	Ultra Violet
VS	Volatile Solids

CHAPTER ONE: INTRODUCTION

Access to energy is a key factor in the socio-economic transformation of every country. While there is no single internationally-adopted definition of energy access (IEA, 2006) (Bhattacharyya, Subhes C., 2012), the definition put forward by the UN Secretary General's Advisory Group on Energy and Climate Change (AGECC) is widely recognised and captures the broader scope of access to energy. AGECC defines energy access as access to;

"A basic minimum threshold of modern energy services for consumption and productive uses. Access to these modern energy services must be reliable and affordable, sustainable and where feasible, from low GHG-emitting sources" (AGECC, 2010).

This minimum threshold of energy access is essential for the provision of other services such as clean water, good health care, quality education, efficient lighting, clean cooking and heating services, whilst also boosting economic activity.

Global estimates indicate that many people, particularly in the developing world, lack access to modern energy services. In sub-Sahara Africa, for example, it is estimated that about 634 million people have no access to electricity while over 750 million have no access to clean and efficient cooking methods. Most households rely on traditional sources of energy to meet their daily energy needs. Solid biomass, in particular, remains the most predominant source of energy for heating and lighting in developing countries. (IEA, 2015). The biomass is converted from its raw form using inefficient energy conversion techniques such as open air cook stoves.

Biogas production offers an opportunity for many households in developing countries to shift from traditional to modern forms of energy. Biogas is a renewable energy resource that is mainly produced from what is usually regarded as waste. Biogas burns cleanly and efficiently and therefore avoids most of the negative aspects associated with the use of solid biomass (Surendra K.C. et al., 2014). The production of biogas can be undertaken locally, either at a small scale by individual households or at a medium and large scale by communities, institutions, industries and cities (Teodorita A. S., et al., 2008). This avoids the over-dependence on imported fuels such as kerosene and natural gas and offers a sustainable alternative to achieve proper waste management in urban areas.

This study therefore assessed the potential of domestic biogas production to improve energy access in Uganda. The approach used is to determine the biogas technical potential from available feedstock, identify the most suitable biogas production technology and carry out an economic analysis on domestic biogas production in Uganda.

1.1 Background

1.1.1 Location and size

Uganda is a land locked country located in the East African Region. It is bordered by Kenya to the East, South Sudan to the North, Democratic Republic of Congo (DRC) to the West, Rwanda to the South West and Tanzania to the South. Uganda lies across the equator at latitude 4°12'N & 1°29'S and longitude 29°34'E & 35°0'E. It covers a total surface area of 241,550.7 km^2 of which area under land is equal to 200,523.2 km^2. Uganda's minimum altitude is 620 m above sea level while the maximum altitude is 5111 m above sea level (UBOS, 2015).

Figure 1.1: Map of Uganda
Source: (Furian P.H., 2016)

1.1.2 Demographic characteristics

The population of Uganda is estimated at about 34.6 million people (2014 data) and has grown at an average of 3.0% per annum over the last 12 years. With a sex ratio[1] of 94.6, Uganda's female population exceeds that of males. Uganda has a young population with an estimated 68% of the total population below 25 years. Majority of Uganda's population is rural based with over 80% of households situated in rural areas. The major economic activity is agriculture which employs about 68% of the population. Most of the agricultural production is, however, carried out on a subsistence scale (UBOS, 2016).

1.1.3 Climate

Most regions of Uganda experience four well marked seasons every year; two dry seasons and two wet seasons. Variations in mean temperature and annual rainfall are experienced across the country as a result of differences in altitude, landscape as well as proximity to water bodies (NEMA, 2010). The temperature varied from 14°C to 31°C in 2014 while rainfall averaged at 1303 mm in the same year (UBOS, 2015).

1.1.4 Soils

Uganda's soils are majorly ferralitic soils, defined by geological parent rock and age of soil. These soils are mostly loamy soils with distributed patches of clay and sandy soils. The soils support agricultural activities as well as the growth of a variety of vegetation including tropical rainforests, savannah woodlands/grasslands and shrubs in the dry or semi-arid areas (NEMA, 2010).

1.1.5 Energy Access in Uganda

Energy resources and potential

Uganda is gifted with substantial and diverse energy resources both renewable and conventional in nature. The most prominent of these resources include solar, hydropower, biomass, geothermal, peat and most recently crude oil/petroleum. Recent estimates put Uganda's hydropower potential at about 2000 MW from

[1] Sex ratio is defined as the number of males per 100 females in a population and is an indicator used to show the prevailing parity between the number of males and females.

potential large scale, small scale and mini hydropower sites across the country. With an average solar irradiation of 5.1 kWh/m^2/day on a horizontal surface, Uganda also has a substantially high potential for solar energy utilisation. The irradiation remains relatively constant throughout the year due to Uganda's location near the equator. The maximum yearly variation is estimated to be about 20%. Solar energy potential is highest in the semi-arid areas in the north-east and lowest in the mountain ranges of east and south-west.

The total biomass potential for Uganda is estimated to be over 284 million tonnes of standing biomass stock. Of this, about 45 million tonnes can be sustainably utilised without significant ecological or environmental consequences. Biomass cogeneration potential is also estimated at 1650 MW. Other resource potentials include geothermal (450 MW), peat (800 MW), as well as 3 billion barrels of crude oil.

Energy demand and consumption

The annual total primary energy consumption for Uganda was estimated by the US Energy Information Administration to be 0.065 Quadrillion BTU in 2013. As shown in Figure 1.2 below, the energy demand is highest in the residential sector, followed by commercial, industrial and transport sectors respectively. Energy demand and use in the agricultural sector remains very low (MEMD, 2012).

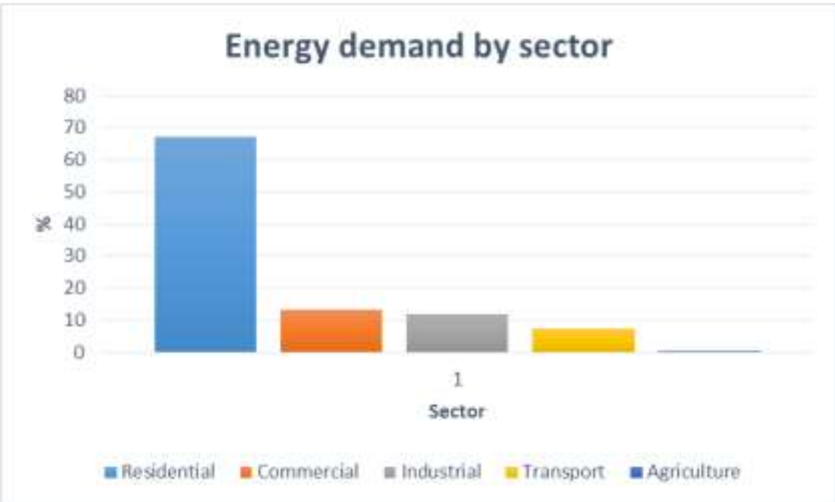

Figure 1.2: Energy demand by sector in Uganda

Biomass remains the most popular source of energy used by most people in the country. This is followed by oil products and electricity respectively. As shown in Figure 1.3, about 89% of the total primary energy consumption of Uganda is derived from biomass. Biomass is utilised in both rural and urban households mainly for cooking and heating purposes. Commercial and industrial establishments that require heat in their processes also use considerable amounts of biomass because it is a more economical option. Oil products are largely used as fuel for vehicles or to operate thermal power plants or small electrical generators while electricity is used majorly for lighting and to power industrial machinery.

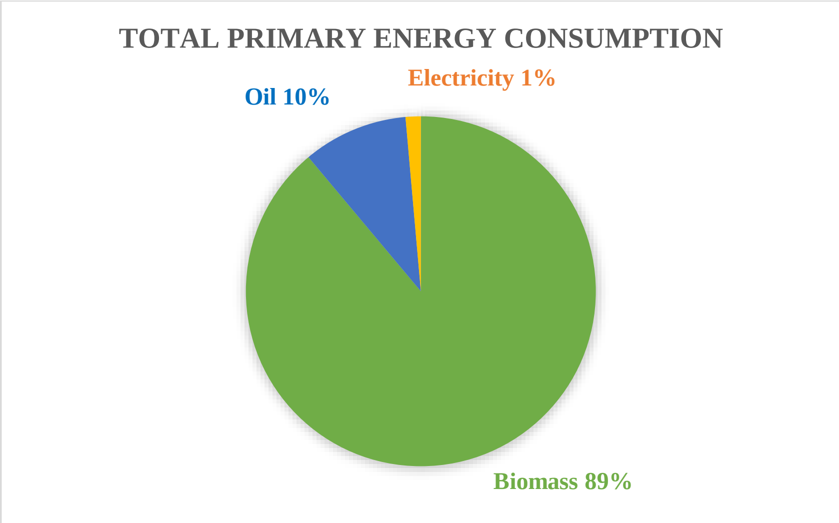

Figure 1.3: Total primary energy consumption by source in Uganda

Energy for lighting

Most of the energy for lighting in Uganda comes from the use of kerosene lamps, both traditional and improved lanterns. Kerosene based lighting accounts for over 60% of all lighting energy consumed in Uganda (see Figure 1.4). These lamps are used mainly in rural areas where access to electricity is estimated to be only 10%, which is well below the official national electrification rate figure of 20% (UBOS, 2016). Uganda's installed power capacity is also low and is estimated at 873.34 MW, mainly from hydro resources. The per capita electricity consumption rate is estimated to be 500 kWh/capita/year (MEMD, 2015).

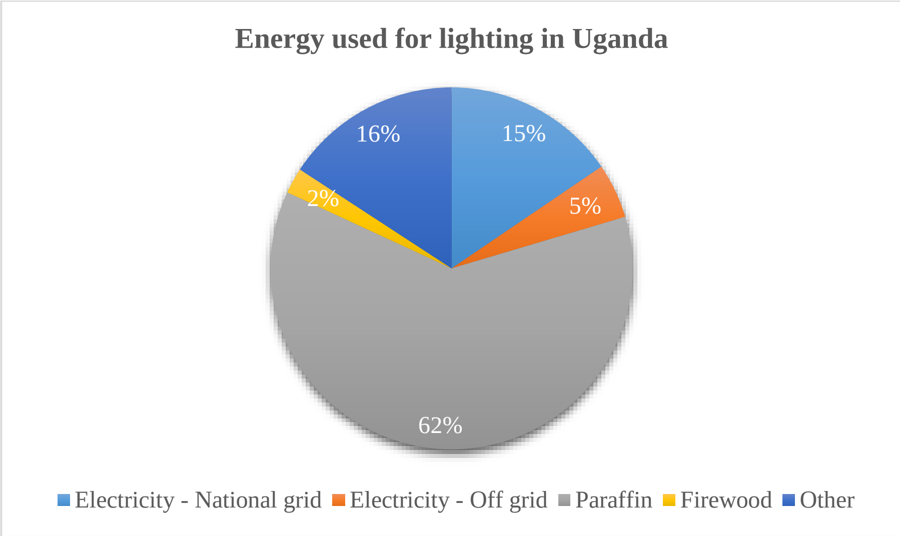

Figure 1.4: Energy for lighting by source in Uganda

Energy for cooking

Firewood and charcoal remain the most commonly used sources of energy for cooking and heating. While the use of firewood and charcoal has continued to reduce over the years, the two still account for an estimated 94% of all the energy used for cooking in Uganda (see Figure 1.5). Firewood is mainly used by households in rural areas and in some industries, while charcoal use is predominantly used in urban households (UBOS, 2016).

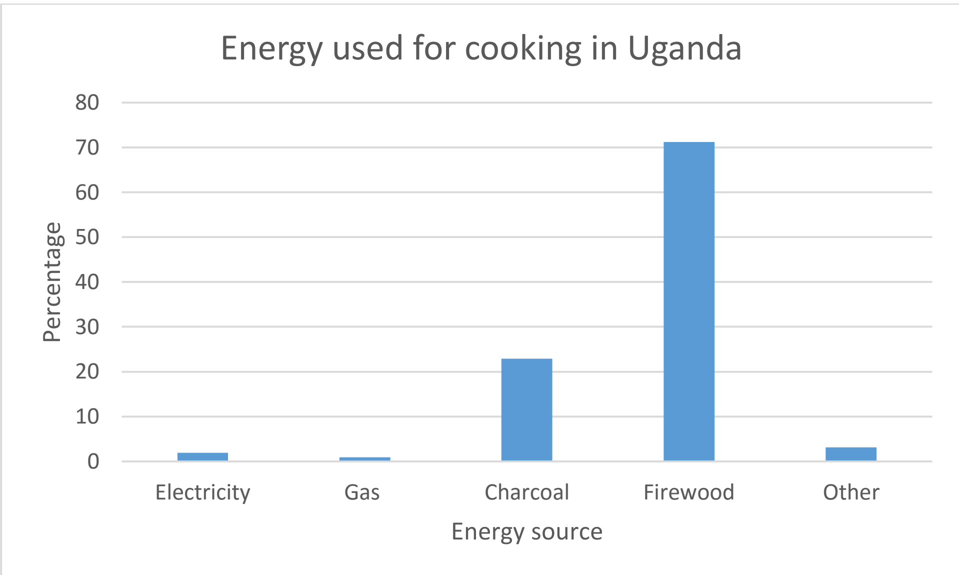

Figure 1.5: Energy for cooking by source in Uganda

1.2 Problem Statement

Efforts to improve energy access in developing countries have garnered a lot of attention in the recent past. Globally, *"Ensuring access to affordable, reliable, sustainable and modern energy for all"* is one of the 17 sustainable development goals recently adopted under the UN's post-2015 development agenda. At a national level, many countries have adopted similar initiatives to encourage and speed up access to and use of modern energy services. In Uganda, for example, energy access objectives, strategies and interventions have been included in previous and current National Development Plans (NPA, 2010) (NPA, 2015). However, even with such efforts, millions of people in the country still lack access to modern energy services.

Globally, many energy access programmes have a disproportionate emphasis on electrification as opposed to energy for cooking or heating As such, while tremendous progress has been registered regarding electricity access in many countries, there is still a lot of effort required to reduce the over-reliance on traditional forms of biomass for cooking (Wesley Fell, et al., 2011). In Uganda, electricity access improved to 20% in 2014, while the use of solid biomass for cooking remains at a staggering 94% (UBOS, 2016).

Widespread use of traditional forms of biomass including firewood, charcoal and agricultural residues is not only an inefficient energy utilisation technique, but is also associated with a number of negative environmental, social, and health effects (Y. von Schirnding, et al., 2002). The burning of solid fuels using inefficient conversion technologies is a major source of indoor air pollution with its associated health complications including lung cancer, pneumonia, stroke chronic obstructive pulmonary disease and acute respiratory infections. Increased demand for fuel wood and charcoal has also been linked to serious environmental concerns particularly deforestation and increased greenhouse gas emissions (Surendra K.C. et al., 2014).

Biogas is seen as a suitable solution to address energy access issues in many developing countries. However, in Uganda, there is a general lack of awareness about the available biogas potential, the most suitable technology and the economic viability of domestic biogas production in the country. This study, therefore, investigated the potential for domestic biogas production in Uganda by assessing the biogas technical potential of the available feedstock, identifying the most suitable biogas production technology and determining the economic viability of domestic biogas production.

1.3 Objectives of the study

General objective

To investigate the potential of domestic biogas production to improve energy access in Uganda.

Specific objectives

- To estimate the biogas technical potential for major feedstock in Uganda.
- To determine the most suitable domestic biogas production technology in Uganda.
- To carry out an economic analysis for domestic biogas production and use in Uganda.

1.4 Justification

Various options for improving energy access in Uganda need to be studied due to the prevailing energy situation in the country. Biogas production is one of the most promising options to address the lack of access to modern energy. This study unveils the potential, technological and economic aspects and considerations necessary to stimulate biogas production and use in Uganda.

A number of studies have been done to assess biogas production in Uganda. Some studies were centred on specific aspects of biogas production and use while some others focused on assessing the biogas production for specific regions and localities. There was no study found in literature that evaluated the potential of biogas production at a national level by merging the different aspects of potential, technology and economics. Such an all-inclusive approach to assessing biogas production is necessary to better appreciate the essential role that biogas can play to bring modern energy to millions of people in Uganda.

The tool used for biogas technology selection had also not been used before in the selection of biogas technologies in Uganda. The tool offers an opportunity to incorporate information obtained from assessments done by both potential biogas technology users and biogas experts.

This study is therefore important because it provides practical and cohesive information which can be used by policy makers and other biogas sector players to scale up biogas use in Uganda.

1.5 Scope of the research

The purpose of this research was to assess the potential for domestic biogas production to enhance energy access in Uganda. The research was therefore limited to determining the biogas technical potential, selecting the best biogas technology and carrying out an economic analysis of biogas production at an individual household level. Livestock manure, being the most common feedstock available to many households in Uganda, was chosen for the estimation of the biogas technical potential. Moreover, information about other possible domestic feedstock such as agricultural residues was largely insufficient to facilitate the accurate evaluation of their biogas technical potential.

However, a section on municipal solid waste technical potential was included in this study in order to raise awareness about the existing potential and opportunities for communal biogas production in the country.

Selecting the best biogas technology was limited to the technologies that are commonly used or promoted in the country.

CHAPTER TWO: LITERATURE REVIEW

2.1 Biogas as an Alternative Energy Source

2.1.1 Properties of Biogas

Biogas is a mixture of various gases, mainly methane and carbon dioxide which are produced through the anaerobic digestion process. It is a flammable gas with a calorific value of 6.0 – 6.5 kWh/m^3, depending on the percentage of methane present (Vogeli Y., et al., 2014). Variations in biogas composition exist for biogas produced from different substrates and digestion systems. The estimated quantities of the constituent gases in biogas are shown in Table 2.1 below.

Table 2.1: Biogas composition

Constituent gas	**Composition (% vol.)**
Methane	50 – 75
Carbon dioxide	25 – 45
Water vapour	2 – 7
Nitrogen	<2
Oxygen	<2
Hydrogen	<1
Hydrogen sulphide	<1
Ammonia	<1

Source: (Teodorita A. S., et al., 2008)

2.1.2 Brief history of biogas use and current world trends

The use of biogas is believed to date as far back as the 10th century BC. However, documented evidence indicates that biogas was first directly used by human beings as a source of energy in the 19th century. The application of biogas technologies, however, remained largely limited until the 1970s when increasing oil prices inspired technological innovations in the sector. As a result of increased oil prices, biogas technology use was promoted in many countries (Bond T. & Templeton M. R., 2011).

Today, China is the world leader in the number of biogas installations and quantity of biogas produced. With about 40 million small scale biogas installations and 6300 large-scale biogas plants, China generated about 19.4 billion cubic metre of biogas in 2010 (Dong, 2012). This milestone was achieved due to 40 years of research and development, training and implementation (Bhattacharyya, 2012) (Catania, 1999). Other countries, including Germany and India, have also developed extensive biogas programs. In the developing countries of Asia, Latin-America and Africa, biogas use also experienced its fastest growth during the oil crisis of the 1970s but later slowed down in late 1980s (Ni JQ, 1996). However, towards the end of the 20th century, there was a renewed interest in the use of biogas in a number of countries (He PJ., 2010).

In many sub-Saharan Africa countries, various biogas initiatives have also been introduced and biogas use is on the increase. Since 2007, national biogas programs have been started by SNV in at least nine African countries namely; Rwanda, Ethiopia, Tanzania, Uganda, Kenya, Burkina Faso, Cameroon, Senegal and Benin (Ghimire, 2013). The total number of biogas installations in these countries increased by over 15,000 units from 2007 to 2012 (SNV, 2012).

2.1.3 Biogas production and use in Uganda

Biogas production and use in Uganda dates back to the 1950s and 60s when the first biogas plants were built by the missionaries. Subsequently, in the 1970s and 80s, some studies were carried out to assess the feasibility of biogas technology use in Uganda. The results from these studies showed that biogas production was a viable option within Uganda’s context. Despite these scientific revelations, the uptake and use of biogas technologies remained minimal due to political instability at that time. By the 1990s, the number of biogas installations in Uganda was estimated to be below 200 units. This number had increased to about 600 units by 2007 (Pandey B., et al., 2007).

Recent estimates show that the number of biogas plants in Uganda have increased to 3100 units, (SNV, 2012) largely due to the work done by non-governmental organisations. These systems are majorly small scale family-sized plants that produce biogas to meet the daily household energy needs. The common sizes of bio-digesters installed in Uganda range between 8 m^3 and 16 m^3 and are sized basing on the amount of substrate available daily. A few medium-sized biogas plants have also been constructed in some institutions that have substantially huge quantities of feedstock. For example, the 50 m^3 biogas system at the Kampala city abattoir was constructed to utilise the huge amounts of organic waste produced from slaughtering animals. The biogas produced is used to meet the heating needs of the abattoir. The main substrate used in most bio-digesters in Uganda is cow manure. This is because most NGOs usually support biogas production in individual households which own livestock, particularly, cattle (Walekhwa P. N., et al., 2009).

Drivers for biogas use in Uganda

Biogas use in Uganda is motivated by a combination of factors including;

- The known potential benefits/advantages of biogas over other local energy resources.
- Supportive government policies which have enabled the biogas sub-sector to take off.
- International support through various non-governmental organisations that provide financial and technological support.

Government support programs for the biogas sub-sector

Adequate policy support tools for the promotion of renewable energy use exist in Uganda. Key among these are the Energy Policy of Uganda, 2002 and the Renewable Energy policy, 2007. The energy policy seeks to develop among others the use of renewable energy systems on both small and large scales through supporting dissemination, financing and quality assurance programs (GOU, 2002).

Similarly, Uganda formulated a renewable energy policy in 2007 to scale up renewable energy use in the country. One of the proposed approaches in the policy is to promote the production and use of biogas at both the household level and on an industrial scale. This policy move was informed by the fact that many households own zero-grazing cattle and therefore have substantial feedstock (in form of manure) to produce biogas. As such, the policy stated an ambitious target of 100,000 household biogas units by 2017. Larger commercial dairy farms, waste water treatment plants and industrial establishments were also envisioned to build thousands of biogas plants by the same year (GOU, 2007).

2.2 Anaerobic Digestion Process

The anaerobic digestion process involves the breakdown of suitable biodegradable/organic matter using anaerobic microorganisms in an oxygen free environment to generate biogas. The production of biogas through this process is possible from any form of biodegradable matter or substrate and takes place naturally in sediments at the bottom of water bodies, and in the stomach/intestines of ruminant animals such as cattle. Suitable organic matter for biogas production through the anaerobic process include food leftovers, agricultural crops/residues, animal/human waste and organic industrial waste (Teodorita A. S., et al., 2008).

The anaerobic digestion process consists of four main stages namely: hydrolysis, acidogenesis, acetogenesis and methanogenesis. At each stage within the process, the products of one stage become the raw materials for the next stage, and are acted on by relevant microorganisms until the final products are formed (Teodorita A. S., et al., 2008). Figure 2.1 is a simple representation of the anaerobic digestion process.

Hydrolysis

This is the initial step of the anaerobic digestion process. In this stage, extra-cellular enzymes (cellulose, amylase, and lipase) produced by facultative microorganisms (bacteria) breakdown long chain complex organic compounds including fats, proteins and carbohydrates into simpler molecules. For example, the hydrolysis of proteins produces amino acids and peptides while lipids are converted into fatty acids and glycerol (Teodorita A. S., et al., 2008).

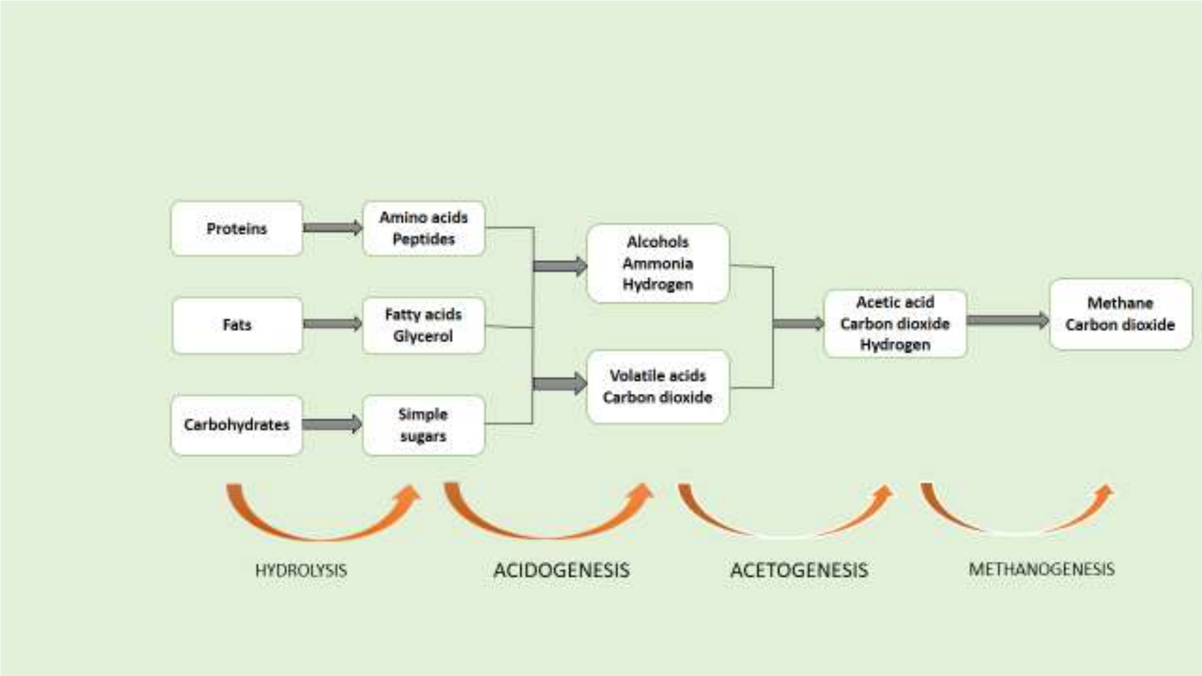

Figure 2.1: Anaerobic digestion process

Acidogenesis

This is known as the acid forming stage. The products from the hydrolysis stage are further broken down by fermentative bacteria to produce majorly organic acids. Examples of products obtained in this process include alcohols, acetic acid, carbon dioxide, ammonia, hydrogen, butyric acid and other volatile fatty acids (Teodorita A. S., et al., 2008).

Acetogenesis

In this stage, acetogenic bacteria decompose some of the products from the acidogenesis stage including alcohols, volatile fatty acids and aromatic compounds to produce acetic acid, carbon dioxide and hydrogen. The symptotic relationship of hydrogen producing acetogenic bacteria and hydrogen consuming methanogenic bacteria, both of which are active in this stage, ensures that the hydrogen concentration remains below inhibitory levels (Teodorita A. S., et al., 2008).

Methanogenesis

This is the final stage of the anaerobic digestion process and is the methane producing stage. Here, methanogenic microorganisms utilise acetic acid, carbon dioxide and hydrogen to produce methane and other by-products including water and more carbon dioxide. These methanogens are strictly anaerobic microorganisms and are very sensitive to changes in the operational conditions of the anaerobic digester (Teodorita A. S., et al., 2008).

2.3 Design, Operational and Process Factors for Anaerobic Digesters

The success of the anaerobic digestion process is influenced by a number of design, operational and process factors. These factors include temperature, pH, hydraulic retention time, carbon to nitrogen ratio and organic loading among others. The factors determine the survival and effectiveness of the micro-organisms in the system.

Temperature

Anaerobic digestion can occur at three different temperature ranges namely; psychrophilic, mesophilic and thermophilic temperature ranges. The corresponding temperatures for each range are shown in Table 2.2 below.

Table 2.2: Temperature ranges and retention time for anaerobic digestion processes

Thermal range	**Temperature**	**Retention time**
Psychrophilic	< 30 °C	70 – 80 days
Mesophilic	30 – 42 °C	30 – 40 days
Thermophilic	43 – 55 °C	15 – 20 days

Source: (Teodorita A. S., et al., 2008)

In general, biogas production from an anaerobic digester increases with increasing temperature. As such, the thermophilic temperature range is usually preferred to mesophilic or psychrophilic temperatures due to a number of reasons including the following;

- At higher temperatures, substrates are easily available and digestible, increasing the efficiency of the digestion process. As seen in Table 2.2, this also has a benefit of significantly lowering the retention time.

- Higher temperatures also facilitate faster growth rates for rate limiting methanogenic bacteria (see Figure 2.2) resulting into a faster methane production process.

However, a thermophilic process requires a higher input of energy and increases the risk of ammonia toxicity. Also, for thermophilic processes, small variations in environmental conditions can lead to significantly higher reduction in methane production (Vogeli Y., et al., 2014) (Teodorita A. S., et al., 2008).

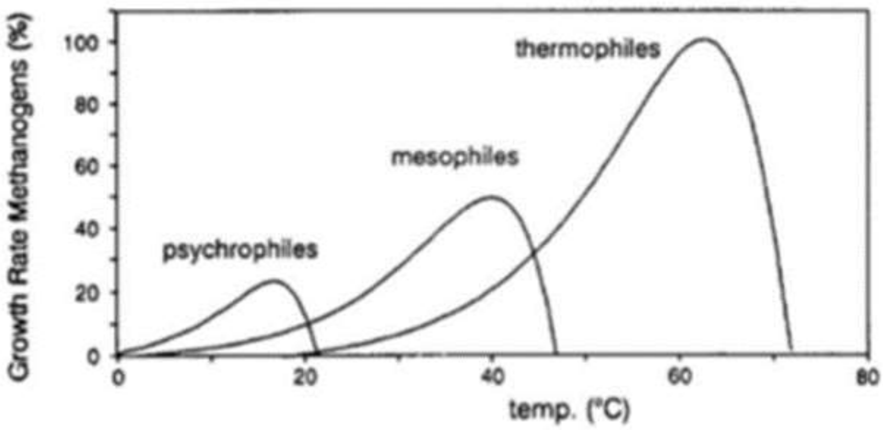

Figure 2.2: Effect of temperature on growth rate of methanogens
Source: (Teodorita A. S., et al., 2008)

pH

pH is the measure of the concentration of hydrogen ions in a given solution. pH can be used to indicate the level of acidity/alkalinity of a substrate solution fed into a bio-digester. pH is important to the anaerobic digestion process because different microorganisms grow and function well at different levels of acidity/alkalinity. For example, methanogenic bacteria have an optimum pH range of 6.5 – 8.2, while acidogenic bacteria perform well at lower pH values of 5.5 – 6.5 (Vogeli Y., et al., 2014).

Thermophilic digestion processes usually have a higher pH value compared to the mesophilic processes because, at high temperatures, the solubility of carbon dioxide in water is lower than at lower temperatures. Ammonia produced during the breakdown of some substrates can also lead to an increase in pH within the solution. To maintain the pH of an anaerobic digestion system within a specific range, a buffer system of bicarbonate is used. The bicarbonate acts by varying the partial pressures of carbon dioxide to counteract changes in pH (Teodorita A. S., et al., 2008).

Toxic compounds (Inhibitors)

Toxic compounds are compounds that can inhibit the growth and functioning of microorganisms and therefore hinder the anaerobic digestion process. These compounds, which include ammonia, hydrogen sulphide, and heavy metals may be introduced into the digester together with the substrate or produced during the breakdown of the substrate. Some of these compounds are useful during the digestion process but become toxic only beyond certain limits of concentrations or environmental conditions. For example, though ammonia is an important precursor useful in the anaerobic digestion process, its concentration should be kept below 80mg/l to avoid its inhibitory effect on methanogenic bacteria (Teodorita A. S., et al., 2008).

Hydraulic Retention Time

Hydraulic retention time is the minimum interval of time that the substrate remains in the digester before being removed. It is an important design parameter of a bio-digester and is a function of the digester size (volume) and the feedstock flow rate, that is, volume input per unit of time.

$$HRT = V_d/V_f \qquad \textit{(Equation 1)}$$

Where; V_d is the volume of the digester, and V_f is the feedstock flow rate.

Therefore, for a given fixed digester volume, V_d, when the feedstock flow rate, V_f, is increased, the hydraulic retention time decreases. A shorter HRT means that more organic load is treated in a shorter period of time. This is especially beneficial where there are large quantities of wastes to be treated and disposed. A short HRT is, however, not always beneficial since large populations of microorganisms can be washed out with the digester slurry before they can reproduce. This will affect the digester performance and lower the gas yield. HRT is generally lower for substrates that are readily available for digestion and for processes operated at higher temperatures (see Table 2.2) (Teodorita A. S., et al., 2008).

Organic Loading Rates

This refers to the quantity of dry organic matter that can be added to the reactor per unit volume and time. Different digestion systems, substrate types and process parameters such as temperature require different organic loading rates. The organic load of a particular digester and substrate can be determined using the following equation.

$$L_r = m*C/V_d, \quad \text{(Equation 2)}$$

Where; *m* is mass flow rate of substrate (kg/day), *C* is concentration of organic matter in the substrate (%), V_d is the volume of the digester (m^3) and L_r is the Organic Load.

Maintaining an optimum organic loading rate is important to ensure efficiency of the digestion process. Too high or too low organic loading brings about a nutrient imbalance which affects the performance of the microorganisms (Teodorita A. S., et al., 2008).

Carbon to Nitrogen ratio

The carbon to nitrogen ratio (C:N) depicts the concentrations of carbon and nitrogen within the digester substrate. This ratio is used to predict whether or not there are enough nutrients required by the micro-organisms. For a stable digestion process to be achieved, the C:N ratio should be between 16 and 25 (Deublein D. & Steinhauser A., 2011). If a C:N ratio is higher than the recommended optimal range, it indicates that the rate of nitrogen consumption by the methanogens is high. In the long run, the microorganisms may be rendered inactive due to insufficient nitrogen levels. Low C:N values are also undesirable because excess nitrogen in the substrate leads to the formation of ammonium ions and thus an increase in the pH. In order to achieve an optimal C:N ratio for the system, a mixture of different feedstock with high and low carbon content should be used (Vogeli Y., et al., 2014).

2.4 Major feedstock for the Anaerobic Digestion Process in Uganda

Various types of organic materials can be used as substrates for the anaerobic digestion process. Suitable substrates include animal manure, OFMSW, energy crops and agricultural residues, organic wastes from food/agro industries as well as sewage sludge. This sub-section gives a detailed explanation of some of the substrates that are relevant to the Ugandan context, including trends and characteristics.

2.4.1 Livestock manure

Livestock rearing activities such as dairy farming, pig rearing and poultry farming generate large quantities of organic wastes particularly manure. Livestock manure is a valuable resource that can be used as a fertilizer in crop and pasture growing as well as to generate bio-energy through the anaerobic digestion process. The potential benefits from livestock manure depend on the quantity and composition of the manure generated. Estimated compositions of different livestock manures are shown in Table 2.3 below.

Table 2.3: Estimated livestock manure compositions

	Nitrogen	Phosphorous	Potassium	Calcium	Magnesium	Organic matter	Moisture content
	(N)	(P_2O_5)	(K_2O)	(Ca)	(Mg)		
Fresh manure	%	%	%	%	%	%	%
Cattle	0.5	0.3	0.5	0.3	0.1	16.7	81.3
Pigs	0.6	0.5	0.4	0.2	0.03	15.5	77.6
Sheep/goats	0.9	0.5	0.8	0.2	0.3	30.7	64.8
Poultry	0.9	0.5	0.8	0.4	0.2	30.7	64.8

Source: American Society of Agricultural Engineers

Animal manure is a suitable feedstock for anaerobic digestion because of its organic nature. It also has a high moisture content which enhances effective mixing and flow of the substrate, making it easy to digest in a wet digestion process. Manures also naturally contain anaerobic bacteria necessary for the anaerobic digestion process. As such, they can be used either singly or in combination with other substrates. Livestock manure is indeed a common feedstock used in anaerobic digesters on large scale livestock farms in developed countries and in many rural households in developing countries (Teodorita A. S., et al., 2008).

Livestock rearing in Uganda

Like crop growing, livestock rearing is one of the common activities carried out in many households in Uganda. It is estimated that over 70% of the total households in Uganda rear at least one kind of livestock or poultry (UBOS, 2010). The common livestock reared in Uganda include cattle, goats, sheep, pigs, poultry, ducks, turkey and other domestic animals. About 26% of all households in Uganda rear cattle, close to 40% raise goats, 9% own sheep, 17.8% raise pigs while slightly over 50% rear poultry. Livestock and poultry rearing in Uganda is majorly carried out on a subsistence scale by smallholder farmers who rear small herd sizes on small landholdings using traditional methods. This is also evidenced by the overreliance on family labour for most of the livestock rearing activities. Only a few farmers practice intensive rearing of livestock and poultry for commercial purposes (UBOS, 2010). Recent estimates of the population of major livestock and poultry for the years 2010 – 2014 are shown in Table 2.4.

Table 2.4: Population of major livestock and poultry (in 000's) in Uganda

Livestock type	2010	2011	2012	2013	2014
Cattle	12,104	12,467	12,840	13,020	13,623
Goats	13,208	13,604	14,012	14,614	14,011
Sheep	3,621	3,730	3,842	3,937	3,842
Pigs	3,378	3,480	3,584	3,692	3,584
Poultry/Chicken	43,200	40,904	42,131	38,064	44,698

Source: (UBOS, 2015)

The factors that determine quantity and composition of manure produced include:

- Species, size, age and number of livestock,
- Feeding practices including type of feeds and feeding patterns,

- Environmental conditions, and
- Animal productivity.

For Uganda, the manure production rates and available quantities have been estimated and are shown in Table 2.5 below. For purposes of biogas production at a household level, sufficient manure is required to guarantee technical feasibility. Estimates of the minimum number of livestock or poultry required per household, the number of households owning the minimum number of livestock, and the total number of livestock owned by these households are also in Table 2.5.

Table 2.5: Determinations for major livestock and poultry in Uganda

Livestock type	Estimated average manure production rate per livestock (kg/day)*	Estimated manure availability*	Required minimum number of livestock per household	Number of households owning the required minimum number of livestock	Total number of livestock owned by these households
Zero-grazing exotic/crossbreed cattle	15	90%	2	118,018	849,072
Open-grazing indigenous cattle	10	40%	5	450,959	10,277,830
Pigs	2.2	90%	10	16,232	1,228,037
Sheep	1.5	30%	45	9,490	861,625
Goats	1.5	30%	45	11,236	2,817,042
Poultry	0.1	90%	200	326,451	11,497,854

Source: (Pandey B., et al., 2007) (UBOS, 2004) (UBOS, 2010) (UBOS, 2015) (GUO G. L., 2010) (Ulrike D. et al., 2014) (Slobodan C., 2014)

Some of the information was determined or estimated by the researcher during the numerous field visits carried out in the case study area.

Zero grazing cattle are usually well fed and produce more manure estimated at 15 kg daily. Their manure is also easily recovered. As such, only two animals are required for biogas production. Open-grazing cattle generate about 10 kg of manure daily due to poor feeding practices used. Most of their manure is also lost during grazing and therefore an estimated five cattle are required for biogas production (Ghimire P. C., 2008). Pigs produce more manure than goats and sheep due to differences in body size and feeding practices in the study area. Additionally, most of the manure for sheep and goats is also lost during the grazing period. Therefore, the required number of pigs is less than for sheep and goats. Chicken produce very little manure due to their small body size. A large flock is therefore required for biogas production to be technically feasible.

Traditional methods of manure management such as field spreading are still a common practice in Uganda. On large scale dairy farms, the manure slurry is collected and pumped to fertilize forage crop fields. Small scale farmers in rural areas collect dried manure and apply it in their gardens. Some rural households use wet manure to polish their houses while some others use dried manure to cook food. Few households use manure for biogas production[2].

2.4.2 Municipal solid waste

Characteristics and generation trends

Municipal solid waste (MSW) is a combination of solid waste generated from residential areas, commercial areas (offices, shops, and markets), institutions (schools, hospitals), industries, streets and other public areas within a given locality (Kaseva, M. E. & Mbuligwe, S. E., 2005) (Hoornweg, D. & Bhada-Tata, P., 2012). Some of the constituent wastes of municipal solid waste are food waste, garden and other plant waste, paper, wood and cardboard waste, glass and metal waste, textiles,

[2] This is based on observations made during site visits in the case study area

stone and debris. Others include rubber and leather, ash, dust and electronic waste (Guerrero, Maas, & Hogland, 2013).

The specific compositions of the constituent wastes also vary from one place to another depending on economic, social and environmental factors. As shown in Table 2.6, high income countries usually have more inorganic content (glass, paper, plastics) in their wastes while organic waste (food and yard waste) usually accounts for over 50% of the waste generated in low and middle income countries (Hoornweg, D. & Bhada-Tata, P., 2012).

Table 2.6: Composition of municipal solid waste generated for different income levels

Income level (%)	Organic (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Other (%)
Low Income	64	5	8	3	3	17
Low middle income	59	9	12	3	2	15
Upper Middle Income	54	14	11	5	3	13
High Income	28	31	11	7	6	17

Source: (Hoornweg, D. & Bhada-Tata, P., 2012)

Over the years, the quantity of municipal solid waste generated globally per year has increased rapidly due to the increasing population. In 1900, an estimated 110 million tonnes of municipal solid waste was generated worldwide. This increased to 1.3 billion tonnes generated in 2012 and is projected to increase to 2.2 billion tonnes by 2025 (Hoornweg D. et al., 2013) . Solid waste generation trends vary for different regions around the world being largely influenced by the level of economic development, the culture and lifestyle of the population among others (Hoornweg, D.

& Bhada-Tata, P., 2012). In developing regions, where the population has less disposable income, the per capita waste generation rates tend to be lower than for developed regions as shown in Table 2.7.

Table 2.7: Quantities of municipal solid waste generated in different regions

Region	Current available data		
	Total Urban population (millions)	Urban waste generation	
		Per Capita (kg/capita/day)	Total (tons/day)
AFR	260	0.65	169,119
EAP	777	0.95	738,958
ECA	227	1.1	254,389
LCR	399	1.1	437,545
MENA	162	1.1	173,545
OECD	729	2.2	1,566,286
SAR	426	0.45	192,410

Source: (Hoornweg, D. & Bhada-Tata, P., 2012)

Municipal solid waste management

Municipal solid waste management is one of the major challenges faced by most cities especially in developing countries. Most urban centres in developing countries lack effective waste collection and disposal mechanisms. In developed countries, well mechanized and efficient systems facilitate the collection and proper disposal of over 90% of the waste generated while in developing countries less than 50% of the waste generated is collected (Hoornweg, D. & Bhada-Tata, P., 2012). As such, most people in developing regions do not access adequate waste management services and therefore use rudimental methods to dispose their wastes.

Most of the uncollected waste is usually burnt or dumped on street corners, back yards and in open water channels, and this has become a big public health and environmental concern. However, some waste is reused or recycled by some individuals in order to recover its economic value (Okot-Okumu & Nyenje, 2011).

Worldwide, several waste disposal techniques have been used to properly dispose municipal solid waste with minimal negative effects on the people and the environment. These include landfilling, composting, recycling, and waste-to-energy conversion. Accounting for almost 340 million tonnes/year, landfilling is the most popular waste disposal technique used worldwide. In Africa and other developing regions, the collected MSW is almost exclusively disposed in landfills and dump sites (Hoornweg, D. & Bhada-Tata, P., 2012) (Scarlat, N. et al., 2015). However, the landfills are often uncontrolled or poorly planned and managed and are therefore a big risk to the local population and environment. The landfills generally lack procedures for waste segregation, leachate control and methane collection (USAID, 2007).

Composting has also been used to convert the organic fraction of municipal solid waste into fertilizer in some countries. Currently, about 50,000 tonnes of the MSW generated in Africa annually is composted (Hoornweg, D. & Bhada-Tata, P., 2012). In Uganda, composting of MSW was pioneered by NEMA in 2005, under the Clean Development Mechanism funded by the World Bank, and by 2012, it was being used in at least 11 urban centres around the country (NEMA, 2007; Kumar, 2006).

The conversion of municipal solid waste into energy using various waste-to-energy conversion techniques offers a unique opportunity to turn MSW into a valuable energy resource. The energy potential of municipal solid waste has been widely studied in literature and estimates put the global potential at 8-18EJ/year in 2010. In Africa, the energy potential of municipal solid waste from urban centres was estimated to reach 1125 PJ in 2012 (Scarlat, N. et al., 2015).

Various waste-to-energy conversion technologies are being used in many countries especially in the developed regions. The common waste-to energy technologies include thermo-chemical processes (incineration, direct combustion, pyrolysis or gasification) and biochemical conversion (anaerobic digestion). Waste incineration is being used in countries such as Germany, USA, Switzerland, and Japan (Scarlat, N. et al., 2015) while China and India are leaders in using anaerobic digestion systems (Teodorita A. S., et al., 2008). Anaerobic digestion is also being studied and promoted in a number of developing countries including Uganda.

Municipal solid waste in Uganda

Like in many other developing countries, municipal solid waste generation in Uganda's urban centres has increased due to increased urban population. As shown in Table 2.8, Uganda's urban population has grown rapidly over the last two decades, increasing from 1,669,653 people in 1991 to 7,425,864 people in 2014. The number of urban centres also increased from 67 to 259 urban centres over the same period. As a result of increased urban population, Uganda's capital city, Kampala generates an estimated 1,500 tons of solid waste daily (KCCA, 2012).

Table 2.8: Urban population of Uganda (1991 - 2014)

Type of urban centre	1991		2002[3]		2014	
	Number	Population	Number	Population	Number	Population
City	1	774,241	1	1,189,142	1	1,507,080
Municipality	13	480,922	13	745,036	33	3,249,609
Town Council	33	338,901	61	1,065,209	163	2,361,033
Town Board/Township	20	75,589	20	Na	62	308,142
TOTAL	67	1,669,653	95	2,921,981	259	7,425,864

Source: (UBOS, 2016)

Most of the waste generated in urban areas in Uganda comes from residential areas, markets and other commercial areas (see Table 2.9). The average MSW

[3] The Urban population of 2002 excludes the population enumerated in Town Boards

generation rate is estimated to be 0.55kg/capita/day. High income households generate more waste (0.66kg/capita/day) compared to their lower income counterparts who produce 0.33kg/capita/day (Okot-Okumu & Nyenje, 2011). These values and trends are similar to those determined for countries like Cameroon, Tanzania and Sri Lanka (Achankeng, 2003) (Kaseva, M. E. & Mbuligwe, S. E., 2005) (Vidanaarachchi, C.K. et al., 2006).

Table 2.9: Municipal solid waste generation in Uganda by source

MSW stream	**Composition (%weight)**
Residential areas	52 - 80
Markets	4 – 20
Commercial areas (excluding markets)	3.7 – 8
Institutional areas (such as government ministries, educational establishments, sports facilities, clubs)	5
Industrial/manufacturing	3
Health care (Hospitals, clinics, drug shops)	1
Others	11 – 11.4

Source: (OKot-Okumu J., nd)

The composition of municipal solid waste streams in selected urban centres in Uganda is also shown in the table below.

Table 2.10: Municipal solid waste composition for selected urban centres in Uganda

Composition	Fort Portal	Jinja	Kabale	Kasese	Lira	Mbale	Mbarara	Mukono	Soroti	Kampala
Food (%)	36.6	31.9	40.5	49.8	36.4	31.9	55.6	28.8	28.3	58.2
Garden (%)	36.1	36.7	29.6	24.2	32.3	36.0	24.5	46.2	37.7	22.1
Paper (%)	6.8	8.0	5.2	5.4	5.5	7.5	2.6	5.7	7.2	6.1
Plastic (%)	8.4	7.9	8.1	5.1	6.8	10.8	4.7	7.9	8.8	7.2
Glass (%)	0.7	0.7	0.5	0.4	1.9	0.9	0.6	0.4	0.7	0.7
Metals (%)	0.0	0.5	0.5	0.1	2.2	1.0	0.2	0.3	0.4	0.3
Textiles (%)	1.0	1.8	1.8	0.5	1.2	1.0	0.3	0.4	2.5	1.8
Soil & Debris (%)	10.2	12.5	13.7	14.7	13.7	10.8	11.5	10.2	14.4	3.6
Others (%)	9.8	9.0	10.1	13.4	12.2	7.7	9.9	8.4	11.1	2.6

Source: NEMA

2.5 Anaerobic Digestion Technologies in Uganda

Bio-digester technologies are systems used for the anaerobic transformation of organic matter to produce biogas. There are three main digester categories widely used in developing countries. These are fixed dome digesters, floating drum digesters and tubular digesters. They are all wet digester systems which are continuously fed and operate largely under mesophylic temperatures (Vogeli Y., et al., 2014). In Uganda, these digester types are promoted by various organisations supporting the biogas sector. They are said to be suitable for the local climatic conditions. Below is a detailed description of the different digester systems.

2.5.1 Fixed dome digesters

A fixed dome anaerobic digestion system is basically composed of a digestion tank with a dome-shaped rigid gas holder, substrate mixing tank and inlet, and a displacement tank as shown in Figure 2.3. Other supplementary components such as temperature control system and mixer can be added to the digester depending on the design needs and operating environment. The simple design used in most developing countries has no moving or corroding parts and is usually expected to last long with minimum maintenance.

Wet organic matter (usually 8% solid content) is fed into the digester through the inlet. In the digester, it is then acted upon by anaerobic bacteria to produce biogas. When gas is produced, it bubbles upwards through the slurry and is collected in the top part of the digester. As more and more gas is produced, the gas pressure in the top of the digester increases and pushes some of the slurry into the displacement tank. The gas pressure reduces in the tank when the outlet gas valve is opened and the gas utilised, allowing some of the slurry to flow back into the digester (Vogeli Y., et al., 2014).

Most fixed dome digesters are constructed below the ground in order to avoid significant temperature variations at night or during cold seasons. The soil on top of the digester also helps to counteract the internal digester pressure. Fixed dome digesters are normally constructed using locally available construction materials. To ensure that the digester remains gas tight, special sealants including bee wax-engine oil mixture or acrylic emulsion can be used to plaster the inside of the gas holder (Vogeli Y., et al., 2014).

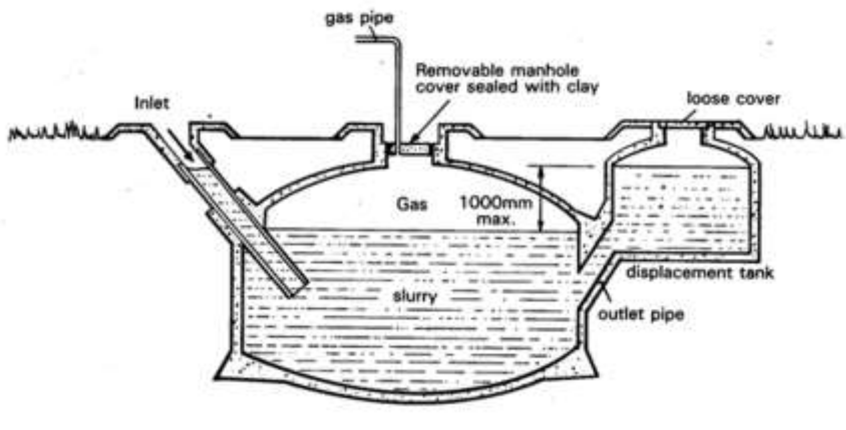

Figure 2.3: Fixed dome digester

There are a number of different designs of fixed dome digestion units around the world. The most common design is the Chinese fixed dome type, which is the archetype of all fixed dome digesters (see Figure 2.3). In many sub Saharan Africa countries including Tanzania, Lesotho, Ethiopia, and Kenya, several modifications also exist including the CAMARTEC design, TED design, LUPO design, SINIDU design and SimGas GeshiShamba design. Digester modifications are usually intended to make the digester function effectively under local conditions. The design modifications could target minimising water usage, improving structural strength, and increased gas storage capacity and fertiliser use among others (G. V. Rupf et al., 2016).

In Uganda, the CAMARTEC design (shown in Figure 2.4) is the most popular modification of the fixed dome digester. This design was developed in the 1980s at the Centre for Agricultural Mechanization and Rural Technology in Tanzania. In this design, the structural strength of the digester is optimised by using a simplified structure of a hemispherical dome based on a rigid foundation ring and a calculated joint of fraction. In Uganda, it is constructed using fired bricks or interlocking stabilised soil blocks (ISSB) which are a combination of both local soil and 5 percent cement. The use of ISSB instead of normal fired bricks is said to achieve a 30 percent cost reduction whilst also saving time and avoiding the use of fire wood to burn the bricks (G. V. Rupf et al., 2016).

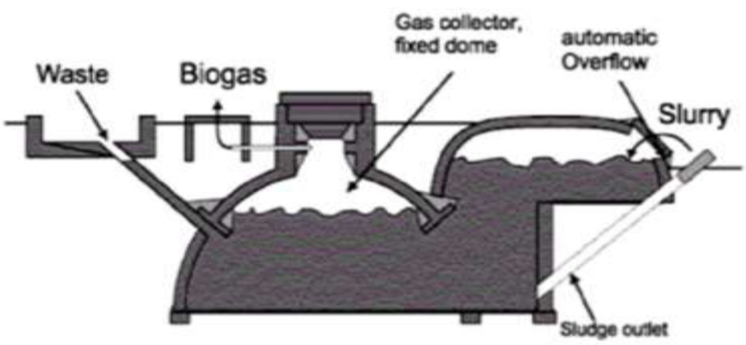

Figure 2.4: Modified CAMARTEC digester design

2.5.2 Floating drum digesters

The floating drum digester, also known as the cup digester is usually constructed more or less like the fixed dome digester but with a moving, floating gas holder instead of a rigid one. The digester tank is normally constructed underground while the gas holder remains above the ground. The common materials used for the digester tank are bricks and concrete. Simpler designs can be made from plastic or metallic drums (see Figure 2.5). Floating drum covers are usually made of steel metal, covered with a suitable paint coating to protect it from corrosion. Glass-fibre reinforced plastic and high density polyethylene have also been successfully used to make floating drums albeit at higher costs than steel drums (G. V. Rupf et al., 2016).

The floating cover, where the gas is stored, is suspended either directly on the substrate slurry or in an external water jacket surrounding the tank. The use of an external water jacket helps to minimise methane leakages and avoids the risk of the drum getting stuck in the slurry. When biogas is produced from the feedstock, it is collected in the floating drum. Depending on the amount of gas produced, gas pressure within the drum increases and forces the drum to rise up to a level corresponding to the internal gas pressure exerted. When gas is utilised, the drum level begins to fall until the gas is used up. To ensure that the drum keeps in an upright position during the up and down movements, a guiding frame is usually incorporated to provide stability and balance (Vogeli Y., et al., 2014).

Several models of the floating drum digester exist, based on simple variations in the construction materials used. The first floating drum digester, the KVIC model, was developed in the 1950s in India. It has a fixed cylindrical digester tank constructed from bricks and concrete and a metallic gas holder. Some of the simpler models that are being used in some SSA countries include the Botswana model and the ARTI model. The ARTI model, also developed in India, has been promoted as an appropriate low cost, small scale option for households in Uganda and Tanzania. It is made of two high-density polyethylene tanks of different sizes, with the bigger one acting as the digestion tank and the smaller one being the floating drum. The Botswana model is similar to ARTI but is made from steel tanks (G. V. Rupf et al., 2016).

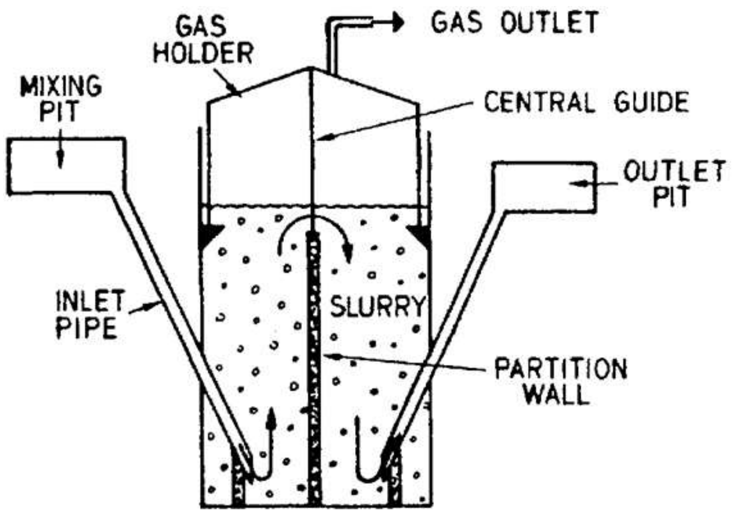

Figure 2.5: Floating drum digester

2.5.3 Flexible balloon/Tubular digesters

The tubular digester (shown in Figure 2.6) is a plug flow type digester that is made of a flexible plastic or rubber material that serves both as a digester and gas holder. Some of the materials used for construction include industrial grade tarpaulin, polyethylene, UV resistant bags and polyvinyl chloride material. These are usually readily available locally and easy to handle and transport to isolated had-to-reach areas. Tubular digesters are usually installed longitudinally in an open shallow trench allowing space for expansion of the balloon as gas is produced. Tubular digesters are usually batch digesters and generally have no internal mixing mechanisms (Vogeli Y., et al., 2014). In Kenya, flexible balloon digesters have been found to be a suitable, sustainable and low cost option for small scale household biogas production (Nzila C. et al., 2012).

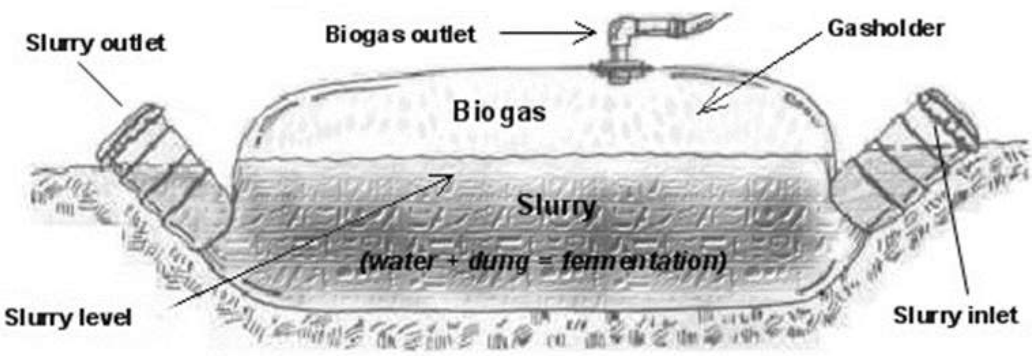

Figure 2.6: Tubular digester

2.6 The Analytical Hierarchy Process

The analytical hierarchy process (AHP) employs a mathematical approach to structure and analyse relevant information which helps in obtaining the best option from many alternatives. The mathematical computations done in the AHP involve, first and foremost, pairwise comparisons. These comparisons are crucial for obtaining pertinent data suitable for use in the AHP tool. By carrying out pairwise comparisons of the evaluation criteria, the weights of importance of the criteria can be obtained with the higher weight showing the more important criterion. Then, for each criterion, the relative performance of each alternative/option is also obtained. The input data into the AHP analysis is relatively simple and can be determined from both quantitative measurements and qualitative determinations based individual preferences, opinions or feelings of the decision maker (Saaty T. L., 1980).

AHP can be useful in common day-to-day scenarios such as choosing which type of car to buy based on criteria such as initial price, fuel consumption, service and comfort, or even colour. In more technical and advanced engineering applications, AHP has been used to assess the flexibility of manufacturing systems and in integrated manufacturing. The AHP tool has also been applied in a number of studies in energy related topics. AHP was used to determine the suitability of different energy crops for processing into biogas (Vindiš P. et al., 2010), and to select the priority of financing different renewable energy projects (Simeoni P. & Alessandro M. , 2009).

Table 2.11: Scale of relative importance

Intensity of importance	Definition
1	Equally important
3	Slightly more important
5	More important
7	Strongly more important

9	Absolutely more important
2,4,6,8	Intermediate values between the two adjacent judgements
Reciprocal of above non-zero values	If activity i has one of the above non-zero values assigned to it with respect to activity j, then j has the reciprocal value when compared to i

Source: (Saaty T. L., 1980)

The AHP tool is implemented in three simple steps as explained below.

Step 1: Determining the criteria weight vector

Pairwise comparisons of m number of evaluation criteria are carried out based on the scale of relative importance (see Table 2.11). The comparisons yield matrix, A (shown in Table 2.12) which is an $m \times m$ real matrix. For the matrix A, consider that every entry is denoted by a factor a_{jk} representing the importance of the j^{th} criterion relative to the k^{th} criterion. An entry of $a_{jk} > 1$ implies that the j^{th} criterion is more important than the k^{th} criterion and vice versa. Also, it follows that $a_{jk} = 1/a_{kj}$. Also for any two criteria where $a_{jk} = 1$, the two criteria are of equal importance; while a_{jj} is always equal to 1 (Saaty T. L., 1980).

Table 2.12: Pairwise comparison matrix, A

	Criterion 1	Criterion 2	Criterion 3	…	Criterion m	Weight, w
Criterion 1	1	$a_{12} = 1/a_{21}$				w_1
Criterion 2	a_{21}	1				w_2
Criterion 3			1		$a_{3m} = 1/a_{m3}$	w_3
…				...		...
Criterion m			a_{m3}		1	w_m

To determine the criteria weight, w, matrix A is first standardised by dividing each entry in a given column with the sum of the entries in that column. The criteria weights are then obtained by averaging the entries of each row of the standardised vector, A', to give a column of weights corresponding to each decision criterion.

Step 2: Determining the matrix of alternative priority scores

For any given number of alternatives, *n* and criteria, *m*, the alternative option scores matrix, S (shown in Table 2.13) is an *n x m* real matrix where every entry s_{ij} is the score of the i^{th} alternative relative to the j^{th} criterion. To arrive at the score s_{ij}, all the *n* alternative options undergo pairwise comparisons, based on the scale of relative importance shown in Table 2.11, for each of the *m* criteria. This gives a matrix B_j, which is an *n x n* real matrix for the j^{th} evaluation criterion. Each entry, b_{ih}^{j}, into this matrix denotes the evaluation of the i^{th} alternative compared to the h^{th} alternative with respect to j^{th} criterion. If $b_{ih}^{j} > 1$, then the i^{th} alternative is better than the h^{th} alternative with respect to the j^{th} criterion and vice versa. The same considerations as in the matrix, A are applicable here, that is, $b_{ih}^{j}=1/b_{hi}^{j}$, $b_{ii}^{j} = 1$, and $b_{ih}^{j} = 1$ for two alternatives considered to be of equivalent weight with respect to j^{th} criterion (Saaty T. L., 1980).

Table 2.13: Alternative priority scores matrix, S

	Criterion 1	Criterion 2	Criterion 3	…	Criterion m
Option 1	s_{11}	s_{12}	s_{13}	…	s_{1m}
Option 2	s_{21}	s_{22}	s_{23}	…	s_{2m}
Option 3	s_{31}	s_{32}	s_{33}	…	s_{3m}
…	…	…	…	…	…
Option n	s_{n1}	s_{n2}	s_{n3}	…	s_{nm}

A similar procedure as explained for matrix, A, above is followed to normalise matrix B_j and calculate the alternative option scores, s_{ij}, which indicates the score of each alternative option, *i* with respect to the j^{th} criterion.

Step 3: Determining the rank of the alternatives

With criteria weight vector, *w* and alternative score matrix, S, the combined scores of each alternative are obtained as follows:

Scores vector, v = S x w *(Equation 3)*

The scores are then ranked in descending order with the highest score indicating the best alternative option.

Checking for consistency

The existence of a large number of evaluation criteria and alternative options poses a challenge of maintaining consistency while carrying out a large number of pairwise comparisons. To determine whether the judgements for the comparisons are consistent, the AHP involves the determination of the consistency index, CI, given by:

CI = (λ – m) / (m - 1), where λ is the Eigen value, which is a scalar quantity that is determined from the built matrices, and *m* is the number of decision criteria

For a given evaluation to be perfectly consistent, CI should be equal to zero. However, small inconsistencies in the evaluation are tolerated. As put forward by (Saaty T. L., 1980), if CI/RI < 0.1, the inconsistencies are tolerable and the results from the AHP are expected to be reliable. RI is the Random Index, which is the consistency index when the entries of a given matrix are completely random. The RI values have been determined in literature and are indicated *in Table 2.14 below* for m ≤ 10.

Table 2.14: Random Index values

M	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Source: (Saaty T. L., 1980)

CHAPTER THREE: METHODOLOGY

3.1 Introduction

This section details the relevant methods used and procedures followed during the research. The section includes a brief description of the case study area, data collection and analysis tools, and methods and procedures for determining biogas technical potential, suitable biogas production technology and economic viability of biogas production.

3.2 Case Study

3.2.1 Selecting the case study area

The case study area selected for this research was Wakiso district, located in the central region of Uganda. Wakiso district was selected because it was recommended by the researcher's contact person at Biogas Solutions Uganda (BSU), an organisation involved in the promotion of biogas technologies in Uganda. Also, most of the masons recommended by BSU, who would act as guides during the data collection exercise were either working or residing in the Wakiso district. The case study area was also located about 20 km from the researcher's place of residence.

Wakiso district was also a suitable choice for case study because it has an almost equal number of rural and urban population. This facilitated a balanced assessment by incorporating the needs of both rural and urban dwellers. Wakiso district also offered an advantage that many people were already aware about or involved in biogas related activities due to the promotional work done by BSU and other organisations. The district also neighbours the capital city, Kampala, from where additional information would be sought from biogas experts.

3.2.2 Description of case study area

Wakiso district covers a total area of 1907 km^2 and is bordered by Nakaseke district and Luweero district to the north, Kalangala district to the south, Mukono district to the east, Mpigi district to the southwest and Mityana district to the northwest. The district also partly encircles the capital city, Kampala. Wakiso district has a population estimated at 1,997,418 people and is currently the most populated district in Uganda. The rural population is estimated at 814,517 people while the urban population stands at 1,182,901 people. Wakiso district is currently the most urbanised district in Uganda and is home to the top three largest urban centres outside the capital city (UBOS, 2016). The main economic activity carried out in the district is agriculture. However, due to rapid urbanisation, there has been an increasing shift to trade and industry.

3.2.3 Sites visited

During the stay in the case study area, the researcher visited several sites to collect primary information. The site visits were intended to determine the livestock rearing practices used by farmers in the district and assess the manure production rates and availability. Five sites were visited for each category of livestock or poultry under consideration. A brief description of some of the sites visited is given below.

John's farm

John's farm is a cattle farm that covers an area of 30 acres and has about 20 heads of cattle. The farm is owned by John and his wife for subsistence purposes to get milk for home consumption. Occasionally, some cows are sold to raise money to meet other needs such as education or medical bills. The farm is managed by John with the help of one domestic worker. The farm is located in Namusera parish, Wakiso district. John grazes his cattle on natural pasture during the day and pens them twice a day in an open-air enclosure for milking and at night for security purposes. The manure left behind in the enclosure is collected and hipped daily and is used as fertilizer in the gardens. The grazing and penning practices at John's farm are common with similar farmers who were visited during the site visits.

Figure 3.1: John's cattle farm

David’s cattle shelter

David is one of the most known farmers in his sub-county. David owns a small cattle shelter located in Lukwanga parish, Wakiso district. The shelter has 3 exotic and 2 crossbreed cattle all of which are females, reared under the zero-grazing system. The cattle are penned for 24 hours a day and are fed three times daily on cultivated pastures or hay. Water is also provided to the cattle as required. The cattle are reared for commercial purposes to produce milk which is sold at a local milk collection centre. The manure produced is cleaned daily into a well-built pit from where it is removed for use in the fields. Some of the manure is also sold to neighbouring residents.

Other farmers in the district, who practice the zero grazing system for their cattle and were visited by this researcher, revealed similar practices as those at David’s shelter regarding feeding of cattle and manure management.

Figure 3.2: David's cattle shelter

Simon’s piggery

Piggeries are a common sight in many households in Wakiso district. An estimated 50% of all the households in Wakiso district rear pigs (UBOS, 2010). Pig rearing is almost exclusively for commercial purposes. Simon owns a piggery located in Buloba parish, Wakiso district. The piggery has 7 pigs that are reared under a semi-intensive system. The pigs are penned at all times and are mainly fed on left-over food and natural vegetation, but occasionally recommended pig feeds are purchased for them. Manure from the pig sty is dumped in the backyard agriculture plantations. The above practice are common with almost all households owning at least 5 pigs. However, of the piggeries visited, those which had more than 30 pigs fed their pigs mostly on commercial pig feeds purchased from feed manufacturers.

Figure 3.3: Simon's piggery

Andrew’s sheep and goats farm

Sheep and goats are among the least reared animals in the district. Only 20% of the households in the district own sheep or goats (UBOS, 2010). Andrew owns a flock of sheep and goats which he rears at his ancestral land located in Mende parish, Wakiso district. The flock is composed of 22 goats and 13 sheep which he exclusively grazes on natural pasture. The flock spends about 10 hours every day grazing in the fields and is penned in a built shelter for the night. Manure from the shelter is collected daily and dumped into the backyard gardens. The grazing practices and manure handling techniques were similar for most of the sheep and goat owning households visited.

Figure 3.4: Andrew's sheep and goats farm

Bagalaliwo poultry farm

Poultry keeping, particularly the rearing of chicken, is carried out by most of the households in Wakiso district. Most households own small numbers for domestic purposes but an increasing number of households are taking to commercial chicken farming. One of the commercial chicken farms that was visited is Bagalaliwo chicken farm. Bagalaliwo chicken farm is a family owned farm located in Kaliiti parish, Wakiso district. Close to 500 chicken are reared at the farm under battery cage system both for egg production and for meat. The chicken are fed on commercial chicken feeds purchased from nearby feed producers. Manure produced is collected on a daily basis and sold as fertilizer to local farmers.

Visits to other households owning chicken in the district revealed that indigenous chicken breeds are usually reared in small flocks using the traditional free range system and are penned only in the night time. Exotic or improved breeds are usually reared in large numbers and are almost exclusively confined due to their susceptibility to contract diseases.

Figure 3.5: Bagalaliwo poultry farm

3.3 Data Collection

For this research, both primary and secondary data was collected from various sources. These sources include;

- Livestock owners,
- Potential biogas users,
- Biogas experts and masons,
- Literature.

The primary data collected included common livestock rearing practices including housing and feeding practices. Information was also collected about the common characteristics of biogas technologies used in Uganda, as well as the considerations of potential biogas users when selecting biogas technologies. The data collection methods used are explained below.

Interviewing: The interviewing method was the main method used by the researcher to obtain primary information from livestock owners, potential biogas users, and biogas experts and masons. It involved well-structured questions designed to capture information relevant to the study objective.

Observation: The observation method is one of the methods that was used by the researcher especially during the site visits. The method was used both to collect additional information and to verify some of the information obtained during interviews. During observation, some photographic evidence was captured and a few of those photographs are included as part of this report.

Focus group discussion: This is a qualitative method of data collection that was used to obtain opinions and preferences of potential biogas users when selecting a suitable biogas technology.

Literature review: Literature review was also used to obtain secondary information that could not be obtained by using the above methods of data collection. This involved carrying out an extensive search of various sources of literature including reports, academic journals and other scientific publications in order to obtain information relevant to the study objective.

3.4 Biogas Technical Potential for Major Feedstock in Uganda.

3.4.1 Introduction

The technical potential is that part of the total theoretical potential that is technically feasible. In this sub-section, the methodology used to assess the biogas technical potential for major feedstock in Uganda is explained. The methodology included in this section is for determining the technical potential from livestock manure and municipal solid waste.

3.4.2 Biogas technical potential for livestock manure

The biogas technical potential for livestock manure was used to represent the potential for biogas generation at a household level. This is because most households in Uganda own livestock or poultry from which manure for biogas production can be obtained. In order to accurately estimate the domestic biogas technical potential for livestock manure in Uganda, some assumptions and considerations were made. The assumptions were based on the information provided by biogas experts and are within the scope of the study.

Assumptions:

- The smallest domestic biogas system that can be installed in Uganda is a 6 m^3 volume digester.
- The daily feeding requirement for a 6 m^3 digester is 45 kg of substrate of which 20 kg is fresh manure (Ghimire, 2013) and the remaining 25 kg is the added water.
- Only individual households which have the minimum number of livestock that can provide enough manure for at least the 6 m^3 bio-digester are considered in this evaluation. As such, the possibility of two or more households, with fewer livestock, putting their resources together was not evaluated.

The biogas technical potential from livestock manure in Uganda was estimated based on the information given in Table 2.5. Complimentary information on manure dry matter content, volatile solids content and biogas yield was obtained through literature review and is given in Table 3.1 below.

Table 3.1: Manure characteristics for major livestock and poultry

	Manure (slurry) dry matter content, DM (%)	Volatile solids, VS (% of dry matter)	Biogas yield (m^3/kgVS)
All cattle	8.5	80	0.25
Sheep and goats	10	78	0.31
Pigs	5.5	75	0.38
Poultry	20	75	0.48

Source: (Ileleji, Klein E. et al.)

The technical potential for biogas production from livestock manure was therefore calculated according to the following equation.

$$B_P = xN_LP_RD_MV_SY_B \quad \text{(Equation 4)}$$

Where, B_P is the biogas potential; x is the fraction of manure that is available for anaerobic digestion; N_L is number of livestock; P_R is daily manure production rate (kg/head/day); D_M is the manure dry matter content (%); V_S is volatile solids content (%); Y_B is biogas yield (m^3/kgVS).

3.4.3 Biogas technical potential for municipal solid waste

The biogas technical potential from municipal solid waste was estimated in order to show the potential for biogas production at a communal level in Uganda. Accurate estimation of this potential required an extensive review of various literature sources because official statistics on solid waste generation, collection and disposal for Uganda could not be found in any major databases. The following assumptions and considerations, which are derived from the literature search, were necessary to achieve the objective of the study.

- Only municipal solid waste generated in urban centres was included in the analysis. This is because information on waste generation trends in rural areas is largely unavailable (Scarlat, N. et al., 2015). Moreover, the scattered nature of households in rural areas would make the collection of solid waste difficult.
- The biogas production potential is evaluated with an assumption that the waste will be used in a communal bio-digester. This is because individual households may not generate sufficient waste daily to necessitate an individual digester. Moreover, space and land use restrictions in urban areas may not allow for every household to own their own biogas system.

For the evaluation of the technical potential of biogas production from municipal solid waste in Uganda, the information given in Table 3.2 was used.

Table 3.2: Municipal solid waste characteristics

	Waste generation rate (tons/person/year)	Dry matter content, DM (%)	Biogas yield (m^3/t_{DM})
MSW	0.2	40	308

Source: (Omari M. A., 2015) (Slobodan C., 2014)

The annual waste generation rate was determined from the average daily solid waste generation rate of 0.55kg/capita/day (Okot-Okumu & Nyenje, 2011). The total urban population for Uganda was estimated to be 7,425,864 people in 2014 (UBOS, 2016). 78% of the municipal solid waste generated was estimated to be biodegradable and therefore suitable for biogas production. The waste collection rate was estimated to be 43.7% of the total waste generated (Okot-Okumu & Nyenje, 2011).

Using the above information, estimates for the biogas production potential from municipal solid waste were determined using the following equation.

$$B_P = 0.34P_U R_w D_M Y_B \qquad \text{(Equation 5)}$$

Where B_P is biogas potential (m^3/year), P_U is the urban population of Uganda in 2014; R_W is waste generation rate per person per year (tons/person/year); D_M is the estimated percentage of dry matter in MSW (%); and Y_B is the biogas yield (m^3/t_{DM}).

3.5 Most Suitable Domestic Biogas Production Technology in Uganda

3.5.1 Introduction

This section gives a brief description of the methodology used to select the most suitable domestic biogas technology in Uganda.

3.5.2 Data from potential biogas technology users

A list of biogas masons operating in Uganda was obtained from Biogas Solutions Uganda. Five biogas masons operating in the case study area were then identified and consulted to propose potential biogas technology users who could provide information relevant to the study objective.

A focus group discussion approach was used to identify major criteria and sub-criteria considered of importance when selecting a biogas system. Twenty-seven potential biogas users, who had already expressed interest to acquire biogas systems, were involved in the focus group discussion. The focus group discussion was used to facilitate meaningful and productive exchanges among the respondents on the possible criteria or sub-criteria to be considered when selecting a suitable biogas technology. The overall goal of the discussion was to arrive at a concrete and unified position from all the respondents about the most important criteria.

After identifying the criteria, individual interviews were carried out with each potential biogas technology user. The purpose of the interviews was to carry out a pairwise comparison of the identified criteria, indicating the importance attached by the respondent to one criterion or sub-criterion over another. The respondents were asked to use the scale of relative importance (see Table 2.11) to assign numerical ratings to their judgements. The focus group discussion and the interviews were organised and conducted with the help of the biogas masons who already had contact and friendly relations with the respondents. All the respondents were facilitated with some money to cater for their transport and lunch.

3.5.3 Data from biogas experts

Biogas experts under the Uganda Biogas Association were interviewed in order to obtain more technical information about the different biogas technologies in Uganda. The Uganda Biogas Association brings together different players with knowledge, interest and experience in Uganda's biogas sector. This was therefore considered to be the best source of accurate and complete technical information on biogas related issues in Uganda. Twelve biogas experts who had relevant qualifications, training and experience in biogas were selected from a list of association members.

The respondents were asked about the different biogas technologies in Uganda; particularly to identify common technology characteristics that are related to the criteria and sub-criteria put forward by the potential biogas users. The experts were also asked to carry out pairwise comparisons of the technologies for each of the identified criteria. Interviews with biogas experts were carried out by the researcher himself using a questionnaire from where the questions were read out to the respondents and the responses noted down by the researcher. This approach was preferred to handing out questionnaires to respondents because through such interactions, the respondents would be able to give more detailed information which would enable the researcher to capture any other information that would be helpful in the study.

3.5.4 Tool for determining the most suitable biogas production technology

The AHP method was used for identifying the most suitable biogas technology for this study. AHP is a multi-criteria decision making tool which employs scientific properties to support effective decision making on different issues where the existence of many criteria and alternatives make the decision making process complex. This tool structures the decision problem into different hierarchical levels of objective, criteria, sub-criteria and alternative options. By applying a pairwise comparison approach for different criteria and alternatives, the AHP tool offers a levelled ground for quantifying empirical data and the subjective opinions of the decision maker. It is therefore a suitable tool for both qualitative and quantitative measurements (Saaty T. L., 1980).

3.5.5 Constructing the AHP Model

Different criteria and sub-criteria that are important in selecting the most suitable biogas technology as well as the different alternative technologies available are considered when developing the AHP model. The criteria chosen could be grouped as economic, social, technical or environmental criteria. The technical criteria are related to the design characteristics of the technology while the economic criteria take into account the monetary expenditure related to the technology. Social criteria usually indicate the impact of the technology on the society while environmental criteria measure the technology's impact on the surrounding environment. The AHP model can be diagrammatically represented as shown in Figure 3.6 below.

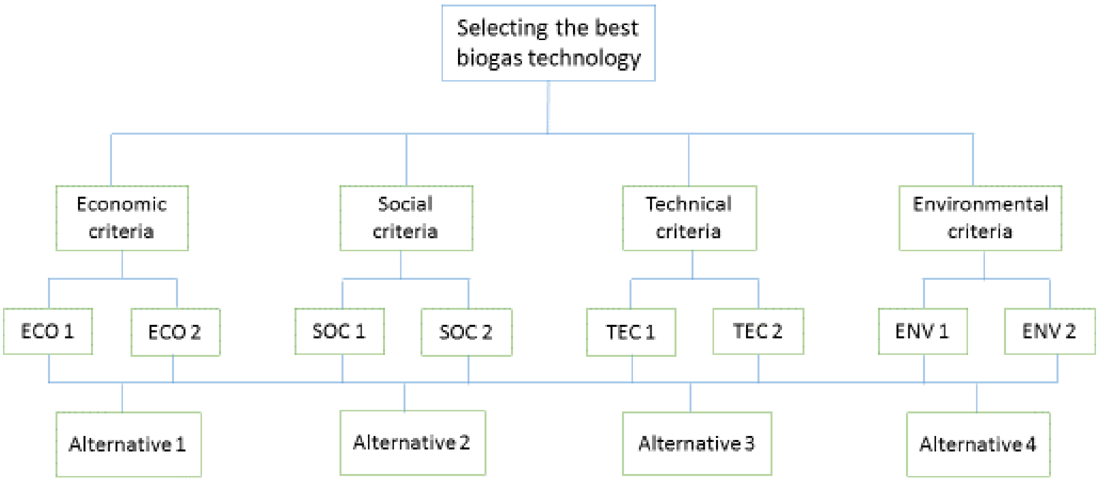

Figure 3.6: Schematic representation of the Analytical Hierarchy Process

The hierarchical form of the AHP model is built in such a way that the objective occupies the top most level (level 1) of the hierarchy. Level 2 of the hierarchy is the criteria level while level 3 is occupied by the sub-criteria under each criteria. The last level in the hierarchy, which is level 4, is filled by the alternative biogas technologies from which the best choice is sought.

3.5.6 Sensitivity analysis

A sensitivity analysis was carried out to determine the effect of changes in biogas user preferences/considerations on the overall outcome of the biogas technology selection process. The changes considered in this study were;

- Reversed preferences for technical and economic criteria
- Changes in preferences for the sub-criteria under the technical criteria

3.6 Economic Analysis of a Domestic Biogas System

3.6.1 Tool for estimating the economic viability of a biogas system

A cost-benefit analysis approach was used to carry out an economic analysis of a small domestic biogas system in Uganda. In the cost-benefit analysis approach, information on the potential economic costs and benefits of the biogas plant was collected and analysed. Most of the potential costs and benefits were assigned a monetary value. The analysis included benefits that are available both to the individual biogas system owner as well as to the society.

For purposes of this analysis, the following assumptions were adopted.

- A 6 m^3 fixed dome biogas plant will be installed for an individual household in a rural setting to provide biogas for both cooking and lighting.
- The household currently uses collected firewood for cooking and kerosene for lighting.
- Biogas production will meet 75% of the household's cooking and lighting needs.
- The household has enough free land and feedstock for the biogas system.
- The biogas plant has a lifespan of 20 years.
- No subsidies or loans are involved in the acquisition of the biogas system.
- Assume 95% biogas system functionality.

3.6.2 Quantifying costs and benefits

The production and use of biogas has its potential costs and benefits to the user and the society. Some of the costs and benefits associated with biogas plants are indicated in Table 3.3.

Table 3.3: Potential costs and benefits of a biogas plant

Costs	Benefits
• Capital costs of the entire biogas system including; ✓ Cost of labour ✓ Cost of materials • Repair and maintenance costs for both the plant and accessories • Annual operating costs	• Direct monetary savings including savings on fuel purchases • Time benefits • Health benefits • Environmental benefits including ✓ GHG emission reduction ✓ Local environmental benefits • Social benefits such as job creation • Increased agricultural productivity

The estimated monetary value for the various costs and benefits was obtained from literature sources and quantified on an annual basis. An exchange rate of 1 USD = UGX 3,350 was used.

Quantifying costs

Here, the costs associated with the biogas system were quantified as detailed below.

Capital costs: The capital cost of a 6 m^3 biogas plant is estimated to be UGX 1,500,000. This includes cost of materials as well as for labour. However, the owner is expected to provide domestic support during the construction period. Details of materials used and other requirements can be found in appendix A.

Annual repair and maintenance costs: The annual repair and maintenance costs are expected to be minimal for this system. It is believed that the technology provider continues to provide free maintenance services once a year. However, the owner purchases the required materials. More so, the use of biogas lamps necessitates regular cleaning and replacement of the filament. The total annual maintenance was therefore estimated to be about 1.5% of capital cost (Pandey B., et al., 2007).

Annual operating costs: Operating a biogas plant involves spending considerable time collecting and mixing fresh substrate and water. While domestic labour is usually used in most cases, the value of this time can be determined by assuming that the time spent on biogas related activities would have been used for other productive purposes. With an estimated 1.05 hours spent on biogas related activities daily and considering a wage rate of UGX 737 for unskilled labour in Uganda, the annual operating cost was determined to be UGX 282,405 (Renwick M., et al., 2007) (Pandey B., et al., 2007).

Quantifying benefits

Direct monetary savings: These are savings that accrue from the reduced expenditure on cooking and lighting fuel. A household that uses collected firewood (as considered in this study) does not directly save any money by cooking with biogas. However, the use of biogas for lighting results in reduced kerosene purchases. A rural household uses about 5 litres of kerosene for lighting every month and spends about UGX 184,250 annually on kerosene purchases. With a 75% reduction in kerosene use, direct savings amount to UGX 138,188 per year (Pandey B., et al., 2007).

Time benefits: Firewood collection in rural households takes about 0.9 hours daily. A 75% reduction in firewood results in significant time savings, which time can be used for other productive purposes. Assuming that there is limited productive employment in rural areas, especially for women and children, 20% of the saved time was allocated a monetary value which is equivalent to UGX 36,314 per year (Pandey B., et al., 2007). Biogas is also a clean fuel which burns efficiently. As such, there is time saved in cooking and cleaning activities which has an estimated value of UGX 302,639 per year. Biogas lighting also provides sufficient lighting for extending the study time for children whose value was estimated to be UGX 9,045 per household per year (Pandey B., et al., 2007) (Renwick M., et al., 2007).

Health benefits: Replacing firewood and kerosene with biogas reduces the prevalence of many diseases related to indoor pollution and hard labour in households. Therefore, expenditure on health related issues is reduced while productivity increases due to good health. The estimated annual value of health benefits was UGX 121,739, excluding the value of saved life[4] (Pandey B., et al., 2007) (Renwick M., et al., 2007).

Environmental benefits: Global estimates indicate that a small household biogas plant reduces GHG emissions by up to 5 tonnes per year. Considering the average price of 1 tonne of carbon to be UGX 33,500, then the annual benefits from GHG emission reduction was determined to be UGX 167,500. Other local environmental benefits associated with using such a biogas system such as reduced desertification and reduced cost of reforestation were valued at UGX 28,006 per year (Pandey B., et al., 2007) (Renwick M., et al., 2007).

Evaluating the value of a saved life as a result of biogas use is difficult. It has therefore been excluded from this analysis

3.6.3 Sensitivity analysis

For this study, a sensitivity analysis was also carried out to assess the impact of changes in some factors on the results of the economic analysis of the biogas system. The following variations were considered:

- Increase or decrease in capital cost by 25%.
- Incremental variations in discount rate starting with a discount rate of 1%.
- Exclusion of direct monetary savings and environmental benefits from the analysis.

3.7 Data Analysis

The data collected using the methodologies described above was analysed using Microsoft excel spreadsheets, where the relevant calculations were carried out to determine the biogas potential, suitable biogas technology as well as provide an economic analysis for the selected biogas system. For selecting the most suitable biogas technology in Uganda, the priority estimation tool (PriEsT) software was also used to determine the overall weights and rank the alternatives. PriEsT is an open source, multi-criteria decision making software based on the analytical hierarchy process method. The software supports pairwise comparisons and automatically generates weights and ranks for decision criteria and alternative options.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results obtained following the methodology described before.

4.2 Biogas Technical Potential for Major Feedstock in Uganda

The following sub-section gives the results obtained from the assessment of biogas technical potential for major feedstock in Uganda. The potential assessed was for livestock manure and municipal solid waste and the corresponding results are shown in Table 4.1 below.

Table 4.1: Biogas technical potential for major feedstock in Uganda

Type of feedstock	Biogas potential (million m^3/year)
Livestock manure (total)	380.7
Cattle manure (total)	326.2
Exotic/crossbreed cattle	71.1
Indigenous cattle	255.1
Pigs	12.6
Sheep	3.4
Goats	11.2
Poultry (Chicken)	27.2
Municipal solid waste	62.2

As shown in the table above, the biogas technical potential for livestock manure was found to be 380.7 million m^3/year. Of this, cattle manure accounted for 326.2 million m^3/year, pig manure potential was 12.6 million m^3/year, sheep and goats contributed 3.4 and 11.2 million m^3/year respectively, while chicken manure potential was estimated at 27.2 million m^3/year. The total potential obtained in this study is less than the total theoretical potential of 1 billion m^3/year estimated by (Pandey B., et al., 2007) because the current study considered only major livestock and poultry. Other livestock and poultry types such as donkeys, horses, turkeys and guinea fowls were not included due to insufficient statistical information. More so, the study excluded the numbers of major livestock and poultry that could not support biogas production at an individual household level. Biogas production from livestock manure was also largely reduced by the low levels of manure availability due to the traditional feeding methods used by most livestock owners. As noted before, for most of the animals, especially indigenous cattle, sheep and goats, over half of the manure is left in the grazing fields and is difficult to collect.

The highest individual potential of 255.1 million m^3/year was obtained for indigenous cattle because these are the most predominant cattle breeds reared in the country (UBOS, 2015). Even with a low manure availability of 0.4, the biogas potential for these cattle is still high. Using a minimum calorific value of 6 kWh/m^3 of biogas (Vogeli Y., et al., 2014), the total energy content of the biogas from livestock manure was calculated to be 2.3 TWh/year. This is about 12% of Uganda's total primary energy consumption in 2013.

The technical potential for biogas production from municipal solid waste in Uganda was estimated in this study to be 62.2 million m^3/year. This shows that MSW can be a significant source of energy for use in urban areas. The use of MSW to produce biogas is a more viable option compared to other waste disposal alternatives in Uganda due to the high organic and moisture content of the generated waste. Considering that the unit cost of electricity remains high in Uganda, the biogas produced can be used to generate electricity which can be supplied at relatively lower prices to the urban poor. Electricity generation from MSW can also help urban authorities to generate important revenues necessary to extend waste management services to all urban dwellers. This will help to address the challenge of poor waste management which has persisted largely due to limited funds allocated for waste management programmes (Okot-Okumu & Nyenje, 2011).

Biogas production from MSW is even more beneficial because it can divert an estimated 78% of the waste generated in Uganda's urban centres away from the dumpsites and landfills and therefore significantly minimise on space requirements for waste disposal. This will also address serious environmental and public health concerns arising from poorly managed landfills.

It is worth noting that with the rapid increase in population and urbanisation in Uganda, the quantities of MSW generated are expected to increase. This means that the potential for biogas production from MSW will continue to grow.

However, in order to realise the biogas potentials estimated for livestock manure and MSW in this study, a number of other factors that may limit biogas production need to be understood and addressed, for example;.

Biogas production requires significant quantities of water to mix with the fresh feedstock before feeding into the digester. As such, easy access to water should be guaranteed for biogas production to be justifiable. In Uganda, estimates indicated that about 78% of households can access water within 1 km distance (Pandey B., et al., 2007).

4.3 Most Suitable Domestic Biogas Production Technology in Uganda

4.3.1 Attributes/criteria for selecting a suitable biogas technology

From the focus group discussion, a number of attributes were identified by the potential biogas users to be of most importance when selecting a suitable biogas technology. These attributes are grouped under two major criteria groups as shown in Table 4.2 below.

Table 4.2: Criteria and sub-criteria for selecting suitable biogas technology

Technical criteria	**Economic criteria**
• Lifespan • Performance • Physical attributes	• Capital cost • Maintenance cost

Three sub-criteria of lifespan, performance and physical attributes were identified under the technical criteria while two sub-criteria of capital cost and maintenance cost were identified under the economic criteria. The choice of the above sub-criteria is explained below.

Capital cost: The capital cost is defined in this study as the cost incurred by the technology user to install or construct a biogas plant. It includes costs for the digester tank, piping and other support structures necessary for the proper operation of the biogas plant. It also includes the cost of the labour force. The capital cost was considered a vital attribute due to the fact that most of the potential biogas users have limited disposable income that they can commit to acquiring a biogas system. This limitation is characteristic of most households in the study area and in the whole of Uganda. Also, cheaper options to biogas such as firewood and charcoal exist in the study area and in the country; more reason why the capital cost of a biogas system should be competitive.

Maintenance cost: This refers to the cost incurred to maintain, repair or replace any component or part of the biogas system before the end of the system's lifespan. The annual maintenance cost incurred is determined by the level and frequency of maintenance related activities. It was observed that some technologies which require frequent maintenance, or employ expert labour and/or expensive materials for maintenance activities, can increase the overall cost of the system in the long run. Therefore, potential biogas users agreed that just like capital cost, the maintenance cost is a vital economic criteria for the biogas technologies.

Lifespan: Lifespan refers to the total amount of time that the system is expected to last before it is necessary to decommission it and completely replace it. The respondents considered lifespan as an important criteria due to the desire to have stability and continuity. The lifespan of a system was also identified as a key component, together with the overall cost (capital coat and maintenance cost), in evaluating whether there is value for money invested in the biogas system.

Performance: Whether or not the bio-digester is reliable and can perform consistently was one of the factors considered to be of great importance by potential biogas technology users in the study area. Performance in this case refers to the ability of the system to consistently produce maximum biogas volumes and deliver it at constant pressures to the end user when properly operated. The choice of performance as one of the key criteria was informed by the fact that many of the biogas systems in the study area have been abandoned due to inconsistent biogas volumes and fluctuating gas pressures delivered by these systems.

Physical attributes: The physical attributes of a biogas system have an important part to play in the technology selection process because they have an impact on space requirements and therefore the location of the system. The physical attributes also determines the flexibility and/or movability of the system as well as its safety and security.

4.3.2 Characteristics of biogas production technologies in Uganda

Information was sought from the biogas experts on the characteristics of each biogas production technology, in relation to the criteria proposed by potential biogas technology users. The characteristics of each technology are explained below.

Capital cost: The capital cost of a biogas plant varies due to differences in size, location, construction materials used, and number and skills of labour force employed. In this study, the cost of a 6 m^3 biogas plant, which is a very common biogas unit in Uganda, has been used to evaluate the different biogas technologies. Table 4.3 below shows the costs of installing a 6 m^3 biogas plant in the study area for each bio-digester technology as given by biogas masons and experts in Uganda.

Table 4.3: Capital costs of 6 m^3 biogas systems in Uganda

Digester type	Capital cost (UGX)
Tubular digester	1,100,000
Fixed dome digester	1,500,000
Floating drum digester	3,400,000

From the table above, the tubular digester has the least capital cost while the floating drum digester has the highest capital cost. The cost of the floating drum digester is more than double that of the other two systems, while the costs of tubular and fixed dome digesters are comparatively close.

Maintenance cost: As stated before, the cost of maintaining a biogas system generally depends on the level and the frequency of maintenance required. The level of maintenance determines the kind and number of labour force to be employed in maintenance activities. Complex maintenance usually requires well trained labour force and therefore carries higher costs. More frequent maintenance also implies higher maintenance costs because more materials will be purchased. In Table 4.4, a summary of the possible maintenance requirements and characteristics of the three biogas technologies is given as identified by biogas experts in Uganda.

Table 4.4: Maintenance requirements for biogas technologies in Uganda

Digester type	Maintenance requirements
Tubular digesters	Materials used for constructing tubular digesters are generally light and simple. While maintenance requirements might be frequent, trained local technicians and users can easily repair a damaged digester in a short time. Materials required for repair or maintenance are also usually few and cheap. However, it is difficult to remove the scum from the digester because it is usually half buried.
Fixed dome digesters	Fixed dome digesters generally require labour force trained in dome construction to construct and repair. Maintenance frequency is generally low because they are robust and constructed underground. However, underground construction means that they are largely inaccessible and may take slightly more time to maintain/repair. The materials required are also relatively few and cheap.
Floating drum digesters	Some floating drum digesters require frequent painting especially when using metallic drums. Excessive rusting may necessitate completely replacing the floating drum. However, the plastic type digesters used in Uganda are largely maintenance free. These digesters only require occasional draining and cleaning which is a simple process that takes a short time. This design therefore has a very low maintenance cost associated with it.

Lifespan: Different digester types have different lifespans particularly due to differences in materials used and the local conditions. Digesters of the same type can also have varying lifespans depending on the operation and maintenance practices of the user. However, there are standard lifespans estimated for the biogas technologies commonly used in Uganda, assuming that appropriate procedures are followed in construction, operation and maintenance of the digesters. The standard lifespans, which are shown in Table 4.5 below, were given by the biogas experts based on the conditions in the study area and the materials used for construction.

Table 4.5: Lifespan of biogas systems

Digester type	**Lifespan (years)**
Tubular digester	1 – 5
Fixed dome digester	20
Floating drum digester	8 – 15

As shown in the table above, the fixed dome digester has the longest lifespan of 20 years while the tubular digester has the shortest lifespan of 1 – 5 years. The lifespans of tubular digesters and floating drum digesters are given as ranges because they are usually constructed using different materials with different characteristics. For example, tubular digesters constructed using locally available plastic bags are usually weak and can last for only one year while those constructed from the stronger imported plastic material can last for up to 5 years. Also, floating drum digesters constructed entirely from plastic tanks are generally weak and last for only 8 years. However, those constructed as a concrete digester tank with a floating metallic drum usually last for up to 15 years.

Performance. The performance of a biogas system is an important factor for most potential biogas users in the study area. As noted by the biogas experts, whether or not a particular biogas system generates enough biogas to the expectation of the owner depends largely on how well it is operated. However, receiving gas supply at constant pressures from the digester is subject to the type of system used. Table 4.6 below indicates the characteristics of the biogas technologies with respect to performance as given by the biogas experts.

Table 4.6: Performance characteristics of biogas systems in Uganda

Digester type	Performance
Tubular digesters	Tubular digesters generally supply biogas at low pressures because the materials used for their construction cannot withstand high pressures. As such, gas pumps are used to achieve higher gas pressures whenever required. Also, when gas is being utilized, the pressure drops. However, in some cases, gas pressure can be enhanced by applying external pressure on the digester using weights. Slight mixing of the substrate is also possible, in some cases, by slowly moving the digester.
Fixed dome digesters	Fixed dome digesters produce enough gas when well operated. However, gas utilization is not effective due to substantial fluctuations in gas pressure as the gas is being utilized. A pressure regulator is necessary for appliances/machines that require gas at constant pressure. The design of fixed dome digesters makes it difficult to establish how much gas is in the digester at any given time. An extra stirrer is also required to achieve mixing of the substrate in the tank.
Floating drum digesters	Floating drum digesters, by virtue of their design, supply gas at constant pressures. The gas pressure is a function of the weight of the floating gas holder used which moves up and down as the gas is produced and utilized. In floating drum digesters, the quantity of the gas in the digester is usually determined by checking the level of the floating gas holder. The floating drum is also used to create turbulence and achieve mixing of the substrate in the digester.

Physical attributes: The physical attributes of a biogas system depend on the initial design developed by the inventor/innovator and also on the type of the materials used. The characteristics of biogas digesters that relate to its physical attributes were given by the biogas experts and are outlined in Table 4.7 below.

Table 4.7: Physical attributes of biogas systems in Uganda

Digester type	Physical attributes
Tubular digesters	This is constructed in a tubular form using materials such as polyethylene and is usually installed in a trench. It is characterized by low structural strength due to the nature of materials used. It is also usually constructed in a shelter or enclosure and therefore requires a considerable amount of space. The lightweight materials used make the tubular digester flexible and easy to move. However, these materials deteriorate easily and can be easily damaged by animals or children. It is also easy to steal.
Fixed dome digesters	It is constructed as a wide-bodied tank with a spherical gas holder on top. Usually, it is constructed underground using materials such as bricks, sand, cement and stones. The structure is therefore strong and protected from external damage or tampering. However, it is not moveable. Also, the fixed dome digester requires a lot of space due to its wide body. Fluctuations in gas pressure during usage sometimes cause fractures in the structure leading to gas leakages.
Floating drum digesters	The models used in Uganda are usually two differently sized prefabricated tanks made from plastic materials. They are installed above the ground and require little space for installation. They are moveable, but require a lot of labour to lift and transport. Floating drum digesters have a lower strength compared to the fixed dome digester but are stronger than tubular digesters. The plastic tanks can also be damaged by heavy falling objects.

4.3.3 Criteria and sub-criteria weighting

Weighting criteria is essential for achieving fair decision making. The weights of the criteria or sub-criteria show the importance attached to each particular criterion or sub-criterion by the decision maker based on the decision maker's subjective opinion. Basing on the responses from individual assessments carried out by each respondent, the mean values of the assessments were calculated, which were used to develop pairwise comparison matrices for the criteria/sub-criteria.

Weight of criteria

The assessment of the importance of technical and economic criteria was done by individual potential biogas users and the average values and calculated weights from the pairwise comparison are shown in Table 4.8 below.

Table 4.8: Scores and weights of criteria

	Technical criterion	Economic criterion	**Criteria weight**
Technical criterion	1	1.33	**0.571**
Economic criterion	1/1.33	1	**0.429**

Consistency ratio, CR= 0.00

The weight of the technical criterion, which is 0.571, is slightly higher than the weight of the economic criterion of 0.429. The small difference in the weights of these two criteria indicates that whereas the economic criteria are considered to be very important in selecting a suitable biogas system, on average potential biogas users attach slightly more importance to the technical criteria. Since there are only two criteria being compared, the analysis is perfectly consistent as evidenced by a consistency ratio of 0.00.

Weights of sub-criteria

Technical criteria

Under the technical criteria, the importance of sub-criteria of lifespan, performance and physical attributes were compared. The average results from the 27 assessments carried out by the potential biogas users are given in Table 4.9 below.

Table 4.9: Scores and weights of sub-criteria under the technical criterion

	Lifespan	Performance	Physical attributes	**Sub-criteria weight**
Lifespan	1	1.67	3.33	**0.526**
Performance	1/1.67	1	2.0	**0.316**
Physical attributes	1/3.33	1/2	1	**0.158**

Consistency ratio, CR = 0.052

From the table above, the sub-criterion of lifespan has the highest weight of 0.526 while the sub-criterion of physical attributes has the least weight of 0.158. This shows that lifespan is considered to be the most important technical sub-criterion. Lifespan has an impact on the economic performance of the system as well as on the continuity of biogas use in the long run. Most potential biogas users prefer to do a one-time investment in a technology that will last for many years because it is deemed to be an economical option. Lifespan of a biogas system is also important for stability since the user will have learnt the dynamics of the system's operation.

The performance of the biogas system, with a weight of 0.316, is considered to be the second most important sub-criteria. System performance determines whether the potential biogas user will be able to maximally enjoy the benefits of acquiring the biogas technology. However, it is not the most important criterion because most potential biogas users prefer to use biogas together with firewood or charcoal and therefore can easily substitute it. A system that produces and delivers consistent volumes and pressures of biogas to the end user without the use of any external hardware to boost performance is also highly desired. Fluctuating gas volumes and pressures may create anxiety and uncertainty among the technology users and undermine efforts to encourage the uptake of biogas technologies.

The physical attributes sub-criterion is considered to be of least importance mainly because most of the potential biogas users already have enough land on which to construct/install a biogas system. Movability of the system is also not of much concern since most of the potential biogas users are living on their own land and expect to remain there. However, concerns about whether the safety and security of the system can be guaranteed were outstanding. This gave the physical attributes sub-criterion a relatively fair weight of 0.158. The consistency ratio calculated for this comparison is 0.052, indicating that the assessment was done consistently.

Economic criteria

The averaged results from the comparison of the sub-criteria under the economic criteria, that is, capital cost and maintenance cost are given in Table 4.10 below.

Table 4.10: Scores and weights of sub-criteria under the economic criterion

	Capital cost	Maintenance cost	**Sub-criteria weight**
Capital cost	1	4.5	**0.818**
Maintenance cost	1/4.5	1	**0.182**

Consistency ratio, CR = 0.00

From the table above, the capital cost, with a weight of 0.818, is considered to be of very high importance when compared with the maintenance cost which has a weight of 0.182. The capital cost is usually a lump sum of money that the potential biogas technology user should expend in order to acquire the biogas system. As such, it is usually a big sum of money and is of concern to most potential biogas users. As noted by both the biogas experts and potential technology users, the cost of biogas systems in Uganda is still relatively higher than what most people can afford. The maintenance cost is a long term cost which is distributed over the entire lifetime of the technology and is therefore of little concern to the potential biogas users. Just like the comparison between technical and economic criteria, the comparison of capital cost and maintenance cost is perfectly consistent with a consistency ratio of 0.00.

4.3.4 Alternative priority comparison

The pairwise comparison of the different biogas technologies in Uganda was carried out individually by the selected biogas experts. The respondents relied on the characteristics given in Table 4.3, Table 4.4, Table 4.5, Table 4.6, and Table 4.7 to assess each technology against another for each of the sub-criteria given. The mean values of the assessments from the respondents were then calculated and used to determine the alternative priority vector for each sub-criterion.

Technical criteria

Lifespan

By carrying out pairwise comparisons of the three biogas technologies in Uganda with respect to lifespan, the following averaged results were obtained, and are tabulated together with the calculated alternative priority vector in Table 4.11 below.

Table 4.11: Digester pairwise comparisons and priority scores for the lifespan sub-criterion

	Tubular	Fixed dome	Floating drum	**Priority vector**
Tubular	1	1/7	1/3.33	**0.084**
Fixed dome	7.0	1	3.17	**0.673**
Floating drum	3.33	1/3.17	1	**0.244**

Consistency ratio, CR = 0.0174

The fixed dome digester, with a priority weight of 0.673, is the most preferred technology followed by the floating drum digester with a weight of 0.244, while the tubular digester has a weight of 0.084, and is therefore the least preferred technology when comparing lifespans. The fixed dome digester has a lifespan of 20 years and is therefore very superior to the tubular digester whose lifespan can be as low as 1 year. The floating drum digester is slightly competitive, but the 8-year lifespan of most of the models used in Uganda does not reach even half the lifespan of the fixed dome digester. The consistency ratio calculated for this comparison was 0.0174. This indicates that the analysis was near perfect consistency.

Performance

The average results of the pairwise comparisons among the biogas technologies for the performance sub-criterion are given in Table 4.12 below.

Table 4.12: Digester pairwise comparison and priority scores for the performance sub-criterion

	Tubular	Fixed dome	Floating drum	**Priority vector**
Tubular	1	2.0	1/2.83	**0.242**
Fixed dome	1/2	1	1/4.33	**0.132**
Floating drum	2.83	4.33	1	**0.626**

Consistency ratio, CR = 0.0085

From the table above, the floating drum digester system, with a priority score of 0.626, is considered to have the best performance among the three biogas technologies. The floating drum digester, by virtue of its design, assures a constant pressure supply of biogas to the users without the use of external pumps or pressure stabilisers. The floating drum is also advantageous because the mixing of the substrate inside the digestion tank can be achieved by simply rotating the floating drum. A well-mixed substrate in the digester tank facilitates consistent biogas production. Tubular digester systems with a score of 0.242 are considered to be more reliable than fixed dome digesters which have a score of 0.132. Tubular digesters are generally flexible and light weight in nature. As such, simple methods such as placing weights on top of the digester, are used to boost the gas pressure from a tubular digester. Fixed dome digesters are generally rigid digesters that require external hardware such as mixers and pumps in order to improve their performance.

Physical attributes

Table 4.13 indicates the mean values from the comparison of three biogas technologies in Uganda for the physical attributes sub-criterion and the corresponding priority scores.

Table 4.13: Digester pairwise comparison and priority scores for the physical attributes sub-criterion

	Tubular	Fixed dome	Floating drum	**Priority vector**
Tubular	1	1.17	1/1.5	**0.295**
Fixed dome	1/1.17	1	1/2	**0.242**
Floating drum	1.5	2.0	1	**0.463**

Consistency ratio, CR = 0.0008

As shown in the above table, the floating drum digester performed best for the physical attributes sub-criterion among the three biogas technologies. The floating drum digester has a priority score of 0.463. The floating drum digester occupies the least space of the three technologies and is also competitive in movability since it is assembled on site. It is also largely secure because the materials used for its construction are heavy. The tubular digester with a score of 0.295 is the most flexible and is easy to move because it is made of lightweight materials. However, its safety and security are a concern because it can be stolen and is easy to damage. It also occupies considerable space. These affected its overall weight under this assessment. The fixed dome digester has the least weight of 0.242. This is largely because it requires a lot of space for its construction and is not movable. However, it is the safest and secure system with the least susceptibility to external damage. This gave it an improved score. The assessment carried out was also mostly consistent with a consistency ratio of 0.0008.

Economic criteria

Capital cost

The results of the capital cost comparison of the biogas technologies based on the cost of a 6 m^3 biogas system are given in Table 4.14 below together with the priority vector scores.

Table 4.14: Digester pairwise comparison and priority scores for the capital cost sub-criterion

	Tubular	Fixed dome	Floating drum	**Priority vector**
Tubular	1	1.5	4.33	**0.523**
Fixed dome	1/1.5	1	3.17	**0.360**
Floating drum	1/4.33	1/3.17	1	**0.117**

Consistency ratio, CR = 0.0020

From the above table, the tubular digester has a moderately higher priority score of 0.523 as compared to that of fixed dome digester which is 0.360. This is because the difference between the capital costs of both digesters is relatively small as seen in Table 4.3. The materials available on the local market, from which tubular digesters are constructed, are generally cheap. The process of installing a tubular digester also takes less time and requires less labour force as compared to fixed dome digesters. All these lead to a lower capital cost requirement for the tubular digester. Floating drum digesters have the least score of 0.117 because the prefabricated plastic materials used in its construction are very expensive compared to the materials for other digesters. Also, there are very few companies that are involved in manufacturing floating drum digesters. As such, the cost of transporting the digester to the end users, who are usually in distant locations, increases the overall capital cost. The consistency ratio of this assessment was determined to be 0.002.

Maintenance cost

Table 4.15 shows the averaged results from the pairwise comparison of biogas technologies for the maintenance cost sub-criterion with the respective calculated priority scores.

Table 4.15: Digester pairwise comparison and priority scores for the maintenance cost sub-criterion

	Tubular	Fixed dome	Floating drum	**Priority vector**
Tubular	1	1.17	1/1.17	**0.331**
Fixed dome	1/1.17	1	1/1.33	**0.286**
Floating drum	1.17	1.33	1	**0.383**

Consistency ratio, CR = 0.0008

With a priority score of 0.383, the floating drum digester technology performs slightly better than both the tubular and the fixed dome digesters which have priority scores of 0.331 and 0.286 respectively for the maintenance cost sub-criteria. The plastic floating drum digester models that are used in Uganda are generally maintenance free apart from the occasional draining and cleaning to remove the scum. This is simple work that can be done by the technology user using common tools at almost no cost. Cleaning a tubular or fixed dome digester can be achieved with slightly more effort as compared to a floating drum digester since the digesters are either fully buried or half buried under the ground. However, a tubular digester can be easily repaired in a short time in case of any damage while repairing a damaged fixed dome digester requires slightly more preparation and labour. In general, all the digester designs in Uganda have low maintenance requirements. The comparisons in this assessment were found to be consistent with a consistency ratio of 0.0008.

4.3.5 Final combined priority scores and ranking

The summary of results for criteria weights, sub-criteria weights and alternative priority scores are shown in Table 4.16. These summarised results were used to calculate the final combined priority scores of the alternative technology options. The final scores were then used to rank the biogas technologies in order identify the most suitable technology out of the three alternatives.

Table 4.16: Summarised results of criteria weights and alternative priority scores

Criteria	Sub-criteria	Alternatives	Priority scores
Technical criterion (0.571)	Lifespan (0.526)	Tubular	0.084
		Fixed dome	0.673
		Floating drum	0.244
	Performance (0.316)	Tubular	0.242
		Fixed dome	0.132
		Floating drum	0.626
	Physical attributes (0.158)	Tubular	0.295
		Fixed dome	0.242
		Floating drum	0.463
Economic criterion (0.429)	Capital cost (0.818)	Tubular	0.523
		Fixed dome	0.360
		Floating drum	0.117
	Maintenance cost (0.182)	Tubular	0.331
		Fixed dome	0.286
		Floating drum	0.383

By considering the technical criteria only, the overall weights obtained for the tubular, fixed dome and floating drum digesters are shown in Figure 4.1. The fixed dome digester has the highest score of 0.434 and is therefore the most suitable when considering technical criteria, while the tubular digester has the least score of 0.167

and is the least preferred in this case. The floating drum has a relatively competitive score of 0.399.

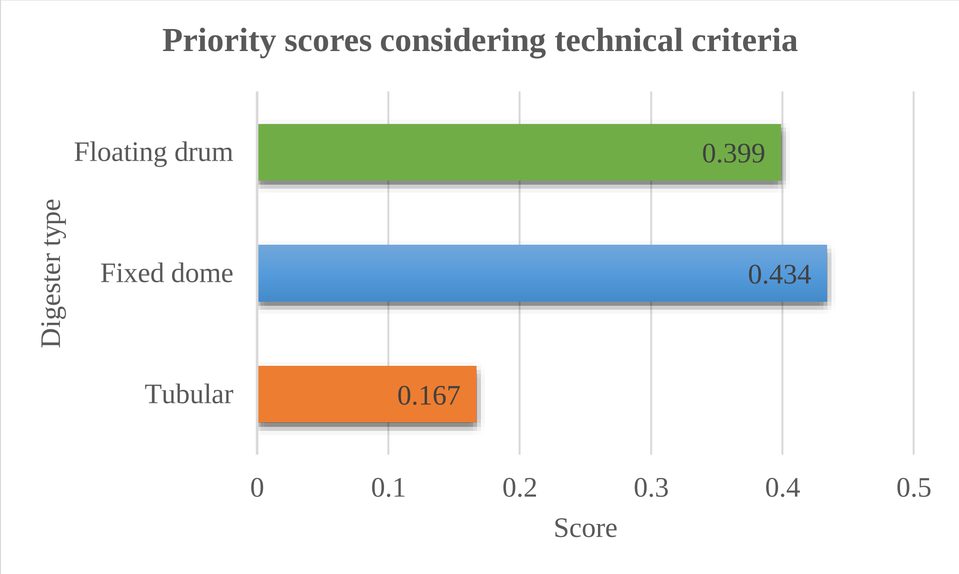

Figure 4.1: Digester priority scores considering technical criteria only

For the economic criteria, the tubular digester is the most suitable option with a weight of 0.488, followed by the fixed dome digester with a weight of 0.346. The floating drum digester, with a weight of 0.166, comes last as shown in Figure 4.2 below.

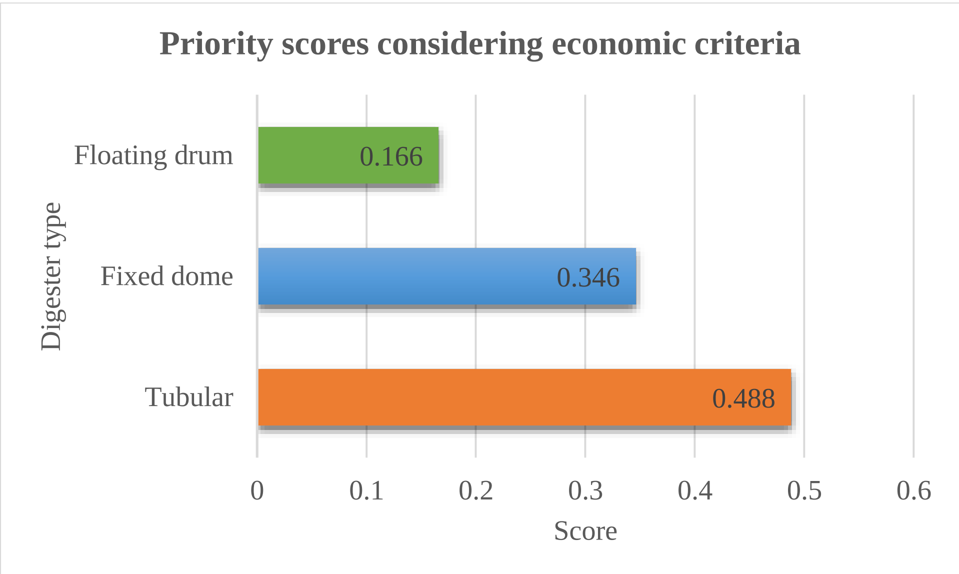

Figure 4.2: Digester priority scores considering economic criteria only

By combining both the technical and economic criteria, the respective overall priority scores of the three biogas technologies were obtained and are shown in Figure

4.3 below. The fixed dome digester has the highest overall priority score of 0.396 and is therefore the most suitable biogas system selected in this study. This is followed by the tubular digester with a score of 0.305 while the floating drum digester with the least priority score of 0.299 occupies the last position.

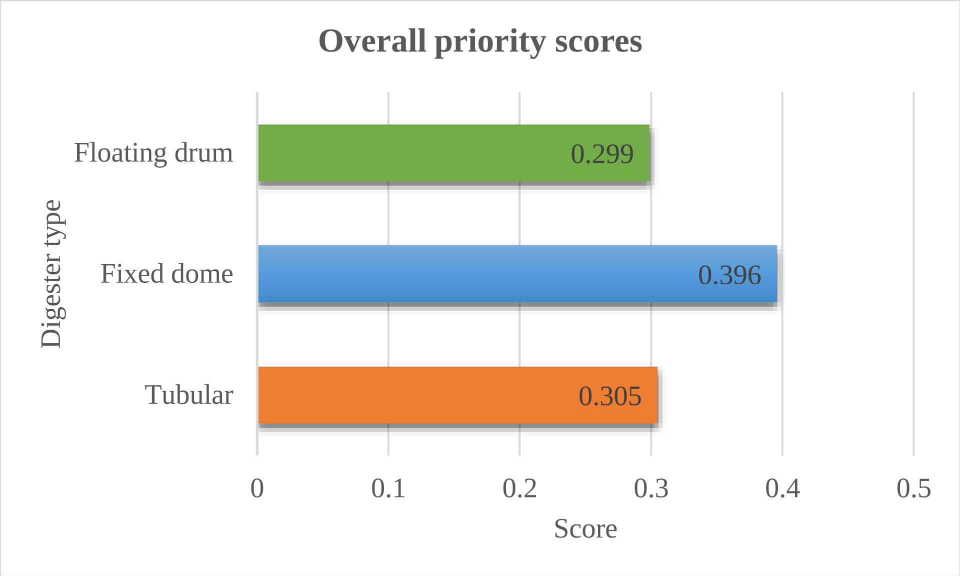

Figure 4.3: Overall priority scores for biogas technologies in Uganda

4.3.6 Sensitivity analysis

Because the analytical hierarchy process method relies on the subjective opinion of the decision maker, many possible variations in criteria/sub-criteria weights are possible. The considerations in this sensitivity analysis are therefore just examples of the possible variations in the final results, if the values of some criteria or sub-criteria were different.

Reversed preferences for technical and economic criteria

In the process of selecting the most suitable biogas technology, some potential biogas users may consider the economic criteria to be more important than the technical criteria. To determine the effect of this change in preference on the overall result of the study, the pairwise comparison results of the two major criteria were reversed. The economic criterion was considered to be slightly more important with a score of 1.33 in which case the resultant score of the technical criterion was reduced to 0.75. The resultant overall priority scores for the different digester systems are as shown in Figure 4.4.

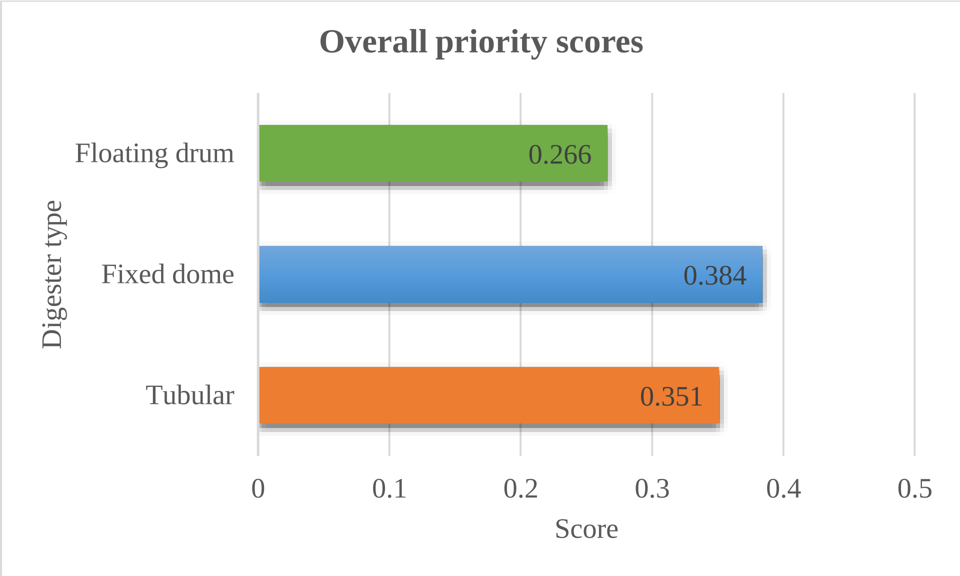

Figure 4.4: Sensitivity analysis of overall priority scores to reversed criteria preferences

As can be seen from the figure above, the general ranking of the three biogas technologies was not affected, with the fixed dome digester remaining as the most suitable biogas technology albeit with a lower overall priority score of 0.384. The tubular digester has an improved score of 0.351 while floating drum digester remains the least ranked technology with a reduced score of 0.266.

Changes in preferences for the sub-criteria under the technical criterion

As expressed by the closeness of the comparison result for the lifespan and performance, some potential biogas users might prefer a better performing system as compared to one with a longer lifespan. Also, some potential biogas users may prefer a flexible/movable system if they intend to relocate to a different location in the near future. To check for the sensitivity of the results in such cases, lifespan and physical attributes were considered to be of equal importance (comparison score 1), while performance was given a high comparison score of 1.67 with respect to both lifespan and physical attributes. As shown in Figure 4.5 below, changes in comparison scores resulted in changes in the priority scores when comparing technical criteria only. The floating drum digester had the highest priority score of 0.477 and emerged as the best ranked technology for the technical criteria. The tubular digester remained the least ranked under technical criteria with a score of 0.213.

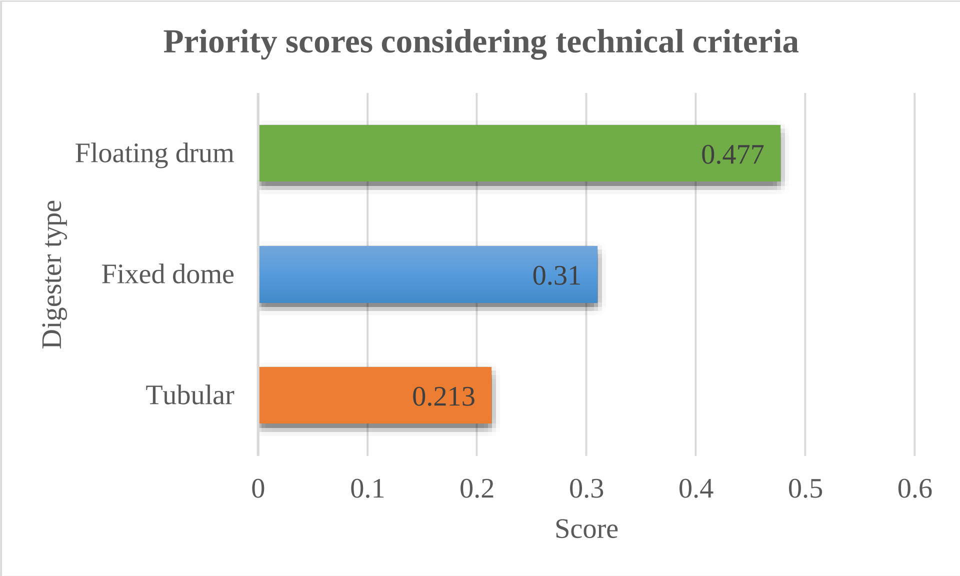

Figure 4.5: Sensitivity analysis of technical priority scores to changes in preferences of sub-criteria under the technical criterion

Considering the overall results, this sensitivity scenario shows that the floating drum digester had the highest score of 0.344 and is therefore ranked first. This was followed by the tubular digester with a score of 0.331 while the fixed dome digester dropped to the least preferred technology with a score of 0.325 (see Figure 4.6). It is, however, worth noting that the difference in the overall priority scores for this sensitivity scenario is low, indicating that the fixed dome digester remains a competitive choice even in this case.

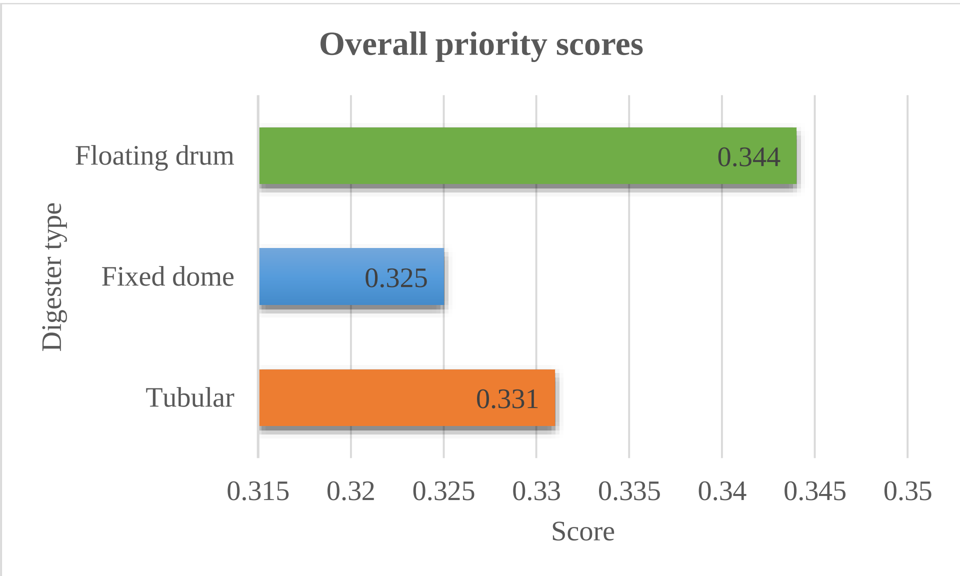

Figure 4.6: Sensitivity analysis of overall priority scores to changes in preferences of sub-criteria under the technical criterion

4.4 Economic Analysis of Domestic Biogas Production and Use in Uganda

4.4.1 Base case calculations

Key economic parameters including Net Present Value, Internal Rate of Return, and Benefit-Cost Ratio and Payback period were calculated using the quantifiable costs and benefits of owning a biogas system. The obtained results are shown in Table 4.17. The Microsoft excel spreadsheet used for the economic analysis calculations is shown in appendix B.

Table 4.17: Results of the economic analysis

ITEM	MONETARY VALUE
Costs	
Capital cost	UGX 1,500,000
Annual maintenance cost	UGX 22,500
Annual operating cost	UGX 282,405
Total costs	***UGX 1,804,905***
Benefits	
Direct monetary savings	**UGX 138,188**
Fuel savings	*UGX 138,188*
Time benefits	**UGX 347,998**
Reduced time for firewood collection	*UGX 36,314*
Reduced cooking and cleaning time	*UGX 302,639*
Increased study time for children	*UGX 9,045*
Health benefits	**UGX 121,806**
Reduced health expenditure	*UGX 113,967*
Health related productivity	*UGX 7,839*
Environmental benefits	**UGX 195,506**
GHG emission reduction	*UGX 167,500*

Local environmental benefits	*UGX 28,006*
Total benefits	***UGX 803,498***
Other relevant information	
Annual discount rate	5.4%
Lifespan	20 years
Confidence factor	95%
Calculated results	
Net Present Value (NPV)	UGX 7,668,362
Internal Rate of Return (IRR)	37%
Benefit-Cost Ratio (BCR)	2.21
Discounted Payback	3.95 years

A net present value of UGX 7,668,362 and internal rate of return of 37% indicates that the biogas system has high positive cash flows over its entire lifespan. This implies that higher benefits are realised from the biogas system compared to the costs incurred. The benefit-cost ratio of 2.2051 also shows that the monetary value of the benefits from the biogas system is high compared to the monetary costs involved. This particularly reflects the relatively low capital cost of installing a biogas system in a rural setting in Uganda where some costs such as land costs are avoided. Benefits of a biogas system are also enhanced by considering using biogas for lighting because grid electricity connections are largely inexistent in most rural areas.

The BCR and the IRR obtained for this analysis are far less than the 6.84 and 166% respectively obtained by (Pandey B., et al., 2007). This is because some factors such as latrine access, value of saved life and fertilizer use, were not considered in this assessment. The value of increased crop productivity due to the use of bio-slurry was not included in the economic analysis due to insufficient information on the monetary value of the bio-slurry. The assessment by (Pandey B., et al., 2007) also considered subsidies for the system which were neglected in this assessment.

4.4.2 Sensitivity analysis

Changes in some key input factors may have a significant effect on the results of the economic analysis of a biogas plant. In order to determine the impact of key factors on economic performance, a sensitivity analysis was carried out. The factors that were varied or excluded are capital cost, direct monetary savings, environmental benefits and discount rate. Table 4.18 shows the results obtained for the different sensitivity analyses carried out.

Table 4.18: Sensitivity of economic analysis to changes in key factors

	BASE SCENARIO	CAPITAL COST VARIATIONS		WITHOUT DIRECT MONETARY SAVINGS	WITHOUT ENVIRONMENTAL BENEFITS
		25% REDUCTION	25% INCREASE		
NPV (UGX)	7,668,362	8,155,862	7,180,862	5,042,790	3,953,748
IRR (%)	37	49	30	28	24
BCR	2.21	2.31	2.11	1.83	1.67
Discounted Payback	3.95	3.22	4.65	5.01	5.85

As anticipated, changes in the capital cost have an effect on the results of the economic analysis since it is the major cost involved in the analysis. Reducing capital cost increases NPV, IRR, and BCR while at the same time reducing the discounted payback and vice versa. A 25% reduction in capital cost increases the net present value from UGX 7,668,362 to UGX 8,155,862 while the IRR increases to 49% from 37%. For a 25% increment in capital cost, the NPV reduces to UGX 7,180,862 while IRR reduces to 30%. The reduction/increment in key economic parameters with changing capital cost is due to the fact that the benefits from the system are expected to remain constant even with varying capital costs. Capital cost variations can be brought about by changes in the costs of the materials, transportation and labour which do not have a direct impact on the benefits of the system.

More significant changes in the economic parameters are observed when either direct monetary savings or environmental benefits are excluded from the analysis. Without considering environmental benefits, there is a reduction in the net present value from UGX 7,668,362 to UGX 3,953,748 while the IRR reduces from 37% to 24%. This is a likely scenario if there are no efforts by the government to harness the benefits of greenhouse gas abatement by engaging in international carbon trade or the clean development mechanism[5]. The absence of direct monetary savings also significantly reduces the NPV to UGX 5,042,790 and IRR to 28%. This is possible when a rural household already has another source of lighting such as solar, and does not utilise biogas for lighting.

Net Present Value variation with discount rate

The need to test the sensitivity of NPV to variations in discount rate is justified by the fact that most of the costs of the biogas system are incurred in the initial year while the benefits accrue over many years. As shown in Figure 4.7, the NPV of the biogas system decreases with increasing discount rate. This is because the discount rate reduces the present worth of the future benefits while having no effect on the initial investment cost which is the major cost of the biogas system. A plot of NPV against discount rate generates a smooth curve where rate of decrease in NPV is high at lower discount rates and decreases with increasing discount rates.

[5] Small scale individual carbon saving projects need to be supported by their governments in order to collectively harness the benefits under the clean development mechanism.

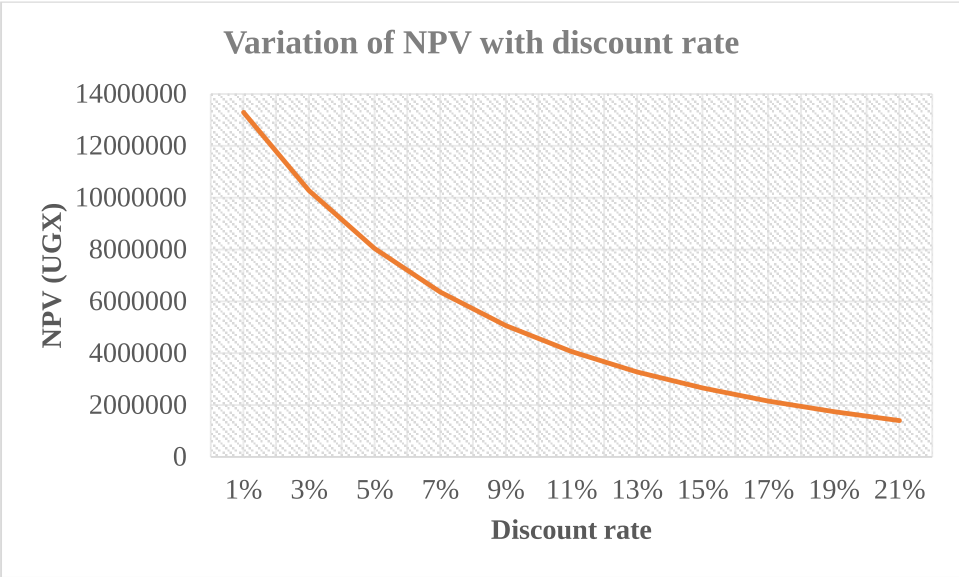

Figure 4.7: Variation of NPV with discount rate

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter presents the conclusions and recommendations derived from the results obtained in this study. The conclusions are intended to summarise the overall outcome of the study while the recommendations give a future course of action and suggestions for improvement.

5.2 Conclusion

The potential of biogas production to enhance access to modern energy services is widely recognised globally. In Uganda, and in other developing countries, various scientific studies have been carried out to support biogas use. This thesis is therefore an addition to this ever increasing body of literature on the subject. As a general conclusion from this study, domestic biogas production has a high potential to enhance energy access in Uganda. A substantial potential also exists for communal scale biogas production.

The results obtained from this study indicate that the biogas technical potential for domestic biogas production using livestock manure is high. Among the livestock assessed, cattle have the highest technical potential followed by chicken, pigs, goats and sheep in that order. This technical potential is expected to increase every year due to increasing livestock numbers. Municipal solid waste also offers significant biogas technical potential for biogas production if consideration is made for communal biogas systems. The biogas potential for MSW is also expected to increase over time with increased urbanisation in the country. The biogas technical potential for other feedstock was not assessed due to insufficient information and the limited scope of this study.

Basing on the methodology used in this study, a fixed dome digester system was found to be the most suitable technology option for domestic biogas production in Uganda. The technical and economic criteria identified to be of importance to the biogas system selection process are lifespan, performance, physical attributes, capital cost and maintenance cost. Most potential biogas users considered lifespan to be the most important criterion under technical criteria followed by performance. The capital cost criterion far outweighed maintenance cost under the economic criteria. The fixed dome digester ranks well for lifespan and capital cost criteria and remains competitive in the remaining criteria. The AHP tool used in the analysis helped to merge input information obtained from both potential technology users and the biogas experts in order to arrive at an all-inclusive result. The AHP tool is, however, a subjective tool and is therefore sensitive to changes in user preferences. It is therefore important that the results obtained in this study are used within the context of the study area.

Investing in a small scale biogas system, for a household with sufficient feedstock, is an economically viable option in Uganda. The monetary benefits of acquiring a biogas system outweigh the costs involved over the system's lifespan. Whereas the direct monetary savings resulting from the use of biogas are usually minimal, other indirect benefits such as time benefits, health benefits and environmental benefits make biogas use economically competitive. The only major costs involved are the capital costs while the operation and maintenance costs remain minimal. As such, the cash flows over the system's lifespan are positive except in the initial year. The economic parameters of net present value, internal rate of return, benefit cost ratio and discounted payback calculated over the lifespan of the system are competitive and support investment in biogas systems. The economic viability is, however, affected by changes in capital costs, benefits as well as discount rates. But NPV, IRR, BCR and discounted payback period results obtained for the sensitivity analyses indicate that the biogas system is economically robust and its economic viability is not greatly compromised by small variations in key factors.

5.3 Recommendations

The biogas technical potential for livestock manure and MSW in Uganda has been found to be substantially high in this study. However, this study did not assess all the possible feedstock for biogas production. As such, a more comprehensive study is required in order to give a complete estimation of the biogas production potential from all feedstock in the country. This will go a long way in informing policy formulation and biogas promoters on where to focus energy and resources.

The findings in this study reveal that user preferences can affect the choice of biogas technology to be adopted. While there should be technical guidance for potential biogas users on a suitable biogas system, biogas technology promoters and implementers should also consider individual user preferences especially for the non-technical issues. This will ensure that the biogas users acquire a system that matches with their present and future needs.

The use of biogas provides an independent, continuous and largely unlimited source of cooking and lighting fuel for households. However, the high upfront costs for acquiring the technologies coupled with low direct monetary savings usually hinder the acquisition of biogas systems especially for households that do not currently purchase cooking fuel. Therefore, in order for more households to acquire biogas systems, the multi-dimensional benefits of biogas use should be well understood and appreciated. The biogas promoters should clearly explain to the people the indirect benefits of biogas use such as time savings, improved health, improved agricultural productivity and environmental protection to the people, probably in monetary terms.

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APPENDICES

APPENDIX A: Requirements for constructing a 6 m^3 fixed dome biogas plant

ITEM	QUANTITY/COST
General bulk goods	
Sand (plaster)	1 Trip (Elf)
Gravel ¼”	6 w/b
Cement	8 bags
Bricks	700
Emulsion paint	2 litres
Welded/Square mesh	1 piece
Twisted bar (Y-12)	1 piece
PVC pipe 4” 10 feet (MEDIUM)	1 piece
PVC pipe ½”	5 pieces
Pressure gauge	1 piece
Ring wire (6mm)	½ piece
Biogas materials and excavation	
Dome gas pipe + valve	1 piece
Biogas stove + tap with accessories	1 piece
Water drain valve	1 piece
Fitting material and sundry	Varies with distance
Excavation, site preparation	Provided by beneficiary

Other services and fees	
Labour fee	UGX 350,000
Accommodation	Provided by beneficiary
Meals for Masons	Provided by beneficiary
Quality Control	Provided by biogas company
Helpers/porters	Provided by beneficiary
Grand total	**UGX 1,500,000**

APPENDIX B: Excel sheet for economic analysis of fixed dome biogas system

Year		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Costs																	
Capital cost	$	500.00	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Repair and maintenance cost	$	-	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50	$ 7.50
Operating cost	$	-	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30	$ 84.30
Total costs by year	$	500.00	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80	$ 91.80
Grand Total Costs	$	2,264.20															
Benefits																	
Direct monetary benefits	$	-	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25	$ 41.25
Time benefits	$	-	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88	$ 103.88
Health benefits	$	-	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34	$ 36.34
Environmental benefits	$	-	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36	$ 58.36
Total benefits per year	$	-	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83	$ 239.83
Confidence factor		95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%	95.00%
Benefits claimed for Analysis	$	-	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84
Grand Total Benefits	$	4,328.93															

Year		2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
Undiscounted cash flows																	
Costs	$	-500.00	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80	$ -91.80
Benefits	$	-	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84	$ 227.84
Net Cash Flow	$	-500.00	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04	$ 136.04
Discount Factors																	
Discount Rate		5.40%															
Base Year		2016															
Year Index		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Discount Factor		1	0.948767	0.900158	0.85404	0.810285	0.768771	0.729384	0.692015	0.656561	0.622923	0.591009	0.560729	0.532001	0.504745	0.478885	0.4543503
Discounted Flows																	
Costs	$	-500.00	$ -87.10	$ -82.63	$ -78.40	$ -74.38	$ -70.57	$ -66.96	$ -63.53	$ -60.27	$ -57.18	$ -54.25	$ -51.47	$ -48.84	$ -46.34	$ -43.96	$ -41.71
Benefits	$	-	$ 216.17	$ 205.09	$ 194.58	$ 184.61	$ 175.16	$ 166.18	$ 157.67	$ 149.59	$ 141.93	$ 134.65	$ 127.76	$ 121.21	$ 115.00	$ 109.11	$ 103.52
Net	$	-500.00	$ 129.07	$ 122.46	$ 116.18	$ 110.23	$ 104.58	$ 99.22	$ 94.14	$ 89.32	$ 84.74	$ 80.40	$ 76.28	$ 72.37	$ 68.66	$ 65.15	$ 61.81
Cumulative	$	-500.00	$ -370.93	$ -248.48	$ -132.29	$ -22.06	$ 82.52	$ 181.74	$ 275.88	$ 365.20	$ 449.94	$ 530.34	$ 606.62	$ 679.00	$ 747.66	$ 812.81	$ 874.62
Net Present Value	$	1,139.29															
Internal Rate of Return		26.98%															
Benefit-Cost Ratio		1.7093															
Discounted Payback (years)		4.2674															