KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY,

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METHANE GENERATION POTENTIAL AND ENERGY PRODUCTION BENEFITS OF LANDFILLS IN GHANA: A CASE STUDY OF THE TAMALE LANDFILL SITE

BY

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OCTOBER, 2019

DECLARATION

I hereby declare that this thesis is the result of my own original work undertaken under the supervision of the undersigned, that all works consulted have been referenced and that no part of the thesis has been presented for another degree in this University or elsewhere

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ABSTRACT

As the world's population increases, the demand for improved sanitary conditions also increases steadily. Rapid population growth and high rates of urbanisation coupled with increasing prosperity in developing countries require a serious examination of the waste management process and the role of integrated solid waste management to safeguard the environment against air and water pollution, protect public health and maximise the value added elements (energy and materials recovered). Many developing countries have resulted to the use of some form of solid waste disposal site to manage the emerging situation, with engineered landfills being the chief amongst them. Landfills provide a conducive environment for the decomposition of organic waste leading to the emission of landfill gas (composed of methane, carbon dioxide and NMOCs). The methane produced is of high environmental significance since it is a potent greenhouse gas and has a relatively shorter life span. The amount of methane generated depends on the composition, quantity and moisture content of the waste. The objective of the study was to estimate the methane generation potential of the Tamale landfill site and its corresponding energy production This was achieved by characterisation of the waste disposed at the landfill site over the wet and dry season, moisture content analysis, the use of various models to estimate the methane generation potential and the potential energy and environmental benefits from the site. The results indicate that about 77% of the total waste disposed can decompose to generate methane gas. The average moisture content of the landfill was 36.4% conducive for the production of LFG. The models showed that an average of 921.95m^3/hr of methane gas will be generated during the 30year lifespan of the project. This amount of methane corresponds to an average electrical energy generation potential of 1150kW capable of supplying 688 homes with electricity daily. The project has a rate of return of 55% on investment and a payback period of 3 years making it a very profitable venture. It also reduces the yearly methane emissions by 2290.87 tons.

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ABBREVIATIONS

ASTM -	American Standard Testing Methods
BOD -	Biological Oxygen Demand
COD -	Chemical Oxygen Demand
C&D -	Construction and Demolition
CHP-	Combined heat and power
DOC-	Degradable Organic Carbon
DOCf -	Degradable Organic Carbon fraction
EPA -	Environmental Protection Agency
GHG -	Greenhouse Gas
GMI -	Global Methane Initiative
GNP -	Gross National Product
HDPE -	High Density Polyethylene
IPCC -	Intergovernmental Panel on Climate Change
ISWM -	Integrated Sustainable Waste Management
kW -	Kilowatt
KNUST -	Kwame Nkrumah University of Science and Technology
LandGEM -	Landfill Gas Emission Model
LFG -	Landfill gas
LFGE -	Landfill gas to Energy
m^3/hr -	cubic metres per hour
MCF -	Methane Correction Fraction
$MMTCO_2E$ -	million metric tonnes of carbon dioxide equivalent emissions
MSW -	Municipal Solid waste
MSWM -	Municipal Solid Waste Management
NESSAP -	National Environmental Sanitation Strategy and Action plan
NMOCs -	Non-Methane Organic Compounds
NGO -	Non Governmental Organisation
OECD -	Organisation for Economic Co-operation and Development
O&M -	Operation and Maintenance
PET -	Potential Evapotranspiration
RCRA -	Resource Conservation Recovery Act
SWD -	Solid Waste Disposal
USEPA –	United States Environmental Protection Agency

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

Waste generation due to human activities is inevitable. Solid waste is any substance produced as a result of domestic, commercial and industrial activities of humans. These materials have no value to the person who owns it as such it is regarded as worthless and hence discarded.

Due to the increase in the population of the world, the demand for improved sanitation has increased steadily (Population Reference Bureau, 2011).In times past, habitations were less dense, land was plentiful hence disposal of waste did not pose a threat to the inhabitant of the towns because the waste was always disposed far away from the human settlement. With the surge of urbanisation, where many people started to converge in comparatively small areas in pursuance of livelihoods, waste disposal has become an issue of major concern (Shafiul & Mansoor, 2003). Presently, about 30 to 60% of the waste generated in various cities in lower and middle income countries are not collected and hence scattered in the streets or burnt in the open (Shafiul & Mansoor, 2003), some also end up in water bodies hence reducing the water quality (U.S Environmental Protection Agency, 2012). Rapid population growth and urbanisation has led to the adaptation of various modes of solid waste disposal. Over the last 30 to 40 years, waste management in high income countries has been characterized by an increased environmental responsiveness on the part of city authorities. There has been a concerted effort towards the phasing out of unrestrained disposal, along with the introduction and gradual increment in the benchmarks with respect to the environment. Many developing countries are yet to migrate fully to controlled waste disposal.

Majority of waste discarded in landfills mitigates many public health issues but creates additional environmental concerns. Landfills are capable of providing the required anaerobic conditions for the decomposition of wastes causing the emission of landfill gas, odours and other environmental pollutants. The emission of methane from landfills is greatly significant to the environment. Methane is a gas which contributes immensely to the greenhouse effect with a global warming potential about 20 times more that of carbon (IV) oxide (US EPA, 2012).

Landfills are the third major source of methane through human activities worldwide. They account for nearly 11% methane emissions globally which is equivalent to about 800 million metric tons of carbon (IV) oxide (MMTCO2) emissions in 2010. (US EPA, 2011).

The quantity of methane generated depends mainly on;

i. The composition,
ii. Amount of waste disposed
iii. Amount of moisture in the waste.
iv. The design,
v. Managerial and operational procedures of the landfill

Sanitary landfills, designed with the intention to increase the anaerobic degradation of waste, generate more methane than other SWD options such as open dumps that facilitate aerobic degradation. As developing countries phase out uncontrolled disposal with the promotion of sanitary landfills, methane emissions will increase as a major part of the waste produced is handled in a way that is conducive to its generation (U.S Environmental Protection Agency, 2012).

Landfill gas (LFG) recovery is a crucial segment of Integrated Sustainable Waste Management (ISWM). The utilisation of LFG as an alternate energy source is an effective way of reducing indiscriminate emissions and improving the safety of the general public. With various socioeconomic benefits, the recovery of LFG is vital in waste management at the municipal level.

With the increasing concerns on the global warming and climatic change, coupled with the search of alternative energy sources, LFG recovery and utilization has the promise of helping to mitigate these issues of global concern.

1.2 Problem Statement

Tamale is the fourth largest town in Ghana and one of the rapidly developing cities in West Africa. It has an inter-censal growth rate of 3.5% (Puopiel, 2010). Accompanying this very rapid population growth rate is a surge in the amount of waste produced by the inhabitants of the city and the corresponding management techniques employed to handle the situation. 216 tonnes of solid waste are hauled daily to the Tamale landfill for disposal(Puopiel, 2010). The disposal is usually done without sorting.

The use of the landfill in waste management, though indispensable, can have negative environmental impact if not well managed due to the production of leachate, methane, carbon dioxide and other nuisances like flies, odour etc.

Methane is a very potent greenhouse gas which can lead to global warming and landfills are considered as one of the major sources. However, there is no scientific study done to quantify the amount of methane gas produced from the Tamale landfill and the potential benefits that can be derived from the capture and utilisation of the methane produced.

1.3 Justification for the Research

Landfills are the third major source of the emission of methane caused by human activities in the world. Methane, a very potent gas which causes global warming, has a short lifespan of between 10 to 14 years when released into the atmosphere. The short lifespan of methane and its global warming potency makes methane emission reduction from landfills one of the most prudent measures to lessen the human impact on climatic change. (US EPA, 2015)

The estimation of the methane generation potential and the energy production benefits of the Tamale landfill site would provide a basis or baseline data for which the utilisation of the methane generated from the various landfills in Ghana could be explored to help mitigate the climatic change and provide an alternate energy source to offset the existent non-renewable sources

1.4 Objectives

1.4.1 Main Objective

The goal of this study is to quantify the amount of methane produced at the Tamale landfill site and to estimate the energy generation potential of the site.

1.4.2 Specific Objectives

The specific objectives intended to be achieved are to:

a. Perform a waste characterisation study of the waste disposed of at the landfill site
b. Determine the moisture content of waste samples
c. Estimate the landfill gas generation rate using various estimation models
d. Estimate the corresponding energy generation potential from the methane generation potential of the landfill
e. Perform a cost-benefit analysis to ascertain the profitability of an energy project using LFG

1.5 Scope of the Study

This study revolves around the use of various models to approximate the landfill gas generation potential of the Tamale landfill site rather than the use of a well to quantify the amount of gas generated at this site. This is mainly due to limited resources.

1.6 Structure of the Thesis

The structure of the thesis is organised into five main chapters. Chapter one comprises the background of the study which is introduction, the problem statement, justification for the research and objectives. Chapter two deals with the literature review of the study and chapter three describes the materials used and the research methodology employed in the study. In chapter four, all the results obtained in the study were analysed and discussed. Finally, conclusions and recommendations based on the research are made in chapter five

CHAPTER TWO

LITERATURE REVIEW

2.1 Definition of Waste

Waste is any substance that has outlived its usefulness to the owner and is to be discarded according to the stipulated conditions of the nation. It can be viewed as the by-product of a production process and/or the end product of a consumption process. According to NESSAP 2010, waste substances can be described as materials in transition. This is to create awareness for a change in attitude in relation to dealing with waste to show that some components of waste are still valuable. It emphasises the fact that materials are not consumed but rather they are used and returned to the environment in an altered state. Waste can be categorised into mainly solid waste and liquid waste (Ministry of Local Government and Rural Development, 2010). Solid waste is the subject for this study.

2.2 Classification of Solid Waste

Solid waste can be grouped based on

- Source
- Contents
- Hazardous potential

2.2.1 Classification of Solid Waste according to their Source

Solid waste can be described according to their origin that is where the waste was produced from. The sub-categories under this group are:

- Domestic waste: This describes waste that produced in the course of domestic activities like cooking
- Industrial waste: This describes waste generated due to industrial activities. Industrial wastes include a wide variety of materials and their actual compositions is dependent on the type of industries in that country. Waste from industries may occur as

relatively pure materials or as a mixture of different compositions and in different physical and chemical states. The most essential characteristic of industrial wastes is that they are potentially poisonous hence requires special means of safe disposal

- Commercial waste: This category includes waste from stores, restaurants, markets, print shops etc
- Construction and demolition waste: This category deals with waste from constructing, and repairing buildings. They are mainly made of stones, concrete, brick, plaster, lumber, electrical parts etc. Apart from asbestos which requires special disposal methods, they are usually inert in nature.
- Institutional waste: Waste from office buildings, schools, medical facilities etc.

2.2.2Component-Based Classification of Solid Waste

- Organic material
- Glass
- Plastic
- Metal
- Paper

2.2.3 Classification of Solid Waste Based on their Hazardous Potential

- Toxic
- Non-toxic
- Flammable
- Radioactive
- Infectious

2.3 Municipal Solid Waste (MSW)

2.3.1Municipal Solid Waste Definition

Municipal Solid Waste is the solid waste from homes, offices and public places which are primarily the duty of municipalities. (Zurbrugg & SANDEC/EAWAG, 2003). Municipal Solid waste is a heterogeneous waste produced in urban areas. The nature of MSW differs from region to region (Diaz , et al., 2005)

2.3.2 Generation of Municipal Solid Waste

The usage of goods leads to the generation of solid waste in various municipalities. Generally as the standard of living of people begins to rise, there is a surge in the quantity of municipal waste generated. It is estimated that the quantity of waste increases at an annual rate of 3% (Bassanini, et al., 2001).This can be attributed to the changing consumption pattern of the people. Due to the increasing standard of living, the people can now afford certain luxuries which hitherto they could not. These items later on end up in the trash can as waste (SANDEC, 2008).

Also the average lifetime of many products has reduced significantly and hence disposed causing an inordinate increase in the volume of waste generated (SANDEC, 2008)

Rural-urban migration also has adverse effects on the amount of waste that is generated in our various cities because of the rapid increase in the population of the cites, the resources available would not suffice. (SANDEC, 2008)

Estimating the amount of waste that is generated globally is difficult because of the unavailability data and in other cases the data available is unreliable especially that from developing countries. In 2006, it was estimated that 2billion tons of MSW is produced yearly. The population in 2006 was 6.5billion hence the average per capita generation rate was about 300kg per year. At this rate the municipal solid waste is expected to increase to about 7 billion tonnes in 2025 (Bassanini, et al., 2001)

Table 2.1: Estimates of the Worldwide MSW Generation

Global MSW	Kg/capita/day	Billion tonnes/year	
		2006	2025
Current estimates	300	2.0	2,4
At average current rate for OECD	580	3.8	4.6
Currently for San Francisco	880	5.7	7.0

(Bassanini, et al., 2001)

Table 2.2: Current Urban MSW Generation in Selected Asian Countries

Country	**Gross National Product Per Capita(1995US$)**	**Current Urban Population(% of total)**	**Current urban MSW Generation(kg/capita/day)**
Low Income	**490**	**27.8**	**0.64**
Napal	200	13.7	0.50
Bangladesh	240	18.3	0.49
Myanmar	240	26.2	0.45
Vietnam	240	20.8	0.55
Mongolia	310	60.9	0.60
India	340	26.8	0.46
Lao PDR	350	21.7	0.69
China	620	30.3	0.79
Sri Lanka	700	22.4	0.89
Middle Income	**1410**	**37.6**	**0.73**
Indonesia	980	35.4	0.76
Phillipines	1050	54.2	0.52
Thailand	2740	20.0	1.10
Malaysia	3890	53.7	0.81
High income	**30990**	**79.5**	**1.64**
Korea republic	9700	81.3	1.59
Hong Kong	22990	95.0	5.07
Singapore	26730	100	1.10
Japan	39640	77.6	1.47

(RETHINK,W, 1999)

Table 2.3: Projected Waste Generation Rate of Asian Countries In 2025

Country	Gross National Product Per Capita(1995US $)	2025 Urban Population(% of total)	2025 Urban MSW Generation(kg/capita/ day)
Low Income	**1050**	**48.8**	**0.60-1.0**
Napal	360	34.3	0.60
Bangladesh	440	40.0	0.6
Myanmar	580	47.3	0.6
Vietnam	580	39.0	0.7
Mongolia	560	76.5	0.9
India	620	45.2	0.7
Lao PDR	850	44.5	0.8
China	1500	54.5	0.9
Sri Lanka	1300	42.6	1.0
Middle Income	**3390**	**61.1**	**0.8-1.5**
Indonesia	2400	60.7	1.0
Phillipines	2500	74.3	0.8
Thailand	6650	39.1	1.5
Malaysia	9400	72.7	1.4
High income	**41140**	**88.2**	**1.1-4.5**
Korea republic	17600	93.7	1.4
Hong Kong	31000	97.3	4.5
Singapore	36000	100.0	1.1
Japan	53500	84.9	1.2

(RETHINK,W, 1999)

2.3.3 Composition of Municipal Solid Waste

Municipal solid waste can be grouped into two broad categories namely:

- Inorganic waste
- Organic waste: the components can be sub-divided into three groups

- Putrescible wastes: this category of waste tends to decompose rapidly and with the production of objectionable odours which can be controlled under stringent management protocols. This category usually becomes unsightly. A major source of degradable waste is food hence it varies with lifestyle, standard of living and seasonality of foods.

- Non-Fermentable waste: This kind of waste tends to resist decomposition and therefore breakdown very slowly
- Fermentable : these are waste which tend to decompose rapidly but without the objectionable odour

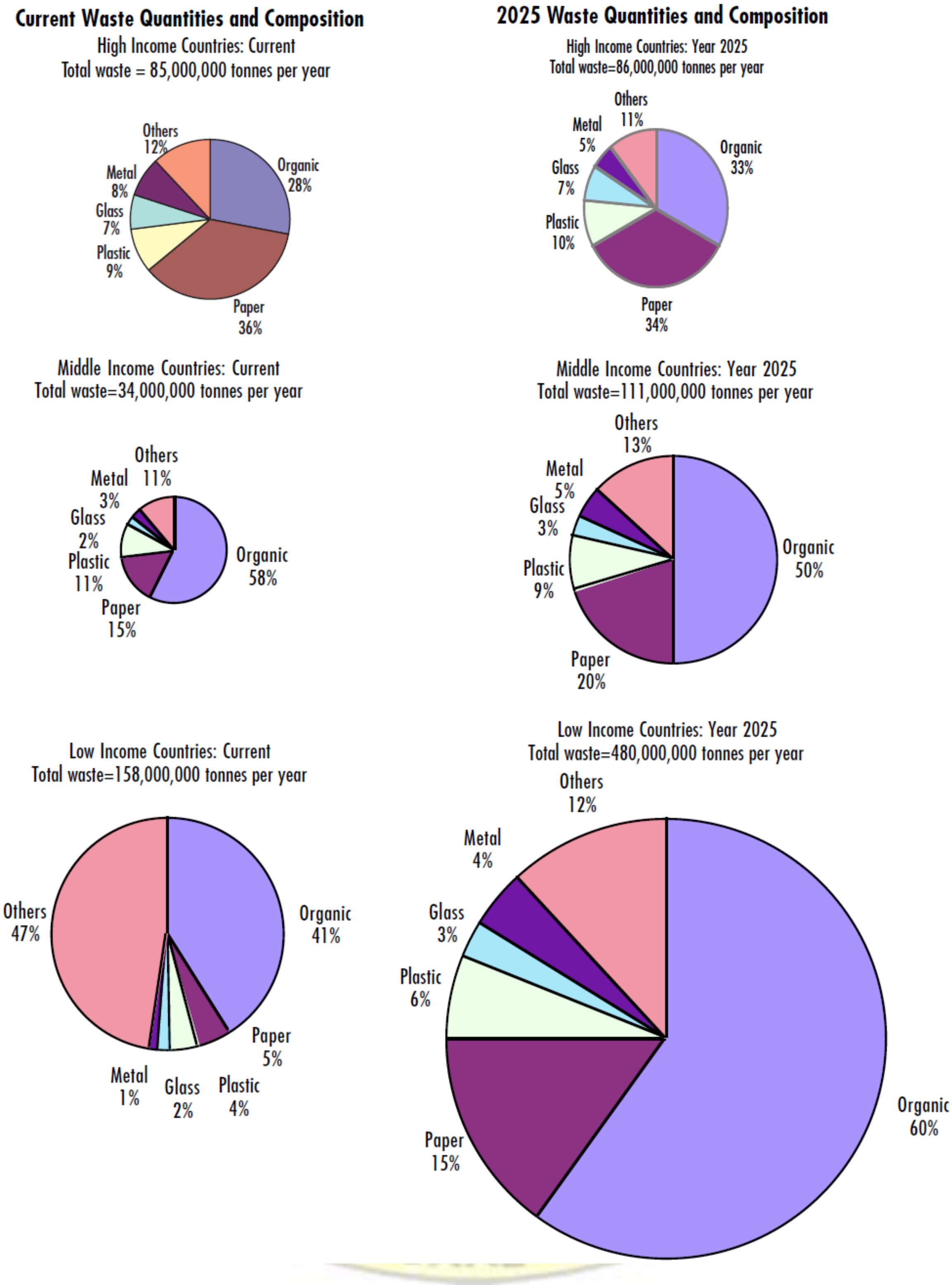
  (RETHINK,W, 1999)

Generally, MSW contains mainly organics and paper, with lower amounts of plastics, glass and metals. Economic growth, income level, lifestyle and location also affect the constitution of MSW. Poorer households produce more organic waste than richer ones. MSW from developed countries have a higher percentage of inorganic materials than that from developing countries. This is due to the consumption of processed food and packaged products. In Europe, almost half of the generated MSW comes from packaging material

Table 2.4: Municipal Solid Waste Composition in Cities Across the world

Material	Quezon	San Francisco	Nairobi
Organics	52.1%	30.9%	61.4%
Paper	17.1%	24.3%	11.8%
Plastic	21.4%	10.5%	20.6%
Glass	3.1%	3.3%	0.8%
Metal	3.2%	4.3%	0.6%
C&D	2.3%	12.2%	
Bulky waste		5.3%	
Textiles		3.9%	0.6%
Other	0.89%	5.3%	4.2%
Waste generated(kg/capita/day)	0.7%	2.4%	0.8%

(Bassanini, et al., 2001)



(RETHINK,W, 1999)

Figure 2.1: Waste Composition of countries from different economic levels

The volumes and composition of waste affect the waste management practices. High organic content of waste produces dense, humid waste which affects the collection and transportation potential as well as the recycling potential. Higher fractions of the inorganic content increases the recycling potential of the waste which bring about economic gain (SANDEC, 2008).

2.3.4 Management of Municipal Solid Waste

The activities of humans lead to the generation of waste. The methods employed in the handling, storage, collection and disposal of the waste generated can become a hazard to the health of the society. The main aim is to protect the population health, promote environmental quality, develop sustainability and provide support to the economic productivity. (Zhu, et al., 2007).

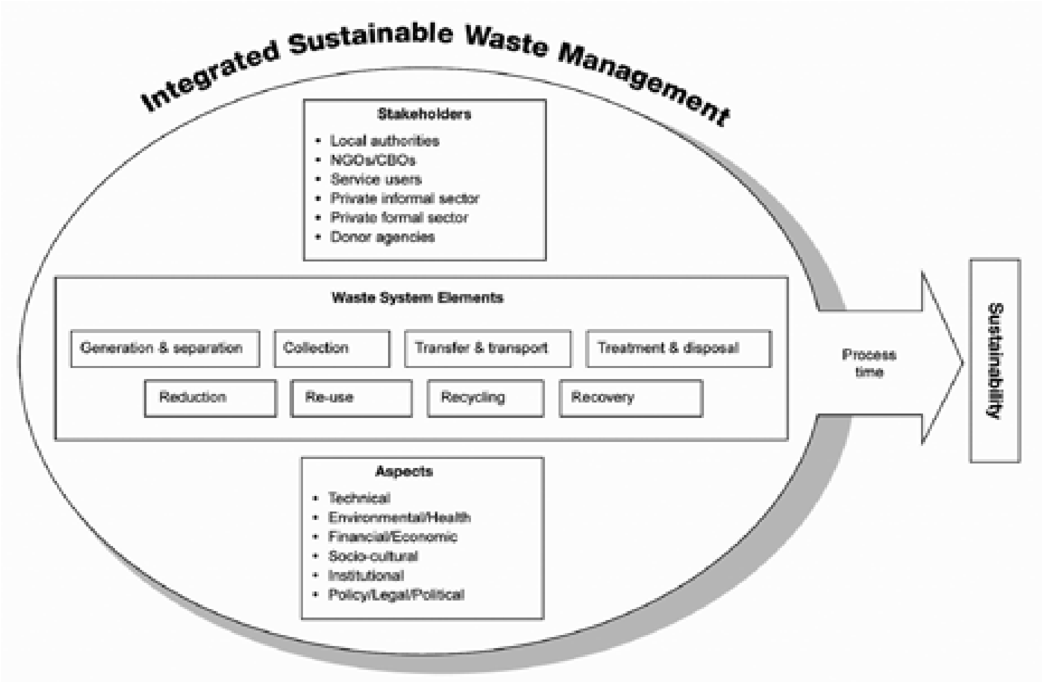
In the rapidly developing cities, matters concerning municipal solid waste management (MSWM) are very essential. However, the ability of authorities in many municipalities to provide basic services to aid the management of municipal solid waste does not match up to the needs of the municipalities due to rapid population growth. Due to the inadequacy of resources, up to about 60% of the solid waste generated is not collected and hence dumped arbitrarily along the major streets and in open drains and hence causing floods and also serving as a breeding ground for the disease causing organisms. In the cases where the waste is collected, it is often discarded at uncontrolled dumpsites and/or burnt causing air and water pollution. (Zurbrugg & SANDEC/EAWAG, 2003)

Prudent and efficient systems for managing solid waste are required to guarantee improved public health, safety of workers and protect human health by forestalling the transmission of disease. Additionally, an efficient system for managing solid waste should be sustainable both economically and environmentally. It is arduous to reduce cost and impact to the environment, simultaneously. There will always be some form of compromise to ensure effective waste management. The balance is to minimise to the barest minimum the general effects of waste management regime to the environment at an affordable cost. A financially and ecologically economical solid waste management system is efficient if it follows a coordinated approach i.e. it manages a wide range of solid waste materials from the various sources of solid waste. A multi-material, multi-source administrative approach is normally efficient economically and in environmental terms than an approach which in terms of source and material. Specific wastes must be treated in such a framework but in separate streams

2.3.4.1 Municipal Solid Waste Management Systems

Integrated sustainable waste management (ISWM), is a model that was initiated in the mid-1980's by an NGO known as WASTE. ISWM is a framework approach which perceives three essential dimensions which should be dealt with when builiding a solid waste administrative framework. They are

- Stakeholders: the main recognized stakeholder include the local authority, the national environment protection agency, the local government and private companies
- Elements: they refer to the technical sectors of a waste management system
- Aspects: A sustainable waste management system takes into consideration all of the operational, financial, social, institutional, political, legal and environmental aspects. They provide a sequence of analytical views which can be used to appraise the state of affairs, ascertaining the feasibility, figuring out priorities or setting adequacy standards



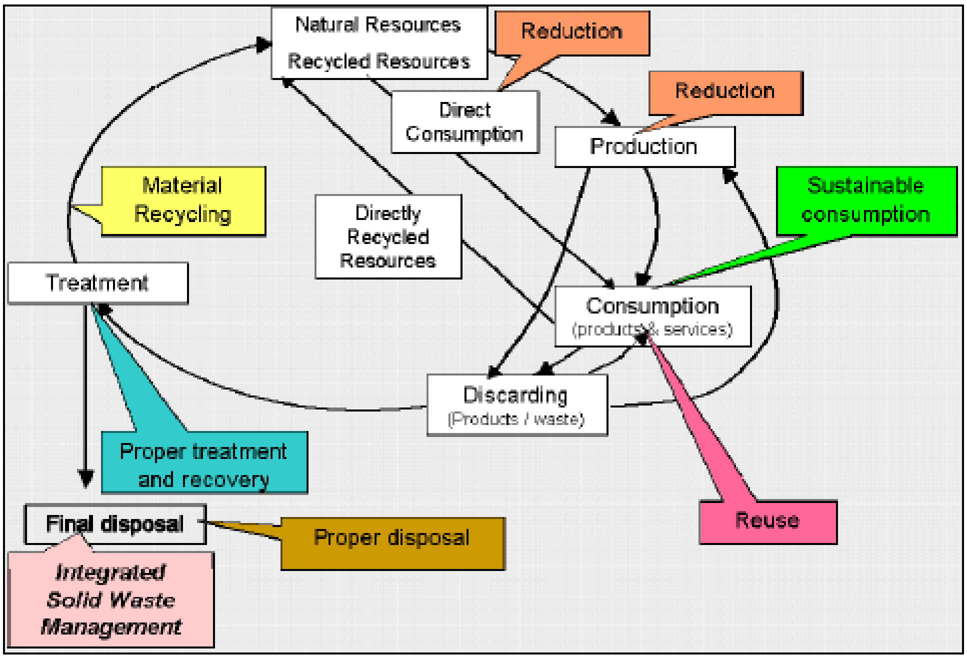
(Bassanini, et al., 2001)

Figure 2.2 The Integrated Sustainable Waste Management Framework

The idea of integrated solid waste management can viewed from three positions:

- Lifecycle-based Integrated Solid Waste management:

The primary idea of ISWM is based on lifecycle appraisal of a product from its generation and utilisation perspective .The minimization in consumption, and usage of waste products within the production chain as an alternative for new raw materials, can lead to a reduction in the end-of-cycle waste generation; thus, less resources would be involved in the process of discarding the waste properly.

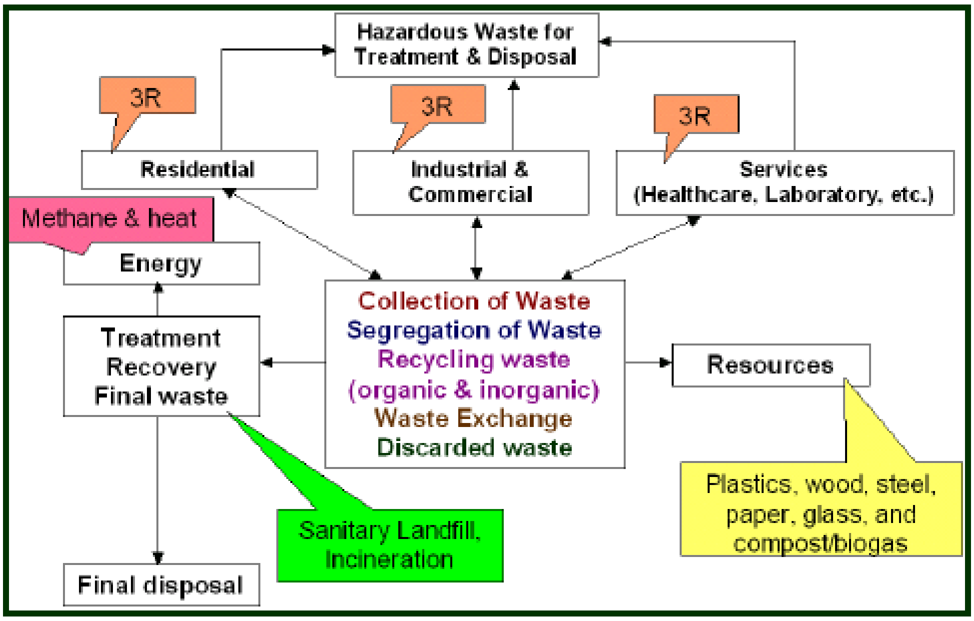


(Fantahun, 2010)

Figure 2.3: Lifecycle Based ISWM

- Generation-based Integrated Solid waste management

This idea of ISWM is founded on the basis that waste is generated from different sources such as residential, commercial, industrial and agriculture. The waste could then be categorised as either hazardous or non-hazardous waste .The hazardous waste is separated at source and prepared for disposal in conformity with stringent laws. 3R approach (reduce, reuse and recycle) is relevant both at source and at the various stages of solid waste management cycle.

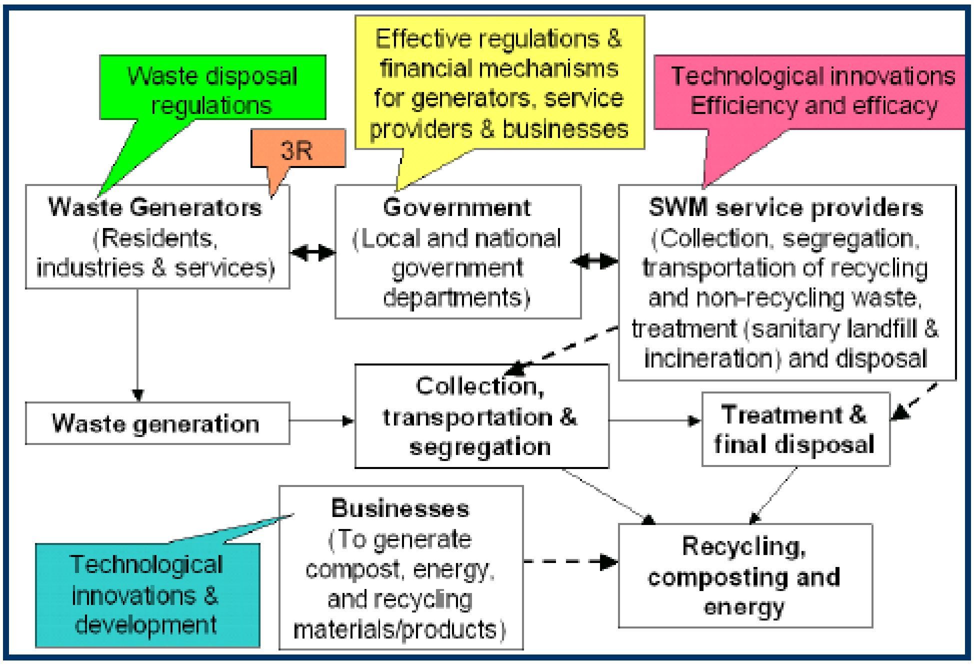


(Fantahun, 2010)

Figure 2.4 Generation Based ISWM

- Management-based Integrated Solid waste Management

The third idea of ISWM depends on its administration which comprises regulations and laws, institutions, financial framework, technology and infrastructure and role of partners in the solid waste administration



(Fantahun, 2010)

Figure 2.5 Management Based ISWM

2.3.4.2 Waste Management Hierarchy

The hierarchy of waste management is a scheme of ranking the waste management alternatives based on their impact on the environment. It prioritises waste prevention but if waste is generated, then the priority shifts to re-use, recycling, recovery, and finally disposal.

Figure 2.6: The Waste Management Hierarchy

- Disposal

This is the most ancient method of treating waste but due to the many potentially menacing impacts it can have it is the least preferred choice. The gravest impacts is the generation and emission of methane which can accumulate in the landfill and cause explosion.

The decomposition of biodegradable waste in the landfill site may discharge chemicals such as heavy metals bringing about run-off called leachate. This liquid can pollute the ground water and surface water presenting a serious threat to the environment.

- Recovery:

Recovery of solid waste is reclamation of valuable products such as metals and energy, resulting from chemical reaction of solid waste. Recovery relates predominantly to energy recouped from waste. Waste that cannot be reused or recycled can be, for instance, incinerated to generate heat or electricity. The suitability of such recuperative methods is dependent on the composition and energy content of the waste.

- Recycling:

This involves converting waste into a new substance or product. When a material is recycled, it is utilised in place of new inputs in the manufacturing process. Greenhouse gas emissions do not take place at the MSW management stage due to the diversion of recycled material from waste management facilities.

- Reuse:

This involves checking, cleaning, repairing, whole items or spare-parts to be used to form new products

- Prevention:

This is the most important stage of the hierarchy that seeks to actually prevent the generation of waste altogether.

2.4 Energy Recovery from Waste

Energy recovery from waste is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel through various processes, including combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas (LFG) recovery. Energy recovery is also known as waste-to-energy (WTE). Energy recovery from waste is part of the non-hazardous waste management hierarchy. Converting non-recyclable waste materials into electricity and heat generates a renewable energy source, reduces carbon emissions by offsetting the need for energy from fossil sources and reduces methane generation and emission from landfills. (US. EPA, 2016)

2.4.1 Incineration/Combustion

MSW incineration involves the controlled burning of MSW at a temperature of 870–1200 °C such that almost all of the organic matter content in the waste undergoes oxidation to produce steam at high pressure for the generation of power. Waste incineration causes a very significant reduction in weight and volume. (Murphy & McKeogh, 2006)

Controlled incineration systems for the production of electricity and heat are similar to most thermal power plants which use fossil fuel as their source of fuel. WTE production via incineration can occur in four main stages namely waste pre-treatment, waste combustion, gas scrubbing (including air pollution control) and electricity/steam generation.

MSW incineration system is a reliable technology of energy production from wastes. It is capable of reducing the amounts of dioxin and other dangerous substances produced. The efficiency of an incineration plant depends largely on the calorific value of the MSW which is approximately 7000 kJ/kg (Barducci, 1990)

According to Murphy and McKeogh, in any MSW incineration system, about 15% of the wastes is available as electricity. Again, MSW from 1,000,000 person equivalent could power 12,400 cars; provide electricity for 30,900 houses and heat 15,100 houses in Europe and United States (Murphy & McKeogh, 2006)

2.4.2 Gasification

Gasification of MSW is the partial combustion of MSW at high temperatures under controlled conditions such that almost all the MSW is converted into gas and chars. This process occurs in two stages (Arena, 2012)

During the first stage, the MSW is partially combusted to form producer gas (comprising CO_2 and H_2O) and char. During the second stage, the CO_2 and H_2O are chemically reduced by the char (or charcoal) to form mainly carbon monoxide (CO) and hydrogen gas (H_2). The composition of the resulting gas is 18–20% H_2,18–21% CO, 2–3% CH_4, 8–10% CO_2, and the rest nitrogen (Belgiomo, et al., 2003). These two stages are separated in the gasifier.

The optimum temperature range for gasification to occur is 750–800 °C and at atmospheric pressure (1 atm) or higher. The density of the produced gas is generally less than 5.6 MJ/m3 which far lower than that for natural gas (38 MJ/m3). Gasifiers are coupled with gas turbines (hybrid gasifier/ gas turbine system) in order to produce electricity effectively at a cheaper cost compared to fossil fuel derived electricity (Williams & Larson, 1992) The efficiency of this system is found to be 40–55% energy conversion.

A typical gasification system comprises a gasifier, gas scrubber for removing all harmful gases from the produced gas and an energy recovery unit for the production of electricity. Electricity production in a gasifier is more efficient when the wastes are easily combustible hence it is very crucial to perform a waste sorting exercise before gasification.

2.4.3 Pyrolysis

Pyrolysis is the thermal decomposition of wastes in the absence of oxygen to produce bio-char, bio-oil and gases (methane, hydrogen, carbon monoxide, and carbon dioxide). At low temperatures below 450 °C, pyrolysis may produce bio-char while at temperatures above 800 °C, great amount of gases may evolve (Mohan, et al., 2006). However, at an intermediate temperature and under relatively high heating rates, the main product is bio-oil.

The processes involved in pyrolysis can be grouped as slow pyrolysis, fast (or flash) pyrolysis at high temperatures and flash pyrolysis at low temperatures. Flash pyrolysis is currently the most widely used pyrolysis technology. Slow pyrolysis takes several hours to complete and results in bio-char as the main product. On the other hand, fast pyrolysis yields about 60% bio-oil and takes seconds for complete pyrolysis. In addition, it gives 20% bio-char and 20% synthetic gas or syngas. Pyrolysis can produce a net energy of 571 kWh/ton MSW from either the gas or bio-oil produced.

2.4.4 Anaerobic Digestion /Fermentation Under Controlled Conditions.

Biogas technology has emerged as a key environmental technology for integrated solid and liquid waste treatment concepts and climate protection in industrialized and developing countries. Within the anaerobic conversion or fermentation of MSW, over 90% of energy available in the wastes is retained within the biogas as methane and the rest are sludge. This process takes place in enclosed systems or reactors called digesters. With these systems, a ton of MSW can produce 100m^3 of biogas for electricity production (Elango, et al., 2007). Biogas can be utilized to power combustion engines for motive power or electricity generation, space heating, water heating and process heating. When biogas is compressed, it can replace compressed natural gas used in vehicles using either an internal combustion engine or fuel cells. The gas is a clean and efficient fuel which burns without smoke or smell and it's used for direct combustion in cooking or lighting applications. There are several small scale biogas digesters under operation in Ghana. This is the most used technology for organic waste (mostly sewage) management in Ghana whereby the gas produced is used for cooking and lighting. However, this technology may not serve as an efficient technology for MSW management and electricity generation because MSW contains different compositions of wastes which are not sorted at source. Thus the producer gas required for electricity generation would be minimal or insignificant rendering the whole technology cost ineffective.

2.4.5 Landfill Gas Energy Recovery

The process of organic waste decomposition in landfills is synonymous to anaerobic digestion in biogas digesters. However, the biochemical decomposition in biogas reactors is done in a more controlled manner due to its fast rate of reaction coupled with temperature stabilization (Williams & Larson, 1992). Microorganisms that live in the organic materials such as food wastes and paper cause these materials to decompose releasing methane in large amount and CO_2 in small quantities. Landfill gas normally comprises 50% methane and 50% carbon dioxide with an energy content of 18–19 MJ/m^3 (Bramryd & Binder, 2001). The biogas emitted from landfills is trapped, scrubbed and combusted in order to produce electricity. Landfill gas is normally trapped from drilled wells within the landfills via pipes. The raw gas (or mixture with natural gas) is then fed into combustion turbines or combined cycle turbines to generate electricity. In landfills, the decomposition reaction is not monitored. Also, landfill runoffs, landfill gas emissions, the nearby ground water quality as well as the water table level closer to landfills are not monitored. Presently, landfills are engineered in order to minimize environmental pollution. Sanitary (engineered) landfilling has become an acceptable and recommended technology MSW leading to the generation of energy. All the residues from all the other possible MSW management options are dumped in landfills after the conversion process thus landfill is considered to be a better option for MSW management. The MSW that enters as the raw material or feed is spread out and arranged on waterproof materials and left to decompose. After some days, these layers of wastes are compacted and covered periodically with soil or another inert material. Thus leachate from the landfill does not contaminate nearby ground water or stream due to the presence of the waterproof material. The leachate is however collected, treated and disposed of. Methane and carbon dioxide start to come out after few weeks of landfilling but are in small amount. For a longer period of time, the landfill gas can be captured and used to produce electricity. In Ghana, a couple of engineered landfill sites have been commissioned long ago in the main municipal centers with the hope of developing them into electricity generation systems but this aim has been nibbed in the bud. Though engineered landfilling has been found to be a better option for MSW management and electricity production system, unstable economic trends may alter this advantage. Methane is a powerful greenhouse gas, with substantial amounts being derived from unutilized methane production from landfill sites. Its recovery therefore, not only results in the stabilization of the landfill site allowing faster reuse of the land, but also serves to lessen the impacts of biospheric methane emissions on global warming (Bramryd & Binder, 2001).

2.5 Landfill

Uncontrolled dumping of solid waste on land can cause the generation of leachate and emissions of landfill gas that are potential pollutants to the environment and present a breeding site for disease vectors and microorganisms. Uncontrolled solid waste disposal threatens the safety of public health and the environment.

In developing countries, the controlled disposal of waste on land is the best method of dealing with the disposal of waste due to the adaptability and relative straightforwardness of the innovation. Sanitary landfilling limits the exposure of the surroundings and humans to the harmful impacts of solid waste deposited on land. It decreases significantly the contact between waste and the environment such that wastes are confined in a specific area. (Diaz , et al., 2005)

2.5.1 Definition of Landfills

All definitions of a sanitary landfill requires that the landfilled wastes is separated from the environment until it become non-toxic through the biological and physicochemical activities of nature. The main disparities between the diverse definitions are in the extent of separation and the methods of attaining it.

In order for a site to be labelled as a sanitary landfill, the disposal site must satisfy the following fundamental requirements.

- Compaction of wastes
- Daily covering of the waste with soil or other cover material to isolate them from the environment
- Control and prevention of the harmful effects on the general wellbeing of people and the environment
- A sanitary landfill can be defined as a meticulously designed and managed structure for the disposal of household and industrial waste in an isolated manner. It normally

starts with a depression in the ground which is lined at the bottom of the structure to prevent the fluids from infiltrating groundwater, soil and air.

2.5.2 Classification of Landfills

Landfills can be categorized based on two main criteria;

I. According to their waste make up

- Hazardous waste landfill: hazardous wastes are wastes that are potentially dangerous to the general wellbeing of society. Hazardous wastes are classified into two main groups defined under the Resource Conservation and Recovery Act (RCRA) in 40 CFR 261 namely: characteristic waste and listed waste.

  Characteristic hazardous wastes at least one of the following four hazardous traits:

  - Ignitability
  - Reactivity
  - Corrosivity
  - Toxicity

  Listed Hazardous wastes are specified by authorities as hazardous from various sources or discarded chemical products.

- Designated waste landfill: Designated waste is a type of waste that satisfies the specifications as defined by the California water code section 13173;

  - Hazardous waste that has been given a variance from hazardous waste management prerequisites consistent with Section 25143 of the Health and Safety Code.
  - Non-Hazardous waste that consists of toxins that, under ambient environmental conditions could be released in concentrations surpassing applicable water quality objectives or that could reasonably be expected to

affect beneficial uses of the waters of the state as contained in the appropriate state water quality control plan

- Municipal waste landfill: The most important waste to the recovery of methane is municipal solid waste which is largely made of organic materials. It is a heterogeneous mixture of materials, which has no use to consumers is often disposed of as garbage from residential areas; non-hazardous waste from industrial, commercial, and institutional establishments. Hazardous waste and waste from demolition and construction of buildings are not considered to be municipal solid waste (Diaz , et al., 2005)

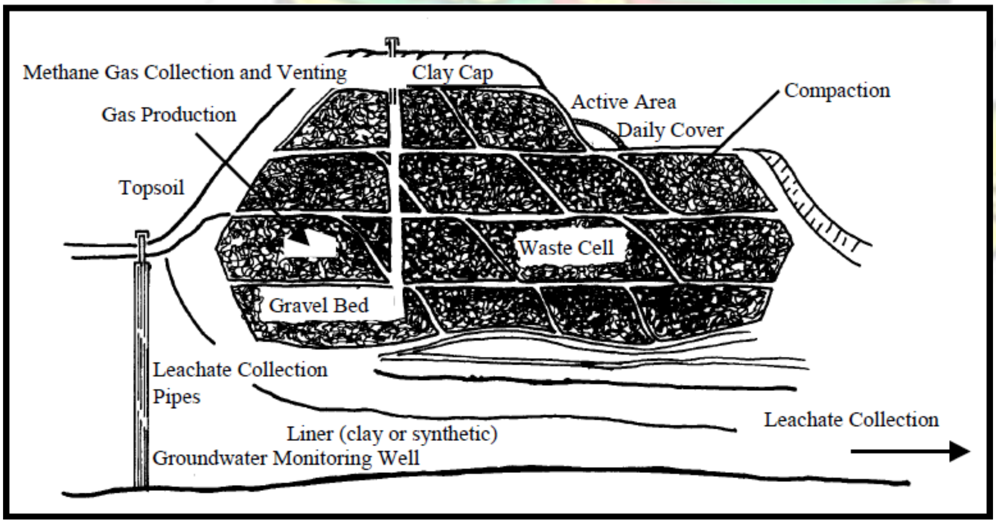
II. According to the technology used in operation of the landfill:

The landfill is a reactor that enhances the decomposition process. The design and operation of various landfills have been an improvement on the previous landfills. For example the controlled sanitary landfills were built in response to the problem of objectionable odours from the dumpsites

- Controlled Dumpsites: They are disposal sites which conform to a majority of the prerequisites for a sanitary landfill with their planned capacity without cell planning as their main defect. These dumps are a minimal threat to the environment with moderate operational and construction costs. They are still accessible by scavengers and so there is some recovery of materials.
- Biocell landfills: Landfill biocell are special designed cells for rapid methane recovery by undergoing an accelerated digestion. These cells are called biocells, biofills or digestion cells. It was introduced to Sweden by the end of the 1980s. They are designed to aim a landfill treatment with minimum of water percolating the waste and a minimum air emission to the environment. Biocells could be characterised as a landfill constructed for methane generation. It involves an optimized operation for gas

collection by means of installation of horizontal gas extraction systems and an effective leachate collect system.

- Bioreactor Landfills: Bioreactor landfills are constructed in a manner similar to most modern sanitary landfills equipped with liners system and landfill gas collection systems. They also have leachate recirculation and alternative cover designs. It is an advanced biocell with an additional leachate recirculation system to optimise the overall process. The main purposes of operating bioreactors are to optimise the operation technique and the anaerobic degradation and to ensure functional systems for gas extraction and leachate collection (NSR(The Northwest Scanian Recycling Company), 2001). The fundamental process used for waste treatment in a bioreactor landfill is leachate recirculation which could speed up microbial decomposition of the biodegradable solid waste therefore accelerate the biological stabilization of the landfilled waste rapidly. In general, the bioreactor landfill is generally defined as a landfill operated to change and stabilize biodegradable waste streams by appropriate control to enhance microbiological processes to their optimised condition for maximal bioenergy and nutrient recovery. (Hsiao, 2001)



(Diaz , et al., 2005)

Figure 2.7: Schematic Diagram of a Sanitary Landfill

2.6 Landfill Gas

2.6.1 Definition and Components of Landfill Gas

Landfill sites act as bio-reactors in which landfill gas is produced in biochemical processes from the decomposition of organic matter (Dudek, et al., 2010). Landfill gas is produced due to the decomposition of solid waste in landfills. It comprises approximately 50% methane (CH_4) and 50% carbon (iv) oxide. (U.S. EPA , 2011 a) . Landfill gas also comprises small amounts of nitrogen, oxygen, ammonia, sulphides, hydrogen, carbon monoxide and non-methane organic compounds (NMOCs) such as trichloroethylene, benzene and vinyl chloride. When waste is first dumped in a landfill, it decomposes aerobically producing small quantities of methane. Afterwards, anaerobic conditions are created and methane-generating bacteria degrade the waste and produce methane and carbon dioxide.

The methane constituent of LFG is a potential energy asset with a high risk of explosion. It is accepted as a GHG adding to global warming; the carbon dioxide portion of LFG is however regarded as biogenic in origin and hence not considered an additional GHG emission. Methane is approximately 25 times more heat absorptive than carbon dioxide of a comparable mass with a time frame of 100 years. . (Tchbanoglous, et al., 1993).

Table 2.5 Typical Landfill Gas Components

Component	Percent by volume	Characteristics
Methane	45-60	Methane is a naturally occurring gas. It is colourless and odourless.
Carbon(IV)oxide	40-60	Carbon (IV) oxide is naturally found at small concentrations in the atmosphere. It is colourless, odourless and slightly acidic
Nitrogen	2-5	Nitrogen comprises approximately 79% of the atmosphere. It is odourless, tasteless and colourless
Ammonia	0.1-1	Ammonia is a colourless gas with a pungent odour
Oxygen	0.1-1	Oxygen constitutes about 21% of the air. It is colourless and odourless
Non-methane organic compounds (NMOCs)	0.01-0.6	NMOCs are organic compounds may occur naturally or synthesised during chemical processes. The most common NMOCs found in landfills include acrylonitrile, benzene, 1,1-dichloroethane,trichloroethylene,vinyl chloride, and xylenes.
Sulphides	0-1	Sulfides are gases which occur in nature. They responsible for the rotten-egg smell on the landfill even if they are in minute quantities
Hydrogen	0-0.2	Hydrogen is an odourless, colourless gas.
Carbon monoxide	0-0.2	Carbon monoxide is an odourless, colourless gas

(Tchbanoglous, et al., 1993)

2.6.2 Production of Landfill Gas

There are three main processes by which landfill gases can be produced. These process are:

- ❖ Bacterial decomposition: Most landfill gas is created by bacterial degradation which takes place when organic waste is decomposed by naturally occurring bacteria present in the waste and in the soil used to cover the landfill. Bacteria decompose organic waste in four phases and the composition of the gas changes during each phase. Landfills often have a 20 to 30 year lifespan as such the landfilled waste may be undergoing different phases of decomposition at the same instant.

- Phase I (Hydrolysis): During the commencement of degradation, aerobic bacteria break down the complex carbohydrates, proteins, and lipids that constitute the waste. This process is known as hydrolysis. The end products of this phase are carbon dioxide, and nitrogen. The nitrogen content during the inception of this stage is high but is subsequently reduced as the landfill passes through the four stages. The hydrolysis proceeds until available oxygen is used up. Phase I decomposition can continue for weeks with the amount of oxygen contained in the disposed waste as a determining factor. Oxygen concentrations will vary depending on the degree of compaction of landfilled waste.
- Phase II (Acidogenesis): Acidogenesis commences after the oxygen in the landfill has been used up. Anaerobic bacteria change compounds created by aerobic bacteria into acetic, lactic, formic acids and alcohols. The landfill becomes highly acidic. As the acids combine with the moisture in the landfill, they cause the dissolution of making nitrogen and phosphorus available to the wide variety of bacteria in the landfill. The by-products of this process are carbon dioxide and hydrogen.
- Phase III (Acetogenesis): This decomposition starts when certain kinds of anaerobic bacteria consume the organic acids produced during the acidogenesis stage to form acetate, hydrogen and carbon dioxide. This process causes the landfill to become a more neutral environment in which the methane producing bacteria begin to thrive.
- Phase IV (Methanogenesis): This Phase commences when the constitution and generation rates of LFG remain fairly constant. The LFG mostly consists of about 45% to 60% methane by volume, 40% to 60% carbon dioxide and 2%to 9% other gases such as Sulphides, NMOCs. Gas production at this stage is at a static rate and can continue for about two decades but the emission of the landfill gas may continue to 50 years based on the prevailing conditions at the landfill.

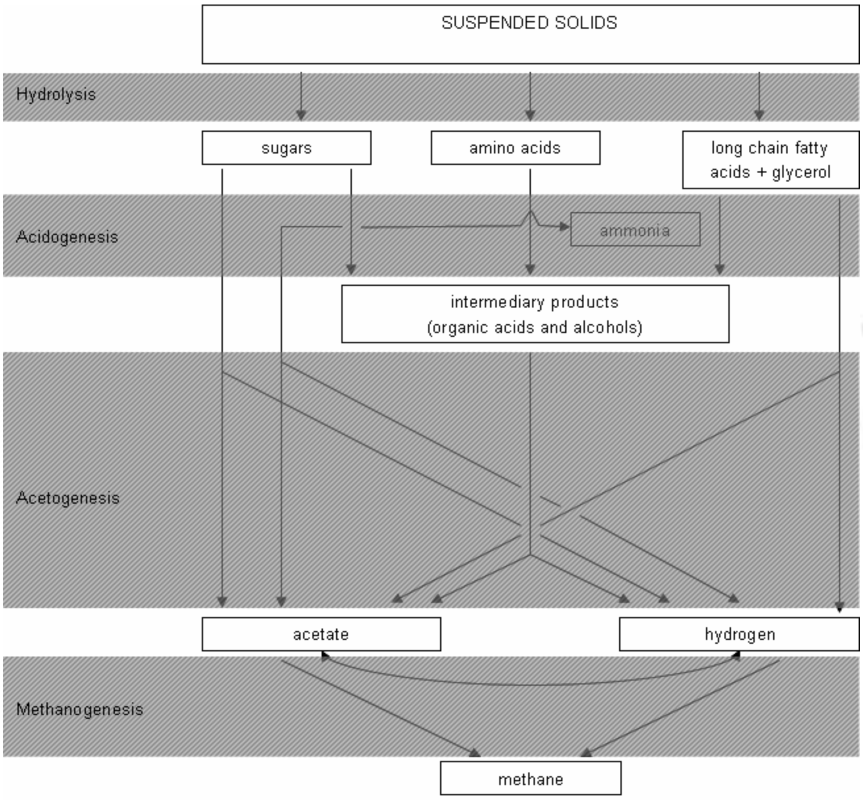
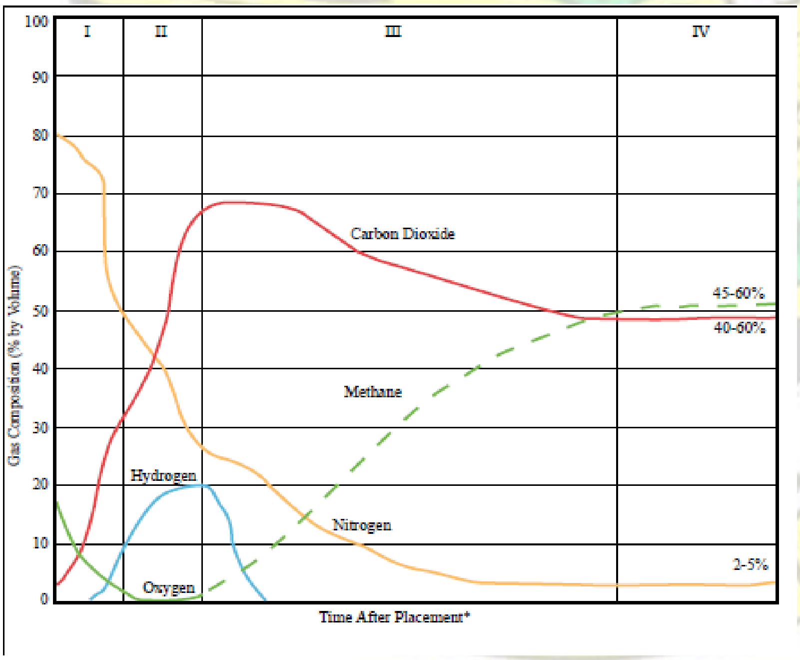


Figure 2.8: Stages in Methane formation



(US EPA, 2001)

Figure 2.9: Production Phases of Typical Landfill Gas

- Volatilization: landfill gases can be produced when certain organic compounds in the waste is converted into gaseous state. This process is known as volatilization. NMOCs in landfill gas may be the result of volatilization of certain chemicals deposited in the landfill

- Chemical reactions: landfill gas including NMOCs can be formed by the reactions of some chemical substances within the waste. for example, if chlorine bleach and ammonia can react to produce a gas.

2.6.3 Factors Affecting Landfill Gas Production Rate

The rate and quantity of landfill gas generated at a specific landfill sites depends on the characteristics of the waste and other environmental factors such as the presence of oxygen, moisture content and temperature.)

- Waste Composition: the composition of waste plays a major role in determining the amount of landfill gas that would be produced. Generally the more organic waste present in a landfill, the more landfill gas is produced by the bacteria during decomposition.
- **Temperature:** The LFG generation increases with increase in temperature to a ceiling temperature of about 57 degrees Celsius (°C). Any temperature above 57°C causes a decline in LFG generation. An increasingly high temperature is an indication of aerobic decomposition rather than the anaerobic decay, eventually causing subsurface fires. Although cold air temperatures can decrease LFG generation as seen mainly in shallow sites, by penetrating through the surface of the waste mass. Most landfills are however insulated from external temperatures and kept warm by the on-going microbial activity. The effects of temperature on LFG generation is complicated, and temperature profiles within the landfill is too variegated to characterize.
- **Moisture:** This is a crucial parameter affecting LFG production. Production increases with a surge in moisture because it causes an increase in the rate of decay of waste,

however increased moisture content does not increase the total amount of LFG generated within the life span of the landfill since the moisture only promotes the activities of the microorganisms that produce LFG. The amount of moisture differs from region to region, and at times even a particular site making it very cumbersome to measure. Mean yearly precipitation is mostly employed as a substitute for moisture

- **Age of Refuse:** Generally newly deposited waste will generate more LFG than older waste. Landfills generate significant volumes of gas within the first three years, however within the fifth to seventh year of operation, gas production reaches its peak. After twenty years of operation, almost all the gas to be generated by the landfill is produced, however small amounts of gas can be given off from the site for about 50 years. Different parts of the landfill might be undergoing varying stages of degradation at the exact instant, based on the time the waste was deposited in each area. The organic matter content in the waste is an essential factor in determining the duration of the LFG generation.
- **Oxygen in the Landfill.** Oxygen promotes aerobic degradation instead of anaerobic degradation methane production therefore commences with the depletion of oxygen in the landfill. Loosely buried waste ensures that the oxygen-dependent bacteria have enough oxygen to survive longer to generate carbon (IV) oxide and water instead of LFG. For highly compact waste, methane generation commences earlier because the aerobic bacteria are substituted by methane-producing anaerobic bacteria in Phase III. (Pierce & Huitric, 2005)

2.6.4 Estimation of Landfill Gas Production

When waste is disposed at the landfill, the LFG production rate is mostly swift after the waste has been discarded and gradually diminishes over the years as biodegradable waste is expended. Optimum LFG generation usually occurs within 2 years after the cessation of disposal of waste to the site. Landfill gas (LFG) modelling is the act of predicting the generation and recovery rates of LFG based on

i. waste disposal histories
ii. future disposal estimates,
iii. collection system efficiency

A landfill methane model is an instrument used to anticipate methane generation from waste per annum. The unit for the parameter time is a year (US EPA, 2012). Landfill gas models are used for:

- Sizing landfill gas collection systems: According to the clean Air Act, large landfills must have a LFG collection and treatment equipment installed for odour control, subsurface migration control etc. modelling can be an efficient means to correctly determine the size of the equipment
- Evaluation and projections of landfill energy uses: with knowledge of the equipment and operating cost, unit energy revenues etc., model projections can be used to predict the LFG yields of landfills, size equipment, estimate cost, and evaluate the spectrum of likely investment returns.
- Regulatory purposes: model predictions have been used to estimate landfill emissions and to affirm the establishment of LFG policies and prerequisites

Landfill gas generation has been relatively well researched. However the gas generation process is influenced by a gamut of factors, given the critical variable site conditions, any theoretical appraisal of gas generation rate is overly complicated. Empirical models have been developed as a result of the need of predictions with very high accuracy, the volume of methane emissions. (Dudek, et al., 2010)

2.6.4.1 The US EPA's Landfill Gas Emission Model (LandGEM)

This model calculates the generation rate of methane using the first order decay equation. It was originally designed for use by regulative institutions in the US but it is now applied globally. The underpinning equation is shown below:

$$Q = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left[\frac{M_i}{10}\right] \left(e^{-kt_{ij}}\right)$$

Where:

$Q = \ maximum \ methane \ generation \ flow \ rate \ expected$

$i = 1 \ year \ time \ increment$

$n = (year \ of \ the \ calculation) - (initial \ year \ of \ waste \ acceptance)$

$j = 0.1 \ year \ time \ increment$

$k = methane \ production \ rate \ (yr^{-1})$

This accounts for the rate at which waste decomposes to produce methane. For small values of k, the methane production is trammelled because only a comparatively small percentage of the landfilled waste decomposes annually to produce LFG. At greater values of k, a larger fraction degrades generating LFG. High values of k results in speedy increase in LFG generation with time while disposal is in progress, but causes a rapid decline after the closure of the landfill site. The k value basically depends on the biodegradability and moisture content (average annual precipitation)

L_o= potential methane generation capacity (m^3/Mg). This describes the quantity of methane gas that can be generated by tonne of waste as it degrades. It is a function of the waste composition, the greater the content of cellulose in the waste, the greater the value of L_0.

M_i= mass of solid deposited in the i^{th}year (Mg)

t_{ij} = age of the j^{th} portion of waste mass M_i discarded in the i^{th} year

The LandGEM equation estimates the methane produced for a particular year from the accumulated waste since inception to the specified year. (U.S Environmental Protection Agency, 2012)

2.6.4.2 The Intergovernmental Panel on Climate Change (IPCC) Model

1. The IPCC Model was outdoored in 2006. It has several characteristics that make it the preferred choice to LandGEM for the appraisal of landfill sites globally. These features includes the application of different first-order decay calculations for the various waste components whose decay rate vary. The model was formulated to approximate the methane generation rates of countries using their population estimates and regional generation rates but can be altered to enable it estimate methane generation from individual landfill sites. The IPCC Model applies a first-order decay equation which uses the yearly rate of disposal of waste together with a waste decay rate variable (k value).

The IPCC model has characteristics that make it suitable for modelling landfill sites outside the U.S, including the following:

- It's the ability to allow the user to input data specific to the landfill. In the absence of site specific data the model uses a regional default value for the estimation.
- It assigns decay rate values for the various waste categories based on their decay rates.
- The model also assign decay rate values based on the climatic conditions of the area.
- The IPCC model includes a methane correction factor MCF to account for aerobic decomposition at unmanaged disposal sites.
- The limitations of the IPCC model includes the following:
- Temperature has a minor effect on LFG production relative to precipitation hence must not be given the same measure in assigning climate categories;

- Potential evapotranspiration (PET) data should not be the fundamental assumption for assigning climate in temperate regions due to the unavailability of data
- The 1,000 mm/year precipitation threshold for the separation of climates into wet and dry is too general to account for wide differences in the precipitations

$$\mathrm{CH_4 generated\ in\ year\ t}\left(\frac{\mathrm{Gg}}{\mathrm{yr}}\right) = \sum_{x}\left[\left(\mathrm{A.k.MSW_T(X).MSW_F(X).L_0(X)}\right).e^{-k(t-x)}\right]$$

For x= initial year to year t

Where

t= year of inventory

x= years for which input data should be added

A= $(1-e^{-k})$; a normalization factor which corrects for summation

k= methane generation constant (yr^{-1})

$MSW_T(x)$ = total municipal solid waste generated in year x (Gg/yr)

$MSW_F(x)$ = fraction of MSW disposed at the landfill in year x

$L_0(x)$ = methane generating potential which is defined as

$$L_0 = \left[\mathrm{MCF(x).DOC(x).DOC_F.F.}\left(\frac{16}{12}\right)\right]\left(\frac{\mathrm{GgCH_4}}{\mathrm{Ggwaste}}\right)$$

Where

MCF(x) = methane correction factor in year x

DOC(x) = degradable organic carbon in year x (fraction) (Gg C / Gg waste)

DOC_F = fraction of DOC dissimilated

F = fraction by volume of CH_4 in LFG

16/12 = conversion from C to CH_4

The methane emitted in any year (t) is defined as

$$\mathrm{CH_4 emitted\ in\ any\ year\ t}\ \left(\frac{\mathrm{Gg}}{\mathrm{yr}}\right) = [\mathrm{CH_4 generated\ in\ year\ t} - \mathrm{R(t)}].(1 - \mathrm{OX})$$

Where

R(t) = recovered CH_4 in inventory year t (Gg/yr)

OX = oxidation factor

(U.S Environmental Protection Agency, 2012)

2.6.4.3 Global Methane Initiative (GMI) country specific models

The GMI country-specific models use a combination of information from each country and the algorithm of LandGEM to produce models which give a true picturesque description of the local prevailing conditions which impart LFG generation and collection. It calculates automatically the waste collection efficiency and assigns the methane generation constant (k) values appropriate for local climate based on information gathered from the countries in question (ibid).

2.7 Landfill Gas Energy Utilisation Technologies

The capture and use of LFG as an alternate energy source has varied benefits ranging from energy through environmental to economic benefits among others. Specifically using LFG has the following benefits:

1. Reduction of emissions of GHGs: MSW landfills are the third largest anthropogenic source of methane in the United States. Depending on the design and effectiveness of the project an LFG energy project can decrease emission of methane from a landfill by between 60 and 90 percent (U.S. EPA , 2011 a).
2. Generation of additional income: when the landfill gas is sold directly to end users or the electricity generated from the LFG is sold to the grid, local governments earn extra revenue

3. Increase economic benefits through job creation: the execution of an LFG energy project has enormous benefits to the local economy. It serves as a source of employment for engineers, construction firms, equipment vendors etc during the construction stage and also sustain certain jobs for the period within which the project operates (U.S Environmental Protection Agency, 2012)
4. Improvement in air quality: Using LFG to produce energy improves the quality of air of the surrounding community. This is because the utilization of LFG reduces the emission of hazardous air pollutants and landfill odours. It also prevents the emission of NMOCs which can lead to formation of smog (U.S. EPA , 2011 a)
5. Conserve land: LFG energy projects can improve the decomposition of solid waste, increase landfill capacity, and alleviate the need to establish new landfills or expand existing ones

There are various ways to effectively use LFG for energy; however, the primary applications are direct use and electricity generation technologies.

2.7.1 Direct Use

In US, Australia and some European countries, LFG has become a commercially viable alternate option to conventional fuels such as natural gas, fuel or coal. The use of LFG directly has proven to be both feasible and useful to the environment. The direct use of LFG can be a boiler, dryer, kiln or thermal applications. It can also be used to directly evaporate leachate. Other innovative uses include heating and powering greenhouses and ice rinks, firing pottery and glass blowing kilns,, aquaculture operation (Goldstein, 2006) . Current industries using LFG include automobile manufacturing, chemical production, food processing, pharmaceutical, cement and brick manufacturing, wastewater treatment, consumer electronics and products, and prisons and hospitals (U.S. EPA, 2009c)

The LFG which has been collected is utilised on site or transported via pipelines to an end user close by. The economic feasibility of the project depends mainly on the length of the pipeline. Within 8km of the landfill, the project is feasible but its profitability outside the 8km radius depends on

i. the quantity of LFG captured
ii. the end user fuel requirements,
iii. the cost of the fuel the LFG will substitute.

One million metric tons of landfilled MSW can produce between 8,000 and 10,000 pounds of steam per hour when LFG is used to fuel a boiler (U.S EPA, 2009D)

2.7.2 Electricity Generation

LFG can fuel turbines to generate electricity. The generated electricity can be used on the landfill or it can be sold to the local electricity grid (ISWA, undated). It is estimated that a majority of the LFG energy projects presently in United States are used for electricity generation. (U.S. EPA , 2011 a)

Several technologies are available that can generate electricity from LFG. It is estimated that about 85% of LFG electricity generation plants use internal combustion engines or turbines. For every one million tons of landfilled MSW, 0.8 MW of electricity can be produced. (U.S. EPA, 2009c)

Electricity projects which have cogeneration systems incorporated into them have higher operating efficiencies. Such systems generate electricity and capture heat energy at the same time. The captured heat energy can be sold to earn additional revenue for the project. (U.S EPA, 2009D). Combined heat and power (CHP) is often a more economical option for end users situated near the landfill who have a great demand for both the electricity and heat. (U.S Environmental Protection Agency, 2012)

2.7.3 Selection Criteria

For landfills seeking after LFGE recuperation, the main options are electricity production or the direct utilisation of LFG as fuel. Several factors are considered when deciding on energy recovery technology for a landfill, some of which include:

- Assurance of waste delivery
- Distance to the grid
- Local and regulatory structure
- LFG recovery potential
- Availability of consumers for direct utilisation of LFG
- Ability to sell electrical energy to the grid
- On-site electricity and heat requirements
- Capital costs and operating costs of utilization system options
- Financial considerations in terms of revenue
- Availability of experts for construction and maintenance of equipment
- Ability to secure contracts

2.7.3.1 Direct Use Considerations

Direct thermal applications increases the usage of the gas such that minimal treatment is required. It also makes it possible to combine it with other fuels. Direct thermal applications of LFG is widely used as long as it can meet the energy demands of the end user. Factors to be considered in assessing the suitability of a direct thermal project include:

- **The quantity and quality of LFG required by the end user.** The methane content of the amount of LFG gas available must be considered and relative to the facility's energy
- End users whose fuel demands fluctuates daily are less desirable because of the inability to store the LFG which is produced at a relatively constant rate onsite.

(ESMAP, 2004). In addition, the quality of the gas and type of LFG treatment required for particular end use must be taken into consideration in examining economic viability.

- **Retrofit Requirements to Accommodate LFG.** There are also considerations for the end user on designing equipment that either co-fires LFG and other supplementary fuels or that uses LFG as primary fuel with natural gas or other fuel as a back-up source only.
- **Location of the user.** The location of the consumer will determine the required length and location of an LFG pipeline. The landfill must be situated within a 10 to 15km radius to attain a sufficient return on investment for direct use. Any distance farther makes the use of LFG less competitive relative to traditional fuels due to increased cost. However, at longer distances, it may be viable, based on the quantity of gas recovered at the landfill, the energy demand of the consumer, and fuel prices. (World Resources Institute, 2002).
- **Cost considerations.** The costs connected with treating the gas, pipeline and retrofitting of equipment to use LFG, together with Operation and maintenance, must be considered. Furthermore, legal issues with respect to the pipeline will have an effect on the costs and the selling price to the end user. (U.S Environmental Protection Agency, 2012). Additionally, the consumer must make investments into equipment capable to switch between LFG and usual fuels to cope with the fluctuations in the supply LFG, as well as pipeline quality value.

2.7.3.2 Electricity Generation Considerations

The limitations associated with the direct use of landfill gas (geographic limitations and need for equipment modification) can be surmounted the usage of LFG as alternate fuel for electricity generating machinery situated at the landfill. Generally, internal combustion engines are the most cost-efficient and dependable technology for generating electricity from LFG (especially projects of moderate sizes). Gas turbines are used for site with generation capacity of about 3 to 5 MW (World Resources Institute, 2002) .Other issues that can be examined in considering the generation of electricity from LFG, include:

- **Electrical conversion efficiency.** The efficiency of Electrical conversion is indicative of the fraction of the calorific value of methane that may be changed into electricity. This varies depending on the chosen technology. Internal combustion engines are highly efficient relative to many gas turbines.
- **Power generation potential.** The actual amount of power generated depends on the dependability of the power generation machinery and the fuel supply to the LFGE plant.
- **LFGE plant maintenance and repair.** The availability experts to man the plant according to best practices and the availability of the required parts for maintenance of equipment must be ascertained so that routine maintenance can be undertaken.
- **Ability to respond to fluctuations in LFG quantity with time.** The chosen technology should allow for increase in operation capacity at a lower cost..
- **Availability of an electric grid interconnection point.** Building new infrastructure for the supply of generated electricity to the market will make the project not viable ab initio hence available of powers substations for connection to the grid will be an added advantage.
- **Cost considerations.** the fixed capital cost and the operating cost must be taken into consideration before embarking on the project.

Table 2.6 Comparative Analysis of the Various LFG Utilization Technologies

Advantages	Disadvantages	LFG Treatment Requirements
Direct-Use Medium Pipeline Quality		
Boiler, dryer, and process heater		
• Can use most of recovered gas flow • Cost efficient • Little treatment is required • Does not need large quantities of LFG and can be mixed with other fuels	• Cost is tied to length of pipeline; energy user must be nearby	Need to improve quality of gas or retrofit equipment
Infrared heater		
• Relatively inexpensive • Easy installation • Does not require a large amount of gas • Can be coupled with another energy project	• Seasonal use may limit LFG utilisation	Limited treatment is required
Leachate evaporation		
• Highly recommended option for landfills where leachate disposal is expensive	• High capital cost	Limited treatment is required.
Electricity		
Internal combustion engine		
• High efficiency compared to the other equipment • Size matches perfectly with the LFG generation of many sites • Relatively installation cost • Waste heat recovery increases efficiency • Can easily manipulate engine size to match gas recovery trends	• Relatively high maintenance cost • Relatively high air emissions • May not be viable for countries with low costs of electricity	Primary treatment of LFG required for optimal engine performance, secondary treatment may be necessary

Con't Table 2.6 Comparative Analysis of the Various LFG Utilization Technologies

Gas turbine		
• Generation cost and efficiency increase with increasing size • Heat recovery increases efficiency • Corrosion resistant • Low nitrogen oxides emissions • Relatively compact	• Efficiencies decreases when the unit is running at partial load • high gas compression required • High parasitic loads • May not be viable for countries with low costs of electricity	Primary treatment of LFG required for optimal engine performance, secondary treatment may be necessary
micro turbine		
• Need low gas flow rate • Can function with reduced	• May not be viable for countries with low costs of	Requires fairly extensive primary and secondary treatment

methane composition • Low nitrogen oxides emissions • Relatively easy interconnection • Can easily manipulate engine size to match gas recovery trends	electricity	of LFG
Direct-Use High pipeline Quality		
Pipeline-quality gas		
• Can be sold into a natural gas pipeline	• Increased cost that results from tight management of wellfield operation needed to limit oxygen and nitrogen intrusion into LFG	Requires extensive and potentially expensive LFG processing
CNG or LNG		
• Alternative fuels for vehicles at the landfill or refuse hauling trucks and for supply to the general commercial market	• Increased cost due to strict management of wellfield operation needed to limit oxygen and nitrogen intrusion into LFG	Requires extensive and potentially expensive LFG processing

(U.S Environmental Protection Agency, 2012)

2.7.4 Treatment of Landfill Gas

Before the recovered LFG can be utilised, it must undergo treatment to get rid of any moisture that was not removed in the condensate removal systems, and other pollutants. The standards for treatment depends on the end user. Moisture removal to prevent corrosion of equipment by the saturated LFG for both direct use and electricity generation. The utilisation of LFG directly in boilers, furnaces or kilns requires very little treatment while treatment for electricity generation projects usually includes many filters to get rid of substances that can destroy the engine and reduce system efficiency

2.8 The Energy Outlook of Ghana

In 2013, the total grid electricity generated in the country was 12874 gigawatt-hours (GWh) which represents more than a 6% increase in the electricity generated in 2012. In 2014 the total electricity demand of the nation was estimated to be in the region of 15725-16500GWh.

The projected electricity demand within the constraints of the limited available supply means that there is bound to be significant supply shortfalls any time a power plant is turned off even for scheduled maintenance.

The estimated energy deficit in 2013 was between 1,700-2,480 GWh which translates into 240–330 MW thermal plant equivalent. A total of about 700-800 MW additional thermal capacity equivalent would be required to cater for the deficit and a minimum of 20% reserve margin for 2014. Annual capacity deficit is approximately between 200-250 MW. (ENERGY COMMISSION,GHANA, 2014). Therefore to ensure continual supply of electricity for various economic activities other sources of energy must be sought to augment the current energy situation in the country. Renewable energy, as defined by the renewable energy act, as energy obtained from non-depleting sources including wind, solar, hydro, biomass, bio-fuel, landfill gas, sewage gas, geothermal energy, ocean energy and any other energy source designated in writing by the minister (The Parliament of the Republic of Ghana, 2011) is one of the most viable options to be explored to solve the power crisis in the country at the moment. Conventional thermal generating systems are most sensitive to the ever fluctuating fuel prices, renewable energy technologies have highest supply security since once they are constructed, fuel is largely indigenous (Energy Commission, Ghana, 2006).

The detailed assessment of the technical feasibility of alternate power generating technologies including an evaluation of the costs and a demonstration of the overall net benefits accruing to the economy shows that for decentralised grid systems, electricity generated from landfills is the least expensive option that can be explored to help ameliorate the power situation in the country (Energy Commission, Ghana, 2004). Tapping power from landfills usually in the ranges of 1 – 2 MW installed capacities per site is potentially the cheapest source of grid electricity for close by communities. Engineered landfills could serve as sources of supplementary power to the centralised grid for urban communities to achieve the 10% contribution of modern renewables by the year 2020 (The Parliament of the Republic of Ghana, 2011)

CHAPTER THREE

MATERIALS AND METHODOLOGY

This chapter provides information of the study area as well as the methods employed to collect and analyse necessary data. The first section presents the profile of the study area. The second section describes the specific method used to characterise the solid waste. The next chapter talks about the determination of the physical properties of the waste sample. The procedure for modelling the landfill gas production is described in the next section. The last section deals with the procedure for determining the profitability of the project

3.1 Description of Study Area

Tamale is the Northern regional capital of Ghana. It is situated in the transitional forest zone and is approximately 600 km north of Accra. It is on latitude 9.4075° N and longitude 0.8533°W, an elevation of 183 m above sea level with an area of about 750km^2. The average minimum temperature is about 22.5 °C and a maximum average temperature of 33.3°C. The average humidity is about 46.8%. The city draws an average of 1090mm of rainfall per year or 90.8 mm per month. On the average there are 97 days per year with more than 0.1mm of rainfall per year. In Tamale, December is the driest month with 3mm of rainfall and September records the highest rainfall of about 231 mm.

The population of Tamale according to the 2010 was estimated to be 537,986. It was projected by the 2010 census that the population in 2013 will be 562,919 making it the one of largest towns in Ghana and the most rapidly developing city in West Africa. The population has grown rapidly over the inter-censal periods from 167,778 in 1984, 293,881 in 200 to 537,986 in 2010. Tamale has an inter-censal growth rate of 3.5% and the population density of the city is 480.77/km^2

Figure 3.1: The Map of Study Area

The Tamale landfill site is an engineered landfill site situated 18km away from the central business district of the tamale municipality. It was commissioned for use by the then vice president Alhaji Aliu Mahama on the 31st July, 2006. The landfill spans over an area of 20 hectares of land. The land serves the people of the tamale municipality which has an average of three hundred thousand (300000) inhabitants. The estimated life span of the landfill is thirty (30) years. The waste collection method employed is the use of trash trucks that undertake both house to house as well as communal container collection.

The landfill was constructed to be an engineered landfill site and is supposed to operate as such however the weighing bridge and the computer control room was out of order; this has been the case for quite a very long time. An average of twenty five (25) trucks visit the landfill site daily. Two hundred and thirty tonnes of waste is received daily at the landfill site. A survey conducted by the Waste Management Division of the Tamale Municipal Assembly showed that the average waste generated by an individual on a daily basis is 0.5kg.

Currently only one out of the four cells on the landfill is in operation. The dumping of refuse is done daily and the waste is spread to height of 1.5 metres before compaction and covering is done. The cover material used on the site is the laterite collected during the construction of the landfill. The landfill has been covered only six times. The covering is done such that the landfill takes the shape of a pyramid. It is done such that the methane gas generated can pass through to get to the gas vents specially situated on the landfill for the gas to escape preventing any possible explosion. Since there is no means of trapping the methane gas, it is released directly into the atmosphere.

The leachate produced together with the liquid waste from the municipality undergoes biological treatment. There are three entry ponds, three facultative ponds and one maturation pond. At the moment only one entry pond, one facultative pond and the maturation pond are in operation. At the entry pond, the leachate undergoes anaerobic degradation. It is then transferred to the facultative pond where it is exposed to sunlight. At the maturation pond, the leachate together with the liquid waste is said to be devoid of any substance harmful to aquatic life. The proof of the above postulation is the presence of fish in the pond. Before water is released into the surrounding water bodies from the maturation ponds, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) tests are carried out by the Environmental Protection Agency (EPA) to ensure that the water reaches the required standard.

There is no laid down plan for the site after it is closed down but it is likely to be used for recreational purposes.

Figure 3.2 The Signpost At The Entrance Of The Landfill

Figure 3.3: The Weighing Bridge

Figure 3.4: The Compactor Used At The Landfill

Figure 3.5 The Tamale Landfill Site

Figure 3.6 A Gas Vent On The Landfill

3.2 Characterisation of the Solid Waste

The method used to carry out the characterisation of the solid waste is the standard test method for determination of the composition of unprocessed municipal solid waste described by the American Society for Testing and Materials D5231-92(2003) (ASTM D5231-92, 2003). This test method describes procedures for measuring the composition of unprocessed municipal solid waste by employing manual sorting.

3.2.1 Summary of Experimental Procedure

The number of samples required for the sorting out process is determined based on chosen statistical standards. Samples are collected from discharged vehicle load and reduced to about 100kg by the quartering and coning method. The sample is manually sorted out into the various constituents. The fractions of the various components are calculated. The average composition of the waste is calculated using the individual sample composition results.

3.2.2 Equipment and Materials

The equipment and materials used in waste management programs is based on the chosen methodology. In this study where the test method was ASTM D 5231-92 (2003), the equipment and materials used were as follows

- Mechanical balance to weigh the waste

- Shovels for collecting the waste
- Trash Polythene bags for collecting waste samples
- Masking tape and markers for labelling
- Protective clothing: hand gloves, nose mask, boots
- Printed data sheets
- Plastic sheet to cover the ground

3.2.3 Sampling Procedure

Selecting a sample to accurately represent the landfill site is a very crucial but arduous task. For characterisation on a landfill site, vehicle loads are sampled. The common vehicles used at disposal sites compactor, roll on-roll off and skip trucks. The compactor trucks are mostly used for house to house collection. Skip trucks are mostly used for collection of communal containers and hence more of second and third class residential areas. The roll on roll off trucks is mostly used for collection of market waste. One of each truck is selected at random on the day the characterisation is supposed to take place.

3.2.3.1 Sample Size Reduction

According to the standard, the recommended weight of a sample of unprocessed waste is between 91-136 kg. The weight chosen for the purposes of this study is 100kg. The Coning and Quartering technique was employed to achieve the required sample size. This process is described as follows;

The waste from a selected truck is dumped onto a tarpaulin on the ground and divided into four equal parts using straight lines that perpendicular to each other. Either pair of opposite corners is removed to leave half the original sample with rakes and shovels. The process is repeated till the required sample size is obtained. (Rockson, et al., 2011)

The number of samples required depends on the different waste components to be sorted and the level of precision desired. The number of samples required for this classification is calculate as follows;

The governing equation for the number of samples (n) is given as follows

$$n = \left(\frac{t^{*}s}{e.\bar{x}}\right)^{2}$$

Where

t* = student t statistic corresponding to the desired level of confidence,

s = estimated standard deviation,

e = desired level of precision, and

$\bar{x}$ = estimated mean

Table 3.1: Values of Mean and Standard Deviation for Within- Week Sampling MSW Component Composition

Component	Standard deviation(s)	Mean ($\bar{x}$)
Paper	0.07	0.10
Plastic	0.03	0.09
Yard Waste	0.14	0.04
Food waste	0.03	0.10
Wood	0.06	0.06
Other Organics	0.06	0.05
Other Inorganics	0.03	0.06

. (ASTM D5231-92, 2003)

Table 3.2: Values of t Statistics (t*) as a Function of Number of Samples and Confidence Interval

Number of Samples,n	90%	95%
2	6.314	12.706
3	2.920	4.303
4	2.353	3.182
5	2.132	2.776
6	2.015	2.571
7	1.943	2.447
8	1.895	2.365
9	1.860	2.306
10	1.833	2.262
11	1.812	2.228
12	1.796	2.201
13	1.782	2.179
14	1.771	2.160
15	1.761	2.145
16	1.753	2.131
17	1.746	2.120
18	1.740	2.110
19	1.734	2.101
20	1.729	2.093
21	1.725	2.086
22	1.721	2.080
23	1.717	2.074
24	1.714	2.069
25	1.711	2.064
26	1.708	2.060
27	1.706	2.056
28	1.703	2.052
29	1.701	2.048
30	1.699	2.045
31	1.697	2.042
36	1.690	2.030
41	1.684	2.021
46	1.679	2.014
51	1.676	2.009
61	1.671	2.000
71	1.667	1.994
81	1.664	1.990
91	1.662	1.987
101	1.660	1.984
121	1.658	1.980
141	1.656	1.977
161	1.654	1.975
189	1.653	1.973
201	1.653	1.972
∞	1.645	1.960

(ASTM D5231-92, 2003)

The number of samples (n') for the selected conditions and components is calculated. The t* value is selected from Table 3.2 for n =∞ for the selected level of confidence. Since the number of samples required for a given criteria differ among the components, a bargain is required in choosing a sample size. The component that is selected to regulate the precision of the composition determination is called the "governing component". After selecting the governing component and the number of samples that correspond to it, (n_o), Use Table 3.2 and select the student t statistic (t^*_o) corresponding to n_o. The number of samples required is calculated again n' and compared to n_o. If the difference between the values is greater than 10 %, the calculation is repeated, if not the greater value is chosen as the required number of samples to be sorted (ASTM D5231-92, 2003).

3.3 Moisture Content Determination

Moisture Content is the amount of water a material contains on a volumetric or gravimetric basis. Moisture content of MSW is a highly important information when the landfill is operated as a bioreactor. The value determines the expected level of decomposition and gas generation. Also it determines the additional amount of moisture to be recirculated to attain the optimum moisture content between 20-40%. The moisture content of MSW is also useful for estimating heat content, landfill sizing and transport prerequisites. For solid waste, moisture content is more usually expressed on a wet basis.

3.3.1 Apparatus Required

- Large bowls
- Balance
- Oven

3.3.2 Test Methodology

The oven is switched on and set to 105°C. The weight of the empty containers is determined using the balance. Before sorting is done, 1kg of the waste is collected randomly and put into the bowl. The weight of the bowl and its contents is determined. The bowl is put into the pre-set oven at 105° C and allowed to dry for 24 hours. After 24 hours, the new weight is determined and the moisture content can be calculated as follows

$$\text{weight of wet waste} = (\text{weight of empty can} + \text{wet waste}) - (\text{weight of empty can})$$

$$\text{weight of dry waste} = (\text{weight of empty can} + \text{dry waste}) - (\text{weight of empty can})$$

$$\text{weight of moisture} = \text{weight of wet waste} - \text{weight of dry waste}$$

$$\text{moisture content(wet wt basis)\%} = \frac{\text{weight of moisture}}{\text{weight of wet waste}} \times 100\%$$

$$\text{moisture content(Dry wt basis)\%} = \frac{\text{weight of moisture}}{\text{weight of dry waste}} \times 100\%$$

3.4 Modelling Landfill Gas Production

The landfill gas generation potential will be estimated using the following models

- LandGEM
- IPCC model
- GMI Columbia model

3.5 Profitability Analysis

The economic viability for a landfill gas energy project depends to a large extent on the identification of appropriate financing mechanisms, assessing the economic viability of several alternatives and the selection of the most feasible option to meet the goals of stakeholders. The project economic assessment process typically involves the following broad steps;

- Estimate project capital and Operation and maintenance expenses for both scenarios (electricity generation and direct use)
- Estimate the rate of return on investment
- Determine the payback period
- Determine the net present worth

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Characterisation of Waste Material

The composition of waste is a fundamental requirement for the development of waste management strategies in any municipality (Asase, 2011). It is therefore imperative that to implement a landfill gas to energy project, the composition of the waste on the landfill must be first determined.

The results in the table below represent the average waste composition of 60 samples taken at five different locations over a two-week period from the Tamale landfill site. The minimum weight of each sample was 100kg as stipulated by the ASTM D5231-92(2003)

Table 4.1: Average Waste Composition Data

Fraction of waste	Dry Season	Wet Season	Total
Food waste	39.8	46.4	43.1
Plastic waste	18.6	17.0	17.8
Glass bottles	1.9	2.6	2.3
Paper and Cardboards	10.2	7.9	9.0
Metals	3.3	3.2	3.3
Textiles	6.9	7.8	7.3
Inert	18.7	14.4	16.5
Wood	1.0	0.6	0.8
~~Total~~Average	100	100	100

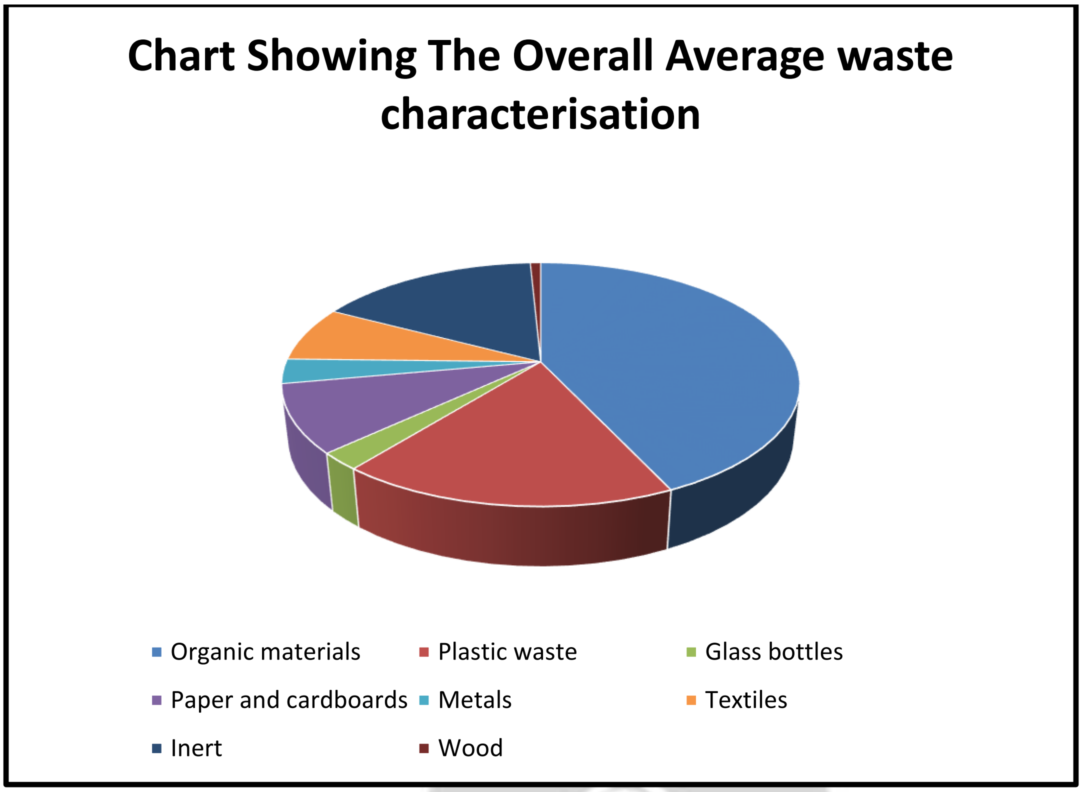


Figure 4.1 The Overall Average Waste Composition

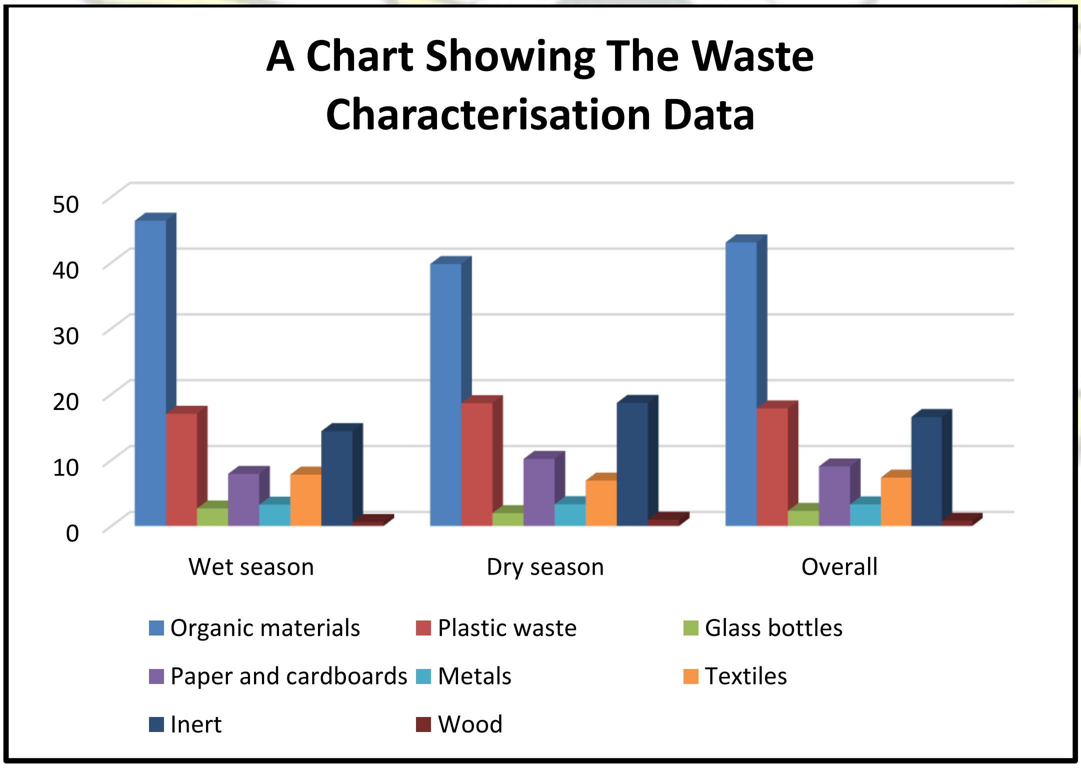


Figure 4.2 The Seasonal Variation of the Waste Composition

The highest waste fraction waste the organic waste fraction, contributing 43.1%. This is in conformity with the observation made by Cointreau et al (1987) who reported that for developing countries the organic fraction is the largest ranging between 40 to 80%. This value varies slightly from the composition of organic waste materials reported by other analysts an example is Rockson et al (2011) whose value for the Tamale landfill was 33.15% but their analysis period was during the transition between the two major seasons in the country as opposed to my time of analysis which was during the two major seasons. It can be concluded then that the difference in the time for analysis accounts for the variation in the composition of organic waste (Osei-Mensah, et al., 2014). The value for organic waste fraction is similar to that (43.87%) reported by Kotoka (2001) for Kumasi and that reported in Mallam, a suburb of Accra by AMA in 1997. This shows a trend of uniformity in the characteristics of wastes generated nationwide. Rockson et al (2011) records an average value for the wastes generated in five major cities in the country as 41.77% which affirms the fact that the compositions of waste generated in the country are not entirely different.

The inert waste fraction, which comprises sand, ash and fine organics, recorded an average percentage of 16.5%. This differs slightly from the value as recorded by Rockson et al (2011) but falls within the range for low middle income countries, 1-40%,(Cointreau et al,1987). The main factor that accounts for the rising amounts of inert material deposited at the landfill site is the lack of waste segregation at both the generation and collection points.

The component of the waste representing the fraction for plastic waste comprises PET bottles, film rubbers and Plastic chairs etc. Plastic films represented 17.8% of the total waste stream. This value is very close to that of 14.99% reported by Rockson et al (2011). It differs greatly from the value recorded by Kotoka (2001) and also out of the range proposed by Cointreau et al, (1987). The gradual increase in the standard of living in the Northern region is a contributing factor to the increasing amount of plastic waste. (SANDEC, 2008). This is because with a higher income levels and economic growth, the lifestyle of the inhabitants gradually changes; a classical example is the increased consumption of packaged products and processed foods. This trend is not only found in Ghana but also in both the developed and developing countries as well. This poses a major threat to the environment and strict measures must be taken by the various authorities to curb the plastic waste menace.

The metal component of the waste stream was further categorized into cans and crowns, and scrap metals. All metals represented 3.3% of the total waste sample. This is very close to the national average value of 2.29% and the average value for Tamale, 2.40%, recorded by Rockson et al (2001). The value for metals agrees with Cointreau's average value for low income countries.

Another major component of the waste stream was textiles representing 7.3% of the total waste stream. This value corresponds to the various values, 7.71% and 9.08%reported by Rockson et al (2011) for the national average and Tamale respectively. It falls within the range of values proposed by Cointreau (1987)

A comparison of the waste compositions of the various seasons showed no major difference. The table below shows the waste compositions within the wet and dry seasons

Table 4.2: Comparative Analysis of Waste Composition in the Two Major Seasons

Fraction of waste	Dry Season	Wet Season
Food waste	39.8	46.4
Plastic waste	18.6	17.0
Glass bottles	1.9	2.6
Paper and Cardboards	10.2	7.9
Metals	3.3	3.2
Textiles	6.9	7.8
Inert	18.7	14.4
Wood	1.0	0.6
Total	100	100

Figure 4.3: Weighing The Collected Sample

Figure 4.4: Collection of the Randomly Selected Portion

Figure 4.5: Sorting of the Collected Waste Sample

4.2 Moisture Content Analysis

The moisture content of the readily biodegradable components was determined and the average results are as follows

Table 4.3: Moisture Content Analysis of the Readily Biodegradable Waste Components during the Year

Waste composition	initial weight	final weight	moisture content	% moisture content
Paper	1252.6	902.8	349.8	27.9
Food	5482.0	2956.6	2525.4	46.1
Textiles	1466.0	1013.1	452.9	30.9
Wood	1779.1	1257.3	521.8	29.3
Other	2748.2	1971.3	776.9	28.3
Total	12728.0	8101.1	4626.8	36.4

The degradation process of solid waste leading to the generation of methane gas is regulated by several factors. Moisture content plays a major role in the decomposition of the waste. Optimum moisture content is known to generally enhance the decomposition process. The Tamale landfill was found to have an average moisture content of 36.4% which is within the range (35-45%) for optimum anaerobic degradation. (Waste Management Inc, 2016)

Figure 4.6: Sample in the Oven

Figure 4.7: Oven Used For the Moisture Content Determination

Figure 4.8: Chemical Balance Used For Moisture Content Determination

4.3 Landfill Gas Estimation

The landfill gas generation potential was estimated using the models specified in the methodology.

4.3.1 Results for the Columbia model

The Global Methane Initiative (GMI) has created specific models for selected countries. The Columbia model is part of these models. It applies the structure of the LandGEM model combined with detailed information from Columbia to reflect accurately the local conditions which affect the landfill gas generation. The following are the inputs required by the model

Table 4.4 Parameters Used In the Columbia Model

Parameter	Input Value
Landfill Name	Tamale Landfill Site
City	Tamale
Geographical Region	Andina
Average Annual Rainfall range	1000-1499 mm/yr
Year Opened	2006
Annual disposal for latest year with data in tonnes per year	83950 Mg
Year of disposal estimate	2014
Waste in place	671600 Mg
Projected Closure year	2036
Estimated growth in annual disposal	7.5%
Regular compaction	No
Daily cover present	No
Presence of surface ponds	Yes
Calculated collection efficiency	20%

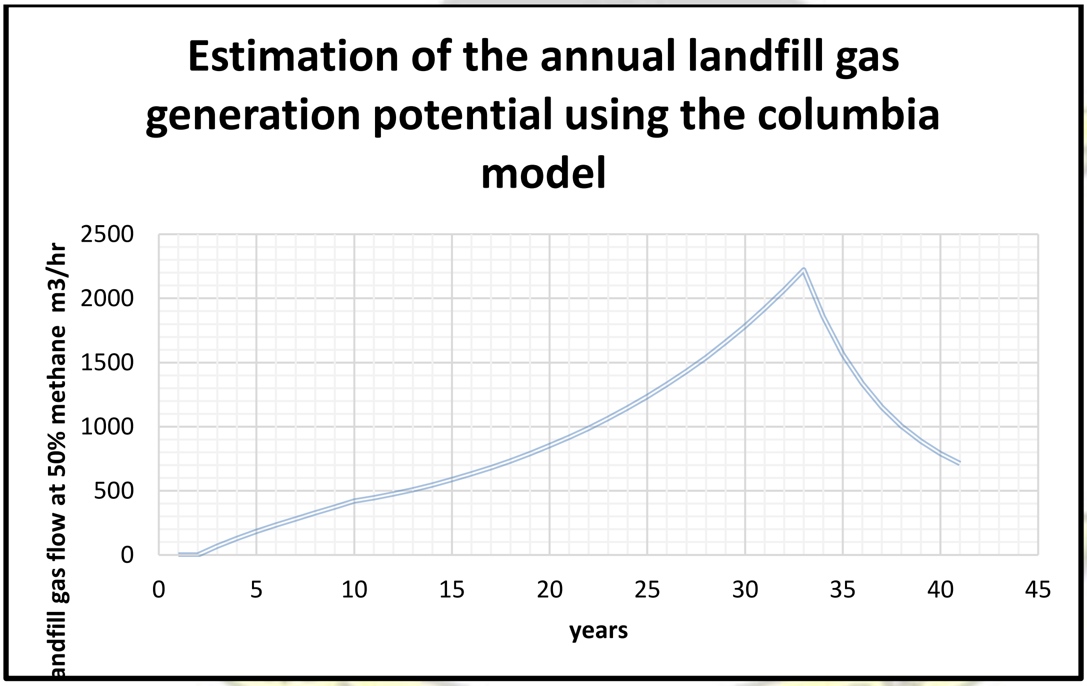


Figure 4.9 The Estimated LFG Generation Potential Using The Columbia Model

4.3.2 Estimated landfill gas generation potential using the IPCC model

The IPCC Model was released in 2006. It applies individual first-order degradation calculations for different biodegraded groups with different decay rates. The inputs of the

IPCC Model is the characterisation data of the site, the amount of waste deposited and the climate description of the area

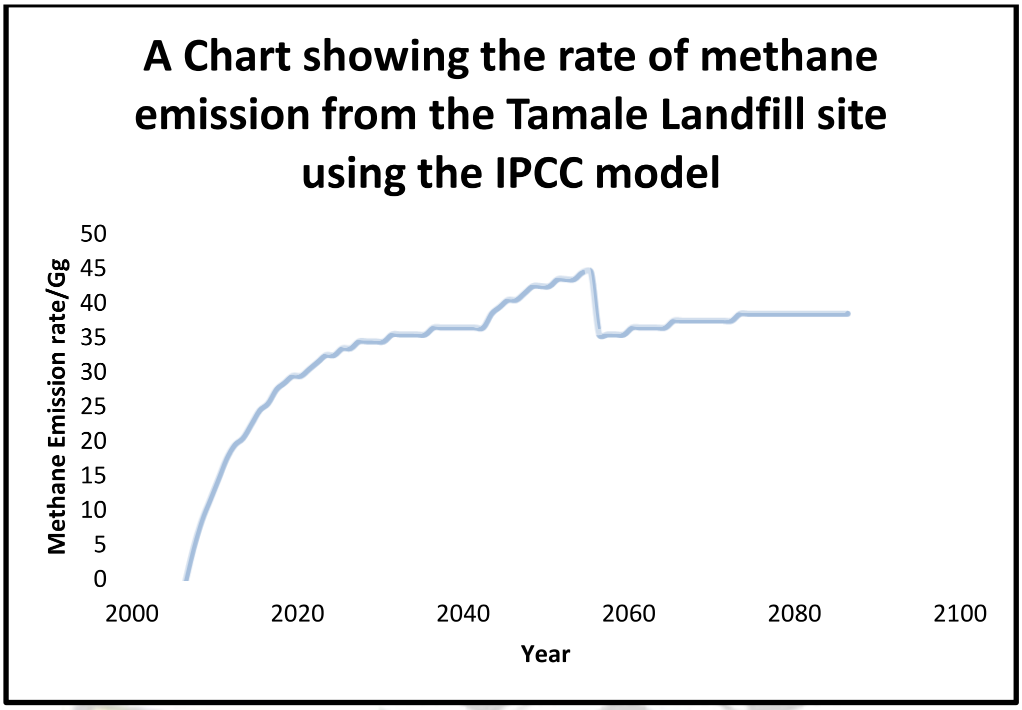


Figure 4.10 The Estimated LFG Generation Potential Using The IPCC Model

4.3.3 The Estimated Landfill Generation Potential Using the LandGEM Model

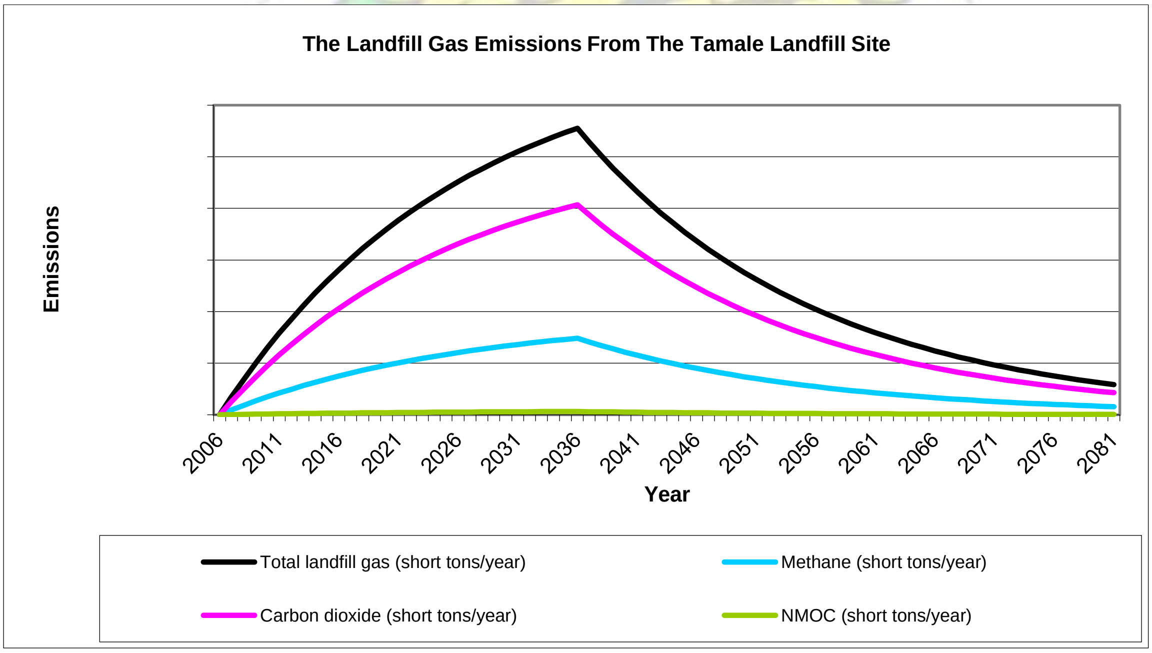


Figure 4.11 Estimated Landfill Gas Generation Potential Using the LandGEM

4.4 Energy Generation Potential

The amount of energy that can be generated from the landfill gas was calculated using the equations below

$\text{Thermal energy} = \text{m} \times \text{LH}\dot{\text{V}}_{\text{ch4}} \times \text{R}$

$\text{electrical energy} = \text{m} \times \text{LH}\dot{\text{V}}_{\text{ch4}} \times \text{R} \times \eta_{\text{el}}$

(Surroop & Mohee, 2011)

Where,

m = mass flow rate of methane (kg/h)

$\text{LHV}_{\text{ch4}} = \text{lower heating value of methane(MJ/kg)}$

R = recovery rate of methane =75%

$\eta_{\text{el}} = \text{electrical efficiency} = 33\%$

<u>Sample Calculations</u>

$$Annual\ mass\ flowrate = annual\ volumetric\ flow\ rate \times density$$

$$Annual\ mass\ flow\ rate = 5.694 \times 10^5 \times 0.676 = 384914.4\frac{kg}{yr}$$

$$annual\ thermal\ energy\ generated = 384914.4 \times 37.5 \times 10^6 \times 0.75$$

$$= 1.0826 \times 10^{13}\ J/yr$$

$$annual\ electrical\ power\ generated = 113282.8W$$

$$electrical\ energy = 992357.4\ kWh$$

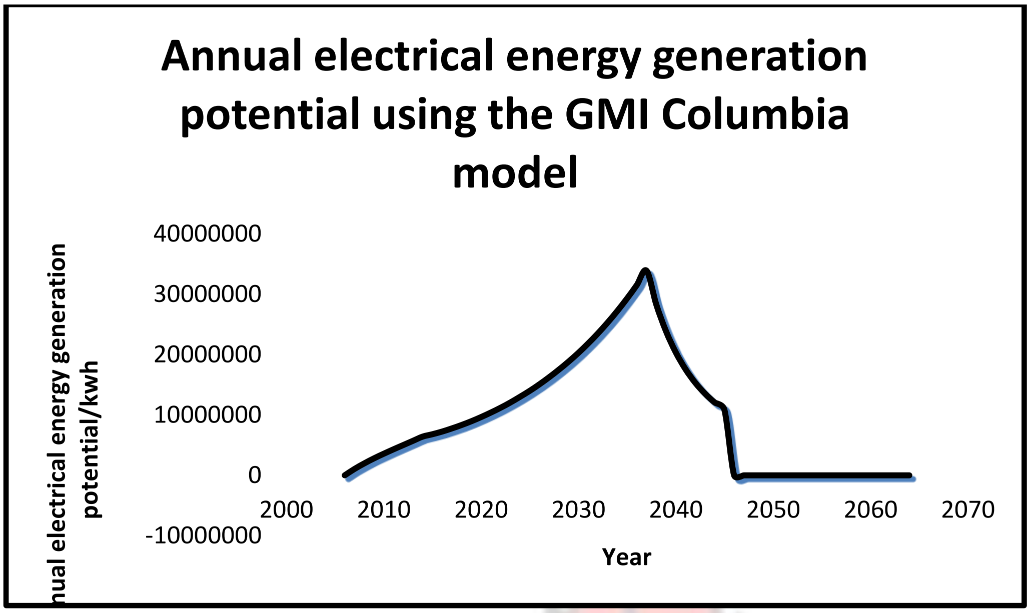


Figure 4.12 The Annual Electrical Generation Potential Using the Columbia Model

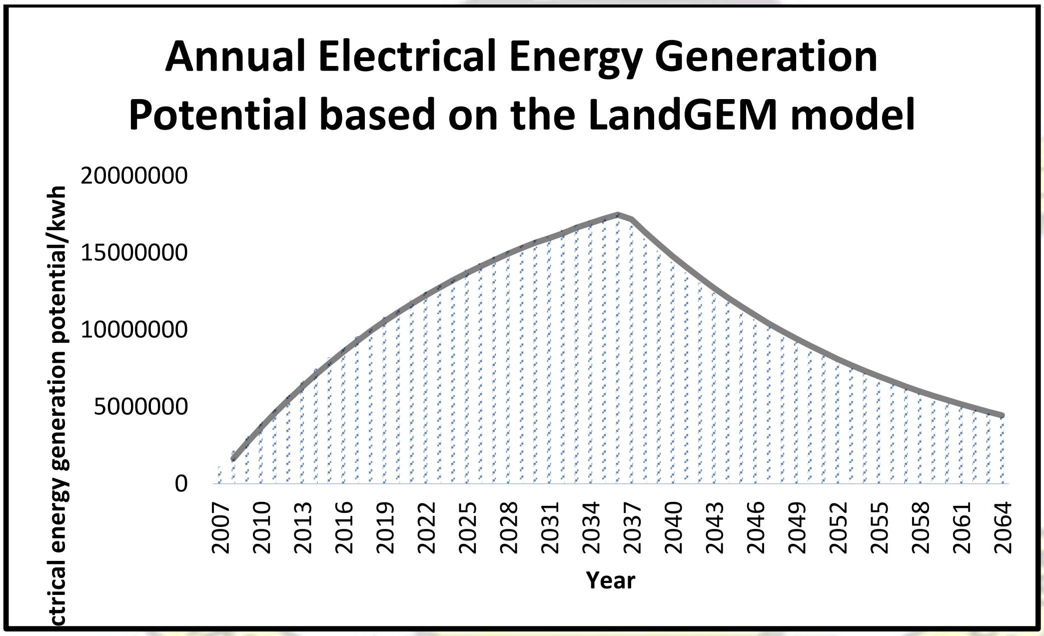


Figure 4.13 Annual Electricity Generation Based on the LandGEM Model

Based on the project size input, the electricity generated from the landfill can power 688 homes.

4.5 Profitability Analysis

TOTAL LFGE PROJECT COST

LFGE project costs usually consist of capital costs. Cost elements common to LFGE the initial startup capital, working capital and the operation and maintenance cost.

Table 4.5: Cost Summary for Electricity Generation Projects

Technology	Optimal Project size range	Typical Capital cost($/kW)	Typical Annual O&M cost($/kW)
Microturbine	1000kW or less	2800	230
Small Internal combustion engine	800kW or less	2400	220
Large Internal Combustion Engine	800kW or greater	1800	180
Gas Turbine	3MW or greater	1400	130

(US EPA, 2015)

For the LFG generation potential and its corresponding energy generation potential, the preferred technology for the Tamale landfill site is the use of an Internal Combustion Engine(large size) (Loening, 2010) because it has an optimal size of 1MW.

Total capital cost

$$\text{Average project capacity} = 1501\ \text{kW}$$

$$\text{total capital cost} = \text{cost per kilowatt} \times \text{project capacity}$$

$$\text{total capital cost} = \left(\frac{\$1800}{\text{kW}}\right) \times 1501\text{kW}$$

$$\text{total capital cost} = \$2{,}701{,}800$$

Typical Annual Operation and Maintenance Cost

$$\text{Annual Operation and Maintenance cost} = \text{cost per kilowatt} \times \text{project capacity}$$

$$\text{Annual Operation and Maintenance cost} = \left(\frac{\$180}{\text{kW}}\right) \times 1501\text{kW}$$

$$\text{Annual Operation and Maintenance cost} = \$270{,}180$$

Total Project Cost

$$(\text{total project cost}) = (\text{total capital cost}) + (\text{Annual Operation \&Maintenance cost})$$

$$\text{total project cost} = \$2{,}701{,}800 + \$270{,}180$$

$$\text{total project cost} = \$2{,}971{,}980.00$$

Using an exchange rate of $1 =₵3.97,

The Total Project Cost = ₵11,798,760.60

ANNUAL CASH FLOW

The cost of electricity to the average consumer is ₵ 0.6 per kilowatt hour.

$$\text{Annual electricity sales} = \text{annual electricity generated } \times \text{cost per kilowatt hour.}$$

Assuming the year of construction of the plant is 2014

For year 2015;

$$\text{Annual electricity sales} = \text{annual electricity generated } \times \text{cost per kilowatt hour.}$$

$$\text{Annual electricity sales} = 6366355 \ \times 0.6$$

$$\text{Annual electricity sales} = ₵3{,}819{,}813.00$$

$\text{Annual project cost} = 270{,}180 \times 3.97 = ₵1{,}072{,}614.60$

$\text{Gross Annual Profit} = \text{Annual Income} - \text{Annual Cost}$

$\text{Gross Annual Profit} = ₵3{,}819{,}813.00 - ₵1{,}072{,}614.00$

$\text{Gross Annual Profit} = ₵2{,}747{,}199$

$\text{Income Tax} = 25\% \text{ ofAnnual profit}$

(Ghana Revenue Authority, 2016)

$\text{Income Tax} = (0.25) \times 2{,}747{,}199$

$\text{Income tax} = ₵686799.75$

$\text{Income after tax deductions} = \text{Annual Profit} - \text{Income Tax}$

$\text{income after tax deductions} = 2{,}747{,}199.00 - 686799.75$

$\text{Income After tax deductions} = ₡2{,}060{,}399.25$

$Cumulative\ Annual\ Cash\ Flow = Income\ in\ 2014 + income\ in\ 2015$

$Cumulative\ Annual\ Cash\ Flow = -11{,}798{,}760.60 + 2{,}060{,}399.25 = -₡9{,}738{,}361.35$

Table 4.6: Cumulative Cash Flow

year	Gross Annual Cost/₡	Gross Annual Profit/₡	Net Profit/₡	Cumulative Annual Cash Flow/₡	Net Present Worth/₡
2006	0.00	0.00	0.00	0.00	0.00
2007	0.00	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00	0.00
2009	0.00	0.00	0.00	0.00	0.00
2010	0.00	0.00	0.00	0.00	0.00
2011	0.00	0.00	0.00	0.00	0.00
2012	0.00	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00	0.00
2014	11798760.6	-11798760.6	-11798760.6	-11798760.6	-3828.9
2015	1072614.6	2747198.2	2060398.6	-9738362.0	-3160.3
2016	1072614.6	3003684.4	2252763.3	-7485598.7	-2429.2
2017	1072614.6	3287651.3	2465738.5	-5019860.2	-1629.0
2018	1072614.6	3608259.1	2706194.3	-2313665.8	-750.8
2019	1072614.6	3965507.8	2974130.8	660465.0	214.3
2020	1072614.6	4341076.9	3255807.7	3916272.7	1270.9
2021	1072614.6	4762447.1	3571835.3	7488108.0	2430.0
2022	1072614.6	5211298.0	3908473.5	11396581.5	3698.4
2023	1072614.6	5696789.8	4272592.4	15669173.9	5084.9
2024	1072614.6	6228082.7	4671062.0	20340236.0	6600.8
2025	1072614.6	6786856.3	5090142.2	25430378.2	8252.6
2026	1072614.6	7400591.2	5550443.4	30980821.6	10053.9
2027	1072614.6	8050967.0	6038225.3	37019046.8	12013.4
2028	1072614.6	8756304.1	6567228.1	43586275.0	14144.6
2029	1072614.6	9507442.4	7130581.8	50716856.7	16458.6
2030	1072614.6	10313542.0	7735156.5	58452013.2	18968.8
2031	1072614.6	11192923.3	8394692.5	66846705.7	21693.0
2032	1072614.6	12127266.0	9095449.5	75942155.2	24644.6
2033	1072614.6	13134890.5	9851167.9	85793323.1	27841.5
2034	1072614.6	14206636.5	10654977.4	96448300.5	31299.3
2035	1072614.6	15369984.8	11527488.6	107975789.1	35040.1
2036	1072614.6	16615775.0	12461831.3	120437620.4	39084.2
2037	1072614.6	17962327.8	13471745.8	133909366.2	43456.1
2038	1072614.6	14802051.0	11101538.2	145010904.4	47058.7
2039	1072614.6	12310470.5	9232852.9	154243757.3	50055.0
2040	1072614.6	10341022.6	7755767.0	161999524.3	52571.9

2041	1072614.6	8774624.6	6580968.4	168580492.7	54707.5
2042	1072614.6	7510513.9	5632885.4	174213378.1	56535.5
2043	1072614.6	6493729.2	4870296.9	179083675.0	58116.0
2044	1072614.6	5669309.2	4251981.9	183335656.9	59495.8
2045	1072614.6	4991452.7	3743589.5	187079246.4	60710.7
2046	1072614.6	6821436.1	5116077.1	192195323.5	62370.9

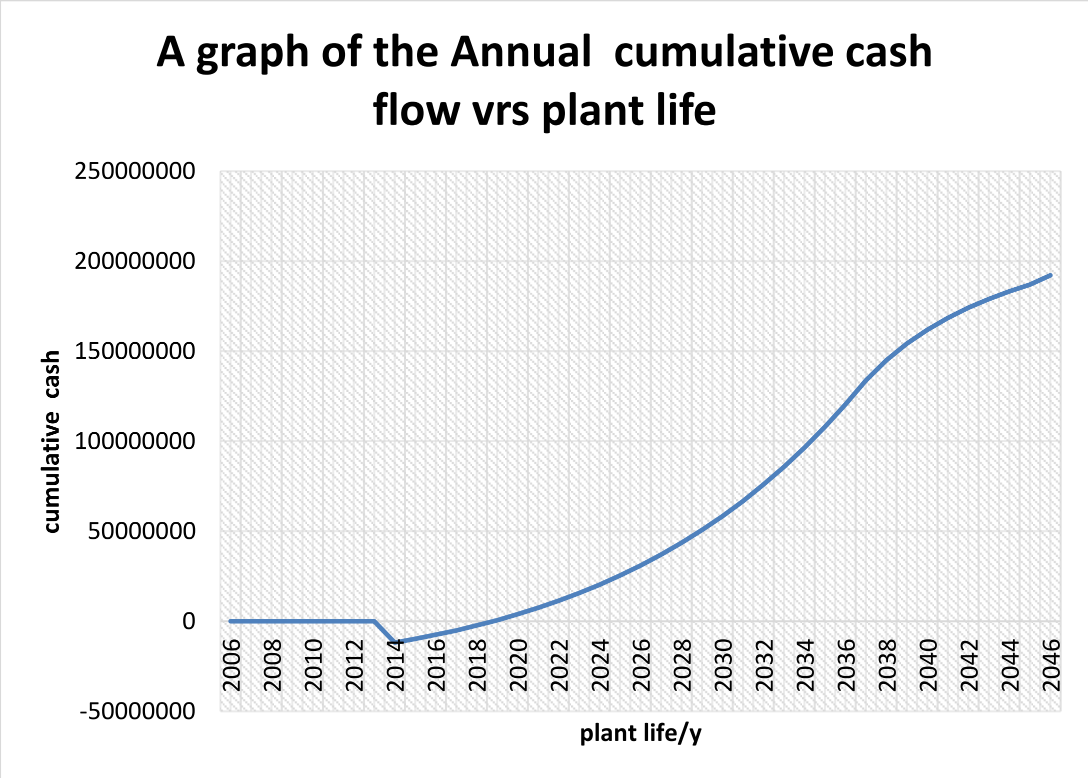


Figure 4.14 The Cumulative Annual Cash Flow against the Plant Life

Payback period;

From the cumulative cash flow, the payback period is the third year after construction that is 2017

Rate of return (ROR)

The Rate of return of the project is given as

$$\text{ROR} = \frac{\text{Cumulative net cash flow at the end of the project}}{\text{project life} \times \text{original investment}} \times 100\%$$

$$\text{ROR} = \frac{181963610.4}{9039690.00 \times 36} \times 100\%$$

$$\text{ROR} = 55.91\%$$

4.6 Environmental Benefits

Environmental benefits to be accrued when using a LFG energy project is determined yearly. The benefits are calculated separately for projects depending on the type of technology in use. The calculations for each type of project are:

- **Methane generated** –The quantity of methane that is produced at the landfill site

$$\left(\text{Methane generated}\left(\frac{\text{ft}^3}{\text{yr}}\right)\right)$$
$$= \left(\text{Annual gas collection}\left(\frac{\text{ft}^3}{\text{yr}}\right)\right) \times (\%\text{ methane in landfill gas})$$

- **Direct methane reduced** – Total yearly quantity of methane (MMTCO2E/yr) that is captured and either flared or used by the LFG energy project

$$(\text{Direct methane reduced}(\text{MMTCO}_2\text{E/yr}))$$
$$= \left(\text{Methane generated}\left(\frac{\text{ft}^3}{\text{yr}}\right)\right) \times \left(\frac{0.0423\text{ lbs methane}}{\text{ft}^3\text{ methane}}\right) \times \left(\frac{\text{short ton}}{2000\text{lbs}}\right)$$
$$\times \left(\frac{0.9072\text{MT}}{\text{short ton}}\right) \times (\text{Global Warming Potential of methane}) \times \left(\frac{\text{MMT}}{10^6\text{MT}}\right)$$

- **Methane used by project** – annual amount of methane (in MMTCO2E/yr) that is consumed by the LFG energy project.

$$(\text{Methane utilised by project }(\text{MMTCO}_2))$$
$$= (\text{actual gas utilisation}(\text{ft}^3/\text{yr})) \times (\%\text{methane in LFG})$$
$$\times \left(\frac{0.0423\text{ lbs methane}}{\text{ft}^3\text{ methane}}\right) \times \left(\frac{\text{short ton}}{2000\text{lbs}}\right) \times \left(\frac{0.9072\text{MT}}{\text{short ton}}\right)$$
$$\times (\text{Global Warming Potential of methane}) \times \left(\frac{\text{MMT}}{10^6\text{MT}}\right)$$

- **Avoided carbon dioxide emissions** – annual carbon dioxide emissions averted due to the usage of LFG as an alternative to fossil fuels (MMTCO2E/yr).

The emission factor of 0.12037 pounds carbon dioxide per cubic foot natural gas. (Energy Information Administration, 2010)

$$(\text{Direct} - \text{use avoided carbon dioxide emissions}(\text{MMTCO}_2\text{E/yr}))$$

$$= (\text{Actual utilisation}(\text{ft}^3/\text{yr})) \times (\%\ \text{methane in LFG}) \times \left(\frac{1012\text{Btu}}{\text{ft}^3\ \text{methane}}\right) \times \left(\frac{\text{ft}^3\text{natural gas}}{1050\text{Btu}}\right) \times \left(\frac{0.12037\text{lbs CO}_2}{\text{ft}^3\text{natural gas}}\right) \times \left(\frac{\text{short ton}}{2000\text{lbs}}\right) \times \left(\frac{0.9072\text{MT}}{\text{short ton}}\right) \times \left(\frac{\text{MMT}}{10^6\text{MT}}\right)$$

The emission factor of 1.18 pounds carbon dioxide per kilowatt-hour represents the estimated average 2014 U.S. power emissions. (Energy Information Administration, 2010)

$$(\text{Electricity generation avoided carbon dioxide emissions}(\text{MMTCO}_2\text{E/yr}))$$

$$= \left(\frac{1.18\text{lbs CO}_2}{\text{kWh}}\right) \times (\text{Net electricity produced}(\text{kWh/yr})) \times \left(\frac{\text{short ton}}{2000\text{lbs}}\right) \times \left(\frac{0.9072\text{MT}}{\text{short ton}}\right) \times \left(\frac{\text{MMT}}{10^6\text{MT}}\right)$$

On the basis of the capacity of the electricity generation project, the following are the potential environmental benefits of LFG utilisation using the landfill gas emission reduction and environmental benefits model developed by the Landfill Methane Outreach Programme (LMOP) of the US EPA.

The input into the model is the estimated electrical energy produced at the landfill site.

For the Tamale Landfill site, the estimated average electricity generation potential is 1.15MW

Direct Equivalent Emissions (DEE) Reduced Calculations for Electricity Generation projects ($MMTCO_2E/yr$)

$$DEE = [(generation\ capacity\ inMW) \times (gross\ capacity\ factor) \times (8760 hours/year) \times (1000kW/MW) \times [\frac{\frac{11{,}700Btu}{kWh}}{\frac{1012Btu}{Scf} methane}] \times (0.0423\ lb\ methane/scf methane) \times$$

$(2000 lb/short\ ton) \times (\frac{0.9072\ metric \frac{tons}{short} ton}{1\times10^6 metric \frac{tons}{million} metrictons}) \times$

$(Global\ warming\ potential\ of\ methane)]$

Gross Capacity Factor (accounts for availability and operating load) = 0.93 (Energy Information Administration, 2010)

Global Warming Potential (GWP) of methane =25 (Intergovernmental Panel on Climate Change (IPCC), 2014)

$$\mathrm{DEE(MMTCO2E/yr)} = 1.15 \times 0.93 \times 8760 \times 1000 \times \left(\frac{11700}{1012}\right) \times \left(\frac{0.0423}{2000}\right) \times \left(\frac{0.9072}{1 \times 10^6}\right) \times 25$$

$$\mathrm{DEE(MMTCO2E/yr)} = 0.0678$$

Direct Equivalent Emissions (DEE) Reduced Calculations for Electricity Generation projects (tons CH_4/yr)

$$\mathrm{DEE}\left(\mathrm{tons}\frac{\mathrm{CH4}}{\mathrm{yr}}\right) = \mathrm{MMTC}O_2E/yr \times (\frac{\mathrm{1E+06\ metric\ tons/million\ metric\ tons}}{\frac{\mathrm{0.9072\ metric\ tons/short\ ton}}{\mathrm{GWP\ of\ methane}}})$$

$$\mathrm{DEE\ (tons\ CH4/yr)} = \frac{0.0678 \times 1 \times 10^6}{0.9072 \times 25}$$

$$\mathrm{DEE} = 2989.42\ \mathrm{(tons\ CH4/yr)}$$

Avoided Equivalent Emissions (AEE) Reduced Calculations for Electricity Generation Projects (MMTCO_2E/yr)

$AEE = \mathrm{megawatts\ (MW)\ of\ generating\ capacity} \times \mathrm{(net\ capacity\ factor)} \times \mathrm{(8{,}760\ hours/year)} \times \mathrm{(1{,}000\ kilowatts/megawatt)} \times \left(\frac{\mathrm{(1.18\ pounds\ carbon\ dioxide/kilowatt-hour)}}{\mathrm{(2{,}000\ pounds/short\ ton)}}\right) \times \left(\frac{\mathrm{(0.9072\ metric\ tons/short\ ton)}}{\mathrm{(1E+06\ metric\ tons/million\ metric\ tons)}}\right)$

Net capacity factor (accounts for availability, operating load and parasitic losses) =0.85 (Energy Information Administration, 2010)

$$AEE = 1.15 \times 0.85 \times 8760 \times 1000 \times \left(\frac{1.18}{2000}\right) \times \left(\frac{0.9072}{1 \times 10^6}\right)$$

$\boldsymbol{AEE = 0.006}$ **MMTCO₂E/yr**

Avoided Equivalent Emissions (AEE) Reduced Calculations for Electricity Generation Projects (tons CO_2/yr)

$$AEE = \frac{\text{MMTCO2E}}{\text{yr}} \times \left(\frac{1E + 06 metric\ tons/million\ metric\ tons}{(0.9072 \text{ metric tons/short tons})}\right)$$

$$AEE\left(tons\,\frac{CO_2}{yr}\right) = 0.0046 \times \frac{1 \times 10^6}{0.9072}$$

$$AEE = 6613\ tons\ CO_2/yr$$

Total Equivalent Emissions (TEE) Reduced= DEE +AEE

Total Equivalent Emissions (TEE) Reduced = 0.0678+0.006

Total Equivalent Emissions (TEE) Reduced = 0.0738 $MMTCO_2E$/yr

Table 4.7 Environmental Benefits

Direct Equivalent Emissions Reduced		Avoided Direct Equivalent Emissions Reduced		Total Direct Equivalent Emissions Reduced		
$MMTCO_2E$/yr	Tons CH_4/yr	$MMTCO_2E$/yr	Tons CO_2/yr	$MMTCO_2E$/yr	Tons CH_4/yr	Tons CO_2/yr
0.0678	2989.42	0.006	6613	0.0738	2989.42	6613

The total emission reductions achievable from the LFG recovery during the 30 year lifespan of the project is estimated as 1476000 tons of CO_2 equivalents. There is therefore the possibility of using the Clean Development Mechanism of Kyoto Protocol, of which Ghana is a signatory to, by selling certified emission reduction. Assuming a cost of 12US$ for each ton of CO_2, the income from the carbon credit will be about 17,712,000 US$

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

This chapter concludes the thesis by highlighting the most important findings from the study as well as providing suggestions for future research.

5.1 Conclusions

The waste deposited at the Tamale landfill site is ~~heterogeneous in nature~~a mixture of different waste components with the average compositions as shown in table 4.5. The high organic content of the waste deposited at the landfill which is about 77% of the total waste means that enough methane gas can be generated from the landfill for the various utilisation options. The slight variations in the composition during the dry and wet season show that seasonality has little effect on the waste generated in the Tamale metropolis.

The moisture content of the waste at the landfill as shown in table 4.11 can provide the ambient conditions for the degradation of organic waste to produce methane all year round.

The estimated average amount of methane gas generated (using the Columbia model) from the landfill during the 30-year lifespan is 921.95 m^3/hr. and the peak methane generation rate is 2222 m^3/h and it is expected to occur in 2037. The average amount of methane gas generated shows that enough gas can be generated for a LFGE project

The average electrical energy generation potential is 1150kW and this amount of energy is capable of supplying about 688 homes in the United States with electricity. Considering the low standard of living of the people living around the Tamale landfill as compared to the standard of living in the united states, it can be concluded that the 1150kW capacity will supply about 1000 homes hence if implemented will help attenuate the current pressure on the country's electricity generating facilities.

With a total project cost of GH₵9,039,690.00, annual cumulative cash flow of GH ₵4,928,325.00 and annual net profit of GH₵3,079,901.25, the project has a rate of return on investment of 55.91% hence it will take three years after construction to break-even. This makes it a very lucrative venture for any investor. It has added societal benefits like job creation in the both temporary and long-term jobs that is from the construction phase to the operation phase.

Table 4.20 gives the total amount of emissions that will be avoided with the implementation of LFGE project. Also the LFG utilisation also improves the quality of surrounding communities by reducing landfill odours.

5.2 Recommendations

The results from this study is useful in understanding the potential benefits of the utilisation of landfill gas. However other factors can adversely affect the amount of landfill gas generated at the landfill. It is therefore recommended that

1. A study on the effects of landfill management methods on the rate of methane generation be carried out
2. The actual experiments be carried out to ascertain the actual amount of methane generated from the landfill

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APPENDICES

APPENDIX A: WASTE COMPOSITION DATA

Table A1: Waste Composition During The Dry Season (Morning Session)

Sample	Waste Composition								
	Food	Plastic	Glass	Paper	Metals	Textiles	Inert	Wood	Total
1	33.8	22.9	1.1	13.2	2.5	7.4	16.5	2.7	100
2	38.6	13.5	0.7	3.2	3.4	5.4	34.9	0.4	100
3	44.5	17.6	1.4	14.7	3.4	4.3	13.3	0.9	100
4	35.3	25.1	1.0	9.1	3.4	9.5	15.8	0.8	100
5	38.8	20.4	1.2	12.5	4.2	6.3	15.6	1.0	100
6	37.1	19.7	3.9	12.2	2.1	6.2	18.7	0.2	100
7	41.8	17.3	2.19	13.2	2.0	4.3	18.3	1.0	100
8	43.8	19.6	0.7	10.7	3.3	9.5	12.1	0.4	100
9	43.7	31.0	0.3	1.3	6.1	2.1	15.3	0.2	100
10	36.5	17.5	11.9	1.0	5.5	9.5	17.8	0.2	100
11	38.3	24.8	1.2	12.5	4.0	6.3	12.0	0.9	100
12	35.7	17.6	2.1	7.6	3.7	4.3	26.5	2.5	100
13	32.1	19.8	4.0	15.2	1.9	11.3	14.7	1.0	100
14	44.7	19.3	2.0	13.2	1.8	2.9	15.9	0.2	100
15	44.9	19.6	0.3	9.1	4.0	9.5	13.0	2.5	100
Average	39.3	20.2	2.3	9.9	3.4	6.6	17.4	1.0	100

Table A2: Waste Characterisation Data During The Dry Season (Afternoon Session)

Sample	Waste Composition								
	Food	Plastic	Glass	Paper	Metals	Textiles	Inert	Wood	Total
1	37.6	15.3	1.1	13.2	5.7	9.5	14.9	2.7	100
2	44.8	13.9	0.7	5.0	5.3	7.4	22.5	0.4	100
3	43.8	15.9	1.7	11.5	2.4	9.5	14.3	1.0	100
4	41.8	16.0	1.0	12.0	5.5	9.3	13.5	0.9	100
5	38.6	13.4	0.7	13.1	3.5	5.4	24.9	0.4	100
6	35.7	20.1	2.5	10.6	3.4	9.5	17.3	0.9	100
7	27.6	19.6	4.0	12.2	1.6	6.3	28.7	0.2	100
8	41.4	17.7	2.1	3.2	2.1	4.4	28.0	1.0	100
9	43.8	16.5	1.2	13.0	3.8	5.4	16.2	0.2	100
10	38.8	18.5	1.0	10.1	1.1	9.5	18.1	2.9	100
11	42.0	14.9	4.0	20.2	1.9	11.3	14.7	1.0	100
12	38.6	23.3	1.1	3.2	2.9	8.0	23.3	0.4	100
13	43.5	14.2	1.1	8.2	1.9	3.4	26.9	0.8	100
14	42.3	20.8	1.2	12.5	4.0	6.3	12.0	0.9	100
15	43.8	16.4	1.1	8.3	2.8	2.8	24.7	0.2	100
Average	40.3	17.1	1.6	10.4	3.2	7.2	20.0	0.9	100

Table A3: Waste Composition During The Wet Season (Morning Session)

Sample	Waste Composition								
	Food	Plastic	Glass	Paper	Metals	Textiles	Inert	Wood	Total
1	52.8	19.9	2.6	5.9	5.3	8.4	5.1	0.0	100
2	48.5	13.3	1.7	7.4	0.7	5.1	23.1	0.2	100
3	42.8	20.2	5.1	10.4	2.4	8.0	10.1	0.9	100
4	44.3	16.1	2.6	5.9	4.2	8.2	18.1	0.6	100
5	51.8	22.5	1.7	9.7	3.6	5.6	5.1	0.0	100
6	44.3	17.6	2.1	8.9	2.7	5.8	17.1	0.8	100
7	48.4	13.3	2.7	10.4	1.3	8.0	15.2	0.7	100
8	42.8	17.1	2.2	8.8	7.4	8.2	12.6	0.9	100
9	41.8	17.9	1.8	5.8	1.3	8.4	23.1	0.0	100
10	42.3	20.5	2.1	6.1	2.2	8.1	18.1	0.6	100
11	51.6	17.6	2.0	10.8	4.1	8.1	5.8	0.0	100
12	44.0	15.7	2.2	8.4	2.6	7.7	18.4	1.1	100
13	43.5	16.6	3.3	8.5	2.8	6.5	18.0	0.9	100
14	49.8	13.1	1.2	6.5	3.5	9.4	16.4	0.1	100
15	48.9	12.7	1.5	7.5	2.1	7.9	19.0	0.3	100
Average	46.51	16.93	2.32	8.05	3.08	7.56	15.03	0.47	100

Table A4: The Table Showing The Waste Composition During The Wet Season (Afternoon Session)

Sample	Waste Composition								
	Food	Plastic	Glass	Paper	Metals	Textiles	Inert	Wood	Total
1	41.8	16.5	1.7	4.9	2.4	8.4	23.4	1.0	100
2	44.2	14.4	5.1	7.3	1.3	4.0	23.2	0.6	100
3	42.2	20.4	5.2	10.2	2.8	8.1	10.1	0.9	100
4	47.5	16.6	10.4	6.2	3.5	12.7	3.0	0.0	100
5	49.7	17.9	2.9	5.9	6.1	12.5	1.3	3.8	100
6	43.1	19.0	2.1	7.4	2.0	8.1	18.1	0.6	100
7	42.0	16.8	1.7	10.4	2.3	8.3	18.4	0.2	100
8	51.7	20.9	1.7	9.9	4.7	1.0	10.1	0.0	100
9	42.8	17.1	2.6	8.4	7.5	8.1	12.6	0.9	100
10	44.3	16.1	2.6	5.8	4.3	7.6	18.8	0.6	100
11	51.6	15.8	1.3	6.2	2.4	8.2	14.5	0.0	100
12	49.4	17.1	1.8	8.5	3.9	7.9	10.7	0.7	100
13	48.4	16.8	1.8	7.4	2.7	8.4	14.6	0.2	100
14	46.8	16.3	1.6	8.5	2.0	9.8	14.3	0.7	100
15	48.4	15.5	1.9	9.3	3.2	7.6	13.4	0.9	100
Average	46.3	17.1	3.0	7.7	3.4	8.0	13.8	0.74	100

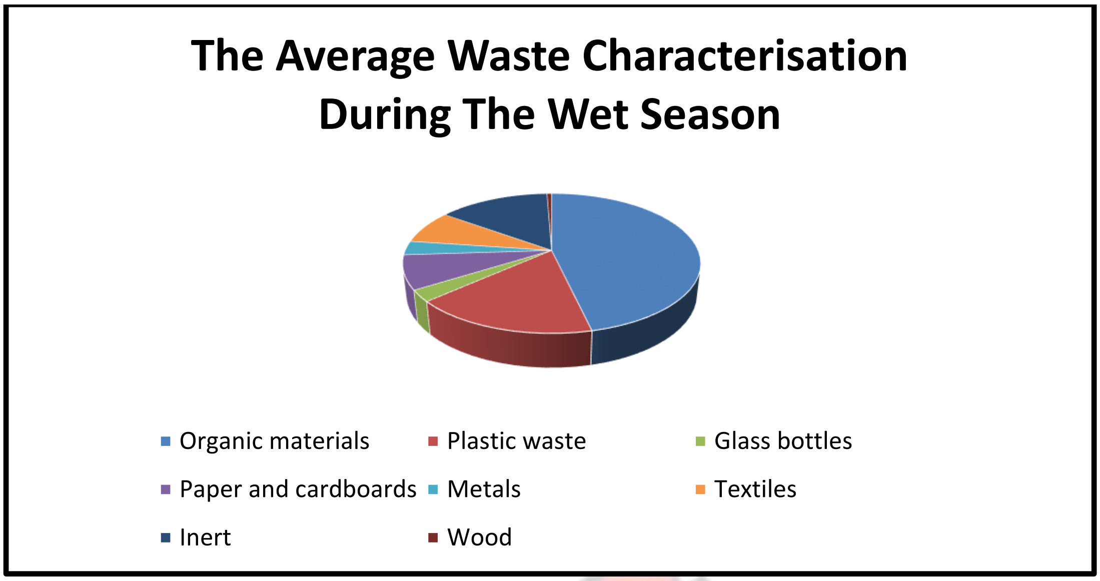

Figure A1: Average Waste Characterisation During the Wet Season

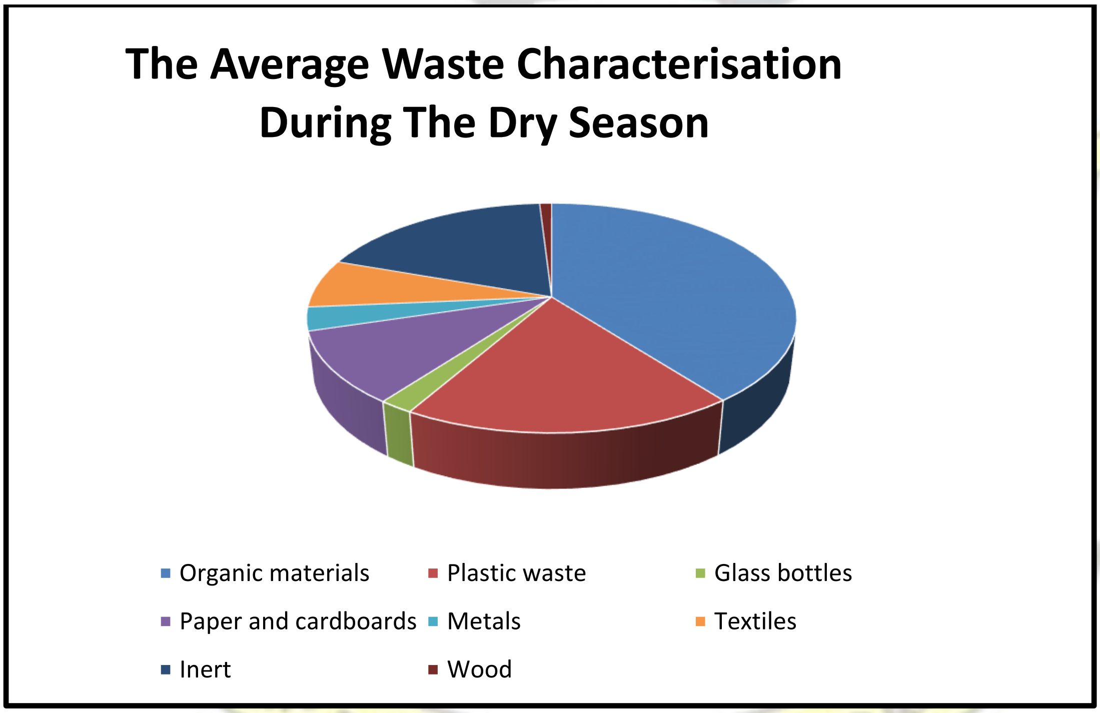

Figure A2: Average Waste Characterisation During the Dry Season

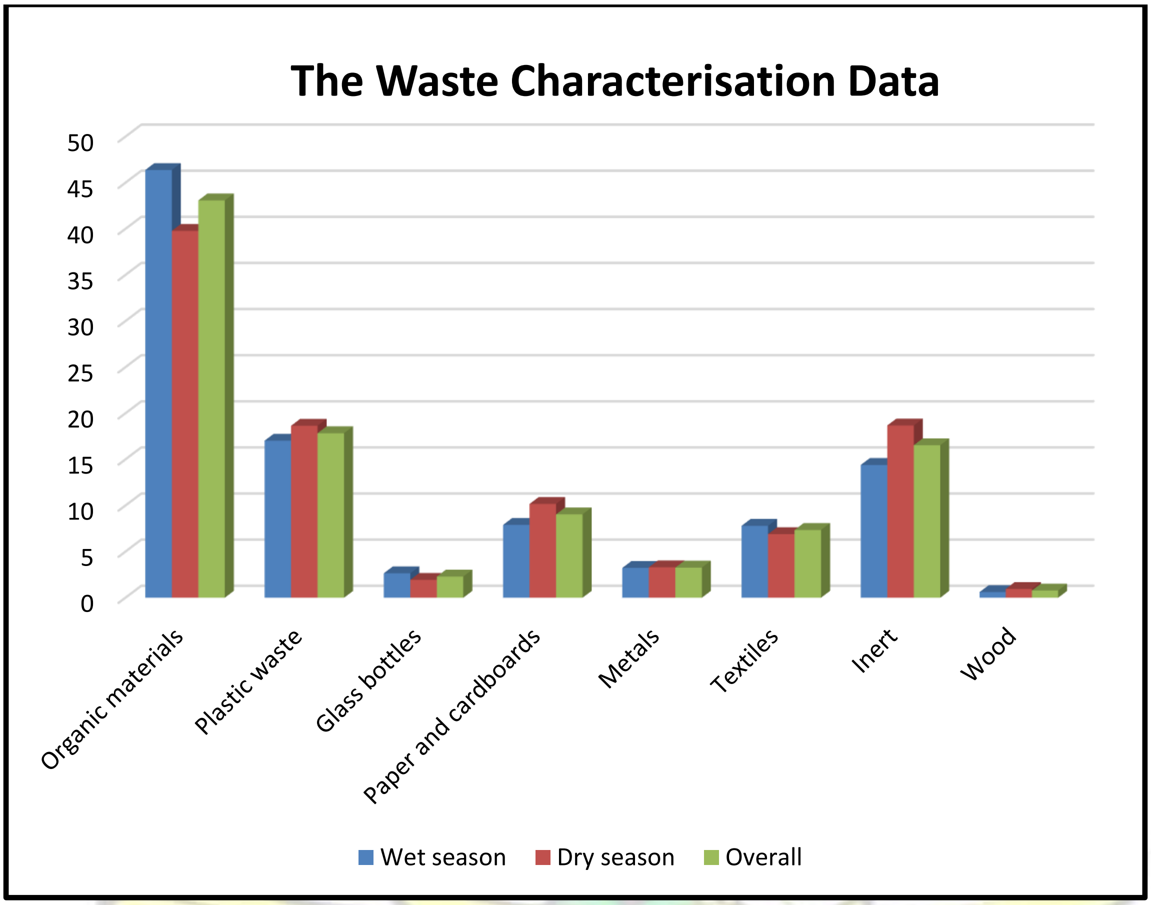

Figure A3: Comparative Analysis of the Various Waste Components

APPENDIX B: MOISTURE CONTENT ANALYSIS

Table B1: Moisture Content Analysis of the Readily Biodegradable Waste Components During the Wet Season

Wet Season					
WORKING PHASE		INITIAL WEIGHT	FINAL WEIGHT	MOISTURE CONTENT	% MOISTURE CONTENT
Sample 1	Paper	51.5	15.1	36.4	70.68
	Food	329.7	104.3	225.4	68.37
	Textiles	46	33.3	12.7	27.61
	Wood	79.6	43.8	35.8	44.97
	Other	170.9	119.7	51.2	29.96
	Total	**677.7**	**316.2**	**361.5**	**53.34**
Sample 2	Paper	43.2	28.5	14.7	34.03
	Food	227.2	42.3	184.9	81.38
	Textiles	43.5	30.4	13.1	30.11
	Wood	77.4	47.2	30.2	39.02
	Other	72.8	37.9	34.9	47.94
	Total	**464.1**	**186.3**	**277.8**	**59.86**
Sample 3	Paper	63.2	41.6	21.6	34.18
	Food	285.3	93.4	191.9	67.26
	Textiles	35.7	28.3	7.4	20.73
	Wood	95.3	65.9	29.4	30.85
	Other	92.6	43.8	48.8	52.70
	Total	**572.1**	**273**	**299.1**	**52.28**
Sample 4	Paper	69.4	51.7	17.7	25.50
	Food	218.5	81.5	137	62.70
	Textiles	78.5	56.3	22.2	28.28
	Wood	87.3	72.5	14.8	16.95
	Other	98.6	80.4	18.2	18.46
	Total	**472.3**	**342.4**	**129.9**	**27.50**
Sample 5	Paper	48.8	11.8	37	75.82
	Food	292.8	126.7	166.1	56.73
	Textiles	72.9	43.4	29.5	40.46
	Wood	126.7	98.2	28.5	22.49
	Other	80.3	55.7	24.6	30.63
	Total	**621.5**	**335.8**	**285.7**	**45.97**
Sample 6	Paper	98.3	77.5	20.8	21.16
	Food	265.2	178.4	86.8	32.73
	Textiles	79.4	45.1	34.3	43.20
	Wood	65.8	43.9	21.9	33.28
	Other	102.5	84.6	17.9	17.46
	Total	**611.2**	**429.5**	**181.7**	**29.73**

Sample7	Paper	67.3	46.4	20.9	31.05
	Food	393.7	185.9	207.8	52.78
	Textiles	98.5	54.6	43.9	44.57
	Wood	95.6	73.8	21.8	22.80
	Other	124.3	95.4	28.9	23.25
	Total	**779.4**	**456.1**	**323.3**	**41.48**
Sample 8	Paper	103.5	87.7	15.8	15.27
	Food	259.5	188.3	71.2	27.44
	Textiles	91	73.4	17.6	19.34
	Wood	75.1	43.9	31.2	41.54
	Other	128.6	82.5	46.1	35.88
	Total	**657.7**	**475.8**	**181.9**	**27.65**
Sample 9	Paper	63.7	54.5	9.2	14.44
	Food	253.3	128.4	124.9	49.31
	Textiles	67.3	43.8	23.5	34.92
	Wood	98.5	71.9	26.6	27.01
	Other	78.5	56.7	21.8	27.77
	Total	**561.3**	**375.3**	**186**	**33.14**
Sample 10	Paper	43.3	17.3	26	60.05
	Food	275.3	160.5	114.8	41.70
	Textiles	75.9	30.5	45.4	59.82
	Wood	118.3	84.9	23.4	21.61
	Other	59	41.5	17.5	29.66
	Total	**571.8**	**334.7**	**237.1**	**41.47**

Table B2: Moisture Content Analysis of the Readily Biodegradable Waste Components During the Dry Season

DRY SEASON					
WORKING PHASE		INITIAL WEIGHT	FINAL WEIGHT	MOISTURE CONTENT	%MOISTURE CONTENT
Sample 1	Paper	36.4	24.5	11.9	32.69
	Food	305	184.8	120.2	39.41
	Textiles	23.6	20.1	3.5	14.83
	Wood	59.5	43.8	15.7	26.39
	Other	170.9	149.7	21.2	12.44
	Total	**595.4**	**422.9**	**172.5**	**28.97**
Sample 2	Paper	43.2	28.5	14.7	34.03
	Food	127.2	72.3	54.9	43.16
	Textiles	42.1	29.5	12.6	29.93
	Wood	97.4	47.2	50.2	51.54
	Other	172.8	137.9	34.9	20.20
	Total	**482.7**	**315.4**	**167.3**	**34.66**
Sample 3	Paper	13.9	12.3	1.6	11.51
	Food	105.6	69.4	36.2	34.28
	Textiles	33.8	30.3	3.5	10.36
	Wood	75.3	65.9	9.4	12.48
	Other	73.5	37.4	36.1	49.16
	Total	**302.1**	**215.3**	**86.8**	**28.73**
Sample 4	Paper	69.4	51.7	17.7	25.50
	Food	93.3	56.5	36.8	39.44
	Textiles	78.5	56.3	22.2	28.28
	Wood	57.3	42.5	14.8	25.83
	Other	92.6	44.7	47.9	51.73
	Total	**391.1**	**251.7**	**139.4**	**35.64**
Sample 5	Paper	61.4	56.3	5.1	8.31
	Food	359.4	232.7	126.7	35.25
	Textiles	198.2	186.4	11.8	5.95
	Wood	126.7	98.2	28.5	22.49
	Other	381.2	298.7	82.5	21.64
	Total	**1126.9**	**872.3**	**254.6**	**22.59**
Sample 6	Paper	98.3	77.5	20.8	21.16
	Food	486.2	259.1	227.1	46.71
	Textiles	79.4	55.1	24.3	30.60
	Wood	65.8	43.9	21.9	33.28
	Other	258	188.6	69.4	26.90
	Total	**987.7**	**624.2**	**363.5**	**36.81**

Sample 7	Paper	57.3	46.4	10.9	19.02
	Food	393.7	275.9	117.8	29.92
	Textiles	94.5	54.6	39.9	42.22
	Wood	95.6	69.8	25.8	26.99
	Other	124.3	105.4	18.9	15.21
	Total	**765.4**	**552.1**	**213.3**	**27.87**
Sample 8	Paper	103.5	87.7	15.8	15.27
	Food	269.5	188.3	81.2	30.13
	Textiles	81	67.4	13.6	16.79
	Wood	75.1	43.9	31.2	41.54
	Other	128.6	82.5	46.1	35.85
	Total	**657.7**	**469.8**	**187.9**	**28.57**
Sample 9	Paper	73.7	58.5	15.2	20.62
	Food	263.3	158.4	104.9	39.84
	Textiles	67.3	43.8	23.5	34.92
	Wood	98.5	71.2	27.3	27.72
	Other	78.5	56.7	21.8	27.77
	Total	**581.3**	**388.6**	**192.7**	**33.15**
Sample10	Paper	43.3	27.3	16	36.95
	Food	278.3	169.5	108.8	39.09
	Textiles	78.9	30.5	48.4	61.3
	Wood	108.3	84.9	23.4	21.61
	Other	259.7	171.5	88.2	33.96
	Total	**768.5**	**483.7**	**284.8**	**37.06**

Table B3: Average Moisture Content Analysis of the Readily Biodegradable Waste Components during the Wet Season

Waste composition	initial weight	final weight	moisture content	% moisture content
Paper	652.2	432.1	220.1	33.75
Food	2500.5	1289.7	1210.8	48.42
Textiles	688.7	439.1	249.6	36.24
Wood	919.6	646	273.6	29.75
Other	1008.1	698.2	309.9	30.74
Total	5769.1	3505.1	2264	39.24

Table B4: Average Moisture Content Analysis Of The Readily Biodegradable Waste Components During The Dry Season

Waste composition	initial weight	final weight	moisture content	% moisture content
Paper	600.4	470.7	129.7	21.60
Food	2681.5	1666.9	1014.6	37.84
Textiles	777.3	574	203.3	26.16
Wood	859.5	611.3	248.2	28.88
Other	1740.1	1273.1	467	26.84
Total	6658.8	4596	2062.8	30.98

APPENDIX C: ESTIMATED LANDFILL GAS GENERATION POTENTIAL

Table C1: The Estimated Landfill Gas Generation Potential Using The Columbia Model

Year	Disposal(Mg/yr)	Refuse In-Place (Mg)	LFG Generation rate(m^3/hr)
2006	57,030	57,030	0
2007	61,310	118,340	69
2008	65,910	184,250	129
2009	70,850	255,100	184
2010	76,160	331,260	234
2011	81,870	413,130	282
2012	88,010	501,140	328
2013	94,610	595,750	374
2014	83,950	679,700	420
2015	90,250	769,950	446
2016	97,020	866,970	475
2017	104,300	971,270	509
2018	112,120	1,083,390	546
2019	120,530	1,203,920	587
2020	129,570	1,333,490	632
2021	139,290	1,472,780	681
2022	149,740	1,622,520	733
2023	160,970	1,783,490	790
2024	173,040	1,956,530	852
2025	186,020	2,142,550	917
2026	199,970	2,342,520	988
2027	214,970	2,557,490	1,065
2028	231,090	2,788,580	1,147
2029	248,420	3,037,000	1,235
2030	267,050	3,304,050	1,329
2031	287,080	3,591,130	1,431
2032	308,610	3,899,740	1,540
2033	331,760	4,231,500	1,658
2034	356,640	4,588,140	1,784
2035	383,390	4,971,530	1,920
2036	412,140	5,383,670	2,065
2037	0	5,383,670	2,222
2038	0	5,383,670	1,855
2039	0	5,383,670	1,565
2040	0	5,383,670	1,336
2041	0	5,383,670	1,153
2042	0	5,383,670	1,006
2043	0	5,383,670	888
2044	0	5,383,670	791
2045	0	5,383,670	712

Table C2: The Estimated Landfill Gas Generation Potential Using The IPCC Model

Year	Methane Emission/ Gg
2006	0
2007	5
2008	9
2009	12
2010	15
2011	18
2012	20
2013	21
2014	23
2015	25
2016	26
2017	28
2018	29
2019	30
2020	30
2021	31
2022	32
2023	33
2024	33
2025	34
2026	34
2027	35
2028	35
2029	35
2030	35
2031	36
2032	36
2033	36
2034	36
2035	36
2036	37
2037	37
2038	37
2039	37
2040	37
2041	37
2042	37
2043	39
2044	40
2045	41
2046	41
2047	42
2048	43
2049	43
2050	43
2051	44

2052	44
2053	44
2054	45
2055	45
2056	36
2057	36
2058	36
2059	36
2060	37
2061	37
2062	37
2063	37
2064	37
2065	38
2066	38
2067	38
2068	38
2069	38
2070	38
2071	38
2072	38
2073	39
2074	39
2075	39
2076	39
2077	39
2078	39
2079	39
2080	39
2081	39
2082	39
2083	39
2084	39
2085	39
2086	39

Table C3: Waste Acceptance Rates Using LandGEM

Year	Waste Accepted		Waste-In-Place	
	(Mg/year)	(Short tons/year)	(Mg)	(short tons)
2006	76318	83950	0	0
2007	76318	83950	76318	83950
2008	76318	83950	152636	
2009	76318	83950	228,954	251,849
2010	76318	83950	305,272	335,799
2011	76318	83950	381,590	419,749
2012	76318	83950	457,908	503,699
2013	76318	83950	534,226	587,649
2014	76318	83950	610,544	671,598
2015	76318	83950	686,862	755,548
2016	76318	83950	763,180	839,498
2017	76318	83950	839,498	923,448
2018	76318	83950	915,816	1,007,398
2019	76318	83950	992,134	1,091,347
2020	76318	83950	1,068,452	1,175,297
2021	76318	83950	1,144,770	1,259,247
2022	76318	83950	1,221,088	1,343,197
2023	76318	83950	1,297,406	1,427,147
2024	76318	83950	1,373,724	1,511,096
2025	76318	83950	1,450,042	1,595,046
2026	76318	83950	1,526,360	1,678,996
2027	76318	83950	1,602,678	1,762,946
2028	76318	83950	1,678,996	1,846,896
2029	76318	83950	1,755,314	1,930,845
2030	76318	83950	1,831,632	2,014,795
2031	76318	83950	1,907,950	2,098,745
2032	76318	83950	1,984,268	2,182,695
2033	76318	83950	2,060,586	2,266,645
2034	76318	83950	2,136,904	2,350,594
2035	76318	83950	2,213,222	2,434,544
2036	0	0	2,289,540	2,518,494
2037	0	0	2,289,540	2,518,494
2038	0	0	2,289,540	2,518,494
2039	0	0	2,289,540	2,518,494
2040	0	0	2,289,540	2,518,494

Table C4: Landfill Gas Generated Using LandGEM

Year	Total Landfill gas			Methane		
	(Mg/year)	(m^3/year)	(short tons/year)	(Mg/year)	(m^3/year)	(short tons/year)
2006	0	0	0	0	0	0
2007	1.584E+03	1.269E+06	1.743E+03	4.232E+02	6.343E+05	4.655E+02
2008	3.091E+03	2.475E+06	3.401E+03	8.258E+02	1.238E+06	9.083E+02
2009	4.525E+03	3.623E+06	4.977E+03	1.209E+03	1.812E+06	1.330E+03
2010	5.889E+03	4.715E+06	6.478E+03	1.573E+03	2.358E+06	1.730E+03
2011	7.186E+03	5.754E+06	7.904E+03	1.919E+03	2.877E+06	2.111E+03
2012	8.420E+03	6.742E+06	9.262E+03	2.249E+03	3.371E+06	2.474E+03
2013	9.593E+03	7.682E+06	1.055E+04	2.563E+03	3.841E+06	2.819E+03
2014	1.071E+04	8.576E+06	1.178E+04	2.861E+03	4.288E+06	3.147E+03
2015	1.177E+04	9.426E+06	1.295E+04	3.144E+03	4.713E+06	3.459E+03
2016	1.278E+04	1.024E+07	1.406E+04	3.414E+03	5.118E+06	3.756E+03
2017	1.374E+04	1.100E+07	1.512E+04	3.671E+03	5.502E+06	4.038E+03
2018	1.466E+04	1.174E+07	1.612E+04	3.915E+03	5.868E+06	4.307E+03
2019	1.553E+04	1.243E+07	1.708E+04	4.147E+03	6.217E+06	4.562E+03
2020	1.635E+04	1.310E+07	1.799E+04	4.368E+03	6.548E+06	4.805E+03
2021	1.714E+04	1.373E+07	1.885E+04	4.578E+03	6.863E+06	5.036E+03
2022	1.789E+04	1.432E+07	1.968E+04	4.778E+03	7.162E+06	5.256E+03
2023	1.860E+04	1.489E+07	2.046E+04	4.968E+03	7.447E+06	5.465E+03
2024	1.928E+04	1.544E+07	2.121E+04	5.149E+03	7.718E+06	5.664E+03
2025	1.992E+04	1.595E+07	2.191E+04	5.321E+03	7.976E+06	5.854E+03
2026	2.053E+04	1.644E+07	2.259E+04	5.485E+03	8.222E+06	6.034E+03
2027	2.112E+04	1.691E+07	2.323E+04	5.641E+03	8.455E+06	6.205E+03
2028	2.167E+04	1.735E+07	2.384E+04	5.789E+03	8.677E+06	6.368E+03
2029	2.220E+04	1.778E+07	2.442E+04	5.930E+03	8.888E+06	6.523E+03
2030	2.270E+04	1.818E+07	2.497E+04	6.064E+03	9.089E+06	6.670E+03
2031	2.318E+04	1.856E+07	2.550E+04	6.191E+03	9.280E+06	6.810E+03
2032	2.363E+04	1.892E+07	2.600E+04	6.312E+03	9.462E+06	6.944E+03
2033	2.406E+04	1.927E+07	2.647E+04	6.428E+03	9.635E+06	7.071E+03
2034	2.447E+04	1.960E+07	2.692E+04	6.537E+03	9.799E+06	7.191E+03
2035	2.487E+04	1.991E+07	2.735E+04	6.642E+03	9.956E+06	7.306E+03
2036	2.524E+04	2.021E+07	2.776E+04	6.741E+03	1.010E+07	7.415E+03
2037	2.401E+04	1.922E+07	2.641E+04	6.412E+03	9.612E+06	7.054E+03
2038	2.284E+04	1.829E+07	2.512E+04	6.100E+03	9.143E+06	6.710E+03
2039	2.172E+04	1.739E+07	2.389E+04	5.802E+03	8.697E+06	6.382E+03
2040	2.066E+04	1.655E+07	2.273E+04	5.519E+03	8.273E+06	6.071E+03

Table C5: Landfill Gas Generated Using LandGEM

Year	Carbon dioxide			NMOC		
	(Mg/year)	*(m^3/year)*	*(short tons/year)*	*(Mg/year)*	*(m^3/year)*	*(short tons/year)*
2006	0	0	0	0	0	0
2007	1.161E+03	6.343E+05	1.277E+03	1.819E+01	5.075E+03	2.001E+01
2008	2.266E+03	1.238E+06	2.492E+03	3.549E+01	9.902E+03	3.904E+01
2009	3.316E+03	1.812E+06	3.648E+03	5.195E+01	1.449E+04	5.715E+01
2010	4.316E+03	2.358E+06	4.747E+03	6.761E+01	1.886E+04	7.437E+01
2011	5.266E+03	2.877E+06	5.793E+03	8.250E+01	2.302E+04	9.075E+01
2012	6.171E+03	3.371E+06	6.788E+03	9.667E+01	2.697E+04	1.063E+02
2013	7.031E+03	3.841E+06	7.734E+03	1.101E+02	3.073E+04	1.212E+02
2014	7.849E+03	4.288E+06	8.634E+03	1.230E+02	3.430E+04	1.353E+02
2015	8.628E+03	4.713E+06	9.490E+03	1.352E+02	3.771E+04	1.487E+02
2016	9.368E+03	5.118E+06	1.030E+04	1.468E+02	4.094E+04	1.614E+02
2017	1.007E+04	5.502E+06	1.108E+04	1.578E+02	4.402E+04	1.736E+02
2018	1.074E+04	5.868E+06	1.182E+04	1.683E+02	4.695E+04	1.851E+02
2019	1.138E+04	6.217E+06	1.252E+04	1.783E+02	4.973E+04	1.961E+02
2020	1.199E+04	6.548E+06	1.318E+04	1.878E+02	5.238E+04	2.065E+02
2021	1.256E+04	6.863E+06	1.382E+04	1.968E+02	5.490E+04	2.165E+02
2022	1.311E+04	7.162E+06	1.442E+04	2.054E+02	5.730E+04	2.259E+02
2023	1.363E+04	7.447E+06	1.500E+04	2.136E+02	5.958E+04	2.349E+02
2024	1.413E+04	7.718E+06	1.554E+04	2.213E+02	6.175E+04	2.435E+02
2025	1.460E+04	7.976E+06	1.606E+04	2.287E+02	6.381E+04	2.516E+02
2026	1.505E+04	8.222E+06	1.655E+04	2.358E+02	6.577E+04	2.593E+02
2027	1.548E+04	8.455E+06	1.702E+04	2.425E+02	6.764E+04	2.667E+02
2028	1.588E+04	8.677E+06	1.747E+04	2.488E+02	6.942E+04	2.737E+02
2029	1.627E+04	8.888E+06	1.790E+04	2.549E+02	7.111E+04	2.804E+02
2030	1.664E+04	9.089E+06	1.830E+04	2.606E+02	7.271E+04	2.867E+02
2031	1.699E+04	9.280E+06	1.869E+04	2.661E+02	7.424E+04	2.927E+02
2032	1.732E+04	9.462E+06	1.905E+04	2.713E+02	7.569E+04	2.985E+02
2033	1.764E+04	9.635E+06	1.940E+04	2.763E+02	7.708E+04	3.039E+02
2034	1.794E+04	9.799E+06	1.973E+04	2.810E+02	7.839E+04	3.091E+02
2035	1.822E+04	9.956E+06	2.005E+04	2.855E+02	7.964E+04	3.140E+02
2036	1.850E+04	1.010E+07	2.035E+04	2.898E+02	8.083E+04	3.187E+02
2037	1.759E+04	9.612E+06	1.935E+04	2.756E+02	7.689E+04	3.032E+02
2038	1.674E+04	9.143E+06	1.841E+04	2.622E+02	7.314E+04	2.884E+02
2039	1.592E+04	8.697E+06	1.751E+04	2.494E+02	6.958E+04	2.743E+02
2040	1.514E+04	8.273E+06	1.666E+04	2.372E+02	6.618E+04	2.610E+02

APPENDIX D: ESTIMATED ENERGY GENERATION POTENTIAL

Table D1: The Energy Generation Potential Using The Columbia Model

Year	Annual Volumetric flow rate m^3/yr of CH4	Annual Mass flow rate Kg/yr of CH4	Thermal Energy Generation J/yr	Electrical Power J/yr	Electrical Power W(J/s)	Electrical Energy Wh	Electrical Energy KWh
2006	0.00E+00	0	0	0	0	0	0
2007	604440	408601.4	1.149E+13	3.79E+12	120254.1	1.05E+09	1053426
2008	1130040	763907	2.148E+13	7.09E+12	224822.8	1.97E+09	1969448
2009	1611840	1089604	3.065E+13	1.01E+13	320677.5	2.81E+09	2809135
2010	2049840	1385692	3.897E+13	1.29E+13	407818.1	3.57E+09	3572487
2011	2470320	1669936	4.697E+13	1.55E+13	491473.1	4.31E+09	4305305
2012	2873280	1942337	5.463E+13	1.8E+13	571642.5	5.01E+09	5007588
2013	3276240	2214738	6.229E+13	2.06E+13	651811.9	5.71E+09	5709872
2014	3679200	2487139	6.995E+13	2.31E+13	731981.3	6.41E+09	6412156
2015	3906960	2641105	7.428E+13	2.45E+13	777294.4	6.81E+09	6809099
2016	4161000	2812836	7.911E+13	2.61E+13	827835.9	7.25E+09	7251843
2017	4458840	3014176	8.477E+13	2.8E+13	887091.6	7.77E+09	7770922
2018	4782960	3233281	9.094E+13	3E+13	951575.6	8.34E+09	8335802
2019	5142120	3476073	9.776E+13	3.23E+13	1023031	8.96E+09	8961751
2020	5536320	3742552	1.053E+14	3.47E+13	1101458	9.65E+09	9648768
2021	5965560	4032719	1.134E+14	3.74E+13	1186855	1.04E+10	10396853
2022	6421080	4340650	1.221E+14	4.03E+13	1277482	1.12E+10	11190738
2023	6920400	4678190	1.316E+14	4.34E+13	1376822	1.21E+10	12060960
2024	7463520	5045340	1.419E+14	4.68E+13	1484876	1.3E+10	13007516
2025	8032920	5430254	1.527E+14	5.04E+13	1598159	1.4E+10	13999873
2026	8654880	5850699	1.646E+14	5.43E+13	1721899	1.51E+10	15083833
2027	9329400	6306674	1.774E+14	5.85E+13	1856095	1.63E+10	16259395
2028	10047720	6792259	1.91E+14	6.3E+13	1999006	1.75E+10	17511292
2029	10818600	7313374	2.057E+14	6.79E+13	2152373	1.89E+10	18854791
2030	11642040	7870019	2.213E+14	7.3E+13	2316198	2.03E+10	20289893
2031	12535560	8474039	2.383E+14	7.86E+13	2493965	2.18E+10	21847131
2032	13490400	9119510	2.565E+14	8.46E+13	2683931	2.35E+10	23511238
2033	14524080	9818278	2.761E+14	9.11E+13	2889583	2.53E+10	25312748
2034	15627840	10564420	2.971E+14	9.81E+13	3109178	2.72E+10	27236395
2035	16819200	11369779	3.198E+14	1.06E+14	3346200	2.93E+10	29312712
2036	18089400	12228434	3.439E+14	1.13E+14	3598908	3.15E+10	31526432
2037	19464720	13158151	3.701E+14	1.22E+14	3872529	3.39E+10	33923357
2038	16249800	10984865	3.089E+14	1.02E+14	3232917	2.83E+10	28320355
2039	13709400	9267554	2.606E+14	8.6E+13	2727502	2.39E+10	23892914
2040	11703360	7911471	2.225E+14	7.34E+13	2328398	2.04E+10	20396762
2041	10100280	6827789	1.92E+14	6.34E+13	2009463	1.76E+10	17602894
2042	8812560	5957291	1.675E+14	5.53E+13	1753269	1.54E+10	15358640
2043	7778880	5258523	1.479E+14	4.88E+13	1547618	1.36E+10	13557129
2044	6929160	4684112	1.317E+14	4.35E+13	1378565	1.21E+10	12076227
2045	6237120	4216293	1.186E+14	3.91E+13	1240883	1.09E+10	10870131

Table D2: Annual Electricity Generation Potential using the LandGEM Model

Year	Annual Volumetric flow rate m^3/yr of CH4	Annual Mass flow rate Kg/yr of CH4	Thermal Energy Generation J/yr	Electrical Power J/yr	Electrical Power W(J/s)	Electrical Energy Wh	Electrical Energy KWh
2006	0.00E+00	0	0	0	0	0	0
2007	6.34E+05	428786.8	1.206E+13	3.98E+12	126194.7	1.11E+09	1105466
2008	1.24E+06	836888	2.354E+13	7.77E+12	246301.6	2.16E+09	2157602
2009	1.81E+06	1224912	3.445E+13	1.14E+13	360499.6	3.16E+09	3157976
2010	2.36E+06	1594008	4.483E+13	1.48E+13	469126.9	4.11E+09	4109552
2011	2.88E+06	1944852	5.47E+13	1.81E+13	572382.6	5.01E+09	5014072
2012	3.37E+06	2278796	6.409E+13	2.12E+13	670664.5	5.88E+09	5875021
2013	3.84E+06	2596516	7.303E+13	2.41E+13	764171.6	6.69E+09	6694143
2014	4.29E+06	2898688	8.153E+13	2.69E+13	853102.7	7.47E+09	7473180
2015	4.71E+06	3185988	8.961E+13	2.96E+13	937657	8.21E+09	8213875
2016	5.12E+06	3459768	9.731E+13	3.21E+13	1018232	8.92E+09	8919714
2017	5.50E+06	3719352	1.046E+14	3.45E+13	1094629	9.59E+09	9588954
2018	5.87E+06	3966768	1.116E+14	3.68E+13	1167446	1.02E+10	10226824
2019	6.22E+06	4202692	1.182E+14	3.9E+13	1236880	1.08E+10	10835065
2020	6.55E+06	4426448	1.245E+14	4.11E+13	1302732	1.14E+10	11411936
2021	6.86E+06	4639388	1.305E+14	4.31E+13	1365402	1.2E+10	11960922
2022	7.16E+06	4841512	1.362E+14	4.49E+13	1424888	1.25E+10	12482023
2023	7.45E+06	5034172	1.416E+14	4.67E+13	1481590	1.3E+10	12978725
2024	7.72E+06	5217368	1.467E+14	4.84E+13	1535505	1.35E+10	13451027
2025	7.98E+06	5391776	1.516E+14	5E+13	1586835	1.39E+10	13900673
2026	8.22E+06	5558072	1.563E+14	5.16E+13	1635777	1.43E+10	14329404
2027	8.46E+06	5715580	1.608E+14	5.3E+13	1682132	1.47E+10	14735480
2028	8.68E+06	5865652	1.65E+14	5.44E+13	1726300	1.51E+10	15122384
2029	8.89E+06	6008288	1.69E+14	5.58E+13	1768278	1.55E+10	15490118
2030	9.09E+06	6144164	1.728E+14	5.7E+13	1808267	1.58E+10	15840423
2031	9.21E+06	6224608	1.751E+14	5.78E+13	1831943	1.6E+10	16047818
2032	9.46E+06	6396312	1.799E+14	5.94E+13	1882476	1.65E+10	16490492
3033	9.64E+06	6513260	1.832E+14	6.05E+13	1916895	1.68E+10	16791998
2034	9.80E+06	6624124	1.863E+14	6.15E+13	1949523	1.71E+10	17077820
2035	9.96E+06	6730256	1.893E+14	6.25E+13	1980758	1.74E+10	17351441
2036	1.01E+07	6827600	1.92E+14	6.34E+13	2009407	1.76E+10	17602406
2037	9.61E+06	6497712	1.827E+14	6.03E+13	1912319	1.68E+10	16751914
2038	9.14E+06	6180668	1.738E+14	5.74E+13	1819011	1.59E+10	15934535
2039	8.70E+06	5879172	1.654E+14	5.46E+13	1730279	1.52E+10	15157240
2040	8.27E+06	5592548	1.573E+14	5.19E+13	1645923	1.44E+10	14418288
2041	7.87E+06	5319444	1.496E+14	4.94E+13	1565547	1.37E+10	13714192
2042	7.49E+06	5060536	1.423E+14	4.7E+13	1489349	1.3E+10	13046694
2043	7.12E+06	4813120	1.354E+14	4.47E+13	1416533	1.24E+10	12408825
2044	6.77E+06	4578548	1.288E+14	4.25E+13	1347496	1.18E+10	11804069

2045	6.44E+06	4355468	1.225E+14	4.04E+13	1281843	1.12E+10	11228941
2046	6.13E+06	4143204	1.165E+14	3.85E+13	1219372	1.07E+10	10681698
2046	5.83E+06	3941080	1.108E+14	3.66E+13	1159885	1.02E+10	10160597
2048	5.55E+06	3748420	1.054E+14	3.48E+13	1103184	9.66E+09	9663895
2049	5.28E+06	3565900	1.003E+14	3.31E+13	1049468	9.19E+09	9193336
2050	5.02E+06	3392168	9.54E+13	3.15E+13	998337.1	8.75E+09	8745433
2051	4.77E+06	3226548	9.075E+13	2.99E+13	949594.1	8.32E+09	8318444
2052	4.54E+06	3069040	8.632E+13	2.85E+13	903238.4	7.91E+09	7912369
2053	4.32E+06	2919644	8.211E+13	2.71E+13	859270.2	7.53E+09	7527207
2054	4.11E+06	2777008	7.81E+13	2.58E+13	817291.5	7.16E+09	7159474
2055	3.91E+06	2641808	7.43E+13	2.45E+13	777501.3	6.81E+09	6810911
2056	3.72E+06	2512692	7.067E+13	2.33E+13	739501.6	6.48E+09	6478034
2057	3.54E+06	2390336	6.723E+13	2.22E+13	703491.4	6.16E+09	6162585
2058	3.36E+06	2273388	6.394E+13	2.11E+13	669072.9	5.86E+09	5861078
2059	3.20E+06	2162524	6.082E+13	2.01E+13	636444.9	5.58E+09	5575257
2060	3.04E+06	2057068	5.786E+13	1.91E+13	605408.5	5.3E+09	5303378
2061	2.90E+06	1957020	5.504E+13	1.82E+13	575963.7	5.05E+09	5045442
2062	2.75E+06	1861704	5.236E+13	1.73E+13	547911.6	4.8E+09	4799706
2063	2.62E+06	1770444	4.979E+13	1.64E+13	521053.2	4.56E+09	4564426
2064	2.49E+06	1684592	4.738E+13	1.56E+13	495786.4	4.34E+09	4343089

APPENDIX E: SAMPLE CALCULATIONS

Determination of the Number of Samples

$$\boldsymbol{n} = \left(\frac{\boldsymbol{t}^{*}\boldsymbol{s}}{\boldsymbol{e}.\,\overline{\boldsymbol{x}}}\right)^{2}$$

Using food waste the governing component,

S= 00.3

e= 10%

x^{-}=0.1

t^{*}(n=∞) =1.645

$$n = \left(\frac{1.645 * 0.03}{0.1 * 0.1}\right)^{2} = 24.35$$

For n=24.35, $t^{*} = 1.714$ then

$$n = \left(\frac{1.714 * 0.03}{0.1 * 0.1}\right)^{2} = 26.44$$

Hence the number of required sample attained = 26 samples

Moisture content calculations

$\text{weight of wet waste} = (\text{weight of empty can} + \text{wet waste}) - (\text{weight of empty can})$

$\text{weight of wet food waste} = 379.7\text{g} - 50\text{g}$

$\text{weight of wet food waste} = 329.7\text{g}$

$\text{weight of dry waste} = (\text{weight of empty can} + \text{dry waste}) - (\text{weight of empty can})$

$\text{weight of dry food waste} = 154.3\text{g} - 50.0\text{g}$

$\text{weight of dry food waste} = 104.3\text{g}$

$\text{weight of moisture} = \text{weight of wet waste} - \text{weight of dry waste}$

$\text{weight of moisture} = 329.7\text{g} - 104.3\text{g}$

$\text{weight of moisture} = 225.4\text{g}$

$$\text{moisture content(wet wt basis)\%} = \frac{\text{weight of moisture}}{\text{weight of wet waste}} \times 100\%$$

$$moisture\ content\ (wet\ basis)\% = \frac{225.4}{329.7} \times 100\%$$

$$mositure\ content\ (wet\ basis)\% = 68.37\%$$

Estimated Methane Generation Rate Using the Columbia GMI model

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} 2kL_o \left(\frac{M_i}{10}\right) \left(e^{-kt_{ij}}\right) (MCF)(F)$$

i = 1-year time increment =1

n=year of calculation – initial year of waste acceptance = 2014-2006 =8

j= 0.1-year time increment

k= methane generation rate = 0.260 year^{-1}

L_0 = Potential Methane Generation Capacity = 47 m^3/Mg

M_i = mass of solid waste disposed of in the ith year = 83950 Mg

t_{ij} = age of the jth section of waste mass disposed in the ith year

MCF= Methane correction factor = 0.8

F= fire factor =2/3

$$Q_{CH_4} = 2kL_o \left(\frac{M_i}{10}\right) (e^{-kt_{1,0.1}})(MCF)(F) + 2kL_o \left(\frac{M_i}{10}\right) (e^{-kt_{1,0.2}})(MCF)(F) + \cdots$$

$$+ 2kL_o \left(\frac{M_i}{10}\right) (e^{-kt_{1,0.9}})(MCF)(F)$$

$$Q_{CH_4} = \sum_{i=1}^{8} \sum_{j=0.1}^{1} 2 \times 0.260 \times 47 \left(\frac{83950}{10}\right) \left(e^{-0.260t_{1,0.1}}\right) (0.8) \left(\frac{2}{3}\right)$$

$$Q_{CH_4} = 420m^3/hr$$

$$Q_{CH_4} = 3.679 \times 10^6 m^3/yr$$

Estimated Methane Generation Rate Using the LANDGEM

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_o \left(\frac{M_i}{10}\right) \left(e^{-kt_{ij}}\right)$$

i = 1-year time increment =1

n=year of calculation – initial year of waste acceptance = 2014-2006 =8

j= 0.1 year time increment

k= methane generation rate = 0.050 year^{-1}

L_0 = Potential Methane Generation Capacity = 170 m^3/Mg

M_i = mass of solid waste disposed of in the ith year = 83950 Mg

t_{ij} = age of the jth section of waste mass disposed in the ith year

$$Q_{CH_4} = kL_o\left(\frac{M_i}{10}\right)(e^{-kt_{1,0.1}}) + \ kL_o\left(\frac{M_i}{10}\right)(e^{-kt_{1,0.2}}) + \cdots + kL_o\left(\frac{M_i}{10}\right)(e^{-kt_{1,0.9}})$$

$$Q_{CH_4} = \sum_{i=1}^{8}\sum_{j=0.1}^{1} 0.050 \times 170\left(\frac{83950}{10}\right)(e^{-0.260t_{1,0.1}})$$

$$Q_{CH_4} = 489.5m^3/hr$$

$$Q_{CH_4} = 4.288 \times 10^6 m^3/yr$$