EVALUATION OF THEORETICAL MODELS TO ESTIMATE LANDFILL GAS (LFG) POTENTIAL AS A RENEWABLE ENERGY SOURCE: A CASE STUDY OF CHUNGA LANDFILL

by

PATRICK SIPATELA

A dissertation submitted to the University of Zambia in partial fulfilment
of the requirements for the degree of
Master of Engineering in Environmental Engineering

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LUSAKA

2017

DECLARATION

I declare that the contents of this dissertation are entirely my own work, except for the specific and acknowledged references to the published work of others made in the text.

To the best of my knowledge and belief, it contains neither material previously published by another person nor material to which a substantial extent has been accepted for the award of any other degree of this or any other university.

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ABSTRACT

According to the World Bank, Zambia generates approximately 0.9 kg of solid waste per person per day. The strategies in place for Municipal solid waste (MSW) management include a combination of three techniques: recycling, combustion, and landfill disposal. In Lusaka, at least 22.5 % of the waste generated is disposed at Chunga landfill. Landfills pose as environmental threats due to uncollected landfill gas (LFG) emissions generated by biochemical processes arising from the disposed waste but if properly managed, methane in LFG can be a valuable energy resource.Currently no landfill gas to energy (LFGTE) project exists in Zambia for utilization of LFG and little information is available on the potential of electricity generation from the gas. With the electricity demand in Lusaka increasing at 10 % per annum coupled with electricity deficits, exploiting LFG will not only provide a segment of the needed energy, but also help curb the environmental problems.The main objective of this study therefore was to, "investigate the energy potential of LFG and the feasibility of LFGTE project at Chunga landfill by applying appropriate LFG estimation models". A mixed method research approach was used in conducting this study. Secondary data was collected by literature review while primary data through interviews, surveys and manipulation of pre-existing data using analytical and numerical methods was collected. Three LFG estimation models namely, LandGEM, Afvalzorg and IPCC were used to estimate methane generation based on site specific data and waste acceptance history for the landfill considering both conventional and bioreactor operations of the landfill. The electricity generation potential was then estimated based on the results. Peak LFG flows were used to design the gas collection system for the purpose of conducting cost analysis using LFG-Cost WEB model. The study revealed that installation of a microturbine operating as a bioreactor landfill provides an estimated average annual energy of 19.2 million kWh capable of powering at least 3500 residential houses with a consumption band between 100-300 kWh per month. The model estimated a capital cost of US$ 4.71 million (K 45 million) at US$ 0.094 (K 0.89) per kWh to achieve an investment payback period of 5 years.

DEDICATION

I dedicate my dissertation work to my son,

Aiden

and beautiful wife,

Margaret,

who have been a constant source of encouragement during the challenges of graduate school life. I am truly thankful for having you in my life.

This work is also dedicated to my parents, Anastasia and John Chikumbi who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

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I would like to thank the participants involved in this research, especially those who took part in the interview process. Their involvement was essential to this research, and I am very grateful they took the time out of their busy schedules to be involved.

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ABBREVIATIONS

BMP	Biochemical Methane Potential
CSO	Central Statistics Office
CAD	Computer Aided Design
DDOCm	Decomposable Degradable Organic Carbon Matter
DOC	Degradable Organic Carbon
DoE	Department of Energy
EMA	Environmental Management Act
EPA	Environmental Protection Agency
EPRTR	European Pollutant Release and Transfer Register
FOD	First-order Decay
GWP	Global Warming Potential
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
kWh	Kilowatt Hour
LFG	Landfill Gas
LFGTE	Landfill Gas to Energy
LCC	Lusaka City Council
MCF	Methane Correction Factor
MCA	Millennium Challenge Account:
$mtCO_2e$	Million Metric tTns of Carbon Dioxide Emissions
MSW	Municipal Solid Waste
NPV	Net Present Value
NMOCs	Non-Methane Organic Compounds
PRTR	Pollutants Release and Transfer Registers
PPP	Public Private Partnership
LandGEM	The Landfill Gas Emission Model
UNFCCC	United Nations Framework Convention on Climate Change
WMU	Waste Management Unit
WtE	Waste to Energy
ZEMA	Zambia Environmental Management Agency

CHAPTER ONE: INTRODUCTION

1.1 Introduction

This chapter introduces the research topic and gives an overview of the whole research process. It begins by giving a background of the research, its contextual setting and a detailed articulation of the research problem. The objectives for the research are outlined thereafter together with a brief explanation of the methodological approach used. It ends with a brief description of the overall layout of the dissertation and a brief summary.

1.2 Background

Zambia's population is growing rapidly at an average rate of 2.7 % per annum. The country's total population is projected to grow from 13.7 million recorded in 2011 to 17.9 million in 2020 and further rise to 26.9 million by 2035 (Central Statistics Office, 2013). The urbanization rate is gradually increasing and in the next 25 years, the total population living in urban areas will rise from 40.6 % recorded in 2011 to 46.1 % by 2035 (Central Statistics Office, 2013). Urbanization and population increase have inflicted pressure on available resources and services such as municipal solid waste management services, increased demand for health care, water supply and electricity. The growth rate of electricity demand has been estimated at 5.7 % per annum up to 2020 and 4.4 % up to 2030 (Department of Energy, 2010). Exclusively, the demand for electricity in Zambia's capital, Lusaka, has been increasing at a rate of 10 % per annum since 1994 with an overall increase of over 100 % between 1994 to 2004 (LCC and ECZ, 2008).

With the current levels of industrialization and urbanization, there is need to explore the different renewable energy options in order to meet the current and future energy needs of the country in a sustainable, environmentally friendly and cost effective manner. Deployment of biomass for electrical energy production is one of the available options that can be explored since biomass is widely available in the country including; industrial/municipal organic wastes, agricultural waste, forestry waste, energy crops and products and animal waste (Department of Energy, 2010). In most urban centers in Zambia, tonnes of waste are produced each year with the majority coming from agricultural, mining and domestic waste. Less than 14 % of this waste is produced in Lusaka alone and disposed off by dumping or incineration as these are the most prominent waste disposal methods in Zambia (Chifungula, 2010). Municipal Solid Waste (MSW) at a global level has become increasingly acknowledged as an essential negative contributor to the local environment and human health. A typical MSW content is assumed to include all waste that are generated in a community with the exception of industrial waste and agricultural solid waste (Tchobanoglous, et al., 1993). Managing high quantities of wastes from multiple sources is a challenge in developing countries, where 20 % to 50 % of the available budget for municipalities is spent on solid waste management (Scarlet, et al., 2015). Numerous suggestions have been made on methods of managing MSW from simple methods such as dumping to more complex solutions such as sending waste into space. Overtime, different waste management methods have been applied and only a few solutions remain viable, including landfilling, incineration and recycling. These solutions to waste management are being utilized to different extents. Sanitary landfilling is the common method for the disposal of solid waste and "Kamalan (2009)" recognized it as an imperative source of methane gas which is the major element of greenhouse gases. Furthermore, landfilling is the most favourable solution worldwide and is the broadly used waste disposal alternative owing to its economic advantages (Amini, 2011; Surroop, et al., 2011). However, landfills continue to be key distresses for environmental regulating and protecting organizations due to their impending probability to generate odours, leachate, and landfill gas (Amini, 2011).

Landfills are significant in this context as Landfill Gas (LFG) is emitted from decomposing organic wastes. LFG is produced in landfills through anaerobic degradation of organic matter and is comprised of roughly 50 % methane (CH_4) and 50 % carbon dioxide (CO_2) (Amini, 2011; Willumsen, 1990). The fact that methane and carbon dioxide are two major greenhouse gases (GHGs) with Global Warming Potential (GWP) enhances the importance of studying LFG. On a mass basis, methane gas has 21 times the global warming potential as compared to carbon dioxide over a 100 year time frame (Shariatmadari et al, 2007). On this basis, regulatory bodies have been formed worldwide to manage, estimate and reduce the landfill methane gas such as the Kyoto Protocol and Protocol on Pollutants Release and Transfer Registers (PRTRs) (also known as Kiev Protocol) (Scharff and Jacobs, 2006). In addition, in 2006 "Sabour and Kamalan (2006)" established that methane gas has a great amount of energy and encourages scientists and decision makers to estimate and turn the liability into an asset.

While being a threat to the environment as the major air pollutant, LFG if managed correctly is a valuable energy resource, with an energy value of 18-22 Mega Joules per cubic meter (MJm^3) due to the methane content (Spokas, et al., 2006). Methane is considered as an alternative source of green energy due to the high calorific value it possesses. Thus, strong interest emanates in the collection of landfill gas and utilizing it as a source of energy. One of the many ways in which LFG can be used is in electricity generation by using it to fuel a reciprocating engine or turbine. The electricity produced by the gas can be used for powering equipment under day to day operations on site or it can be distributed through the local power grid and sold to the targeted consumers.

The composition of waste and quantities deposited at the landfill are the most important factors in assessing the LFG generation potential and gas composition. Other factors which have an effect on the rate of LFG generation include moisture content; nutrient content; bacterial content; pH level; temperature; and the site-specific design and operations plans. The amount of the methane generated from the decomposing waste in a landfill is an important factor as it forms the basis on which decisions are made for the type of benefit that can be exploited from the gas. Therefore, the methane potential from a landfill needs to be estimated prior to any energy investments. A variety of approaches can be employed to estimate the methane quantity in LFG. The simplest method of estimating the gas generated from a landfill site is through rough estimations by assuming a rate at which the gas is produced from a ton of waste within a particular period. On the other hand, the most reliable method for estimating gas quantity is to drill test wells and perform pump tests to measure the gas collected from these wells. The minimum number of test well required to predict landfill gas quantity depends on the size of the landfill and waste homogeneity. Although test wells provide site specific data on gas production rate at a particular time, landfill gas estimation models also predict gas generation on a landfill from the time the landfill was first opened for waste disposal up to the time when landfilling is closed. These, models typically require the period of land filling, the amount of waste in place, and the types of waste in place as the minimum data required to predict gas production.

There are numerous mathematical models available to calculate LFG production. The model outcomes can be used to assess the potential for LFG emissions, and also the feasibility of the LFG management project. LFG models predict the gas generation over a period of time and the estimates of total gas yield and rate at which the gases are generated vary somewhat depending on the model used and parameters applied. However, the most important input parameter for all models is the fraction of waste that decomposes to produce gases (organic waste). Other parameters may differ depending on the model used.

The prominent landfill gas estimation models discussed in this study include; LandGEM, IPCC, TNO, GasSim, Afvalzorg and the French E-PTTR model. LFG generation was determined by using models that were established as highly applicable to Chunga landfill based on the availability of the model, accuracy of modelled outcomes, scientific basis of the model, transparency, ability of the model to handle waste changes and applicability to climate zones different from the climate conditions where the model was developed. Chunga landfill was constructed at a cost of US$ 2.8 million and has been operated since 2007. It was designed to handle waste generated in Lusaka for a period of 25 years making 2032 as the closure year of the landfill.

Inadequately managed landfills produce methane gas which is released to the atmosphere and causes odour, nuisance, explosive danger and poses as a health hazards to the environment. It is therefore, the purpose of this study to estimate the gas emissions at Chunga landfill and assess the financial feasibility of turning this liability into an assert through electricity generation from methane.

1.3 The Problem Statement

Landfills produce harmful gases which are released to the atmosphere and poses as a global warming potential, if not correctly recovered for subsequent utilization. The traces of the gas in the atmosphere and around the landfill premises may result in odour, nuisance, explosive danger and health hazard to the environment. In Zambia there is currently no Landfill Gas to Energy (LFGTE) project or utilization of LFG and little information is available on the potential of electricity generation from the gas. Therefore, an estimation of the quantity of gas emissions at Chunga landfill and the electrical energy potential in kilowatt hour (kWh) is necessary in order to environmentally benefit the city by reduction of gas emissions and economically benefit the residents from increased power supply.

Carbon credit trading markets have recently been rising and trading platforms in the United States, Europe, India and China have been created. Trading in carbon emissions has provided financial benefits for LFGTE projects and trends suggest that collecting LFG can result into major economic benefits for landfill owners. In this regard, landfill owners and operators can benefit from every ton of emissions that is captured and used to create another form of energy. The study of landfill gas estimation models is essential in reducing GHG emissions and creating an alternative source of energy by estimating the probable amount of electrical energy that can be produced from the landfill gas.

The problem statement of this study can therefore be summarised as follows:

> ***"If the current emissions, odour, nuisance and health hazards to the residents around Chunga landfill are to be substantially mitigated, there will be need to investigate and predict the current and future greenhouse gas emissions, and explore the feasibility and viability of converting the harmful gaseous emissions into an assert in order to radically address the threat"***

This study will therefore seek to find answers to the many questions that this problem currently poses.

1.4 Research Questions

The research questions were formulated for the purpose of establishing the scope of the research. These are:

1) What gas emission estimation models are used in estimating LFG?
2) What parameters can be manipulated, removed or introduced to the theoretical models to reduce errors in quantifying gas emissions at Chunga landfill?
3) What landfill gas extraction system is suitable for gas capture and utilisation?
4) What is the cost of construction and operations against the rate of return on the investment of the methane recovery plant and electrical energy production?

1.5 The Research Objectives

The principal aim of this study was to investigate the energy potential of landfill gas and the financial feasibility of a landfill gas to energy (LFGTE) project at Chunga landfill by applying theoretical landfill gas estimation and cost models based on site conditions. The specific objectives will be to:

a. Investigate the prominent theoretical gas emission models and establish which models are highly applicable to Chunga landfill based on site conditions and available waste data.
b. Estimate the quantity of landfill gas production and electrical energy that can be produced from the landfill.
c. Design a landfill gas collection system.
d. Investigate the financial feasibility of capturing landfill gas and converting it to electricity.

1.6 Scope of the Research

The research study will focus on the estimation of landfill gas produced from solid waste generated from urban and commercial centres in Lusaka city. The study will use landfill gas estimation models and landfill gas to energy cost models to assess the financial feasibility of converting the gas produced by decomposing waste at Chunga landfill in Lusaka.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The previous chapter presented the background to the study. This chapter presents relevant literature relating to landfill gas modelling. It begins by reviewing the literature concerning the formation of landfill gas. This is followed by a presentation of various theoretical models used in estimating landfill gas. Thereafter, the models established to be more applicable to the case study are articulated further to establish the model default parameter. The chapter proceeds by presenting the different methods of landfill gas collection. Further, different wastes to energy technologies are discussed and some identified wastes to energy projects in Africa are outlined.

2.2 Landfill Gas Formation

When waste is landfilled, the organic matter in the waste is transformed to landfill gas by biological and chemical processes. According to Amini (2011) and Oonk (2010), landfill gas is a combination of methane (45-60%), carbon dioxide (40-55%) and trace components (hydrogen sulphide, mercaptanes, organic esters and other volatile hydrocarbons, all of them giving landfill gas its characteristic smell.

Farquhar & Rovers (1973) as quoted by Oonk (2010), biodegradation of organic matter proceeds in a sequential process that begins with hydrolysis of the solid organic materials (e.g. hemicellulose, cellulose) into larger soluble organic molecules, then fermentation of these materials occurs yielding organic acids and finally methanogenesis.

Organic material is not a single component, but a complex expansive collection consisting of molecules with varying degradability. Simple sugars and fats are an example of smaller molecules that are easily degraded. Likewise, hemicellulose is also relatively easily converted while cellulose is somewhat degraded slower depending on the accessible by enzymes and bacteria. Contrariwise, lignin is resistant to biodegradation under anaerobic (no oxygen present) conditions and protects cellulose by shielding it from biodegradation (Oonk , 2010). The relationship that exists between lignin content and the maximum biodegradability of organic material under anaerobic conditions is indicated in the figure 2.1:

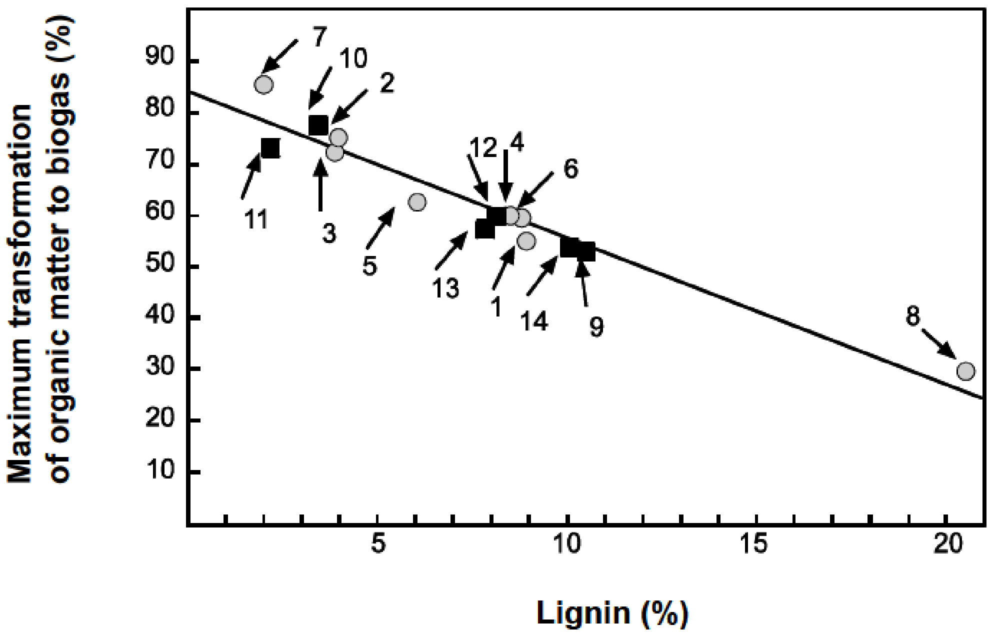

Figure 2.1: Relationship between fraction of organic waste ultimately converted and the lignin ratio of the waste (1 = Wheat Straw, 2 = Corn Stalks, 3 = Corn Leaves, 4 = Purple Loosestrife, 5 = Seaweed, 6 = Water Hyacint, 7 = Corn Flour, 8 = Newspaper, 9 = Elephant Manure, 10 = Chicken Manure, 11 = Pigs Manure, 12 & 13 = Cow Dung; Chandler, et al., (1980) and Oonk (2010),

Therefore, not all organic material deposited in the landfill is converted to landfill gas simply because conditions in parts of the waste inhibit biological activities. There are many possibilities that inhibit the degradation for example when the waste is too dry or temperatures are too low to support the enzymatic activities. Another possibility is the presence of excess water in the waste, leading to stagnant saturated zones in the waste, which results in fast proceeding of the first two steps of biodegradation resulting in a drop of pH, thus limiting methanogenesis. Consequently, the methane generation potential is generally based on the total amount of organic material, corrected for: (i) the amount of organic material that does not degrade under anaerobic conditions; and (ii) the amount that doesn't degrade because conditions are not favourable (Oonk , 2010). The first amount is dependent on the waste composition and estimated by taking into account the organic components in the waste while the second part is determined by landfill design and operation, and is most likely also influenced by climate conditions.

2.3 Five Phases of Municipal Solid Waste Decomposition

The conversion of organic matter in solid waste to carbon dioxide and methane is due to microorganisms that break down the organic segment of waste for their nutrition and replication. The generation of gas from a landfill has been under investigation since the 1970s and the phases involved during waste decomposition and production of landfill gas are outlined below and shown in figure 2.2.

1. Phase I: Aerobic Biodegradation

This phase involves the aerobic biodegradation of organic matter and begins soon after the waste is placed in a landfill. Oxygen is used by aerobic bacteria for cell growth, respiration and breaking down proteins, lipids and carbohydrate which are present in solid waste as organic matter. The duration of this phase is dictated by the amount of air trapped in the voids that are present in the waste after compaction and settlement (Barlaz, et al., 1997b; Barlaz, et al., 1990a). The primary by-product at the end of this phase is carbon dioxide (CO_2) which is released in gaseous form or dissolved in water (William, 1998). This phase is also characterised by high nitrogen content due to its presence in the air, but decreases over time. Other by-products include; water, residual organics, and heat. According to Qian, et al. (2002), aerobic biodegradation may continue from 6 to as long as 18 months for the waste placed at the bottom of the landfill provided oxygen is present in the voids. In the upper lifts of the waste disposed at the bottom of the landfill, aerobic decomposition may take 3 to

6 months because the methane-rich landfill gas from below flushes the oxygen from voids in the disposed waste and prevents aerobic conditions.

2. Phase II: Acidogenesis or Transition Phase

During this phase, all entrapped oxygen is depleted and decomposition enters a transitional phase which is regarded as the beginning of anaerobic processes. In the transition phase, the acid forming bacteria begins to hydrolyse and ferment the complex organic compounds in the waste. This stage is distinguished by the hydrolysis of macromolecules and acidogenesis (acid generation). In the sub-phases of acidogenesis, products from hydrolysis are decomposed into simple compounds such as hydrogen, water, and volatile fatty acids (VFA). An important characteristic under this phase is the increase in chemical oxygen demand (COD) of the leachate which signifies the increase of anaerobic bacteria. The by-products of this phase are CO_2 which is approximately 80 % and 20 % hydrogen both in gaseous state (William, 1998).

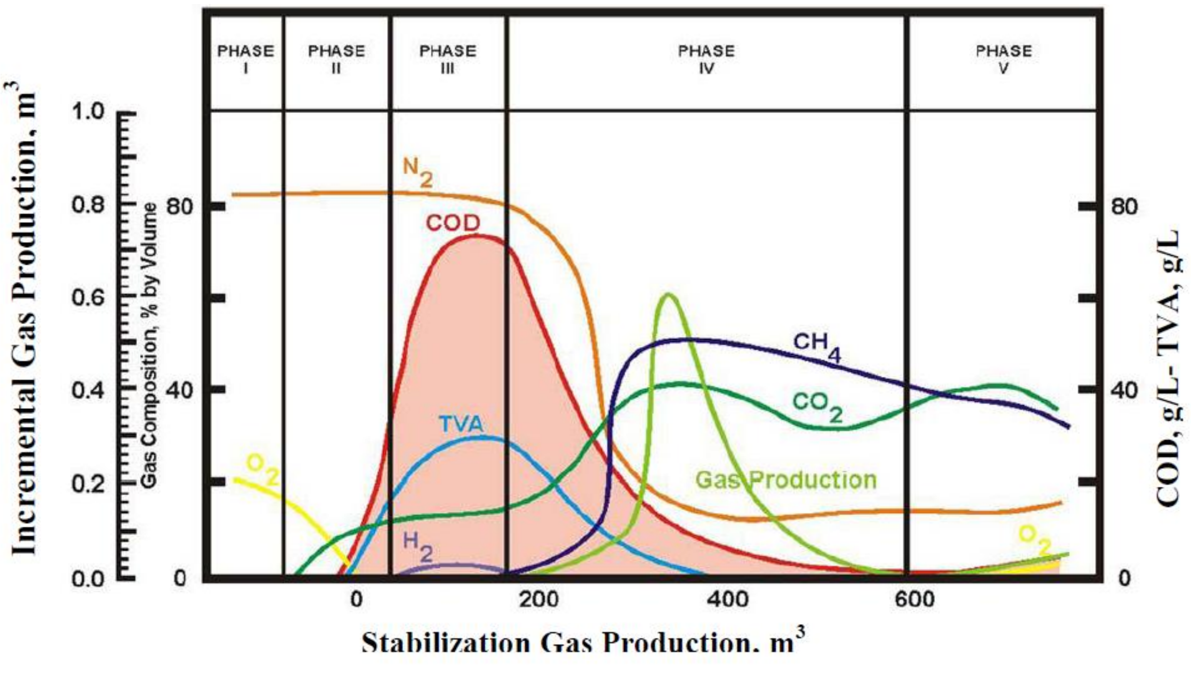

Figure 2.2: Five phases of methane generation (Qian, et al., 2002)

3. Phase III: Acid Phase

In this phase, acid is produced by anaerobic bacteria which converts compounds created by aerobic bacteria into acetic, lactic and formic acids and alcohols such as methanol and ethanol. The principal gas produced here is CO_2 and an important characteristic of the phase is the peak COD and biological organic demand (BOD) levels in leachate and the rapid degradation of pH which contributes to more acidic leachate (US Environmental Protection Agency, 2015). The end of this phase is symbolised by stabilised concentration of CO_2 and methane (CH_4) with very low nitrogen concentrations in the landfill gas.

4. Phase IV: Methane Generation

This phase marks the ultimate landfill gas production in which methane forming bacteria thrives due to the oxygen deficient environment. There is predominant generation of CH_4 and CO_2 from acetic acid products of the previous phases in which methane concentrations are significantly higher (45 % to 57 %), than CO_2 concentrations (40 % to 48 %). In this phase, the gas production rate is almost constant and there is a rise in pH to a more neutral value, ranging from 6.8 to 7.5 due to the conversion of acid and hydrogen into CH_4 and CO_2 (William, 1998).

5. Phase V: Maturation or Stabilisation Phase

In this phase, the stages of decomposition have run their course and begin to stabilize back to aerobic digestion. Stabilisation marks the end of the biodegradation. Biodegradation activities are not completed in the fourth phase due to the heterogeneity of the waste and random distribution of organic matter. As a result, the moisture that continuously migrate through the waste causes the recalcitrant molecules to undergo biotransformation that leads to the production of humus similar to compost constituents (Pichler & Kogel-Knaber, 2000). During the final phase, there is a drop in gas generation and a stable concentration of leachate constituent.

2.4 History of Landfill Gas Modelling

Studies of landfill gas production and attempts to model the formation of the gas stem from the early 80’s. The emissions of methane in those days was not recognized as a potential problem, however, researchers knew the energetic potential of landfill gas and were eager to exploit this alternative energy source. Subsequently the first landfill gas formation models predicted how much gas was formed, projections of future gas formation and which part of landfill gas was necessary to be recovered.

Over the years, there has been more emphasis in the quantification of methane emissions both on a national scale and landfill to landfill basis. On a national level, in the framework of obligation under the United Nations Framework Convention on Climate Change (UNFCCC), countries are required to report their greenhouse gas emissions while on a landfill to landfill basis, emissions are reported in the framework of the European Pollutant Release and Transfer Register (EPRTR). As a result of the comparisons of UNFCCC reported emissions by a country with the emissions reported by individual landfills in the country, accurate, transparent and state of the art emission models have resulted (Oonk , 2010).

2.5 Available Landfill Gas Generation Models

According to Christensen (2011), LFG generation is affected by several factors including, among others, the quantity of waste disposed, waste composition, moisture content, temperature, and landfill operation. This makes it is very difficult to estimate gas emissions by deterministic mathematical approaches (Mou, et al., 2014). However, in the past years a number of models have been developed to enable the calculation of methane generation in a specific year from landfilled waste. Mou, et al. (2014) reports that several researchers and scientists have highlighted their achievements in recent years, though their advanced models lack support of realistic data and remain highly uncertain. The Monte Carlo method by Zacharof & Butler (2004) based on the stochastic method and the fuzzy synthetic evaluation method by Garg et al. (2006), both of which lack realistic data support are examples of the highly unreliable models.

When modelling LFG, the ultimate goal is to achieve maximum accuracy of model outputs. LFG generation can generally be modelled using zero-order, first-order, second-order, and/or multi-phase generation models (Amini, 2011). Research and studies on modelling LFG have shown that outcomes from the zero-order model are unreliable owing to relatively high inaccuracies induced by the model’s inability to reflect the biological LFG generation processes (Amini et al., 2012).

According to Oonk, et al. (1994) as reported by Amini (2011), relatively lower inaccuracies are obtained when comparing higher model outcomes to actual site measurement data. Studies have shown that most users stick to the first-order model since moving from a first-order to a second-order or a multi-phase model makes the modelling process more complex. In addition, second-order models are not commonly used because the accuracy of model outcomes is negatively affected due to the high uncertainty of required parameters in the model (Tintner, et al., 2012). Because of these limitations associated with the respective models coupled with the complexity of numerical and mathematical models, simplified empirical methods established on first-order decay (FOD) of organic waste are commonly used for research and industrial purposes (Amini, 2011; Scharff & Jacobs, 2006; Weitz et al., 2008), and are officially regulated as the methodology for landfill gas emission estimation (Council of the European Communities (CEC), 2006; Intergovernmental Panel on Climate Change (IPCC), 2006); US Environmental Protection Agency (EPA), 2005).

In this study, various landfill gas generation models were studied, as shown in table 2.1, in terms of their default parameter values and assumptions on which they are based. Some of these models have been developed as computer software and Microsoft excel spread sheet programs to make it even more user-friendly, including the US EPA LandGEM, the E-PLUS, the IPCC, the Dutch Multiphase (AMPM), and the French ADEME models.

2.6 Overview of the Landfill Gas Estimation Models

In this study, various landfill gas generation models were studied in terms of their default parameters and assumptions on which they are based. A summary of the models evaluated in this research are presented in table 2.1, and an overview of the models is presented thereafter:

The LandGEM model is a FOD model developed by the US Environmental Protection Agency (EPA) that estimates gas emission rates from landfills in terms of methane, carbon dioxide, non-methane organic compounds (NMOCs) and other toxic air pollutants (Pierce et al., 2005). It is intended to model the LFG generation from traditional MSW disposal sites with relative homogeneous waste fractions by applying one biochemical methane potential (BMP) value for all categories of waste. Therefore, this model only requires the users to input the total annual weight of disposed waste for modelling LFG. The E-PLUS model, also developed by the US EPA, is used to estimate the costs and benefits of landfill gas recovery projects including projections of methane flow, landfill gas flow and NMOCs emissions (Pierce et al., 2005).

The TNO model estimates the generation of landfill gas based on the assumption that degradation of organic matter in the waste follows the first order decay kinetics. The parameters used in this model were based on real data of landfill gas generation from a group of landfills. Oonk & Boom (1995) and Scharff, et al. (2003) validated the TNO model by using methane and carbon dioxide emission measurements. This model has both first-order and multi-phase modelling approaches that describe landfill gas generation as a function of amount of waste deposited from different waste streams (commercial, domestic, industrial etc).

The Afvalzorg model also known as Multiphase model was developed by the Dutch landfill operator, Afvalzorg in the Netherlands (Afvalzorg, 2014). The model is based on incorporation of literature from the IPCC model and own experiences with landfill gas generation and measured emissions at the Nauerna, Braambergen and Wieringermeer Afvalzorg sites. It is intended for modelling landfill gas production from waste with low carbon content or less household waste.

Gas simulation model (GasSim) was developed by Golder Associates (2010) for the Environmental Agency of England and Wales. GasSim calculates all problems that landfill gas poses on waste dump sites, ranging from amount of methane emissions, effects of utilization of landfill gas on local air quality to landfill gas migration and transport through the subsoil to adjacent buildings (Oonk , 2010). The earlier version of this model, GasSim Lite version 1.5 is available as freeware while the most recent version, GasSim 2.1 is commercially available. In the recent version of GasSim the default values used, algorithms applied and assumptions made are hidden in the program. However, this information is provided by Golder Associates staff upon demand (Oonk , 2010)

Table 2.1: Overview of Empirical LFG Models in terms of L_0 and k values (Mou, et al. (2014); Machado et al. (2009); Oonk (20

Model	Main Parameters	Type of Waste or Landfill	CH_4 Generation Potential (L_0) (kg CH_4/ton waste)	CH_4 Generation Rate k (yr^{-1})	Data Resource	Reference
IPCC	Decomposable degradable organic carbon (DDOCm) and k	Food	100	0.185	default values were determined by international experts and cited from various literature	IPCC (2006)
		Garden	133	0.1		
		Paper/wood	267	0.06		
		Textile	160	0.06		
		Sludge	33	0.185		
		Industrial	37	0.9		
TNO	Organic content (C_0) and degradation rate constant (k)	Household/MSW	60		k were based on real data of landfill gas generation from a group of landfills	Oonk & Boom (1995); Scharff, et al. (2003)
		Industrial	50			
GasSIM	Waste input carbon content and degradation rate constant (k)	Incinerated ash	3	Fast degrading 0.116	k values were determined based on water saturation level of different waste categories	Scharff & Jacobs (2006); Gregory, et al. (2003)
		Sludge	24			
		Composted organic waste	34	Moderate degrading 0.076		
		Civic amenity	47			
		Domestic	79	Slow degrading 0.046		
		Commercial	121			
LandGEM	Methane generation potential (L0) and methane generation rate constant (k)	Bioreactor/Wet landfill	96	0.7	k values were determined by US Clean Air Act 1990.	US EPA (2005)
		Conventional landfill	72-122	0.05		
		Arid area landfill	72-122	0.02		
Afvalzorg	Organic content (C_0) and degradation rate constant (k)	Contaminated soil	3	Fast degrading 0.187	k values were determined based on IPCC model default values and field measurements in Dutch landfills	Afvalzorg (2014); Scharff & Jacobs (2006)
		Construction&Domolitio nwaste	11			
		Commercial	56	Moderate degrading 0.079		
		Shredder	13			
		Street sweepings	19	Slow degrading 0.03		
		Mixed bulky	80			
		Sludge	25			
E-PRTR (Fr)	Methane generation potential (FE) and degradation rate fraction (k)	Fast degradable	56 for MSW, sludge & yard waste; 28 for industrial and commercial waste	0.5	k values were determined based on field measurements in approximately 50 French landfills	Ademe (2003); Oonk (2010); Scharff & Jacobs (2006)
		Moderate degradable		0.4		
		Slow degradable		0.1		

The French E-PRTR model (Ademe, 2003) as reported by Oonk (2010) is a simplified first order decay model. The model estimates methane generation of 4.8kg per ton of waste per year in the first 5 years after landfilling followed by 2.4 kg methane production per ton of waste per year in the next 5 years, thereafter, 1.3 kg per ton of waste per year in the second decade and finally 0.6 kg methane production per ton of waste per year in the third decade after landfilling. This model is not obtainable as a spreadsheet, but exists as a simple fill-in table.

The IPCC model was developed by an international team of experts involved in the Intergovernmental Panel on Climate Change (IPCC) whose primary purpose is to give guidance to national authorities in the quantification of methane generation from all landfills at a national level (Mou, et al., 2014: Oonk , 2010). The model is a freeware that can be downloaded from the IPCC website as a spreadsheet with its default values, algorithms applied and assumptions made clearly indicated.

The empirical models presented here fall under the single or multi-phase first-order decay model irrespective of the k value assigned for a particular waste category. The single-phase model only utilises one k value by assuming homogenous waste and on this account fails to distinguish various decay rates that exist in different waste categories. LandGEM is a single-phase model that defines only one decay rate and one methane generation potential value for all waste categories. This model is intended for modelling LFG generation from traditional MSW disposal sites with relative homogeneous waste fractions (Mou, et al., 2014). Modelling of disposed waste using this model only requires the user to input the total annual weight of disposed waste. The E-PRTR (Fr) model is yet another single-phase model that defines three k values for fast, moderate and slow degradable waste, but only applies one decay rate at a period of 0, 5 and 10 years after landfilling, respectively. Mou, et al. (2014) presents that the 2007 old version of the IPCC model, had a single-phase sheet named IPCCb, which applied only one k value to both MSW and industrial waste for each selected climate type (dry temperate, wet temperate, dry tropical, and moist and wet tropical).

According to Mata-Alvarez et al. (2011) and Thompson et al. (2009) as quoted by Mou, et al. (2014), Afvalzorg, GasSim and IPCC models are multi-phase models, which operate with a number of more detailed waste categories. Waste categories defined in the IPCC model for traditional MSW include food, garden, paper, and other high organic content fractions. Each waste category is assigned to a k value that defines the rate of decay for that particular waste category. The GasSim model defines three k values that are applied to fast, moderate and slow degradable waste.

The Afvalzorg model, holds datasets that define specific decay rates for different waste fractions with low organic content, such as soil, construction and demolition (C&D) waste, commercial waste, shredder waste (shredded pieces of abandoned vehicles or machines), street cleansing waste, mixed bulky waste (i.e. coarse household waste), and sludge waste (Mou, et al., 2014).

Literature shows that the LFG generation models presented by US EPA and the Intergovernmental Panel on Climate Change (IPCC) are the most widely used models by operators, designers, and evaluators. These models may differ in some minor approaches, but the main parameters have very similar definitions in both methods.

2.7 Landfill Gas Model Applications Parameters and Accuracies

Machado et al. (2009) and Garg et al. (2006) established that the methane degradation rate designated as k in model equations is affected by waste depth, density, pH, and other environmental conditions. Different types of waste contain different fractions of organic matter that degrade at different rates, for each waste category (Machado et al., 2009), however, most models assume a single overall value for k. Amini (2011) presents that through laboratory studies, pilot-scale cells, or by comparing measured LFG from full scale sites to model outcomes the value of k can be defined. Another known factor that affects the degradation rate is moisture content, for example, waste with high moisture content degrades faster and consequently results in a higher k value than waste that has low moisture (Machado et al., 2009).

US EPA reports that the methane generation potential designated as L0 is a function of the waste composition and ranges from 6 to 270 cubic meters per megagram (m^3/Mg) of waste depending on the composition of the waste stream and the ultimate methane yield of each component (U.S. Environmental Protection Agency, 2008; US Environmental Protection Agency AP-42, 1997). Amini (2011) reports that L0 can be defined using waste degradation stoichiometry, laboratory values, or fitting the model to full sale data. Eleazar, et al. (1997) measured methane generation potential for biodegradable components using laboratory tests, however the accuracy of applying results from such laboratory studies with well-defined wastes and environment to full scale landfill conditions has not yet been evaluated (Amini, 2011). The default methane generation value suggested by US EPA is 100m^3/Mg (US Environmental Protection Agency, 2008; US Environmental Protection Agency AP-42, 1997).

LFG emission models of different kinds have been used by research groups to estimate LFG generation, however, few have compared model outcomes to actual collected LFG data (Amini, 2011). A summary of some of these studies is presented in table 2.2. Amini (2011) reports that these studies were generally based on short term data and default model parameters. A substantial number of these models overestimated LFG generation, however, the LandGEM model was reported to generally underestimate gas generation (Thompson et al., 2009; Ogor and Guerbois, 2005).

2.8 Evaluation of Models

Several attempts and efforts have been made by different researchers to validate the formation and emission predictions made by empirical LFG models. Some efforts have yielded positive results while other attempts have failed which has led to questioning the integrity of the models due to the unreasonable discrepancies noticed between the modelled results and those measured on site. The following paragraphs give examples of research efforts and attempts made to validate LFG generation and emission models.

Table 2.2: Summary of empirical landfill gas generation model applications (Amini. 2011)

Study	Years of data	Models	Landfill characteristics	k, yr^{-1}	L0, m^3/Mg	Error(1)	Reference
Validating LFG generation models based on 35 Canadian landfills	N.A.	Zero-order German EPER TNO Belgium Scholl Canyon LandGEM version 2.01	35 Canadian landfills	0.023 - 0.056	90 - 128	(-81%) – (+589%)	Thompson et al., 2009
The CDM landfill gas projects by the World Bank	1 - 3 years	IPCC First-order Rettenberger First-order E-PLUS US EPA LandGEM Dutch Multiphase Scholl Canyon	Six landfills in South America and Europe	0.014 - 0.28	68 - 102	(-3%) – (+1109%)	Willumsen and Terraza, 2007
Comparison of landfill methane emission models: A case study	N.A.	US EPA LandGEM French ADEME UK GasSim IPCC Tier 2	Four French landfills	0.04 – 0.50	44 - 170	(-65%) – (+140%)	Ogor and Guerbois, 2005
Landfill gas energy recovery: Economic and environmental evaluation for a case study	N.A.	Scholl Canyon	Casa Rota Landfill, Tuscan, Italy	0.07 - 0.36	13 - 30	+5%	Corti et al., 2007

A study by “Scharff & Jacobs (2006)” compared the outcome of the TNO model, Afvalzorg model, LandGEM, GasSim and a Zero-order model with measured emissions at three Dutch landfills. The study reviewed enormous differences between models for individual landfills. The difference between the lowest and highest estimation was more than a factor of 10 and in some case as much as 20. However, the inconsistency between different measured emissions is much less as compared to the difference between modelled emissions (Scharff & Jacobs, 2005).

In 2007, “Fredenslund et al. (2007)” compared modelled results to observed outcomes at a landfill site in Denmark for four generation models (i.e. LandGEM, IPCC model, GasSim and the Afvalzorg). Huge differences were observed between models, with highest generation in LandGEM and lowest generation was observed for GasSim and the Afvalzorg model.

A number of generation models were validated in a study that compared modelled outcomes with observed recovery results at Canadian landfills. However, Oonk (2010) described the findings of “Thompson et al. (2009)” as erratic and requiring a lot care during interpretation because in some of the models reviewed, landfill gas generation (in m^3/yr) was mistaken for methane generation (in kg/yr). This causes overestimations in the methane generation by about 2.5 times.

According to “Oonk (2010)”, the evaluation of models is not only related to accuracy, but indicators such as scientific basis, transparency and validation are also used to indicate whether the model assumptions are clear and in agreement with science. Table 2.3 summarises the evaluation of LFG generation models and the indicators established by Oonk (2010) are as follows:

1 *Availability*

All models are freeware including GasSim Lite, which is the freeware version of GasSim. GasSim Lite allows landfill owners to accomplish their reporting responsibilities in the framework of EPRTR. In the evaluation table, ‘++’ means that the model can easily be downloaded from the web while ‘+’ means the model is available on demand. A ‘-’or ‘--’ means that users need to make substantial efforts to obtain a version of the model.

2 *Ease of Operation*

Refers to the level of expertise required by the user with the specific model and the complexity of choices required to be made by the user through different manipulations or actions before a result is obtained. In the case of GasSim a '-' is given, because the model requires information that is not used in calculating methane emissions. Likewise, other models not presented in the evaluation table below are difficult to be used owing to the language set in the model such as Finnish, French, etc.

3 *Transparency*

Refers to the accurate explanation of the model, parameters used in the model, assumptions made and attempts performed to validate the results of the model. Models that are based on a Microsoft Excel spreadsheet are more transparent than executable models such as GasSim and Calmin, because the calculation method and default values applied can be traced back by the user.

4 *Required Input*

A model that requires the user to input more details is advantageous as it permits a more accurate prognosis of LFG generation, since it may induce flexibility of incorporating specific site conditions and circumstances that exist at the landfill being modelled. A positive evaluation of the model results when the input parameters are defined in a manner that is in line with the type of data available at the landfill. The TNO and Afvalzorg model specify waste according to its source (i.e. domestic waste, commercial waste, industrial waste, etc.) rather than its composition (putrescibles, paper, plastics, cardboard, glass, etc. as in the IPCC model). It is preferable to specify waste according to the source than the waste composition, since the former connects to the manner in which information is available at the landfill. Under the GasSim model it is possible to change the amounts of waste per waste category and the model also accommodates changes in composition of the waste streams. Therefore, a landfill operator using GasSim can calculate the effect of both less household waste and a change in household waste composition. In the case of LandGEM and the French E-PRTR model, there is very little or no possibility to specify waste composition and the detail of input is considered too low for an accurate model.

5 *Scientific Basis*

Refers to whether a model can be regarded as ‘state of the art’ from a scientific point of view. According to Oonk (2010), the IPCC model, TNO model and the Afvalzorg model can be considered state of the art. Likewise, GasSim can be regarded state of the art as well, however, it is given a neutral value in the evaluation table, because the scientific basis that govern this model cannot be evaluated due to lack of transparency. Furthermore, the French E-PRTR model is a very simple model when compared to other models. However, the methane generation potential (L_0) and half-life applied by this model are in line with other models, and the results are about the same with other models. Therefore, no evidence exists that consider its prediction of methane generation as less accurate than other model estimations. On the other hand, the scientific basis of LandGEM is considered minimal, because of the high values of L_0 assumed in the model and therefore a neutral value is assigned under the scientific basis indicator in the evaluation table.

6 *Validated Model*

Only the TNO model is extensively validated. The model parameters applied were determined in a study that compared modelled outcomes with landfill gas recovery at 9 landfills. The resultant LFG generation was validated through comparison with measurements of LFG emissions on 25 Dutch landfills, using a one dimensional (1D) mass balance method. The Afvalzorg model is a validated model, though the efforts of its validation are limited. This is because the validation was based on the use of experiences from only one Danish and three Dutch landfills. The validation of LandGEM is based on the results presented by Vogt & Augenstein (1997).The IPCC model is not validated, however a large part of this model is based on the TNO model and the resulting values L_0 are comparable to the TNO model despite the different ways of calculating L_0. Validations of the models were not presented under this indicator but captured on the evaluation table are unclear.

7 *Waste Changes*

The IPCC, TNO, GasSim and Afvalzorg model are able to handle changes in the composition of waste. The approach used in the IPCC and GasSim in modelling

LFG generation differs from the approach in the Afvalzorg and TNO. In IPCC and LandGEM, the composition of the waste can be defined as amount of putrescibles, paper, plastics, etc whereas, in the Afvalzorg and TNO model changes in origin of the waste are defined as amount of household waste, offices waste, commercial waste, etc. For this reason, the Afvalzorg model is more suited to deal with changes in origin of the waste, whereas the IPCC model is suited for modelling LFG generation in waste with changes in composition. The GasSim model can handle both changes in the origin of the waste and changes in the composition of each individual waste stream. LandGEM and the French E-PRTR model do not accommodate for changes in waste composition.

8 *Applicability to various climate zones*

Climate affects both the amount of methane generated per ton of waste, and the rate at which methane is generated. According to Oonk (2010), only the IPCC model and LandGEM distinguish model parameters between different climate zones. The two models define the effect of ‘wet’ and ‘dry’ climate conditions on half-life of methane generation.

9 *Accuracy*

Refers to the correctness of the model outcomes when modelling different types of waste and climate conditions for which the model was developed. According to Oonk (2010), “Apart from the TNO model, which is validated for waste landfilled in the Netherlands in the period up to 2000, there is little or no information available on the basis of which methods mutually can be compared”. Generally, most LFG models are founded on sensible assumptions and it is impossible to determine that one set of reasonable assumptions produces a more accurate result than the other set.

Therefore, in summary, the IPCC model, GasSim and French E-PRTR model appear to be in fair to good agreement with the TNO model for domestic or municipal solid waste (MSW). The Afvalzorg model underestimates the methane generation from MSW, but the strength of this model lies in landfills which receive waste from other sources such as commercial, industrial etc. Contrariwise, assumptions in LandGEM are less reasonable since the methane generation potential, L_0, in this model is high and this was also acknowledged by the validation efforts of Vogt & Augenstein (1997). Therefore, due to the high value of L_0, LandGEM most likely overestimates LFG generation at most landfills.

Table 2.3: Summary of evaluation of methane generation models

Indicators	**IPCC**	**TNO-model**	**GasSim**	**LandGEM**	**Afvalzorg**	**E-PRTR (Fr)**
Operational						
- availability	++	+	++	++	+	+
- ease of operation	+	+	-	+	+	++
- required input	0	+	+	0	+	0
Performance						
- scientific basis	+	+	0	0	+	+
- transparency	++	+	-	0	0	+
- validated	0	+		0	0	0
Constraints						
- waste changes	+	0	+	-	+	-
- climate zones	0/+	-	-	0	-	-
Accuracy	0	0	0	-	0	0

In this table '++' means very good and '--' means very poor. If a generation model scores '-' or less on one of the evaluation parameters, users of the model should be well aware of the limits of the model.

2.9 Modeling Landfill Gas Emissions

Landfill Gas (LFG) emissions are theoretically estimated using models which generally base their calculations on LFG emission mass-balance:

Emissions = LFG Generation - Recovery - Oxidation *Equation 2.1*

The methane generation can also be estimated as a fraction of the LFG generation through:

Methane Generation = LFG Generation x Methane Content *Equation 2.2*

In the sections below the IPCC, LandGEM and Afvalzorg models are explained more in detail since these are the empirical models that are going to be used to estimate the LFG production at Chunga.

2.10 Landfill Gas Models

In this study, various landfill gas generation models were studied in terms of their default parameters, applicability to different climate conditions and assumptions on which they are based. The models that were applied in the simulation of gas generation at Chunga landfill are presented below.

2.10.1 LandGEM Model

The Landfill Gas Emission Model (LandGEM) is a predictive gas generation rate model that was written and improved by EPA for U.S. regulatory applications but has been used in estimating emissions of total landfill gas, methane, carbon dioxide, non-methane organic compounds (NMOCs) and other toxic air pollutants from municipal solid waste landfills in the U.S. and worldwide (Pierce, et al., 2005). The generation rate applied in LandGEM model is based on the first-order decomposition rate equation and the model uses certain default parametric values developed by the agency. This model requires the design capacity of the landfill, amount of waste in place (annual acceptance rate), methane generation rate constant k, methane generation potential L_0 and the number of years of waste acceptance as inputs into the model to estimate the amount of LFG generated.

According to Reinhart et al (2005), LandGEM model specifically fits conventional landfills characterised by short term waste deposits with long term gas generation potential which is contrary to more efficiently designed landfills. This is because the later are operated as bioreactors which necessitate redesigning of the methane generation potential and rate constants to suit the high production rates in such landfills.

2.10.1.1 Development of the LandGEM Model

From first order kinetics, the rate of Degradable Organic Carbon (DOC) after a period of time and the methane generation rate are respectively represented by the following expressions,

$$\frac{d\,M_r}{d\,t} = -k\,M_r$$

Equation 2.3

$$\frac{dV}{d\,t} = k\,M_r\,L_0$$

Equation 2.4

Where M_r is the quantity (kg) of DOC after a period of time (kg), t is the Organic Carbon (OC) degradation time (yr), k is the first order rate constant (yr^{-1}), V is the cumulative volume of methane generated from the beginning of the degradation to a time t (yr^{-1}), L_0 represents the methane generation potential (m^3/kg) and M is the initial quantity of DOC (kg).

Mathematically, the integral to equation 2.3 is represented as,

$$M_r = M\,e^{-k\,t}$$ *Equation 2.5*

Equation 2.5 is the representation of the decay of DOC that occurs in waste according to first order kinetics.The methane generation rate in (m^3/yr), is equivalent to $\frac{dV}{d\,t}$, and symbolising it by Q, equation 2.4 changes to:

$$Q = k\,L_0\,M\,e^{-k\,t}$$ *Equation 2.6*

“Cavaleiro et al., 2013” guides that degraded organic carbon in waste generates LFG with equal fractions of CH_4 and CO_2 as represented in the chemical degradation reaction of carbon as shown in equation 2.7

$$C \rightarrow \frac{1}{2}(CH_4 + CO_2)$$ *Equation 2.7*

This means that methane contributes 50% of the total LFG generated and therefore, to obtain the overall gas produced equation 2.6 is multiplied by a factor of 2 as represented in equation 2.8:

$$Q = 2\,k\,L_0\,M\,e^{-k\,t}$$ *Equation 2.8*

Taking into account the waste acceptance rate, which depicts the period in which the waste is dumped into the landfill. The gas generation rate takes the form:

$$Q_T = 2\sum_{i=1}^{n} k\,L_0 M_i\,e^{-k\,t_i}$$

Equation 2.9

Where Q_T is the total LFG generation rate at time t in (m^3/yr) and M_i is the quantity of waste placed in year i (kg).

LandGEM model is based on general equations 2.8 and 2.9 and estimates the methane generation rate for each 1/10th year as shown in equation 2.10.

$$Q_{CH_4} = \sum_{i=1}^{n}\sum_{j=0.1}^{1} k\,L_0\left(\frac{M_i}{10}\right)e^{-k\,t_{j\,i}}$$

Equation 2.10

Where:

Q_{CH_4} = Annual methane generation in the year of the calculation (m^3/yr)

i = Time period of waste disposal, (yr)

n = (Year of the calculation) – (Initial year of waste acceptance), (yr)

j = 1/10 time increment, (yr)

k = First order rate constant or methane generation rate, (yr^{-1})

L_0 = Methane generation potential, in (m^3/Mg)

M_i = Mass of waste accepted (disposed) in the i^{th} year, (kg).

t_{ji} = Age of the j^{th} section of waste M_i accepted in the i^{th} year, (yr)

This model used equation 2.10 to estimate the total landfill gas produced and the methane composition. It also provides the option to calculate the amount of carbon dioxide generated within the landfill and produces graphs for each gas produced.

2.10.1.2 Model Parameters and Model Accuracies

The model is validated by the theoretical or stoichiometric determination of k and L_0. The determination of the model parameters increasingly becomes complex owing to the tight dependence between k and L_0, and the site specific conditions related to the quality and availability of data. No advanced method exists that allows the absolute determination of L_0 without inaccuracy (US Environmental Protection Agency (EPA), 2005). Biochemical Methane Potential (BMP) is the only existing experimental means of determining L_0 while the determination of k is achieved by integration with field data.

Methane generation rate (k)

Machado et al. (2009) and Garg et al. (2006) established that higher values of k are caused by increased moisture content in the waste which results in faster waste degradation. The value k is a main function of four factors:

i. Moisture content of the waste mass,
ii. Availability of the nutrients for microorganisms that break down the waste to form methane and carbon dioxide,
iii. pH of the waste mass, and
iv. Temperature of the waste mass.

Each waste component generally degrades at a different rate (Machado et al., 2009), nonetheless most models assume a single overall value for k. Furthermore, the value of k can be determined through laboratory studies, pilot scale cells, or by comparing measured LFG from full scale sites to model outcomes (Amini, 2011).

LandGEM uses five k values that are determined using the US EPA Method 2E based on user specified data that is precise to the site. The k values are dependent on the landfill type and the default type. The Clean Air Act (CAA) defaults and inventory defaults are the two default types that exist in LandGEM. Estimations that are based on inventory defaults yield average emissions while those made with CAA defaults tends to yield conservative emissions (US Environmental Protection Agency (EPA), 2005). The five k values used in LandGEM are shown in table 2.4:

Table 2.4: LandGEM methane generation rate default values

Default Type	**Landfill Type**	***k* Value (yr^{-1})**
CAA	Conventional	0.05
CAA	Arid Area	0.02
Inventory	Conventional	0.04
Inventory	Arid Area	0.02
Inventory	Wet (Bioreactor)	0.7

Methane generation potential (Lo)

The Methane generation potential, L_0 , is a function of the waste composition and depends only on the type and composition of waste placed in the landfill. L_0 expresses the total volume of methane gas potentially produced from a metric ton of decaying waste. Literature reports L_0 values ranging from 6 to 270 m^3/Mg of waste, depending on the composition of the waste stream and the ultimate methane yield of each waste stream component (US EPA, 2008a; US EPA AP-42, 1997). This means that waste streams with higher cellulose or organic content yield higher values of C.

Laboratory tests, waste degradation stoichiometry or model fitting using full scale data are methods used to define L_0. In 1997, Eleazar et al. (1997) conducted laboratory tests and measured the methane generation potential for biodegradable components of waste. However, no evaluation has been undertaken to ascertain the accuracy of applying laboratory study results obtained from well-defined wastes and environment to actual landfill conditions (Amini, 2011). The default value set by LandGEM is 170 m^3/Mg for a conventional landfill.

Similar to the first order methane generation rate, CAA and inventory defaults are the only two emission types used in the model for estimating the methane generation potential. The table below summarises L_0values.

Table 2.5: LandGEM methane generation potential default values

Emission Type	Landfill Type	L_0 Value (m^3/Mg)
CAA	Conventional	170
CAA	Arid Area	170
Inventory	Conventional	100
Inventory	Arid Area	100
Inventory	Wet (Bioreactor)	96

2.10.1.3 Limitation of LandGEM for use in Modelling Landfill Sites Outside the U.S.

Default alternative values of k and L_0 are provided in LandGEM model from which the user can choose depending on whether the model is being used for U.S. Clean Air Act compliance or for inventory applications, whether the site is in an arid area (less than 60cm rainfall per year) or conventional (non-arid area), and whether the landfill is designed and managed for organic diversion, accelerated waste decay through leachate recirculation (bioreactor) and storm-water management.

The model precision is dependent on the accurate assumptions made about the variables such as organic content, future disposal rate, site closure dates or collection efficiencies. Inaccurate assumptions result in errors in predicting future methane recovery. Likewise, significant model errors are introduced if good record of disposal data is unavailable.

The default k and L_0 values are suitable for estimating LFG production from U.S. landfills that are in agreement with these conditions. Otherwise, these values are not appropriate when applied to landfill sites that exhibit very different site conditions and waste composition. Since the LandGEM model is centred on data from solid waste dump sites in the U.S., the model assumes that an engineered sanitary landfill site is being modelled. Consequently, it may not be suitable for modelling completely unmanaged dump sites where LFG generation and collection is limited as a result of inadequate soil cover, insufficient or poor waste compaction, high leachate levels, and other conditions that define unmanaged sites. Furthermore, LandGEM may not be applicable for countries with considerably different climates or a different mix of waste types. However, LFG modellers from different countries need to be aware of factors that can induce errors within a model and apply appropriate inputs to avoid significantly overestimating the amount of recoverable LFG (US Environmental Protection Agency (EPA), 2005).

2.10.2 Multiphase Model (Afvalzorg)

The Multiphase model was **e**stablished by the Dutch landfill operator, Afvalzorg. The model is founded on a combination of literature from the 2006 IPCC model as well as the know-how of landfill gas generation and measured emissions at the Afvalzorg sites, Nauerna, Braambergen en Wieringermeer (Oonk , 2010). It is used to predict the LFG production by considering eight (8) waste categories and three (3) degradability fractions. The model has been validated for three Afvalzorg landfill sites and produces realistic prognosis of methane generation of landfills with little or no household waste (low organic matter) (Scharff & Jacobs, 2006). This model is used by Netherlands and Demark because of it’s suitability for low organic carbon landfills, and is recommended for use by countries that have landfill bans for biodegradable waste to aid in individual landfill reporting purposes. The Multiphase model is a first order model and can be described mathematically as shown using equation 2.11:

$$\alpha_t = \varsigma \sum_{i=1}^{3} c\, A\, C_{0,1}\, k_{1,i}\, e^{-k_{1,i}t}$$

Equation 2.11

Where:

α_t	= is the landfill gas formation at time t (m^3/yr)
ς	= is the dissimilation factor taken as 0.58
c	= is a constant taken as 1.87 which symbolises the transformation factor (m^3LFG/KgOM degraded)
A	= is the amount of waste in place in units of megagrams (Mg)
$C_{0,1}$	= is the quantity of organic carbon for each category (KgOM/Mg)
i	= is the waste fraction with degradation rate $k_{1,i}$
$k_{1,i}$	= degradation rate constant of fraction i (yr^{-1})

Three fractions of organic matter that degrade rapidly, moderately and slowly are distinguished in this model and for each category of waste, the rate constant and the amount of organic matter are predefined (Scharff & Jacobs, 2006).

Table 2.6 presents decay rate constant for different types of waste that degrade slowly, moderately and rapidly whereas table 2.7 shows the organic content for 8 waste categories as applied in the multiphase model.

Table 2.6: Rate constants for different types of waste as applied in the Multiphase Model (Afvalzorg, 2014)

Degradability	Type of waste	Climate Zone							
		Boreal & temperate (MAT<20°C)				Tropical (MAT>20°C)			
		Dry (MAP/PET<1)		Wet (MAP/PET>1)		MAP<1000mm		MAP>1000mm	
		Default	Range	Default	Range	Default	Range	Default	Range
Slow	Paper, textile	0.040	0.03–0.05	0.060	0.05–0.07	0.045	0.04–0.06	0.070	0.06–0.085
	Wood, straw	0.020	0.01–0.03	0.030	0.02–0.04	0.025	0.02–0.04	0.035	0.03–0.05
Moderate	Other putrescible, Garden, park	0.050	0.04–0.06	0.100	0.06–0.10	0.065	0.05–0.08	0.170	0.15–0.20
	Bulk MSW	0.050	0.04–0.06	0.090	0.08–0.10	0.065	0.05–0.08	0.170	0.15–0.20
	Industrial	0.050	0.04–0.06	0.090	0.08–0.10	0.065	0.05–0.08	0.170	0.15–0.20
Rapid	Food, sewage sludge	0.060	0.05–0.08	0.185	0.10–0.20	0.085	0.07–0.10	0.400	0.17–0.70

Because different types of waste contain different fractions of organic matter that degrade at different rates, the Afvalzorg model applies k values of 0.185, 0.090 and 0.030 for fast, moderate, and slow degradable waste fractions respectively. For each waste category, the model calculates LFG generation from the degradable organic carbon (DOC) fraction separately based on FOD equation (Scharff and Jacob, 2006).

Table 2.7: Organic matter content as applied in the Multiphase Model (Afvalzorg, 2014

Waste Category	Minimum organic matter content [KgOM.Mg-1]				Maximum organic matter content [KgOM.Mg-1]			
	Rapid	Moderate	Slow	Total*	Rapid	Moderate	Slow	Total*
Contaminated soil	0	2	6	40	0	3	8	42
C&D	0	6	12	44	0	8	16	46
Shredder waste	0	6	18	60	0	11	25	70
Street cleansing water	9	18	27	90	12	22	40	100
Sewage sludge & compost	8	38	45	150	11	45	48	160
Coarse household waste	13	39	104	260	19	49	108	270
Commercial waste	13	52	104	260	19	54	108	270
Household waste	60	75	45	300	70	90	48	320

The presented total organic matter content in Table 2.7 is higher than the sum of each category owing to the presence of organic matters that are not considered biodegradable under anaerobic conditions; examples are lignin and plastic (Scharff & Jacobs, 2006).

2.10.3 IPCC Model

The model was developed by a team of international experts to aid national authorities in the estimation of methane emissions from all landfills in a country. Under this model, emissions are estimated from waste disposed using regional per capita waste generation rates and population estimates, with deductions for LFG collection and oxidation. The IPCC Model contains a number of features that make it more appropriate than LandGEM for assessing solid waste dump sites worldwide, including applying separate first-order decay calculations for different organic waste categories with varying decay rates. Furthermore, despite the model being designed to estimate methane generation from the entire country, this model is flexible in that it can be modified and applied in estimating methane generation from individual landfills or solid waste dump sites (U.S. Environmental Protection Agency, 2012a).

Inputs into the model include the amount of waste disposed per year and classification of waste composition by origin (household waste, industrial waste, etc.). IPCC model uses the first-order decay equation and estimates gas emission from solid waste by applying a waste decay rate variable (k-value) and other variables which are combined together to yield methane generation potential variable (L_0-value) equivalent to the one used in LandGEM. Alternatively the model can also estimates gas generation from waste by applying the decay rate, and equivalent methane generation variable together with the waste composition, where waste is defined in % food waste, % paper, % wood, % soil, etc.

IPCC's methane generation model is based on the amount of decomposable degradable organic carbon matter (DDOCm) in the waste disposed. The basic first-order equation used in this model is:

$$DDOC_m = DDOC_{m(0)} (e^{-kt})$$

Equation 2.12

Where $DDOC_{m(0)}$, is the amount of decomposable degradable organic carbon (DOC) in (Mg) at the start of the reaction when time t is 0 and e^{-kt} is 1, k is the decay rate constant in (yr^{-1}) and t is time in (yr). The quantity of degradable organic matter (DOCm) in the waste is assessed from the information about the waste placed in the landfill, and its constituents such as paper, food waste, yard waste, and textile. Where this information not available at the landfill, a good estimate is the application of statistical data such as waste generation rate per capita, population growth estimates, percentage of waste generated that deposited at the landfill, etc. The DDOC is defined as the amount of DOC from waste material that can be degraded in a landfill under anaerobic conditions and this mass at any time is calculated as:

$DDOC_{md(T)} = (W_{(T)})\ (DOC)\ (DOC_f)\ (MCF)$

Equation 2.13

Where:

$DDOC_{md(T)}$ = is the amount of decomposable DOC deposited in year T (Mg)

$W_{(T)}$ = is the mass of waste deposited in year T (Mg)

DOC = degradable organic carbon under aerobic conditions (Mg C /Mg waste)

DOC_f = fraction of DOC decomposing under anaerobic conditions

MCF = methane correction factor (takes into account aerobic decomposition before anaerobic decomposition starts in the year of waste deposition)

The default values of methane correction factors used in the model are based on the landfill management types. Table 2.8 shows the landfill management types and the methane correction factors associated with them.

Table 2.8: Landfill management types (IPCC, 2006; Afvalzorg, 2014)

Type of Site	IPCC Default MCF
Managed anaerobic [1]	1
Managed semi-aerobic [2]	0.5
Unmanaged - deep (>5m) and/or high water table [3]	0.8
Unmanaged - shallow (<5m waste) [4]	0.4
Uncategorised landfill [5]	0.6

1. **Managed anaerobic landfill solid waste disposal sites** have well organised placement and monitoring of waste disposal. These sites are characterised by waste deposition on specific designated areas, controlled level of scavenging and fires, and after the waste is dumped at the designated area one of the following is performed on managed anaerobic site: (i) soil cover material; (ii) mechanical compacting; or (iii) levelling of the waste.
2. **Managed semi-aerobic sites** have well-ordered placement of waste and include the following structures that introduce air the deposited waste layer: (i)

permeable soil cover material; (ii) a leachate drainage system; (iii) erosion and ponding regulating structure; and (iv) gas ventilation system. Because air is added to the waste layer, these sites are partially aerobic in nature.

3. **Unmanaged deep dump sites** are solid waste disposal sites where the thickness of the waste layer is greater than 5m and/or the water table is high: All waste disposal site or landfills which do not meet the standards of managed solid waste dump sites and are of great depths with a high water table fall under this type of site.
4. **Unmanaged shallow dump sites** are all solid waste disposal sites that do not meet the standards of managed dump sites and are characterised by shallow depths of waste.
5. **Uncategorised Landfills** are all waste disposal sites that cannot be categorised under managed or unmanaged waste disposal sites (Intergovernmental Panel on Climate Change (IPCC), 2006).

In first order reactions, the quantity of the product is always proportional to the quantity of reactive material meaning that the year in which the waste material was deposited in the solid waste disposal site is irrelevant to the quantity of methane produced each year. However, it is the total mass of decomposing material currently in the site that is of great importance. The IPCC model uses the first order decay equation shown to estimate the amount of DDOC accumulated in the solid waste disposal site at the end of deposition year T:

$$DDOCma_{T} = DDOCmd_{T}\ DDOCma_{T-1}(e^{-k})$$

Equation 2.14

Where:

T	= inventory year
$DDOCma_T$	= is DDOCm accumulated in the SWDS at the end of year T, (Gg)
$DDOCma_{T-1}$	= is DDOCm accumulated in the SWDS at the end of the previous year (T-1), (Gg)
$DDOCmd_T$	= is DDOCm deposited into the SWDS in year T, (Gg)

The model also estimates the total amount of DDOCm that is decomposed at the end of year T using the first order decay equation:

$$DDOCm\ decomp_{T} = DDOCma_{T-1}\ (1 - e^{-k})$$

Equation 2.15

Where:

DDOCm $decomp_T$ is DDOCm decomposed in the SWDS in year T, (Gg) and

k is the first order decay constant, (yr^{-1})

The IPCC model accommodates for 4 different climate regions: wet boreal or temperate; dry boreal or temperate; wet tropical and dry tropical. In addition, the model also guides on different types of waste that degrade slowly, moderately and rapidly. The climate condition and type of waste chosen affects the k-value. Table 2.9 present k-values for different waste types and climate conditions that are provided by the model (Intergovernmental Panel on Climate Change (IPCC), 2006).

Table 2.9: Methane generation rate values for different climate conditions and degradability of waste (Intergovernmental Panel on Climate Change (IPCC), 2006).

Type of Waste		**Temperate**				**Tropical**			
		Dry		**Wet**		**Dry**		**Moist and Wet**	
		Default Value	**Range**	**Default Value**	**Range**	**Default Value**	**Range**	**Default Value**	**Range**
Slowly degrading waste	**Paper/textile waste**	0.04	0.03–0.05	0.06	0.05–0.07	0.045	0.04–0.06	0.07	0.06–0.085
	Wood/ straw/ rubber waste	0.02	0.01–0.03	0.03	0.02–0.04	0.025	0.02–0.04	0.035	0.03–0.05
Moderately degrading waste	**Garden and park waste**	0.05	0.04–0.06	0.1	0.06–0.1	0.065	0.05–0.08	0.17	0.15–0.2
Rapidly degrading waste	**Food waste/ sewage sludge**	0.06	0.05–0.08	0.185	0.1–0.2	0.085	0.07–0.1	0.4	0.17–0.7
Bulk MSW or Industrial Waste	**Mixed composition**	0.05	0.04–0.06	0.09	0.08–0.1	0.065	0.05–0.08	0.17	0.15–0.2

The model defines the climates conditions presented in the table above as follows:

Table 2.10: IPCC Climate Zone Definition

	Mean Annual Temperature (MAT)	**Mean Annual Precipitation (MAP)**	**MAP/PET**
Dry temperate	0 - 20°C	-	<1
Wet temperate	0 - 20°C	-	>1
Dry tropical	> 20°C	<1000 mm	-
Moist and wet tropical	> 20°C	>1000 mm	-

The methane that is generated from the decomposable material is mathematically established by multiplying the fraction of methane in generated landfill gas, and the methane to carbon molecular weight as provided in equation 2.16:

$$CH_4 \text{ generated}_T = DDOCm \text{ decomp}_T (F)\left(\frac{16}{12}\right)$$

Equation 2.16

Where:

CH_4 generated$_T$	= is the amount of methane generated from the decomposable material in year T, (Gg)
F	= is the fraction of methane, by volume in the generated landfill gas, (fraction)
16/12	= is the molecular ratio of methane to carbon, (ratio)

2.10.3.1 Limitation of the IPCC Model

Despite the IPCC model having four climate categories which is an improved approach for specifying the rate of methane generation (k) as compared to LandGEM's two climate category approach. The following are the limitations associated with this model as pointed out by U.S. Environmental Protection Agency (EPA).

i. Temperature has a lesser effect on LFG generation as compared to precipitation and should not be assigned equal weight in assigning climate categories.
ii. Potential Evaporation (PET) data are usually not available for most locations and should not be a basis for assigning climate in temperate regions even if they are scientifically more valid.
iii. The 1000 mm/year precipitation threshold for separating tropical climates into dry vs wet categories is better than the LandGEM threshold of 635 mm/year but is too rigid to account for the effects of precipitation across the wide range of values encountered. This means that Landfills in areas with more than 2000 mm/year precipitation would be treated the same (identical k-

values) in the IPCC Model, which wrongly implies that there are no noticeable effects from increasing precipitation above 1000 mm/year.

2.11 Landfill Gas Collection

The development of landfill gas extraction and utilization plants stem as far as the mid 1970's in the US. This technology started to appear in other places particularly in Europe shortly after success stories in the US. In 2005, Willumsen (2005) estimated the number of active LFG extraction and utilization plants to be around 1150 worldwide. According to Amini (2011), the principal purpose for recovering LFG are: odour control, GHG emission control, environmental and safety protection, energy recovery, and subsurface migration prevention. The capture of LFG reduces the direct emission of methane into the atmosphere, which would otherwise contribute to the greenhouse effect. Furthermore, the production of energy from landfill gas replaces the use of fossil fuels such as oil, coal, and natural gas, which all contribute to the greenhouse effect. Hazards related to fire and risks of explosion in surrounding facilities are also minimized when the gas is recovered.

The two major components in LFG are methane and carbon dioxide. However, methane is of greater concern to landfill gas collection project considering its global warming potential (GWP) and energy potential as compared to carbon dioxide. The generated LFG has multiple fates, including recovery, emission, and oxidization, as presented in equation 2.17 (Amini, 2011):

$$Q = Q_c + Q_{em} + Q_{ox}$$ *Equation 2.17*

Where:

Q_c = annual collected LFG, m3yr-1

Q_{em} = annual emitted LFG, m3yr-1

Q_{ox} = annual oxidized LFG, m3yr-1

The US Environmental Protection Agency (2012b) reports that capturing LFG and using it as an energy resource produces significant energy, environmental, economic, and other benefits including:

1. *Reducing emissions of GHGs*: A LFGTE project reduces CH_4 emissions from a landfill by about 60 % to 90 %, depending on project design and effectiveness (U.S. Environmental Protection Agency, 2012a). As reported by Scarlat, et al., (2015), emissions from landfilling of solid waste as of 2010 were estimated at 29 million tons (mt) CH_4, accounting for approximately 8 % of estimated global emissions. This is equivalent to emissions of about 735 mt carbon dioxide emissions (CO_2e). Therefore, based on these estimations, the collection and utilisation of LFG would reduce CO_2e by a minimum of 441 mt.
2. *Generate additional revenue:* revenue can be earned by local governments or landfill owners by selling LFG directly to end users or into the pipeline, or by selling electricity generated from LFG to the grid. Other ways in which revenue can be generated by local government include; selling renewable energy certificates (RECs) and trading GHG emissions offsets.
3. *Providing additional local capture and separation technology development, manufacturing, and marketing as well as potential associated businesses.*
4. *Increase economic benefits through job creation and market development:* local economies benefit vastly from LFG projects. For example, a typical 3 megawatts (MW) LFG electricity generation project can create more than 20 jobs during its construction phase (US Environmental Protection Agency, 2012b). Projects that collect and utilise LFG involve engineers, construction firms, equipment vendors, utilities, and end users, whose jobs are sustained each year the project operates. Furthermore, some materials and services are obtained from local economies and in some cases, new businesses can emerge near the landfill that make use of the ash from the LFG energy project to manufacture ceramic tiles and interlocking bricks (Amini, 2011). Likewise, the by-products of waste to energy (WtE) projects such as organic fertilisers and biochar can be used for carbon abatement through soil conditioning and for improving soil fertility (Ennis et al., 2013; Ghani et al., 2013)
5. *Improve air quality:* collecting LFG to produce energy improves the air quality of the surrounding community by reducing emissions of hazardous air

pollutants (HAPs) and minimizing landfill odours. Capturing and using LFG indirectly avoids emissions of several air pollutants, including sulphur dioxide (SO_2), a major contributor to acid rain, particulate matter (which are of great respiratory health concern) and oxides of nitrogen (NO_x).

6. *Conserve land:* the collection and utilisation of LFG enhances decomposition of solid waste which in turn increases landfill capacity and reduces the need of building new landfills or expand existing ones (Psomopoulos, et al., 2009). In addition, waste to energy projects contribute to the reduction of waste volumes by up to 90 % and thereby reducing the amount of waste landfilled (Stengler, 2015).

In summary, LFGTE projects can be associated with socio-economic, environmental, health and energy benefits as summarised in Table 2.11:

Table 2.11: Benefits attainable from waste to schemes

Sector	**Benefits**
Socio-economic	• Employment opportunities across the value chain • Alleviation of energy poverty • Reduced demand for land used for landfills
Energy	• Improved energy security and diversification of energy mix
Environmental	• Climate change mitigation (CH_4 capture, CO_2 reduction and abatement) • Organic fertiliser production and soil conditioning
Health	• Reduction of diseases that breed in waste piles and detraction of rodents • Potential for reduced local pollution (if managed properly)

2.11.1 Landfill Gas Collection System

A LFG control systems generally consists of collection, conveyance, treatment and utilisation components. The extraction system commonly consists of vertical pipes and horizontal pipes that are designed to be either passive or active. In a passive system, the generated gas moves through the wells and trenches by means of natural pressure gradient forces without mechanical assistance (Amini, 2011). Passive systems only assist in collecting the gas and conveying it to the next process unit and do not regulate gas flow or indicate gas characteristics (US Army Corps of Engineers, 2008). Active extraction of LFG is more effective than the natural flow and is employed whenever the forecasted gas collection is important and can be converted into a form of energy.

The operation and initial costs in a passive system are low and gas collection is inefficient. Contrariwise, the active system has higher initial and operation costs with advantages such as greater collection capacity and higher efficiency (Amini, 2011). These advantages have led to the utilisation of active systems by most landfill owners. LFG is generally collected using gas collection wells, blankets, or trenches and components of an active LFG collection system are described as follows:

1. Extraction Wells

Well systems consist of a series of vertical gas extraction wells which penetrate up to a depth near the bottom of the disposed waste. The design and sizing of extraction wells is dependent on the gas generation rate and radius of influence. Radius of influence (ROI) is defined as the point around the well at which negative pressure goes to zero. In such systems, boreholes are drilled into the waste mass whose diameter typically ranges from 300 mm to 900 mm (1 ft to 3 ft) and a minimum of 100mm (4inch) diameter high density polyethylene (HDPE), polypropelene (PP) or polyvinyl chloride (PVC) pipe casings are placed in the bore. HDPE and PP pipes are usually used due to their flexibility and resistance to fracturing during settlement of the refuse as compared to PVC pipes which are usually more brittle and susceptible to fracturing. The bottom two-thirds of pipes are fitted with perforated or slotted casings that act as screens (US Army Corps of Engineers, 2008). A gravel pack is installed around the screens which extend to a minimum of 300 mm (12 inches) above the end of screen. A bentonite layer with a thickness ranging between 600mm to 1300 mm (2 ft to 4 ft) is placed on top of the gravel to prevent ingress of air into the landfill. Thus the gases developed in the landfill travel through the perforated pipes and are collected at the top of the pipe. Figure 2.3 shows a typical LFG vertical extraction well detail (Global Methane Initiative, 2012):

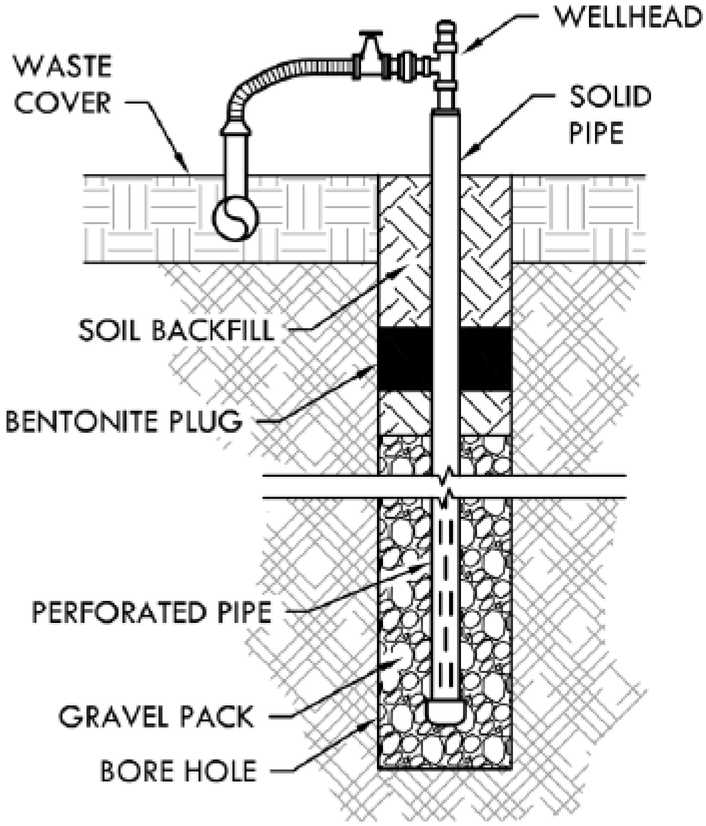

Figure 2.3: Typical vertical extraction well detail (Global Methane Initiative, 2012)

In comparison to vertical wells, horizontal wells consist of perforated pipes which are sensitive to leachate flooding and differential settlement, and pipes in horizontal systems are placed in the refuse during deposition. A noteworthy advantage of the vertical system is the reduction in the number of wells required and its larger zone of influence. However, the main problem in this system is the operating costs and frequency of maintenance since vertical wells fill with water and leachate, thus extraction pumps are required to be installed in each well. This water accumulation is a great challenge for landfills in wet climates that utilise vertical wells. In recent years, landfill owners in wet climates have been applying horizontal extraction wells and the reason may be attributed to water accumulation in vertical wells (Amini, 2011). On the other hand, the main advantage of horizontal collectors is that they can be installed and operated within the active waste disposal zone as compared to vertical wells where it is a requirement for the landfill to first reach its final elevation before the wells can be drilled in the landfilled waste. Figure 2.4 shows a typical LFG horizontal collection system.

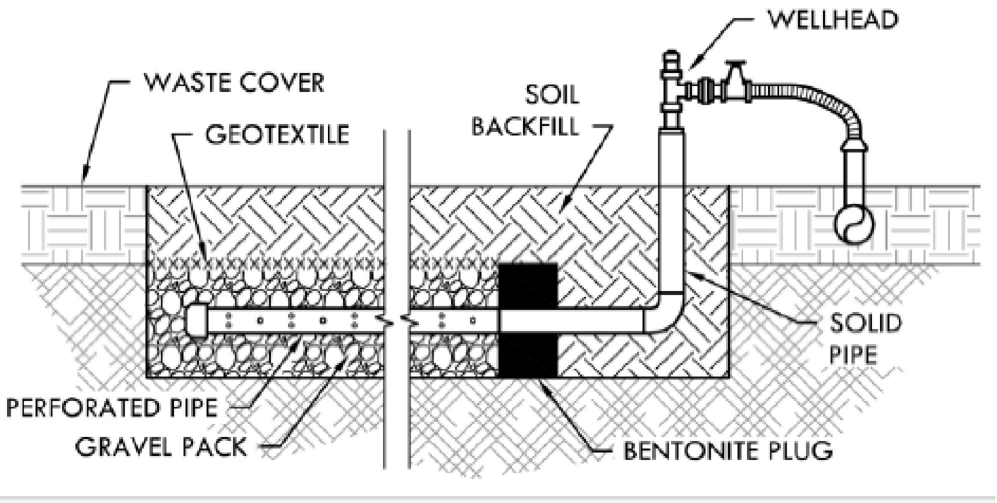

Figure 2.4: Typical horizontal collection system (Global Methane Initiative, 2012)

2. Header Piping

The most common method of transporting LFG to the utilization system such as a flare is by connecting the wells and trenches to a main collection pipe known as the header pipe. The piping system will typically have several branches and each branch is attached to multiple extraction wells. The amount of gas flow coming from individual wells and branches is controlled by valves. Flexible hoses which are smaller than the header pipes are commonly used to connect vertical wells to headers. Header pipes are typically made of PVC or HDPE.

Head losses due to long branching networks and breaks or leaks in the network are the common problems associated with the piping system. Therefore, pipes are sized to deliver the minimum head losses in the system as well as sufficient in size to provide extra capacity if additional wells are added later. The optimum head loss or pressure drop per 30 m (100 ft) of pipe is 25 mm (1 in) of water column (wc). In the pipe system the desired LFG velocity should be less than 15m/s in cases where LFG and its condensate are flowing concurrently. This maximum velocity is important as it enables the condensate to condense on the LFG header piping side walls. For counter-current flow of LFG and its condensate, the velocity of is limited to 9m/s so as to avoid the condensate from damming up and blocking the flow of LFG (US Army Corps of Engineers, 2008). Header pipes are slopped as indicated in table 2.12:

Table 2.12: Header pipe slopes (US Army Corps of Engineers, 2008)

Position	In direction of gas flow	Opposite direction of gas flow
On Landfill	2 % slope	4 % slope
Off Landfill	1 % slope	3 % slope

3. ***Extraction Compressors***

LFG is extracted from the landfill by a compressor also known as a blower by applying a negative pressure in the transmission pipes. This negative pressure created is necessary to pull the gas from the collection wells into the collection header and convey the gas to downstream treatment and energy recovery systems. The type, sizing and number of blowers required is dependent on the gas flow rate and distance to downstream processes (U.S. Environmental Protection Agency, 2012a).

4. ***Valves and Gauges***

The quantity and quality of collected LFG should be measured including flow, temperature, pressure and methane content in order to control and analyse the effectiveness of the gas collection system and to measure fugitive gas emissions. Valves are utilized in LFG collection systems for flow rate control and on/off control. Similarly, gauges are also installed at well heads but used to measure the collected LFG flow, temperature, and pressure. The valves may be manually controlled or automatically actuated by an electric or pneumatic power source.

2.11.2 Landfill Gas Collection Efficiency

The efficiency of a LFG collection system is generally assessed by measuring the collected gas at the landfill and comparing the results to gas generation model outcomes. There has been an improvement in LFG collection systems over the years, however, inefficiencies are encountered due to operational and design flaws. The US EPA uses a default LFG collection efficiency value of 75% (US Environmental Protection Agency, 2008). However, According to Amini (2011), the default values used by US EPA are based on results from a survey in which experts in LFG were asked to give their opinion for a proper LFG collection efficiency. From this survey an average collection efficiency figure of 75 % was arrived at. Due to high costs, few research studies have been done at field-scale level regarding LFG collection efficiency. Contrary to the US EPA default value, a study by Huitric et al. (2007) indicates higher collection efficiencies for landfills with proper cover, capping, and collection system. Huitric et al. (2007) employed two methods, the Integrated Surface Methane concentration data (ISM) or Industrial Source Complex air dispersion model (ISC) and the Flux Chamber method to measure the gas collection efficiency in Palos Verdes Landfill, Los Angeles, California. Both methods measured collection efficiencies above 99 %.

The collection efficiency of LFG varies depending on the design, installed hardware, and operational conditions. Field studies performed by Spokas et al. (2006) and Ogor & Guerbois (2005) propose that the capture of LFG with a geomembrane cap significantly exceeds 90 %. A study by Spokas et al. (2006) on three landfills established that 35 % collection efficiency can be achieved for a landfill with no cover but has an operating cell with an active LFG collection system, 65 % collection efficiency for a cell that has an active LFG collection system with a temporary cover, 85% collection efficiency for a cell that has an active LFG collection system with a final clay layer covering, and 90 % collection efficiency for a cell with an active LFG collection system that has a final geomembrane covering. Likewise, in a report prepared by SCS Engineers for the Solid Waste Industry for Climate Solutions (SWICS), the proposed collection efficiencies were as follows (SCS Engineers, 2008):

- 50 % to 70 % with an average of 60 % for an active landfill with an active gas collection system and under daily soil cover;
- 54 % to 95 % with an average of 75 % for an active landfill with an active gas collection system and intermediate cover material; and
- 90 to 99 % with an average of 95 % for an active landfill with an active gas collection system and final soil and/or geomembrane cover.

2.12 Waste to Energy Technologies

Waste-to-energy (WtE) technologies are used to convert the energy content in different kinds of waste into various forms of valuable energy such as electricity, heat/steam and biofuels. Electricity generated from waste can be distributed through national and local grid systems. Heat or steam that is produced from waste can be transported through a district heating system or used on site by the industries producing this form energy for specific thermodynamic processes. Furthermore, a number of different kinds of biofuels can be extracted from organic waste to produce fuels that after refining can be sold on the market. Other benefits that can be realised from WtE technologies are the reduction of waste volume, reduction of land used for landfills, and reduction of the environmental impact landfills have on the environment (Psomopoulos et al., 2009; World Energy Council, 2013; Stengler, 2015).

Different energy outputs are obtained from different WtE technologies and the feasibility of the technology is dependent on the waste composition and the waste flow. Every technology applied has its pros and cons. There is no technology that provides a universal solution that always suits a particular area. It is important for each technology to be scrutinised in relation to the available waste as well as the demanded output coupled with the social impact the technology has on the region (Rawlins, et al., 2014).

Rawlins, et al. (2014) presents that WtE technologies are divided into two categories, chemical conversion technologies and thermal processing categories as shown in figure 2.5:

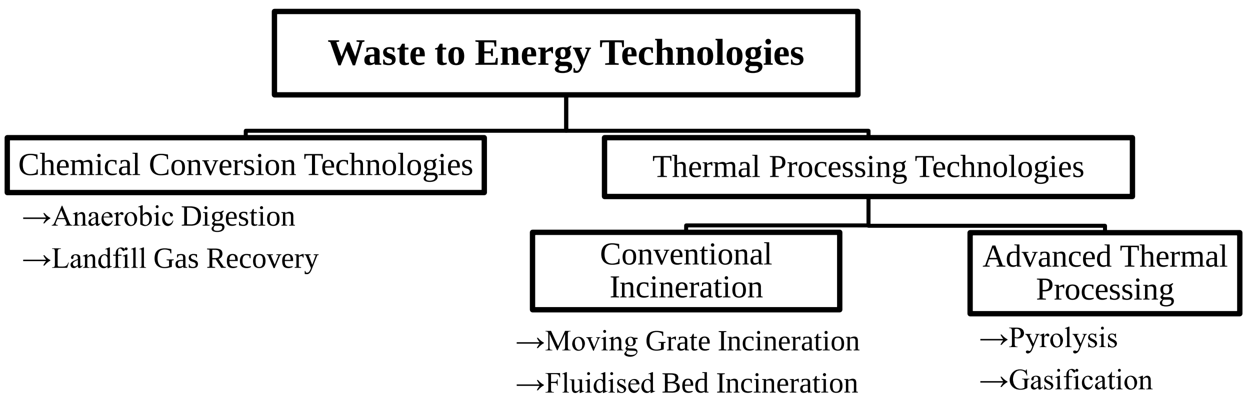

Figure 2.5: Waste-to-energy technologies (Rawlins, et al., 2014)

Chemical conversion technologies involve the bio-chemical decomposition of organic waste which creates biogas. The biogas produced by decomposition of organic matter is burned for direct heat and power use, or refined to biofuels. The main chemical conversion methods under this technology are anaerobic digestion and landfill gas recovery (Rawlins, et al., 2014). On the other hand, thermal processing technologies involve the combustion of solid waste to generate energy. The combustion generates heat that can be used directly or converted into electrical energy. The most common thermal processing technology is conventional incineration which employs two methods, moving grate incineration and fluidised bed incineration. Advanced thermal processing is yet another category under thermal processing technologies that uses advanced methods such as pyrolysis and gasification to produce more versatile range of products such as syngas (combination of methane, carbon dioxide and hydrocarbons), liquid and solid fuels, heat, and electricity.

2.13 Landfill Gas to Energy

LFGTE projects vary across the African region due to various factors that affect the rates and quantities of MSW generated. According to Simelane & Mohee (2012), the rates and quantities of waste generation on the African continent differ in accordance with local economies, urbanisation and population, level of industrialisation, lifestyles and waste management systems of the various countries. Table 2.13 shows some LFGTE projects in Africa and the respective installed electricity generation capacity.

It is evident from table 2.13 that African countries have realised that waste can be converted to energy by chemical conversion and thermal processing technologies. For instance, Zambian has entered into a Public Private Partnership (PPP) with Genniz Engineering, Surveying and Environmental Consultant Services Limited (GESECSL), a European company that is planning to invest in treating solid waste and establishing energy production plants to generate energy through gasification. However, despite the increased number of WtE schemes in Africa, there is limited information on the specific projects presented in the table to evaluate the accomplishments and challenges encountered in each of the countries.

Table 2.13: Waste-to-energy technologies

Title	Country	City / Province	Year	WtE Scheme,	Power Generation	Waste(t)
Akouédo Landfill Rehabilitation and Electricity Generation Project	Ivory Coast	Abidjan	2009	Landfill gas	30MW	200,000p.a
Alton Landfill Gas to Energy Project Landfill gas	South Africa	KwaZulu-Natal	2006	Landfill gas	0.4	77,000p.a
Durban Landfill-gas-to-electricity project – Bisasar Road Landfill	South Africa	KwaZulu-Natal		Landfill gas	10	
Durban Landfill-gas-to-electricity project – Mariannhill and La Mercy Landfills	South Africa	KwaZulu-Natal	2015	Landfill gas	0.5	200,000p.a
La Chaumiere waste to Energy	Mauritius	La Chaumiere	2013	Ultra-High temperature Gasification	20	300,000p.a
North East & Centre UHT Gasification WtE Projects	Mauritius	North East & Central	2017	Ultra-High temperature Gasification	36	1,300p.d
50MW Waste to Energy Plant	Ethiopia	Addis Ababa	2013	Landfill gas	50MW	350,000p.a
Yaoundé and Douala Waste to Energy Plant	Cameroon	Yaoundé	Proposed	-	100MW	-
Dandora Waste to Energy	Kenya	Nairobi (Dandora)	Proposed	Landfill gas	70MW	3,000p.d
Accra Waste to Energy	Ghana	Accra	2014	Landfill gas	6MW	270,000p.a
Accra Waste to Energy	Ghana	Accra	2014	Landfill gas	10MW	360,000p.a
Energy production from solid waste	Zambia	Lusaka & Copperbelt	Proposed	Ultra-High temperature Gasification		
Lagos Landfill gas to Energy	Nigeria	Lagos (Olusonsun)	-	Landfill gas	25MW	10,000p.a

CHAPTER THREE: METHODOLOGY

3.1 Introduction

The previous chapter presented reviewed literature on landfill gas estimation models, types of gas collection systems and waste to energy technologies.

This chapter will outline the methodology which was used to conduct the research in order to address the formulated aim and objectives thereby answering the research questions. Methodology is defined by Dawson (2007) as the philosophy or the general principle which guides one's research. This chapter therefore highlights the various methodologies and methods that can be adopted for the purpose of the research. It also presents the approach used to investigate the research problem and outlines the tools used in this endeavour. The chapter further describes the essential traits of the research sample and the methods of analysing collected data.

3.2 Research Approach

A funnel approach was used in undertaking the study. The funnel approach is where one starts with broad or general known information referring to the wide part of the funnel then proceeds to elaborate on the general information, becoming more and more specific, or narrow in focus as the researcher proceeds. This was done by obtaining and reviewing literature on the available landfill gas estimations models, landfill gas to energy cost models, and what innovations other nations have in place with regards to converting waste to energy, and thereafter assessing the feasibility of landfill gas to energy at waste dump sites in the Zambia, particularly Chunga landfill.

3.3 Pragmatism Research Paradigm

This research has been grounded in the pragmatic paradigm as it supports the use of both qualitative and quantitative research methods in the same research. Pragmatism is reported by (Tashakkori & Teddlie, 2003) as the best paradigm for justifying the use of mixed methods and several authors have supported the use of this paradigm. The flexibility of this paradigm enables implementation of elements of other paradigms, since the general sense to pragmatism is to perform what best fits the research.

3.4 Mixed Method Research

The understanding of people differs and the use of a single method cannot reveal all aspects required for a particular research, which is why researchers need to use a mixture of appropriate methods Tunnicliffe and Moussouri (2003). Through amalgamation of qualitative and quantitative data, a better understanding of a research problem can be achieved as compared to using either approach alone (Creswell, 2003). Patton (2002) and Giddings & Grant (2006). presents that mixed methods research are useful in survey, evaluation, and field research because of the broader focus it bears coupled with the capability of gathering more information in different modes about a phenomenon than single method design.

The challenge of mixed methods research is presented by Ary et al. (2009) as time consuming and the requirement of expertise to combine quantitative and qualitative research within one study. This is a limitation that has been acknowledged in this study and addressed through cautious yet strategic time management in order to complete the research within the academic year and also through additional training in research methods individually as well as postgraduate lectures.

3.4.1 Mixed Methods Research Designs

Concurrent and sequential designs are the two main characteristics which emerge from mixed methods. According to Bergman, (2008), the concurrent design brings together qualitative and quantitative data in parallel whereas the sequential design uses one type of data to build on the other. The concurrent design uses quantitative and qualitative methods separately in order to offset any weaknesses within one method with the strengths of the other method. In this design, both forms of data are collected in parallel or at the same time and then united into a single interpretation of the overall results (Creswell, 2003, p. 16). On the other hand, sequential designs arise when the researcher collects and analyses one type of date before using the other data type by implementing the methods in two distinct phases (Creswell, 2003). The researcher can either collect quantitative data first or qualitative data first, both approaches are possible.

As established earlier under the research design component of this study, mixed methods combine qualitative and quantitative data using four designs namely: explanatory, exploratory, transformative or nested designs. The reasons that influence selecting a type of mixed method design are presented by Rossman & Wilson (1991) as:

1. to enable confirmation or corroboration via triangulation
2. to elaborate or develop analysis, providing richer detail, and
3. to initiate new lines of thinking through.

In a mixed method research, a researcher has to prioritise one type of data than the other data type (Creswell et al., 2003). Priority refers to the giving of either quantitative or qualitative method more emphasis in the study.

Each design of the four presented has its own utility, procedures, strengths and weaknesses that are dependent upon the research context, however based on the research questions and objectives of this study, the selected design was the Sequential Exploratory Design (Creswell 2003; Creswell et al. 2003; Creswell & Plano Clark (2007).

3.4.2 Selection of Mixed Method Sequential Exploratory Design

This research seeks to review the theoretical landfill gas estimation models and utilise the models that are more applicable to the case study landfill (Chunga) in estimating gas production, and assessing the financial feasibility of converting methane gas to electricity. A research design was needed to explore methane production from decomposing solid waste in landfills under the theoretical framework of existing scholarly work which considers approaches and incentives in estimating gas production and the renewable energy potential of methane. Therefore, to undertake this study and answer the research questions, a mixed methods sequential exploratory design was chosen.

The research design adopted in this study is an approach to research that is conducted across two sequential phases. Greene et al. (1989) in (Creswell, 2003) established that the intent of the two phase exploratory design is that the results of the first method (qualitative) help inform the second method (quantitative). Figure 3.1 shows the mixed methods representation of an exploratory sequential design. The lower notation of 'qual' is used in the figure to indicate that the qualitative source will be less dominant while the uppercase 'QUAN' shows dominant, quantitative source.

Phase One			**Phase Two**			
Qualitative Phase			**Quantitative Phase**			
Qual data collection	Qual data analysis	Qual findings	Identify variables to study quantitatively	QUAN data collection	QUAN data analysis	Integration and interpretation of QUAN and Qual data

Figure 3.1: Graphical representation of mixed methods research processes (Myers &Oetzel, 2003: Creswell & Plano Clark, 2007)

According to Creswell et al. (2003), a design which begins qualitatively is best suited for exploring a phenomenon. This design is particularly useful when a researcher needs to: a) build a new instrument because a suitable one is not available or b) identify important variables to study quantitatively when the variables are unknown (Creswell et al., 2003). Sequential exploratory designs are also appropriate when a researcher wants to generalise results to different groups (Morse, 1991), to test aspects of an emergent theory or classification (Creswell and Plano-Clark, 2007) or explore a phenomenon in depth and measure its prevalence.

In most sequential exploratory designs, the initial qualitative phase is given more emphasis, followed by a second quantitative one. Though there are examples in literature of the quantitative element taking priority or both phases being treated equally (Creswell 2003). Therefore, this study puts emphasis on the quantitative element. The aim of the sequential explanatory design is to collect and analyse qualitative data to provide a general understanding of the research problem. The findings of this initial phase are then used to inform the conduct of the second phase, which collects and analyses quantitative data. The sequential exploratory design utilises the initial phase to identify variables to study quantitatively and integrates the findings after both phases have been completed.

3.5 Research Process

The research process explains the manner in which the data collection and data analysis within this research was carried out. The actions are explained in a sequential manner; in line with what actually happened, and in the order that it occurred.

In order to contribute to the body of knowledge, the study avoided replicating previous work by making a broader and in-depth understanding of landfill gas estimation models, decomposition of waste in a landfill, the energy potential of methane gas, operation of landfill gas to energy projects, design of landfill gas collection and utilisation system, existing landfill gas to energy projects and the assessment of financial feasibility of converting landfill gas to electricity through literature review. This accounted for the secondary data and was done throughout the course of the study so as not to miss any relevant information at any stage of the research, and inform the type of primary data to be collected. Primary research data collection was conducted through interviews in which the questions were unstructured so as to encourage a historical background of the waste dump site and encourage a conversation with in-depth answers.

The research process was conducted over a two phase approach with the initial phase covering secondary data collection and analysis, and a final phase that identified variables to study quantitatively through analysis and manipulation of statistical data and interview responses to produce primary data.

3.5.1 Phase One

This study focuses on estimations of landfill gas production at Chunga landfill, electricity generation from methane gas produced by decomposing waste and a financial feasibility of landfill gas conversion to energy. In order to accomplish the research questions and objectives, an extensive and relevant literature review was conducted in an attempt to provide a theoretical foundation for the research project. The initial phase in the sequential exploratory design adopted in this study, was literature review. This provided scientific explanations for the research questions, and enabled verification of findings and comparisons with other findings by scholars in the field of waste to energy projects.

As per the exploratory research design, phase one comprises of qualitative data collection, analysis and results. It addresses the first two research questions:

1. Describe the prominent gas emissions models used in estimating LFG?
2. What parameters can be manipulated, removed or introduced to the theoretical models to reduce errors in quantifying gas emissions from the landfill?

Qualitative Phase Population Selection and Sampling

To eliminate any ambiguity, the target population was clearly defined before making sampling choices (Daniel, 2012). The study focused on Chunga landfill which is managed by Lusaka City Council (LCC) under the Department of Public Health. The Environmental Management Act (EMA), 2011 mandates the continued existence of Zambia Environmental Agency (ZEMA) whose overall responsibility is the provision for integrated environmental management and the protection and conservation of the environment. ZEMA collaborates with Government agencies, appropriate authorities, and other institutions to control pollution and protect the environment. For this to be possible, the Waste Management Unit (WMU) manages disposal sites and is a regulatory unit of waste management under LCC that is mandated to plan, organise, execute and supervise waste management services in some selected areas in the city. Physical access to the landfill for the purpose of face to face interviews with landfill operators and observations of activities at the landfill were made possible by LCC Public Health Department.

In this research, sampling was done by selecting a subset of a population (LCC staff) for inclusion in the study (Daniel, 2012). Sampling was done strategically to provide reliable data as well as save on resources such as money and time. To collect in-depth information about the landfill, a non-probability sampling approach was adopted which ensured that elements in the target population were not given an equal chance of being selected for inclusion in the study (Daniel, 2012). Therefore, the findings cannot be inferred or generalised from the sample to the population. Non-probability sampling also allowed the researcher to select participants based on their level of involvement in the management of activities at Chunga landfill.

During the qualitative phase of the study, the researcher's intention was to include only participants with information required to attain the research objectives. This dictated implementation of a purposive sampling approach which is a technique under non-probability sampling (Dawson, 2007; Mugenda & Mugenda). The information provided by the participants assisted in establishing the level of management at the landfill which increased the accuracy during estimations of landfill gas production. Owing to the above reasons, probability sampling was rendered inconsistent with the research objectives (Mugenda & Mugenda, 2003). This formed the basis on which non-probability sampling was chosen.

The targeted respondents at LCC were, the head of public health department, environmental engineers, cleansing superintendent at the landfill, landfill foreman and technicians. They were selected as they are likely to be the most knowledgeable about past, current and future activities at the landfill that could aid in understanding the life history of Chunga landfill. Another non-probability sampling approach utilised in the study was the 'respondent assisted sampling technique', which selected elements from the target population after assistance of previously selected elements (participants). This provided an opportunity to identify and engage additional participants which were not identified by the researcher. Additional participants that were identified through the respondent assisted sampling included: two multi-disciplinary international engineering consultants operating in solid waste management and landfill design with offices in Lusaka, namely COWI and SMEC Holding. These organisations offered a perspective on the operations of landfills and gave insights on landfill gas to energy projects.

Physical meetings with the participants were arranged and in cases where additional information was required and instances when it was not possible for face to face meeting due to unavailability of respondents, telephonic and email consultations were used.

Quality in Qualitative Research

Quality concepts such as validity, reliability and generality have been the subject of debate in qualitative research, particularly their appropriateness in the qualitative paradigm as opposed to quantitative paradigm. “Yardley (2008)” presents that validity, reliability and generality are inappropriate for qualitative research and stresses that quantitative research depends on the elimination of error caused by the influence of the researcher while qualitative research accepts this influence and works with it. On the other hand, “Spencer et al. (2003)” as cited by “Brannen (2005)” recognises that quality concepts such as generalisability, validity, reliability and replicability are appropriate in quantitative research.

The quality criteria which is used in a research study depends on whether the qualitative method has more emphasis than the quantitative method or the opposite and type of data analysis used within the research (Bryman, 2006). In this research the qualitative component is less dominant and therefore, reliability and generalizability play a relatively minor role (Creswell, 2003).

According to “Patton (2002)” as quoted by “Cottrell & McKenzie (2011)”, credibility in research depends on rigorous methods, the credibility of the researcher, and the philosophical belief in the value of qualitative research. Rigorous methods in the qualitative phase of this research were employed through a systematic approach to research design, careful data collection and analysis, and effective communication (Cottrell & McKenzie, 2011). This ensured the adoption of a research design which was appropriate to answer the research objectives and questions. It informed the timing of the research stages and the information to be extracted from engineers, operators and technicians at the landfill. This guided the type of data required to be analysed in the quantitative phase in order to achieve the research objectives.

3.5.2 Phase Two

The second phase in the exploratory research design comprised quantitative data collection, analysis and integration of the qualitative and quantitative findings. The qualitative phase informed the conduct of the quantitative phase. The quantitative sampling comprised of various data bases, specifically waste generation, waste composition, population statistics and energy supply costs. Building on phase one, phase two addressed the last two research questions:

1. What landfill gas extraction equipment is suitable for the gas recovering system designed?
2. What is the cost of construction and operations against the rate of return on the investment of methane recovery and electrical energy production?

3.6 Data Sources and Collection Techniques

3.6.1 Secondary data collection

Secondary data collection was done through the review of literature written on the subject matter. The review of literature was essential because, it assisted in making clear the prominent landfill gas estimations models, assumptions made by different models and factors affecting the accuracy of model outcomes. Literature also reviewed the guidelines on financial feasibility of waste to energy projects and gave an introduction to any other research material which would be beneficial to this study (Dawson, 2007). Further, the review of literature was to guarantee that the study was in the context of what had been done by other researchers before. The intention of this author was not develop a theory or a model but to use the existing models and theories to answer the research questions and develop a solution to the research problem. In order to avoid reviewing irrelevant information the following ground rules were formulated:

1. Review literature relating to solid waste management, landfill gas generation, methane conversion to electricity, costing of landfill gas to energy projects,

design and operation of landfill gas collection system, and feasibility of waste to energy projects.

2. The review of literature should endeavour to clarify the research questions and establish the relevance of the aim as well as the objects.

Secondary data was also collected using unstructured interviews that triggered in-depth information from the respondents on life history of the landfill. The information provided reviewed the operations, design, number of cells and life span of the landfill. This was necessary to establish a reasonable assumption of the cross section of the landfill which assisted in the design of a gas collection system

3.6.2 Unstructured Interviews

The unstructured interviews were conducted between 2nd January 2016 and 16th March 2016. The target population were the employees of Lusaka City Council (LCC) and private engineering firms with technical know-how of landfill operation and management. The interviews were administered to landfill operators, technicians, engineers and personnel from private consulting firms with solid waste management expertise. A total of 7 interviews were conducted to establish the level of management at the landfill, collect any waste disposal data, capture the techniques and operations at the landfill. The collected data was used in depicting the site conditions of the landfill which assisted in applying appropriate parameters during gas emission modelling. Further, the collected data also established the year the landfill was opened and a personal grading of the functionality of the landfill. This information was very important as it increased the accuracy of the model outcomes since the parameter used for gas emission modelling were related to the prevailing site conditions at Chunga landfill. The data collected from personnel at the two private engineering firms consulted, gave an insight of landfill collection system design and operations which was very important in the preliminary landfill gas collection system design.

The 5 respondents from LCC indicated that consistent waste disposal data was not available and the tonnage of waste landfilled was estimated through personal judgments by the technicians who considered the level of waste carried in truck and waste composition. An average level of management and functionality was established as 50 %, however, the study adopted a conservative value of 40% as the worst case since spreading and compaction of the disposed was is done intermittently due to plant breakdowns and delayed repairs.

Sources of literature

The validity, reliability and adequacy of the literature were considered to largely depend on the source (Kothari, 2004). According to Yardley (2008), validity is the degree to which findings are accepted as sound, legitimate and authoritative. Valid findings were regarded as trustworthy and useful. The main sources of literature for the study were:

1. Journal and conference proceedings index.
2. Abstracts.
3. Theses and dissertations.
4. Government publications.

3.6.2 Primary data collection

Primary data consisted of first-hand information (Kumar, 2005) which allowed the researcher to collect information unique to the research and not easily accessible through secondary platforms. This was achieved by conducting unstructured interviews with experts in landfill gas to energy projects, field surveys and manipulation of pre-existing statistical data by using analytical and numerical computational methods.

3.7 Method of Data Analysis

Data collected from the statistical publications and interviews was analysed through the use of graphic statistics such as graphs, tables, pie charts and bar charts. Other types of data collected and analysed include; satellite images, and computer aided design (CAD) drawings and simulations. The analysis of data was performed in a neat, methodical and enhanced accuracy manner by utilising first principles, CAD software and computer statistical software package particularly, Microsoft excel.

Analysis was done on available literature of previous researches on municipal solid waste in Lusaka. Municipal solid waste generation in the city was estimated using the per capita generation rate of 0.5 kg per person per day. The waste was characterized as paper and cardboard, metals, plastics, glass, textiles (cloth), putrescibles (food waste), and gritty material (soil, dust and street sweepings). Consistent records of waste disposal from the landfill were not available, thus population data was used since opening of the landfill in 2007 to estimate the quantity of waste in place as well as forecast waste generation until the closure year of the landfill. The United States Environmental Protection Agency standard procedure for qualifying landfills for energy recovery projects (U.S. EPA, 1996) was then used to determine whether the Lusaka City Council landfill is a good candidate for energy recovery. The study further investigated the amount of gas production from the landfill using the LandGEM, IPCC and Afvalzorg models. These models utilise the first order decay equation to approximate the gas production from a given quantity of waste, decomposable organic carbon content and organic carbon content respectively that has been landfilled for a given period of time in years.

3.7.1 Description of Chunga Landfill and Waste Characteristics of Lusaka

The Chunga Engineered Landfill Site is located at Chunga, a suburb of Lusaka city at a geographic latitude and longitude of -15º21'2919" and 28º14'39.79" respectively. Chunga landfill was opened in 2007 and originally designed to receive waste over a period of 25 years. The landfill is owned by Lusaka City Council and managed by Waste Management Unit, a regulatory unit of waste management. The engineered landfill consists of a single lined cell with no gas collection system in place.

In 2001, only 15 % of the total waste generated by the city was collected and disposed off at a designated dump site (ILO, 2001). In 2016, the Millennium Challenge Account Zambia (MCA Zambia) established that only 30 % of the waste generated by the city is deposited at Chunga landfill (MCA Zambia, 2016).

Domestic waste in Lusaka accounts for 80 % of the total waste generated in the city and the remainder is commercial waste coming from industries, markets, hotels and hospitals (LCC, 2003). The characteristics of domestic and commercial waste are presented in table 3.1:

Table 3.1: Characteristics of Domestic and Commercial waste (LCC, 2003; ILO, 2001)

Waste Component	**Domestic Waste**				**Commercial Waste**
	High Density	**Medium Density**	**Low Density**	**City Average**	
Paper and Cardboard (%)	2.7	4.2	7.3	4.7	12.0
Metals (%)	1.6	1.8	2.3	1.9	6.0 *
Plastics (%)	3.0	4.8	6.7	4.8	7.0
Glass (%)	0.8	2.6	2.5	2.0	1.5 *
Textiles (%)	1.7	1.4	1.1	1.4	0.5 *
Putrescibles (%)	24.8	55.0	68.7	49.5	23.0
Soil, Ashes & Dust (%)	65.6	30.2	11.7	35.8	50.0
Weight (kg/day)	0.56/cap	0.54/cap	0.41/cap	0.50	1.7/stall
Density (kg/m^3)	395.0	309.0	495.0	399.7	12.0
* total of 8 % for metals, glass and textiles as established in secondary data sources reviewed and distributed as shown based on recycled waste characteristics at the landfill					

3.7.2 Waste Composition

The waste composition at the landfill was characterised as; paper and cardboard, metals, plastics, glass, textiles (cloth), putrescibles (food waste), and gritty material (soil, dust and street sweepings). The waste composition for the domestic and commercial stream deposited at Chunga landfill is as shown in figure 3.2 and 3.3 respectively:

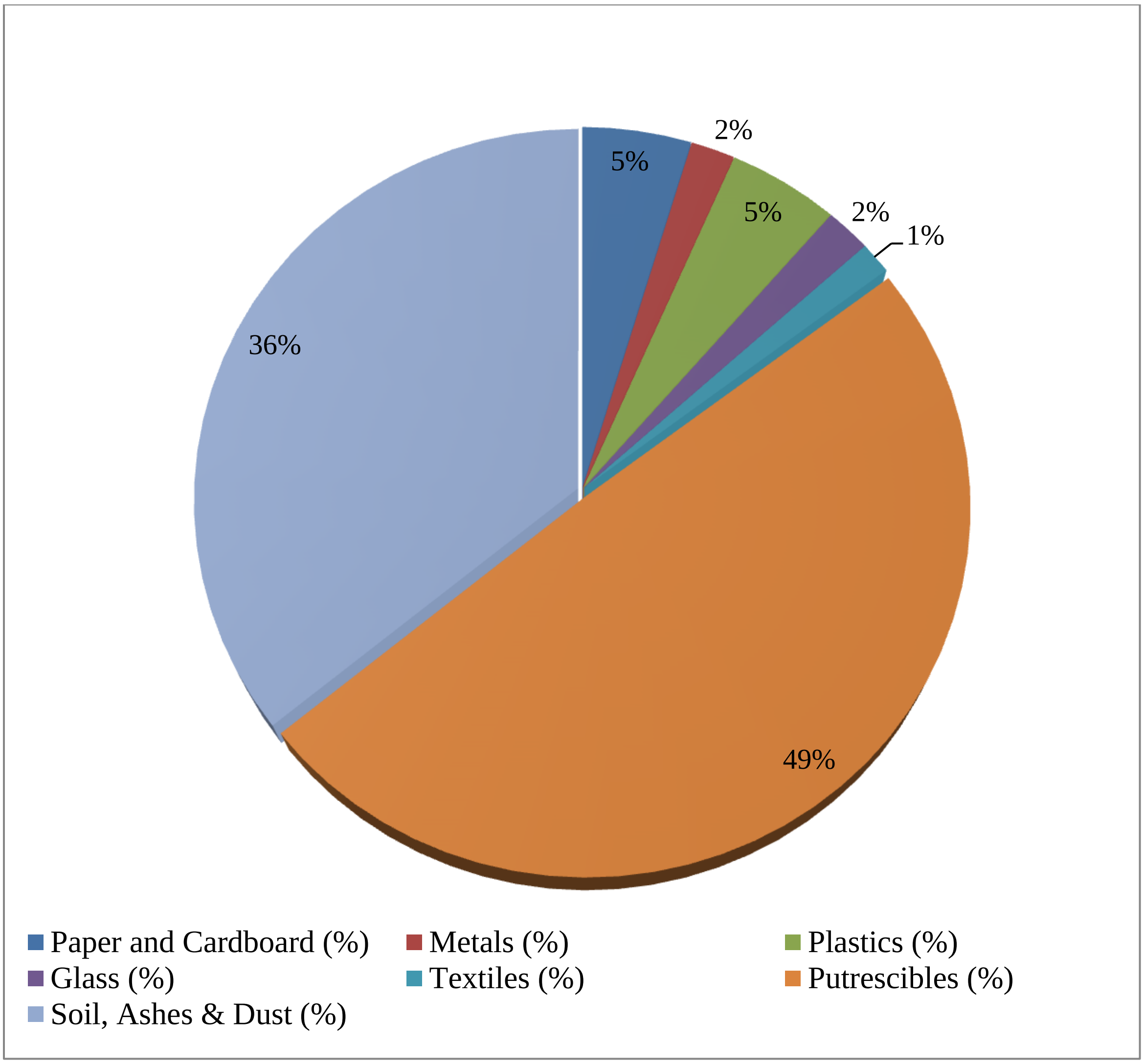

Figure 3.2: Domestic waste composition

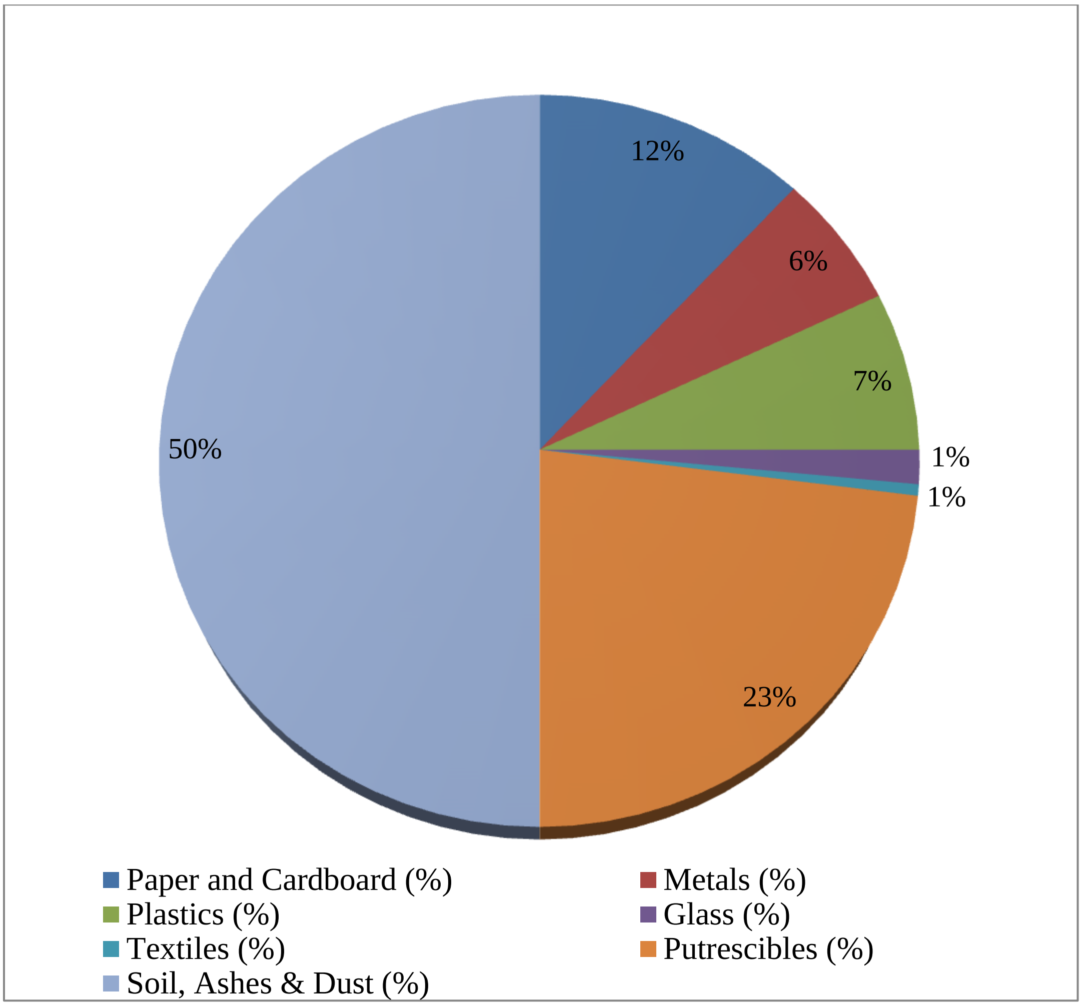

Figure 3.3: Commercial waste composition

3.7.3 Waste Generation

Consistent records of waste disposal from the landfill were not available, thus population data was used since opening of the landfill in 2007 in order to estimate the quantity of waste in place as well as forecast waste generation until the closure year of the landfill. Swapan & Bidyut (2014) used population statistics to estimate waste generation and future trends for Kolkata, a metropolitan area in India. Likewise, Khajuria, et al. (2010) estimated future population based on present trends and established the future amount of municipal waste generation for the studied developing Asian countries. Therefore, present population trends and statistical data on population growth in Lusaka city as established by the Central Statistics Office (CSO) were used in estimating past, present and future population and subsequently waste generation by employing equation 3.1 and 3.2 respectively (Swapan & Bidyut, 2014; Khajuria, et al. 2010).

$$P_{forecast} = P_{initial} \left(\frac{1 + \%\ growth\ rate}{100}\right)^{year}$$

Equation 3.1

$$DW_i = \frac{W_{generation}\ P_{forecast}\ F_{collection}\ N_{days}}{1000\ /ton}$$

Equation 3.2

Where:

$P_{forecast}$	= population recorded or forecasted
$P_{initial}$	= initial population
DW_i	= domestic waste generated in a particular year (tons)
$W_{generation}$	= waste generation per capita (kg/cap/day) taken as 0.5kg
N_{days}	= number of days in a year (taken as 365)
$F_{collection}$	= fraction of waste collected and deposited at the landfill. The collection efficiency factor applied between 2007 up to 2016 was taken as 0.225, which is the average of 15% established in 2001 (ILO, 2001) and 30 % estimated in 2016 (MCA Zambia, 2016). Starting from 2017 up to the closure year of the landfill, the collection efficiency factor was taken as 0.3.

The annual population growth rates used are as shown in Table 3.2. The population statistics and demographic projections that were applied in the calculations were obtained from Population Central Statistics Office (2013) and Central Statistics Office (2012).

Table 3.2: Annual population growth rates for Lusaka

Year	Population Growth Rate (%)
2000	3.4
2005	4.6
2010	4.6
2015	4.6
2020	4.2
2025	3.8
2030	3.5
2035	3.2

The portion of the waste that is landfilled with a commercial origin accounted for 20 % of the total waste deposited (LCC, 2003). To estimate the waste generated in a particular year from the commercial stream, equation 3.3 was applied:

$CW_i = DW_i \, C_{factor}$

Equation 3.3

Where:

CW_i = amount of commercial waste landfilled in a particular year $(tons)$

C_{factor} = conversion factor from domestic to commercial waste

The total waste generated (TW_i) and deposited at the landfill in a particular year was calculated as the sum of domestic and commercial waste by making use of equation 3.4:

$TW_i = DW_i + CW_i$

Equation 3.4

3.7.4 Landfill Gas Modelling

Determination of organic matter

Production of landfill gas is through decomposition of the organic portion of waste deposited at the landfill. Only the decomposable part of the waste was used in modelling landfill gas generation. The sum of the decomposable matter in the waste was taken as putrescibles, textile, paper and cardboard. By making use of equation 3.5, the total organic matter deposited at the landfill was calculated.

$OW_i = (DW_i \, f_{DW}) + (CW_i \, f_{CW})$

Equation 3.5

Where:

OW_i = organic waste deposited at the landfill

f_{DW} = factor or portion representing organic matter in domestic waste, calculated as 55.6 %

f_{CW} = factor or portion representing organic matter in commercial waste, calculated 35.5 %

Landfill gas estimation

The three models used in this research were adopted based on the availability of model, accuracy of modelled outcomes, scientific basis of the model, transparency, ability of the model to handle waste changes and application to climate zones different from the climate conditions where the model was developed. LandGEM, IPCC and Afvalzorg were the models adopted for estimating landfill gas generation.

Methane generation at Chunga landfill was estimated considering the operation of landfill as a conventional landfill and bioreactor landfill. For the conventional landfill operation, the default parameters provided by the models were used. During the modelling of landfill gas generation for conventional landfill operation, the Clean Air Act and Inventory default parameters were used in the LandGEM model. Likewise, when modelling landfill gas production using IPCC and Afvalzorg model, the default parameters used were based on the climate conditions defined in the model corresponding to the conditions in Lusaka.

The average midday temperature for Lusaka varies from a maximum of 31 degrees celsius in October to a minimum of 10 degrees in June. The average annual rainfall is 83 cm falling mainly between November and March. According to Afvalzorg model parameters in table 2.6 and IPCC model parameters in table 2.9, Chunga landfill falls under "Tropical, Dry" category for conventional operation and therefore, corresponding methane generation rate values were applied in landfill gas modelling. Similarly, from the LandGEM model parameters indicated in table 2.4 and table 2.5, Chunga landfill is not arid and therefore, methane generation rate and methane production potential values corresponding to CAA and Inventory category were selected for conventional operations of the landfill.

An important factor applied under the Afvalzorg and IPCC models was the Methane Correction Factor (MCF). This factor accounted for less methane production due to inconsistent management of the landfill as compared to high production of methane in properly managed anaerobic landfills that restrict gas leakages to the surrounding environment (IPCC, 2006). Based on Table 2.5, Chunga landfill is "unmanaged, deep" and MCF for conventional operation is 0.8. For bioreactor landfill operation, MCF = 1 was adopted as recommended by IPCC (2006). In a bioreactor operation, leachate is recirculated in the landfill or moisture introduced into the waste with the purpose of increasing the rate of decomposing organic matter and the rate of methane production. For bioreactor operation, "Tropical, Moist & Wet" was selected in IPCC and Afvalzorg model while "Inventory Wet" was applied in LandGEM model.

According to SCS Engineers (2008), gas collection efficiency lies between 54 % to 95 % with an average of 75 % for an active landfill with an active gas collection system and intermediate cover material. Similarly, the US Environmental Protection Agency presents that methane collection efficiency ranges from 60 % to 85 %, with an average of 75 % (Global Methane Initiative, 2012). On this basis, 0.75 was used as the fraction of methane recovered. Table 3.3 depicts a summary of the parameters adopted during landfill gas modelling.

Landfill gas production was also estimated under bioreactor operation of the landfill and was assumed to start in the year 2020. Due to waste compaction at the landfill, 33 % of waste volume was assumed to be recovered over a time-span of 8 years resulting into 2040 as the closure year of Chunga landfill under bioreactor operations (Environmental Research and Education Foundation (EREF), 2003). This allowed additional waste placement starting from 2028 up to a period when the landfill cannot accommodate waste disposal, 2040. A reduction factor of 0.4 (40 %) was applied to the recovered volume because of inconsistent compaction of waste at the landfill. This factor was arrived at by calculating the average level of management as provided by the respondents during unstructured interviews. Table 3.4 shows the waste deposited at the landfill and the projected waste in place for conventional and bioreactor operations during the life span of the landfill (25 years).

Table 3.3: Summary of default parameters adopted in landfill gas modelling

Parameter	**LandGEM**			**Afvalzorg Model**		**IPCC Model**	
	CAA Conventional	**Inventory Conventional**	**Wet Bioreactor**	**Conventional**	**Wet Bioreactor**	**CAA Conventional**	**Wet Bioreactor**
Operation period	2007 - 2032	2007 - 2032	2007 - 2040	2007 - 2032	2007 - 2040	2007 - 2032	2007 - 2040
Proportion of methane recovered	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Methane Content (%)	50	50	50	50	50	50	50
Methane generation rate (y^{-1})	0.05	0.04	0.7	Defaults based on degradability (0.065, moderate degrade)	Defaults based on degradability (0.4, rapid degrade)	Defaults based on degradability (0.065, moderate degrade)	Defaults based on degradability (0.4 for degrade)
Methane production potential (m^3/Mg)	170	100	96	Defaults based decomposable organic carbon	Defaults based decomposable organic carbon	Defaults based decomposable organic carbon	Defaults based decomposable organic carbon
Lag Time (months)	-	-	-	6	6	6	6
Management	-	-	-	unmanaged - deep (>5m waste) MCF=0.8	managed anaerobic MCF=1.0	unmanaged - deep (>5m waste) MCF=0.8	managed anaerobic MCF=1.0

Table 3.4: Waste acceptance history

Year	Population Projections (number of people in Lusaka)	Conventional		Bioreactor	
		*Waste Accepted in Landfill (Mg/Year)	**Waste In-Place (Mg)	*Waste Accepted in Landfill (Mg/Year)	**Waste In-Place (Mg)
2007	1,918,919	78,580	0	78,580	0
2008	2,009,108	82,499	78,580	82,499	78,580
2009	2,103,536	86,140	161,079	86,140	161,079
2010	2,191,225	89,731	247,219	89,731	247,219
2011	2,292,021	93,858	336,949	93,858	336,949
2012	2,397,454	98,445	430,807	98,445	430,807
2013	2,507,737	102,692	529,253	102,692	529,253
2014	2,623,093	107,416	631,945	107,416	631,945
2015	2,743,755	112,357	739,360	112,357	739,360
2016	2,858,993	117,397	851,717	117,397	851,717
2017	2,979,071	162,657	969,115	162,657	969,115
2018	3,104,192	169,489	1,131,772	169,489	1,131,772
2019	3,234,568	176,607	1,301,261	176,607	1,301,261
2020	3,370,420	184,530	1,477,868	184,530	1,477,868
2021	3,498,496	191,018	1,662,399	191,018	1,662,399
2022	3,631,439	198,277	1,853,417	198,277	1,853,417
2023	3,769,433	205,811	2,051,693	205,811	2,051,693
2024	3,912,672	214,219	2,257,504	214,219	2,257,504
2025	4,061,353	222,359	2,471,723	222,359	2,471,723
2026	4,203,501	230,142	2,694,082	230,142	2,694,082
2027	4,350,623	238,197	2,924,224	238,197	2,924,224
2028	4,502,895	246,533	3,162,420	465,970	3,162,420
2029	4,660,496	254,463	3,408,954	279,677	3,628,390
2030	4,823,614	263,369	3,663,417	289,542	3,908,068
2031	4,977,969	271,797	3,926,786	298,964	4,197,610
2032	5,137,264	281,265	4,198,583	309,542	4,496,574
2033	5,301,657	289,470	4,479,848	318,822	4,806,116
2034	5,471,310	298,734	4,769,319	30,379	5,124,938
2035	5,646,392	308,293	5,068,052	31,442	5,155,316
2036	**Landfill Closed (Cannot accept waste beyond design life)**		5,376,345	61,508	5,186,758
2037			5,376,345	36,917	5,248,266
2038			5,376,345	38,220	5,285,184
2039			5,376,345	39,463	5,323,403
2040			5,376,345	40,860	5,362,867
2041			5,376,345	42,084	5,403,726
2042			5,376,345	4,010	5,445,811
2043			5,376,345	4,150	5,449,821
2044			5,376,345	8,119	5,453,971
2045			5,376,345	4,873	5,462,090
2046			5,376,345	5,045	5,466,963
2047			5,376,345	5,209	5,472,008

2048		5,376,345	5,393	5,477,217
2049		5,376,345	5,555	5,482,611
2050		5,376,345	529	5,488,166
2051		5,376,345	548	5,488,695
2052		5,376,345	1,072	5,489,243
2053		5,376,345	643	5,490,315
2054		5,376,345	666	5,490,958
2055		5,376,345	688	5,491,624
2056		5,376,345	712	5,492,312
2057		5,376,345	733	5,493,024
2058		5,376,345	70	5,493,757
2059		5,376,345	72	5,493,827
2060		5,376,345	141	5,493,899
2061		5,376,345	85	5,494,040
2062		5,376,345	88	5,494,125
2063		5,376,345	91	5,494,213
2064		5,376,345	94	5,494,304
2065		5,376,345	97	5,494,398
2066		5,376,345	9	5,494,495
2067		5,376,345	10	5,494,504
2068		5,376,345	19	5,494,514
2069		5,376,345	11	5,494,532
2070		5,376,345	12	5,494,543

*Estimated waste deposited at the landfill based on waste generation per capita per day
**Cumulative waste in place at the end of the year

3.7.5 Design of Landfill Gas Collection System

i) Landfill Gas Flow Rate

Landfill gas collection system was designed based on the peak landfill gas flow estimated by the model. Based on the design life of the landfill, the height and other dimensions of the landfill were were estimated by analysing aerial images of the landfill during construction and operation as shown in Figure 3.4. The dimensions shown on figure 3.4 are in millimetres. Using the assumed cross section, the waste volume was calculated. The flow rate of landfill gas in a particular well was calculated by making use of equation 3.6 (US Army Corps of Engineers, 2008).

$$Q_{well} = \pi \left(R^2 - r^2\right) t \, \rho_W \, G$$

Equation 3.6

Where:

Q_{well} = landfill gas flow rate per well (m^3/hr)

R = radius of influence (m)

r = borehole radius (m) varies between 0.3m to 0.45m, 0.3m adopted (m)

t = waste thickness (m)

ρ_W = waste density (kg/m^3)

G = peak methane production rate (m^3/hr), determined from model outcomes

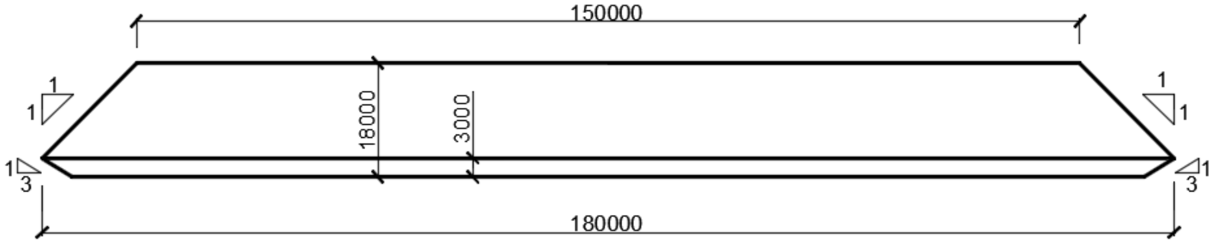

Figure 3.4: Chunga landfill cross section

ii) Spacing of Vertical Gas Collection Wells

The depth of the vertical wells was taken as 75 % the thickness of the waste (0.75t) and was within 3 m to 5 m range above the base of the waste (US Army Corps of Engineers, 2008). The radius of influence of the collected gas was taken as twice the vertical depth of wells. Further, the spacing of wells was assesed based on the know radius of influence. The spacing between wells was calculated as indicated in figure 3.5 (Qian, et al., 2002)

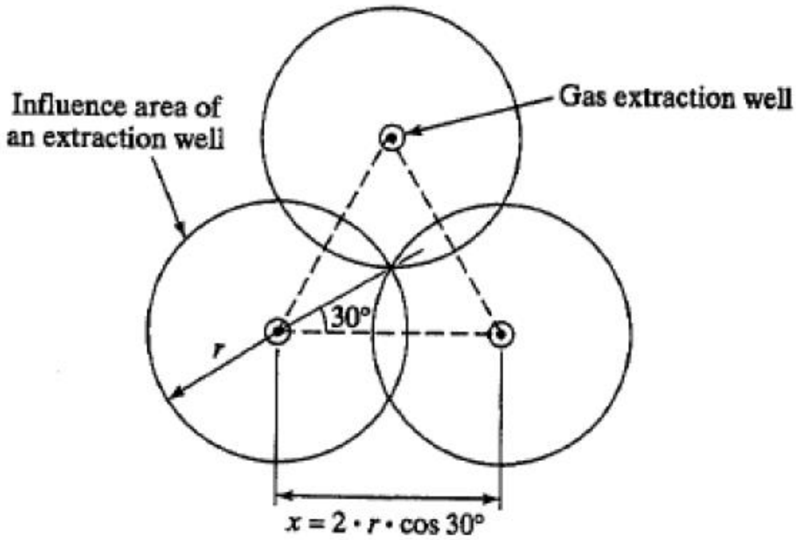

Figure 3.5: Equilateral pattern of gas collection wells (Qian et al. 2002)

By making use of equation 3.7, the spacing of gas collection wells was established:

$$x = 2\ r \cos 30°$$

Equation 3.7

Where:

x	= spacing of gas collection well (m)
r	= radius of influence, taken as 2(0.75 t) (m)
t	= waste thickness (m)

This approach made certain that the wells were placed in such a way that the radii of influence of the neighbouring wells just overlap each other. This guaranteed gas collection from the entire landfill as well as maximizing the efficiency of gas collection. Figure 3.5 shows an equilateral triangle pattern, which is an efficient method of collecting the gas, considering uniform conditions throughout the landfill.

iii) Number of gas collection wells required

The ratio of the peak flow obtained from the waste generation graph based on model outcomes and the landfill gas flow per well calculated using equation 3.6, resulted in the required number of wells for the landfill. The number of wells required was based on equation 3.8:

$$N_{well} = Q_{total} / Q_{well}$$

Equation 3.8

Where:

N_{well} = number of collection wells

Q_{total} = total landfill gas or methane flow rate from the landfill (m^3/hr)

Q_{well} = landfill gas or methane flow rate per well (m^3/hr)

The estimated number of vertical wells was designed geometrically using AutoCAD. In order to maximise gas collection efficiency, the spacing of gas collection wells did not exceed the maximum spacing distance calculated from equation 3.7.

iv) Flow Velocity In Each Well

From the relationship of volumetric flow rate, cross section area and velocity of flow, the gas flow velocity in each well was calculated. This was done by making using equation 3.9.

$$V_{well} = Q_{well} / A_{well}$$

Equation 3.9

Where:

V_{well} = landfill gas or methane flow velocity (m/s)

Q_{well} = landfill gas or methane flow rate per well (m^3/hr)

A_{well} = cross-sectional area of gas collection pipe (m^2), calculate as $A_{well} = \pi\ (D/4)$, D is the diameter of the pipe.

v) Head Losses

Head loss calculations were made in order to determine pressure drops required at each well to maintain the required radius of influence. To achieve this, calculations based on first principles of fluid mechanics were performed.

The head losses for the collection system were calculated as the sum of pressure drops in meters of water column due to; suction of gas through the waste within the radius of influence, wall frictional losses and losses in valves and fittings, and sudden cross sectional changes. The pressure loss incurred in pulling the gas through the waste was calculated by using equation 3.10 (US Army Corps of Engineers, 2008):

$$\Delta P = \mu\, G_{tot}\, \rho_W \left[R^2 \ln\left(\frac{R}{r}\right) + \left(\frac{r^2}{2}\right) - \left(\frac{R^2}{2}\right)\right] \frac{1}{2K_s}$$

Equation 3.10

Where:

ΔP	= pressure difference from the outer edge of the radius of influence to the gas well
μ	= absolute viscosity of the landfill gas (1.24×10^{-5} N.s/m^2)
G_{tot}	= total landfill gas production rate (estimated from model outcomes)
ρ_W	= waste density (kg/m^3)
R	= radius of influence (m)
r	= borehole radius (m), varies between 0.3 m to 0.45 m, 0.3 m adopted (m)
K_s	= apparent permeability of the refuse (1.477×10^{-11} m^2)

From equation 3.10, a factor called Malema (M) was derived (US Army Corps of Engineers, 2008):

$$M = \frac{\mu\, G_{tot}\, \rho_W}{2K_s}$$

Equation 3.11

The aim behind using the Malema factor was to simplify equation 3.10 by combining several parameters to represent a simple parameter M as indicated in equation 3.11.

The friction losses from the subsurface, the straight pipe lengths, sudden cross sectional changes, and the valves and fittings were added together to obtain the total friction loss for the determined flow rate. All the losses were calculated assuming that the valves are fully open. The frictional head losses in straight pipes were calculated using Darcy-Weisbach equation (US Army Corps of Engineers, 2008; Edward & Pope, 1997):

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

Equation 3.12

Where:

h_f	= head loss, m of fluid
f	= moody friction factor for the pipe, dimensionless
L	= length of segment (m)
D	= inside pipe diameter (m)
V	= average velocity of the flow, (m/s)
g	= acceleration due to gravity (9.81 m/s^2)

To estimate the Moody Friction Factor, the type of flow had to be decided through calculations of a dimensionless value known as the Reynolds Number (Re). Re was calculated by making use of equation 3.13 and the value established characterised whether laminar or turbulent flow regime is to be considered for estimating the friction factor.

$$Re = \frac{\rho_{LFG} V D}{\mu}$$

Equation 3.13

Where:

Re	= Reynolds Number, dimensionless unit
ρ_{lfg}	= density of landfill gas, taken as 1.25 Kg/m^3
D	= inside pipe diameter (m)
V	= average velocity of the flow, (m/sec)
μ	= absolute viscosity of the landfill gas (1.24 × 10^{-5} N.s/m^2)

For Re values less than 2000, laminar flow was considered and the friction factor estimated as $\frac{64}{\mathrm{Re}}$, whereas, values of Re greater than 5000, turbulent flow regime was considered and the Moody Friction Factor calculated by numerical analysis using equation 3.14.

$$f = \frac{1.325}{\left[\ln\left(\frac{e}{3.7D} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2}$$

Equation 3.14

To estimate head losses through valves and fitting, the tabulated values in table 3.5 were used to represent the equivalent length of a straight pipe. Thereafter, equation 3.12 was then used to calculate the head losses in valves, fittings and sudden cross sectional changes.

The sum of head losses was required in sizing a blower (compressor) that is capable of creating sufficient vacuum in the pipes in order to pull the landfill gas at the required flow rate from the waste into the pipes. The greatest head losses achieved from a particular well to the final meeting point of the main headers was considered in the sizing of a compressor.

Table 3.5: Equivalent lengths of pipes and sudden cross-sectional changes (Constance & Cliffside, 2005)

Nominal pipe size, in.	Globe valve	Angle valve / Ball check	Return bend / Swing check	Standard tee / Square elbow	Standard elbow / Reduced tee ½	Medium elbow / Reduced tee ¼	Long elbow / Run of standard tee	45 deg elbow	Gate valve	Ball valve	Plug cock straight way Full port
1½	40	21	10	7	4	4	3	2	1	1	2
2	50	27	13	10	5	5	3	2.5	1	2	3
2½	60	33	15	12	6	6	4	3	1.5	2	4
3	80	40	18	15	8	7	5	4	2	2	5
4	115	55	23	20	11	9	6	5	2.5	3	6
6	160	80	36	30	16	14	9	7.5	3.5	4	9
8	225	110	50	40	20	18	14	10	4.5	5	12
10	290	135	60	50	25	22	18	13	7	7	16
12	350	160	70	60	30	25	20	16	8	8	18
14	400	190	85	66	35	30	23	18	9	9	20
16	450	220	100	76	40	35	27	21	10	10	23
18	500	250	110	86	45	40	30	24	12	11	26
20	550	280	125	96	50	45	35	26	13	13	29
22	600	300	155	105	55	50	38	29	15	15	32
24	660	335	190	116	60	56	45	32	18	16	35
30	–	–	–	146	75	–	50	40	21	20	–
36	–	–	–	176	90	–	60	48	25	24	–
42	–	–	–	205	105	–	70	56	30	27	–
48	–	–	–	235	120	–	80	64	35	31	–
54	–	–	–	265	135	–	90	72	40	35	–
60	–	–	–	295	150	–	100	80	45	40	–

3.7.6 Landfill Gas Potential for Electricity Generation

Options for the utilisation of landfill gas include; direct use, electricity generation, and production of alternate fuels such as pipeline quality natural gas and transportation fuels like compressed or liquefied natural gas. Electricity generation options include the use of internal combustion or reciprocating engines, gas turbines, microturbines, and combined heat and power systems (Landfill Methane Outreach Program (LMOP), 2016). The project types that were analysed are presented in chapter 4. The best project type that is appropriate for the amount of electricity generated from the methane was selected. The possibility of generating electricity from landfill gas was assessed using Landfill Gas Cost Web Model.

i) Investment Estimations

In order to determine if the investment in converting landfill gas to electricity is economically feasible, different investment calculation methods were used. In this study, the Landfill Gas Cost Web model version 3.1 was used to conduct an initial economic analysis of prospective landfill gas energy recovery for Chunga considering both conventional and bioreactor operations of the landfill (Landfill Methane Outreach Program (LMOP), 2016). Other investment methods incorporated in the model and used in this study include the payback time and Net Present Value (NPV).

Investment calculations were based on assumed interest rates, discount rates, general inflation rate, discount rate, marginal tax rate and equipment inflation rate based on trending economics in Zambia. The ranges of rates assumed for investment calculations are displayed in table 3.6.

Table 3.6: Investment calculations rates and sensitivity analysis assumptions

Investment Calculation Rates	
Financial Rate	**Adopted Values**
Interest Rate	11 %
Discount Rate	9 %

The calculations were based on two scenarios; tax inclusion for importing equipment, materials and tools which is applicable for private investors who are not exempted from tax, and without taxes scenario for a government funded project or funding through Public Private Partnership (PPP) in which tax payments are exempted. Other parameters used in the cost model for economic analysis of converting landfill gas to electricity are as follows:

1. Energy project type (types assessed are presented in chapter 4)
2. The project start year was taken as 2019 since it is not known when a landfill gas collection and utilisation system would be installed and operational for energy production.
3. Marginal tax rate, the highest corporate marginal tax rate recorded in Zambia is 35 %. The marginal tax rate was used to estimate tax payment and was only applied to scenario 1 which assumes a project funded and developed by private entities.
4. Down payment was taken as payments on the project loan and taken as 2 0% and 100 %. The 20 % value is the default in the model based on landfill gas energy

project experiences with commercial projects, and 100% was tried as a best case for decreasing the number of years to payback.

5. General inflation rate, taken as 6.8 % based on trading economics reports for Zambia, This inflation rate was applied to operation and maintenance costs of landfill gas utilisation for generating electricity.

Since no landfill gas collection system is present at Chunga, cost analyses were included to cover the cost of a system that collects and utilises the gas for electricity production as well as a flare system that burns excess methane captured. The collection efficiency of the system was taken as 75 %, which is recommended by US Environmental Protection Agency for LandGEM modelling. The cost of electricity was varied since the target recipient of the energy is not known. For this reason, average electricity cost of US$ 0.05 per kilowatt hour (kWh) was assessed (Ministry of Energy and Water Development, 2016) including residential and commercial cost, adopted as US$ 0.094/kWh and US$ 0.057/kWh respectively based on one dollar being equivalent to Nine Kwacha Fifty Ngwee (K9.50) (ZESCO Limited, 2017).

LandGEM provides a default methane generation rate value of 0.7 per year for modelling bioreactor landfills, while the Landfill Methane Outreach Program recommends assigning a k-value of 0.3 for bioreactors based on a study conducted by the University of Florida (US Environmental Protection Agency (EPA), 2005). The IPCC model recommends k-value of 0.4 for rapidly degrading waste and 0.17 for moderately degrading bulk waste with moist and wet climate condition. Therefore, for this study to be conservative, a k-value of 0.3 was applied since it depicts less methane generate rate than the actual, Thus, if the project is financially feasible using the lower k-value, then greater financial returns would be gained if the project is implemented.

ii) Environmental Benefits from Emission Reduction

The environmental benefits of utilising landfill gas to produce electricity were determined for both conventional and bioreactor operations of the landfill. The benefits for each operation were calculated separately since the gas produced by each operation is different. The procedure outlined by the Landfill Methane Outreach Program (2016) was used. The annual amount of methane that is collected and either destroyed by the flare or utilised by the landfill gas energy project was estimated by making use of equation 3.15:

$$MD_{project} = GC_{project} \; F_{CH_4}$$

Equation 3.15

Where:

$MD_{project}$ = annual amount of methane collected and either destroyed by flare or landfill gas energy project (m^3CH_4/year)

$GC_{project}$ = methane collected and destroyed (m^3CH_4/year)

F_{CH_4} = fraction of methane in landfill gas, adopted as 50%

The direct methane reduced was presented in terms of equivalent carbon dioxide captured and destroyed by applying the global warming potential (GWP) of methane. This was calculated by using equation 3.16:

$$MR_{project} = MD_{project} \; GWP_{CH_4}$$

Equation 3.16

Where:

$MR_{project}$ = direct annual amount of methane reduced by the flare or landfill gas energy project (tCO_2/year)

GWP_{CH_4} = global warming potential value for methane, adopted as 21 tCO2e/tCH_4.

The methane utilised for producing electricity by the landfill gas energy project was estimated by making use of equation 3.17;

$$MU_{project} = GU_{project} \; F_{CH_4} \; GWP_{CH_4}$$

Equation 3.17

Where:

$MU_{project}$ = annual amount of methane utilised to generate electricity by the landfill gas energy project (tCO_2/year)

$GU_{project}$ = actual amount of methane utilised ($m^3 CH_4$/year)

Based on the three equations, the environmental benefits of landfill gas energy were established. A comparison of reduced emissions between bioreactor and conventional operations was made.

3.8 Conclusion

This chapter highlighted the methodology adopted in carrying out this research in order to address the aim and objectives thereby answering the research questions. It presented different research designs and articulated reasons why the adopted design was selected. The chapter also outlined the methods of data analysis. The chapter concluded by presenting landfill gas conversion to energy and estimations of environmental benefits that can be realised from the investment.

The next chapter will present the analysis and discussion of the data collected in the survey.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

The previous chapter presented the methodology adopted in this study. This involved the outlining of the research design and the method of data analysis employed.

This chapter presents the analysis and deductions made from the data collected. The chapter concludes by discussing the results.

4.2 Estimation of Waste Generation

Due unavailability of consistent waste disposal data for the landfill, estimations of the waste generated in Lusaka was done by analysing statistical data on current and forecasted population in the city (Swapan & Bidyut, 2014; Khajuria, et al. 2010). The organic fraction of the waste deposited at the landfill considering conventional and bioreactor operations was established as shown in table 4.1:

Table 4.1: Quantity of organic content deposited at Chunga Landfill

Year	Conventional		Bioreactor	
	Waste Accepted in Landfill (Mg/Year)	**Waste In-Place (Mg)**	**Waste Accepted in Landfill (Mg/Year)**	**Waste In-Place (Mg)**
2007	49,505	0	49,505	0
2008	51,974	49,505	51,974	49,505
2009	54,268	101,480	54,268	101,480
2010	56,530	155,748	56,530	155,748
2011	59,131	212,278	59,131	212,278
2012	62,021	271,409	62,021	271,409
2013	64,696	333,429	64,696	333,429
2014	67,672	398,125	67,672	398,125
2015	70,785	465,797	70,785	465,797

2016	73,960	536,582	73,960	536,582
2017	102,474	610,542	102,474	610,542
2018	106,778	713,016	106,778	713,016
2019	111,263	819,794	111,263	819,794
2020	116,254	931,057	116,254	931,057
2021	120,341	1,047,311	120,341	1,047,311
2022	124,914	1,167,652	124,914	1,167,652
2023	129,661	1,292,567	129,661	1,292,567
2024	134,958	1,422,228	134,958	1,422,228
2025	140,086	1,557,185	140,086	1,557,185
2026	144,989	1,697,272	144,989	1,697,272
2027	150,064	1,842,261	150,064	1,842,261
2028	155,316	1,992,325	293,561	1,992,325
2029	160,312	2,147,641	176,197	2,285,886
2030	165,923	2,307,953	182,411	2,462,083
2031	171,232	2,473,875	188,347	2,644,494
2032	177,197	2,645,107	195,012	2,832,841
2033	0	2,822,305	18,491	3,027,853
2034	0	2,822,305	19,139	3,046,344
2035	0	2,822,305	19,808	3,065,483
2036	0	2,822,305	38,750	3,085,291
2037	0	2,822,305	23,258	3,124,041
2038	0	2,822,305	24,078	3,147,299
2039	0	2,822,305	24,862	3,171,378
2040	0	2,822,305	25,742	3,196,240
2041	0	2,822,305	2,441	3,221,981
2042	0	2,822,305	2,526	3,224,422
2043	0	2,822,305	2,615	3,226,948
2044	0	2,822,305	5,115	3,229,563
2045	0	2,822,305	3,070	3,234,678
2046	0	2,822,305	3,178	3,237,748
2047	0	2,822,305	3,282	3,240,926
2048	0	2,822,305	3,398	3,244,208
2049	0	2,822,305	322	3,247,606
2050	0	2,822,305	333	3,247,928
2051	0	2,822,305	345	3,248,262
2052	0	2,822,305	675	3,248,607
2053	0	2,822,305	405	3,249,282
2054	0	2,822,305	420	3,249,687

2055	0	2,822,305	433	3,250,107
2056	0	2,822,305	449	3,250,540
2057	0	2,822,305	43	3,250,989
2058	0	2,822,305	44	3,251,031
2059	0	2,822,305	46	3,251,075
2060	0	2,822,305	89	3,251,121
2061	0	2,822,305	53	3,251,210
2062	0	2,822,305	55	3,251,263
2063	0	2,822,305	57	3,251,319
2064	0	2,822,305	59	3,251,376
2065	0	2,822,305	6	3,251,435
2066	0	2,822,305	6	3,251,441
2067	0	2,822,305	6	3,251,446
2068	0	2,822,305	12	3,251,452
2069	0	2,822,305	7	3,251,464
2070	0	2,822,305	7	3,251,471

4.3 Estimation of Landfill Gas Generation

4.3.1 Conventional Operation of Landfill

The organic quantity of waste deposited at the landfill together with the default parameters presented in chapter 3 were applied for gas generation modelling using LandGEM, IPCC and Afvalzorg models. The model outcomes represented the total amount of methane that is produced by the decomposing waste each year. It was found that LandGEM model with CAA defaults overestimated the methane generated which was in accordance to the findings by “Oonk (2010)”. This volumetric flow of gas was taken as the worst-case upper bound and avoided in the design and sizing of a landfill gas collection system. The LandGEM inventory defaults and Afvalzorg model outcomes were comparable while the IPCC model outcomes were somewhat in-between the CAA defaults and Afvalzorg model outcomes. The outcomes from the three models are presented in table 4.2.

Table 4.2: Methane generation from conventional operation of Chunga Landfill

CONVENTIONAL LANDFILL METHANE GENERATION				
Year	LandGEM Model		Afvalzorg Model	IPCC Model
	CAA Defaults	Inventory Defaults		
	Methane (m^3/hour)	Methane (m^3/hour)	Methane (m^3/hour)	Methane (m^3/hour)
2007	0	0	0	0
2008	47	22	27	41
2009	94	45	53	81
2010	141	67	79	121
2011	188	90	104	159
2012	235	113	129	198
2013	282	136	154	237
2014	330	160	179	275
2015	378	184	204	313
2016	427	209	229	352
2017	476	234	255	391
2018	550	270	294	451
2019	624	308	333	510
2020	700	346	371	570
2021	776	384	410	629
2022	852	423	449	689
2023	929	462	488	748
2024	1,007	502	527	808
2025	1,086	543	566	868
2026	1,166	585	606	929
2027	1,246	627	645	990
2028	1,328	670	685	1,051
2029	1,411	713	725	1,113
2030	1,494	757	766	1,175
2031	1,578	802	807	1,237
2032	1,664	847	848	1,300
2033	1,751	893	889	1,364

2034	1,666	858	833	1,279
2035	1,584	825	781	1,198
2036	1,507	792	732	1,123
2037	1,434	761	686	1,052
2038	1,364	731	643	986
2039	1,297	703	602	924
2040	1,234	675	564	866
2041	1,174	649	529	811
2042	1,116	623	496	760
2043	1,062	599	464	712
2044	1,010	575	435	667
2045	961	553	408	625
2046	914	531	382	586
2047	869	510	358	549
2048	827	490	336	515
2049	787	471	314	482
2050	748	453	295	452
2051	712	435	276	423
2052	677	418	259	397
2053	644	401	242	372
2054	613	386	227	348
2055	583	371	213	327
2056	554	356	199	306
2057	527	342	187	287
2058	502	329	175	269
2059	477	316	164	252
2060	454	303	154	236
2061	432	291	144	221
2062	411	280	135	207
2063	391	269	127	194
2064	372	259	119	182
2065	354	248	111	170
2066	336	239	104	160
2067	320	229	-	150
2068	304	220	-	140
2069	289	212	-	131
2070	275	203	-	123
TOTAL	**49,538**	**27,300**	**22,515**	**35,083**

It is evident that maximum methane production for all the models occurs in 2033, a year after closure of the landfill. A graphical representation of methane generation from disposed waste is as shown in figure 4.1 below.

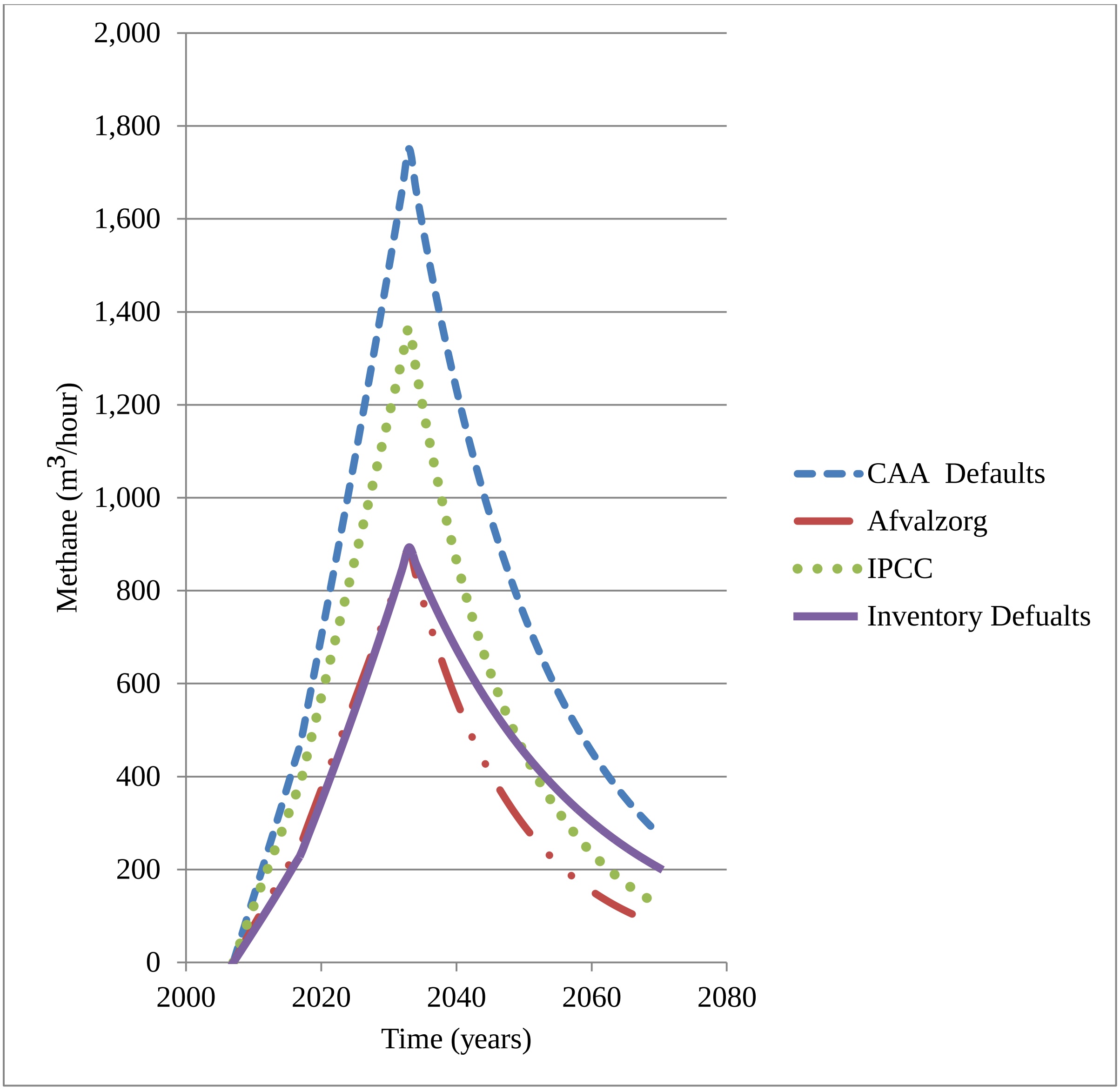

Figure 4.1: Methane Generation from conventional operation of Chunga Landfill

4.3.2 Bioreactor Operation of Landfill

Bioreactor reactor operation was also assessed by assuming wet operation of the landfill through leachate recirculation or addition of moisture to the deposited waste to speed up the rate of decomposition and methane production. For bioreactor operations, it is assumed that 33% of the landfill waste volume will be recovered every 8 years due to the degradation of organic waste (EREF, 2003).

The waste quantities in table 4.1 and model input parameters presented in chapter 3 were used to estimate methane production from the deposited organic waste in the landfill. Table 4.3 depicts the methane generation through bioreactor operation of landfill while figure 4.2 gives a graphical representation of the same. The sudden kinks in the figure are as a result of additional waste placement caused by decomposition and consolidation of the waste due to self-weight which increases the capacity of the landfill.

Table 4.3 Methane generation through bioreactor operation of Chunga Landfill

BIOREACTOR LANDFILL METHANE GENERATION			
Year	**LandGEM Model**	**Afvalzorg Model**	**IPCC Model**
	Methane (m3/hour)	**Methane (m3/hour)**	**Methane (m3/hour)**
2007	0	0	0
2008	283	82	127
2009	437	156	240
2010	527	222	341
2011	585	282	432
2012	628	336	516
2013	666	387	594
2014	700	434	666
2015	734	479	735
2016	769	522	801
2017	804	564	865
2018	985	646	992
2019	1,099	723	1,110
2020	1,181	796	1,220
2021	1,251	865	1,327
2022	1,308	930	1,427
2023	1,363	993	1,523
2024	1,418	1,054	1,617
2025	1,475	1,114	1,709
2026	1,533	1,173	1,800
2027	1,589	1,231	1,889

2028	1,646	1,289	1,977
2029	2,494	1,577	2,419
2030	2,245	1,624	2,491
2031	2,157	1,674	2,568
2032	2,147	1,726	2,648
2033	1,765	1,781	2,732
2034	1,188	1,533	2,352
2035	699	1,326	2,034
2036	460	1,151	1,766
2037	450	1,036	1,589
2038	356	913	1,400
2039	314	810	1,243
2040	298	725	1,112
2041	295	655	1,004
2042	147	556	853
2043	73	474	726
2044	36	404	619
2045	18	349	536
2046	9	300	460
2047	4	258	396
2048	2	223	343
2049	1	194	298
2050	1	164	252
2051	0	139	213
2052	0	118	181
2053	0	101	154
2054	0	86	131
2055	0	73	112
2056	0	62	95
2057	0	53	82
2058	0	45	69
2059	0	38	58
2060	0	32	49
2061	0	27	42
2062	0	23	35
2063	0	20	30
2064	0	17	25
2065	0	14	22
2066	0	12	18

2067	0	0	15
2068	0	0	13
2069	0	0	11
2070	0	0	9

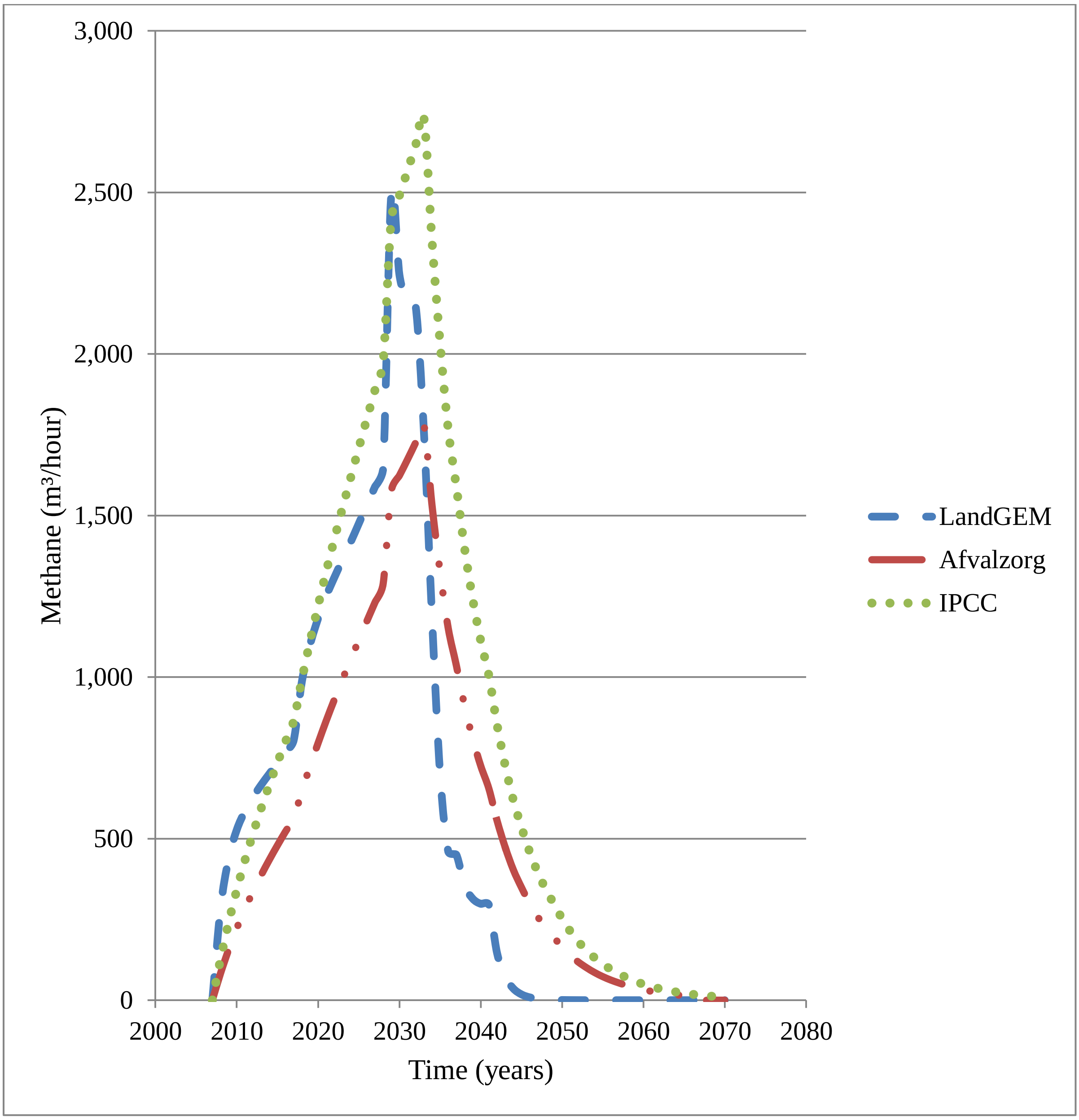

Figure 4.2: Methane generation through bioreactor operation of Chunga Landfill

In the LandGEM model, methane production seizes in 2050, which is earlier that the outcomes from IPCC and Afvalzorg model results. This is because the k-value assumed in the model causes fast methane production and therefore no decomposable waste is present after 2050. The peak volumetric flow of methane occurs in 2030 for LandGEM while in the IPCC and Afvalzorg model, maximum methane flow occurs in 2033. A comparison of the total methane that can be produced by conventional and bioreactor operations at Chunga landfill up to 2065 is presented in figure 4.3.

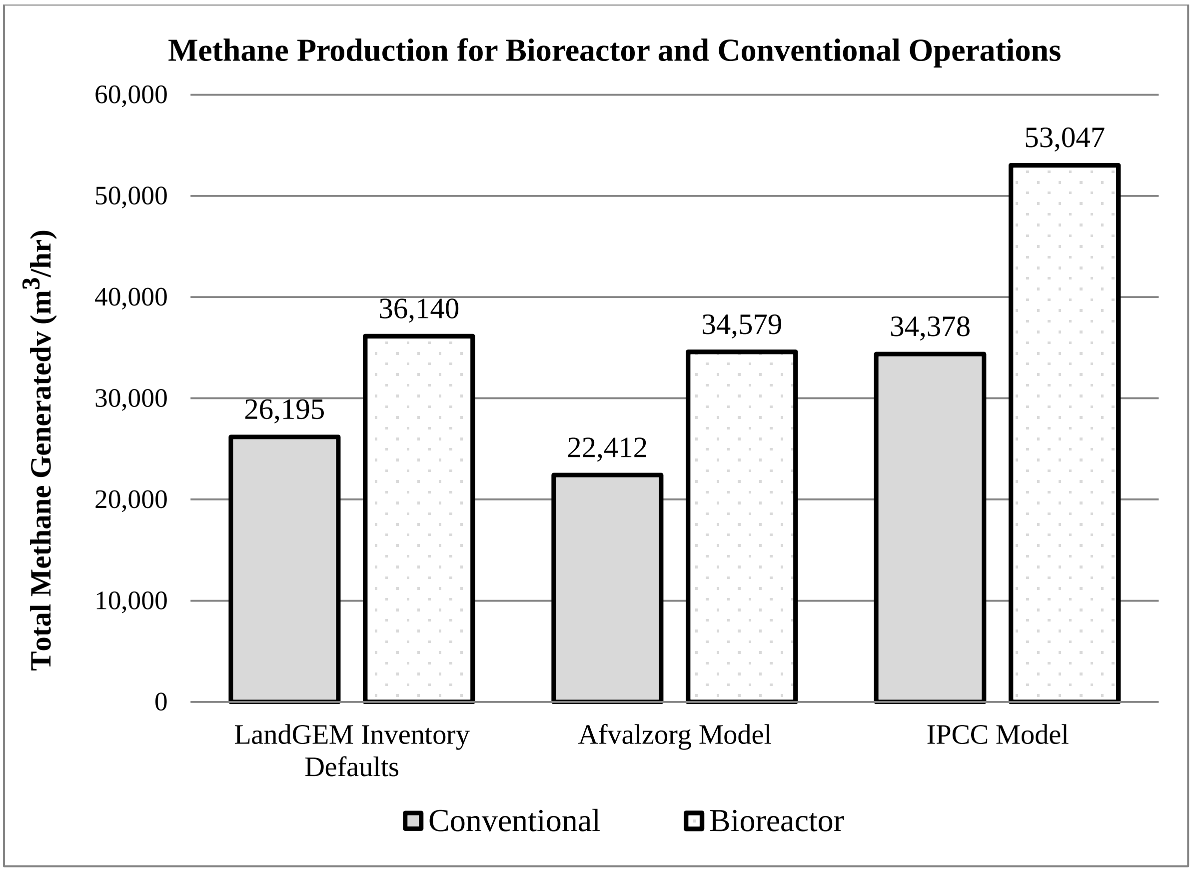

Figure 4.3: Total methane generation at Chunga Landfill until 2065

A difference of 38 % in the total volumetric flow of methane is evident between conventional and bioreactor operations under the LandGEM model. Whereas a consistent increment of 54 % is noticed between conventional and bioreactor operations of the landfill for both IPCC and Afvalzorg model.

From the model outcomes, the differences between LandGEM and Afvalzorg models is minimal as compared to the IPCC model. Therefore, the two models agree with each and for conservativeness to be attained, the Afvalzorg model outcomes were used for sizing the LFG collection and utilisation system.

4.4 Landfill Gas Collection System Design

4.4.1 Design Flow Rate of Extracted Gas

The sizing of landfill gas collection systems dictates the use of peak volumetric gas flow from the model used. Therefore, in order to size the gas collection system for Chunga landfill, the peak volumetric methane flow calculated as 893 m^3/hour by LandGEM with inventory default values of methane generation rate (k-value = 0.04 $year^{-1}$) and methane production potential (L_0=100 m^3/Mg) was selected. This approach made certain that a conservative gas collection system is designed.
As it is assumed that methane is 50% of the landfill gas produced, a total flow rate of extracted gas was taken as twice the methane flow rate.

For bioreactor landfill gas collection system, the peak flow calculated by the Afvalzorg model was used for conservativeness in the design. The calculated landfill gas flow rate of 3562 m^3/hour was applied in the sizing calculations.

4.4.2 Sizing of Chunga Conventional Landfill Gas Collection System

Based on the design life and measurements of the landfill extents using Google Earth, a cross-section of the landfill was generated and the depth of the waste established based on the projected waste deposition in cell. The diameter of boreholes to be drilled, size of vertical gas extraction wells, screen size and depth, and well radius of influence were typical values according to Global Methane Initiative (2012) and US Army Corps of Engineers (2008).

The depth of waste after closure of the landfill was estimated as 18 m and 75% of this value resulted in the depth of vertical extraction wells of 0.15 m radius. The number of vertical extraction wells was established as 16. This was arrived at by dividing the total landfill gas flow by the flow rate in each well. The information required for the design of vertical extraction wells including other relevant paramters and standards are presented in table 4.4.

Table 4.4: Vertical gas extraction well design, characteristics and materials

	Characteristics and Components	Value	Units	Design Parameters and Comments
Waste Parameters	Waste Volume	665,725	m^3	Calculated from landfill cross section
	Waste Tonnage	2,645,107	tons	Total waste in-place at landfill
	Waste Density	1.25	kg/m^3	Established from LandGEM model outcomes
	Waste Depth	18.0	m	As per cross section of landfill
Well Characteristics	Vertical Well Depth	13.5	m	75 % of waste depth
	Vertical Well Radius	0.15	m	0.05 m – 0.15 m
	Borehole Radius	0.3	m	0.3 m -0.45 m
	Casing Material	PVC	NA	HDPE or PVC
	Casing Diameter	0.15	m	Minimum of 100 mm
	Radius of influence (ROI)	27	m	2 to 2.5 times the depth of well
Screens	Screen Length	10.13	m	70 % to 80 % of casing being screened
	Diameter of Perforations over screen length	12	mm	12 mm – 15 mm diameter holes every 0.15 m to 0.3 m over entire perforation length
	Spacing of Perforations over screen length	300	mm	
	Screen Cap Material	PVC	NA	HDPE or PVC with same diameter as casing
Aggregates and Seals	Gravel Pack or Washed stone	50	mm	25mm - 75mm aggregates, extending a min of 0.3m above the end of screen and 0.6m below the screen
	Bentonite Plug and Isolation Layer	0.9	m	Bentonite seal with Geotextile or isolation sand layer on top of gravel pack with min 0.9 m bentonite seal above
	Clay backfill	1.2	m	Compacted clay backfill or bentonite grout.
Landfill Gas	Peak Methane Generation	893	m^3/hr	As estimated by LandGEM Inventory Defaults
	Total Landfill Gas Generation	1,786	m^3/hr	As estimated by LandGEM Inventory Defaults
	Methane Fraction	50	%	Taken as 50 % of total landfill gas
	LFG Flow rate for a particular vertical well	110.6	m^3/hr	Calculated using the cylinder methods
Number of Wells and	Number of Wells needed with regards to flow	16	no.	Ratio of total LFG generation to LFG flow rate per well

Spacing	(number rounded to the nearest whole number)			
	Well Spacing	47	m	With known ROI, spacing = ROI*2cos30
	Number of Wells needed with regards to spacing.	16	no.	Based on Geometry of the landfill with 47m spacing between wells
	Adopted number of Wells (greater of flow or spacing)	16	no.	The greater number obtained between the flow basis and spacing standpoint is adopted.

In order to maximise efficiency of collecting methane from landfill, the radius of influence was taken as 27 m, which was twice the depth of vertical gas extraction wells. Based on this radius, the spacing of well was calculated as 47 m. With this spacing in mind, the geometry of the landfill gas collection system was designed as depicted in figure 4.4 with all dimension in millimetres.

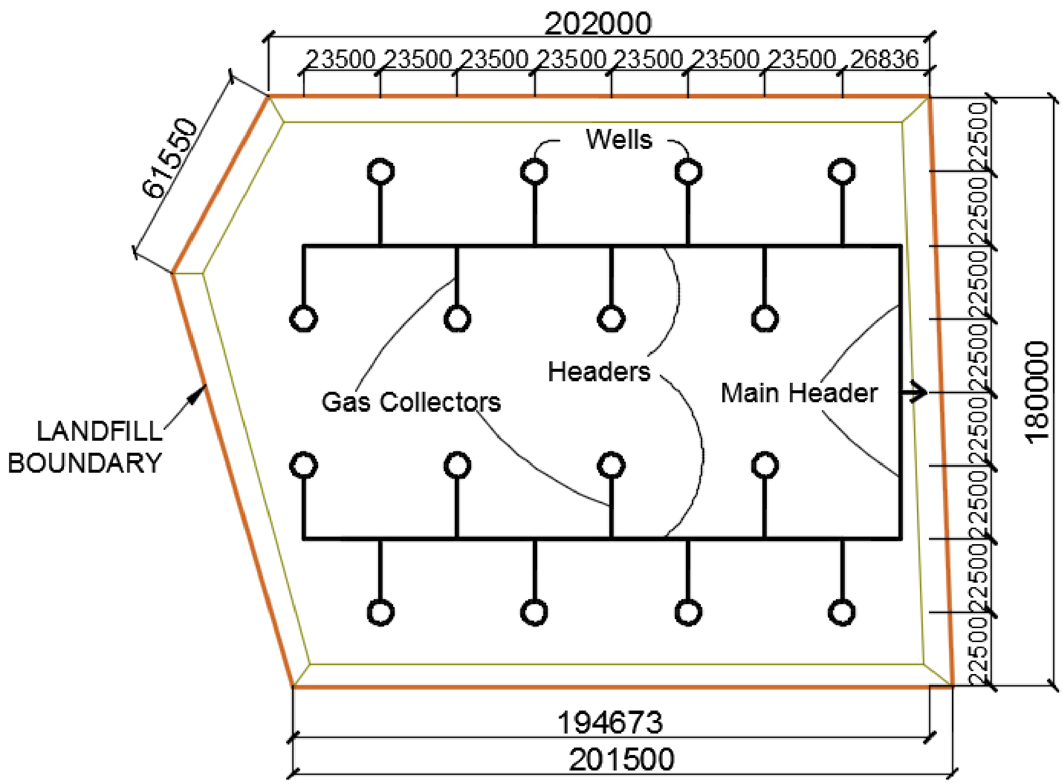

Figure 4.4: Chunga landfill gas collection system layout design

The figure shows the general layout of the gas collection system in millimetres, with 16 vertical wells, 2 headers, and 16 gas connectors. The main headers are responsible for conveying the extracted gas to the utilisation equipment. Each gas well collects 110.6 m^3/hour of landfill gas. Based on landfill flow rate and the permissible gas velocity in the pipes, the connectors and headers were designed as shown in table

4.5. The main headers convey 1170 m^3/hour of landfill gas to the utilisation point. The size of the main header pipes is chosen as 0.25 m, which according to the continuity equation gives a velocity of gas in the pipe as 10.01 m/sec which is less than the maximum value of 15 m/sec allowed, for gas flowing concurrently with the slope of the pipe.

Each of the two headers conveys 885 m^3/hour of landfill gas to the main header pipes. Based on this flow rate, the velocity of the gas was estimated as 13.9 m/sec using the continuity equation and the standard size of the pipe chosen as 0.15 m for the header pipes. The connectors in the landfill gas collection system transport the gas extracted by the wells to the headers. Based on figure 4.4, 16 headers are needed to extract gas from 16 wells. Each connector conveys 110.6 m^3/hour of landfill gas at a velocity of 6.95 m/sec. To achieve this velocity, a standard pipe size of 0.075 m is chosen.

Table 14: Design of collector and header pipes for conventional operation of Chunga landfill

Name of Pipe	Characteristics and Components	Value	Units	Design Parameters and Comments
Header Pipe Details	Number of wells connected	8	no.	Number of wells calculated based on 47 m spacing between wells
	Total Flow in Header Pipe	885.0	m^3/hr	Cumulative flow in all 8 wells
	Number of Header Pipes	2	no.	Determined by well layout geometry
	Total Flow collected by all Header Pipes	1,770	m^3/hr	Cumulative flow in all Header Pipes
	Header Pipe size	0.15	m	Rule of thumb for header design is dependent on maximum allowed LFG flow velocity.
	Header pipe length	190	m	Measured from design layout
	Velocity of LFG in Header pipe	13.91	m/sec	The ratio of LFG flow rate to the cross sectional area of header. Max velocity of 15m/s is specified.
	Header pipe material	PVC	NA	HDPE or PVC
	Slope of header pipes	2.0	%	2% slope on landfill in direction of gas flow.
Connector Pipe Details	Flow in connector pipes	110.6	m^3/hr	Equal to LFG flow rate in vertical well
	Number of connector Pipes	16	no.	Determined by general well layout and geometry arrangement of pipes.
	Total Flow collected by all connector Pipes	885.0	m^3/hr	Equal to LFG flow in one header

	Connector Pipe size	0.075	m	Dependent on maximum LFG flow velocity in the pipe.
	Connector pipe length	22.5	m	Measured from design layout
	Velocity of LFG in connector pipe	6.95	m/sec	The ratio of LFG flow rate to the cross sectional area of connector pipe.
	Connector pipe material	PVC	NA	HDPE or PVC
	Connector pipe length	22.5	m	Measured from design layout
Main Header Pipe	Total LFG flow in main header pipe	1,770	m^3/hr	Equal to total LFG flow in all headers
	Main header pipe size	0.25	m	Rule of thumb for header design is dependent to maximum allowed LFG flow velocity
	Main header pipe length	157.5	m	Measured from design layout
	Velocity of LFG in main header pipe	10.01	m/sec	The ratio of LFG flow rate to the cross sectional area of header. Max velocity of 15m/s is specified.
	Main header pipe material	PVC	NA	HDPE or PVC recommended.
	Slope of main header pipes	2.0	%	2% slope on landfill in direction of gas flow. 4% is used when slope is against the LFG flow direction

Head Losses in the Gas Collection System

The head losses for the system are calculated as, losses due to pulling the gas from the waste (subsurface losses), frictional losses in the straight pipe lengths, and losses in valves and fittings. Calculations performed assumed that all valves are fully open. The subsurface head losses calculated for the system are presented in table 4.6.

Table 4.6 Subsurface head losses calculation for conventional operation of Chunga landfill

Radius of Influence (m)	Radius of Borehole (m)	LFG Viscosity (N.s/m^2)	Apparent Permeability Ks (m^2)	Waste Volume (m^3)	Total LFG Production Gtot (m^3/sec)	Melema Factor (N/m^4)	ΔPwell N/m^2	m of water colum n (m)	Total head lost (m wc)
27.0	0.30	0.0000124	1.4774×10^{-11}	665,725	0.5	0.313	911.91	0.0912	1.46

The subsurface head losses for each vertical well were calculated as 0.091 meters of water column (m. wc) making a total of 1.46m. wc for all the 16 wells. To estimate the frictional losses in the pipes and fittings, a landfill gas piping flow diagram was designed as shown in figure 4.5:

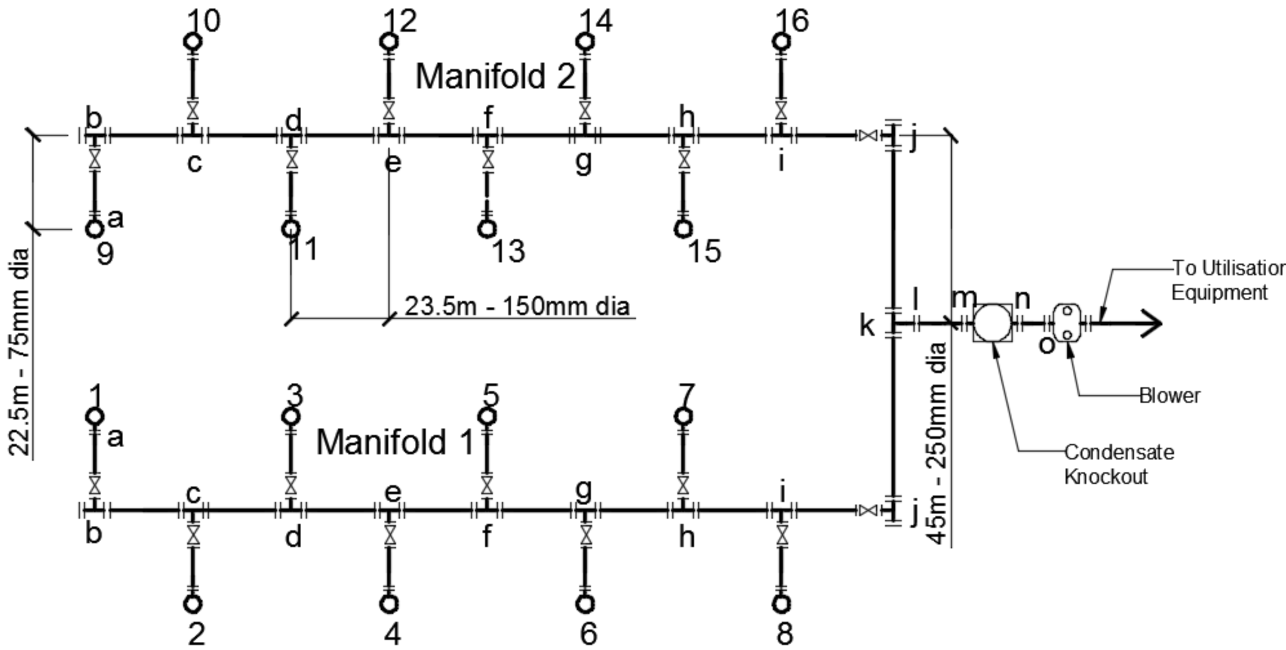

Figure 4.5: Landfill gas piping flow diagram

Head losses were calculated on a junction to junction basis using one manifold and generalised to the other because the two manifolds are exactly the same. The calculated frictional losses in the pipes, valves, fittings and sudden cross-sectional changes from junction a up to k are as shown in table 4.7.

The total head losses from well 1 up to junction k was calculated as -0.307 m. wc vacuum. The negative sign represents a negative pressure or vacuum required in the piping system so as to size a blower of sufficient magnitude for sucking landfill gas from the waste through the piping system up to the utilisation point. Table 4.8 shows the calculation of head losses from junction k up to the blower intake.

Table 4.7 Head Losses in straight pipes, fittings and sudden cross-sectional changes from a to k

Node		**Component Type**	**Flow Rate (m^3/sec)**	**Diameter of Pipe (m)**	**Cross Sectional Velocity (m/s)**	**Length of Pipe (m)**	**Equivalent Pipe Length (m)**	**Reynolds Number Re**	**Friction Factor f**	**Well Head Loss (m wc)**	**Piping Head Loss (m wc)**	Fittings Head Loss (m wc)	Total Head Loss (m wc)
From	**To**												
a	***b***	Well 1 (Subsurface)	0.031	0.15	1.74	-	-	26,284	0.024	0.09119	-	-	0.09119
		Well head	0.031	0.15	1.74	-	-	26,284	0.024	0.00229102	-	-	0.00229
		Piping	0.031	0.075	6.95	22.5	22.5	52,568	0.029	-	0.0016429	-	0.00164
		Globe valve	0.031	0.075	6.95	-	24.5	52,568	0.029	-	-	0.028623	0.02862
		75 to 150 Reducer	0.031	0.075	6.95	-	2.4	52,568	0.029	-	-	0.000058	0.00006
		Tee (branch)	0.031	0.15	1.74	-	9.2	26,490	0.024	-	-	0.000278	0.00028
		Sub-Total											**0.12408**
b	***c***	Piping	0.031	0.15	1.74	23.5	22.5	26,284	0.024	-	0.00071	-	0.00071
		Tee (run)	0.031	0.15	1.74	-	2.7	26,490	0.024	-	-	0.000082	0.00008
		Sub-Total											**0.00079**
c	***d***	Piping	0.062	0.15	3.49	23.5	22.5	52,799	0.021	-	0.0025071	-	0.00251
		Tee (run)	0.062	0.15	3.49		2.7	52,799	0.021	-	-	0.000288	0.00029
		Sub-Total											**0.00280**
d	***e***	Piping	0.093	0.15	5.25	23.5	22.5	79,314	0.019	-	0.0051186	-	0.00512
		Tee (run)	0.093	0.15	5.25	-	2.7	79,314	0.019	-	-	0.000588	0.00059
		Sub-Total											**0.00571**
e	***f***	Piping	0.124	0.15	7.00	23.5	22.5	105,829	0.018	-	0.0086334	-	0.00863
		Tee (run)	0.124	0.15	7.00	-	2.7	105,829	0.018	-	-	0.000992	0.00099
		Sub-Total											**0.00963**
f	***g***	Piping	0.155	0.15	8.75	23.5	22.5	132,344	0.017	-	0.0127514	-	0.01275
		Tee (run)	0.155	0.15	8.75	-	2.7	132,344	0.017	-	-	0.001465	0.00147

		Sub-Total											**0.01422**
g	***h***	Piping	0.186	0.15	10.51	23.5	22.5	158,860	0.016	-	0.0172919	-	0.01729
		Tee (run)	0.186	0.15	10.51	-	2.7	158,860	0.016	-	-	0.001987	0.00199
		Sub-Total											**0.01928**
h	***i***	Piping	0.217	0.15	12.26	23.5	22.5	185,375	0.016	-	0.0235461	-	0.02355
		Tee (run)	0.217	0.15	12.26	-	2.7	185,375	0.016	-	-	0.002705	0.00271
		Sub-Total											**0.02625**
i	***j***	Piping	0.248	0.15	14.01	26.8	26.8	211,890	0.016	-	0.0350836	-	0.03508
		Tee (run)	0.248	0.15	14.01	-	2.7	211,890	0.016	-	-	0.003535	0.00353
		Sub-Total											0.03862
j	***k***	90deg elbow	0.248	0.15	14.01	-	5	211,890	0.016	-	-	0.006545	0.00655
		Piping	0.248	0.15	14.01	45	45	211,890	0.016	-	0.058909	-	0.05891
		Sub-Total											**0.06545**
		Total losses from Well 1 up to junction *k* (Well 9 up to junction *k*)											**0.30682**

Table 4.8: Total head loss calculations up to Blower intake

Node		**Component Type**	**Flow Rate (m^3/sec)**	**Diameter of Pipe (m)**	**Cross Sectional Velocity (m/s)**	**Length of Pipe (m)**	**Equivalent Pipe Length (m)**	**Reynolds Number Re**	**Friction Factor f**	**Well Head Loss (m wc)**	**Piping Head Loss (m wc)**	**Fittings Head Loss (m wc)**	**Total Head Loss (m wc)**
k	*k*	Manifold Vacuum	**Total frictional losses from junction a to k**										0.30682
k	*l*	Piping	0.495	0.15	28.03	6	6	423,780	0.014	-	0.0274909	-	0.02749
		Tee (Branch)	0.495	0.15	28.03	-	9.2	423,780	0.014	-	-	0.042153	0.04215
		150 to 250 Reducer	0.495	0.25	10.09	-	5	254,268	0.015	-	-	0.001909	0.00191
		Sub-Total											**0.07155**
m	*n*	Condensate Tank	0.495	0.25	10.09	6	6	254,268	0.015	-	0.0022904	-	0.00229
n	*o*	Piping	0.495	0.25	10.09	6	6	254,268	0.015	-	0.002290	-	0.00229
o	*o*	Blower inlet vacuum	0.495	0.25	10.09	6	6	254,268	0.015	-	0.002290	-	0.00229
		Blower Intake Vacuum											**0.38525**

A Blower capable of providing a gas flow rate of 3540 m^3/hr with a head loss of 0.398 m water column on the suction side of the blower is required. Based on this criterion, M-D Plus blowers manufactured by Tuthil that only minimally exceed the calculated requirements are presented in table 4.9 (Tuthill Vacuum and Blower Systems, 2016).

Table 4.9: Blower Characteristics, M-D Plus Series

Model	Flow Rate (m^3/hr)	Power (kW)	Suction Head (m wc)
5511	258 - 1991	2 - 62	6
7013	757 - 3652	5 - 136	6

Therefore, a combination of two M-D Plus model 5511 blowers in series or M-D Plus model 7013 as the only blower is sufficient to meet the flow and head losses encountered.

4.4.3 Chunga Bioreactor Operation Landfill Gas Collection System

The bioreactor operation for Chunga landfill was designed based on the peak methane flow of 1781 m^3/hour estimated by Afvalzorg model. The collection system geometry, number of wells, vertical gas extraction well and pipe connectors were kept the same as for the conventional operation scenario, as shown in figure 4.4. The diameters of the header and main header pipes were redesigned ensuring that the gas flow velocity in these pipes does not exceed the allowable velocity of 15 m/sec. Since the gas volumetric flow is higher in bioreactor operation, the subsurface and wall frictional losses in the wells and pipes are higher than in the conventional operation because the same pipe diameters were used. The volumetric flow and pipe diameters designed for the header and main header pipes are as shown in table 4.10.

Table 4.10: Design of collector and header pipes for bioreactor operation of Chunga landfill

Name of Pipe	Characteristics and Components	Value	Units	Design Parameters and Comments
Header Pipe Details	Number of wells connected	8	no.	Number of wells calculated based on 47 m spacing between wells
	Total Flow in Header Pipe	1,765.1	m^3/hr	Cumulative flow in all 8 wells
	Number of Header Pipes	2	no.	Determined by well layout geometry
	Total Flow collected by all Header Pipes	3,530	m^3/hr	Cumulative flow in all Header Pipes
	Header Pipe size	0.25	m	Rule of thumb for header design is dependent on maximum allowed LFG flow velocity.
	Header pipe length	190	m	Measured from design layout
	Velocity of LFG in Header pipe	9.98	m/sec	The ratio of LFG flow rate to the cross sectional area of header. Max velocity of 15m/s is specified.
	Header pipe material	PVC	NA	HDPE or PVC
	Slope of header pipes	2.0	%	2 % slope on landfill in direction of gas flow.
Connector Pipe Details	Flow in connector pipes	220.6	m^3/hr	Equal to LFG flow rate in vertical well
	Number of connector Pipes	16	no.	Determined by general well layout and geometry arrangement of pipes.
	Total Flow collected by all connector Pipes	1,765.1	m^3/hr	Equal to LFG flow in header
	Connector Pipe size	0.075	m	Dependent on maximum LFG flow velocity in the pipe.
	Connector pipe length	22.5	m	Measured from design layout
	Velocity of LFG in connector pipe	13.87	m/sec	The ratio of LFG flow rate to the cross sectional area of connector pipe.
	Connector pipe material	PVC	NA	HDPE or PVC
	Connector pipe length	22.5	m	Measured from design layout
Main Header Pipe	Total LFG flow in main header pipe	3,530	m^3/hr	Equal to total LFG flow in all headers
	Main header pipe size	0.3	m	Rule of thumb for header design is dependent to maximum allowed LFG flow velocity
	Main header pipe length	157.5	m	Measured from design layout
	Velocity of LFG in main header pipe	13.87	m/sec	The ratio of LFG flow rate to the cross sectional area of header. Max velocity of 15m/s is specified.
	Main header pipe material	PVC	NA	HDPE or PVC recommended.

	Slope of main header pipes	2.0	%	2 % slope on landfill in direction of gas flow. 4 % is used when slope is against the LFG flow direction

The subsurface losses and frictional losses through the straight pipes, valves, fittings and sudden cross-sectional changes were calculated in the same manner as in the conventional operation. The head loss of 0.18 m water column is produced in each well due to the pull of landfill gas from the waste. Table 4.11 shows parameters used and the calculated subsurface loss in the collection system. The total head losses equivalent to 0.35 m water column results in the gas collection system for bioreactor operation of the landfill. The summary of calculations and results for head losses at each stage in the system are shown in table 4.12.

Based on calculations, a blower must be sized for a flow of 7060 m^3/hour and capable of overcoming a total head loss of 0.35 m water column. From table 4.9, a combination of two M-D Plus model 7013 blower in series is sufficient to meet the flow and head losses encountered in system.

Table 4.11: Subsurface head losses calculation for bioreactor operation of Chunga landfill

Radius of Influence (m)	Radius of Borehole (m)	LFG Viscosity (N.s/m^2)	Ks (m^2)	Waste Volume (m^3)	Total LFG Production G_{tot} (m^3/sec)	Melema Factor (N/m^4)	ΔP_{well} (N/m^2)	m of water column (m)	Total head lost m. wc
27.0	0.30	0.0000124	1.48E-11	665,725	1.0	0.624	1818.71	0.18187	2.91

Table 4.12 Head losses in piping system under bioreactor operation

Node From	Node To	Component Type	Flow Rate (m3/s)	Diameter of Pipe (m)	Cross Sectional Velocity (m/s)	Length of Pipe (m)	Equivalent Pipe Length (m)	Reynolds Number Re	Friction Factor f	Well Head Loss (m wc)	Piping Head Loss (m wc)	Fittings Head Loss (m wc)	Total Head Loss (m wc)
a	***b***	Well 1 (Subsurface)	0.061	0.15	3.47	-	-	52,420	0.024	0.18187	-	-	0.18187
		Well head	0.061	0.15	3.47	-	-	52,420	0.024	0.00911283	-	-	0.00911
		Piping	0.061	0.075	13.87	22.5	22.5	104,841	0.029	-	0.0065349	-	0.00653
		Globe valve	0.061	0.075	13.87	-	24.5	104,841	0.029	-	-	0.113853	0.11385
		75 to 250 Reducer	0.061	0.075	13.87	-	7.5	104,841	0.029	-	-	0.000181	0.00018
		Tee (branch)	0.061	0.15	3.47	-	7.5	52,420	0.024	-	-	0.000901	0.00090
		Sub-Total											**0.31245**
b	***c***	Piping	0.061	0.25	1.25	23.5	22.5	31,452	0.023	-	0.0002105	-	0.00021
		Tee (run)	0.061	0.25	1.25	-	5.4	31,452	0.023	-	-	0.000048	0.00005
		Sub-Total											**0.00026**
c	***d***	Piping	0.122	0.25	2.49	23.5	22.5	62,757	0.0199	-	0.000725	-	0.00072
		Tee (run)	0.122	0.25	2.49		5.4	62,757	0.0199	-	-	0.000167	0.00017
		Sub-Total											**0.00089**
d	***e***	Piping	0.153	0.25	3.12	23.5	22.5	78,666	0.019	-	0.0010876	-	0.00109
		Tee (run)	0.153	0.25	3.12	-	5.4	78,666	0.019	-	-	0.000250	0.00025
		Sub-Total											**0.00134**
e	***f***	Piping	0.184	0.25	3.75	23.5	22.5	94,575	0.018	-	0.0014893	-	0.00149
		Tee (run)	0.184	0.25	3.75	-	5.4	94,575	0.018	-	-	0.000342	0.00034

		Sub-Total											**0.00183**
f	***g***	Piping	0.215	0.25	4.38	23.5	22.5	110,484	0.0176	-	0.0019873	-	0.00199
		Tee (run)	0.215	0.25	4.38	-	5.4	110,484	0.0176	-	-	0.000457	0.00046
		Sub-Total											**0.00244**
g	***h***	Piping	0.246	0.25	5.02	23.5	22.5	126,394	0.0171	-	0.002527	-	0.00253
		Tee (run)	0.246	0.25	5.02	-	5.4	126,394	0.0171	-	-	0.000581	0.00058
		Sub-Total											**0.00311**
h	***i***	Piping	0.277	0.25	5.65	23.5	22.5	142,303	0.0167	-	0.0031282	-	0.00313
		Tee (run)	0.277	0.25	5.65	-	5.4	142,303	0.0167	-	-	0.000719	0.00072
		Sub-Total											**0.00385**
i	***j***	Piping	0.308	0.25	6.28	26.8	26.8	158,212	0.0164	-	0.0043305	-	0.00433
		Tee (run)	0.308	0.25	6.28	-	5.4	158,212	0.0164	-	-	0.000873	0.00087
		Sub-Total											0.00520
j	***k***	90deg elbow	0.308	0.25	6.28	-	7.5	158,212	0.0164	-	-	0.001212	0.00121
		Piping	0.308	0.25	6.28	45	45	158,212	0.0164	-	0.007271	-	0.00727
		Sub-Total											**0.00848**
		Total losses from junction *a* to *k*											**0.33986**
Node		**Component Type**	**Flow Rate (m^3/s)**	**Diameter of Pipe (m)**	**Cross Sectional Velocity (m/s)**	**Length of Pipe (m)**	**Equivalent Pipe Length (m)**	**Reynolds Number Re**	**Friction Factor f**	**Well Head Loss (m wc)**	**Piping Head Loss (m wc)**	**Fittings Head Loss (m wc)**	**Total Head Loss (m wc)**
k	***k***	Manifold Vacuum	Total frictional losses from junction a to k										0.33986
k	***l***	Piping	0.617	0.25	12.56	6	6	316,423	0.0143	-	0.0033815	-	0.00338
		Tee (Branch)	0.617	0.25	12.56	-	5.4	316,423	0.0143	-	-	0.003043	0.00304
		250 to 300 Reducer	0.617	0.3	8.72	-	6.9	263,686	0.0148	-	-	0.001617	0.00162
		Sub-Total											**0.00804**
m	***n***	Condensate Tank	0.617	0.3	8.72	6	6	263,686	0.0148	-	0.0014065	-	0.00141
n	***o***	Piping	0.617	0.3	8.72	6	6	263,686	0.0148	-	0.001406	-	0.00141
o	***o***	Blower inlet vacuum	0.617	0.3	8.72	6	6	263,686	0.0148	-	0.001406	-	0.00141
		Blower Vacuum Required											**0.35212**

4.5 Potential of Generating Electricity from Chunga Landfill

Electricity can be produced by burning landfill gas in an internal combustion engine (ICE), a gas turbine or microturbine. The feasibility of electricity production from the three technologies was assessed based on the required landfill gas flow as presented in table 4.13.

Table 4.13: Electricity generation technology and required landfill gas flow to the engines

Type of Technology	Recommended Project Size	Required Landfill Gas Flow Rate	Feasibility
Internal Combustion Engine	800 kW – 3 MW	470 m^3/hr - 1890m^3/hr	Yes, feasible
Gas Turbine	Greater than 3 MW	Greater than 2210 m^3/hr, typically exceeds 3560 m^3/hr	Not feasible for conventional operation but feasible for bioreactor operation
Microturbine	100 kW – 250 kW	35 m^3/hr – 340 m^3/hr	May be feasible but more than one microturbine is required

Based on the analysis on the kind of technology that is feasible with regards to gas flow at Chunga landfill, an economic feasibility of using microturbine, gas turbine and standard reciprocating engine was done in Landfill Cost-Web Model. The net electricity generated in each operation year with bioreactor and conventional operations considering electricity generation through the use of a microturbine and standard reciprocating engine technology are as shown in table 4.14.

Table 4.14: Net electricity generation per year

Landfill Operation	**Conventional Operation Net Electricity Generated (kWh)**		**Bioreactor Operation Net Electricity Generated (kWh)**	
Electricity Production Technology	**Microturbine**	**Standard Reciprocating Engine**	**Microturbine**	**Standard Reciprocating Engine**
2019	3,679,365	5,130,424	12,773,700	17,811,361
2020	4,131,824	5,761,322	13,938,453	19,435,466
2021	4,593,312	6,404,811	15,002,105	20,918,597
2022	5,058,625	7,053,632	15,954,476	22,246,562
2023	5,530,218	7,711,212	16,843,954	23,486,831
2024	6,008,778	8,378,505	17,693,830	24,671,879
2025	6,496,982	9,059,245	18,536,497	25,846,874
2026	6,993,548	9,751,646	19,367,045	27,004,972
2027	7,496,939	10,453,563	20,179,552	28,137,913
2028	8,007,808	11,165,908	20,985,594	29,261,840
2029	8,526,815	11,889,600	21,793,993	30,389,053
2030	9,052,265	12,622,274	22,593,815	31,504,308
2031	9,587,203	13,368,181	23,412,034	32,645,213
2032	10,129,643	14,124,547	24,231,757	33,788,217
2033	10,682,805	14,895,863	25,078,956	34,969,533

A graphical representation of the electricity generation each year is presented in figure 4.6. It can therefore be concluded that, standard reciprocating engines generate more electricity as compared to microturbines and bioreactor operation substantially increases electricity generation.

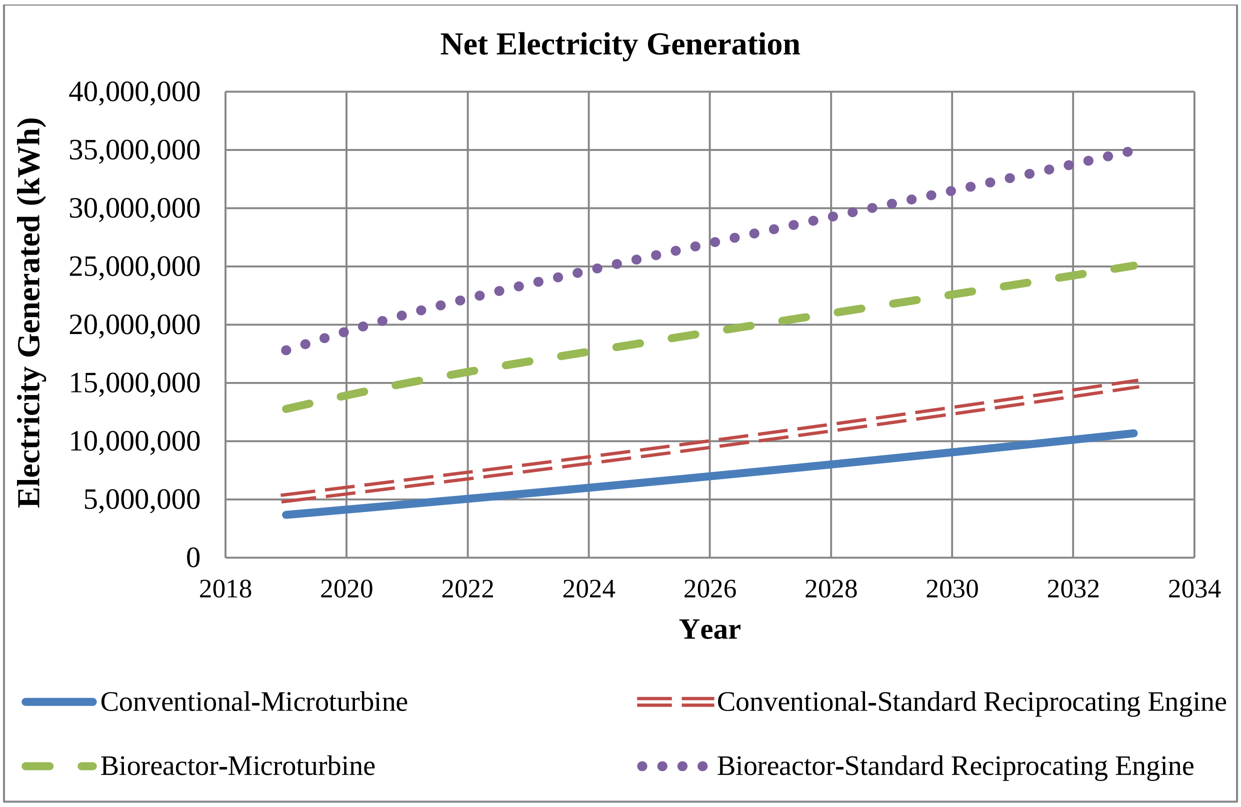

Figure 4.6: Graph of electricity generation against time

The utilisation of standard reciprocating engine and standard turbine generator set was not investigated in conventional operations since it did not have a payback period within 15 year and therefore considered as an unworthy investment.

The analysis under microturbine technology assumed an operation period of 10 years. This meant that after 10 years of operation, another set of microturbines have to be procured and installed in order to maintain the generation of electricity until there is no sufficient landfill gas produced from decomposing waste to generate electricity.

Figure 4.7 shows the minimum number of houses that can exclusively benefit from electricity generation considering only residential utilisation of the electricity produced at the landfill by households designated as R2 and characterised by ZESCO as households with a monthly consumption ranging between 100kWh to 300kWh. The minimum electricity generated occurs at the beginning of the project and seen to rise as more gas is produced due to the increased production of gas from waste deposited at the landfill.

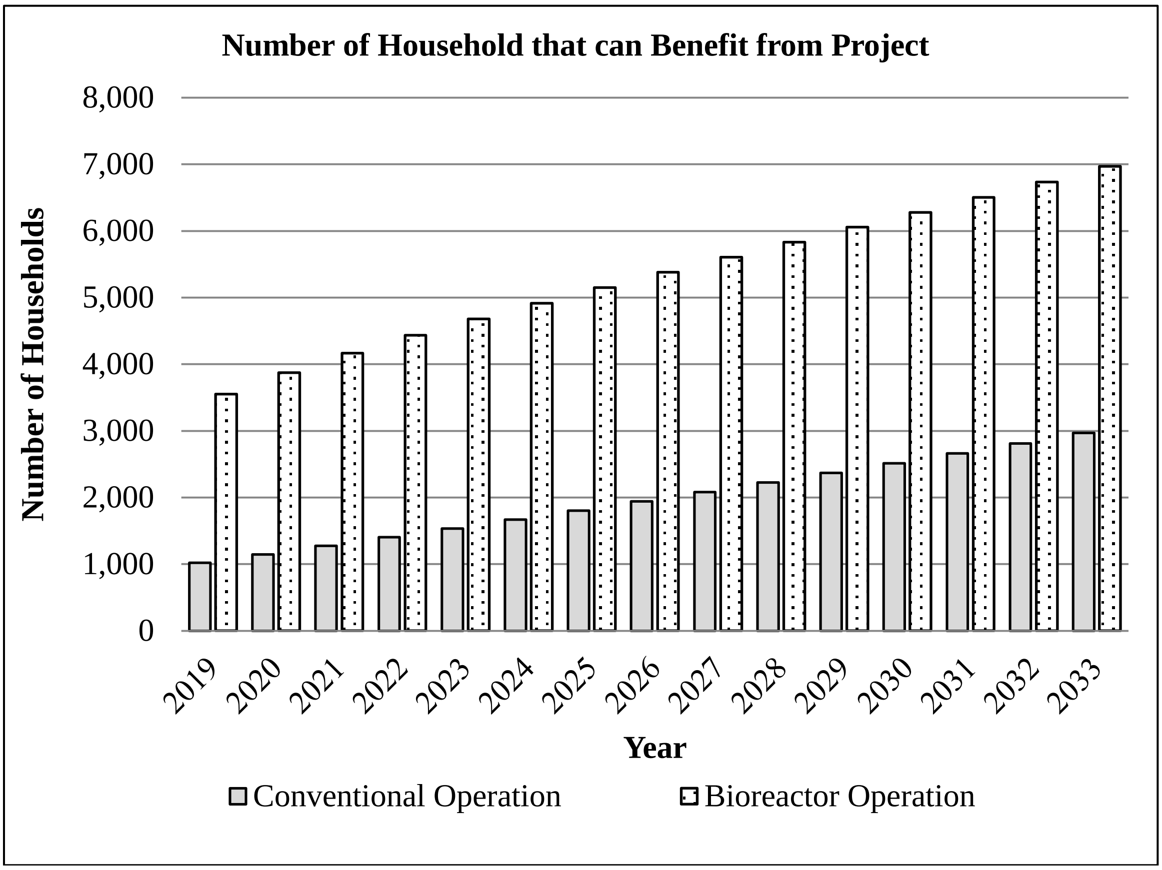

Figure 4.7: Comparison of the minimum number of household that can benefit from electricity produced by conventional and bioreactor operation of the landfill with microturbine

4.5.1 Investment Calculations

The cost of investment was estimated using a landfill gas cost economic assessment model. The model results also include the investment and operation cost of a flaring plant that burns unutilised and excess methane produced. Since the use of standard reciprocating engine and standard turbine generator set under conventional operations did not have a payback period within 15 years, it was deemed as unworthy investment and therefore not presented in the economic feasibility analysis.

Two scenarios were assessed, investment with taxes and investment without taxes. This approach assumed that private investors are mandated to marginal taxes whereas for a government funded project, no marginal taxes are paid for imported equipment and tools. The government funded project adopted a budgeted finance where all the funds required for the investment are secured and available while the private funded project took two assumptions; (1) funding through a loan in which a down payment of 20 % is made towards a project loan and 80 % financed, (2) a best case scenario with 100 % investment fund already secured.

Conventional operation of the landfill for both government and private funded projects produced negative cumulative cash flows. This caused a negative net present value and internal rate of return. Thus, investment analysis and economic feasibility of conventional operation with electricity sales will not be presented in the results. However, further economic feasibility analysis was considered by incorporating carbon trading credits through the sales of reduced carbon emissions at the landfill to major polluters who seek to reduce the greenhouse gas emissions rating through buying carbon credits. The lowest price for European carbon credits was experienced in 2013 when every ton of carbon was selling at 3euros. The average cost of European carbon emissions per ton is currently at € 6 (Peter, 2016). Therefore, this study adopted a conservative value of US$ 4/ton with part of the sales assumed to be paid to companies engaged to link the landfill operator to carbon credit buyers.

i) Private Funded Project (Investment with Taxes) -Bioreactor Operation with Microturbine

For a private funded project the estimated cash flows and net present value (NPV) at a project discount rate of 9 % for 10 years are as shown in table 4.15. A graphical comparison of the cash flows and net present values is presented in figure 4.8.

For 20 % down payment, 80 % financed, the internal rate of return (IRR) for a 10 year period is estimated as 8 % with no breakeven point since the total present value at the end of a 10 year investment is less than 0. This means that a project financed through this avenue is not economically viable. Furthermore, for investment in the project with 100 % down payment yields 10 % IRR with a breakeven point in the 10th year. This means that the return on investment happens at the end of the 10th year. This may be profitable because after 10 years only the microturbine needs replacement and no investment or expenditure is made on the flare plant which reduces the investment cost and in turn increases profits. The breakeven point for two scenarios is presented in figure 4.8 as the point where the curve crosses the year axis.

Table 4.15 Cash flows and net present value for bioreactor operation with microturbine as a private funded project

Year	Bioreactor Operation with 20 % down payment, 80% financed			Bioreactor Operation with 100 % down payment		
	Cash flow	**NPV @ 9% discount rate**	**Cumulative NPVs**	**Cash flow**	**NPV 9% discount rate**	**Cumulative NPVs**
2018	($1,580,736)	($1,450,217)	($1,450,217)	($4,706,797)	($4,318,163)	($4,318,163)
2019	$17,879	$15,048	($1,435,168)	$591,954	$498,236	($3,819,927)
2020	$91,781	$70,872	($1,364,297)	$639,990	$494,190	($3,321,691)
2021	$162,298	$114,976	($1,249,320)	$685,827	$485,857	($2,827,501)
2022	$193,727	$125,909	($1,123,411)	$728,965	$473,777	($2,341,644)
2023	$222,699	$132,788	($990,623)	$771,098	$459,780	($1,867,867)
2024	$250,058	$136,790	($853,833)	$813,064	$444,774	($1,408,086)
2025	$276,897	$138,965	($714,868)	$856,119	$429,657	($963,312)
2026	$302,892	$139,460	($575,408)	$900,113	$414,437	($533,655)
2027	$327,645	$138,401	($437,007)	$944,845	$399,113	($119,218)
2028	$990,823	$383,977	($53,031)	$990,823	$383,977	$279,895
Summary	**$1,255,962**	**($53,031)**	**($106,061)**	**$3,216,001**	**$165,635**	**$663,871**

A graphical representation of yearly cash flows and net present value at the project discount rate is shown in figure 4.8. Calculations of the breakeven point when the net cumulative present values exceed zero is also depicted in figure 4.9.

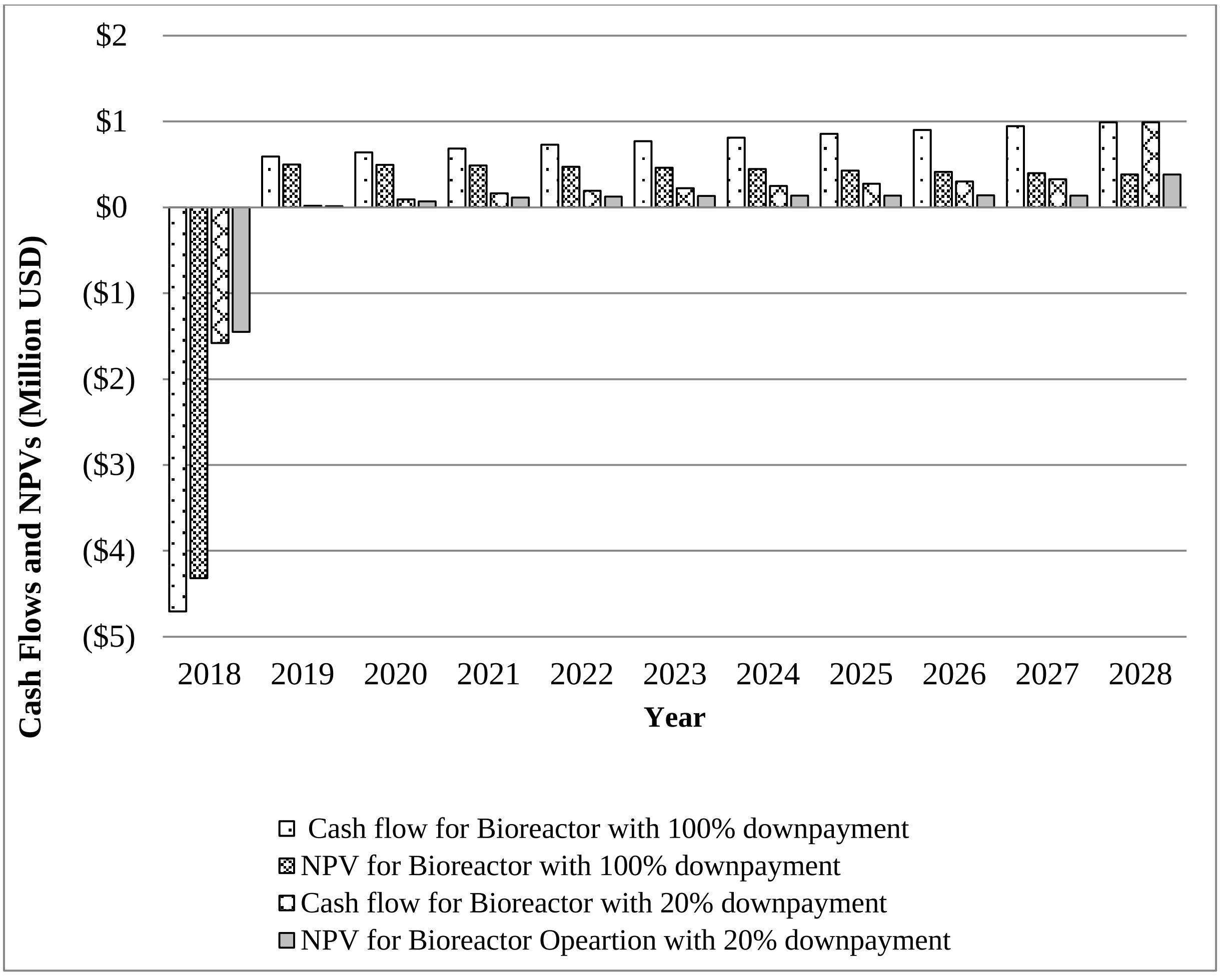

Figure 4.8: Comparison of yearly cash flows and net present values for bioreactor operations with microturbine for a private funded project.

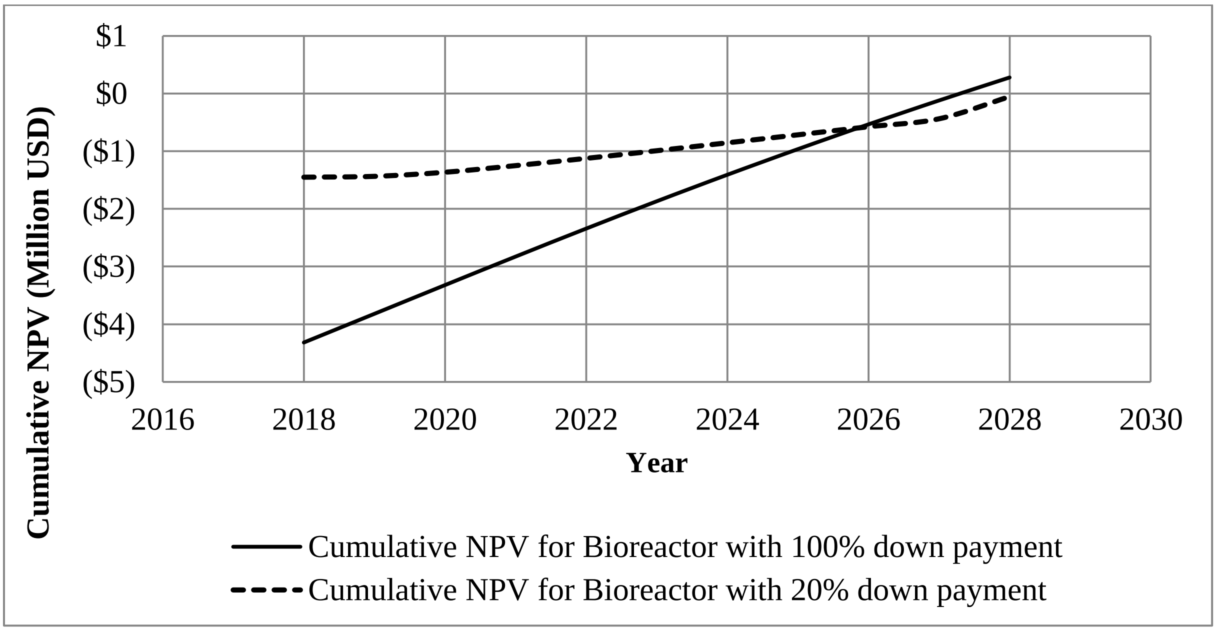

Figure 4.9: Cumulative NPVs to estimate breakeven point for bioreactor operation with microturbine as a private funded project.

ii) Government Funded Project (Without Taxes) - Bioreactor with Microturbine

For a government funded project, marginal tax rates and interest rates on a loan are 0 and down payment is 100 % since a budget financed project is assumed. The cash flows and NPVs for both bioreactor operations are presented in table 4.16.

Table 4.16: Cash flows and net present values for bioreactor operation with microturbine as a government funded project

Year	Bioreactor Operation with 100 % down payment		
	Cash flow	NPV @ 9 % discount rate	Cumulative NPVs
2018	($4,706,797)	($4,318,163)	($4,318,163)
2019	$657,256	$553,199	($3,764,964)
2020	$731,158	$564,588	($3,200,376)
2021	$801,675	$567,927	($2,632,449)
2022	$868,042	$564,168	($2,068,282)
2023	$997,425	$556,235	($1,512,047)
2024	$1,063,663	$545,626	($966,421)
2025	$1,131,346	$533,817	($432,604)
2026	$1,200,165	$520,903	$88,299
2027	$1,270,901	$506,963	$595,261
2028	$1,412,099	$492,516	$1,087,777
Summary	**$5,426,932**	**$1,087,777**	**$2,175,554**

This project scenario yields an IRR of 15 % with cumulative NPV exceeding 0 in 2026, 8 years after operation (breakeven point). Thus investment in Chunga landfill as a government funded or through public private partnership with bioreactor operations to produce electricity is economically feasible with a breakeven point of 8 years. A graphical representation of cash flows and NPVs is as shown in figure 4.10. The year in which the curve of cumulative NPVs for bioreactor operations crosses the year axis signifies the breakeven point.

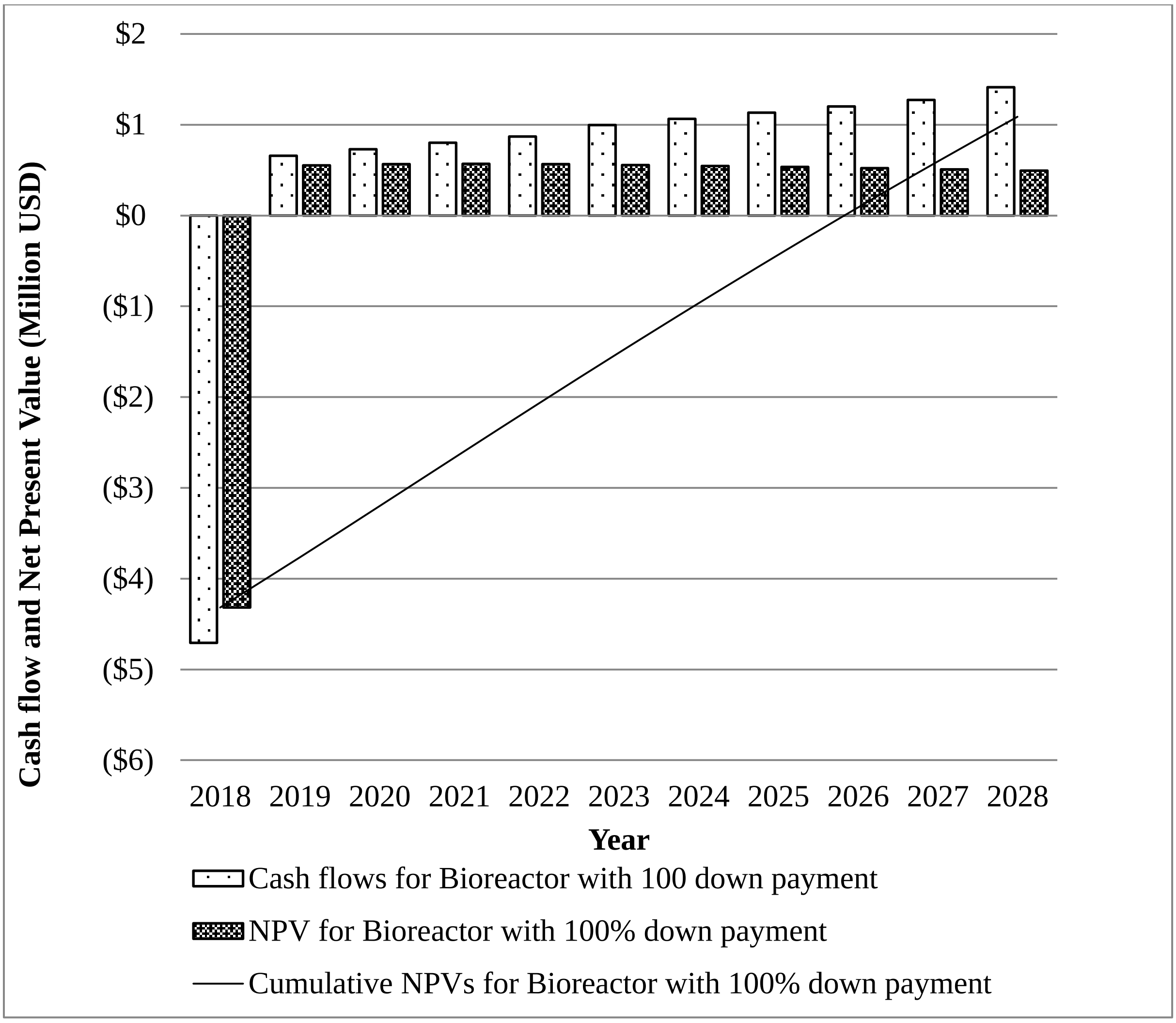

Figure 4.10: Comparison of yearly cash flows with net present values, and estimation of breakeven point using cumulative NPVs for bioreactor operations with microturbine as a government funded project

iii) Government Funded Project (Investment with Taxes) - Bioreactor with Standard Reciprocating Engine

Investment analysis for a standard reciprocating engine was done over a 15 year period which is considered as the period within which the engine is functional. The use of a standard reciprocating engine to produce electricity is not viable as the cumulative cash flows and NPVs is negative. This produces a negative IRR which means that an investment in this type of technology with electricity sales as the only source of revenue is a loss and does not yield any profits. This is shown in table 4.17.

Table 4.17: Cash flows and NPVs for bioreactor operation with standard reciprocating engine as a government funded project

Year	Bioreactor Operation with 100 % down payment		
	Cash flow	NPV @ 9 % discount rate	Cumulative NPVs
2018	($8,855,959)	($8,124,733)	($8,124,733)
2019	$161,467	$135,904	($7,988,830)
2020	$152,118	$117,463	($7,871,367)
2021	$135,335	$95,875	($7,775,492)
2022	$111,132	$72,228	($7,703,264)
2023	$80,110	$47,767	($7,655,497)
2024	$42,336	$23,159	($7,632,338)
2025	($2,308)	($1,158)	($7,633,496)
2026	($54,290)	($24,996)	($7,658,493)
2027	($114,046)	($48,174)	($7,706,667)
2028	($182,063)	($70,555)	($7,777,222)
2029	($258,970)	($92,073)	($7,869,295)
2030	($345,304)	($112,631)	($7,981,926)
2031	($442,086)	($132,293)	($8,114,219)
2032	($549,924)	($150,975)	($8,265,194)
2033	($670,228)	($168,810)	($8,434,004)
Summary	**($10,792,680)**	**($8,434,004)**	**($16,868,007)**

The graphical representation of the results in table 4.17 is shown in figure 4.11 including cumulative NPVs curve used for estimating the breakeven point.

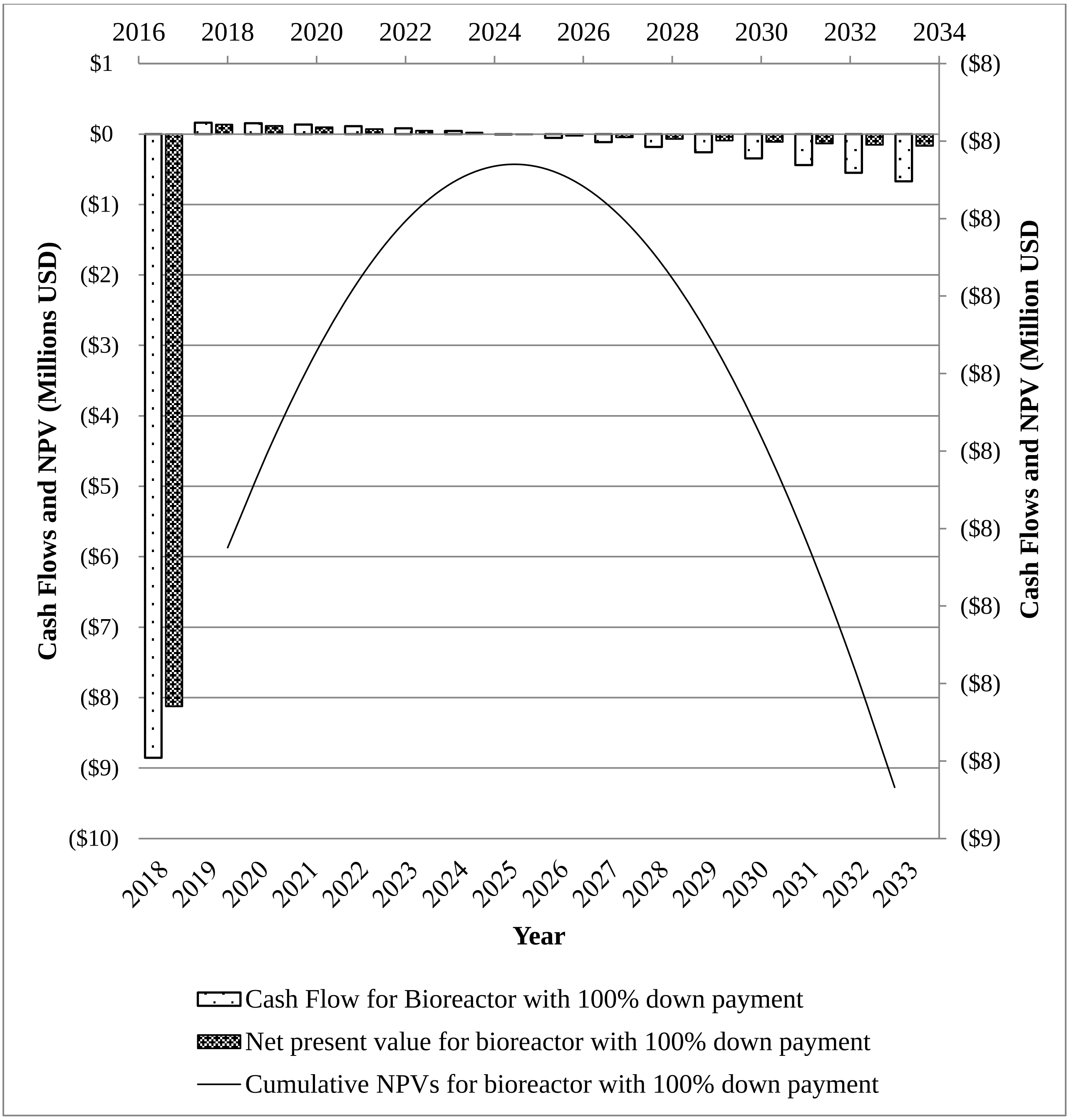

Figure 4.11: Comparison of yearly cash flows with net present values, and estimation of breakeven point using cumulative NPVs for bioreactor operations with standard reciprocating engine as a government funded project

iv) Private Funded Project (Investment with Taxes) - Bioreactor with Standard Reciprocating Engine

Similarly, the use of standard reciprocating engines is an unworthy investment and yields negative cash flows and NPVs as shown in table 4.18 and graphically in figure 4.12.

Table 4.18: Cash flows and NPVs for bioreactor operation with standard reciprocating engine as a private funded project

Year	Bioreactor Operation with 20 % down payment, 80 % Financed			Bioreactor Operation with 100 % down payment		
	Cash flow	NPV @ 9% discount rate	Cumulative NPVs	Cash flow	NPV @ 9% discount rate	Cumulative NPVs
2018	($2,974,195)	($2,728,620)	($2,728,620)	($8,855,959)	($8,124,733)	($8,124,733)
2019	($1,041,536)	($876,640)	($3,605,260)	$161,467	$135,904	($7,988,830)
2020	($1,050,886)	($811,477)	($4,416,737)	$152,118	$117,463	($7,871,367)
2021	($1,067,668)	($756,363)	($5,173,100)	$135,335	$95,875	($7,775,492)
2022	($1,091,872)	($709,642)	($5,882,742)	$111,132	$72,228	($7,703,264)
2023	($1,122,894)	($669,545)	($6,552,287)	$80,110	$47,767	($7,655,497)
2024	($1,160,668)	($634,925)	($7,187,212)	$42,336	$23,159	($7,632,338)
2025	($1,205,312)	($604,905)	($7,792,117)	($2,308)	($1,158)	($7,633,496)
2026	($1,257,293)	($578,893)	($8,371,010)	($54,290)	($24,996)	($7,658,493)
2027	($1,317,049)	($556,336)	($8,927,346)	($114,046)	($48,174)	($7,706,667)
2028	($182,063)	($70,555)	($8,997,901)	($182,063)	($70,555)	($7,777,222)
2029	($258,970)	($92,073)	($9,089,974)	($258,970)	($92,073)	($7,869,295)
2030	($345,304)	($112,631)	($9,202,605)	($345,304)	($112,631)	($7,981,926)
2031	($442,086)	($132,293)	($9,334,897)	($442,086)	($132,293)	($8,114,219)
2032	($549,924)	($150,975)	($9,485,872)	($549,924)	($150,975)	($8,265,194)
2033	($670,228)	($168,810)	($9,654,682)	($670,228)	($168,810)	($8,434,004)
Summary	**($10,792,680)**	**($9,654,682)**	**($9,654,682)**	**($10,792,680)**	**($8,434,004)**	**($8,434,004)**

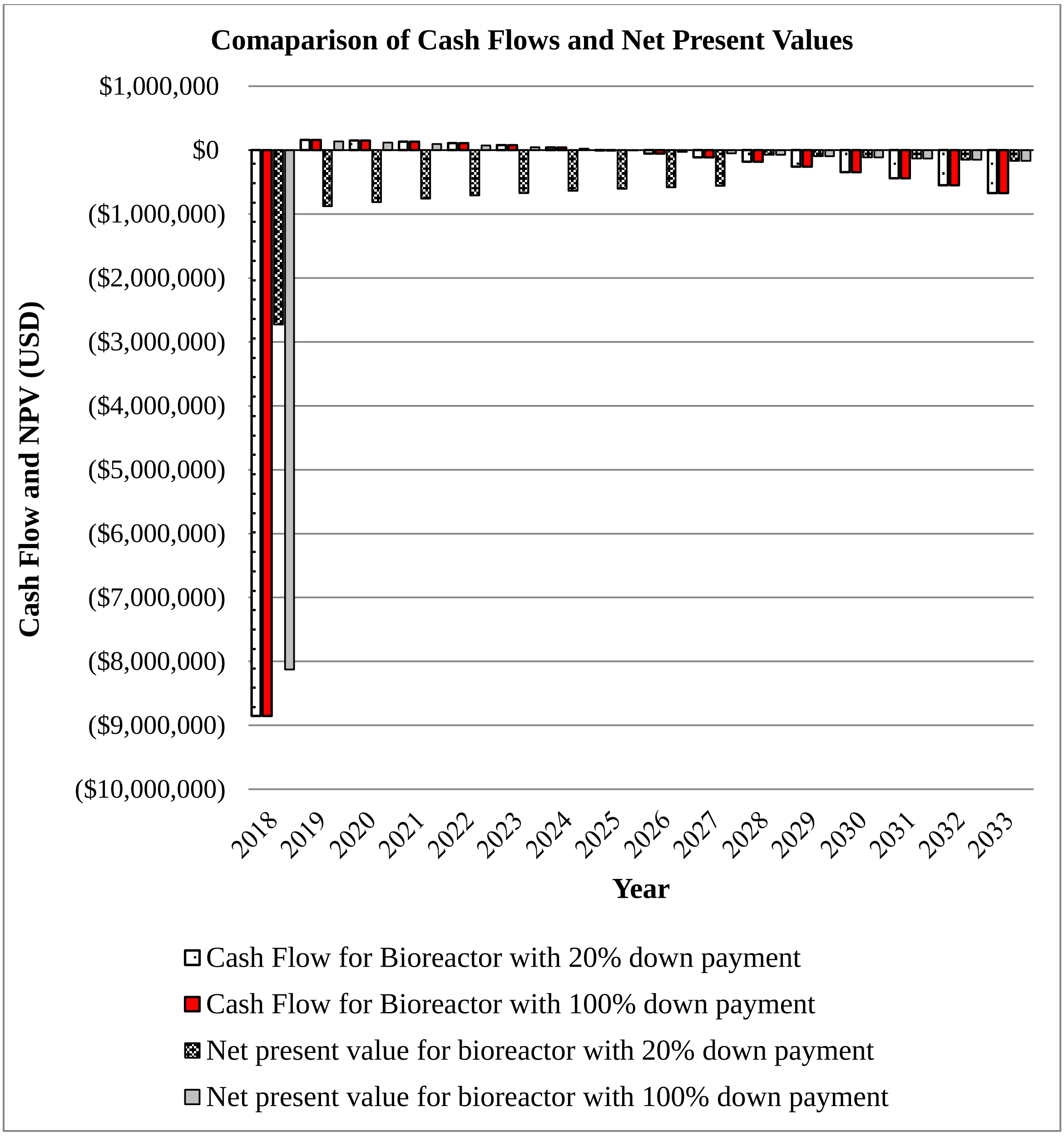

Figure 4.12: Comparison of yearly cash flows with and NPVs for bioreactor operations with standard reciprocating engine as a private funded project

The graph of cumulative NPVs for a project financed by a loan as well as budgeted funds is shown in figure 4.13. Since the cumulative NPVs curve does not cross the year axis, the present values on yearly cash flows does not exceed zero. This means that no return on investment can be achieved under this project scenario.

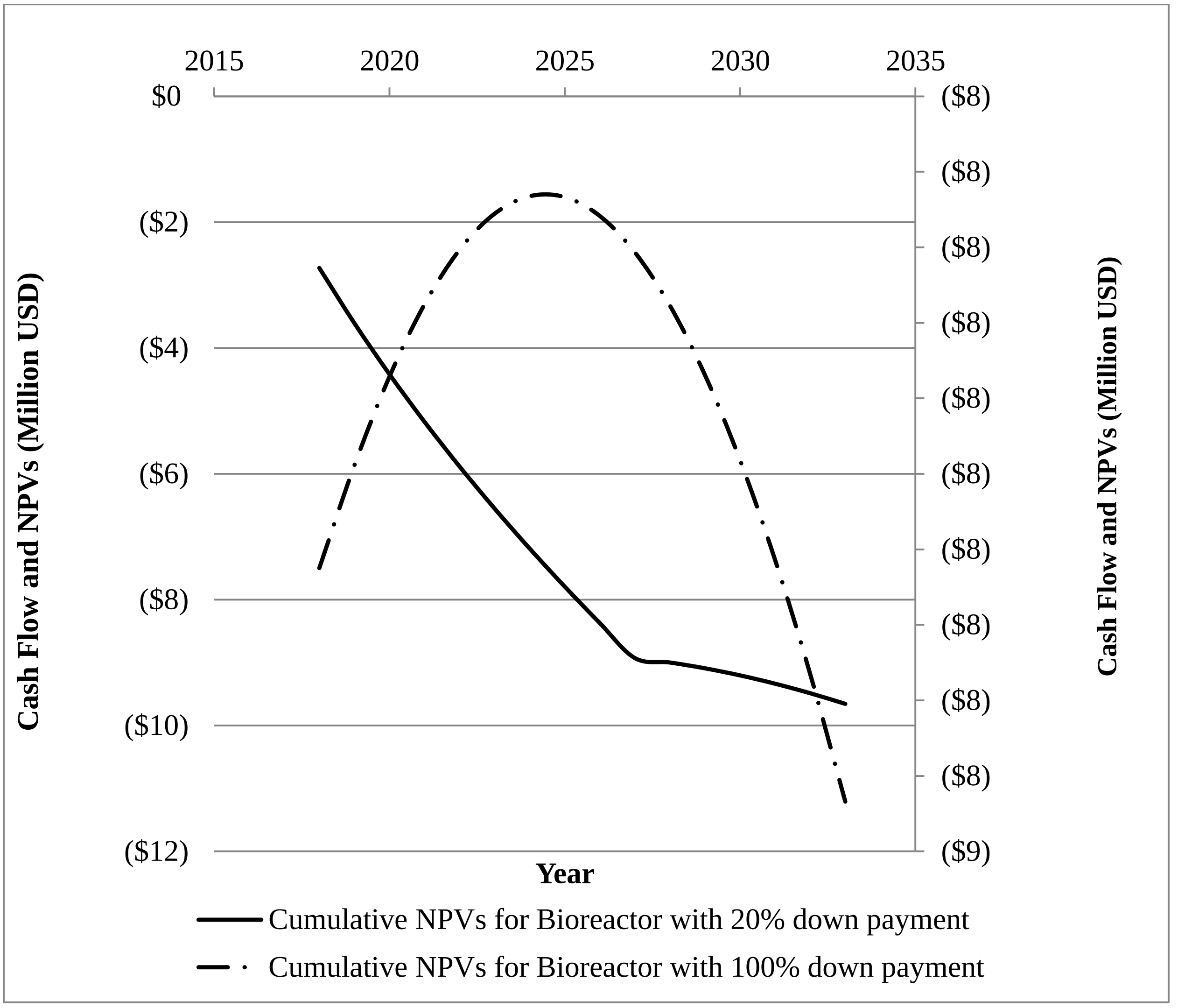

Figure 4.13: Cumulative NPVs for bioreactor operations with standard reciprocating engine as a private funded project

v) Private Funded Project (Investment with Taxes) – Bioreactor with Standard Turbine Generator Set

The use of standard turbine generator sets produces more power as compared to standard reciprocating engines and therefore yields slightly higher cash flows due to high revenue from electricity sales. Despite this advantage, these generator sets also result in a negative IRR due to the negative cash flows. This is shown is table 4.19 and graphically represented using a bar chart in figure 4.14.

Table 4.19: Cash flows and NPVs for bioreactor operation with standard turbine generator set as a private funded project

Year	Bioreactor Operation with 20 % down payment, 80 % Financed			Bioreactor Operation with 100 % down payment		
	Cash flow	NPV @ 9% discount rate	Cumulative NPVs	Cash flow	NPV @ 9% discount rate	Cumulative NPVs
2018	($3,504,731)	($3,215,349)	($3,215,349)	($10,435,681)	($9,574,019)	($9,574,019)
2019	($1,184,004)	($996,552)	($4,211,902)	$233,591	$196,609	($9,377,410)
2020	($1,175,801)	($907,934)	($5,119,836)	$241,794	$186,709	($9,190,701)
2021	($1,173,260)	($831,167)	($5,951,003)	$244,335	$173,093	($9,017,608)
2022	($1,176,526)	($764,661)	($6,715,664)	$241,069	$156,678	($8,860,930)
2023	($1,184,679)	($706,385)	($7,422,049)	$232,916	$138,880	($8,722,049)
2024	($1,197,416)	($655,027)	($8,077,076)	$220,179	$120,446	($8,601,604)
2025	($1,214,432)	($609,483)	($8,686,559)	$203,162	$101,960	($8,499,643)
2026	($1,236,088)	($569,129)	($9,255,688)	$181,507	$83,571	($8,416,073)
2027	($1,262,738)	($533,394)	($9,789,082)	$154,857	$65,413	($8,350,659)
2028	$123,042	$47,683	($9,741,400)	$123,042	$47,683	($8,302,977)
2029	$85,772	$30,495	($9,710,905)	$85,772	$30,495	($8,272,482)
2030	$42,567	$13,884	($9,697,021)	$42,567	$13,884	($8,258,598)
2031	($6,879)	($2,058)	($9,699,079)	($6,879)	($2,058)	($8,260,656)
2032	($63,163)	($17,341)	($9,716,420)	($63,163)	($17,341)	($8,277,997)
2033	($126,841)	($31,947)	($9,748,367)	($126,841)	($31,947)	($8,309,944)
Summary	**($8,427,773)**	**($9,748,367)**	**($9,748,367)**	**($8,427,773)**	**($8,309,944)**	**($8,309,944)**

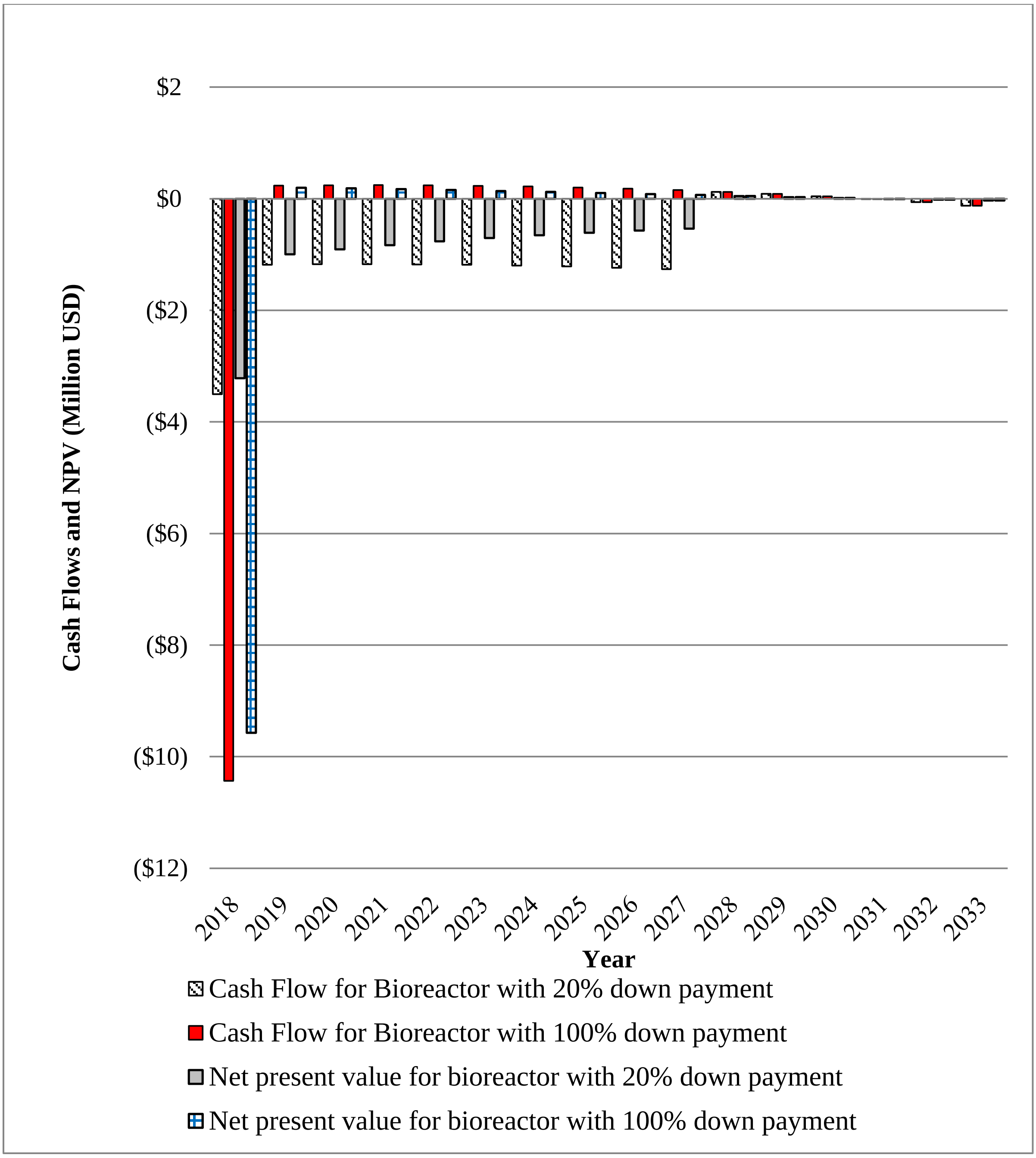

Figure 4.14: Yearly cash flows and NPVs for bioreactor operations with standard turbine generator set as a private funded project

vi) Government Funded Project (Investment with Taxes) - Standard Turbine Generator Set

Table 4.20 shows the estimated cash flows and NPVs for a government funded project utilising a standard turbine generator set to produce electricity under bioreactor operations. This scenario produces positive cash flows from 2019 up to 2030 owing to higher electricity sales as compared to the operation and maintenance costs. As gas production and feeding to the generator increases, the operation and maintenance costs also increase. Despite the positive cash flows, there is no enough net inflow to exceed the capital cost. This produces negative net cumulative NPVs and a negative IRR. The cash flows, NPVs and net cumulative NPVs are shown in figure 4.15. The graph of net cumulative NPV rises and approaches the year axis but fails to cross over and yield a positive NPV due to higher outflows as compared to revenue gains from electricity sales. To achieve the financial goals, the price of electricity per kWh needs to be adjusted upwards in order to increase revenue from electricity sales. Another way is by selling the reduced emissions to organisations and companies seeking to reduce their greenhouse gas emission ratings through purchase of reduced carbon emissions on the carbon market.

Table 4.20: Cash flows and NPVs for bioreactor operation with standard turbine generator set as a Government funded project

Year	**Bioreactor Operation with 100% down payment**		
	Cash flow	**NPV @ 9% discount rate**	**Cumulative NPVs**
2018	($10,435,681)	($9,574,019)	($9,574,019)
2019	$233,591	$196,609	($9,377,410)
2020	$241,794	$186,709	($9,190,701)
2021	$244,335	$173,093	($9,017,608)
2022	$241,069	$156,678	($8,860,930)
2023	$232,916	$138,880	($8,722,049)
2024	$220,179	$120,446	($8,601,604)
2025	$203,162	$101,960	($8,499,643)
2026	$181,507	$83,571	($8,416,073)
2027	$154,857	$65,413	($8,350,659)
2028	$123,042	$47,683	($8,302,977)
2029	$85,772	$30,495	($8,272,482)
2030	$42,567	$13,884	($8,258,598)
2031	($6,879)	($2,058)	($8,260,656)
2032	($63,163)	($17,341)	($8,277,997)
2033	($126,841)	($31,947)	($8,309,944)
Summary	**($8,427,773)**	**($8,309,944)**	**($8,309,944)**

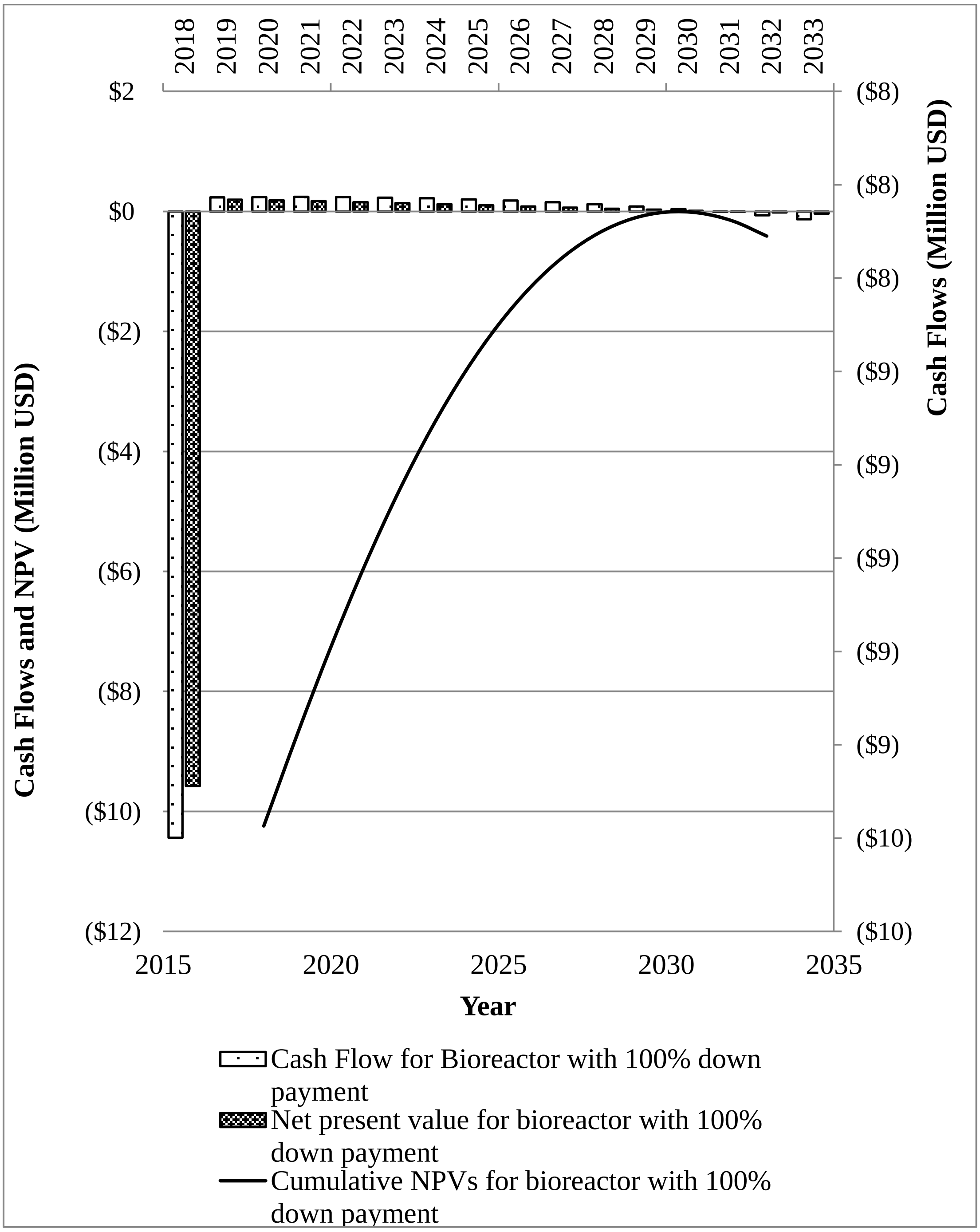

Figure 4.15: Cash flows, NPV and net cumulative NPVs for bioreactor operation with standard turbine generator set as Government funded project

A summary of the technologies assessed, project description, the financing and revenue elements used, and the final results summary are presented in table 4.21. The electricity generation technology that did not meet the financial goals was also assessed at residential and commercial rates, US$ 0.094/kWh and US$ 0.057/kWh respectively. This is because the cost of electricity under these categories is higher than the average cost of US$ 0.05/kWh used. Additional revenue collection was also considered through trading in reduced carbon emissions at a rate of US$ 4 per ton of carbon captured and destroyed. This value is below the current carbon market charges and was adopted as a conservative approach to establish the minimum revenue through carbon trading.

Table 4.21: Financial feasibility summary of private and government funded electricity generation projects at Chunga landfill

Case Study Name	Project Description	Financing and Revenue Elements	Financial Results Summary
Electricity 1 – **Private Funded (Bioreactor)**	• 3.7 MW Microturbine capacity project • LFG collection and Flaring system required	• 20% down payment, 80% financed • 11% interest rate • 9% discount rate • 5¢/kWh (average cost of electricity)	• Capital Cost: $4,706,800 • O&M: -$106,034 (during initial year of operation) • NPV: $1,255,962 (after 10 years) • IRR: 8% • NPV payback(year): none
Electricity 2 – **Private Funded (Bioreactor)**	• 3.7 MW Microturbine capacity project • LFG collection and Flaring system required	• 100% down payment, • 11% interest rate • 9% discount rate • 5¢/kWh (average cost of electricity)	• Capital Cost: $4,706,800 • O&M: -$18,571 (during initial year of operation) • NPV: $165,635 (after 10 years) • IRR: 10% • NPV payback(year): 10
Electricity 3 – **Private Funded (Bioreactor)**	• 3.7 MW Microturbine capacity project • LFG collection and Flaring system required	• 100% down payment, • 11% interest rate • 9% discount rate • 9.4¢/kWh (average cost of electricity)	• Capital Cost: $4,706,800 • O&M: $21,721 (during initial year of operation) • NPV: $2,855,961 (after 10 years) • IRR: 24% • NPV payback(year): 7
Electricity 4 – **Private Funded (Bioreactor)**	• 3.7 MW Microturbine capacity project • LFG collection and flaring system required	• 100% down payment, • 11% interest rate • 9% discount rate • 5¢/kWh (average cost of electricity) • $4/metric ton carbon dioxide equivalent credit revenue included	• Capital Cost: $4,706,800 • O&M: -$18,571 (during initial year of operation) • NPV: $2,130,960 (after 10 years) • IRR: 21% • NPV payback(year): 6
Electricity 5– **Government Funded (Bioreactor)**	• 3.7MW Microturbine capacity project • LFG collection and Flaring system required	• 100% down payment, • 5¢/kWh (average cost of electricity)	• Capital Cost: $4,706,800 • O&M: -$18,571 (during initial year of operation) • NPV: $2,175,554 (after 10 years) • IRR: 15% • NPV payback(year): 8
Electricity 6– **Government Funded (Bioreactor)**	• 3.7MW Microturbine capacity project • LFG collection and Flaring	• 100% down payment, • 9.4¢/kWh (average cost of electricity)	• Capital Cost: $4,706,800 • O&M: $21,700 • (during initial year of operation) • NPV: $5,226,700 (after 10

	system required		years) • IRR: 32% • NPV payback(year): 5
Electricity 7 – **Government Funded (Bioreactor)**	• 3.7 MW Microturbine capacity project • LFG collection and Flaring system required	• 100% down payment, • 5¢/kWh (average cost of electricity) • $4/metric ton carbon dioxide equivalent credit revenue included •	• Capital Cost: $4,706,800 • O&M: -$18,600 (during initial year of operation) • NPV: $4,111,400 (after 10 years) • IRR: 28% • NPV payback(year): 5
Electricity 8 – **Private Funded (Bioreactor)**	• 4.6 MW Standard reciprocating Engine capacity • LFG collection and Flaring system required	• 20% down payment, 80% financed • 11% interest rate • 9% discount rate • 5¢/kWh (average cost of electricity)	Capital Cost: $8,856,000 O&M: $729,100 NPV: -$9,654,700) IRR: negative NPV payback(year): none
Electricity 9 – **Private Funded (Bioreactor)**	• 4.6 MW Standard reciprocating Engine capacity • LFG collection and Flaring system required	• 20% down payment, 80% financed • 11% interest rate • 9% discount rate • 9.4¢/kWh (average cost of electricity)	Capital Cost: $8,856,000 O&M: $769,400 NPV: -$1,986,700) IRR: 2% NPV payback(year): none
Electricity 10– **Government Funded (Bioreactor)**	• 4.6 MW Standard reciprocating Engine capacity • LFG collection and Flaring system required	• 100% down payment, • 5¢/kWh (average cost of electricity)	Capital Cost: $8,856,000 O&M: $729,100 NPV: -$8,434,000) IRR: negative NPV payback(year): none
Electricity 11– **Government Funded (Bioreactor)**	• 4.6 MW Standard reciprocating Engine capacity • LFG collection and Flaring system required	• 100% down payment, • 9.4¢/kWh (average cost of electricity) • $4/metric ton carbon dioxide equivalent credit revenue included	Capital Cost: $8,856,000 O&M: $769,400 NPV: $3,996,100 IRR: 16% NPV payback(year): 9
Electricity 12– **Government Funded (Bioreactor)**	• 4.0 MW Standard turbine generator set • LFG collection and Flaring system required	• 100% down payment, • 9.4¢/kWh (average cost of electricity) • $4/metric ton carbon dioxide equivalent credit revenue included	Capital Cost: $10,435,700 O&M: $536,000 NPV: $2,479,800 IRR: 13% NPV payback(year): 11

4.7 Environmental Benefits of Capturing Landfill Gas

Using the procedure outlined in chapter 3, the environmental benefits of the landfill gas to energy project were estimated for both bioreactor and conventional operations of the landfill. Table 4.22 shows the environmental benefits in million metric tons of carbon dioxide emissions (mtCO_2e)

Table 4.22 Environmental benefits of utilising landfill gas for electricity generation at Chunga

Year	Conventional Operation			Bioreactor Operation		
	Direct CH_4 Reduced (mtCO_2e)	CH_4 Utilized by Project (mtCO_2e)	Avoided CO_2 Emissions (mtCO_2e)	Direct CH_4 Reduced (mtCO_2e)	CH_4 Utilized by Project (mtCO_2e)	Avoided CO_2 Emissions (mtCO_2e)
2019	0.0266	0.0247	0.0029	0.0922	0.0858	0.0082
2020	0.0298	0.0277	0.0032	0.1007	0.0936	0.0090
2021	0.0332	0.0308	0.0036	0.1083	0.1008	0.0096
2022	0.0365	0.0340	0.0040	0.1152	0.1071	0.0102
2023	0.0399	0.0371	0.0043	0.1216	0.1131	0.0108
2024	0.0434	0.0404	0.0047	0.1278	0.1188	0.0114
2025	0.0469	0.0436	0.0051	0.1339	0.1245	0.0119
2026	0.0505	0.0470	0.0055	0.1399	0.1301	0.0124
2027	0.0541	0.0503	0.0059	0.1457	0.1355	0.0130
2028	0.0578	0.0538	0.0063	0.1515	0.1409	0.0135
2029	0.0616	0.0573	0.0067	0.1574	0.1464	0.0140
2030	0.0654	0.0608	0.0071	0.1632	0.1517	0.0145
2031	0.0692	0.0644	0.0075	0.1691	0.1572	0.0150
2032	0.0731	0.0680	0.0079	0.1750	0.1627	0.0156
2033	0.0771	0.0717	0.0084	0.1811	0.1684	0.0161
Total	**0.7653**	**0.7117**	**0.0831**	**2.0825**	**1.9368**	**0.1852**

The total methane collected by the landfill collection system amounts to 0.77 mtCO_2e and only 0.71 mtCO_2e is used to generate electricity while the remaining amount is flared under conventional operation. Due to the rapid degradation of waste, methane production with a specific period is higher for bioreactor operation as compared to conventional operations where the waste degrades moderately. This is evident from the environmental benefits, table 4.22, where more methane is collected and either destroyed or utilised for electricity generation. The total methane utilised for electricity generation amounts to 1.9mtCO_2e out of 2.1mtCO_2e collected. A comparison of the avoided carbon dioxide emissions and total annual methane collected through bioreactor and conventional operations of the landfill is shown in figure 4.16 and 4.17 respectively.

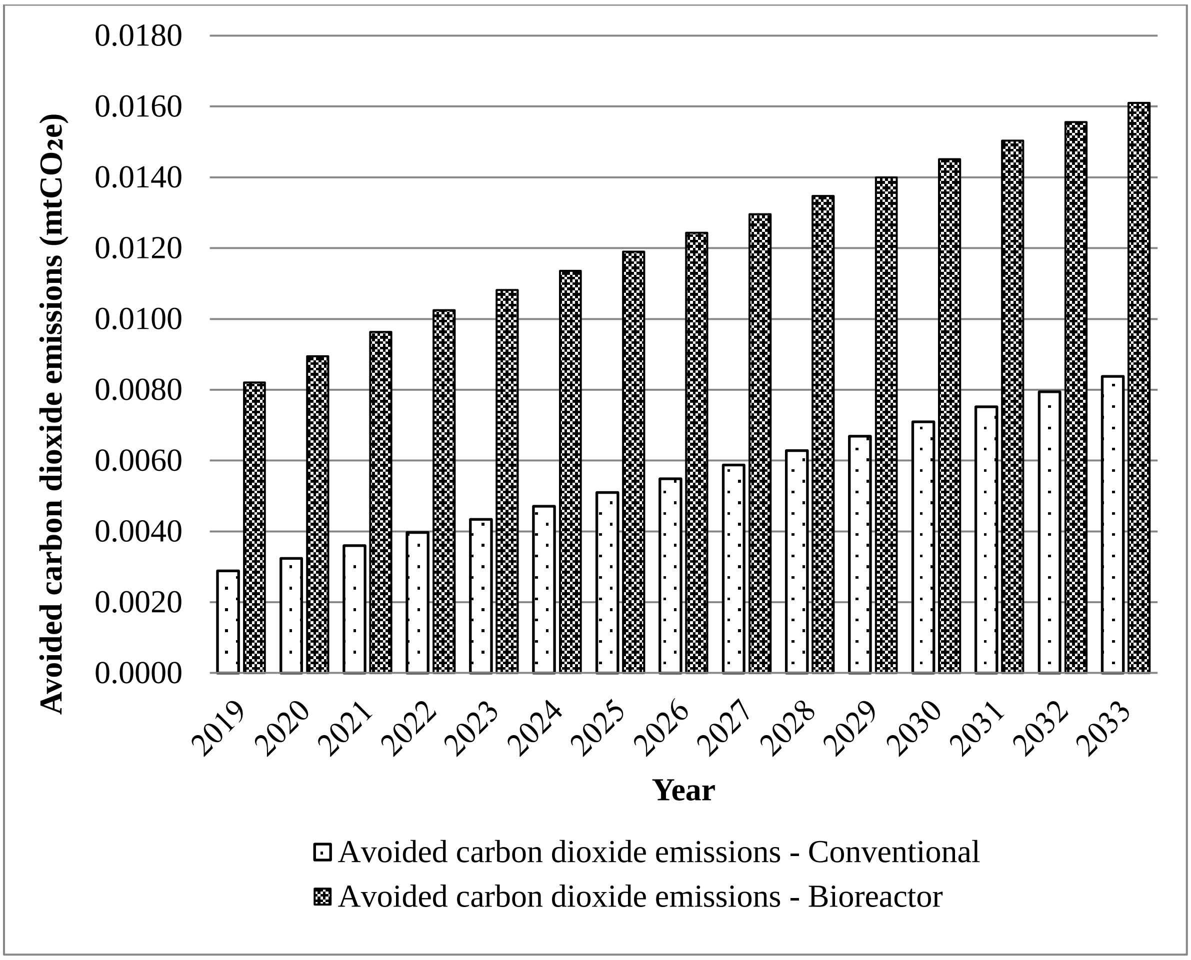

Figure 4.16: Avoided carbon dioxide emissions

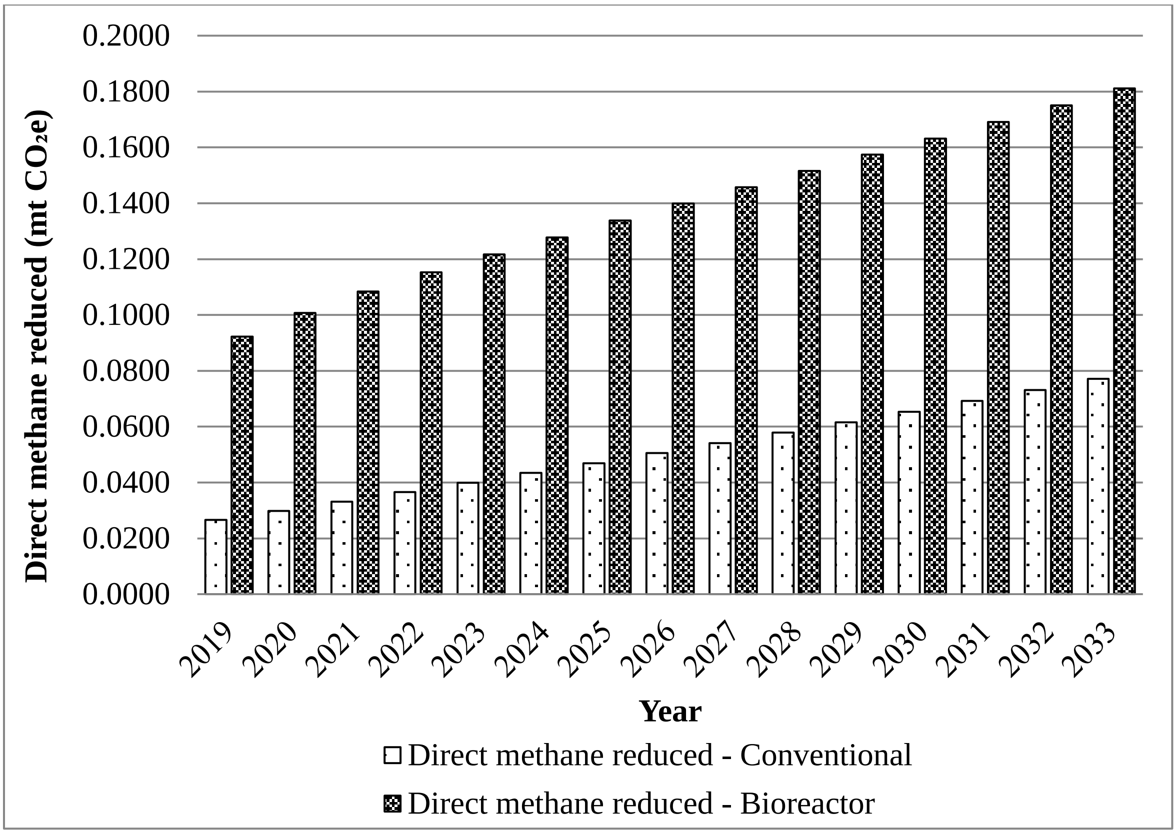

Figure 4.17: Total annual amount of methane collected

Landfill Gas Production and Electricity Generation Potential

Under bioreactor operation, the Afvalzorg model underestimated the production of landfill gas as indicated in figure 4.2. On the other hand, results from the IPCC model were the highest values whereas LandGEM returned the average results of the three models. Thus, the average values obtained from LandGEM were applied to Landfill Gas Cost Web model for financial feasibility analyses. The approach used in LandGEM and Landfill Gas Cost Web in estimating methane generation under bioreactor operations is the same and therefore the waste acceptance at the landfill was applied directly in Landfill Gas Cost web to estimate landfill gas production. These two methods use first order decay equations and require the methane generation rate and methane production potential as the main parameters in determining landfill gas generation. Out of the total produced gas, only 75 % was assumed to be recovered and used for electricity generation.

Landfill Gas Collection System

The landfill gas collection system was designed for both conventional and bioreactor operations. Due to the high landfill gas production in bioreactor operations, the sizes of the pipes required to limit the velocity of landfill gas to 15 m/s were larger than in conventional operations. However, the vertical extraction wells and collectors were the same. The headers were designed with a diameter of 0.15 m for conventional operations whereas in the bioreactor, a diameter of 0.25 m was necessary to limit the velocity of the gas in the pipe. The main headers were sized as 0.25 m and 0.3 m for conventional and bioreactor operations respectively.

A total number of 16 wells was calculated based on the radius of influence of 27 m. This resulted in the maximum spacing of wells as 45 m to the maximum gas collection with minimum number of vertical wells.

Head Losses in the Gas Collection System

A conservative approach was taken in designing the landfill gas collection system by utilising peak flows estimated using gas emission models with least and average results. Using the peak flows, radius of influence, density of landfill gas, the diameter of borehole and absolute viscosity of the gas, the subsurface losses for each well was estimated as 0.091 m of water column under conventional operations of the landfill. This is the loss encountered due to pulling of the gas from the waste.

The highest frictional losses in the pipes was established to be between well head a and junction k. The head losses were calculated by first principles of fluid mechanics and established as 0.307 m water column. A total head loss of 0.398 m water column was estimated from subsurface up to the intake of the blower. This head loss represented the required vacuum in the system to enable a blower to pull the gas from the waste. Using the total frictional head losses in the system and the total volumetric flow of landfill gas (3540 m^3/hr), a blower capable of functioning in these conditions was established as; two M-D Plus model 5511 blowers in series, each accepting a flow of 1770 m^3/hr or M-D Plus model 7013 as the only blower capable of functioning at a landfill gas flow of 3540 m^3/hr.

Under bioreactor operations, the total head loss was estimated as 0.35 m water column and the flow at the blower intake as 7060 m^3/hr. Based on these conditions two M-D Plus model 7013 blowers are required with each blower operating at a landfill gas flow of 3530 m^3/hr.

Despite the bioreactor having the highest landfill gas flow, the total head losses in the conventional operation were lower than the estimates in the bioreactor operation. This was because the gas flow velocity in the pipes under bioreactor operation was lower due to larger diameter of pipes used. Low flow velocities under bioreactor operations resulted in lower Reynolds Number (Re) and subsequently lower friction factor as compared to conventional. This resulted in lower frictional head losses under bioreactor operation.

Electricity Generation Potential from Landfill Gas

Electricity generation using microturbines, standard reciprocating engine and standard turbine generator set was assessed. The amount of electricity that can be produced at Chunga landfill was estimated using Landfill Gas Cost Web model and is presented in table 4.14. Microturbine technology produced the lowest electricity as compared to the reciprocating engine and gas turbine. With the consideration of residential utilisation of the electricity produced at the landfill, a minimum number of 1022 households consuming between 100 kWh to 300 kWh can benefit from microturbine technology under conventional operations of the landfill. Likewise, at least 3548 households can benefit under bioreactor operations. Due to higher electricity generation by engines and gas turbines, the number of houses that can benefit from the electricity generated at the landfill can increase up to two and half times the indicated values for the respective operation of the landfill.

Financial Feasibility of Landfill Gas to Energy Projects

Financial feasibility of a private funded and government funded projects was undertaken. Thirteen scenarios as summarised in table 4.21 were assessed to establish the most viable option based on the number of years it takes for the project to pay back the investment and cumulative net present value at the project discount rate.

A private funded project generating electricity using microturbine technology with bioreactor operation of the landfill financed without a loan (100 % down payment) and selling electricity at US$ 0.05/kWh (average cost in Zambia) will take 10 years to breakeven and generate a net present value of US$ 165,635 for an invested capital of US$ 4,706,800. With this same investment and electricity supply to residential households at a rate of US$ 0.094/kWh (current cost of electricity in Zambia for households consuming between 100 kWh to 300 kWh per month), the payback period reduces to 7 years with a net present value after 10 years equivalent to US$ 2,855,961. Under these same parameters, but increased revenue through reduced carbon emission trading at a rate of US$ 4/tCO_2e, a payback period of 6 years is achieved with net present value of US$ 2,130,960 (after 10 years) and electricity sales fixed at US$ 0.05/kWh. Therefore, for private funded project to achieve financial goals under microturbine technology and bioreactor operation of landfill, the target recipient of the energy generated should be residential houses or other consumers who are willing to pay US$ 0.094/kWh. Another feasible avenue is by both electricity sales and carbon trading by selling the amount of reduced carbon emissions to companies seeking to reduce their greenhouse gas ratings due to previous or current greenhouse gas emissions from their operations.

A government funded project with an investment of US$ 4,706,800 in microturbine technology to produce electricity under bioreactor operations at rate of US$ 0.05/kWh pays back the cost of investment after 8 years with a net present value of US$ 2,175,554 at the end of the project (10 years). For the same investment but a target consumer being residential households paying US$ 0.094/kWh, the payback period reduces to 5 years with a net present value of US$ 5,226,700 at the end of 10 years. Therefore, a government funded project is viable at a minimum average cost of electricity of US$ 0.05/kWh. Higher financial returns can be obtained by entering into the carbon credit market.

For a government investment of US$ 8,856,000 in a standard reciprocating engine for bioreactor operations of the landfill to generate electricity, the payback period occurs after 9 years with a net present value of US$ 3,996,100 after 15 years. This is viable for electricity sales at a rate of US$ 0.094/kWh and trading in reduced carbon emissions at carbon markets. This option is very attractive because a minimum of 5000 households can benefit from the project as compared to the 3500 under microturbine technology. In addition, the operating life span of engines is 15 years as compared to 10 years for microturbines.

A government funded project with an investment of US$ 10,435,700 in a standard turbine generator set for bioreactor operations of the landfill to generate electricity, the payback period occurs after 11 years with a net present of US$ 2,479,800 after 15 years. This is only viable when electricity sales are at US$ 0.094/kWh and also additional revenue gained through trading in reduced carbon emissions at a cost of US $4/t$CO_2$e. This option is not very attractive because of the higher investment cost and payback period as compared to the use of standard reciprocating engine.

Environmental Benefits and Sustainability of Landfill Gas to Energy Project at Chunga

Environmental benefits in form of reduced greenhouse gas emissions are gained in landfill gas to energy projects. The total emissions that can be captured at Chunga landfill are shown table 4.22. Without a landfill gas to energy project, these emissions will eventually find their way to the environment and pose as a health hazard to the residents around the landfill.

For sustainability to occur there is need to create and maintain conditions in which humans and nature are able to exist in productive harmony, permitting the fulfilling of social, economic and other requirements of the present and future generations. One of the three pillars of sustainability is environment. Landfill gas to energy projects have a great deal of environmental benefits owing to the captured methane that has global warming potential 21 times than that of carbon dioxide. This harmful greenhouse gas can be captured and its energy potential exploited to produce electricity as is the case presented in this study. Therefore, converting landfill gas to electricity at Chunga landfill is of higher environmental benefits.

Another pillar of sustainability is economy. The investment in converting methane from the decomposing waste at Chunga landfill into electricity is economically sustainable through revenue generation from electricity sales. In addition, landfill gas energy projects create certain job opportunities during the project life cycle which involves engineers, construction firms, equipment vendors, utilities and end users. Based on this point, landfill gas energy project at Chunga landfill is both economically and socially sustainable.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The previous chapter dwelt on detailed analysis of the feasibility of a landfill gas to energy project at Chunga landfill and established specific technologies that make the case study financial viability. This section summarises the main arguments and outlines the resultant recommendations.

5.2 Landfill Gas Emission Models

The first objective of the study was to investigate the prominent theoretical gas emission models and evaluate which models are highly applicable to Chunga landfill based on site conditions and available waste data. LandGEM, IPCC and Afvalzorg models were used in estimating landfill gas production at Chunga. The model were selected based on the availability of the model, accuracy of modelled outcomes, scientific basis of the model, transparency, ability of the model to handle waste changes and application to climate zones different from the climate conditions where the model was developed. For conventional operations, all the three models predicted a peak methane flow in the 2033, a year after closure of the landfill. LandGEM estimated the peak methane generated as 1751 m^3/hr, IPCC yielded a value of 1364 m^3/hr and Afvalzorg produced the peak methane flow as 893 m^3/hr. With reference to the lowest value, it was established that LandGEM overestimated the methane generated by the decomposing waste deposited at the landfill, whereas the Afvalzorg model produced the least value almost half the peak methane value estimated in LandGEM. On other hand, the peak methane flow estimated using IPCC model was the average of LandGEM and Afvalzorg model estimates.

Due to difference in the model estimates, a conservative approach was taken in designing a landfill gas collection system by applying the average peak methane flow.

5.3 Electricity Generation Potential from Landfill Gas

The second and third objective was to estimate the quantity of landfill gas production, design a primary landfill gas collection system and estimate electrical energy that can be produced from the landfill.

To estimate the quantity of electricity that can be generated from the methane captured, a design of a landfill gas collection system was required. For conventional operations, a primary landfill gas collection system was designed with 16 vertical wells which are connected to 2 headers (0.15 m diameter) by connector pipes (0.075 m diameter) and 1 main header 0.25 m in diameter. The main header is responsible for conveying the total captured gas to the utilisation point. Under bioreactor operations, the size of vertical wells and connectors were not changed with the exception of headers and main header which were sized as 0.25 m and 0.3 m respectively to limit the gas flow velocity in the pipes to a maximum of 15m/s. For conventional operations, a compressor or blower was sized to provide a flow of 3540 m^3/hr and capable of withstanding frictional head losses equivalent to 0.398 m water column whereas in bioreactor operations, the blower was sized for a flow of 7060 m^3/hr and 0.35 m water column frictional head losses.

Based on the annual landfill gas production, the heat content of landfill gas and the power capacity of the chosen electricity production technology, the annual electricity produced from landfill gas was established. For bioreactor operation, minimum electricity produced was established as 12,773,700 kWh and 17,811,361 kWh for microturbine and standard reciprocating engine technology respectively. This power output is capable of servicing a minimum of 3500 and 5000 households respectively whose monthly consumption is less than 300 kWh.

5.4 Financial Feasibility of Converting Landfill Gas to Electricity at Chunga

The fourth objective was to investigate the financial feasibility of capturing landfill gas and converting it to electricity.

The cost of investment was estimated using a landfill gas cost economic assessment model. The model results also included the investment and operation cost of a flaring plant that burns unutilised and excess methane produced. The technologies assessed were electricity production using microturbines, standard turbine generator set and standard reciprocating engine for bioreactor operations of the landfill.

It was established that a private funded project with an investment of US$ 4,706,800 in microturbine technology generating electricity under bioreactor operations only makes financial sense when electricity sales are set at US$ 0.094/kWh in order to achieve a payback period of 7 years with a net present value of US$ 2,855,961 after 10 years. Furthermore, greater financial benefits can be obtained through increased revenue from reduced carbon emission trading at a rate of US$ 4/tCO_2e which produces a payback period of 6 years with a net present value of US$ 2,130,960 (after 10 years) and electricity sales fixed at US$ 0.05/kWh.

For a government funded project with the same investment of US$ 4,706,800 and the target consumer being residential households paying US$ 0.094/kWh, the payback period reduces to 5 years with a net present value of US$ 5,226,700 at the end of 10 years. Therefore, a government funded project is more viable and higher financial returns can be obtained by entering into the carbon credit market unlike sales of electricity only.

It was also established that a government investment of US$ 8,856,000 in a standard reciprocating engine for bioreactor operations of the landfill to generate electricity, the payback period occurs after 9 years with a net present of US$ 3,996,100 after 15 years. This is viable for electricity sales at a rate of US$ 0.094/kWh and trading in reduced carbon emissions at carbon markets. This option is very attractive because a minimum of 5000 households can benefit from the project as compared to the 3500 under microturbine technology. In addition, the operating life span of engines is 15 years as compared to 10 years for microturbines. Therefore, with the thought the governments' primary purpose is for the betterment of its people, an investment in standard reciprocating engine is more favourable as it generates more electricity which can be used to provide a portion of the required electricity to reduce power deficits in the city.

In conclusion, the implementation of landfill gas energy project for Chunga landfill is economically feasible due to sufficient landfill gas generation potential. An investment in landfill gas energy project at Chunga could provide electricity to a minimum of 1000 and maximum of 9700 households, depending on project type and landfill operation.

5.5 Recommendations

The research assessed the quantity of landfill gas production and estimated the potential electricity that could be generated from methane in landfill gas. A financial feasibility of landfill gas energy projects was also assessed and the options with the best financial returns were presented. The following are the recommendations emanating from the findings and analysis:

1. Implementation of Chunga landfill gas energy project using standard reciprocating engines under bioreactor operations of the landfill because of the greater electricity generation potential and favourable economics. This is to be done through government funding or public private partnership so as to avoid marginal taxes which would create a financial liability to the project. The estimated capital for this project is US$ 8,856,000 with average annual operations and maintenance cost of US$ 1,645,021 and net pack period within 9 years. The average annual power generation under this scenario is equivalent to 26.8 million kWh. A net present value of US$ 3,996,000 can achieved after 15 years through electricity sales, and carbon credits by selling the equivalent tonnage of reduced carbon emissions to companies seeking to reduce their greenhouse gas emission ratings.
2. Installation of a microturbine under bioreactor operations to provide an estimated average annual power of 19.2 million kWh at an investment cost of US$ 4,706,800 for both private funded and government budgeted finance.

5.6 Recommendations for Future Research

This study was focused on investigating landfill gas production from Chunga landfill and financial feasibility of converting the methane in landfill to electricity. The findings generated indicated that a landfill gas energy project is economically viable at Chunga due to the large quantities of landfill gas produced.

The study of landfill gas to energy projects is a very a complex one and therefore, some assumptions were made in this research in order to limit the study and complete it within the provided timeframe. Suggestions of further research aim to point out studies that could complement this study and the following are therefore recommended as areas for further research in other substantive areas arising out of the outputs of this study:

1. A deeper investigation of the waste composition and moisture content in the waste by doing a pick-analysis.
2. Extensive laboratory investigations of the biochemical methane potential for organic waste respective to the waste deposited at Chunga landfill.
3. A more rigorous analysis of the cost of materials and equipment by engaging in discussions with suppliers and landfill gas to energy experts at current functioning projects.

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APPENDICES

APPENDIX A: COST ANALYSIS FOR A STANDARD RECIPROCATING ENGINE THROUGH GOVERNMENT FUNDING PROVIDED BY LANDFILL GAS COST-WEB MODEL

A1: Costing of Collection and Flaring System for Standard Reciprocating Engine under Bioreactor Operations

Cost Component	Cost (US$)	Cost Unit
Drilling and pipe crew mobilization	$20,000	per system
Installed cost of vertical gas extraction wells	$4,250	per well
Installed cost of wellheads and pipe gathering system	$17,000	per well
Installed cost of knockout, blower, and flare system	$(x)^{0.61}$ * $4,600	$, x = ft^3/min
Engineering, permitting, and surveying	$700	per well
Annual O&M for collection (excluding energy)	$2,600	per well
Annual O&M for flare (excluding electricity)	$5,100	per flare
Electricity price (depends on type of project)	$0.094	per kWh with a 1.0% escalation rate

Project Component	Quantity
Average depth of landfill waste (ft)	60
Number of wells (1 well per acre)	10
Number of flares (1 flare per system)	1
Collected landfill gas design flow rate (ft^3/min)	1,710
Electricity usage by blowers (kWh/ft^3)	0.002

Installed Capital Costs:	2018
Mobilization:	$22,082
Extraction Wells:	$46,923

Wellheads and Pipe Gathering System:	$187,694
Knockout, Blower, and Flare System:	$476,356
Engineering, Permitting, and Surveying:	$7,729
Total Capital Costs	$740,783

Annual Costs:

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
O&M for Collection	$34,842	$36,585	$38,414	$40,335	$42,351	$44,469	$46,692	$49,027	$51,478	$54,052	$56,755	$59,592	$62,572	$65,701	$68,986
O&M for Flare	$6,834	$7,176	$7,535	$7,912	$8,307	$8,723	$9,159	$9,617	$10,098	$10,603	$11,133	$11,689	$12,274	$12,887	$13,532
Electricity	$86,078	$94,866	$103,126	$110,770	$118,115	$125,315	$132,596	$139,922	$147,251	$154,664	$162,228	$169,863	$177,775	$185,839	$194,260
Total Annual Costs	$127,755	$138,627	$149,075	$159,016	$168,773	$178,507	$188,447	$198,566	$208,826	$219,318	$230,115	$241,145	$252,621	$264,427	$276,777

A2: Costing Of Standard Reciprocating Engine under Bioreactor Operations

Cost Component	Cost(USD)	Cost Unit
Installed cost of gas compression/treatment, engine/generator, site work, and housings	$1,300(x) + $1,100,000	$, x = kW capacity
Installed cost of electrical interconnect equipment	$250,000	per system
Annual O&M of compression/treatment and engine/generator (excluding energy)	$0.025	per kWh generated

Project Component	Quantity
Gross capacity factor (%)	93%
System operating schedule (hours/year)	8,147
Fuel use rate (Btu/kWh generated)	11,250
Parasitic loss efficiency (%)	93%
Landfill gas heat content (Btu/ft^3)	506
Engine capacity (kW)	4,616

Electricity Generation:

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Net Electricity Generated (kWh)	17,811,361	19,435,466	20,918,597	22,246,562	23,486,831	24,671,879	25,846,874	27,004,972	28,137,913	29,261,840	30,389,053	31,504,308	32,645,213	33,788,217	34,969,533

Installed Capital Costs:	2018
Gas Compression/Treatment, Engine/Generator, Site Work, and Housings:	$7,839,156
Electrical Interconnect Equipment:	$276,020
Total Capital Costs	$8,115,176

Annual Costs:

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
O&M	$641,638	$735,152	$830,814	$927,734	$1,028,429	$1,134,336	$1,247,776	$1,368,868	$1,497,611	$1,635,303	$1,783,212	$1,941,087	$2,111,952	$2,295,192	$2,494,209
Total Annual Costs	$641,638	$735,152	$830,814	$927,734	$1,028,429	$1,134,336	$1,247,776	$1,368,868	$1,497,611	$1,635,303	$1,783,212	$1,941,087	$2,111,952	$2,295,192	$2,494,209

A3: Combined Economic Analysis and Cash Flows (Collection & Flare System + Standard Reciprocating Engine)

Year of Operation	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Revenue																
Electricity sales		$1,674,300	$1,845,200	$2,005,900	$2,154,500	$2,297,400	$2,437,500	$2,579,100	$2,721,600	$2,864,100	$3,008,300	$3,155,400	$3,303,900	$3,457,800	$3,614,700	$3,778,500
Operating Costs		$769,400	$873,800	$979,900	$1,086,800	$1,197,200	$1,312,800	$1,436,200	$1,567,400	$1,706,400	$1,854,600	$2,013,300	$2,182,200	$2,364,600	$2,559,600	$2,771,000
Greenhouse gas credit		$409,000	$446,300	$480,400	$510,900	$539,400	$566,600	$593,600	$620,200	$646,200	$672,000	$697,900	$723,500	$749,700	$776,000	$803,100
Net income	$0	$1,313,900	$1,417,800	$1,506,400	$1,578,700	$1,639,600	$1,691,200	$1,736,400	$1,774,300	$1,803,900	$1,825,700	$1,840,000	$1,845,200	$1,843,000	$1,831,000	$1,810,600
Cash flow	($8,856,000)	$1,313,900	$1,417,800	$1,506,400	$1,578,700	$1,639,600	$1,691,200	$1,736,400	$1,774,300	$1,803,900	$1,825,700	$1,840,000	$1,845,200	$1,843,000	$1,831,000	$1,810,600
Internal rate of return	16%															
Cumulative cash flow	($8,856,000)	($7,542,000)	($6,124,300)	($4,617,900)	($3,039,200)	($1,399,600)	$291,600	$2,028,100	$3,802,400	$5,606,300	$7,432,000	$9,272,000	$11,117,200	$12,960,200	$14,791,200	$16,601,800
Simple payback	5															
Present value of cash flow (at project discount rate)	($8,124,700)	$1,105,900	$1,094,800	$1,067,200	$1,026,000	$977,600	$925,200	$871,500	$817,000	$762,000	$707,500	$654,200	$601,900	$551,500	$502,700	$456,000
NPV (at project discount rate)	$3,996,100															
Cumulative PV	($8,124,700)	($7,018,800)	($5,924,100)	($4,856,900)	($3,830,800)	($2,853,200)	($1,928,100)	($1,056,600)	($239,600)	$522,300	$1,229,900	$1,884,000	$2,485,900	$3,037,400	$3,540,100	$3,996,100

APPENDIX B: COST ANALYSIS FOR A MICROTURBINE THROUGH PRIVATE FUNDING PROVIDED BY LANDFILL GAS COST-WEB MODEL

B1: Costing Of Collection and Flaring System for Microturbine under Bioreactor Operations

Cost Component	**Cost (2013 US$'s)**	**Cost Unit**		
Drilling and pipe crew mobilization	$20,000	per system		
Installed cost of vertical gas extraction wells	$4,250	per well		
Installed cost of wellheads and pipe gathering system	$17,000	per well		
Installed cost of knockout, blower, and flare system	$(x)^{0.61}$ * $4,600	$, x = ft^3/min		
Engineering, permitting, and surveying	$700	per well		
Annual O&M for collection (excluding energy)	$2,600	per well		
Annual O&M for flare (excluding electricity)	$5,100	per flare		
Electricity price (depends on type of project)	$0.094	per kWh with a	1.0%	escalation rate

Project Component	**Quantity**
Average depth of landfill waste (ft)	60
Number of wells (1 well per acre)	10
Number of flares (1 flare per system)	1
Collected landfill gas design flow rate (ft^3/min)	1,431
Electricity usage by blowers (kWh/ft^3)	0.002

Installed Capital Costs:	2018
Mobilization:	$22,082
Extraction Wells:	$46,923
Wellheads and Pipe Gathering System:	$187,694
Knockout, Blower, and Flare System:	$427,292
Engineering, Permitting, and Surveying:	$7,729
Total Capital Costs	$691,720

Annual Costs:

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033

O&M for Collection	$34,842	$36,585	$38,414	$40,335	$42,351	$44,469	$46,692	$49,027	$51,478	$54,052	$0	$0	$0	$0	$0
O&M for Flare	$6,834	$7,176	$7,535	$7,912	$8,307	$8,723	$9,159	$9,617	$10,098	$10,603	$0	$0	$0	$0	$0
Electricity	$86,078	$94,866	$103,126	$110,770	$118,115	$125,315	$132,596	$139,922	$147,251	$154,664	$162,228	$169,863	$177,775	$185,839	$194,260
Total Annual Costs	$127,755	$138,627	$149,075	$159,016	$168,773	$178,507	$188,447	$198,566	$208,826	$219,318	$162,228	$169,863	$177,775	$185,839	$194,260

B2: Costing Of Microturbine under Bioreactor Operations

Cost Component	Cost (2006 USD$'s)	Cost Unit
Installed cost of gas compression/treatment, microturbine/generator, site work, housings, and electrical interconnect equipment	$19,278 * $(x)^{0.6207}$	$, x = kW capacity
Annual O&M of compression/treatment and microturbine/generator (excluding energy)	0.0736 - 0.0094ln(x)	$/kWh generated, x = kW capacity

Project Component	Quantity
Gross capacity factor (%)	93%
System operating schedule (hours/year)	8,147
Fuel use rate (Btu/kWh generated)	14,000
Parasitic loss efficiency (%)	83%
Landfill gas heat content (Btu/ft^3)	506
Microturbine capacity (kW)	3,709

Electricity Generation:

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
Net Electricity Generated (kWh)	12,773,700	13,938,453	15,002,105	15,954,476	16,843,954	17,693,830	18,536,497	19,367,045	20,179,552	20,985,594	21,793,993	22,593,815	23,412,034	24,231,757	25,078,956

Installed Capital Costs:	**2018**
Gas Compression/Treatment, Microturbine/Generator, Site Work, Housings, and Electrical Interconnect Equipment:	$4,015,078
Total Capital Costs	$4,015,078

Annual Costs:

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033
O&M	-$106,034	-$121,487	-$137,296	-$153,312	-$169,953	-$187,454	-$206,201	-$226,212	-$247,487	-$270,241	-$294,684	-$320,774	-$349,010	-$379,291	-$412,180
Total Annual Costs	-$106,034	-$121,487	-$137,296	-$153,312	-$169,953	-$187,454	-$206,201	-$226,212	-$247,487	-$270,241	-$294,684	-$320,774	-$349,010	-$379,291	-$412,180

B3: Combined Economic Analysis and Cash Flows (Collection & Flare System + Microturbine)

Economic Analysis:

Year of Operation	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Revenue																
Electricity sales		$1,200,700	$1,323,300	$1,438,500	$1,545,200	$1,647,600	$1,748,100	$1,849,600	$1,951,800	$2,054,000	$2,157,500	$2,263,000	$2,369,500	$2,479,800	$2,592,300	$2,709,800
Operating Costs		$21,700	$17,100	$11,800	$5,700	($1,200)	($8,900)	($17,800)	($27,600)	($38,700)	($50,900)	($132,500)	($150,900)	($171,200)	($193,500)	($217,900)
Greenhouse gas credit		$397,700	$434,000	$467,100	$496,700	$524,400	$550,900	$577,100	$603,000	$628,300	$653,400	$49,000	$50,800	$52,700	$54,500	$56,400
Down payment	**$4,706,800**															
Taxes		$470,700	$470,700	$470,700	$470,700	$470,700	$470,700	$470,700	$470,700	$470,700	$470,700	$0	$0	$0	$0	$0
Tax liability		$1,106,000	$1,269,500	$1,423,200	$1,565,500	$1,702,600	$1,837,200	$1,973,800	$2,111,800	$2,250,300	$2,391,100	$2,444,500	$2,571,200	$2,703,700	$2,840,300	$2,984,100
Tax before credit		$387,100	$444,300	$498,100	$547,900	$595,900	$643,000	$690,800	$739,100	$787,600	$836,900	$855,600	$899,900	$946,300	$994,100	$1,044,400
Net tax		$387,100	$444,300	$498,100	$547,900	$595,900	$643,000	$690,800	$739,100	$787,600	$836,900	$855,600	$899,900	$946,300	$994,100	$1,044,400
Net income	$0	$718,900	$825,200	$925,100	$1,017,600	$1,106,700	$1,194,200	$1,283,000	$1,372,700	$1,462,700	$1,554,200	$1,588,900	$1,671,300	$1,757,400	$1,846,200	$1,939,700
Cash flow	($4,706,800)	$1,189,600	$1,295,800	$1,395,700	$1,488,300	$1,577,300	$1,664,900	$1,753,700	$1,843,300	$1,933,400	$2,024,900	$1,588,900	$1,671,300	$1,757,400	$1,846,200	$1,939,700
Internal rate of return	**30%**															
Cumulative cash flow	($4,706,800)	($3,517,200)	($2,221,400)	($825,600)	$662,700	$2,240,000	$3,904,900	$5,658,600	$7,501,900	$9,435,300	$11,460,200	$13,049,100	$14,720,400	$16,477,800	$18,324,000	$20,263,700
Simple payback	**3**															
Present value of cash flow (at project discount rate)	($4,318,200)	$1,001,300	$1,000,600	$988,800	$967,300	$940,500	$910,700	$880,100	$848,700	$816,700	$784,700	$564,900	$545,100	$525,900	$506,900	$488,500
NPV (at project discount	**$4,821,300**															

rate)																
Cumulative present value	($4,318,200)	($3,316,900)	($2,316,300)	($1,327,500)	($360,200)	$580,300	$1,491,100	$2,371,200	$3,219,900	$4,036,600	$4,821,300	$5,386,200	$5,931,300	$6,457,200	$6,964,100	$7,452,600