OPTIMIZATION OF EFFICIENCY OF A BIOGAS DIGESTER FOR SMALL-SCALE ELECTRICITY GENERATION

(Alternative energy sources diversification and Environmental Impacts mitigation in Zambia)

By

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A thesis submitted in Partial fulfillment of the requirements for the degree of Master of Engineering Thermofluids Engineering

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DECLARATION

I, **Agripper Kamzalaba Daka** do hereby declare that the contents of the thesis being submitted herein are my original work and they have not been previously submitted to any University for the award of a degree or any other qualification.

Signature………………………………………. Date…………………………………

CERTIFICATE OF APPROVAL

This thesis submitted by, **Agripper Kamzalaba Daka** is approved as fulfilling the requirements for the award of the degree of Master of Engineering in Thermofluids Engineering at the University of Zambia.

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ABSTRACT

Reliance on oil importation, electricity on the national grid, and other conventional fuels has a direct effect on the National Energy security and has become one of the most challenging problems that require to be tackled as the fossil sources are rapidly diminishing and electricity supply unreliable; together with deforestation. A glance beyond these sources is critical for long term energy security and sustainability as there are several uncertainties about these sources coupled with the greater environmental dangers encountered from fuel utilization. Thus, this research focused on the concept of an improved conversion of biodegradable organic matter to produce biogas through anaerobic digestion for the sole purpose of small-scale electricity generation. This is timely especially in view of the current energy (electricity) crisis being experienced in the country.

The objective of this study was to develop models which predict the quantities of biogas and the corresponding feedstock required to generate electricity ranging from 50 kW to 500 kW. This was accomplished by; firstly, identifying the factors that affect the rate of biogas production and electricity generation. These factors were: temperature T, hydraulic retention time HRT, substrate loading rate LR, feedstock characteristics, specific fuel (biogas) consumption of the biogas engine, and number of hours per day of operation by biogas engine etc. and then the feedstock materials readily available in Zambia were also identified i.e. *sludge water – water treatment plant, cow dung, swine manure, chicken droppings, vegetable and fruit waste, catering waste, grass silage, and corn silage.* Using MATlab computer software, and MS Excel, models were developed and; then the findings were validated using data from a selected farm in Chongwe and from authentic literature.

The generic model for predicting biogas production after demand for electricity was established was: $\boldsymbol{fc = 11.22Ep}$, where $\boldsymbol{fc}$ is biogas consumption rate and $\boldsymbol{Ep}$, electricity demand. Under the Zambian climatic conditions, the optimum temperature for better efficiency of biomethanation was determined as 24.7^{o}C; from the developed model (rates of gas production vs average monthly temperatures) with the knowledge of the feedstock characteristics (e.g. Specific gas yield). Also, to generate 300 kW of electricity (for example) would require 21,173.60 tonnes/year of swine manure or 33,190.20 tonnes/year of cow dung or 17,797.64 tonnes/year of chicken droppings or 10,505.02 tonnes/year of grass silage or 8,860.30 tonnes/year of corn silage or 17,056.07 tonnes/year of vegetable and fruit waste or 81,869.16 tonnes/year of sludge waste-water treatment plant and 11,163.98 tonnes/year of catering waste.

The digester sizing was determined with respect to 50 to 500 kW of electric power range. The plotted graphs which were to scale could effectively be used to estimate digester volumes for all the eight selected feedstock materials. A relationship between digester volume and feedstock characteristics showed that the digester volume is inversely proportional to the product of feedstock density and specific biogas yield.

Keywords: Biogas technology, digester, anaerobic digestion (AD), electricity generation.

DEDICATION

This work is particularly dedicated to my dearest sons *Agripper Kamzalaba Daka Junior, Njavwa Kamzalaba Daka, and Yamikani Kamzalaba Daka* who, for their love, stood by my side and unceasingly shared with me the challenges and hardships during my studies at the University of Zambia. I genuinely thank them all inestimably for their unwavering support and understanding when I could not be fully available for them during my studies. For the three of you, this is the grand prize and reward of your patience, endurance, and above all - love.

ACKNOWLEDGEMENTS

With a heart full of gratitude, I am highly indebted to my supervisor, Professor F. D. Yamba, for his continuous reminders and *expected* constructive input to this piece of work; Water and Sanitation Association of Zambia (WASAZA); Southern BioPower Ltd (SBP); and Chimphembela Fish Farm and Restaurant. Their valuable suggestions and objective guidance enriched this study at each step.

Furthermore, I would like to express my sincere heartfelt appreciation to my friend *Chisala Kapump*u for his moral support he gave to me all the way from the beginning of my studies to the very end; I would also like to thank all the members of the academic staff in the school of engineering for their constructive criticism which helped in perfecting this work.

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LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
BIMRU	Building and Industrial Research Unit
C/N	Carbon – Nitrogen ratio
CHP	Combined Heat Power
CI	Compression Ignition
CIMAC	Conseil International des Machines á Combustion (The International Council on Combustion Engines)
Dm	Dry Matter
EAD	Environment Affairs Department
E4A	Energy for Agriculture
EPA	Environmental Protection Agency
ERB	Energy Regulation Board
FAS	Foreign Agricultural Service
FDI	Foreign Direct Investment
ForTran	Formula Translation
GDP	Gross Domestic Product
HRT	Hydraulic Retention Time
IEA	International Energy Agency
kg	Kilogram
KVIC	Khadi Village Industries Commission
kW	Kilo-watt
kWh	Kilowatt-hour
MAD	Mean of Absolute Deviation

MATlab	Matrix Laboratory
MBE	Mean Bias Error
MMEWD	Ministry of Mine, Water and Energy Development
MSW	Municipal Solid Waste
MW	Mega-watt
NCSR	National Council for Scientific Research
NEP	National Energy Policy
NISIR	National Institute for Scientific and Industrial Research
NNFCC	National Non-Food Crops Centre
ODA	Official Development Assistance
OECD	Organization for Economic Co-operation and Development
PV	Photovoltaic
R&D	Research and Development
REN21	Renewable Energy Policy Network for the 21st century
RET's	Renewable Energy Technologies
RMSE	Root Mean Square Error
RNG	Renewable Natural Gas
SADC	Southern African Development Community
SBP	Southern Biopower Ltd
sfc	Specific fuel consumption
SI	Spark Ignition
SNV	Netherlands Development Organization
TDAU	Technology Development and Advisory Unit

TDBP	Tanzania Domestic Biogas Program
TVS	Total Volatile Solids
UNCTAD	United Nations Conference on Trade and Development
UNIDO	United Nations Industrial Development Organization
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
VFA	Volatile Fatty Acids
WASAZA	Water and Sanitation Association of Zambia
WEC	World Energy Council
WEO	World Energy Outlook
ZABS	Zambia Bureau of Standards

NOMENCLATURE

a and b	Constants
E	Energy content of biogas [kWh]
***E*p**	Electricity demand [kW]
***f*c**	Daily biogas consumption [m^3/day]
***f*m**	Methane fraction in biogas
G	Biogas production rate [m^3/day]
***G*y**	Specific biogas yield [m^3/kg]
***H*m**	Heat of combustion of Methane [28 MJ/m^3]
HR	Amount of feedstock [tonnes/year]
***HR*cd**	Cow dung manure [tonnes/year]
***HR*ckn**	Chicken droppings [tonnes/year]
***HR*cs**	Corn silage [tonnes/year]
***HR*cw**	Catering waste [tonnes/year]
***HR*gs**	Grass silage [tonnes/year]
***HR*n**	Quantity of feedstock for a particular biomass [tonnes/year]
***HR*sm**	swine manure [tonnes/year]
***HR*sw**	sludge waste [tonnes/year]
***HR*t**	Sum of biomass resources [tonnes/year]
***HR*vf**	Vegetable and fruit waste [tonnes/year]
LR	Daily loading rate [kg/day]
N	Population of animals
η	Efficiency of biogas appliance
***η*gen**	Electric generator efficiency
***P*eng**	Engine operation power output [kW]
Q	Heat energy [kWh]
Rcc	Compensation chamber radius [m]
Rd	Dome radius [m]
RT	Retention time [days]
sfc	Specific fuel consumption of biogas engine [m3/kWh]
SQ	Specific quantity of excrement [kg]
T	Temperature [^oC]
Ti	Initial temperature [^oC]
***t*o**	Number of hours gas engine operates [hrs]
Tr	Required or final Temperature [^oC]

V	Total volume of biogas plant [m3]
Vb	Buffer volume [m3]
Vd	Bio-digester volume [m3]
Vg	Gas holder volume [m3]
Vw	Volume of water to be heated [m3]
x and *y*	Variables
Δ**T**	Change in Temperature [oC]
ρ	Feedstock density [kg/m3]

CHAPTER 1 INTRODUCTION

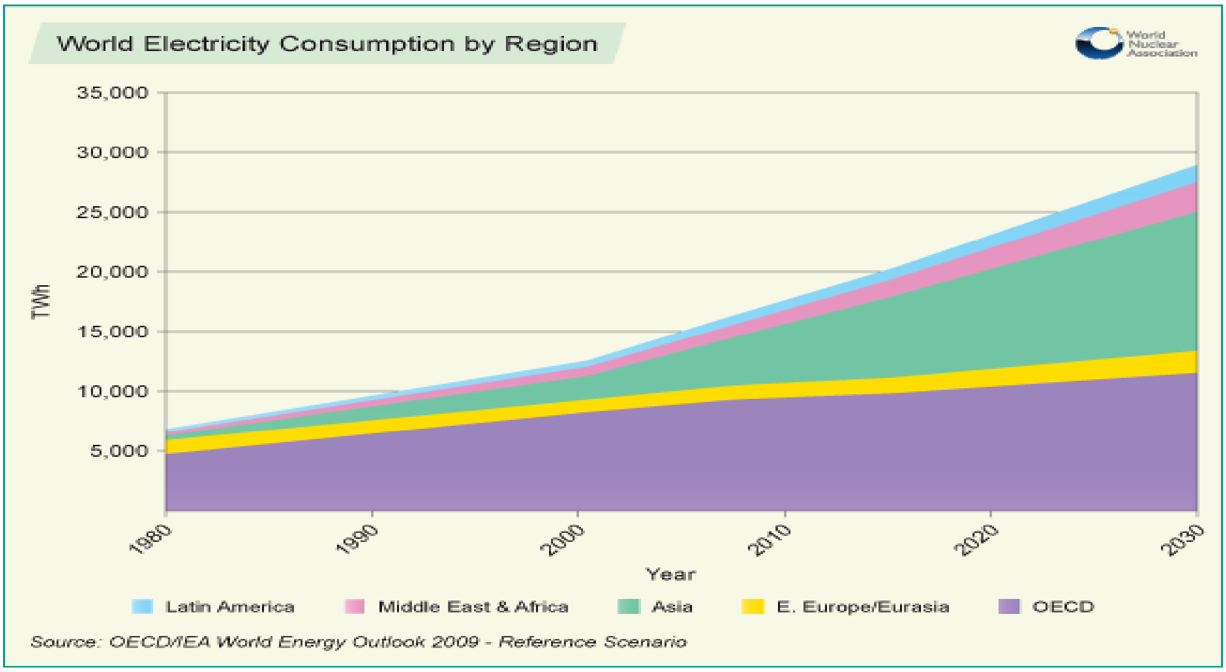
1.0 Overview

Energy is a critical ingredient for any economic development the world over; and it provides an essential constituent for almost all human activities - (cooking, lighting, health, education, etc.). Therefore, access to clean and affordable modern energy is crucial to fostering lasting social and economic development globally.

1.1 World energy scenario

It is currently estimated that around 1.2 billion people (about 17 percent of global population) in the world have no access to electricity (World Nuclear Association, 2017) and that 1 billion more having access only to unreliable electricity networks (WEO, 2016). Figure 1.1 shows global electricity consumption by region presenting Middle east and Africa with one of the least consumption of electricity (WEO, 2009). Furthermore, about 2.5 billion people rely on traditional biomass for cooking and heating. However, smoke from polluting and inefficient cooking, lighting, and heating devices kills nearly 2 million people a year and causes a range of illnesses and other health related problems (WEO, 2016).

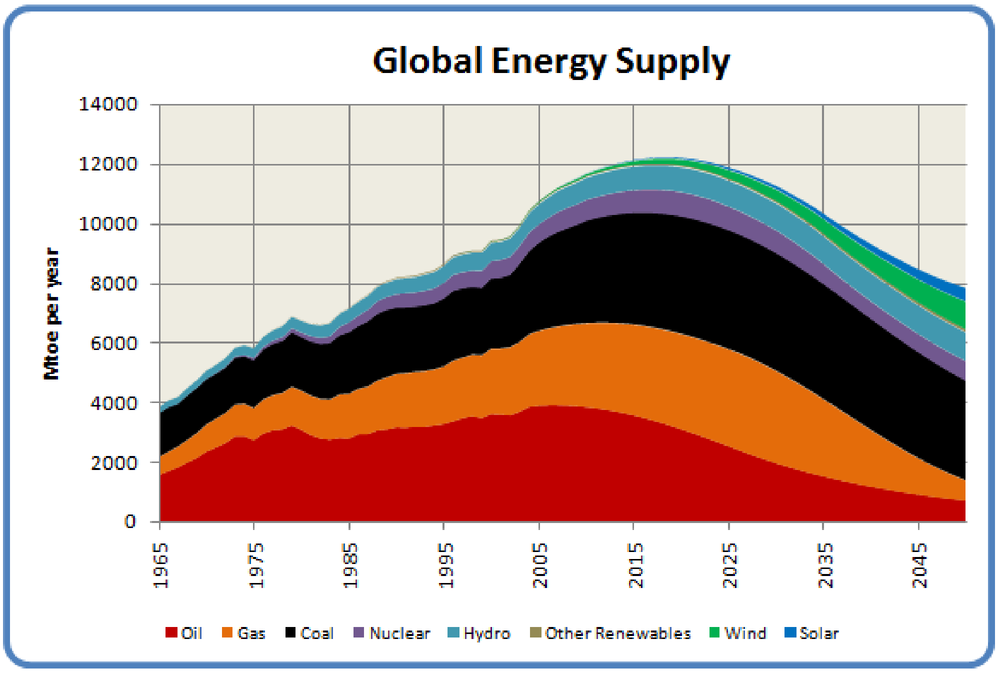
Green-House Gases (GHG) are the main drivers of climate change and local environmental degradation (Foundation, 2013).



Source: OECD/IEA World Energy Outlook, 2009

Figure 1.1: World Electricity Consumption by Region

Furthermore, reliance on oil importation has a direct effect on the national energy security and has become one of the most challenging problems that require to be tackled as the fossil sources are rapidly diminishing. A glance beyond the fossil sources is critical for long term energy security and sustainability as there are several uncertainties about the fossil sources supplies coupled with the greater environmental dangers encountered from fuel utilization. Renewable energy comes from natural resources such as sunlight, wind, tides, and geothermal heat, which are renewable -naturally replenished. As at 2014, about 19.2 percent of global final energy consumption come from renewables, with 8.9 percent coming from traditional biomass, which was mainly used for heating, and 3.9 percent from hydroelectricity. Renewable Energy Sources i.e. small hydro, modern biomass, wind, solar, geothermal, and biofuels accounted for another 10.3 percent. The share of renewables in *electricity generation* is around 19 percent, with 16 percent of global electricity coming from hydroelectricity and 3 percent from other renewables e.g. biomass (REN21, 2016). Figure 1.2 shows the projected global energy supply from several energy sources.



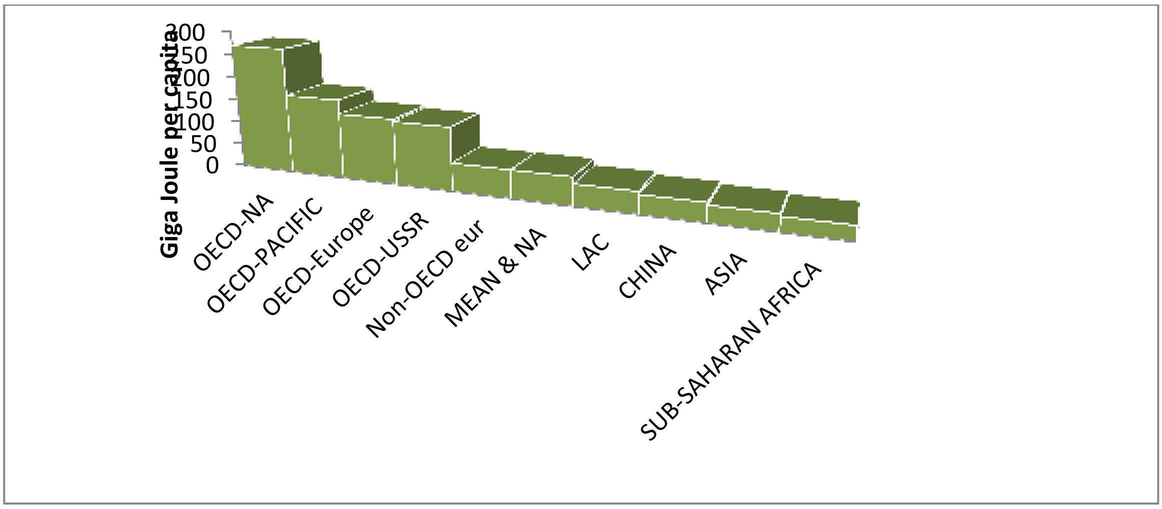
Source: Paul Chefurka/World energy to 2050, 2007

Figure 1.2: Global Energy Supply

1.2 Overview of the energy situation in Africa

Africa has a landmass of over 30.3 million km^2, an area equivalent to the United States of America, Europe, Australia, Brazil, and Japan combined. As of 2004, Africa housed 885 million people (Nyangarika, 2015) in 53 countries of varied and diverse sizes, socio-cultural entities, and resource endowments, including fossil and renewable energy resources. Most of these energy resources were yet to be exploited, which is a contributing factor in making the continent the lowest consumer of energy, as illustrated in Figure 1.3. An African uses only one eleventh, one sixth, and one half of the energy used by a North American, a European, and a Latin American, respectively (IEA, 2014). Therefore, a need for substantial increases in energy consumption in Africa as a whole, if Africa is to be competitive with other developing regions of the world. Africa currently constitutes 14 percent of the world's population, but accounts for only 2 percent of GDP. Although the continent produces 5.2 percent of the world's total energy, it only consumes 3 percent of it. Furthermore, energy intensity in Africa is twice the world average (IEA, 2014). The use of modern energy services is closely linked to development, poverty reduction, and the provision of vital services, but consumption of modern energy sources in sub-Saharan Africa is extremely low (WEO, 2016) owing to the region's reliance on *traditional biomass*.

Traditional biomass in the form of firewood and charcoal is widely used in Africa for providing heat energy in households. However, the methods adopted in the use of woodfuel are *inefficient* and as a result pressure on biomass resources increases, e.g. resulting in deforestation and desertification (Adhola, 2014). Residues from agriculture and forestry can provide major opportunities for modern biomass energy in the region. Mauritius, Kenya, Tanzania, Egypt and *Zambia* are exploiting bagasse for the generation of electricity. Ethanol from sugar cane is also produced as an additive to gasoline in some African countries. There is also potential for biodiesel production and use (UNCTAD, 2014); (WEC, 2016).



Source: IEA, 2000

Figure 1.3: Per Capita energy use (commercial and non-commercial) by world region, 2000

1.3 Energy challenges in Sub-Saharan Africa

The energy challenges in sub-Saharan Africa are many, and they impact seriously on the overall performance of the region's social and economic indicators. Access to electricity, a generally accepted indicator for overall socio-economic development of any country or region, is low in sub-Saharan Africa. Only 53 percent and 8 percent of urban and rural populations, respectively, have access to electricity as compared to 99 percent and 88 percent, respectively, in northern Africa. A few countries in the region, such as Ghana, Mauritius, South Africa, and Zimbabwe, are above the average. The rural areas of sub-Saharan Africa pose specific challenges, mainly because of their low population density and remoteness to the national electricity grid, both of which result in high costs of production, transmission, and distribution of electricity. The energy production-to-consumption ratio is high in Africa, largely due to poor regional and sub-regional networks, as well as to the heavy reliance on external financing (Oliver et al, 2016).

The poor energy demand base due primarily to Africa's low level of industrialization is also a contributing factor. Most countries have not mobilized local finances for energy resource development, though external private investments and official development assistance (ODA) are declining. Hence, energy investments are far below the required level to satisfy the region's needs. Unfortunately, though foreign direct investment (FDI) to the region has shown some increase, it is mainly confined to upstream oil extraction development and limited to less than 10 percent of the countries in the region (Davidson, 2006). There is an urgent need to identify innovative means of financing fossil and renewable energy development.

Electricity, the most important energy source in the delivery of the all-important modern functions such as health, education, lighting, and social services, accounts for only 4 percent of sub-Saharan Africa's total energy consumption. Moreover, in sub-Saharan Africa, between 1980 and 2000, electricity consumption declined from132.6 kWh to 112.8 kWh per capita, even as the world average energy consumption increased substantially (IEA, 2014).

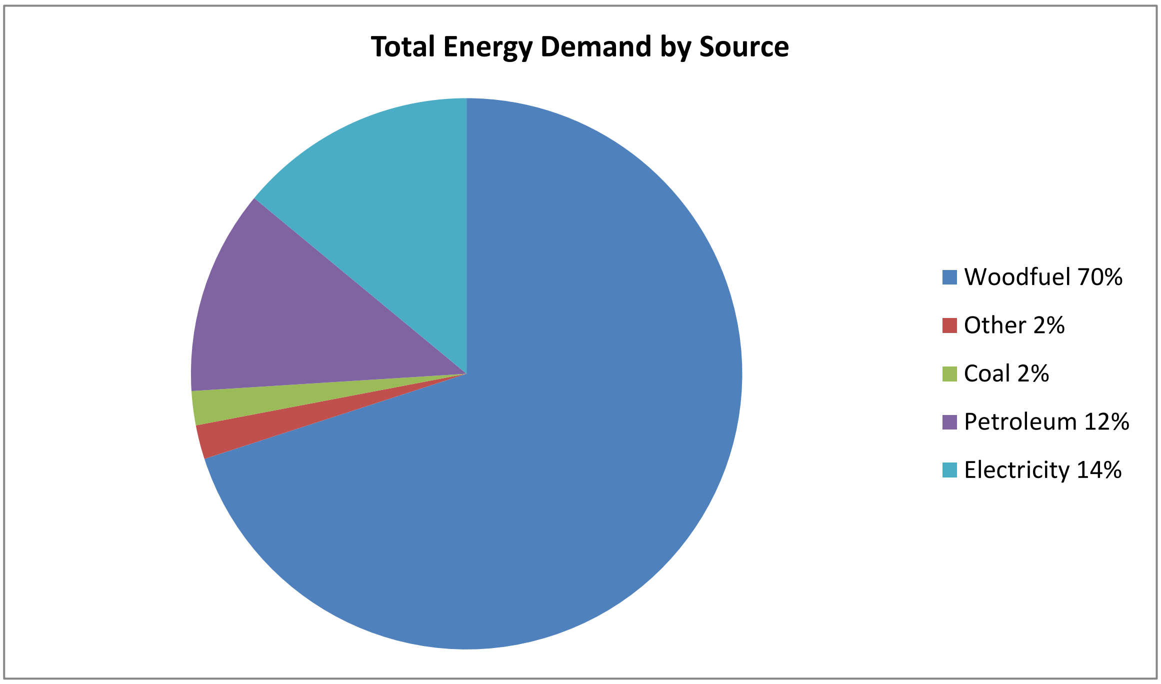
For rural sub-Saharan Africa, where the majority of the African population lives, the reality is worse. Energy-intensive projects should include improved efficiency for economic activity and production/mobility. Sub-Saharan Africa also has significant amounts of renewable energy yet to be exploited (Oliver et al, 2016). Furthermore, renewable energy technologies (RETs) have demonstrated a growing potential to meet energy needs where conventional energy supply options have failed. The costs of any Renewable Energy Technologies (RETs) are also declining with technology improvements and economies of scale in production. For instance, solar and wind power costs are now half of what they were in the mid-1990s (Oliver et al, 2016).

There is also potential to develop modern biomass technologies in Africa such as, *biogas*, ethanol, biodiesel, wood briquetting, wood pelleting, and modern charcoal. Hence there is a need to search for ways that ensure greater use of RETs in Sub-Saharan Africa.

1.4 Overview of Zambia's Energy Sector

1.4.1 Energy Consumption

The energy consumption pattern in Zambia is largely dominated by households and mining. The household sector accounts for 58 percent of total final energy consumption. The largest share of energy consumption by household is attributed to the dependency on firewood which alone accounts for about 80 percent of total household energy consumption (ERB, 2014). Figure 1.4 shows the total energy demand by source.



Source: .UNEP, 2008

Figure 1.4: Total energy demand by source

The significance of the pattern of energy production, conversion and consumption in ensuring sustainable development necessitates stock taking of national energy supplies and demands so as to enable adequate policy formulation. Woodfuel, the only non-commercial energy resource, constitutes 70 percent of the energy consumed in the country through its use as firewood in rural areas and as charcoal in urban areas. Hydropower with an existing installed capacity of 1,670 MW supplies 94 percent of the country's electricity and meets 14 percent of the national energy demand. Shares of electrical energy consumed in mining, industry, household, government and agriculture sectors are 72 percent, 10 percent, 8 percent, 7 percent and 3 percent, respectively. With average annual output of about 470,000 tonnes and enormous reserves of over 80 million tonnes, coal is also abundant and meets 2 percent of the national energy demand. Mining and industry have nearly equal share to account for over 90 percent of the domestic coal consumption. Petroleum contributes 12 percent of the energy demand and is totally imported. Its share in transportation, mining, industry, household, agriculture and services sectors is 49 percent, 27 percent, 14 percent, 4 percent, 3 percent and 3 percent, respectively (Masiliso, 2008).

1.4.2 Renewable energy in Zambia

There are various kinds of renewable energy sources besides micro-hydro and solar power, such as biomass, geothermal, and wind-power. Zambia is said to have more or less a potential of the said renewable energy sources, and the Zambian Government has been keen on expanding the use of renewable energy (ZDA, 2014), which could contribute towards solving issues; such as:

- Achieving the diversity of energy source,
- Increasing the electrification rate in rural areas since renewable energy is an on-site energy source and it is generally available in rural areas, and;
- Improving the living standards of residents in impoverished rural areas, then improving their health condition and educational level, and reducing endemic diseases such as HIV/AIDS.

Table 1.1 shows the classification of Bioenergy Resources.

Table 1.1: Classification of bioenergy resources

Category	
Dedicated plantations	• *Short-rotation forestry* – eucalyptus, willow.*Perennial crops* – miscanthus*Arable crops* – sugarcane, cassava, groundnuts, soybeans, sunflower, Jatropha.
Residues	• Wood from forestry thinning; • Wood felling residues; • Straw from cereals; • Other residues from food and industrial crops (sugarcane, tea, coffee).

By-products and wastes	• Sawmill waste; Manure; Sewage sludge; Organic fraction of municipal waste; Used vegetable oil and fats.

Source: SNV, 2016

Despite a huge potential for bioenergy in Zambia, many issues to be improved still remain unsolved that are indispensable for the expansion of renewable energy, such as:

- Procurement of funds from Government subsidies, private sector investments and donor funds,
- Improvement of organization to operate and maintain the system,
- Settling technological hurdles, and
- Encouraging the equipment and materials market.

At the moment, the Government presents only policy outlines regarding the utilization of renewable energies and there is no specific program. Based on the basic data and the latest technical information, it is necessary to review the possibility of utilization of renewable energies (ERB, 2014).

1.4.3 Biomass resource and electricity potential in Zambia

SNV (2016) determined the biomass resource potential and the corresponding power/energy from agriculture, forest, solid and liquid municipal, and animal waste in Zambia. The total actual electrical power from bioenergy was estimated at 327.26MW. The estimated contribution from agriculture being 299.92MW, waste (5.0MW), municipal solid and liquid waste (20.78MW), and animal waste (81.56MW). This potential represents 13.6 percent of the total energy demand of approximately 2,400MW (SNV, 2016).

Furthermore, Zambia's suitable climate, vast arable land and abundant water resources has the potential to promote cultivation of energy crops for bio-fuel production. For example, Nakambala Sugar has potential to produce 40 million litres of bio-fuel annually, based on their available molasses (SNV, 2016).

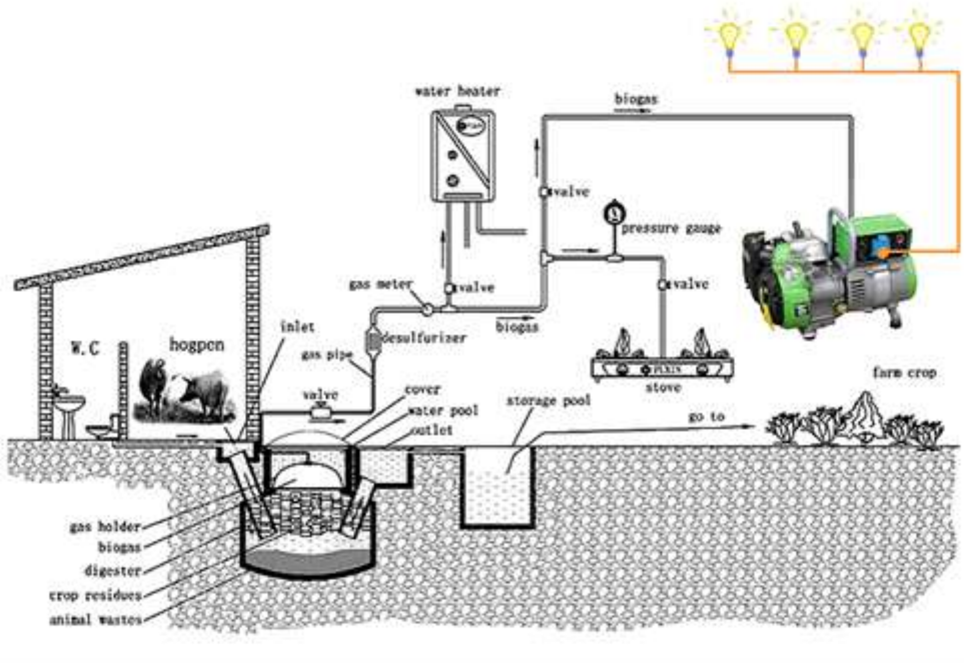
1.5 A review of biogas production for electricity generation

Electric power demand in Zambia constitutes about 11 percent of total national energy demand (SNV, 2016). The dominant energy source being woodfuel (firewood and charcoal), over which more than 90 percent of the rural population depends to meet its domestic energy needs. There is a close correlation between the high prevalence of poverty in rural areas and the low access to electricity which averages about 5 percent. Increased application of electricity would increase productivity and incomes, and therefore greatly reduce poverty in rural areas. The main reasons for non-adoption of clean technologies, including biogas, comprise of limited awareness of off-grid technology options, high (up front) cost of installation and limited quality awareness among the few providers (SNV, 2016).

About 65 percent of the Zambian population live in rural areas. The rural population tends to be dispersed and poor, making provision of *on-grid electricity* services both difficult and un-economical. Nonetheless, sustainable energy is seen as critical to improving local development and stimulating local value addition. Given the size of the country, the dispersed nature of the population, the high agricultural potential, the availability of water and land, there is ample scope for development of *decentralized* energy solutions using alternative biomass energy sources such as ***biogas*** among other biomass energy sources. Bio-digesters fed with bio degradable materials such as cow dung as a raw material, and other biomass resources, can play a vital role in the country (Chae K. et al, 2016). Using biogas for direct combustion in household stoves or gas lamps is somewhat common, whereas, producing electricity from biogas is relatively rare in Zambia (SNV, 2016).

Biogas is produced during anaerobic digestion processes. The raw materials used are: waste water, solid waste, organic waste, (e.g. animal manure), and other sources of biomass. The gas (biogas) can be used in a gas engine and modified gasoline, or diesel internal combustion engine for electricity generation or used to produce steam which is then expanded on a steam reciprocating internal engine to produce electricity. Great opportunities, e.g. for Zambia, exist for producing electricity from poultry farms with a capacity of 100,000 chickens per farm. There are quite a good number of farms with such a good capacity that include: Crest Zambia, Country Choice, Copperbelt Chickens, Supreme Choice, Zamchick, Golden Lay, and Colchi Farms Limited. Equally there are dairy farms with reasonable numbers of cattle e.g. Kusiya and Rosedale Farms who could install biogas generating plants for electricity generation (SNV, 2016).

The share of electricity produced from renewable energy is constantly increasing e.g. in Germany and worldwide. Biomass, more precisely energy from biogas, has the potential to generate electricity flexible on-demand. A demand-driven biogas production is vital for balancing power generation and can generally be achieved by biogas storage or flexible biogas production concepts (Hahn, 2014).



Source: Energypedia, 2011.

Figure 1.5: Biomass conversion to electricity

Table 1.2 shows data on the potential biogas yields of feedstocks commonly used in anaerobic digestion.

1.6 Problem statement

Although the biogas sector is slowly growing in Zambia, the emphasis is mainly bias to biogas production for cooking (ERB, 2014). Here, direct combustion of the gas is employed. However, generating electricity using biogas would prove to be a better option sine electric energy is multipurpose.

The conventional use of biomass has other challenges, for example:

1. Deforestation which would in turn bring about desertification.
2. Green House Gases (GHG) which are the main drivers of climate change as a result of carbon dioxide being released in the atmosphere during direct combustion.
3. Besides, the use of woodfuel and fossil fuels has a negative impact on the environment and on people's health. About 1.3 million deaths are reported annually worldwide from toxic fumes due to burning firewood particularly indoors (Denis, 2011).

In Zambia, electricity on the national grid has remained scarce and inaccessible (EIZ, 20140) to a large segment of the population (97.9 percent of the rural household who solely depend on fuelwood for cooking while only 1.7 percent has access to electricity) (ERB, 2014).

1.6.1 Research questions to be answered

1. Can biogas, and feedstock quantities be predicted for electricity generation using mathematical models?
2. How can biogas production systems be designed for small-scale electricity generation (50 to 500 kW) to satisfy the required demand?
3. How can electricity user pattern at a selected farm be determined so as to facilitate the determination of the required biomass resource potential?
4. Can a biogas plant for the farm be designed that will achieve an optimum biogas yield under different climatic conditions in a year?
5. Would predicted results match actual (field experimental) results?

1.6.2 Objectives of the Study

1.6.2.1 General objectives

i. Develop models for biogas, and feedstock required to generate electricity for a case in Zambia.

1.6.2.2 Specific objectives

i. To develop models which predict the amount of biogas, and feedstock required to generate electricity in the range of 50 to 500kW;

ii. To compare biogas and feedstock quantities needed to generate the same amount of electricity using a different approach against the baseline (i);

iii. To determine the potential biogas and electricity production for a selected farm to meet its energy needs;

iv. To determine an optimum temperature for maximum biogas production rate under Zambian climatic conditions and feedstock characteristics.

1.7 Benefits of the research

This research study will contribute to the subject's knowledge base in the following ways:

i. The provision of a specific approach for selecting suitable digester types with respect to local condition and design configurations;

ii. A thorough understanding and better approach to digester design, operations and maintenance;

iii. Provision of a locally developed detailed and in-depth understanding of biogas to electricity generation for a case in Zambia.

1.8 Justification of the research

Based on the literature reviewed, biogas production in Zambia finds its main application in cooking, heating and lighting only; and no direct mention is found so far on projects for electricity generation. Therefore, this research considered in detail the efficient production of biogas to generate electricity on a small-scale.

How biogas production rate could be predicted and optimized using local substrates - was not known as there was lack of evidence of any systematic or scientific investigations of biogas production rate from digesters used in Zambia. Consequently, in this research models were developed to predict and optimize the biogas production rate.

The total generation sent out from both ZESCO and Independent Power Producers (IPPs) power plants declined by 7.0 percent (1,013 GWh) in 2015. Electricity sent out reduced from 14,453 GWh in 2014 to 13,440 GWh in the same period. In 2015, national electricity consumption increased by 6.8 percent, from 10,720.5 GWh in 2014 to 11,449.9 GWh in 2015. The increase in consumption was mainly attributed to increased demand from the mining sector. Consumption from the mining sector increased by 6.4 percent, from 5,871.3 GWh recorded in 2014 to 6,245.6 GWh in 2015 (ERB, 2015).
However, Shane reported that there is a theoretical biogas potential of 76PJ (2,283MW) per annum from animal manure and crop residues. This is sufficient to provide energy for cooking and lighting in more than 3 million households (Shane, 2015). For electricity generation, this gives about 799MW

1.9 Brief chapter overviews

In addition to this introductory chapter, the thesis also includes chapter 2, 3, 4, 5, 6 and 7. Chapter 2 reviews the literature in the field of biogas production for small-scale electricity generation. In chapter 3, a detailed methodology is presented. Chapter 4 presents results and discussion and chapter 5 presents the conclusion and recommendations.

CHAPTER 2 LITERATURE REVIEW

2.1 Overview

This chapter presents the literature reviewed in connection with enhanced biogas production rates using digesters mainly for electricity generation.

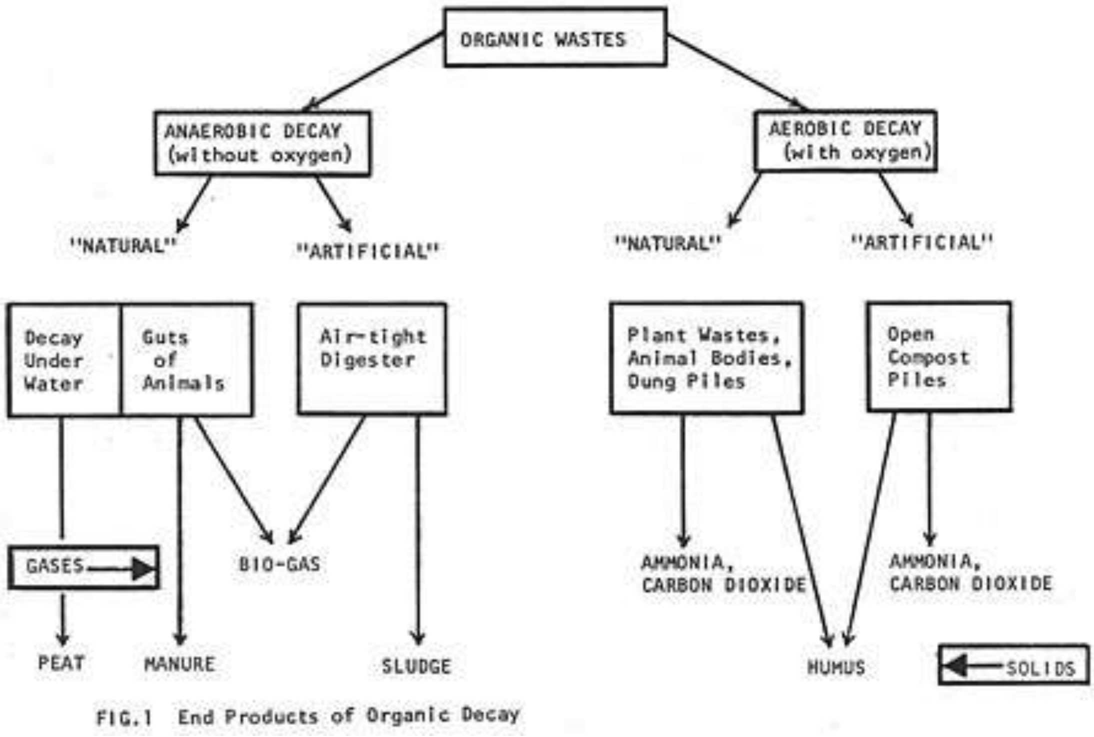
2.2 Theory and research literature specific to research topic

2.2.1 Theory

Biogas is an established fuel for cooking, lighting, space heating, and electricity generation among other uses in several countries. It is a mixture of about 60 percent methane and 40 percent CO_2 which is formed when organic matter, such as animal manure and plant matter decay by microbiological action in the absence of oxygen. This process is called anaerobic digestion, at somewhat raised temperatures mostly between 30-40^{o}C and 50-60^{o}C. (Harilal et al, 2012).

Anaerobic digestion is a series of biological processes in which micro-organisms break down biodegradable material in the absence of oxygen. One of the products being biogas itself, which is combusted to generate electricity and heat, or could be processed into renewable natural gas (RNG) and transportation fuels.

That is, when organic material decays, it yields useful by-products. The kind of by-product depends on the conditions under which decay takes place. Decay can be *aerobic* (with oxygen) or *anaerobic* (without oxygen). Any kind of organic matter can be broken down either way, but the end products will be quite different as presented in Figure 2.1.



Source: Fry, 1973

Figure 2.1: End products of organic decay

It is possible to imitate and hasten the natural anaerobic process by feeding organic wastes - manure and vegetable matter etc. - into insulated, air-tight containers called digesters. Digesters are of two types:

i. Batch-load digesters –these are digesters which are filled all at once, sealed, and emptied when the raw material has stopped producing biogas; and

ii. Continuous-load digesters – these are the ones which are fed a little, regularly, so that biogas and the digestate are produced continuously.

The digester is fed with a mixture of water and wastes, called slurry. Inside the digester, each daily load of fresh slurry flows in one end and displaces a corresponding load on which bacteria and other microbes have already digested. Each load progresses down the length of the digester (fermentation channel) to a point where the methane bacteria are active. At this point large bubbles force their way to the surface where biogas accumulates. The gas can be scrubbed and burned directly for heat, which can be used for electric power generation. It can further be processed to remove carbon dioxide and compressed to produce natural gas. Biogas is similar to natural gas, and can be used in motor vehicles after a certain amount of processing. Digestion gradually slows down toward the outlet end of the digester and the residue begins to stratify into distinct layers as shown in Figure 2.2.

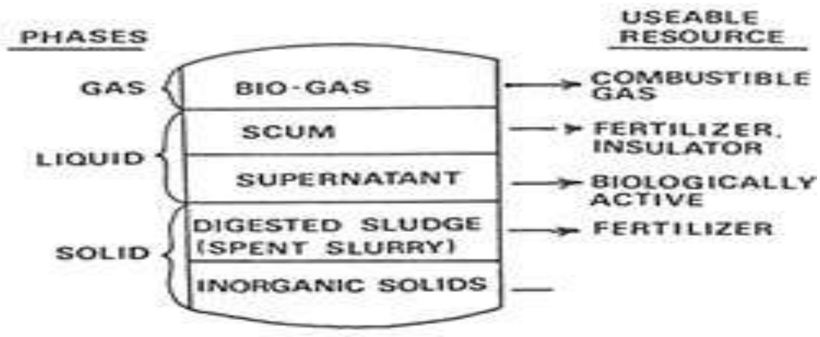


FIG.2 Layering of By-Products In the Digester

Source: Fry, 1973

Figure 2.2: Layers of by-products in the digester

- Sand and Inorganic Materials at the bottom.
- Sludge, the spent solids of the original manure reduced to about 40 percent of the volume it occupied in the raw state. Liquid or dry sludge makes an excellent fertilizer for crops and pond cultures.
- Supernatant, the spent liquids of the original slurry. Note that the fertilizing value of the liquid is as great as sludge, since the dissolved solids remain.
- Scum, a mixture of coarse fibrous material, released from the raw manure, gas, and liquid. The accumulation and removal of scum is one of the most serious problems with digesters. In moderate amounts, scum can act as an insulation. But in large amounts it can virtually shut down a digester (Fry, 1973).

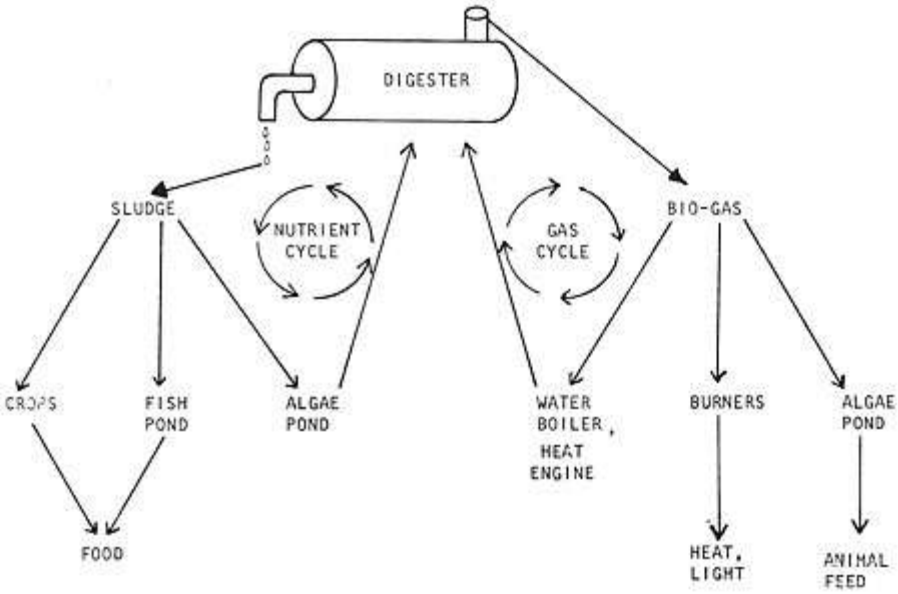
When considering digesters on medium-scale electricity generation, there are two general issues to consider:

i. With the organic wastes and resources at hand, what kind of digester should be built, and how big should it be?

ii. What is the best way of using the gas and sludge produced to satisfy the energy needs of the people involved other than electricity generation?

Whether the sludge should be used to fertilize crops, fish or algae ponds, and whether the gas should be used directly for heat, and light, or stored, or fed back to the digester to heat it, or generate electricity etc. (Denis et al, 2001).

The first aspect involves the digester itself, which is just the heart of a whole energy system or plant. The second one is synergistic; where there is a choice as in, on which products are to be generated by digestion and how to use them or feed the m back to the digester, creating almost an endless cycle. See Figure 2.3.



Source: Fry, 1973

Figure 2.3: The closed nutrient system of a complete digester operation.

The model in Figure 2.3 is idealized from oriental aquaculture systems and other ideas, both old and new. A single pathway can be developed exclusively - have a digester produce only sludge to feed an algae pond or one can develop the potential synergy i.e. many possible systems working together as an integrated whole.

It is now evident that total dependence on conventional fuels, especially in rural areas, is likely to become a serious handicap in the years to come as reserve shortages and specialized technologies hike the costs of fossil and nuclear fuels. But by producing energy from local resources, it is possible to be partially freed from remote sources of increasingly expensive fuel supplies.

Digestion is a biological process. Anaerobic bacteria cannot survive with traces of oxygen. So, because of the oxygen in the manure mixture fed to the digester, there is a long period after loading before actual digestion takes place. This process involves a series of reactions by several kinds of anaerobic bacteria feeding on the raw organic matter. As different kinds of these bacteria become active, the by-products of the first kind of bacteria provide the food for the other kind. Biologically, then, successful digestion depends upon achieving and (for continuous-load digesters) maintaining a balance between those bacteria which produce organic acids and those bacteria which produce methane gas from the organic acids. This balance is achieved by a regular feeding with enough liquid and by the proper pH (6.4), temperature and the quality of raw materials in the digester (Monnet, 2003).

2.2.1.1 Overview of biogas conditioning and utilization

Depending on the final use, different biogas (raw or crude biogas) treatment steps are necessary since the raw gas is mainly composed of methane. The three main contaminants in biogas are: carbon dioxide ($CO_{2)}$, hydrogen sulfide (H_2S), and water vapour which can lead to setbacks when utilizing biogas as a renewable source of energy such as *Renewable Natural Gas (RNG)* (Hidolgo et al, 2016).

For some applications, such as its use in Combined Heat and Power (CHP) plants, and gas engines, biogas can be scrubbed to remove water vapour and hydrogen sulfide. This is also applicable in steam production equipment. The process is known as scrubbing. However, upgrading of biogas involves the removal of carbon dioxide resulting in increased energy density since the concentration of methane is increased to above 95 percent. The process of upgrading biogas can substitute natural gas or compressed natural gas. The upgraded biogas (RNG) can be compressed and used in motor vehicle engines. It can also be used in fuel cells for power generation (Hidolgo et al, 2016).

Thus, biogas cleaning/scrubbing is the first necessary step in biomethane production. This helps in preventing corrosion and mechanical wear in gas engines, steam producing equipment, and also in the upgrading of equipment, in which case the gas needs to be upgraded (Hidolgo et al, 2016). Biogas always contains water vapour which has to be removed to avoid corrosion in pipelines and equipment. Water can be eliminated by physical separation (cooling and compression) and chemical drying (absorption and adsorption) (Rychebosch, 2011). Refrigeration or cooling, preceded or not by compression, is the simplest way of removing excess water vapor. The condensed water can be then separated using demisters, cyclones or water traps (Hidolgo et al, 2016). Adsorption using alumina, silica or zeolites is the most common technique. Also, hygroscopic salts or triethylene glycol can be used.

Removal of hydrogen sulfide (H_2S) concentration in the biogas can be reduced by preventing its migration to biogas during digestion process or by treating the gas stream (Kulkarni et al, 2014). In the first case, the addition of iron ions to the digester precipitates the iron sulfide that will leave the rector with the digestate. In the second case, adsorption on activated carbon, iron oxide or hydroxide (Cherosky et al, 2013), washing with sodium hydroxide or biological treatment are all well-known options. H_2S can also be separated from the biogas by leading the gas by a semi-permeable membrane. Hydrogen sulfide promotes corrosion of equipment e.g. on gas engines (Hidolgo et al, 2016).

Biogas upgrading technologies: Depending on the intended use of the gas, biomethane consists typically of 97 to 99 percent methane and 1 to 3 percent carbon dioxide. Several technologies for biogas upgrading to produce biomethane are available. Some of them are described below and reviewed in terms of recent developments (Hidolgo et al, 2016):

Absorption: - Carbon dioxide is more soluble than methane and the absorption technique is based on this fact. Absorption is usually carried out in a packed absorption column. Biogas is introduced to the bottom of the column and flows up. The *selected* liquid enters the column at the top and flows downward, so that mass transfer occurs in a counter-flow way. Purified biogas (biomethane) leaves the column at the top and the liquid saturated with carbon dioxide is let out at the bottom. Examples of the absorption technology using different types of absorbents are water scrubbing, organic physical scrubbing and chemical scrubbing.

Water Scrubbing: - This process also enables to remove simultaneously hydrogen sulfide (H_2S), hence pretreatment for H_2S is not necessary. Water scrubbing is the most common upgrading technique (Hidolgo et al, 2016).

Organic Physical Scrubbing: - Instead of water, polyethylene glycol and other ionic solvents can also be used. H_2S, CO_2 and water vapour can be absorbed together, since they have a higher solubility in polyethylene glycol than methane. About 90 percent is the maximum methane yield reported for biomethane with this method (Zhang et al, 2015).

Chemical Scrubbing: - The most employed solvents in chemical scrubbing are amides (monoethanolamine, diethanolamine or diglycolamine), which in comparison to water can dissolve considerably much more CO_2 per unit volume. This method requires previous H_2S removal and later amino solution regeneration, usually by heating (Niesner et al, 2013).

Adsorption: - Pressure Swing Adsorption (PSA) separates CO_2 from the biogas using a sieve filled with an adsorbent (activated carbon, silica-gel, alumina, zeolite, etc.) under elevated pressure. The concentration of CH_4 can be more than 98 percent after this upgrading process. PSA can separate CO_2, but also oxygen (O_2), H_2S and nitrogen (N_2), from CH_4. Effectiveness of simultaneous H_2S and CO_2 capture depends on water content on the biogas. It is usually better to separate the H_2S previously to avoid any potential destruction of the adsorbent when water is present (Lestinsky et al, 2015).

Membranes: - Conventional membrane-based gas separation is commonly done by gas permeation, with a gas phase at both sides of the membrane. Gas-gas separation is a high-pressure system. Membranes can be made of silicone rubber, cellulose acetate or polyimides. Usually, membranes are in the form of hollow fibers bundled together. The raw gas can be purified to a maximum of 92 percent methane in one step. When two or three steps are used, a gas with 96 percent or more methane could be achieved. The appropriate cleaning is required for any undesirable compound in biogas and the intensity of the cleaning depends on membrane material (Scholz, 2013). Thus, biogas has many energy utilizations as shown in Figure 2.4, which depend on scrubbing or/and upgrading processes.

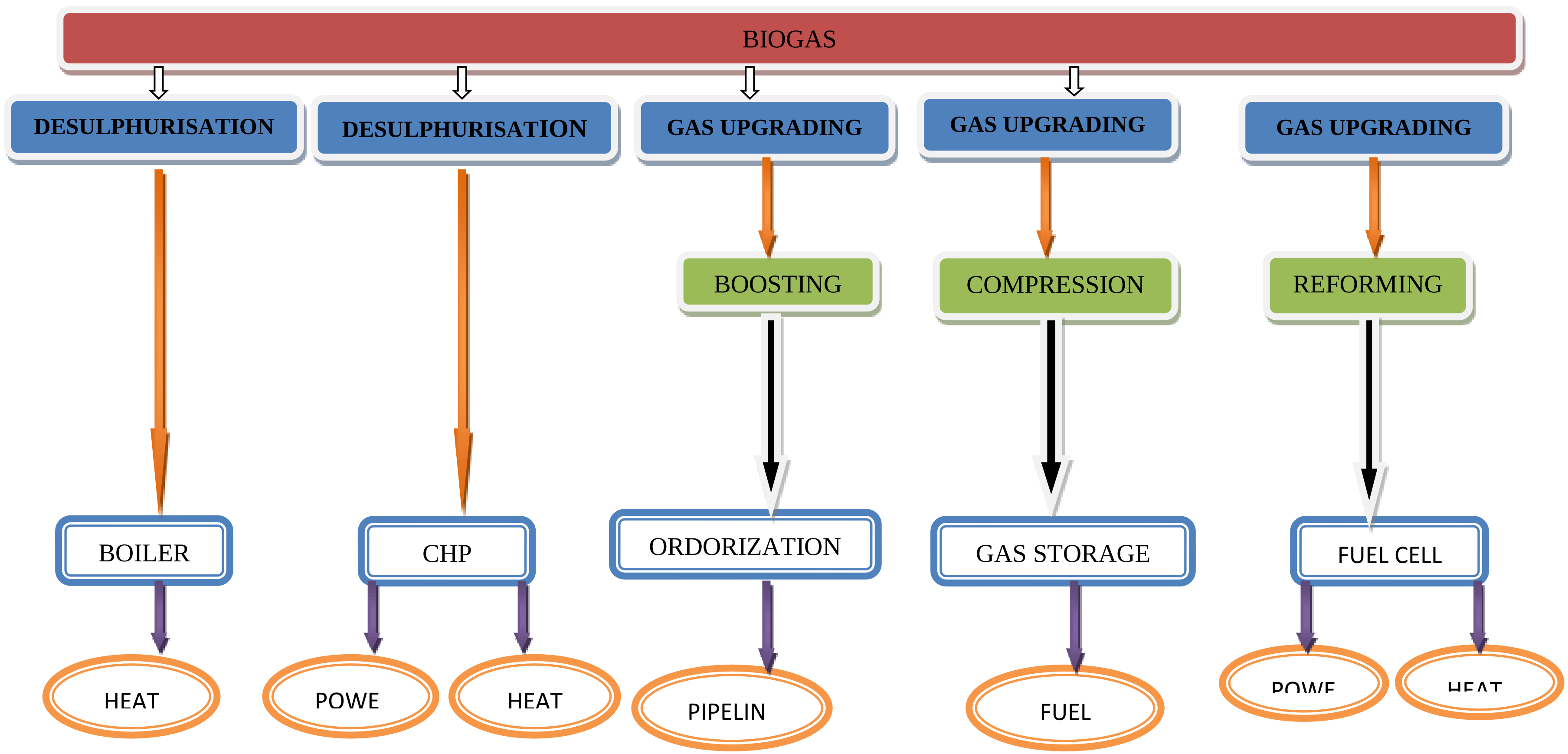


Figure 2.4: Multiple paths through which biogas can be used as renewable energy/fuel (Weiland, 2006).

Table 2.1: Methane (CH_4) yield from Anaerobic Digestion (AD) of different plant material (Braun et al., 2010)

CH_4 Yield (m^3 per tonne VS)			
Maize (whole crop)	205–450	Barley	353–658
Wheat (grain)	384–426	Triticale	337–555
Oats (grain)	250–295	Sorghum	295–372
Rye (grain)	283–492	Alfalfa	340–500
Grass	298–467	Sudan grass	213–303
Red clover	300–350	Ryegrass	390–410
Hemp	355–409	Nettle	120–420
Flax	212	Miscanthus	179–218
Sunflower	154–400	Rhubarb	320–490
Oilseed rape	240–340	Turnip	314
Jerusalem artichoke	300–370	Kale	240–334
Peas	390	Chaff	270–316
Potatoes	276–400	Straw	242–324
Sugar beet	236–381	Leaves	417–453
Fodder beet	420–500	-	-

2.2.2 Optimization of efficiency of a biogas digester.

Anaerobic digestion depends on several different parameters for an optimum performance. Different microorganisms are involved in the biogas production and optimal conditions have to be established to keep all the microorganisms in balance. That is, the operating parameters of the digestion must be controlled so as to enhance the microbial activities and hence, increase anaerobic digestion efficiency. Some of these parameters are: pH, temperature, mixing rate, substrate characteristics, C/N ratio, and hydraulic retention time (HRT). Digestion is a slow process and it takes at least three weeks for microorganisms to adapt to new conditions when there is a change in substrate or temperature (Dobre et al, 2014).

Temperature: - The two conventional operational temperature levels for anaerobic digesters determine the species of methanogens in the digesters (Dobre et al, 2014):

- Mesophilic digestion takes place *optimally* around 30 to 38 °C, or at ambient temperatures between 20 and 45 °C, where mesophiles are the primary micro-organism present.

- Thermophilic digestion takes place optimally around 49 to 57 °C, or at elevated temperatures up to 70 °C, where thermophiles are the primary micro-organisms present (Dobre et al, 2014).

However, the optimum temperature for digestion can vary depending on the composition of the feedstock and type of digester used. But in most anaerobic digestion processes, it should be maintained relatively constant to sustain the gas production rate.

Thermophilic digesters are more efficient in terms of retention time, loading rate and normally gas production rate as well; but they need a higher heat input and have a greater sensitivity to operating and environmental variables – which make this process more problematic than mesophilic digestion (Monnet, 2003).

pH: - The optimum pH values for acidogenesis bacteria and methanogenesis stages are different. During acidogenesis, acetic, lactic and also propionic acids are formed and then the pH falls. And low pH can inhibit acidogenesis activities – pH below 6.4 can be toxic for methane forming bacteria. The optimum range for methanogenesis is between 6.6 and 7.0 though an optimum pH for all is between 6.4 and 7.2 (Monnet, 2003).

Hydraulic Retention Time (HRT): - Most anaerobic systems are designed to retain the feedstock or waste for a fixed number of days. The number of days the feedstock is retained in the tank is called the Hydraulic Retention Time (HRT). The Hydraulic Retention Time equals the volume of the tank divided by the daily flow (HRT=V/Q). This parameter is important since it establishes the quantity of time available for bacterial growth and subsequent conversion of the organic matter to biogas. A direct relationship exists between the hydraulic retention time and the volatile solids converted to gas. Also, the retention time varies with process parameters such as process temperature and waste composition (Dennis, 2001).

Loading Rate: - A more appropriate measure of the waste on the digester’s size and performance is the loading rate. Feeding the system above its sustainable rate results in low biogas yields due to accumulation of inhibiting substances in the digester slurry e.g. fatty acids. Under such circumstances, the loading rate of the system must be reduced. The loading rate is particularly an important parameter in continuous systems. Many plants have reported system failures due to overloading (Monnet, 2003).

C/N ratio: - The relationship between the amount of carbon dioxide and nitrogen present in the organic matter is represented by the C : N ration (Carbon – Nitrogen ratio). The optimum C : N ratio in anaerobic digesters is 20:30. A high C:N ratio is an indication of a rapid consumption of nitrogen by the methanogens and results in lower biogas yields. On the other hand, a lower C : N ratio causes ammonia accumulation and pH values exceeding 8.5; that which is toxic to methanogenic bacteria. Thus, the optimum C : N ratio of feedstocks can be achieved by mixing waste of low and high C : N ratios, such as organic solid wastes mixed with sewage or animal manure (Monnet, 2003).

Mixing: - Mixing within the digester improves the contact between the micro-organisms and substrate. It also improves the bacterial population's ability to obtain nutrients. Prevention of the formation of scum is achieved; and the development of temperature gradients within the digester is also prevented. However, excessive mixing can disrupt the micro-organisms and therefore, slow mixing is preferred. In case of co-digestion, the different feedstocks should be mixed before entering the digester to ensure a sufficient homogeneity (Monnet, 2003).

Biogas is a substitute for firewood and cattle dung that can meet the energy needs of the rural population. Biogas is a renewable source of energy that can be used as a substitute for natural gas or liquefied petroleum gas (Bhattacharya et al, 2000). There are different models to assess the energy content of different energy sources, which includes water boiling test, controlled cooking test and kitchen performance test. The energy content of 1.0 m^3 of purified biogas is equal to 1.1 L of gasoline, 1.7 L of bioethanol, or 0.97 m^3 of natural gas (Converti et al, 2009). The application for rural and urban waste biogas production is widely spread. It is a challenge for engineers and scientists to build efficient small-scale digesters with the materials available, at the same time taking the local and economical considerations into account. Although many digesters have been built, additional research and awareness are needed to meet the changing needs and conditions (Walter et al, 2015).

2.2.2.1 Chemical reaction equations

The initial conversion of raw waste to soluble organics can be expressed as (Chang, 2004):

$$C_6H_{13}NO_5 + H_2O + H^+_4 \longrightarrow C_6H_{12}O_6 + NH_4^+ \text{……………………..Equation 2.1}$$

In this research, methane production will be simplified by converting $C_6H_{12}O_6$ to methane, CH_4 and carbon dioxide, CO_2 through chemical reaction. The theoretical CH_4 and CO_2 ratios of substrates will be determined using the following equation developed by McCarty, 1964:

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right) H_2O \Leftrightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right) CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right) CH_4 \text{..............................Equation 2.2}$$

Where $C_nH_aO_b$ is organic matter, and a, b, and n are dimensionless coefficients.

Substituting n = 6, a = 12 and b = 6 into Equation 2.2, the chemical reaction of $C_6H_{12}O_6$ becomes:

$$C_6H_{12}O_6 = 3CO_2 + 3CH_4 \text{……………………………………………………Equation 2.3}$$

The mixture has three species - the reactant, $C_6H_{12}O_6$ and the simplified biogas products, CO_2 and CH_4.

2.3 Research in biogas generation in Zambia

In the 1980's and 1990's, work on biogas was pioneered by the then National Council for Scientific Research (NCSR) in Zambia. However, dissemination of the biogas technology was, at the time, not successful. Among the factors which were identified to prevent scale up was lack of funding, policy, regulatory framework and strategies, and awareness of the benefits among leaders, and inadequate expertise to design, build, operate and maintain biogas technologies (SNV, 2016). In the recent past, there have been, however, good attempts to revive the biogas industry. The Energy for Agriculture (E4A) project is being implemented by the Netherlands Development Organization (SNV) over a period of three years (2015 to 2018) and supports construction of 3,375 bio-digesters in Zambia. The E4A project, which is market based, has trained 115 Masons who will anchor the construction of the biogas digesters. Altogether 111 bio-digesters have been constructed, and 40 are under construction. Other organisations involved in biogas are Water and Sanitation Association of Zambia, WASAZA, who have been installing general purpose bio-digesters in conjunction with Southern and North-Western Water and

Sewerage Companies, and Southern Biopower Company, which executes custom-tailored multi-purpose biogas waste management solutions for farms, lodges, households, agro-processing, and public institutions. From the policy and regulatory aspect, Zambia Bureau of Standards has developed standards for Zambia (SNV, 2016).

***Modern bioenergy technologies for on grid and off grid electricity*: -** Opportunities exist in Zambia for use of abundant agriculture and forest waste, animal waste, and municipal solid and liquid waste in modern bio-energy technologies for producing electricity on-grid and off-grid. For on-grid, the technologies which range from 10MW to 50MW include biomass combustion through the steam turbine route, integrated gasification system involving production of electricity on the gas turbine and steam turbine routes, and anaerobic digesters for use of biogas in gas engines. For off-grid technologies, which are of smaller engine capacities between 50kW to 2MW, this can come as gasifiers, and anaerobic digesters for producing biogas coupled to gas engines or steam reciprocating engines. Despite the existence of these technologies, their use in Zambia is limited due to a variety of reasons including awareness and information, inadequate financing and lack of business models for implementation. In Zambia, Zambia Sugar and Kafue Sugar produce their own electricity in the range of 40MW and 80MW, respectively using low pressure boilers, but can produce more for own use and export to the national grid if high pressure boilers were in use (SNV, 2016).

***Biomass Resource Potential in Zambia*: -** The biomass resource potential and corresponding power/energy from agriculture, forest, solid and liquid municipal, and animal waste was determined. The total actual electric power from bioenergy was estimated at 327.26 MW, coming from agriculture 299.92MW, waste (5.0 MW), municipal solid and liquid waste (20.78MW), and animal waste (81.56MW). This potential represents 13.6 percent of the total energy demand of approximately 2,400MW (SNV, 2016).

Biogas for electricity generation: - Biogas is generated during anaerobic digestion processes using waste water, solid waste, organic waste, (e.g. animal manure), and other sources of biomass. It can be used in a gas engine and modified gasoline, or diesel internal combustion engine for electricity generation or used to produce steam which is then expanded on a steam reciprocating internal engine to produce electricity. There are great opportunities for producing electricity from poultry farms with a capacity of 100,000 birds per farm. There are quite a good number of farms with such a good capacity that include: Crest Zambia, Country Choice, Copperbelt Chickens, Supreme Choice, Zamchick, Golden Lay, and Colchi Farms Limited. Equally there are dairy farms with reasonable numbers of cattle e.g. Kusiya and Rosedale Farms who could install biogas generating plants (SNV, 2016).

Most installed biogas digesters in the region are non-operational – which also brings about lack of confidence in the technology (ClimateTechWiki, 2011). Even with the huge resource potential (feedstock abundance) in Zambia, the situation on the ground still remains somewhat bleak (Shane et al, 2015).

The Building and Industrial Research Unit (BIMRU) of National Institute for Scientific and Industrial Research (NISIR) embarked on a number of experimental works in various fields. In trying to popularize the biogas technology in rural communities of Zambia, BIMRU of NISIR undertook a survey of a number of possible pilot project sites in Kasisi, Namwala, Keembe, Lealui and Moonze. The purpose of carrying out experimental works under the Biogas project was to acquire data on the ***performance*** of biogas plants and appliances under the prevailing local conditions in Zambia so that their designs and performance could be ***optimized*** to satisfy the local needs and requirements (NISIR, 2005).

From the initial results, it was observed that the biogas technology was well received in the pilot areas. And people managed to *use the gas for cooking and lighting purposes for some time*. However, in some places people suddenly stopped using the plants mainly because of *lack of further knowledge* in operating and maintaining of the plants and in some cases due to lack of feedstock materials especially after one lost the animals (NISIR, 2005).

Potential for biogas plants in Zambia was estimated by NISIR based on the livestock population, average temperature throughout the year and availability of water. A detailed and scientific market survey was carried out to find the interest of potential households, including willingness to pay and perceived benefits. A sample was taken and its representation limited the size of the population of rural Zambia in relation. It however gave a better understanding of the factors to be addressed in making biogas technology accessible as a household energy option in the country.

The summary of the findings indicated that Zambia was not ready for a wide scale biogas promotion programme. As at now, the experience with the technology is still emerging (i.e. not yet matured) and the necessary institutional, technological and market capacity has not been tested nor developed. Knowledge and confidence in the technology is still restricted to foreign examples and the little that has been done in the country has failed. The target population mainly rural small-scale farmers although in need of alternatives to current fuelwood intensive household energy solutions, are still to be turned into an effective demand.

Poor quality of materials, workmanship and design were noted as the major reasons for currently high failure rate in existing plants. 80 percent were leaking as the steel floating drum had not been to airtight levels. The few domestic digesters visited indicated short lifespan due to low quality or recycled materials used in construction. A cost comparison between the promoted Indian Floating Drum design and the CARMATEC and Nepal BSP GGC 2047 for the Zambia context showed the CARMATEC model as the most competitive due to:

i. Simpler design and the convenience of handling the cow dung.
ii. Availability of skilled masons from the CARMATEC training and the SADC Biomass Energy Technology Course (BETC) run by Mananga in Swaziland
iii. It can be constructed using local materials (stones, clay or cement bricks)

There is need for significant costs to be borne by donors and government to build demonstration units in the target areas to build initial confidence and develop a cadre (a nucleus of trained personnel) of artisans capable of delivering a larger scale promotion programme. There is good technical capacity and interest in the NISIR and Technology Development and Advisory Unit (TDAU) to act as base for technical testing, standardization, innovation in bringing the cost of biogas plants down. Given the less exploited nature of biogas technology in Zambia, subsidy is deemed to be essential at least initially and tied to quality assurance. Zambia appears specifically fertile to a promotion programme for the following reasons:

i. Fertilizers
ii. Desertification
iii. Small scale dairy
iv. Ambient temperature

2.4 Generation of biogas in other countries

Currently, around two billion people worldwide are living without access to a modern energy supply. This means they have no or little opportunity to lift themselves out of poverty and improve their standards of living conditions through their own efforts. Enabling these people with a sustainable energy supply is the key to reducing global poverty. This is why *promoting renewable energies and energy efficiency* is an objective of many countries globally e.g. **Germany** under the "German development policy" (Bernd, 2016).

A sustainable energy supply not only reduces poverty, it also reduces dependency on costly fossil fuels, especially oil. It helps to *protect the environment* – both locally and globally. Germany therefore supports the dissemination of sustainable and local energy production technologies, and aims to help achieve efficient energy production and utilization (Bernd, 2016).

As of 2015, Germany had an estimated number of 8, 928 biogas plants with about 190 of them having biomethanation injection. This corresponded to an installed electricity capacity of 4, 177 MW. Households supplied with biogas based electricity totaled 9.2 million, whereas carbon dioxide reduction by biogas was 21.2 million tonnes. Thus, the biogas sector ultimately created 45, 000 jobs in German. The technologies in use in Germany are as follows: 1). wet digestion (Complete Mixed Reactor) with less than 15 percent dry matter (dm) under both thermophilic and mesophilic temperature conditions; 2). Dry continuous digester (Plug Flow Reactor) with 15 to 30 percent dry matter under thermophilic conditions; 3). Dry batch digestion (Garage System) under mesophilic temperature conditions with greater than 30 percent dry matter (George, 2016).

Biogas as compared with other bioenergy sources in the country shows several advantages as follows: It can be produced sustainably from various biomass resources and its energy can be used in several ways and needs (George, 2016). The following are the percentages by energy output of several biomass resources: bio-waste (3 percent); liquid and solid manure (13 percent); energy crops (77 percent); and industrial and agricultural residues (7 percent). And the success of the biogas technology is measured not only in the continuous growth of plant numbers, but also to the *efficient and sustainable production of electricity*, heat and fuel. Biogas plants are then economically and ecologically meaningful, if they are *process-optimized operated and if resources are used effectively* (Helmut et al, 2009).

India is the second largest commercial energy consumer in non – OECD East Asia, comprising of 19 percent of the region's total primary energy consumption. As per the 2011 census, 44.7 percent rural households had no access to electricity – although per capita energy consumption had increased by 42 percent in two decades, resulting into an increase in total energy usage to 91 percent – the largest source of energy being coal followed by petroleum. India depends heavily on imported crude oil, mostly from the Middle East (Pranav, 2013).

India's renewable installed contribution has increased to 26, 267 MW or 12.45 percentage of the total capacity by end of 2012. The total power potential for renewable power generation in the country as of 2012 was estimated at 89, 774 MW (Pranav, 2013).

Biogas potential: India has a potential of generating $6.38*10^{10}$ m^3 of biogas from 980 million tonnes of cow dung produced annually. In addition, 350 million tonnes of compost would also be produced. Every year, there is an estimated 30 million tonnes of solid waste and 4, 400 million m^3 of liquid waste generation in the urban areas of India (Pranav, 2013).

Biogas industrial scenario: the biogas industry in India faces stiff completion from other renewable sources like solar, wind and specifically biomass. The industry has also very few competent players; though it has a huge potential for small (family size) plants. Furthermore, there is a possibility to convert this potential into large size plants, but very little work has been done in this area (Pranav, 2013).

Issues and challenges: lack of technology standardization; coupled to it is the availability of biogas plant components at economically viable rates which poses to be a challenge. Also, availability of waste in large quantities is an issue. There is no policy framework; yet there are a lot of hurdles in the legislation (Pranav, 2013).

Due to lack of technology and lack of awareness, a huge amount of biodegradable waste remains un-used or un-processed. There is demand for technology provision for industrial scale biogas plants with high level of automation – otherwise majority of plants are manually operated and the biogas is used for cooking. Thus, mechanical automated feeding can reduce human efforts and *speed up* the process.

Biogas engines: biogas engines of smaller size are not available in India; therefore, diesel engines are modified to run on biogas – (high risk, low efficiency). This is translated into a huge demand for smaller biogas gensets in rural India especially where the area is off-grid or un-electrified (Pranav, 2013).

China is a world leader in household small scale digester construction for biogas production for rural farmers; this is mainly due to long-term and sturdy support from the Chinese Central Government. In the 1970's and 80's, biogas production was further promoted by continuing government support. 2003 to 2013 proved to be a period of rapid development in rural areas;

41.68 million household small scale digesters of capacity 8 to 12 m^3 were built. Also, anaerobic digestion started being used in *municipal* and industrial sectors (Xiujn, 2013).

The status quo based on agricultural and the rural sector shows that 160 million people in rural areas are provided with clean energy from the 41.68 units. There are 24,000 small-scale biogas plants mainly used for medium and large-scale biogas plants. Biogas plants on animal farms total 80,500 units. All this provide jobs to about 290, 000 people with an annual biogas production of 15 billion m^3 (Xiujn, 2013).

Anaerobic digestion technology is used in the municipal sector mainly for *municipal solid waste treatment*. For sludge, there are about 51 units; refuse has about 10 units; and food waste with about 40 units. Future project developments in municipal solid waste in China stands at 165 million tonnes/annum with 60 percent organic matter; industrial waste (water) at 1, 200 million tonnes/annum; and agricultural waste at 4, 000 million tonnes/annum with almost 100 percent organic matter. The following is China's biogas potential: a) MSW with 15 billion m^3; b) industry with 48 billion m^3; and agriculture with 288.9 billion m^3 (Xiujn, 2013).

The value addition to biogas is its use as a vehicle fuel - replacing gasoline, injection in the gas grid, and also for other industrial uses like *electricity generation.* However, technology R&D is needed for industrialized large-scale biogas plants, including feedstock characteristics analysis, pretreatment, reactor, agitator, upgrading, monitoring equipment etc. One of the challenges the country is facing is that financial support (bonus, tax exemptions etc.) is still restricted to the agricultural sector. Otherwise it should be extended to the municipal and industrial sectors. The financial support should also be changed from "construction" to the end-product-biogas (Xiujn, 2013).

2.5 Generation of electricity from biogas

As earlier alluded to in the preceding sections, the generation of electricity using conventional methods is in itself a costly concern. Severe environmental problems will be caused on account of electricity production using for example, coal, diesel etc. Even in the case of hydroelectric projects, many environmental problems will arise in and around the project area through deforestation, displacement of people from their source of livelihood etc. That is why, electricity generation using a biogas engine as a prime mover is critical in this undertaking (Feiges et al, 2015).

Biogas Engine Application: - Biogas provides a clean fuel for both Spark Ignition (SI) i.e. petrol engine, and Compression Ignition (CI) i.e. diesel engines. Diesel engines require a combination of biogas and diesel, while petrol engines run fully on biogas.

Biogas SI Engine Applications- Biogas fuel allows the use of high compression ratios in SI engines on account of its high self-ignition temperature. Its wide flammability limit permits operation with lean mixtures. The high flame velocity of *scrubbed* biogas in comparison to conventional fuels leads to a higher increased combustion rate, and ultimately develops a higher thermal efficiency. If biogas is directly used in SI engines, the presence of CO_2 lowers its calorific value (Barik, 2013). Biogas also contains a small percentage of H_2S, which can cause corrosion to metal parts. The performance of a biogas fueled SI engine can be increased by scrubbing H_2S, water vapour, and better still removing CO_2 (Biotech, 2016).

Biogas CI Engine Applications - Biogas generally has a high self-ignition temperature hence; it cannot be directly used in a CI engine. As a result, it is useful in dual fuel engines. The dual fuel engine is a modified diesel engine in which usually a gaseous fuel called the primary fuel is inducted with air into the engine cylinders. This fuel/air mixture does not auto ignite due to high octane number. A small amount of diesel, usually called pilot fuel is injected for promoting combustion. The primary fuel in dual fueling system is homogeneously mixed with air which leads to very low level of smoke. Dual fuel engine can use a wide variety of primary and pilot fuels (Ray et al, 2013). The pilot fuels are generally of high cetane fuel. Biogas can also be used in dual fuel mode with vegetable oils as pilot fuels in diesel engines. (Barik, 2013).

Problems associated with the use of Biogas in I.C. Engines: - High CO_2 content reduces the power output, making it uneconomical as a transport fuel. It is possible to remove the CO_2 by scrubbing the gas with water. The solution produced from scrubbing out the CO_2 is acidic and needs careful disposal. Hydrogen sulfide is acidic, and if not removed can cause corrosion of engine parts within a matter of hours. It is easy to remove H_2S by passing the gas through iron oxide

(Fe_2O_3) or zinc oxide (ZnO) (Ray et al, 2013).

2.5.1 Planning a biogas engine system as a module integrated into an energy system

The supply of mechanical or electric power from biogas is feasible using a biogas engine. The installation of a biogas engine however requires an appropriate planning of the fuel production and also the consumption/operation procedures. An engine in general does not supply energy, but rather transforms one form of energy, here biochemical, into another form, mechanical energy (MITZLAFF, 1988). Thus, its operation requires a source of energy on one side and a consumer of energy on the other. The coordination of the energy source (biogas production plant), the transformer (engine) and the consumer (driven machine e.g. electrical generator) is therefore of utmost importance for a technically and economically satisfactory performance of the whole system (CIMAC, 2015).

Adaptation of the plant, engine and driven machine (electrical generator): - Dimensioning of the biogas plant and gas storage is one of the determining factors for the dimensioning of the biogas plant. Will the biogas production needed to satisfy the fuel demand for the production of mechanical/ electric power per day be met? The combining figure is the biogas consumption of an engine per unit of mechanical power produced, i.e. the specific fuel consumption. It ranges from 0.5 to 0.8 m^3/kWh and is largely dependent on gas quality, temperature, pressure as well as the engine's own efficiency and point of operation. If the anticipated mode of operation of the engine cum driven machine is continuous, the biogas plant must be designed to continuously produce the amount of biogas demanded by the engine at the required power output (Ghazali et al, 2012). The daily consumption of the engine is equal to the product of three quantities as follows: (number of engine operating hours per day), (specific fuel consumption), and (the engine power output i.e. the brake power) (MITZLAFF, 1988).

The production rate of the biogas plant may need to be bigger than the calculated value for the engine if other gas consumers are operated at the same time (cooking, heating, lighting etc.). In the case of non-continuous operation of the engine, e.g. only several hours per day at different loads, the plant still needs to produce the required amount of biogas needed each day but at a lower production rate per hour than consumed by the engine. A storage gas holder can be filled while the engine remains idle. It is emptied while the engine is in operation and consumes more than the plant produces. The actual volume of the gas holder is a function of the plant production rate, engine consumption as well as the frequency and duration of the engine operation periods (Ghazali et al, 2012).

2.6 Critique of validity of appropriate theory and research Literature

The reviewed literature, in this thesis, had shown that presently, the Sub-Saharan Africa is not adequately equipped as far as renewable energy research and development is concerned (Shane, 2015). Other critical issues highlighted on were as follows: Management and monitoring of installed biogas digesters, Feedstock availability and other technical issues, High installation and maintenance costs among others (Shane, 2015).

Based on the literature reviewed, biogas production in Zambia finds its main application in cooking, heating and lighting only and no direct mention or authentic scientific documentation is found so far on projects for electricity generation. Therefore, this work considered deeply the efficient production of biogas to generate electricity at a small-scale level – to provide an authentic document.

Additionally, digesters designed outside Zambia may not reflect the actual required standards of digester designs; especially with respect to the nature of the local feedstock, climatic conditions and national frameworks (legislation and energy policies) (Lungu, 2011).

The extensive literature reviewed ultimately brought out the fact that: - how biogas production rate could be enhanced using local substrates was not known. There was lack of evidence of any systematic or scientific investigations of biogas production rate from digesters used in Zambia. Thus, in this thesis, using a technique, biogas production rate was optimized by studying the effects of parameters such as temperature, hydraulic retention time and organic loading rate, etc. in the production of biogas for small-scale electricity production. Also models to predict the quantity of biogas and feedstock materials for electricity generation were determined and validated. The temperature favourable for optimum biogas production at local level was a parameter to be dealt with as it is a critical factor in biogas production – which was also a missing link in the findings or literature reviewed.

CHAPTER 3 MATERIALS AND METHODS

3.1 Introduction

This chapter presents the Materials and Methods that were used in this work. Firstly, literature was reviewed in detail and development of the models/formulas was carried out using the computer software packages, MATlab. MATlab was used because of the following reasons:

i) It is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation;

ii) Several mathematical operations that work on arrays or matrices are built-in to the MATlab environment;

iii) The graphical output could be optimized for interaction. Data could be plotted easily, and then change colors, sizes, scales, etc., by using the graphical interactive tools;

iv) MATlab's functionality could be greatly expanded by the addition of toolboxes. These are sets of specific functions that provided more specialized functionality e.g. Excel link allows data to be written in a format recognized by Excel, Statistics Toolbox allows more specialized statistical manipulation of data (Anova, Basic Fits etc.);

v) It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python. Typical uses include: Data analysis, exploration, and visualization.

The models developed in this work could predict the quantities of biogas, and feedstock required to generate energy (electricity and heat in a CHP consideration).

Data (average monthly temperatures, biogas production rates, energy expenditure etc.) from the field was acquired and part of it was used to determine the farm energy needs. Thereafter, the biomass resource potential per annum was determined (using the other set of data-i.e. the animal population) to estimate the corresponding quantity of biogas on the farm. With the amount of biogas established; the total energy content of the gas was also computed. Consequently, the respective amounts of electrical power and heat generated were calculated. The two respective quantities were then compared with the afore-determined farm energy needs to ascertain the feasibility of the undertaking or project. In this case, the energy demand and supply were analyzed both for the winter and summer seasons.

Using measured data from the farm, based on the quantities of biogas produced against average monthly temperatures, a *specific model* was further developed using the same software (MATlab). This specific model facilitated the determination of an optimum temperature at which biogas could be produced under Zambian climatic conditions, and feedstock characteristics. Data from the farm and other authentic publications was used to validate the models. However, the very farm is currently not generating any electricity though the plans are underway. Therefore, validation of models for electricity generation alone depended on other sources.

3.2 Model development

3.2.1 Development of a model that predicts the quantity of biogas required to generate electricity

Development of the model which predicts the amount of biogas needed to generate a known quantity of electricity (***E***p) required the knowledge of the range of electricity to be generated i.e. 50 to 500 kW; feedstock characteristics such as density and specific biogas yield of a particular feedstock; and the relationship that 2.14 kWh of electricity is generated from 1m^3 of biogas. For example, to generate ***E***p kW of electricity, irrespective of the type of feedstock used; the relationship employed was as shown by equation 3.1 (Banks, 2009):

$$\boldsymbol{fc} = \frac{(\boldsymbol{E}p * 24)}{2.14} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.1}$$

Using Equation 3.1 for the electricity (***E***p) range of 50 to 500 kW, the corresponding volumes of biogas (***fc***) required were determined. Then the values of ***E***p and ***fc*** were input into MATlab so as to develop a generic model – which could predict the amount of biogas required when the quantity of electricity is predetermined or known.

3.2.2 Specific models which predict the quantity of biomass resources (feedstock) required to generate electricity

Specific models which predict the amount of feedstock required for the eight selected feedstocks (sludge water, cow dung, swine manure, chicken droppings, vegetable and fruit waste, grass silage, corn silage, and catering waste) were developed by determining the quantities of biogas, ***fc***, required to generate electricity based on the 50 to 500 kW, (***E***p) range. For this, Equation 3.1 was used. Then the feedstock quantities were computed using equation 3.2 (EPA, 2012).

$$\boldsymbol{LR} = \frac{\boldsymbol{G}}{\boldsymbol{G}y} \ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.2}$$

The results for ***LR*** and ***E***p were tabulated into the MATlab software to generate models for each of the eight biomass resources. Therefore, each specific case of a particular feedstock material, the coefficients were determined using MATlab software. The specific equations were expected to be of the form shown in Equation 3.3:

$$\boldsymbol{LR} = a\boldsymbol{E}p + b \ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.3}$$

Thereafter, the relative percentages for the eight selected feedstock materials were determined – to show how much of the feedstock was required to generate the same quantity of electricity. This was achieved by; for-example, adding all the eight feedstock materials which can produce ***E***p kW each. The percentages were calculated using Equation 3.4.

$$\boldsymbol{Relative\ percentage\ of\ feedstock} = \frac{\boldsymbol{HR}n}{\boldsymbol{HR}t} \ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.4}$$

3.3 Comparing biogas, and feedstock quantities needed to generate the same amount of electricity using a different approach from (3.2.1)

3.3.1 Development of a model that predicts the quantity of biogas consumed by a gas engine to generate electricity

The quantities of biogas, ***f***c, consumed by an engine to generate the corresponding amounts of electricity, ***Ep***, were determined by firstly considering Equation 3.5.

$$\boldsymbol{fc} = \boldsymbol{t}o * sfc * \frac{\boldsymbol{E}p}{\boldsymbol{\eta}\mathrm{gen}} \ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.5}$$

For an optimum scenario, $\boldsymbol{t_o}$ was taken to be 24 hours as electricity generation was to be continuous; *sfc* practically ranges from 0.5 to 0.8 m^3/kWh (MITZLAFF, 1988). Thus, 0.5 m^3/kWh was used so as to have an optimal case (i.e. minimum biogas is consumed for maximum power output); the electrical power, was chosen to be in the range of 50 to 500 kW; generator efficiency was assumed to be 90 percent since electric generators are capable of operating at that efficiency. Then the values of biogas consumption were calculated and together with the corresponding values of electric power provided an input into the computer software. Then the coefficients were determined and a generic model was developed; and this was compared with Equation 3.3.

3.3.2 Development of specific models that predict the quantity of the biomass resource or feedstock from different biomass resources – using gas engine parameters

With the volumes of biogas known; as calculated using equation 3.7, the feedstock quantities of the eight selected sources were determined using equation 3.8.

$$\boldsymbol{LR} = \boldsymbol{f}c/\boldsymbol{G}y \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.6}$$

Since the values of $\boldsymbol{f}c$ used had corresponding values of $\boldsymbol{E}p$ as shown in Equation 3.3; a relationship between $\boldsymbol{LR}$ and $\boldsymbol{E}p$ was established and a set of data was input in MS excel and then imported into MATlab to determine the coefficients of the linear equation and ultimately developed specific models for the selected feedstock materials. The models took the form described by Equation 3.3.

Also, the relative percentages for the feedstocks in-terms of quantity needed per annum were determined using Equation 3.4.

3.4 Determination of the potential biogas production to meet the farm energy needs

The potential biogas production to meet energy needs on the farm was determined using Equation 3.8. This was achieved with the knowledge of the animal population and the manure characteristics shown by Equation 3.7. After that, the energy demand for the farm was also calculated using Equation 3.10; then the energy consumption (or demand) on the farm was compared to the potential energy available (or supply) in the biogas. This helped to determine as to what extent was the project feasible.

3.4.1 Determination of the potential manure supply by the farm animals

The amount of manure available for biogas production was determined on the basis of population of the animals (pigs and cows) on the farms. The manure yield (***RL)*** per day was calculated through the use of Equation 3.7 (Nijaguna, 2002).

$$\boldsymbol{LR = N * SQ} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots \boldsymbol{Equation\ 3.7}$$

3.4.2 Determination of the daily biogas production at the farm

The amount of biogas generated each day, ***G,*** (m^3/day), was calculated on the basis of the specific biogas yield (***G***y) of the substrate and the daily substrate input, shown by Equation 3.8 (EPA, 2012):

$$\boldsymbol{G = LR * Gy} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.8}$$

3.4.3 Heat energy demand of the fish pond on the farm

Firstly, the volume ($\boldsymbol{V}_{\mathbf{w}}$) of water to be heated was noted; then the initial temperature (***T***i) was measured; and the required temperature (***T***r) which is suitable for fish breeding was noted and set. The change in temperature was calculated using equation 3.9 and the heat energy required to heat the fish pond was determined using equation 3.10.

$$\boldsymbol{\Delta T = Tr - Ti} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \boldsymbol{Equation\ 3.9}$$

$$\boldsymbol{Q = Vw * \Delta T * 10^{6} * 1.16 * 10^{-6}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \boldsymbol{Equation\ 3.10}$$

3.5 Determination of the optimum temperature under Zambian climatic conditions using data measured at the farm

The model which predicts the biogas production rate (***G***) was developed using the MATlab computer software. Actual data from Chimphembala Fish Farm and Restaurant Was used. Considering the specific gas yield of the feedstock, the maximum potential biogas production for the whole amount of feedstock material was determined, show by Equation 3.8. With the maximum biogas known; it was then substituted back into the developed model, Equation 3.11, to determine the optimum temperature ($\boldsymbol{T}$).

Firstly, the general equation based on the Power Law was assumed shown in Equation 3.11. This was because experience had shown that plotted measured values of biogas production rates vs temperature could be estimated using the power law. Appendix 3 supports the assumption especially when generation per hour is increasing with increasing temperature – until maximum.

The Power Law also helps to predict how much a particular quantity would be, based on data already present. It is also time-based average, and automatically adjusts assessment weights to give higher weights to more recent assessments for better prediction (Mitzenmecher M., 2006). Therefore, the data in Appendix 2 was used to provide the model based on the Power Law so that the optimum temperature could be predicted.

$$\boldsymbol{y} = a\boldsymbol{x}^{n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{\textit{Equation 3.11}}$$

To determine the constants, Equation 3.11 was made linear as shown in Equation 3.12.

$$ln(\boldsymbol{G}) = \boldsymbol{n}ln(\boldsymbol{T}) + ln(\boldsymbol{a}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 3.12}$$

Then the calculated values *ln*($\boldsymbol{G}$) and *ln*($\boldsymbol{T}$) were input into MATlab software to determine the constants a and n. The constants were then substituted in the general Equation 3.11 to formulate a specific model under consideration. Measured data from the farm was used i.e. *G* and *T*.

To determine the optimum temperature, the potential maximum biogas production was determined using the total amount of feedstock multiplied by the specific biogas production as in Equation 3.8. Then the maximum potential biogas production rate was substituted in the developed specific model, Equation 3.8, and the optimum temperature was determined. The temperature was assumed to apply to all types of feedstock materials as it is independent of the type and quantity of the feedstock materials.

3.6 Closing remarks

This chapter presented Materials and Methods on the development of models that would predict the quantity of biogas, and feedstock with known electricity demand. Also, the model to determining the optimum temperature for Zambian climatic conditions was developed. In the development of later model, the Power Law was assumed. The next chapter presents the Design and Modeling of a Biogas System as used in this work.

CHAPTER 4 DESIGNING AND MODELLING OF A BIOGAS SYSTEM

4.1 Total volume of a biogas plant

This chapter presents the Designing and Modelling of a biogas system adopted in this work. The adopted type was a Fixed-Dome Biogas Plant; a Modified Camartec Biogas Model was selected. Design details of the plant are shown in Appendix 5. The Criteria for selecting the Fixed-Dome Biogas Plant was:

i) relatively low construction costs,

ii) the absence of moving parts and rusting steel parts.

iii) If well-constructed, fixed dome plants have a long-life span.

iv) The underground construction saves space and protects the digester from temperature changes

In addition, the CAMARTEC model has a simplified structure. This structure is of of a hemispherical dome shell based on a rigid foundation ring only and a calculated joint of fraction.

The total volume of the biogas plant (V) comprised of the biogas digester volume (Vd), gas holder volume (Vg), and the buffer or dead volume (Vb) (Heegde, 2010). The digester volume was determined on the basis of the selected retention time (RT) and feedstock input per day (LR) of the material available for the biogas system. Retention time (given in days) is determined by the given temperature and indicates the period spent by the substrate in the digester. The volume of the digester was given by Equation 4.1:

$$\boldsymbol{Vd = LR * RT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.1}$$

$\boldsymbol{RT}$ is the retention time in days and the recommended number of days, based on Zambia's average temperature, is sixty (60) days i.e. warm climate (SNV, 2010). The gas holder volume

(***V***g) is given by Equation 4.2 and for this plant; it is estimated at 60 percent of the maximum biogas production (***G***) per day.

$$\boldsymbol{Vg} = \left(\frac{\mathbf{60}}{\mathbf{100}}\right) * \boldsymbol{G} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equatin\ 4.2}$$

Also, the buffer volume (***V***b) is given by Equation 4.3 and it is 20 percent of the sum of digester volume (***V***d) and gas holder volume (***V***g).

$$\boldsymbol{Vb} = \left(\frac{\mathbf{20}}{\mathbf{100}}\right) * \ [\boldsymbol{Vd} + \boldsymbol{Vg}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.3}$$

Thus, the total volume of the biogas plant is given by the sum of the digester volume, gas holder volume, and the buffer volume as shown in Equation 4.4:

$$\boldsymbol{V} = \boldsymbol{Vd} + \boldsymbol{Vg} + \boldsymbol{Vb} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.4}$$

4.1.1 Biogas plant dimensioning

In this type of a digester design, the dome (Rd) and compensation chamber (Rcc) radii are critical dimensions and are calculated using Equations 4.5 and 4.6 respectively:

$$\boldsymbol{R}d = (\boldsymbol{V}/[\frac{2}{3}]\pi)^{\frac{1}{3}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.5}$$

$$\boldsymbol{R}\,cc = (\boldsymbol{V}\,g\,/\,[2/3]\pi)^{1/3} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.6}$$

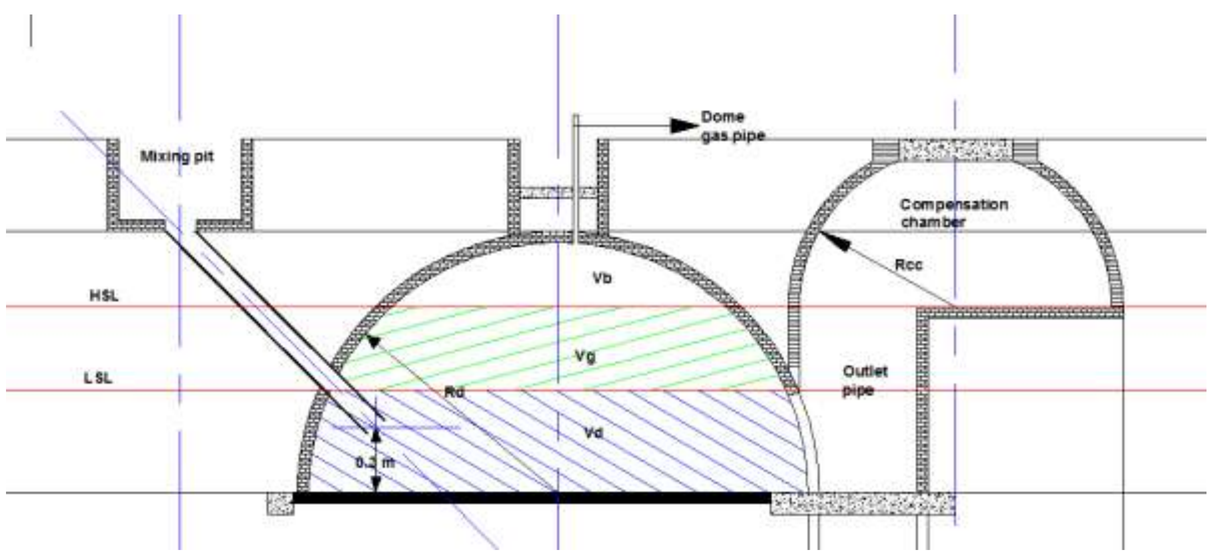


Figure 4.1: Fixed-dome biogas plant (Modified Camartec biogas plant)

Figure 4.1 shows all the critical design parameters of the Modified Camartec biogas plant.

4.2 Adaptation of plant, engine and electric generator

4.2.1 Dimensioning of biogas plant and biogas storage

4.2.1.1 Dimensioning of biogas plant

The biogas production needed to satisfy the fuel demand for the production of mechanical/electrical power per day was one of the determining factors for the dimensioning of the biogas plant (CIMAC, 2015). The combining figure was the gas consumption of an engine per unit of mechanical power produced, that was the specific fuel consumption (***sfc).***The specific fuel consumption ranges from 0.5 to 0.8 m^3/kWh and is largely dependent on gas quality, temperature, pressure as well as the efficiency of the engine and point of operation (Mitzlaff, 1988).

The anticipated mode of operation of the engine cum driven machine was taken to be continuous; thus, the biogas plant was designed to produce the amount of biogas demanded by the engine at the required power output continuously. The biogas consumption per day, by the engine, was given by Equation 4.7:

$$\boldsymbol{fc} = [\boldsymbol{t}o * \boldsymbol{sfc} * \boldsymbol{P}eng] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{\textit{Equation}}\ \mathbf{4.7}$$

The power demand range in this research was 50 kW to 500 kW and was denoted by ***P****el* [kW]; that is, electrical power generated by the generator. It is given by Equation 4.8:

$$\boldsymbol{Pel}\ (\boldsymbol{Ep}) = \boldsymbol{\eta}gen * \boldsymbol{P}eng \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{\textit{Equation}}\ \mathbf{4.8}$$

Combining Equations 3.6, 4.7 and 4.8 yielded Equation 4.9 and 4.10 which relates the Loading rate, ***LR***, to the electrical power generated by the electric generator, ***P****el*:

$$\boldsymbol{LR} = (\boldsymbol{fc} * \boldsymbol{\rho}) = \left[\boldsymbol{t}o * \boldsymbol{sfc} * \frac{\boldsymbol{P}el}{\boldsymbol{\eta}gen}\right] * \left(\frac{1}{\{\boldsymbol{Gy}\}}\right) \ldots\ldots\ldots\ldots\ldots\ldots \textbf{\textit{Equation}}\ \mathbf{4.9}$$

$$fc = [to * sfc * Pel/\eta gen] * \left(\frac{1}{\{Gy * \rho\}}\right) \ldots \textbf{Equation 4.10}$$

The size of the digester, that is the digester volume ***Vd***, is calculated on the basis of the chosen retention time ***RT*** and the daily substrate input quantity ***LR*** as given by Equation 3.7**.**

4.2.1.2 Gas storage capacity / sizing the gas holder

The gasholder volume, ***V***g, depends on the relative rates of gas production, ***G***, and gas consumption, ***f***c. In that case, the gas storage capacity considered the rate of production as well as the rate and the period of gas consumption. Thus, the gas storage volume ***V***g, only had to cater for the difference between the volume consumed (***f***c*t_o), and the volume produced (***G****t_o), during the operational period t_o (in hours) – and was given by Equations 4.11 or 4.12

$$Vg = (fc * to) - (G * to) \ldots \textbf{Equation 4.11}$$

and;

$$Vg = (fc - G) * to \ldots \textbf{Equation 4.12}$$

Due to fluctuations in the gas production and fuel consumption, a certain storage volume was adopted. Thus, the storage tank was oversized by about 10 percent as reported by Mitzlaff (1988). And also existing capacity within the digester reduces the required storage volume accordingly (Mitzlaff, 1988).

The buffer volume was calculated using Equation 4.13.

$$Vb = \frac{10}{100} * (Vg) \ldots \textbf{Equation 4.13}$$

Therefore, the total volume ***V***, of the biogas plant is the sum of ***V***d, ***V***g, and ***V***b and was determined by Equation 4.14:

$$V = Vd + Vg + Vb \ldots \textbf{Equation 4.14}$$

4.3 Computer simulations

Computer simulation is a method which allows carrying out research in virtual environment which provides knowledge of the system by varying input parameters and observe the influence on the output and characteristics of the biogas at different points of operation (Deogratias et al., 2015). This method was selected based on the fact that it saves the cost of the research at a real plant set up and also save time in observing the nature of complex reactions which take place in the digester.

4.3.1 Advanced computer package – MATlab R2011b

In this research, the advanced computer package, MATlab R2011b – MATrix LABoratory – was used to determine the values of the parameters for the general form of the equations. MATLAB is a tool for numerical computations and visualization which permits matrix operations, plotting of functions and data sets, application of algorithms, user interfaces creation, interfacing with programs written in other languages for example, C, C++, Java, and ForTran. Thus, MATLAB computer package manipulates array based data. It is relatively faster to write and run a program in MATLAB (Hiptmair, 2016).

4.3.2 Linear regression – MATlab R2011b

MATLAB allows the modeling of data using linear regression which produces a *model* (a relationship between independent and dependent variables) that is linear in the model coefficients. *Least-square fit* is the most common type of linear regression. It can fit both lines and polynomials (Hiptmair, 2016).).

4.3.3 Residuals and goodness of fit

Residuals are defined as the difference between *observed* values of the dependent variable and values which are *predicted* by the model. When fitting a model, that is appropriate for some particular data, the residuals approximate independent random errors. To calculate fit parameters for a linear model, MATlab minimizes the sum of the squares of the residuals to produce a good fit. By visually examining a plot of the residuals, it is possible to gain insight on the ‘goodness’ of a fit. If the residual plot has a pattern, it indicates that a model does not properly fit the data (Deogratias et al., 2015).

4.3.4 Correlation analysis

To establish if a relationship exists between quantities, it is a good idea to perform correlation analysis before modeling. Correlation is a method for establishing the degree of probability that a linear relationship exists between two measured quantities. If there is no correlation between the two quantities, then there is no tendency for the values of one quantity to increase or decrease with the values of the second quantity (Mathworks, 2007).

4.3.5 Mean bias error, mean of absolute deviations, and root mean square error

In order to gain insight into the performance evaluation of a model, mean bias error (MBE), mean absolute deviation (MAD) and root mean square error (RMSE) are defined in the following sequence:

$$\boldsymbol{MBE = 1/n} \sum_{i=1}^{n} (\boldsymbol{Y}i - \bar{Y}i) \ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.15}$$

$$\boldsymbol{MAD = 1/n} \sum_{i=1}^{n} \left| \boldsymbol{Y}i - \bar{Y} \right| \ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.16}$$

$$\boldsymbol{RMSE = 1/n}[\sum_{i=1}^{n} (\boldsymbol{Y}i - \bar{Y}i) \ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.17}$$

$$\boldsymbol{RMSE = 1/n}[\sum_{k=1}^{n} \binom{\boldsymbol{n}}{\boldsymbol{k}} (\boldsymbol{Yi} - \bar{Y}\boldsymbol{i})^{2} \boldsymbol{a}]^{\frac{1}{2}} \ldots\ldots\ldots\ldots \boldsymbol{Equation\ 4.18}$$

The MBE is given as the arithmetic average of the errors; and if its value is equal to zero, it does not mean that the model yields estimations without error. The MBE provides a measure of the overall trend of a given model that is, predominantly over estimating (positive values) or under estimating (negative values). Though, the smaller the MBE, the better is the model result (Deogratias et al., 2015).

However, in an acceptable model, the MAD value should be as close as possible to zero but never equal to zero in the biogas to electricity modeling. The RMSE is similar to the MAD and provides a measure of squared deviations. In statistics, the RMSE of an estimator is a square root of the expected value of the square of the error. The error is the amount by which the model estimate differs from the corresponding measurement. The error occurs because of randomness or the model does not account for information that could produce a more accurate estimate (Sen, 2008).

4.4 Description of the study site

4.4.1 Overview of the farm

The field study was carried out on a farm in Chongwe, South-East of Lusaka. The purpose of the study at the site was to acquire field data which was used in further analysis of this research work. The choice of the site for this research was based on the fact that the farm had good record keeping; and also, enough animals to produce sufficient feedstock material – considering that this research work was looking at electricity generation with a range of 50 to 500kW.

4.4.2 Baseline scenario of the energy supply and demand for the farm

The farm had a herd of 30 cows which were grazing within the farm and its vicinity. It also had a pig population of 3,000 sows; generating sufficient feedstock for biogas production. The farm had also constructed fish ponds which held 1,200 m^3 of water, distributed in more than 100 basins from which some are for fish growing and others for breeding.

Up to 10 percent (120 m^3) of the total water body was discharged on a daily basis and then replaced; thereby bringing about temperature fluctuation which would affect the productivity of the fish project.

The ideal temperature of the fish water was 28^oC (which is the suitable average temperature for fish breeding) (Sapkale et al, 2011); however, the site was equipped with a borehole and a surface water reservoir. The borehole supplied water at a temperature of 20.5^oC and the reservoir at an average temperature of 17^oC respectively (these measurements were carried out in the winter season). There was a central heating water system for the ponds. The 10 percent replaced water and 90 percent re-circulated water, on a daily basis required to be raised to an ideal temperature of 28^{o}C. This temperature(28^{o}C) is ideal for fish spawning/breeding (Sapkale et al, 2011).

Governing of the energy sources to provide optimum temperature in the fish ponds was especially a challenging element of the project.

4.4.3 Biogas solution and other uses

The project was commenced with 1,000 sows to produce organic matter as feedstock for biogas solutions for especially the fish project. The quantity of biogas produced ranged from 160 m^3 to 330 m^3 (with 800m^3 digester capacity built at the farm) in winter and summer respectively. In summer, the energy requirements were about 4,950.12 and 2,231.04 kWh per day in winter. Thus, more energy was required in the winter period as one quarter of the total energy was needed to heat 120 m^3 of fresh water from 20.5^{o}C to 28^{o}C; then the remaining 75 percent of heat energy was required to heat the remaining 1,080 m^3 of re-circulated water.

Since at the time of the study at the farm, generation of electricity had not yet commenced, biogas was utilized for other activities; for example, there were 7 people living in the farm houses and up to 30 workers were permanently working on the farm. They all need energy for lighting, cooking, heating etc. which was provided by electricity. Therefore, the gas which was produced was only used as a source of heat for piglets; the farm has biogas digester capacity of 800 m^3 – i.e. two 200 m^3 and five 80 m^3 digesters.

Some of the factors which influenced the energy needs for heating were: efficiency of the additional heating equipment (heater and piping); heat loses to the underground; potential overheating during hot seasons; and reliability of the heat governing technology-in case management is done manually by an operator, the probability of human errors had to be taken into consideration. The project owner considered it safer to employ both manual and automatic operation at the facility.

Finally, the farm had been also considering other options to be added to the biogas solutions. This was due to the enormous energy requirements for water heating.

4.5 Summary

This chapter presented the Design and modeling of Biogas Plant Systems. The biogas plant type considered was an underground Fixed-Dome digest because of its advantages over other digester types. In this work, of particular consideration was the Modified Camartec Biogas Plant which is relatively cheap and robust among other advantages. Also, key issues pertaining to the study farm in this work showed that more energy was needed in winter, yet that is when production of biogas was at its lowest e.g. 4,950.12kWh was required winter, and 2,231.04kWh in summer respectively. The respective biogas production rates were $160m^3$ and $330m^3$ per day. However, the farm has the capacity to generate electricity using biogas; considering the digester capacity of $800m^3$. The next chapter presents the results of the findings in this work.

CHAPTER 5 RESULTS

5.0 Overview

This chapter presents the results of this study. The data is presented in accordance with the objectives of the study.

5.1 Development of models which predict the amount of biogas, and feedstock required to generate electricity in the range of 50 to 500 kW

Development of models which predict the amount of biogas required to generate electricity involved calculating the baseline loading rates. Calculation of these loading rates required information on: (i) daily biogas production to satisfy a particular electricity demand, in this study, 50 to 500 kW; (ii) feedstock characteristics (density, and specific biogas yield) and, (iii) the relationship that 2.14 kWh of electricity was generated from 1 m^3 of biogas.

5.1.1 Quantity of daily biogas consumption

Considering the fact that 3.6 MJ is equivalent to 1 kWh; also, biogas has a thermal energy of about 22 MJ/m^3; this gave 6.1 kWh of energy per 1m^3 of biogas. However, in the Combined Heat Power (CHP) generation, only about 35 percent of the energy from biogas is converted to electricity and 50 percent as heat energy. The remaining 15 percent is lost to the environment.

The above relationship was used in this work to have an optimum quantity of biogas, and feedstock from the 8 selected biomass resources. Inputting the 50 to 500 kW into Equation 3.1, the daily biogas consumption was calculated and tabulated in Table 5.1.

TABLE 5.1: Quantities of biogas required to generate electricity (50 to 500 kW).

Electricity *Ep* [kW]	**50**	**100**	**200**	**300**	**400**	**500**
Biogas [m^3/day]	560.75	1,121.50	2,242.99	3,364.49	4,485.98	5,607.48

Figure 5.1 shows plots of daily Biogas consumption with corresponding Electric power generated in the range of 50 to 500 kW. MATlab computer software package was used to make plots.

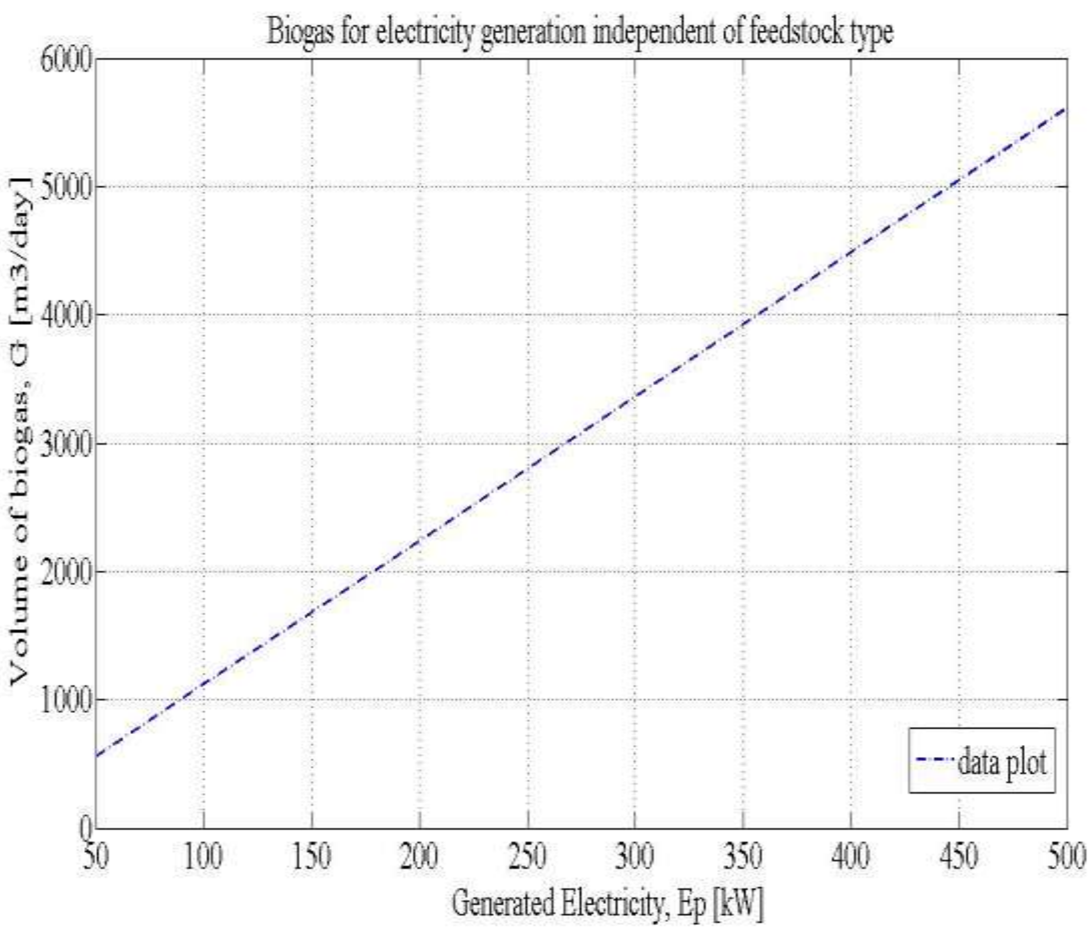


Fig 5.1: Relationship between biogas required for the corresponding generated electricity.

Using MATlab computer software package, a model that predicts quantities of biogas, for a known quantity of electric power, was developed. The developed model took the form shown in Equation 3.3. MATlab was used to obtain the coefficient of *Ep* which is 11.22. Equation 5.1 shows the developed model for the base line scenario.

$$\boldsymbol{G} = 11.22\boldsymbol{Ep} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 5.1}$$

Table 5.2 shows feedstock characteristics used in calculating the daily biogas consumption in Table 5.1. The feedstock characteristics in this work were: density and specific biogas yield for respective biomass resources. These were constants for a particular feedstock and were obtained from empirical research literature.

Table 5.2: Feedstock characteristics of respective biomass from different sources

Feedstock	**Swine manure**	**Cow dung manure**	**Chicken droppings**	**Grass silage**	**Corn silage**	**Vegetable and fruit waste**	**Sludge waste**	**Catering waste**
Density [m^3/kg]	*1,000*	*1,090*	*450*	*260*	*640*	*1,000*	*1,400*	*600*
Gy [m^3/kg]	*0.058*	*0.037*	*0.069*	*0.116*	*0.138*	*0.072*	*0.015*	*0.11*

5.1.2 Quantity of feedstock required per annum

Quantities of biomass resources were determined using Equation 3.6 and tabulated in Table 5.3. This was achieved by using the daily biogas consumption from Table 5.1, together with feedstock characteristics from table 5.2. The two parameters became inputs in Equation 3.6.

Table 5.3: Feedstock materials and the corresponding electricity generated

Ep [kW]	**BIOMASS RESOURCE PER ANNUM [TONNES/YEAR]**							
	Swine manure	**Cow dung**	**Chicken droppings**	**Grass silage**	**Corn silage**	**Vegetable and fruit waste**	**Sludge waste**	**Catering waste**
50	3528.84	5531.70	2966.27	1750.84	1476.72	2842.68	13644.86	1860.66
100	7057.69	11063.40	5932.00	3501.67	2953.43	5685.36	27289.72	3721.33
200	14115.37	22126.80	11865.10	7003.35	5906.87	11370.72	54579.44	7442.65
300	21173.60	33190.20	17797.64	10505.02	8860.30	17056.07	81869.16	11163.98
400	28230.74	44253.60	23730.19	14006.70	11813.73	22741.43	109158.88	14885.30
500	35288.43	55317.00	29662.74	17508.37	14767.16	28426.79	136448.60	18606.63

To obtain the biomass resource per annum, in Table 5.3, daily biogas consumption had to be converted into annual consumption [m^3/year] and specific biogas yield into [m^3/tonne], so that the biomass resource could be in tonnes per annum.

Figure 5.2 shows plots of Biomass Resource per annum with the corresponding electric power needs for a base line scenario. Using tabulated parameters from Table 5.3, MATlab computer software was used to make plots. Also, 8 models were developed for each feedstock material from the data obtained from Table 5.3. The models were shown in Equations 5.3 to 5.10.

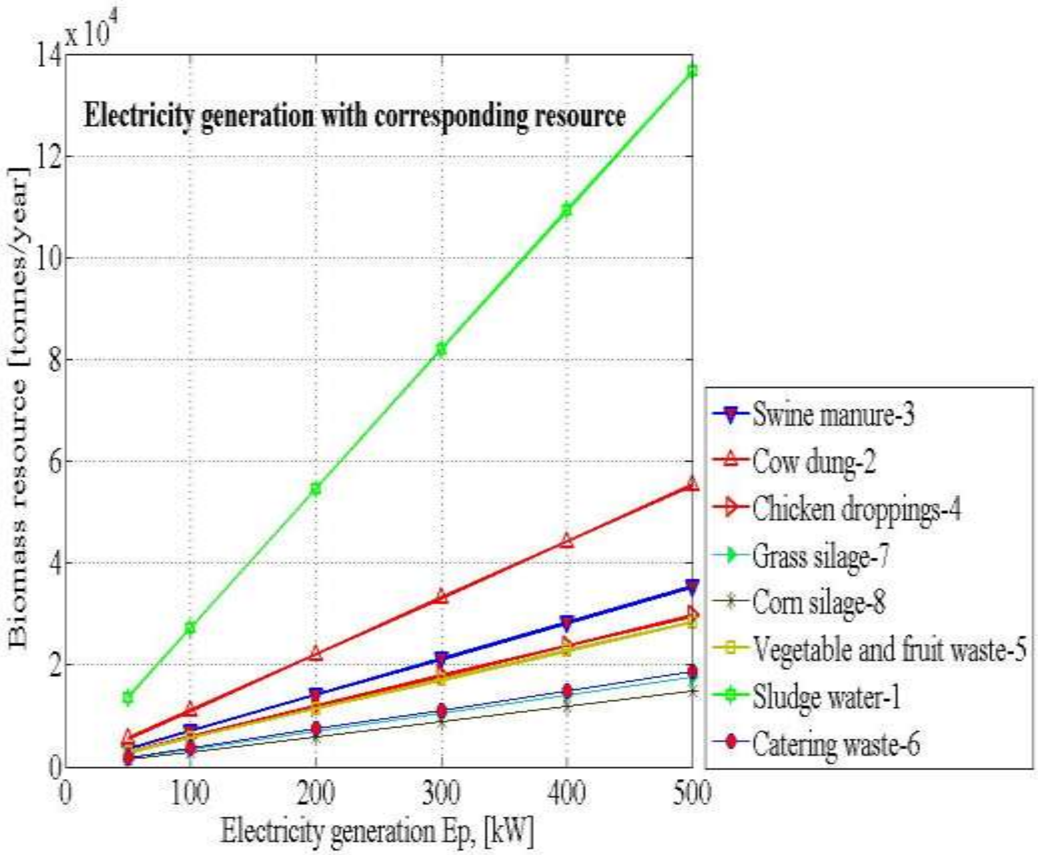


Figure 5.2: Annual biomass (feedstock) requirements for electricity generation (baseline scenario)

5.1.3 Relative percentage of required feedstock per annum

Table 5.4 gave relative percentages of annual feedstock required to generate the same amount of electricity respectively. Equation 3.4 was used to determine the relative percentages for each resource; showing how much would be required to generating a particular amount of electric power.

Table 5.4: Quantities of feedstock required per annum expressed in percentage form

Feedstock	Swine manure	Cow dung	Chicken droppings	Grass silage	Corn silage	Vegetable and fruit waste	Sludge waste	Catering waste
[%] feedstock	10.5	16.5	8.8	5.2	4.4	8.5	40.6	5.5

[tonnes/year]								

Figure 5.3 shows plots of relative percentages against the respective feedstocks. Data used to make the plots was from Table 5.4. MS Excel was used to make the plots.

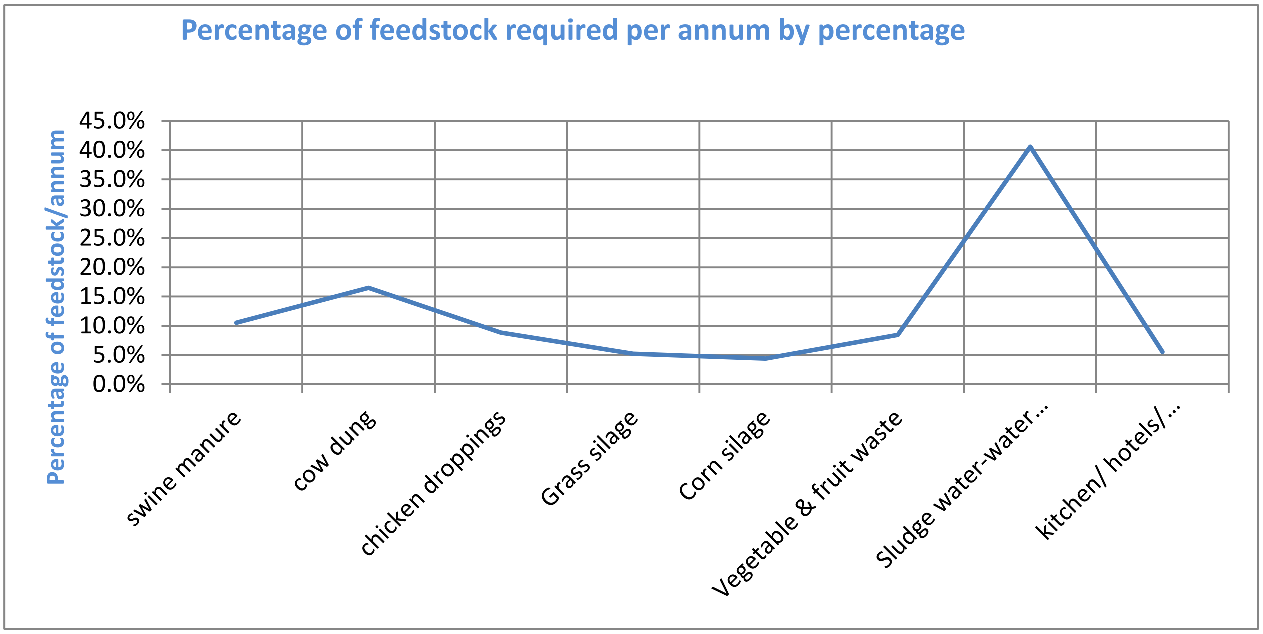


Figure 5.3: Plots of relative percentages of feedstock vs respective feedstock resources

5.1.4 Models for predicting feedstock [tonnes/year] required per annum to generate electricity.

i) Model for sludge water – water treatment plant:

$$HRsw = 272.9Ep \ldots\ldots\ldots\ldots \textbf{Equation 5.3}$$

ii) Model for cow dung:

$$HRcd = 110.63Ep \ldots\ldots\ldots\ldots \textbf{Equation 5.4}$$

iii) Model for swine manure

$$HRsm = 70.58Ep \ldots\ldots\ldots\ldots \textbf{Equaion 5.5}$$

iv) Model for chicken droppings:

$$HRckn = 59.32\boldsymbol{Ep} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\boldsymbol{Equaion\ 5.6}$$

v) Model for vegetable and fruit waste

$$HRvf = 56.85\boldsymbol{Ep} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\boldsymbol{Equaion\ 5.7}$$

vi) Model for catering waste:

$$HRcw = 37.21\boldsymbol{Ep} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\boldsymbol{Equaion\ 5.8}$$

vii) Model for grass silage

$$HR\mathrm{gs} = 35.02\boldsymbol{Ep} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\boldsymbol{Equaion\ 5.9}$$

viii) Model for corn silage

$$HR\mathrm{cs} = 29.53\boldsymbol{Ep} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\boldsymbol{Equaion\ 5.10}$$

5.2 Comparing biogas and feedstock quantities needed to generate the same amount of electricity using an alternative approach against the baseline (5.1)

5.2.1 Quantity of daily biogas consumption using biogas engine

Table 5.5 shows the quantities of biogas consumption rates vs electricity generation. An alternative approach was used to determine biogas consumption and would be compared with that used in Table 5.1. In Table 5.5, Equation 4.10 was used. In this approach, gas engine parameters together with feedstock characteristics were used; i.e. number of hours engine operates per day, specific fuel consumption of engine, and engine break power. For feedstock characteristics (Shown in Table 5.2), density and specific biogas yield were used.

Table 5.5: Daily biogas consumption by biogas engine with corresponding quantities of electricity

ELECTRICITY, Ep [kW]	50	100	200	300	400	500
Biogas required [m^3/day]	666.67	1,333.33	2,666.67	3,999.99	5,333.33	6,666.67

Table 5.5: Daily biogas consumption by the biogas engine with the corresponding quantities of electricity generated

Data from Table 5.5 was input into MATlab and plots were made as shown in figure 5.4. Then model shown as Equation 5.11 was also developed. The model is to be compared with that in Equation 5.1 on the basis that a different approach was used.

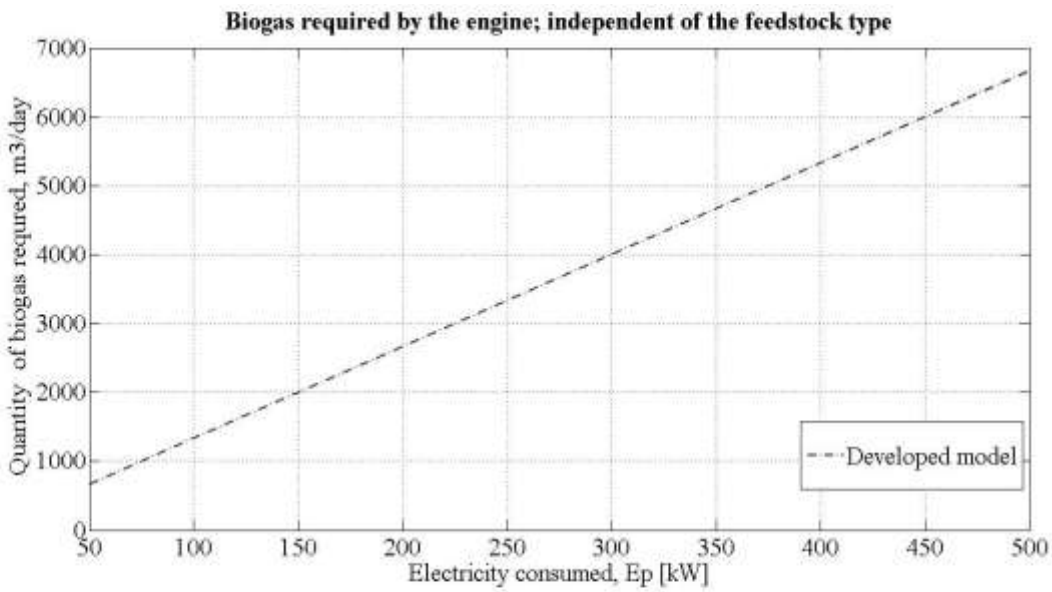


Figure 5.4: Plots of quantity of Biogas vs Electric power demand

$$fc = 13.3\boldsymbol{Ep} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 5.11}$$

5.2.2 Annual biomass resource required to generate electricity using biogas engine

Table 5.6 shows quantities of biomass per annum required to satisfy electricity generation using a biogas engine. Biomass resource was calculated using Equation 3.5 or 3.2.

Table 5.6: Feedstock quantities required for electricity generation using a biogas engine

	BIOMASS RESOURCE PER ANNUM [tonnes / year]							
	Swine manure	**Cow dung**	**Chicken droppings**	**Grass silage**	**Corn silage**	**Vegetable and fruit waste**	**Sludge waste**	**Catering waste**
50	4195.40	6576.60	3526.60	2081.60	1755.65	3379.63	16222.22	2212.12
100	8390.80	13153.20	7053.10	4163.10	3511.30	6759.26	32444.44	4424.24
200	16781.61	26306.30	14106.30	8326.20	7022.61	13518.52	64888.89	8848.48
300	25172.44	39459.50	21159.40	12489.30	10533.91	20277.78	97333.33	13272.73
400	33563.22	52612.60	28212.60	16652.40	14045.21	27037.04	129777.78	17696.97
500	41954.02	65765.80	35265.70	20815.50	17556.52	33796.30	162222.22	22121.21

Figure 5.5 shows plots made from data in Table 5.6. MATlab software was used to do the plots for the 8 selected feedstock materials

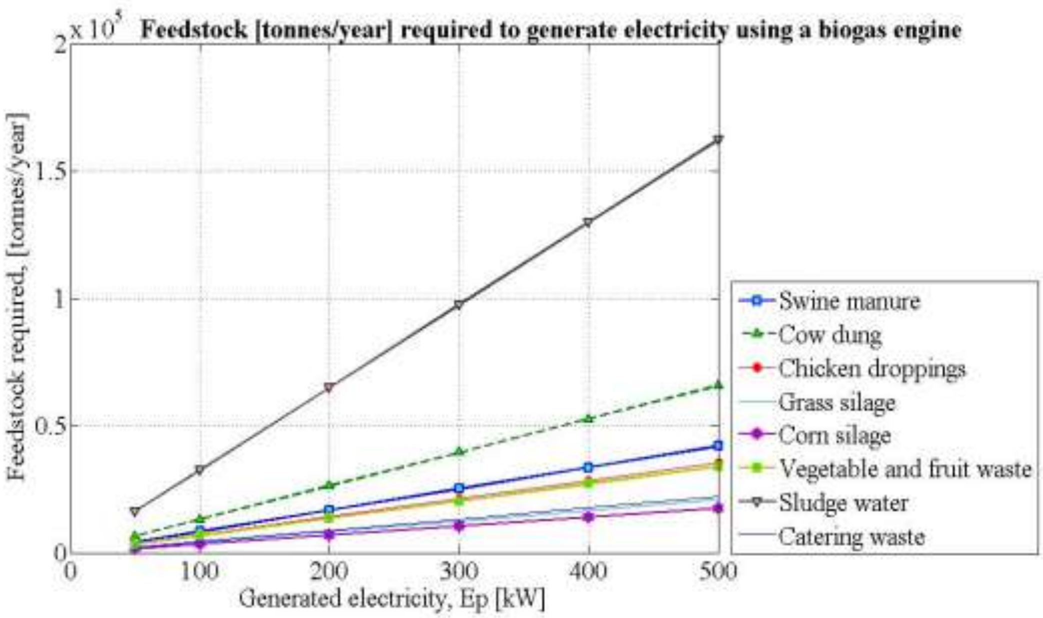


Figure 5.5: Quantities of feedstock required to generate electricity using a gas engine

Table 5.7 also shows relative percentages of feedstock required per annum to generate electricity, using a biogas engine. The methods followed in determining the percentages are those presented on Table 5.4.

Table 5.7: Quantities of feedstock required per annum expressed in percentage form (from gas engine parameters).

Feedstock	**Swine manure**	**Cow dung**	**Chicken droppings**	**Grass silage**	**Corn silage**	**Vegetable and fruit waste**	**Sludge waste**	**Catering waste**
[%] feedstock [tonnes/year	10.5	16.5	8.8	5.2	4.4	8.5	40.6	5.5

Figure 5.6 presents annual feedstock (percentage form) required to generate electricity using biogas engine. Data from Table 5.7 was used in MS Excel.

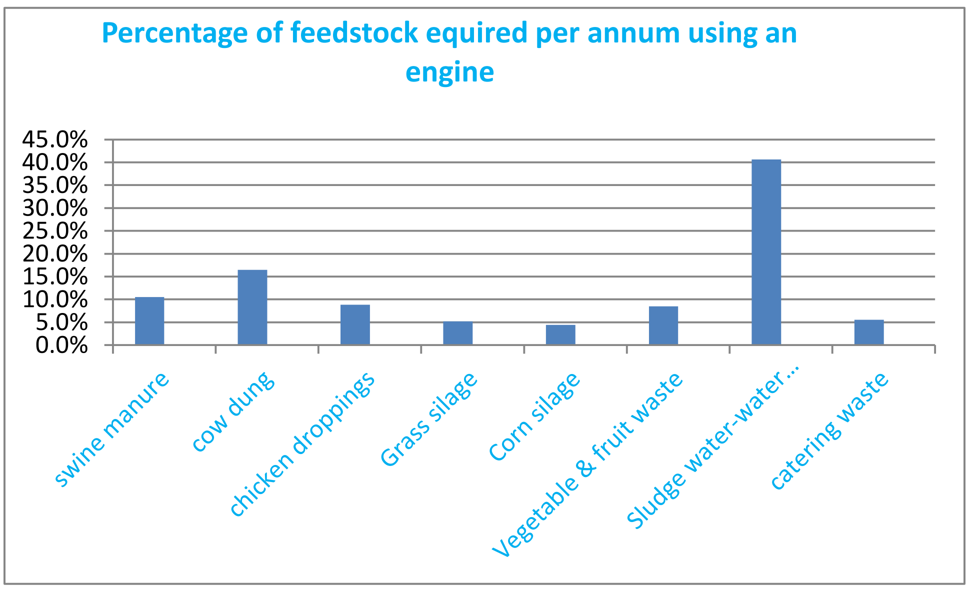


Figure 5.6: Percentage of feedstock required per annum to generate electricity using biogas engine.

5.2.3 Models validation

Universiti Sains Malaysia (USM) conducted a research on a Mini-Biogas Power Plant as an education and Research and Development tool for professionals and researchers (Maydin, 2014). The production of biogas and electricity results indicated that about 26.95 kWh/h (26.95kW) or (646.80 kWh/day) of electricity was generated from the total amount of 1,000 kg catering waste. The methane content was 196.0m^3/day; (daily biogas production was 327 m^3).

In this work, validation could not be done using local data (i.e. study farm) since the farm at the time of the study was not generating electricity. Thus, the adopted approach could still provide a better estimate as particular feedstocks produce biogas in a particular range (Maydin, 2014).

Table 5.8 gives a comparison of the results between experimental and model results. This research considered the range of 50 to 500 kW of electricity to be generated; however, in the validation, 26.95 kW was used considering the fact that the models developed took the form of a straight line. To that end, they can be used successfully for the electricity range other than the set one. The *validating* data here was based on specifically catering waste and the *specific* model used to determine the catering waste (feedstock) quantity was Equation 5.8; whereas the quantity of biogas was calculated using the *generic* model, Equation 5.1.

Table 5.8: Comparison of experimental and model results based on 26.95 kW.

	Quantity of feedstock [kg/day]	**Quantity of biogas [m^3/day]**
Experimental results	1, 000.00	327.00
Model results	**1, 002.81**	**301.80**
Deviation [%]	0.28	7.7

Considering the respective deviations on feedstock and biogas quantities per day of 0.28 percent (0.028); and 7.7 percent (0.077), therefore, it was evident that the models thus far developed could be used successfully to a better estimate for biogas system designs and optimization – while taking care of the known deviations presented in Table 5.8.

5.3 Determining the potential biogas and electricity production for a selected farm to meet its energy needs

Determination of the potential biogas production at a selected farm involved: i) the investigation of the energy use pattern for the farm ii) the determination of the animal population ii) the number of hours of operation by the biogas engine per day iii) the knowledge of the electric generator efficiency and; iv) an estimated specific fuel (biogas) consumption of the biogas engine.

5.3.1 Energy use pattern for the farm – (Energy consumption)

Table 5.9: Energy consumption at the farm.

Fuel service	**Source of Energy**	**Unit**	**Average daily consumption for the farm [kWh]**
Cooking	Electricity	kWh	30
Lighting	Electricity	kWh	44.8
Refrigeration	Electricity	kWh	2.2
Water pumping for fish operations and cleaning the pens	Electricity	kWh	60
Total			**137**

5.3.2 Energy demand of the fish ponds for water heating

Table 5.9 shows the measured data based on the energy expenditure on the farm whereas Tables 5.10 and 5.11 provides the respective calculations on energy demand for the fish pond water heating, for both winter and summer seasons.

Table 5.10: Fish pond Energy Requirements in winter

Winter scenario	**Water**		**Temperature**			**Energy demand**			
		Water volume	Starting temperature.	Achieved temperature.	Change in temperature	Volume * Δ°C	Calories for volume	Calories to kWh	
	[%]	[m^3/day]	[°C]	[°C]	[Δ°C]	[m^3*°C]	[Calories/ day]	Conversion to kWh	[kWh/day]
Total water body	100	1200		28					
Fresh water in	10	120	20.5	29	8.5	1020			
Water recycled	90	1080	26	29	3	3240			
Total heating energy						4260	4260000000	0.000001162	**4950.12**

Table 5.11: Fish pond Energy Requirements in summer

Summer scenario	**Water**		**Temperature**			**Energy demand**			
		Water volume	Starting temperature	Achieved temperature	Change in temperature	Volume * Δ°C	Calories for volume	Calories to kWh	
	[%]	[m^3/day]	[°C]	[°C]	[Δ°C]	[m^3*°C]	[Calories/ day]	Conversion to kWh	[kWh/day]
Total water body	100	1200		28					
Fresh water in	10	120	21	28	7	840			
Water recycled	90	1080	27	28	1	1080			
Total heating energy						1920	1920000000	0.000001162	**2231.04**

5.3.3 Potential daily biogas production with the corresponding amounts of electricity and heat energy

From the population of the animals on the farm, the potential daily biogas production and the corresponding electricity and heat generation provisions were calculated. Table 5.12 shows the potential daily manure, biogas, electricity and heat energy production from the farm. The total number of animals being as follows: Pigs = 3,000 and above; adult sows, and cows = 30.

Table 5.12: Potential manure, biogas, electricity and heat (CHP) on the farm

Manure yield		**Biogas production**			
Source	[kg]	Volume [m3]	Energy content [kWh]	Electricity [kWh]	Heat [kWh]
Pigs	15,000	1,125	6,862.5	2,401.9	3,431.25
Cows	300	15	91.5	32.03	45.75
Total	**-**	**1,140.00**	**6,954.00**	**2,433.93**	**3,477.00**

Thus, the potential biogas production per day was determined to be 1,125 m^3/day based on 3,000 animals. However, the obtained measured results from the farm were based on 1,000 animals. And the average quantity of biogas measured per day was 330 m^3. This meant that 3,000 animals could give a measurement of 990 m^3 of biogas per day or the potential biogas production per day would be 375m^3 as shown in Table 5.13. Equations 3.6 and 3.8 were used.

Table 5.13: Comparing measured and calculated results for the farm.

Potential or calculated biogas production [m^3/day]	**375**
Measured data of biogas production rate [m^3/day]	**330**
Difference	**45**

The difference between measured and calculated data came out to be 12 percent (0.12). This shows that the developed models could successfully be used to a better estimate in practice.

5.3.4 Energy demand and supply

The data obtained on the farm, showed that the energy provision in winter was about 32.65 percent of the maximum energy provision during the summer time. Table 5.14 shows the energy gaps between winter and summer seasons.

Table 5.14: Heat energy demand and supply for the fish ponds

Total heat *supply* from biogas engine [kWh]	1,135.24	3,477.00
Heat energy demand in winter [kWh]	4,950.12	----------
Heat energy demand in summer [kWh]	----------	2,231.04
Energy gap (supply and demand) [kWh]	**-3,814.88**	**1,245.96**

Table 5.15: Energy Demand and Supply in winter

The winter scenario	**[kWh]**	**[%]**
Energy demand for water heating alone in winter	4,950.12	100
Energy provision from pigs, minimum	**1,135.24**	22.93
Energy gap winter	3,814.88	77.07

Table 5.16: Energy Demand and Supply in summer

The summer scenario	**[kWh]**	**[%]**
Energy demand for water heating alone in summer	2,231.04	100
Energy provision from pigs, maximum	34**77**	155.85
Energy gap summer	-1,245.96	-55.85

Tables 5.15 and 5.16 used data from Table 5.14 to show energy gaps in both winter and summer seasons. Summer season shows a surplus of 55.85 percent; and the winter season shows a deficit of 77.07 percent.

5.3.5 Sizing of the biogas plant - Biogas plant dimensioning for purposes other than electricity generation

Using the total manure yield, kg/day and the biogas production rate, m^3/day, the digester, gasholder, buffer and biogas plant volumes were designed for the farm as shown in table 5.17. The basis for the designs was to ascertain the validity of the models developed in this work. Equations 4.2 to 4.6 were used.

Table 5.17: Biogas digester volumes using models developed in this work. (calculated)

	Volume [m^3]		
Digester volume [Vd]	Gas holder [Vg]	Buffer [Vb]	Biogas plant [V]
225	168.75	78.75	472.50
90	67.50	31.50	189.00
1800	**236.25**	**110.25**	**661.5**

5.3.6 Biogas plant main dimensions

The design of the Modified Camartec biogas plant required the dome radii, Rd and also the radii for the compensation chamber, Rcc. These radii are shown in Table 5.18. The drawing of the Modified Camartec biogas plant is shown in Appendix 5. Equations 4.5 and 4.6 were used.

Table 5.18: Dome, and compensation chamber radii for the farm - based on calculations.

Digester size [m^3]	**Radius [m]**	
	Dome [Rd]	Compensation chamber [Rcc]
225	6.09	4.32
90	4.49	3.18
	Actual Rd on the farm	
200	5.45	-
80	4.45	-

Table 5.19 shows key parameters for sizing a Biogas Plant specifically for electricity generation. However, heat produced by the biogas engine could be harnessed in the process, and was included in the same table. Also, the total energy in biogas was included. The following method was used to determine the parameters in the table: i. Equation 4.10 for daily biogas consumption; ii. Equation4.9 for daily loading rate; iii. Equation 4.1 for digester volume; iv. Equation 4.13 for buffer volume of the plant; v. Equation 4.12 for gas holder volume; vi. Equation 4.14 for total volume of plant; and vii Equation 3.8 for daily biogas production. For the amount of heat generated, information from Chapter 5, Section 5.1.1 in this work was used.

Table 5.19: Parameters for adaptation of biogas engine to the biogas plant

***P**el* [kWh]	**50**	**100**	**200**	**300**	**350**	**400**	**500**
fc [m3/day]	666.67	1,333.33	2,666.67	4,000.00	4,666.67	5,333.33	6,666.67
G [m3/day]	1,125.00	1,125.00	1,125.00	1,125.00	1,125.00	1,125.00	1,125.00
***V**d* [m3]	1,406.25	1,406.25	1,406.25	1,406.25	1,406.25	1,406.25	1,406.25
***V**s* [m3/day]	- 458.33	208.33	1,541.67	2,875.00	3,541.67	4,208.33	5,541.67
E [kWh]	2,196.00	4,392.00	8,784.00	13,176.00	15,372.00	17,568.00	21,960.00
Q [kWh]	1,098.00	2,196.00	4,392.00	6,588.00	7,686.00	8,784.00	10,980.00

Figure 5.6 shows plots based on Table 4.19 against electric power; and these parameters are:

i. Rate of biogas consumption,
ii. rated of biogas production,
iii. digester volume, and
iv. storage volume

MATlab software was used to make the plots.

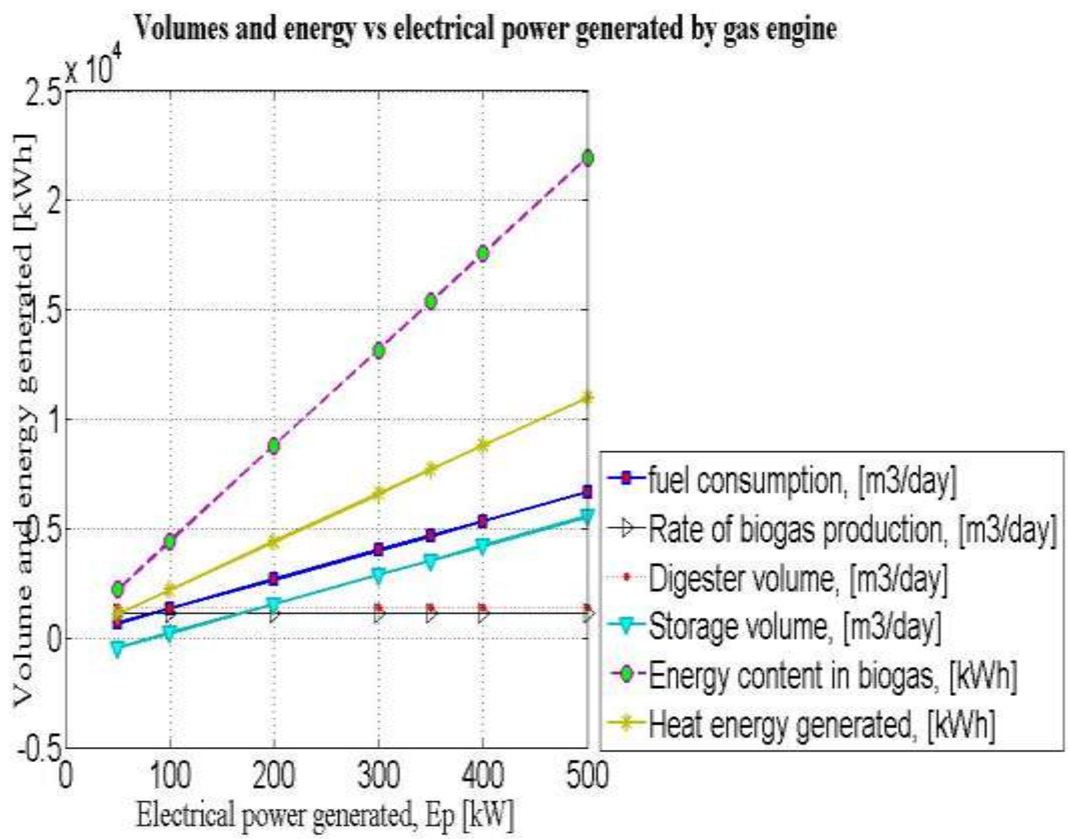


Figure 5.7: Graph of biogas consumption, storage volume, energy content in biogas, heat generated due to CHP, and rate of biogas production vs. electricity generated.

5.3.7 Digester sizing for an electric power range of 50 to 500 kW using selected feedstock materials

Table 4.20 shows the determined results of the volume ranges against the 50 to 500 kW electric power range. A critical observation was noted especially on grass silage. Despite having a relatively higher specific biogas yield, the digester volume required to generate a particular amount of electricity as compared to other feedstock materials was larger than expected. This was to a greater extent similar to chicken droppings. This is shown in Figure 4.10 where the two feedstocks (grass silage and chicken droppings) are only preceded by sludge waste water, which has a relatively much lower specific biogas yield.

There are some parameters of concern at play, for this occurrence – These include: number of hours of operations by the gas engine, specific fuel consumption, the brake power developed by the gas engine, and the hydraulic retention time are normally predetermined at design stage.

Since the volume of the digester is directly influenced by the product of the hydraulic retention time, and the daily loading rate; the above occurrence (with grass silage and chicken droppings) was as a result of the loading rate only. With respect to feedstock characteristics, the daily loading rate (m^3/day) of a particular feedstock is inversely proportional to the product of the feedstock density and the specific gas constant. Thus, this was the only quantity which was varying with varying feedstock materials. That is why grass silage and chicken droppings had larger digester volume as compared to other feedstock with similar energy content. Because of relatively lower densities i.e. 260 kg/m^3 and 450 kg/m^3 for grass silage and chicken droppings respectively; as compared to that of, for example, cow dung (1, 090kg/m^3).

It could then be deduced that feedstock materials with comparatively lower densities could result in lager digesters despite having a higher energy content. As for sludge waste water, a relatively larger digester was expected because it had a much lower specific gas yield of about 0.015 m^3/kg; though with a reasonable density of 1,400 kg/m^3.

Additionally, the plots of Figure 4.10, being linear and to scale, can be used to predict the volume of the digester once electricity demand is established. This is specific to a particular feedstock and hence not generic.

Table 5.20 shows electric power with corresponding digester volumes for 8 selected feedstock materials. Equations 3.6 and 4.10 were used in determining digester volumes.

Table 5.20: Digester volumes based on 8 selected feedstock material for electricity generation

	Digester volume [m^3]							
Electric power, Ep [kW]	**swine manure**	**cow dung**	**chicken droppings**	**grass silage**	**corn silage**	**vegetable and fruit waste**	**sludge waste-water**	**catering waste**
50	689.66	991.82	1288.24	1316.05	450.94	555.56	1904.76	606.06
100	1379.31	1983.64	2576.49	2632.10	901.88	1111.11	3809.52	1212.12
200	2758.62	3967.27	5152.98	5264.20	1803.75	2222.22	7619.05	2424.24
300	4137.93	5950.91	7729.47	7896.30	2705.63	3333.33	11428.57	3636.36
400	5517.24	7934.54	10305.96	10528.39	3607.50	4444.44	15238.10	4848.48
500	6896.55	9918.18	12882.45	13160.49	4509.38	5555.56	19047.62	6060.61

The data in Table 20 was plotted as shown in Figure 5.7 using MATlab computer software. With an established electricity need, the capacity of the digester would be obtained.

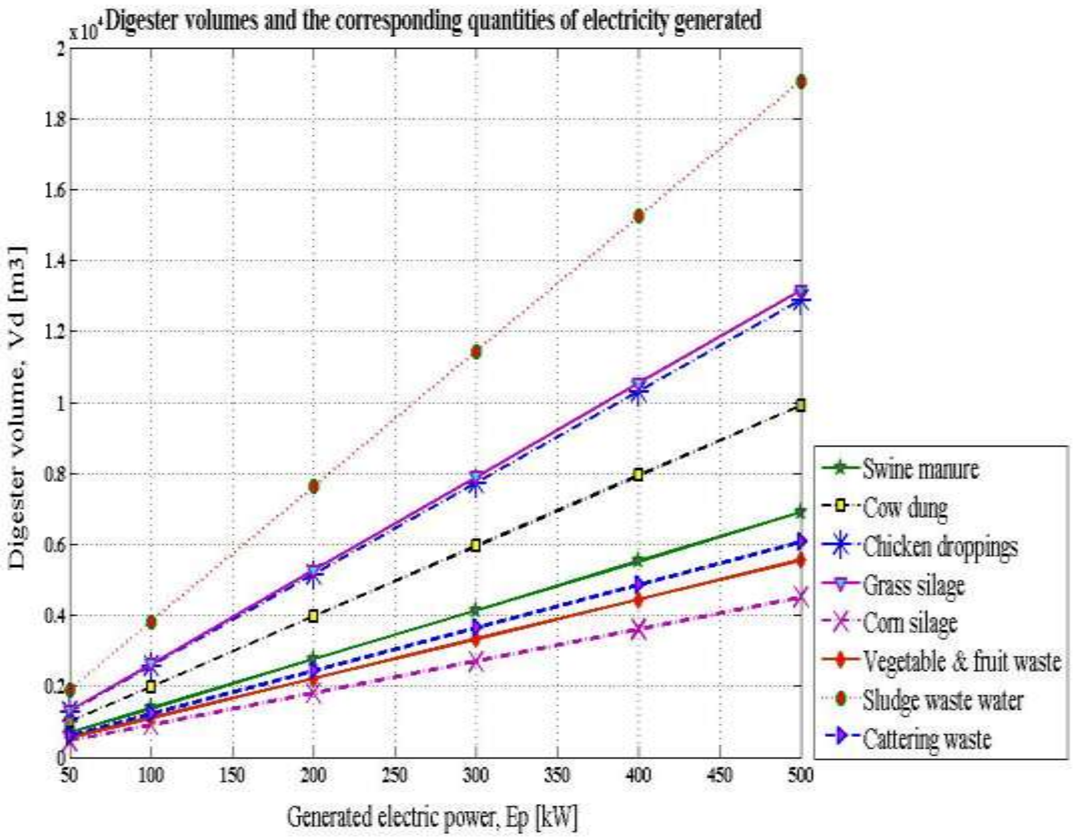


Figure 5.8: Digester sizing and the corresponding amounts of electricity.

5.4 Estimation of the optimum temperature for maximum biogas production rate under Zambian climatic conditions

Figure 5.7 shows the rate of biogas production [m^3/day] against the corresponding monthly average temperatures [^oC] presented in Appendix 2. These measurements were carried out at the Farm in Chongwe. The feedstock used in this specific case was swine manure. Plots for measured data were made as shown in Figure 5.7; and using MATlab computer software, a model which would be used to determine the optimum temperature for biogas generation was developed.

Equation 5.12 presents the model which was developed using Equations 3.11 and 3.12, and MATlab computer software by determining the coefficients of the equation which were 2.6 and 1.51.

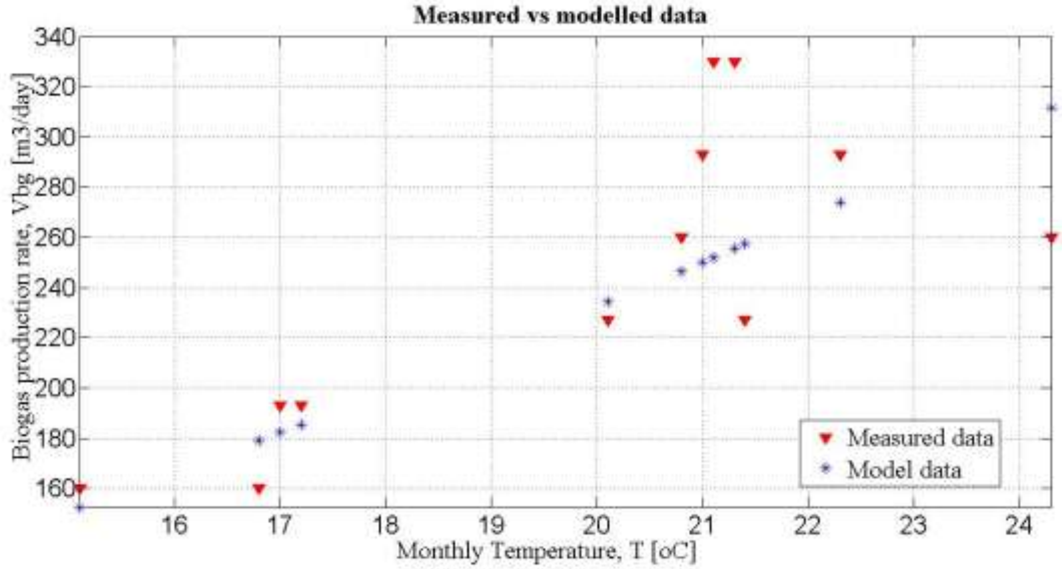


Figure 5.7: A relationship showing monthly biogas production and the corresponding average temperatures.

$$\boldsymbol{G = 2.61 * T^{1.51}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \boldsymbol{Equation\ 5.12}$$

Using Equation 5.12, the optimum temperature was determined at which the biogas production rate would maximum - and was found to be 24.7°C. Equation 3.8 was also used.

CHAPTER 6 DISCUSSION

6.1 Introduction

This chapter discusses the results which were presented in chapter five. The discussion is guided by the research objectives as follows:

6.2 Development of models which predict the amount of biogas, and feedstock required to generate electricity in the range of 50 to 500kW

In this work, the first objective was to develop models which predict the amount of biogas, and feedstock required to generate electricity in the range of 50 to 500 kW. The relationship adopted was that biogas had a calorific value of 22 MJ per cubic metre ($1m^3$) (Banks, 2009). This relationship was converted to kWh, which was the case for all energies in this work, so as to have a common unit of measure for effective comparisons. Therefore, $1m^3$ of biogas contains 6.1 kWh of total energy. However, Banks (2009) reported that a maximum of 35 percent of the total energy is converted to electric energy; 50 percent as heat energy, and 15 percent lost to the environment. Hence, $1m^3$ of biogas contains 2.41kWh of electric energy.

With the 50 to 500 kW range selected, and the above relationship, the quantities of biogas required were determined and tabulated in the Results section shown in Table 4.1; with the accompanying plots presented in Figure 4.1. MATlab computer software was the tool used to make plots. As expected, the quantity of biogas required was directly proportional to the amount of electricity generated i.e. gave a straight line, which was modeled as shown in Equation 4.1 presented as $\boldsymbol{G} = 11.22\boldsymbol{E}p$. Thus, the model being a straight line could be used for a range of electricity generation beyond the selected 50 to 500 kW. The only challenge would be to determining the maximum quantity of biogas production at which optimum efficiency could be sustained, as this has not been researched on, based on findings of this work; i.e. what would be the maximum limit (volume) for a bio-digester to operate at an optimized efficiency; digester volume is directly proportional to biogas produced. This refers not to a combination of digesters but an individual one.

Therefore, the developed model (Equation 4.1) could effectively be used in optimization of biogas plants for electricity generation; since it was developed using maximum parameters. For example, as earlier alluded to, biogas conversion to electricity does not go beyond 35 percent of total energy content; thermal energy content of about 22 MJ per $1m^3$ of biogas. Thus, the model would be used as an indicator for efficiency optimization; in cases where actual or measured data (biogas consumption, ***G***) fails to satisfy the model. It can also successfully be used in designing biogas plant systems. This is explained further in the succeeding paragraphs.

Development of models to predict quantities of feedstock required per annum was achieved by using the relationship presented in Equation 3.6. Table 5.3 shows the results of using Equation 3.6 with 50 to 500 Kw as an input; and plots were made as presented in Figure 5.2. Eight (8) types of different feedstock materials were used in this work based on availability and quantity; that which would satisfy the 50 to 500 kW electricity range. The model (Equation 5.1) was used to determine the optimum quantities of biogas consumption; and these quantities of biogas became an input in determining the optimum amount of feedstock required. Thus, the amount of biogas required was the same for all the 8 feedstock materials. But an observation from Figure 5.2 showed that the graphs were all different despite being derived from the same amount of biogas. This was because each feedstock material had its particular characteristics; i.e. specific biogas yield. For example, comparing sludge waste at a water treatment plant, and corn silage in Figure 5.2 showed that at 50 kW electricity generation, 13,644.86 tonnes per year of sludge waste were required, whereas 1,476.72 tonnes per year of corn silage were required. This was because of having different feedstock characteristics as shown in Table 5.2; which shows sludge waste with specific biogas yield as 0.015 m^3/kg while corn silage with 0.1386 m^3/kg. Therefore, the quantity of feedstock required was found to be inversely proportional specific biogas yield. This was further clarified in Table 5.4 and Figure 5.3 where the eight feedstock materials were shown in relative percentages of feedstock quantity. Corn silage, when compared with the 8 feedstock materials, would require 4.4 percent whereas sludge water would need 40.6 percent. This difference in percentages will be elaborated in detail when discussing digester designs under digester volume vs electricity generation in Table 5.20 and Figure 5.7.

Therefore, optimization of the biogas digester requires that the best parameters be used. In this case corn silage would be selected for an optimal performance of the digester among other parameters.

Based on Table 5.3 and Figure 5.2, specific models were developed for each feedstock material as shown by Equations 5.3 to 5.10, using MATlab computer software. With an established electricity need/demand, quantities of feedstock could be predicted. Further, these models are specific, since each model could only be used on a particular feedstock, as opposed to the model in Equation 5.1 which applies to any type of feedstock, hence generic. The models (Equations 5.3 to 5.10) just like the model (Equation 5.1) could also be used in optimizing digester efficiency.

That is actual data from a biogas plant must satisfy these models or else the best parameter must be reconsidered for the biogas system.

6.3 Comparing biogas and feedstock quantities needed to generate the same amount of electricity using an alternative approach against the baseline (objective number one)

To achieve the second objective, an alternative approach was used; and it required that specific gas engine parameter be used so that a comparison could be made with the finding of objective number one (base line case). Equation 4.10 was used to obtain values of biogas consumption by the engine using 50 to 500 kW electric power; and the results tabulated as shown in Table 5.5. Then the plots were made using MATlab computer software as shown in Figure 5.4.

Comparing the results of Figure 5.1 and Figure 5.5 showed that the two graphs were all straight lines and could be discussed exactly in the same manner. However, the results of the two approaches had a deviation of 0.149 (14.9 percent); based on Tables 5.2 and 5.6. The coefficients of the Equations 5.1 and 5.2 were 11.22 and 13.30 respectively; otherwise they were expected to be the same. This shows that the model for the second objective shown by Equation 5.2 consumes more biogas by 18.5 percent than Equation 5.1. This was because Equation 5.1 was developed from a direct method; feedstock characteristics did not directly come in However, Equation 5.2 considered all the parameters, for example: to determine biogas consumption required number of engine operating hours per day, specific fuel consumption, feedstock characteristics (specific biogas yield, feedstock density, and electric generator efficiency; with a known quantity of electricity demanded. In this particular case, with optimization to be achieved, only the best parameters were considered within a particular range. For example, the number of hours of operation was taken as 24 i.e. a continuous system, specific biogas constant has a range of 0.5 to 0.8 m^3/kWh (MITZLAFF, 1988); where 0.5 m3/kWh was selected because it consumed a minimum quantity of biogas per kWh mechanical energy produced. For the electric generator efficiency, 90 percent was used as generators are capable of reaching that percentage. Thus, it was not known which parameters were assumed in achieving objective number one. To a greater extent, the two results are agreeable because the source of the deviation was discussed. This means that Equation 5.2 (in the second objective) would be more reliable as it incorporated actual engine, and feedstock parameters.

Table 5.6 and Figure 5.5 show feedstock quantities required to generate a corresponding amount of electricity using a biogas engine. Equation 3.6 was used to obtain values of feedstock. Graphs were plotted and could be describe in a similar manner as in objective one (Table 5.3 and Figure 5.2). the graphs had a deviation of 14.9 percent. The plots in figure 5.5 (compared with Figure

5.2) also showed that, at 50 kW, sludge waste required 16,222.22 tonnes per year while corn silage requires 1755.65 tonnes per year with a deviation of 18.9 percent. Figure 5.5 has also shown that the rate of biogas consumption was directly proportional to the product of density and specific biogas yield. This will be developed further in Table 5.20 and Figure 5.7.

In terms feedstock quantities required, Table 5.7 compare well with Table 5.4. There were no differences. This was also the case figures 5.3 and 5.6. it was expected that there would be no differences, because percentages take care of ratios.

6.4 Determining the potential biogas and electricity production for a selected farm to meet its energy needs

To determine the potential biogas and electricity production for the farm, measurements were done; and the relevant documents were reviewed. Table 5.9 presents one part of energy consumption for the farm; and the other part dealt with fish pond heating shown in Tables 4.10 and 4.11; where it was observed that most energy was used for fish pond heating. For example, Table 4.10 shows that 4,950.12 kWh/day of energy was needed to heat the fish ponds from 20.5^{o}C to 29^{o}C in winter; and in summer, 2,231.04 kWh/day from 21^{o}C to 28^{o}C. Comparing the two energy quantities needed to heat the fish ponds in winter and summer, to that in Table 5.9, which is 137 kWh/day, shows a big difference. This means that to achieve this, the farm must have a sustainable source of feedstock materials.

The Tables 5.10 and 5.11 allow the following deductions:

i) Most energy was required in the winter period.
ii) In winter 25 percent (one quarter) of the energy was required to heat the 120m^3 of fresh water from 20.5^{o}C (measured) to 28^{o}C.
iii) Heating the 1,080 m^3 re-circulated and cleaned water from 26^{o}C (average) to 28^{o}C requires 75 percent of the total water heating energy.

A biogas project of 800m^3 digester capacity has too high technical and managerial requirements, and would require substantially more organic matter as feedstock than what can be produced on many farms – in the Zambian context. Although the piggery project could be designed to supply the energy requirements in the form of biogas, it should only be considered if it can be run as a profitable business unit by itself.

The potential biogas volume and energies for the farm were determined to ascertain the feasibility of the project at the farm as presented in Table 4.12. Total biogas volume was 1,140.00m^3, biogas energy content was 6,954.00 kWh, electricity was 2,433.93 kWh, and heat energy was 3,477.00 kWh. However, in this work, only swine manure which had a significant contribution of 1,125m^3 of biogas was considered in the succeeding calculations as compared to cow dung which contributed 15m^3.

Figure 5.13 compares the volumes of measured and potential biogas on the farm. However, measured biogas data was based on 1,000 pigs which gave 330m3/day; and using direct proportion, when 3,000 pigs gave a potential of 1,125m3then 1,000 pigs would give a potential of (1,125*1,000/3,000) 375m3 as shown in Table 5.13. The difference between measured and calculated data was 12 percent (0.12). This showed that the developed models could successfully be used to a better estimate in practice, hence optimization of biogas plant systems.

Table 5.14 shows data obtained from Table 5.12 to show energy gaps between summer and winter seasons. Data in Table 5.12 was further processed in Tables 5.15 and 5.16 to show the same energy gaps in percentage form. The data showed that it would not be a major concern to produce electricity and heat energy during the summer period Table 5.16. There would also be an energy surplus which could be absorbed through other measures which require energy – for example, Table 5.9 shows the energy expenditure for the farm which required 137 kWh of electrical energy. Thus, the surplus energy in the summer season, converted into electrical energy came to 872.17 kWh. This amount also gave 735.17 kWh as extra surplus electrical energy. Table 5.16 indicates a huge surplus of 55.85 percent of energy in the summer season.

However, the renewable energy solution in this case has rather to be governed by the time period in which energy is scarce, i.e. winter time. Table 5.15 provided a startling result of the gap that required to be filled as 77.01 percent.

In winter the biogas installation with on-farm feedstock provided less than one third of the amount of energy required. However, there were possibilities to reduce this gap, for example, by adding other organic matter in any of the digesters or in all of them (this could optimize biogas production in essence). For example, cow manure from other farms could be bought during the cooler period as batch loads of the content of a farm trailer, especially from April to August. Also, kitchen waste from the restaurant and from the households on the farm could be added in and would provide another little buffer. For this, ***jatropha*** press cake was particularly suitable, since it has high energy content and can easily be stored until it is needed. The other option was to reduce electricity generation and directly use biogas for fish pond heating until summer time.

As for pig rearing, it is supposed to provide a heat source for young piglets. Any gas brooder can be modified to operate on biogas. As this gap is required irregularly during the year, its consumption does not have much impact on the total energy available and therefore, the farm owner could not provide the needed data so as to determine that particular energy requirement.

Using models developed in this work i.e. based on Equations 4.1 to 4.6, volumes for the biogas system were determined as presented in Table 5.17; Vb, Vd, Vg, and V. Also, biogas plant main dimensions were calculated i.e. Rcc and Rd as shown in Figure 5.18. Figure 5.18 also compared the calculated data to actual farm parameter. The actual digester volume on the farm was $200m^3$ for the two digesters; whereas the determined volume gave $225m^3$. The farm digester with $80m^3$ gave $90m^3$ as a determined volume. Then the $200m^3$ digester at the farm had a dome radius of 5.45m while the determined one provided 6.09m. With the $80m^3$ farm digester, the dome radius was 4.45m while the determined one was 4.49m.

It was observed that the determined radii were slightly on a higher side than the actual. This was because the designs were based on the amount of manure generated by the animals which was more than the digesters would actually handle. In fact, this was one of the critical observations which was made at the farm. Even the retention time was less than the designated 60 days because of the same reason. Also, the gas produced was on a lower side because cleaning panes required more water than what would otherwise be needed to have the correct feedstock to water ratio. Thus, it could be said that the results were consistent with actual data on the farm.

Table 5.19 considered the parameters for the adaptation of the biogas engine to the biogas plant. Data in the table were arrived at using the following models:

i. Equation 4.10 for biogas consumption by the gas engine;

ii. Equation 3.8 for gas production by digester;

iii. Equation 4.12 for gas storage of the biogas plant;

iv. Equation 4.1 for digester volume;

v. Energy content in biogas and heat energy were calculated using the cited relationship in this work – (Banks, 2009).

Figure 5.6 shows the plots of the parameters presented in Table 5.19. It was observed that, at the point where the storage volume was zero or where gas production was equal to gas consumption, generated electrical power was 84.38 kW. Electric power at this point was *29.5 percent* of the total energy contained in the biogas. This figure (29.5 percent) agrees well with the range that has been reported in the literature and empirical research-(Banks, 2009). The volume of the digester was determined as 1,406.25 m^3 and the optimum biogas consumption rate was optimized at 1,125.00m^3/day- Table 5.12 and 5.17. After this point where storage volume was zero, storage was necessary. However, the above parameters were designed for the biogas plant to run for 24 hours per day; thus, storage cannot be sustained. Otherwise, the plant would have to be shut down during designated times to facilitate for adequate storage.

The challenge would be on the economy of space and the cost involved, since the storage volume would prove to be much larger – especially when larger quantities of electricity are required to be generated. Therefore, designated periods of non-operation must be put in place for the plant to successfully run well – otherwise an integrated energy system is required e.g. an energy mix with solar or any other renewable energy source.

Table 4.20 shows the volumes with corresponding quantity of electricity ranging from 50 to 500kW. Comparing the results of Table 5.4 with Figure 5.7 (derived from Table 5.20) it was observed that grass silage and chicken droppings needed lager digester volumes than feedstocks of similar specific biogas yield; e.g. corn silage with the list volume had specific gas constant equal to 0.1386m3/kg while grass silage had 0.1169 m3/kg. Sludge waste was expected to have a relatively larger volume than grass silage with specific gas yield equal to 0.015m3/kg. It was further observed that from Table 5.4, grass silage was 5.2 percent while by volume it came to 16.86 percent. Sludge waste moved from 40.6 percent by mass to 24.4 percent by volume. This was because grass silage had a lower density as compared to sludge waste, which were 260kg/m3 and 1,400 kg/m3. Therefore, if the digester efficiency was to be **optimized**, *density of feedstock material must be enhanced*. This could be achieved by preprocessing through mechanical means e.g. grinding or crashing the feedstock into very small sizes and possibly have the feedstock compacted though free enough to be acted upon by microbial action.

6.5 Estimation of the optimum temperature for maximum biogas production rate under Zambian climatic conditions and feedstock characteristics

To estimate the optimum temperature at which biogas could be produced at an optimum efficiency; data was obtained from Chimphembela Fish Farm and Restaurant. From the data, average monthly temperatures (Appendix 2) and daily biogas production were used to develop a specific model which could predict the optimum temperature. MATlab computer software was used to develop the model. Firstly, the Power Law was adopted in developing the model. The reasons for choosing the Power Law were stated in Chapter 3; Section 3.1 of this work. The mathematical methods applied to the Power Law were shown in Chapter 4; section 4.5 before using MATlab computer software. The developed model was presented in Equation 5.12.

However, the model was developed using swine manure based on 3,000 pigs under Zambian climatic conditions. Therefore, the model can only be applied to that specific situation; hence, it was a specific model and not generic. The purpose of developing the model was to predict an estimate of the optimum temperature at which biogas production in Zambia could be optimized.

To estimate the optimum temperature using the model, the total manure yield from 3,000 pigs was determined (Equation 3.7); and maximum biogas yield was calculated using Equation 3.8. Thus, the maximum biogas production per day was achieved. under the conditions on which the model was developed; actual maximum biogas production at the farm (330m^3/day in Table 5.13) was substituted into the model; and temperature was calculated as 24.7^{o}C. That was the temperature at which biogas production would be maximum under the conditions on which the model was developed; hence, an optimum temperature for a case of Zambia was determined. At this temperature, the biogas digester would be optimized for better efficiency.

At the optimum temperature (24.7^{o}C), micro-organisms would be under favourable conditions. Therefore, this temperature applies to all 8 selected feedstocks, or all biodegradable matter in general.

This temperature fell in the mesophilic temperature range of 20 to 45^{o}C at ambient temperatures (Deacon, 2000); where the optimum mesophile growth is achieved; which have long been identified as most favorable for anaerobic digestion (Kim, 2002). in contrast, under thermophilic conditions, digesters need heating, while under psychrophilic conditions, hydrolysis is not as extensive, thus, anaerobic digestion is much slower (Connaughton, 2006). With the indicated optimum temperature range; and that 24.7^{o}C which was somewhere around Zambia's average temperature – provided strong proof that the country does not require any heating as that could simply be uneconomical. An exception in winter when temperatures fall below 24.7^{o}C; though this would be averted by a proper energy mix e.g. solar and other renewable energy sources or heating the digester using solar power (though this would increase the cost of the project).

Also, Mydin et al (2014) reported that digesters used under mesophilic conditions operate between temperature ranges of 20 to 25 ^{o}C; via 40 to 45 ^{o}C. Therefore, the determined optimum temperature (in this research work) of 24.7^{o}C is apt as it fits in well in the optimal temperature range under mesophilic conditions.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

This chapter presents the Conclusions from this work. Recommendations for the future work are also made thereafter. In accordance with the research objectives of this work, the following conclusions were made:

i. The results of the study on the eight (8) different feedstock materials demonstrated that the developed models could be used successfully in digester optimization for electricity generation. This was because models were developed using best parameters for performance; and that the models agreed well with field data. In practice, these models would be used to assess the performance (efficiency) of biogas systems for electricity generation i.e. if data from an operating biogas plant is input into the model and does not satisfy the conditions (bio-digester underperforming), then the bio-digester must be optimized.

ii. The rate of biogas production was found to be inversely proportional to the product of feedstock density and specific biogas yield (Equation 4.10). Therefore, digester efficiency could be optimized by increasing both density and specific gas yield as discussed in Chapter 6; Section 6.4 based on Table 4.20 and Figure 5.7.

iii. Findings on the farm (used as a case study in this work), showed that most energy was needed in winter periods. Table 5.15 shows an energy gap (deficit) of 77.01 percent i.e. energy demand in winter was 4, 950.12 kWh; against energy provision from pigs which was 1,135.24 kWh.

   However, the summer period gave a surplus of 55.85 percent (Table 5.16) of energy. i.e. energy demand was 2,231.04 kWh against energy provision on 3477.00.

   In view of these seasonal fluctuations in biogas production, biogas plant systems must be designed with enough storage capacity i.e. if designed for consumption equal to production, a biogas plant would become non-operational during winter periods. Thus, this presents a challenge for a system that was designed to run 24 hours. Hence, the need to design systems that produce more than is required by optimizing the digester through co-digestion with feedstocks which have a higher energy content or those that would improve on the carbon-nitrogen ratio.

iv. Under Zambian climatic conditions and feedstock characteristics, the optimum temperature for maximum biogas production was determined as 24.7^{o}C. this is under mesophilic range, such that no heating of the digester would be required in Zambia. Also, this is a favourable temperature for micro-organisms to perform better. Thus, it could be concluded that, the optimum temperature for all bio-degradable matter in Zambia and those with similar conditions is 24.7^{o}C.

7.2 Recommendations

Undoubtedly, biogas technology has the potential to provide the needed energy for generation of electricity in Zambia. This is especially so for commercial farmers, waste water treatment plants, large hotels, malls and other similar facilities with the capacity to generate enough feedstock materials to meet their energy needs.

Despite the seeming benefits that the technology can offer, it is not wide spread in the country and mainly at pilot stage. Thus, the government must take responsibility in the awareness of this technology and in many cases, provide start-up resources.

As a step to be considered at a later stage, the electricity produced can be fed into the grid, against payment by the electricity utility Zesco. While this is certainly the way forward to mitigate the power deficit in the country, this option requires that such a feed-in scheme is mandated by legislation at economically viable feed-in tariffs.

CHAPTER 7

REFERENCES

Adhola G. A. (2014). "Determinants of energy saving cook stove adoption in rural households of Kisumu North location, Kisumu county. Pp 30-40, Nairobi.

Anaerobic Digestion.Com (2016). "Mesophilic Anaerobic Digestion."

Plants in Africa. Resources, Conservation and Recycling**:** 55, 63-57.

Bernd Althusmann, S. B. (2016). Perspectives on energy security and renewable energies in Sub-saharan Africa. Windhoek, Namibia, Macmillan Education Namibia.

Biotech (2016). Renewable Energy. National Algal Bio fuels Technology Review

Banks C. (2009) Optimizing Anaerobic Digestion. Evaluating the Potential for AD to provide Energy and Soil Management. niversity of Southampton.

Chen Y., Yang G., Sweeney S. and Feng Y. (2010). Household Biogas Use in Rural China: A Study of Opportunities and Constraints Renewable and Sustainable Energy Reviews**:** 14, 545-549.

CIMAC (2015). "Impact of gas quality on gas engine performance."

Claus Von Mitzlaff (1988). "Energies for biogas." Theory, modification economic operations. (GTZ) Gmb

Denis Debila (2011). In der Entwicklungshilfe scheitern viele Projekte, weil sie zu wenig Rücksicht auf die Umstände vor Ort nehmen. Ein Verein ehrenamtlich tätiger Technik-Profis hat daraus Lehren gezogen. Deutschland.

Deogratias K., Quais H., Soundar K., Goudong S. (2015) Integrating data analytics and simulation meyhods to support manufactutring decision making. Morgan State University, Baltimore, MD, Huntington Beach, California.

Dobre P. et al (2014). "Main factors affecting biogas production - an overview." **19**(3).

energypedia.info (2016). "Electricity Generation from Biogas."

Dolores Hidolgo, Martin-Marroquín J. M., Coronas F. (20160). Biogas upgrading technologies

ERB (2014). Energy Sector Report 2014. Zambia, ERB**:** 8.

Feiges S (2015) Climate change mitigation and adaptation potential of basic energy services: Overview of potential heating and decentralized electricity generation. GIZ, 14.2242.7-001.00, Zurich, Switzerland.

Foundation, U. N. (2013). ACHIEVING UNIVERSAL ENERGY ACCESS.

G. W. Roth, A. J. H. (2016). "Corn silage production and management." 6.

Georg Friedl (2016). Biogas production in Germany: Status quo and future trends.

Hahn h, K. b., Wachendor M., (2014). "Renewable and Sustainable Energy Reviews."

Heegde E. W. (2010) Biogas Plant and Dimensions. Domestic biogas plants sizes and dimensions. SNV

Hiptmair R. (2016) Numerical Methods Computational Science and Engineering. URL: http://peole.math.ethzich/~grsam/HS16.pdf

IEA (2014). Africa Energy Outlook; A focus on energy prospects in sub-saharan Africa.

Havukainena J, Uusitalo V, Niskanen A, Kapustina V and Horttanainen M (2015) Evaluation of methods for estimating energy performance of biogas production. Lappeenranta, Finland

IEA/WEO (2016). "Energy Access Database."

Kutawul H. and Bohara A. K. (2010). Biogas: A promising Renewable Technology and its Impact on Rural Households in Nepal. Renewable and Sustainable Energy Reviews**:** 13, 2668-2674.

Lungu H. L. (2011). Government Renewable Energy Programs, Lusaka, Intercontinental Hotel, ERB.

Masiliso S (2008). Energy Statistics - The Case of Zambia. Adis ababa; Ethiopia.

Mitzlaff, Klaus von (1988): Engines for Biogas. GTZ-GATE /Viehweg. pp.164, Documents early approaches of GTZ towards electricity generation from biogas

Monnet Fabien (2003). "An Introduction to Anaerobic Digestion of wastes."

NEP (2008). National Energy Policy. Lusaka.

Nijaguna B. T. (2002). Biogas Technology. New Delhi, New Age International**:** 300.

NISIR (2005). Biogas Project Lusaka.

NNFCC (2016). The Official Information Portal on Anaerobic Digestion.

Practical Action Southern Africa (2014). Biogas for a Better Life: An African Initiative. Harare.

Pranav Gadhia (2013). "Biogas Scenario in India."

REN21 (2011). "Renewable energy and Renewable energy commercialization." 18.

Renene J. (2009). "Biogas purification from anaerobic digestion in water treatment plant for biofuel production."

Shane A., G. H. S., Kasali G., (2015). "Potential, Barriers and Prospects of Biogas Production in Zambia."

USDA/FAS (2008). Cattle Population by Country.

Walter K. A. et al (2015). "Improving cold season biogas digester efficiency for global energy solutions."

Wasser, R. (1997). Elaboration of Coordinate a Biogas Program in Malawi, UNIDO/UNDP.

Anaerobic Digestion.Com (2016). "Mesophilic Anaerobic Digestion."

Bernd Althusmann, S. B. (2016). Perspectives on energy security and renewable energies in Sub-saharan Africa. Windhoek, Namibia, Macmillan Education Namibia.

Biofuels (2010). "Biofuels, The fuel of the future."

biogas plants and dimensions (2010).

Biotech (2016). Renewable Energy.

Chae K. et al (2016). "Anaerobic digestion of swine manure: Sung-Hwan farm-scale biogas plant in Korea ".

Cherosky P., Li Y. (2013). "Hydrogen sulfide removal from biogas by bio-based iron sponge.

ClimateTechWiki (2011). Biogas for cooking and electricity. A. c. e. platform.

Debabrata B., Sudhir S., Muruga S. (2013). "Biogas production and storage for fuelling internal combustion engines

Denis A. et al (2001). "Dairy waste anaerobic digestion handbook."

Denis D. (2011). In der Entwicklungshilfe scheitern viele Projekte, weil sie zu wenig Rücksicht auf die Umstände vor Ort nehmen. Deutschland.

Dobre P. et al (2014). "Main factors affecting biogas production - an overview." **19**(3).

EIZ (2014) Report on Zesco Loadshedding. pp 15, Lusaka

energypedia.info (2016). "Electricity Generation from Biogas."

EPA (2012) Increasing Anaerobic Digester Performance with Codigestion. Agstar

ERB (2014). Energy Sector Report 2014. Zambia, ERB**:** 8.

Foundation, U. N. (2013). ACHIEVING UNIVERSAL ENERGY ACCESS.

G. W. Roth, A. J. H. (2016). "Corn silage production and management." 6.

Georg Friedl (2016). Biogas production in Germany: Status quo and future trends.

Ghazali N. et al (2012). "BIOGAS BUS USE AND OPERATIONAL EXPERIENCES."

Hahn h, K. b., Wachendor M., (2014). "Renewable and Sustainable Energy Reviews."

IEA (2014). Africa Energy Outlook; A focus on energy prospects in sub-saharan Africa.

IEA/WEO (2016). "Energy Access Database."

Kulkarni S. J., Shinde N. L. (2014). "A review on hydrogen sulfide removal from waste gases

Lestinsky P., Vercer M., Navratil P. (2015). "The removal of CO_2 from biogas using a laboratory PSA unit: Design using breakthrough curves

Lungu Hope Langiwe. (2011). Government Renewable Energy Programs, Lusaka, Intercontinental Hotel, ERB.

Masiliso S (2008). Energy Statistics - The Case of Zambia. Adis ababa; Ethiopia.

Mitzzenmecher M. (2006) The Future of Power Law Research. Intrnet mathematics, Vol. 2 (IV) 525-534

MITZLAFF (1988). "Engines for biogas."

Monnet Fabien (2003). "An Introduction to Anaerobic Digestion of wastes."

Mydin M. A. O. (2014). Generating Renewable Energy from Food Waste. EDP Sciences. pp 4, Parak, Malaysia.

NEP (2008). National Energy Policy. Lusaka.

Niesner J., Jecha D., Stehlik P. (2013). "Biogas upgrading technologies: state of art review in European region

NISIR (2005). Biogas Project Lusaka.

NNFCC (2016). The Official Information Portal on Anaerobic Digestion.

Nyangarika (2015). Future Business Energy Modeling and System Development Focus on East Africa Region. https://www.researchgate.net/publication/320322952_Methods_of_Assessing_the_Impact_of_Labour_and_Cost

Oliver C et al (2016). Practical Opportunities and Regulatory Challenges. Namibia, Macmillan Education Namibia.

Practical Action Southern Africa (2007). Biogas for a Better Life: An African Initiative. Harare.

Pranav Gadhia (2013). "Biogas Scenario in India."

Ray N. H. S., Mahanty M. K., Mahanty R. C. (2013)."Biogas as an alternative fuel in diesel engine

Renene J. (2009). "Biogas purification from anaerobic digestion in water treatment plant for biofuel production."

Rychebosch E., Drouillon M., Vervaeren H.(2011). "Techniques for transformation of biogas to biomethanation.

P.H. Sapkale, R.K. Singh & A.S. Desai (2011) Optimal water temperature and pH for development of eggs and growth of spawn of common carp (*Cyprinus carpio*). Journal of Applied Animal Research, vol. 39

Sasse L. (1988). Biogas Plants. A Publication of the Deutsches Zentrum für Entwicklungstechnologien - GATE in: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Eschborn, Germany

Shane A., G. H. S., Kasali G., (2015). "Potential, Barriers and Prospects of Biogas Production in Zambia."

Shcolz M., Melin T., Wessling M. (2913) "Transforming biogas into biomethane using membrane technology

M. Schlegel1 , N. Kanswohl1 , D. Rössel2 and A. Sakalauskas (2008) Essential technical parameters for effective biogas production. Essential technical parameters for effective biogas production, Agronomy Research 6(Special issue), 341–348 Kaunas, Lithuania

SNV (2010) Domestic Biogas Plant Sizes and Dimensions. pp 1

SNV (2016). "Develoment of an overarching comprehenssive framework for assessing the economic basis for supporting investment in biogas technology in Zambia and assessment of investment climate for biomass energy and approaches.

Surendra K. C. et al (2014). "Biogas as a sustainable source for developing countries: Opportunities and challenges, *Renewable and Sustainable Energy Review*." **3**: 846-859.

Technology, B. (2004). "Enhancement of Biogas Production from Solid Substrates using different Techniques-a review " **95**(1): 1-10.

Teodorita A., Dominik R., Heinz P., Michael K., Tobias F., Silke V., Rainer J. (2008) Biogas Hand-book. Published by University of Southern Denmark Esbjerg, Niels Bohrs Vej 9-10, DK-6700 Esbjerg, Denmark http://www.sdu.dk

Walter K. A. et al (2015). "Improving cold season biogas digester efficiency for global energy solutions."

Wang Y. (2016) Waste Management. Vol.47, pp. 91-97

WEO (2016). "Energy Access Database."

Harilal S, Sorathia, Pravin P, Rathod, Arvind S and Sorathiya (2012) BIO-GAS GENERATION AND FACTORS AFFECTING THE BIO-GAS GENERATION – A REVIEW STUDY. International Journal of Advanced Engineering Technology E-ISSN 0976-3945, Kutch, Gujarat .

World Nuclear Association (2017) World Energy Needs and Nuclear Power. www.world-nuclear.org/information-knowledge/current-and-future-generation/world-energy-needs-and-nuclear-power.aspx

Xiujn Li (2013). "Biogas production in China: Current status and future development."

ZDA (2014). "Energy Sector Profile."

www.build-a-biogas-plant.com (2015). What can biogas do for you?

ZABS, (2014). Biogas Systems - Code of Practice

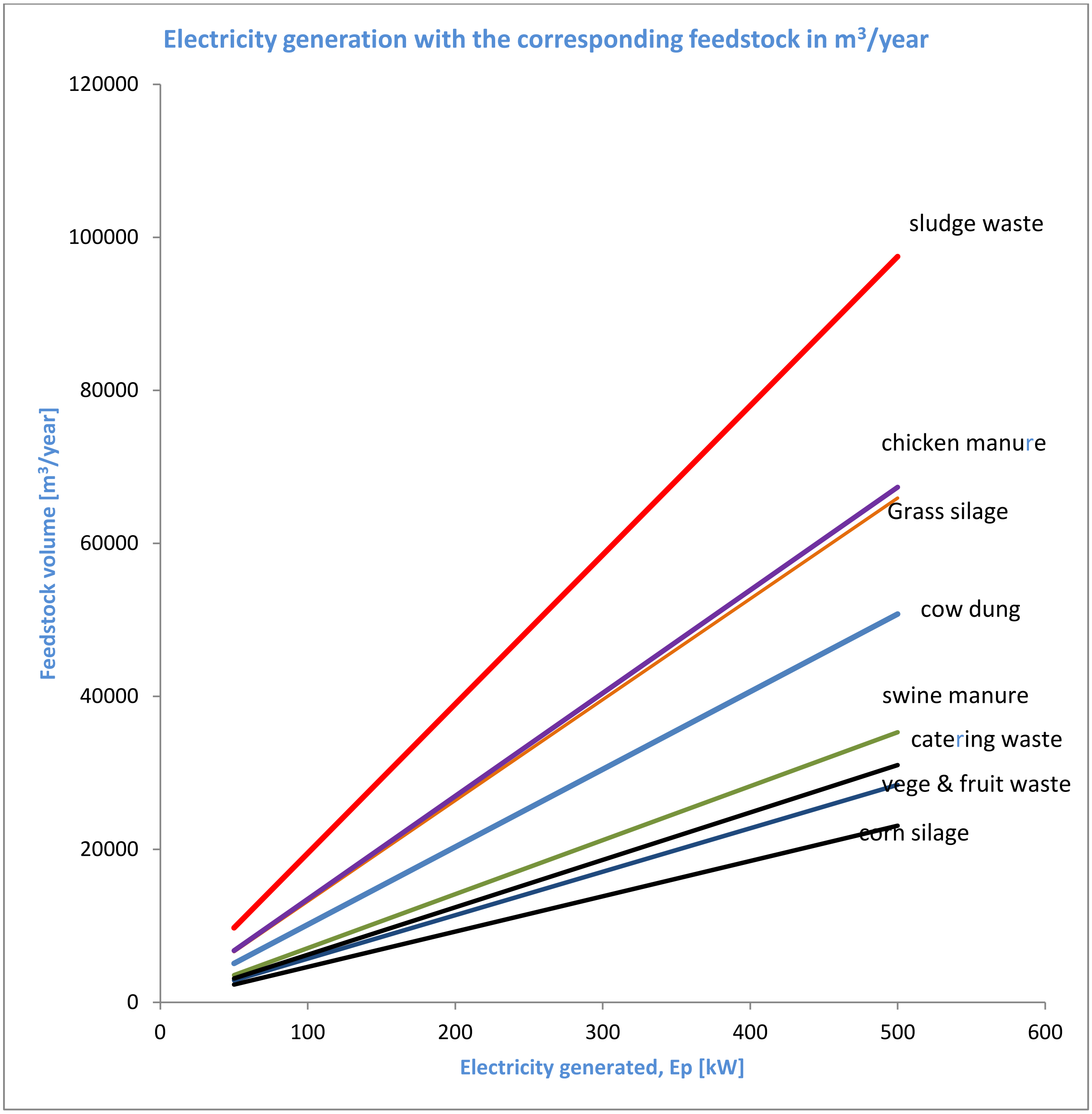
Zhang X., Zhang S., Boa D., Huang Y. (2015). "Absorption degree analysis on biogas seperation with ionic liquid systems

ZDA (2014). Energy sector profile. Zambia

CHAPTER 8

APPENDICES

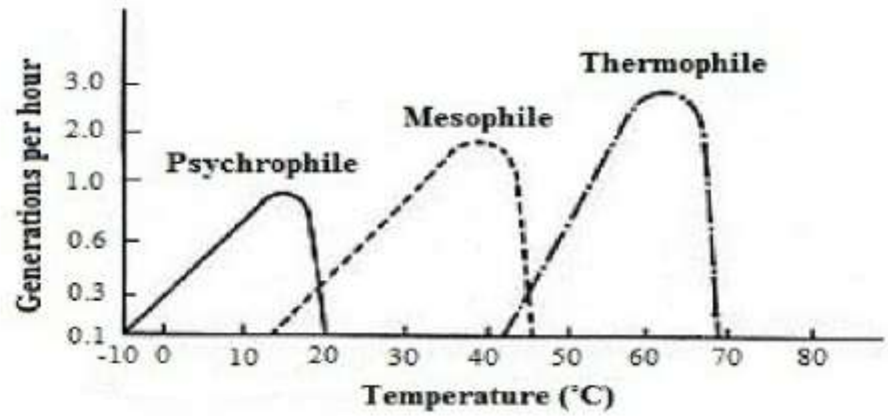
APPENDIX 1: VOLUME OF FEEDSTOCK AGAIST AGAISNT GENERATED ELECTRICITY.



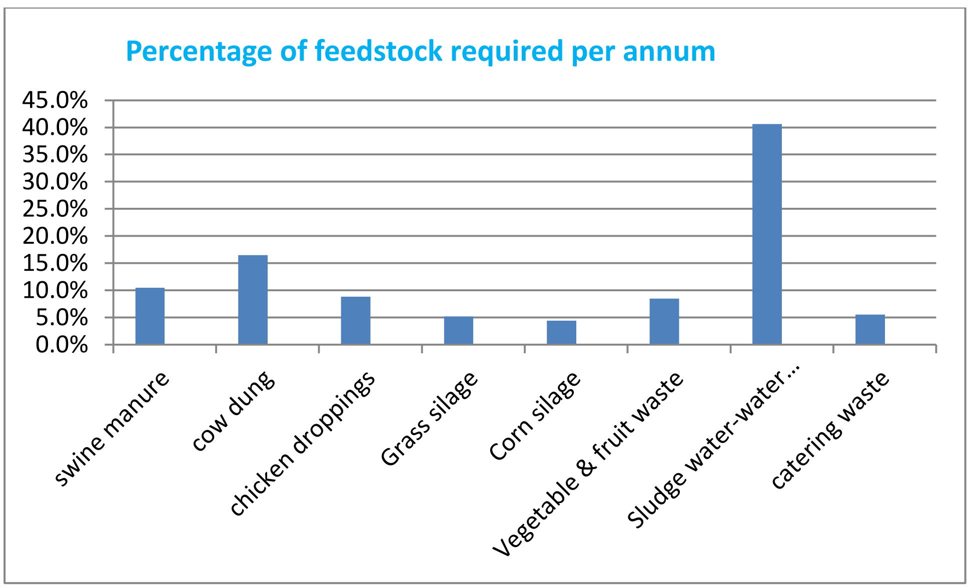
APPENDIX 2: AVERAGE MONTHLY TEMPERATURES

APPENDIX 3: MICROBIO GROWTH AGAINST TEMPERATURE

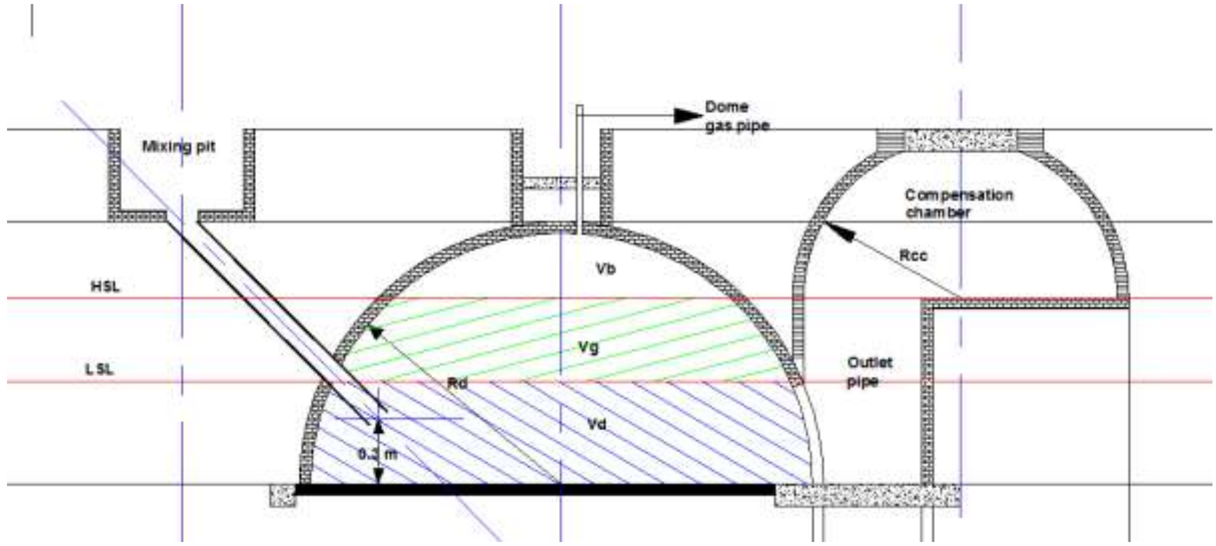
Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
TEMP [^{0}C]	21.1	21.1	20.8	20.1	17.2	16.8	15.1	17.0	21.4	24.3	22.3	21.3



APPENDIX 4: PERCENTAGE OF FEEDSTOCK MATERIAL PER ANNUM



APPENDIX 5: FIXED-DOME BIOGAS PLANT (MODIFIED CAMARTEC BIOGAS PLANT)


Dome
gas pipe
Mixing pit
Compensation
chamber
Rcc
Vb
HSL
Vg
L SL
Outlet
pipe
Rd
Vd