FEASIBILITY STUDIES TO SUPPORT LANDFILL GAS RECOVERY IN GHANA

by

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Abstract

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According to the World Bank, Ghana generates 0.09 kg of solid waste per person per day; there are only 4 engineered landfills in the country. In 2010, Ghana contributed 0.13% of global greenhouse gases emissions, 10% of which was associated with the waste sector. On the other hand, according to the World Bank in 2011, 39.5 % of Ghana's population did not have access to electricity. Tapping landfill gas (LFG) will not only provide a portion of the needed energy for the country, but will also help solve many of the environmental problems.

Currently there is no landfill gas to energy project in Ghana. The objective of this thesis was to study the feasibility of landfill gas to energy projects in two landfills in Ghana, Tema and Temale. To conduct the study, methane generation potential was estimated based on site specific data and waste acceptance history for each landfill using LandGEM, IPCC and UTA-CLEEN models for conventional and bioreactor operations. The electricity generation potential was then estimated based on the modeling results. A preliminary gas collection system was designed for cost analyses purposes. Also, sensitivity cost analyses were conducted for both landfills using LFG-cost WEB model.

Based on the cost analyses results, the Temale LFG to energy project is not currently economically favorable. Installation of a microturbine at the Tema site operating as a bioreactor and perpetual landfill, provides estimated average annual power of 13.2 million kWh, with a payback time of 3 years.

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Chapter 1

Introduction

1.1 Background

Over 1.4 billion people are without access to electricity worldwide, most of them concentrated in about a dozen countries in Africa and Asia (International Energy Agency, 2010). Another 2.8 billion rely on wood or other biomass for cooking and heating, resulting in indoor and outdoor air pollution attributable for 4.3 million deaths a year (UNEP Year Book, 2014)

In addition to lack of access to energy resources in developing countries, abundance of trash creates other issues. Current global municipal solid waste (MSW) generation levels are approximately 1.3 billion tons per year, and are expected to increase to approximately 2.2 billion tons per year by 2025. This represents a significant increase in per capita waste generation rates, from 1.2 to 1.42 kg per person per day in the next fifteen years (World Bank Report, 2012).

On the other hand, 3% of 2004 global greenhouse gas (GHG) emissions were associated with solid waste (IPCC, 2007). Landfill gas (LFG) is generated by anaerobic decomposition of stored biodegradable solid waste. Typically LFG cconsists of about 50 percent methane, about 50 percent carbon dioxide (CO_2) and a small amount of non–methane organic compounds. Methane is a potent heat-trapping gas (more than 21 times stronger than carbon dioxide for 100 years’ time horizon) and can stay in the atmosphere as long as 12 years (IPCC Report, 2007). Landfills and waste produce 55 million tons of methane annually (Bousquet, 2006).

Landfill gas recovery is an integrated solution which can address the needs for renewable energy and sustainable solidwaste management simultaneously. According to US Environmental Protection Agency (EPA), an LFG energy project will capture an estimated 60 to 90 percent of the methane generated in the landfill and burn it to produce electricity or heat. Producing energy from LFG displaces the use of non-renewable resources (such as coal, oil, or natural gas) and avoids greenhouse gas emissions from fossil fuel combustion by an end user facility or power plant.

1.2 Problem Statement

A western Africa country of 25 million people (Ghana Embassy, 2012) and $670 annual income per capita as of 2008 (World Bank, 2010) , Ghana is classified by the World Bank as a low-income country (per capita annual income of $975 or less)Its urban population of 11.7 million currently generates an estimated 0.09 kg of solid waste per person per day (World Bank, 2012).

Ghana currently does not have any landfills with methane recovery systems. There are four main landfill sites in the country. Three of them, Dumpoase (central Ghana), Tamale (Northern Ghana), and the recently-opened Tema (southern Ghana), are engineered landfill sites, while the Takoradi (south-western Ghana) site is yet to be considered for conversion into an engineered landfill site. Recently, the Dumpoase Landfill site was identified as a potential site where methane gas could be tapped. An MOU was signed between the authorities of the country and an Israeli company to start constructing gas wells on the site.

Tapping landfill gas will not only provide needed energy for the country, but will also help solve many of the country's environmental problems. Installing the LFG recovery system will help create awareness of the usefulness of the waste generated and hence encourage its proper disposal. For a landfill gas recovery system to work well, the landfill must be managed properly; this includes adding a leachate collection and treatment system. Leachate collection and treatment will prevent groundwater contamination from the leachate. Finally, the capture of the methane gas for energy use will reduce emissions of gases that contribute to global warming.

In February 2013, the US EPA's Global Methane Initiative (GMI), with the collaboration of the Clinton Climate Initiative – Waste Initiative, conducted a preliminary scoping mission in Accra, Ghana, to assess the potential for developing solid waste management strategies that reduce short-lived climate pollutants (SLCPs) and greenhouse gas emissions. EPA's GMI will be working with Ghana's Environmental Protection Agency and Metropolitan Assembly, as well as the Climate and Clean Air Coalition (CCAC), Global Communities, and Millennium Cities Initiative as international partners, to implement strategies to reduce greenhouse gas emissions from Accra's solid waste sector.

Aligned with the mentioned objective, this project was funded by EPA's GMI to provide a feasibility study for landfill gas recovery systems for the Tema and Temale landfills. This project was conducted by University of Texas at Arlington partnering with Kwame Nkrumah University of Science and Technology, in Kumasi, Ghana.

1.3 Thesis Objectives

The objectives of this thesis are:

- Estimation of landfill gas generation potential, and electricity generation potential
- Identifying preliminary LFG recovery and use system,
- Estimation of project cost & benefits,

for the Tema and Temale landfills in Ghana.

Chapter 2

Literature Review

2.1 Greenhouse Gases

Many gases in the environment exhibit “greenhouse” properties, including those occurring naturally in the atmosphere, such as water vapor, carbon dioxide, methane, and nitrous oxide (N_2O) , and those which are human-made, such as chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).(Environment Canada, 1999).

In general, Global Warming Potential (GWP) is widely used as a qualified measure of the globally averaged relative forcing impacts of a particular greenhouse gas (IPCC, 1996). GWP is also defined as the ratio of global warming from one unit mass of a greenhouse gas to one unit mass of carbon dioxide over a period of time (USEPA, 2002). In other words, it is a measure of the potential for global warming per unit mass of carbon dioxide. For example, carbon dioxide has a GWP of exactly 1 (since it is the baseline unit to which all other greenhouse gases are compared) and methane has a GWP of 21 (measured relatively to GWP of carbon dioxide over a 100 year time horizon). Therefore, GWP values allow policy makers to compare the impacts of emissions and reductions of different gases (US EPA, 2014).

Many chemical compounds, found in the Earth’s atmosphere, act as “greenhouse gases” including carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide. These gases allow sunlight, which is radiated in the visible and ultraviolet spectra, to enter the atmosphere unimpeded. When sunlight strikes the Earth’s surface, some of the sunlight is re-emitted as infrared radiation (heat). Greenhouse gases tend to absorb this infrared radiation as it is re-emitted back towards space, trapping the heat in the atmosphere (Environment Canada, 2001).

In addition, this phenomenon can be explained in term of earth's energy imbalance when the outgoing heat from the earth does not equal the incoming energy from the sun. Although human-made aerosols (fine particles in the air generated by the burning of fossil fuel) increase reflection of sunlight by the earth, this reflection is more than offset by the trapping of heat radiation by greenhouse gases. The excess energy, therefore, warms up the ocean and melts the ice (Scientific American, 2004).

2.2 Landfills as a Source of GHG Emission

Municipal solid waste (MSW) disposed of in a landfill is consisted of several types of waste, such as food, paper, yard, plastic, textiles, and metal waste. Landfill gas (LFG) is formed from degradation of organic parts of municipal solid waste.

Landfill gas primarily consists of methane (about 40-60%); therefore, it is potentially an energy source as well as a greenhouse gas. According to IPCC (2004), methane has 22 times more global warming potential than carbon dioxide (over a hundred year time period). Typical composition of landfill gas is shown in Table 2.1.

Table 2.1 Typical Composition of Landfill Gas (Source: Tchobanoglous et al., 1993)

Component	**Percent (dry volume basis)**
Methane	45-60
Carbon dioxide	40-60
Oxygen	2-5
Sulfides, disulfides, mercaptans, etc.	0.1-1.0
Ammonia	0.1-1.0
Hydrogen	0-0.2
Carbon monoxide	0-0.2
Trace constituents	0.01-0.6

2.3 Economy, Growth and GHG Emissions in Ghana

2.3.1 Economy

Ghana has been maintaining stable economic growth over the years, and has approximately twice the per capita output of most West African nations. The GDP growth rate for 2011 was estimated to be 13.5%, which is an improvement compared to previous years (CIA 2012). However, it remains a low-income economy with about 30% of the population living on less than 1.25 USD a day. Moreover, the country is ranked number 135 on the latest Human Development Index (UNDP, 2012).

2.3.2 Energy Sector

The main energy sources used to support Ghana's economy are petroleum, electricity and fuelwood. Fuelwood from biomass represents the biggest share of consumed energy, and mostly constitutes the energy use in households in the form of either firewood or charcoal. Second to biomass is consumption of oil products (29%), followed by 11% of electricity.(Ghana's Second National Communication to UNFCCC, 2011)

By the end of 2010, the installed electricity production in the country had reached 2,185.5 MW, with 1,865 MW available. Most of the generated power in 2010 came from hydroelectric sources and accounted for nearly 70%, with 30% generated from thermal power. (Energy Commission of Ghana, 2011)

2.3.3 GHG Emissions

Ghana contributed 0.13% to the global GHG emissions in 2011, which was 59.26 $MtCO_2$, including land-use change & forestry, where the global amount was 45,973 $MtCO_2e$). (World Resources Institute, 2014).

The energy sector accounts for most of the emissions, 41%, with residential and transport sub-sectors as the main contributors. Agriculture is the source of 38% of the country's emissions. Both agriculture and energy sectors present upward trends in emissions growth. In the energy sector, increased use of fuels for thermal power generation, poor energy efficiency in road transport, and rising biofuel use in the residential sub-sectors are important contributors to the increase. In the agriculture sector, growth in emissions can be attributed to higher numbers of livestock and fertilizer application.

In addition to energy and agriculture, waste is a major contributor to emissions, with 10%. Disposal of solid waste and wastewater handling were the main sources of these emissions. Figure 2.1 shows waste sector GHG emission breakdown in Ghana as of 2006. (UNFCCC, 2011)

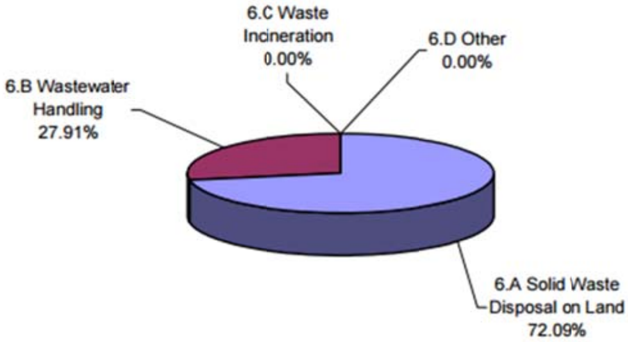

Figure 2.1 Ghana Waste sector GHG emission breakdown in 2006

(source: UNFCCC, 2011)

Unmanaged landfills are sources of highly polluting landfill gasses, most common of which are CO_2 and methane. In Ghana, approximately 23% of methane comes from the waste sector, and is currently not managed in any way. Figure 2.2 shows methane emission breakdown in Ghana as of 2000.

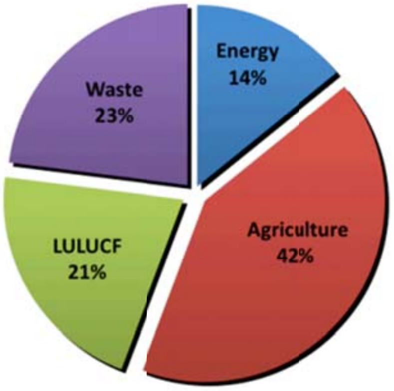

Figure 2.2 Proportion of CH_4 emissions by sector for Ghana in 2000

(source: UNFCCC, 2011)

2.4 Landfill Gas Production

2.4.1 Four Phases in MSW Decomposition

The conversion of solid waste to methane and carbon dioxide is conducted by microorganisms. Gas generation from a landfill has been divided into 4 (or more) sequential phases which are illustrated in Figure 2.1.

Phase I – Aerobic Phase - Aerobic bacteria consume oxygen for respiration and cell growth to break down proteins, lipids and carbohydrates which compromise the organic waste. Phase I continues until available oxygen is depleted and carbon dioxide is produced during this phase. (LFG Project Development Handbook, EPA, 2015)

Phase II - Anaerobic Acid Phase - In this phase anaerobic bacteria convert compounds created by aerobic bacteria into acetic, lactic and formic acids and alcohols such as methanol and ethanol. In this phase, leachate pH drops and landfill gas is mainly carbon dioxide (LFG Project Development Handbook, EPA, 2015).

Phase III - Accelerated Methane Production Phase - The concentration of methane in landfill gas increases until it reaches a constant value (mostly between 40-

60%). The carboxylic acid concentration decreases. The pH stabilizes, and leachate strength decreases. Methanogenic and acid forming bacteria have a mutually beneficial, symbiotic relationship. (Barlaz et al., 1990; Rees, 1980; Tchobanoglous et al., 1993; Farquhar and Rovers 1973)

Phase IV- Decelerated Methane Production Phase- The methane and carbon dioxide concentrations are relatively constant in this phase. However, the methane generation rate decreases. In a landfill, this phase is expected to extend for 20-50 yrs. The pH is similar to phase III (Barlaz et al., 1990; Rees, 1980; Tchobanoglous et al., 1993; Farquhar and Rovers, 1973)

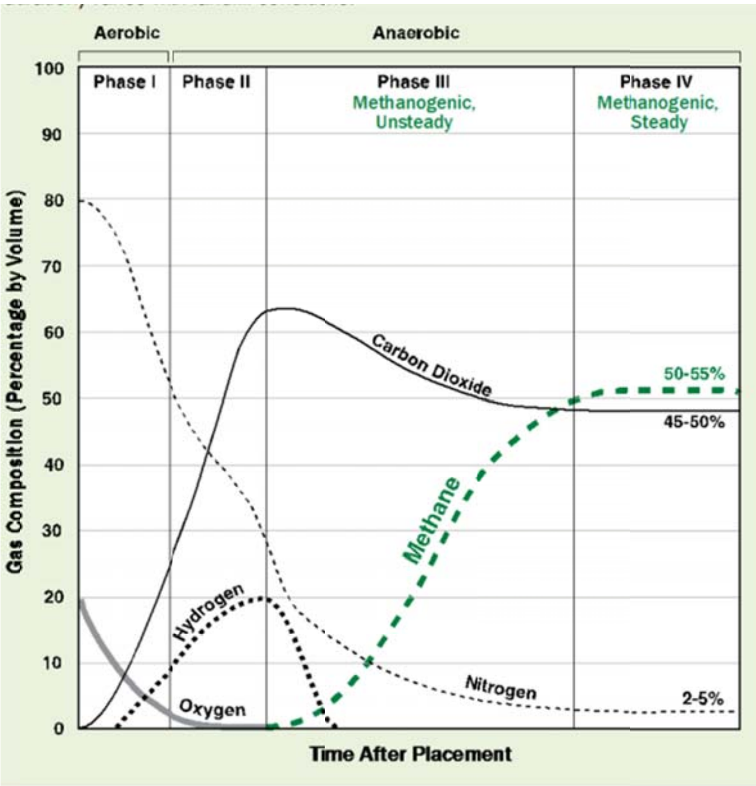

Figure 2.3 Phases in anaerobic degradation of solid waste

(Source: Barlaz et al., 1990)

2.4.2 Factors Influencing LFG Generation (Source: EPA, 2012)

LFG is generated through the action of microorganisms that begin decomposing organic waste within about 3 to 6 months after disposal, if the waste is in an anaerobic state. The rate of LFG generation caused by waste decomposition is sensitive to a number of environmental factors, including moisture, temperature, oxygen and refuse degradability. The effects of each of these variables can be summarized as follows:

Moisture- Moisture is one of the most important variables influencing LFG generation. LFG generation is known to increase with moisture because higher waste moisture content contributes to an increased rate of waste decay, but the total amount of LFG generated over time (“ultimate yield”) may not increase with increases in moisture above a minimum threshold needed to support microorganisms that generate LFG. Moisture conditions can vary widely from desert to tropical sites or even within sites with liquids recirculation. Average annual precipitation is typically used as a surrogate for moisture because moisture within a waste mass is difficult to measure.

Temperature- Increases in temperature up to approximately 57 degrees Celsius (^{o} C) generally cause LFG generation to increase. At higher temperatures, the amount of LFG generation decreases, and the higher temperatures indicate aerobic rather than anaerobic decay, which can lead to subsurface fires. While cold air temperatures can penetrate the surface of the waste mass and decrease LFG generation, particularly in small, shallow sites, most of the waste mass of larger sites will be insulated from outside temperatures and warmed by microbial activity. Temperature effects on LFG generation are complex, and temperature profiles within a waste mass are too varied to characterize for LFG modeling, although some models do incorporate ambient air temperatures into their calculations.

Oxygen- The oxygen in the air can penetrate a waste mass and inhibit anaerobic microorganisms from producing LFG. A significant portion of the waste mass at shallow sites and sites with limited or no cover may be affected by air infiltration and reduced LFG generation. Gas collection systems also can contribute to enhanced air infiltration, particularly when operated aggressively.

Waste Degradability- Refuse degradability has an important influence on the amount and rate of LFG generation. Highly degradable organic materials, such as food waste, will produce LFG rapidly but will be consumed more quickly than less degradable organics, such as paper, which produce LFG slowly but over a longer time. Materials such as wood exhibit little degradation and produce minimal quantities of LFG. Inorganic materials do not produce LFG.

pH- Optimum pH values for anaerobic digestion range from 6.4 to 7.4. The pH values in landfills may be influenced by industrial waste discharges, alkalinity, and clear water infiltration (Boyle, 1977). The average pH in a landfill does not drop below 6.2 when methane is produced (Rare Earth Research Conference, 1978).

2.5 Environmental Benefits of LFG Energy Recovery

As discussed before, methane is both potent and short live. Therefore, reducing methane emissions from landfills is one of the best ways to lessen the human impact on global climate change. In addition, all landfills generate methane, so there are many opportunities to reduce methane emissions by flaring or collecting LFG for energy generation.

Direct GHG Reductions- Typically a LFG energy project captures an estimated 60 to 90 percent of the methane generated in landfill, depending on system design and effectiveness.(International Best Practice for LFG Projects, EPA, 2012).The methane captured is eventually converted to water and carbon dioxide at the final use point.

Indirect GHG Reductions- Energy produced from LFG, reduces the need to use non-renewable resources (such as coal, oil, or natural gas). Therefore, GHG emissions are avoided from fossil fuel combustion by an end user facility or power plant.

2.6 Landfill Gas Modeling

LFG modeling is the practice of forecasting gas generation and recovery based on past and future waste disposal histories and estimates of collection system efficiency. It is an important step in the project development process because it provides an estimate of the amount of recoverable LFG that will be generated over time. LFG modeling is performed for regulatory and non-regulatory purposes. Regulatory applications of LFG models are conducted for landfills in the United States to establish the requirements for installation and operation of the gas collection and control system. Non-regulatory applications of LFG models typically include any of the following:

- Evaluating the feasibility of the LFG energy project
- Determining gas collection and control system design requirements
- Performing due diligence evaluations of potential or actual project performance (EPA, 2015)

2.6.1 Introduction to US EPA's LandGEM

LandGEM was designed for U.S. regulatory applications but has been used for modeling LFG collection in the U.S. and worldwide. It applies the following first-order exponential equation to estimate methane generation:

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\, Lo \left(\frac{Mi}{10}\right) \left(e^{-ktij}\right) \tag{2.1}$$

Where,

Q = maximum expected methane generation flow rate (m3 /yr)

i = 1 year time increment

n = (year of the calculation) – (initial year of waste acceptance)

j = 0.1 year time increment

k = methane generation rate (1/yr)

L_0 = potential methane generation capacity (m3 /Mg)

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

t_{ij} = age of the jth section of waste mass M_i disposed in the i^{th} year (decimal years)

Table 2.2 summarizes default values for LandGEM model parameters.

Table 2.2 Model parameters for LandGEM

(USEPA, 2005)

Default Type	**Landfill Type**	**L (m^3/Mg)**	**k – value ($year^{-1}$)**
CAA[1]	Conventional (Rainfall > 25 in/year)	170	0.05
CAA	Arid Area (Rainfall < 25 in/yr)	170	0.02
Inventory[2]	Conventional (Rainfall > 25 in/yr)	100	0.04
Inventory	Arid Area (Rainfall < 25 in/yr)	100	0.02
Inventory	Wet (Bioreactor)	96	0.7

NOTE: 1. CAA – Clean Air Act; 2. Inventory – AP 42 (1998)

2.6.2 LandGEM Limitations for Modeling Sites Outside of the U.S.

In LandGEM's model users are provided with alternative default values for the input variables k and L_0, depending on whether the model is being used for U.S. Clean Air Act compliance or other ("inventory") applications, whether the site is in an arid or non-arid ("conventional") climate, and whether the site is designed and managed for accelerated waste decay through liquids recirculation (bioreactor or "wet" conditions).

The default k and L_0 values may be appropriate for modeling LFG generation from U.S. landfills that are characterized by these conditions, but they often are not appropriate when applied to SWD sites that may exhibit very different site conditions and waste composition, which cause dramatically different rates of LFG generation. Because LandGEM was based on data from SWD sites in the U.S., it assumes that the site being modeled is an engineered sanitary landfill. Therefore, it may not be appropriate for unmanaged dump sites where limited soil cover, poor waste compaction, high leachate levels, and other conditions can significantly limit LFG generation and collection (International Best Practice for LFG Projects, EPA, 2012).

Additionally, LandGEM may not be appropriate for countries with significantly different climates or a different mix of waste types.

2.6.3 Introduction to IPCC Model

The IPCC Model was released in 2006 and has several features that make it more suitable than LandGEM for assessing SWD sites worldwide, including applying separate first-order decay calculations for different organic waste categories with varying decay rates. The model was developed for countries to estimate methane emissions from waste disposal using regional per capita waste generation rates and population estimates, with deductions for LFG collection and oxidation. Although it was designed for estimating methane generation from entire countries, the IPCC Model can be modified to estimate generation from individual SWD sites. (International Best Practice for LFG Projects, EPA, 2012)

IPCC Model uses a first-order decay equation that applies annual waste disposal rates and a waste decay rate variable (k value). The first-order calculations do not include the LandGEM variable L_0, but include other variables that, when combined together, constitute an L_0 equivalent variable.

IPCC's methane generation model is based on the amount of degradable organic matter (DOC_m) in the waste disposed. The amount of degradable organic matter (DOC_m) in the waste is estimated from the information about the waste deposited in the landfill, and its components such as paper, food waste, yard waste, and textile. The decomposable degradable organic matter (*DDOC*) is defined as the amount of DOC that can be degraded in a landfill under anaerobic conditions and can be calculated as shown in Eq. 2.2.

$$DDOC_m = W * DOC * DOC_f * MCF \qquad (2.2)$$

Where,

W= mass of waste deposited (Mg)

$DDOC_m$= mass of decomposable DOC deposited (Mg)

DOC : degradable organic carbon (fraction) (Mg C/ Mg solid waste)

DOC_F : fraction of DOC than can be decomposed under anaerobic condition

MCF = methane correction factor for aerobic decomposition (before anaerobic decomposition starts) in the year of deposition.

Table 2.3 shows solid waste disposal sites classification and the methane correction factor (MCF) associated with them.

Table 2.3 Solid Waste Disposal Sites Classification and MCF Factor

(IPCC, 2006)

Type of Site	Methane Correction Factor
Managed – anaerobic [1]	1.0
Managed – semi-aerobic [2]	0.5
Unmanaged [3] – deep (>5 m waste) and	0.8
Unmanaged [4] – shallow (<5 m waste)	0.4
Uncategorized SWDS [5]	0.6

in which,

1. Anaerobic managed solid waste disposal sites: These must have controlled placement of waste (i.e., waste directed to specific deposition areas, a degree of control of scavenging and a degree of control of fires) and will include at least one of the following: (i) cover material; (ii) mechanical compacting; or (iii) levelling of the waste.
2. Semi-aerobic managed solid waste disposal sites: These must have controlled placement of waste and will include all of the following structures for introducing air to waste layer: (i) permeable cover material; (ii) leachate drainage system; (iii) regulating pondage; and (iv) gas ventilation system.
3. Unmanaged solid waste disposal sites – deep and/or with high water table: All SWDS not meeting the criteria of managed SWDS and which have depths of greater than or equal to 5 meters and/or high water table at near ground level. Latter situation corresponds to filling inland water, such as pond, river or wetland, by waste.
4. Unmanaged shallow solid waste disposal sites; All SWDS not meeting the criteria of managed SWDS and which have depths of less than 5 meters.

5. Uncategorized solid waste disposal sites: Only if countries cannot categorize their SWDS into above four categories of managed and unmanaged SWDS, the MCF for this category can be used. (IPCC guidelines, 2006)

The amount of DDOC accumulated in the landfill in a particular year is computed based on the first order decay rate equation, as follows:

$$DDOC_{ma\ T} = DDOC_{md\ T} + (DDOC_{ma\ T-1} * e^{-k}) \quad (2.2)$$

$$DDOC_{m\ decomp\ T} = DDOC_{md\ T-1} * (1-e^{-k}) \quad (2.3)$$

Where,

T = inventory year

$DDOC_{ma\ T}$ = DDOCm accumulated in the SWDS at the end of year T (Gg)

$DDOC_{md\ T-1}$ = DDOCm accumulated in the SWDS at the end of previous year T^{-1} (Gg)

$DDOC_{md}$ = DDOCm deposited into the SWDS in year T (Gg)

$DDOC_{m\ decomp\ T}$ = DDOCm decomposed in the SWDS in year T (Gg)

k = first-order decay constant (yr^{-1})

Table 2.4 summarizes IPCC recommended default “k” values.

Table 2.4 IPCC Default “k” Values

(IPCC, 2006)

Type of Waste		Climate Zone							
		Boreal and Temperate (MAT ≤ 20°C)				Tropical (MAT >20°C)			
		Dry (MAP/PET < 1)		Wet (MAP/PET > 1)		Dry (MAP < 1000 mm)		Moist and Wet (MAP ≥ 1000 mm)	
		Default	Range	Default	Range	Default	Range	Default	Range
Slowly degrading waste	Paper/textiles 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 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	Other (non – food) organic putrescible/ 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 Waste		0.05	0.04 – 0.06	0.09	0.08 – 0.1	0.065	0.05 – 0.08	0.17	0.1511 – 0.2

The amount of methane generated from the decomposable organic matter present in the landfill in a particular year is found by using the relationship:

$CH_{4\ generated\ T} = DDOC_{m\ decomp\ T} * F * 16/12$ (2.4)

Where,

$CH_{4\ generated\ T}$ = amount of methane generated from decomposable material in year ‘T’.

16/12 = molecular weight ratio CH_4/C ratio

F = fraction of CH_4 by volume, in generated landfill gas (fraction)

2.6.4 Limitations of the IPCC Model

IPCC Model has four climate categories to specify rate of CH_4 generation (k) which represent an improvement over LandGEM’s two climate category approach. EPA points at limitations in IPCC model as following:

- Temperature has a smaller impact on LFG generation than precipitation and should not be assigned equal weight in assigning climate categories.
- PET (potential evaporation) 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.
- The 1,000 mm/year precipitation threshold for separating tropical climates into dry vs. wet categories is better than the LandGEM threshold of 635 mm/year (25 inches/year) but is likely too coarse to account for the effects of precipitation across the wide range of values encountered. For example, most areas in Colombia experience more than 1,000 mm/year of precipitation and many areas get more than 2,000 mm/year. Landfills in these areas would be treated the same (identical k values) in the IPCC Model, which implies that there are no noticeable effects from increasing precipitation above 1,000 mm/year.

2.6.5 Introduction to UT-Arlington CLEEN Model

Waste composition, rainfall and ambient temperature of a landfill significantly influence its methane generation potential. LandGEM and IPCC are very much simplified and do not incorporate the variations in waste composition, rainfall and ambient temperature. CLEEN (Capturing Landfill Emissions for Energy Needs) allows methane generation to be estimated for any landfill, with basic information about waste composition, annual rainfall, and ambient temperature.

An experimental design was developed using an incomplete block design, where the waste composition served as a blocking variable and combinations of temperature and rainfall are the predictor variables (Karanjekar, 2012). Methane emissions were measured from 27 lab scale landfills reactors with varying waste compositions, rainfall rates, and temperatures. Waste components considered were the major biodegradable wastes, food, paper, yard, and textile, as well as inorganic waste. Based on the laboratory scale data, a comprehensive regression equation was developed using SAS software that used the 7 predictor variables (temperature, rainfall, and five waste components) to estimate the methane generation rate constant, (*k*):

$$k = \beta_0 + \beta_{1F} + \beta_{2Y} + \beta_{3X} + \beta_{4P} + \beta_{5I} + \beta_{6R} + \beta_{7T} + \beta\varepsilon \qquad (2.5)$$

where

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

β s = parameters to be determined through multiple linear regression, using the lab data

F = fraction of land-filled waste that is food

Y = fraction of land-filled waste that is yard waste

X = fraction of land-filled waste that is textiles

P = fraction of land-filled waste that is paper

I = fraction of land-filled waste that is inorganic

R = annual rainfall, mm/year

T = average annual temperature at the landfill location

ε= error uncertainty, modeled as a random variable

The validation process for CLEEN is still ongoing and data from developing countries landfills is limited. Thus, the modeling results from CLEEN were not used in this project.

2.7 Landfill Gas Collection system

Gas collection systems are designed either active or passive; in passive systems, gas collection is done without mechanical assistance where in active systems, mechanical assistance such as blowers is used. The components of active LFG collection system are described as following.

2.7.1 Wells

Well systems consist of a series of vertical wells which penetrate to near the bottom of the disposed waste. Well design is done based on the gas generation rate and radius of influence. Radius of influence is defined as the point around the well at which negative pressure goes to zero.

The borehole diameter for active wells typically range from 1 to 3 ft and a minimum 4 inches diameter HDPE or PVS casing is placed in the boring two thirds of which should be screened (US Army Corps of Engineers, 2008). A gravel pack should be placed around the screen which should extend a minimum of 12 inches above the end of screen. A 4 ft layer of bentonite is place on top of the gravel Figure 2.4 shows a typical LFG extraction vertical well detail.

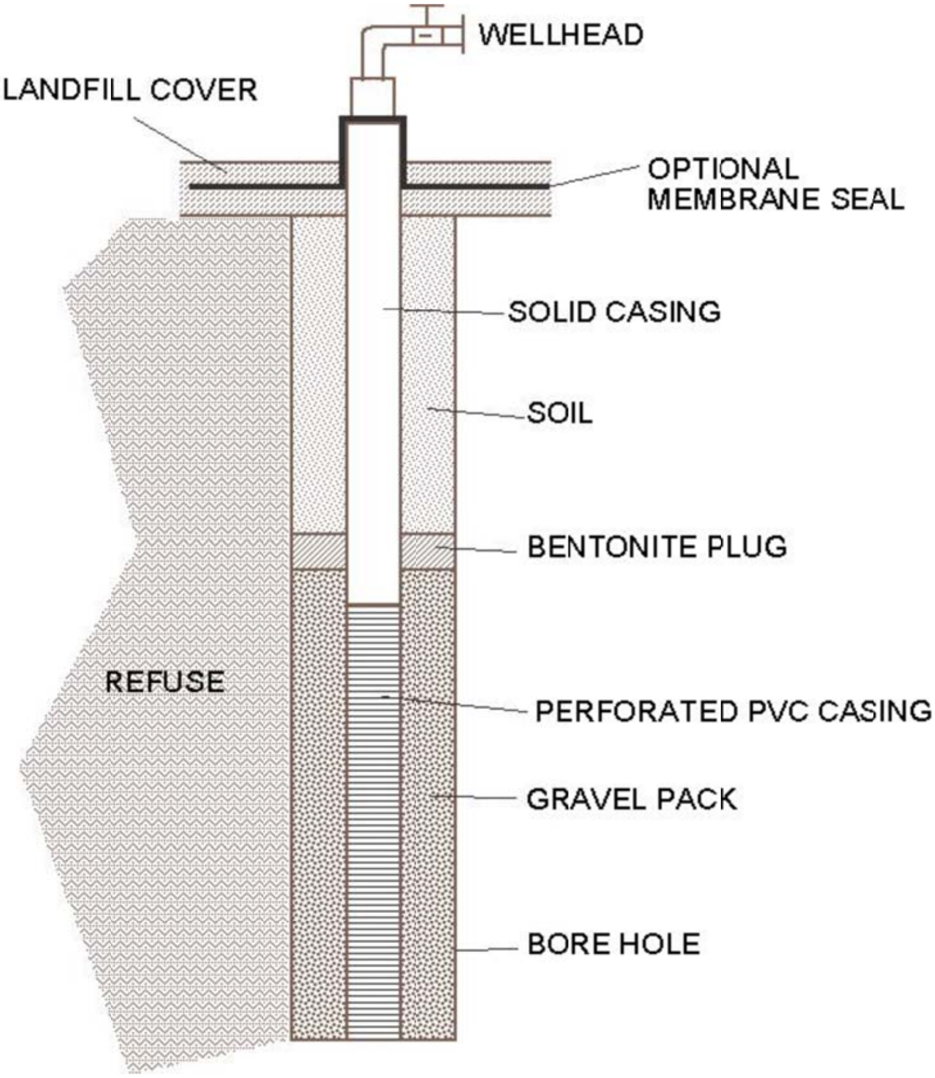

Figure 2.4 LFG Extraction Well (Source: SCS Engineers, date unknown)

2.7.2 Header Piping

Header piping is used for active systems to transport gas from the collection wells to the blower or flare station. The piping system will have several branches to which multiple extraction wells are attached and valves are used to control the amount of flow coming from each well. Flexible hoses which are smaller than header pipes are usually used to connect vertical wells to headers. Header pipes are typically made of

HDP or PVC. Piping should be sized to provide the minimum head losses (optimum 1 inches of water column per 100 ft of pipe) and should provide additional capacity if additional wells are added later. LFG velocity should be less than 12 mps with concurrent flow so condensate will condense on side wells and less than 6 mps with counter-current LFG and condensate flow so condensate will not block flow of LFG (US Army Corps of Engineers, 2008). Header pipes should be sloped according to Table 2.5.

Table 2.5 Header Pipe Slopes

(US Army Corps of Engineers, 2008)

	Condensate flow in direction of LFG flow	Condensate flow opposite direction of LFG flow
On Landfill	2% slope	4% slope
Off Landfill	1% slope	3% slope

2.7.3 Blower

A blower 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 size, type and number of blowers needed depend on the gas flow rate and distance to downstream processes.(International Best Practice for LFG Projects, EPA, 2012)

2.7.4 Flare

A flare is a device for igniting and burning the LFG. Flares are a component of each energy recovery option because they may be needed to control LFG emissions during startup and downtime of the energy recovery system and to control gas that exceeds the capacity of the energy conversion equipment. In addition, a flare is a cost-effective way to gradually increase the size of the energy generation system at an active landfill. As more waste is placed in the landfill and the gas collection system is expanded, the flare is used to control excess gas between energy conversion system upgrades. (International Best Practice for LFG Projects, EPA, 2012)

2.8 Thesis Objectives

As discussed earlier, 23% of the methane emission in Ghana comes from the waste sector which is mainly consisted of unmanaged landfills. This project studies the feasibility of methane recovery and the potential electricity that can be generated from two landfills (Tema & Temale) in Ghana. LFG to energy project will contribute to both supply of the energy and GHG emission reduction in Ghana.

The objectives for this thesis are:

- Estimation of landfill gas generation and electricity generation potential,
- Identifying preliminary LFG recovery and use system,
- Estimation of project cost & benefits,
- Estimation of greenhouse gasses emission reductions through methane utilization and alternative energy resources,

for Tema and Temale landfills in Ghana.

Chapter 3

Methodology

3.1. Landfill Descriptions

3.1.1 Tema Landfill

The Kpone Engineered Landfill Site is located at Kpone, a suburb of Tema. Owned by the Tema Municipal Assembly and managed by Zoomlion company, the landfill opened in January 2013. Originally designed to serve the Tema Metropolitan Assembly, the landfill currently serves the a population of 1 million persons, accepting 95% of waste generated in the greater Accra metropolitan area; its initial expected life of 12 years was estimated to be 2 years due to the high filling rate (1250 tons/day). Based on the latest updates from Tema site, 30% of 2014 waste was sent to another landfill which allows for an additional waste acceptance in 2015. The engineered landfill consists of 4 cells with liners, but no gas collection system at present.

3.1.2 Temale Landfill

The Gbalahi Landfill is located at Kpone, a suburb of Tema. Owned by the Temale Municipal Assembly and managed by Zoomlion company, the landfill opened in 2006, and is designed to operate until 2036. It serves a population of over 579,000 persons. The engineered landfill consists of 2 cells with liners.

3.2 Waste Composition

3.2.1 Tema Waste Composition

Dr. Afotey and his students collected 10 working phase samples (7 at the municipal working face, and one each at the commercial, industrial, and market faces), and 15 landfilled waste samples (5 at each of 3 locations), according to the method provided in the Appendix A. Waste composition was determined by sorting, according to the procedure provided in the Appendix B. Figures 3.1 to 3.4 represent the process of collecting and sorting samples. Table 3.1 & Figure 3.5 represents the average waste composition.

Figure 3.1 Tema Landfill Site

Figure 3.2 Sorting process

Figure 3.3 Weighing process

Figure 3.4 Team members

Table 3.1 Tema Landfill Waste Composition

Waste Components	Weight (kg)	Average percent
Paper	50.5	10.7
Plastic	122.1	25.8
Food	121	25.5
Textiles	43.1	9.1
Wood & Yard Waste	2.5	0.5
Metals	17.7	3.7
Glass	12	2.5
Styrofoam & Sponge	0.6	0.1
C&D	0	0
Others (Soil & Fines)	104	21.9
Total	474	100

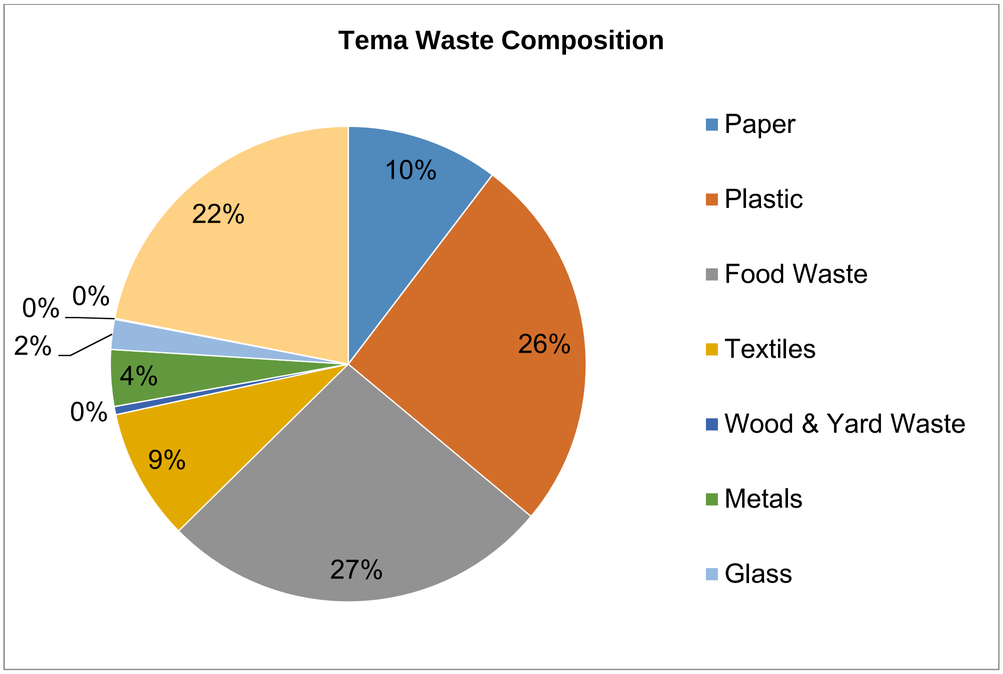

Figure 3.5 Tema Landfill Waste Composition

3.2.2 Tema le Waste Composition

For Temale landfill, Dr. Afotey and his students collected 10 samples were from the commercial working face but for the landfilled waste, the team could not do meaningful sorting into components since everything was virtually reduced to ashes due to hot ash present in the waste. Figures 3.6 to 3.10 represent the process of collecting and sorting samples. Figure 3.11 and Table 3.2 represents the average waste composition.

Figure 3.6 Temale Landfill Site

Figure 3.7 Obtaining Waste Sample

Figure 3.8 Sorting Waste

Figure 3.9 Weighing Waste

Figure 3.10 Team Members

Table 3.2 Temale Landfill Waste Composition

Waste Components	Weight (kg)	Average percent
Paper	652.2	11.04
Food	2310.5	39.11
Textiles	688.7	11.66
Plastics	1248.8	21.14
Other	1008.1	17.06
Total	5908.3	100

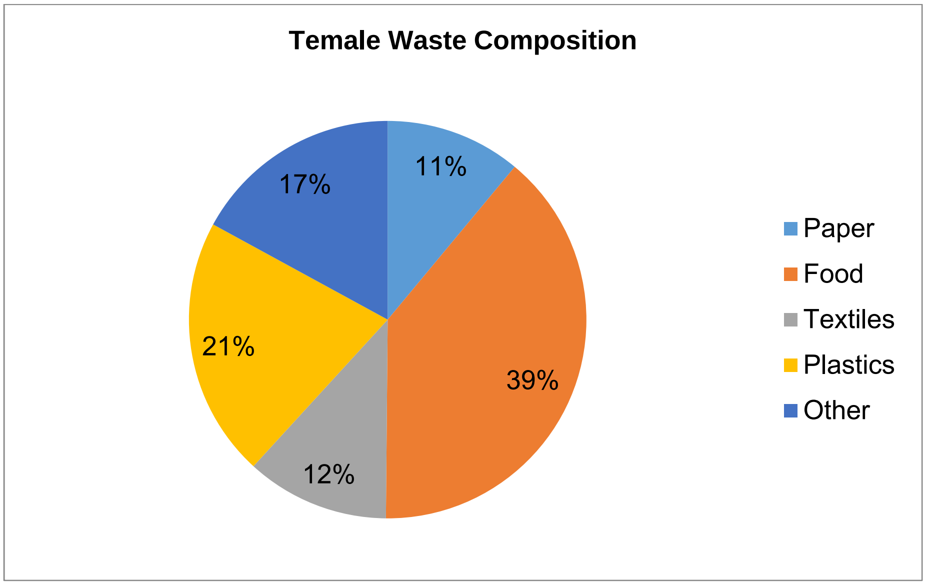

Figure 3.11 Temale Landfill Waste Composition

3.3 Waste Moisture Content

3.3.1 Tema Landfill Moisture Content

Methods for moisture content are described in the excerpt from the laboratory manual, given in the Appendix C.

Moisture data for Tema is summarized in Table 3.3.

Table 3.3 Moisture Content Summary – Tema

Type of Sample	Location	Number of Samples	Moisture Content		
			Min.	Max.	Avg.
Landfill	1	5	45.0	62.9	55.0
	2	5	27.3	44.8	36.2
	3	5	34.6	61.8	43.4
Working Face	Municipal	7	22.7	58.3	44.4
	Industrial	1	27.2	27.2	27.2
	Commercial	1	44.5	44.5	44.5
	Market	1	40.7	40.7	40.7

3.3.2 Temale Landfill Moisture Content

Moisture data for Temale is presented in Table 3.4.

Table 3.4 Moisture Content Analysis - Temale

Commercial (Working Phase)					
Sample 1		Initial Weight, g	Final Weight, g	Moisture Content, g	% Moisture Content
	Others	500	475.9	24.1	
	Food waste	393	235.3	157.7	
	Paper	35	26	9	
	Textile	79.8	77.6	2.2	
	Total	1007.8	814.8	193	19.2

3.4. Landfill Gas Modeling

3 models were used for estimating LFG generation potential for Tema and Temale with traditional operation: LandGEM with CAA and Inventory defaults, the IPCC model, and UTA's CLEEN model.

In addition, LandGEM and IPCC were used for modeling bioreactor operation. CLEEN was not used for modeling bioreactor operation because it has not been validated with bioreactor data for developing countries yet.

3.4.1 Tema LFG Modeling

Table 3.5 illustrates Tema waste acceptance history for conventional & bioreactor operations.

Two scenarios were considered for bioreactor operation. In the first scenario, 33% waste volume recovery was assumed over a time-span of 8 years, due to increased waste compaction (EREF, 2003). This allowed additional waste placement for Tema in years 2023, 2031, and 2039, as shown in Table 3.5, assuming bioreactor operation to begin in 2016.

Perpetual landfill is assumed as the second scenario in which the entire landfill volume would be available for new waste placement every 8 years. The thought is that 33% of the landfill volume would be recovered every 8 years due to complete decomposition of organic waste. The operators could dig out the remaining waste every 8 years, which would consist of plastics and other non-degradables, as well as the soil/fertilizer material resulting from degradation of the organics.

Table 3.5 Tema Waste Acceptance History

Year	Waste Landfilled (1000 tons)		
	Conventional	Bioreactor Scenario 1	Bioreactor Scenario2
2013	503	503	503
2014	478	478	478
2015	25	25	25
2016	0	0	0
2017	0	0	0
2018	0	0	0
2019	0	0	0
2020	0	0	0
2021	0	0	0
2022	0	0	0
2023	0	0	0
2024	0	332	503
2025	0	0	503
2026	0	0	0
2027	0	0	0
2028	0	0	0

Table 3.5-continued.

2029	0	0	0
2030	0	0	0
2031	0	0	0
2032	0	109	503
2033	0	0	503
2034	0	0	0
2035	0	0	0
2036	0	0	0
2037	0	0	0
2038	0	0	0
2039	0	0	0
2040	0	36	503
2041	0	0	503

Average temperature in Tema is 80°F and average annual rainfall is 30 in (source: worldclimate.com). According to IPCC, Table 2.4, Tema falls under "Tropical, Dry" category for conventional operation, where in LandGEM model, according to Table 2.2, Tema is not arid and "CAA & Inventory conventional" methane generation rates (k) were selected.

Methane correction factor, accounts for the fact that unmanaged SWDS produce less CH4 from a given amount of waste than anaerobic managed landfills (IPCC, 2006). Based on Table 2.3, Tema landfill is "managed, semi-aerobic" and MCF for conventional operation is 0.5. IPCC recommends to use MCF=1 for bioreactor operation.

For bioreactor operation, "Tropical, Moist & Wet" was selected in IPCC and "Inventory Wet" in LandGEM model.

According to EPA, methane collection efficiencies range from 60 to 85 percent, with an average of 75 percent (International Best Practice for LFG Projects, EPA, 2012). Therefore, 0.75 was used as the fraction of methane recovered

Table 3.6 Parameters used for LFG modeling for Tema

	LandGEM –			IPCC		CLEEN
Parameter	CAA Conven-tional	Inventory Conven-tional	Bio-reactor	Con-ventional	Bioreactor	Conventional
Years of operation	2013-2015	2013-2015	Table 3.5	2013-2015	Table 3.5	2013-2015
Fraction of methane recovered	0.75	0.75	0.75	0.75	0.75	0.75
Methane content, %	50	50	50	50	50	50
k (yr^{-1})	0.05	0.04	0.7	Defaults by category	Defaults by category	Calculated based on 30 in./yr rainfall, 80°F temp., waste composition
Lo (m^3/Mg)	170	100	96	Defaults by category	Defaults by category	Calculated based on waste composition
Lag time, months	N/A	N/A	N/A	6	6	
Management	N/A	N/A	N/A	Managed semi-aerobic (MCF =0.5)	Bioreactor (MCF = 1)	N/A

3.4.2 Temale LFG Modeling

Table 3.7 illustrates Tamale waste acceptance history for conventional & bioreactor operations.

For bioreactor operation 33% waste volume recovery was assumed over a time-span of 8 years, due to increased waste compaction (EREF, 2003). This allowed additional waste placement for Tamale every 8 years, assuming bioreactor operation to begin in 2016.

Table 3.7 Temale Waste Acceptance History

Year	Waste Landfilled-Conventional (1000 tons)	Available Waste Space-Bioreactor Operation (1000 tons)
2006	25.6	25.6
2007	25.6	25.6
2008	25.6	25.6
2009	25.6	25.6
2010	25.6	25.6
2011	25.6	25.6
2012	25.6	25.6
2013	25.6	25.6
2014	92.6	92.6
2015	92.6	92.6
2016	92.6	92.6
2017	92.6	92.6
2018	92.6	92.6
2019	92.6	92.6
2020	92.6	92.6
2021	92.6	92.6
2022	92.6	92.6
2023	92.6	92.6
2024	92.6	251.3
2025	92.6	123.5
2026	92.6	123.5
2027	92.6	123.5
2028	92.6	123.5
2029	92.6	123.5
2030	92.6	123.5

Table 3.7-continued.

2031	92.6	123.5
2032	92.6	175.3
2033	92.6	133.4
2034	92.6	133.4
2035	92.6	133.4
2036	92.6	133.4
2037	0.0	40.8
2038	0.0	40.8
2039	0.0	40.8
2040	0.0	58.4
2041	0.0	44.1
2042	0.0	44.1
2043	0.0	44.1
2044	0.0	44.1
2045	0.0	13.2
2046	0.0	13.2
2047	0.0	13.2
2048	0.0	18.7
2049	0.0	14.3
2050	0.0	14.3
2051	0.0	14.3
2052	0.0	14.3
2053	0.0	4.4
2054	0.0	4.4
2055	0.0	4.4

Average temperature in Temale is 82°F and average annual rainfall is 43 in (source: worldclimate.com). According to IPCC , Table 2.4, Temale falls under “ Tropical, Moist & Wet” category for conventional operation, where in LandGEM model (Table 2.2) Temale is not arid and “CAA & Inventory conventional” methane generation rates (k) were selected for conventional operation. For bioreactor operation according to Table

2.4, “Tropical, Moist & Wet” was selected in IPCC, with MCF=1 (IPCC 2006) and “Inventory Wet” in LandGEM model. According to EPA, methane collection efficiencies range from 60 to 85 percent, with an average of 75 percent (International Best Practice for LFG Projects, EPA, 2012). Therefore, 0.75 was used as the fraction of methane recovered.Parameters used for LFG modeling are summarized in Table 3.8.Parameters used for LFG modeling are summarized in Table 3.8.

Table 3.8 Parameters used for LFG modeling for Temale

	LandGEM –			IPCC		CLEEN
Parameter	CAA Conventional	Inventory Conventional	Bio-reactor	Conventional	Bio-reactor	Conventional
Wasted accepted per year (metric tons)	23,198 through 2013 then 83,950	23,198 through 2013 then 83,950	See Table 3.7	23,198 through 2013 then 83,950	See Table 3.7	23,198 through 2013 then 83,950
Years of operation	2006-2036	2006-2036	2006-2060	2006-2036	2006-2060	2006-2036
Fraction of methane recovered	0.75	0.75	0.75	0.75	0.75	0.75
Methane content, %	50	50	50	50	50	50
k (yr^{-1})	0.05	0.04	0.7	Defaults by category	Defaults by category	Calculated based on 43 in./yr rainfall,82 °F temp., waste composition
Lo (m3/Mg)	170	100	96	Defaults by category	Defaults by category	Calculated based on waste composition
Lag time, months	N/A	N/A	N/A	6	6	N/A
Management	N/A	N/A	N/A	Unmanaged – shallow (<5 m waste) (MCF =0.4)	Bio-reactor (MCF = 1)	N/A

3.5 Landfill Gas Collection System Design

LFG collection systems were designed based on peak LFG generation estimations from models.

Waste volume was calculated from the landfill dimensions and waste height, assuming a cross-section as shown in Figure 12 for Tema & Figure 13 for Temale . The LFG flow rate per well was calculated according to (USACE, 2008):

$$Q_{well} = \pi(R^2 - r^2)(T)(\rho_w)(G)/(\%\ \text{methane}) \qquad (3.1)$$

where

Q_{well} = LFG flow rate per well (e.g. scfm)

R = radius of influence (e.g. ft)

r = borehole radius (e.g. ft)

T = waste thickness (e.g. ft)

ρ_w = waste density (e.g. lb/ft^3)

G = peak methane production rate (e.g. ft^3/(lb waste)/day), from LandGEM or other model

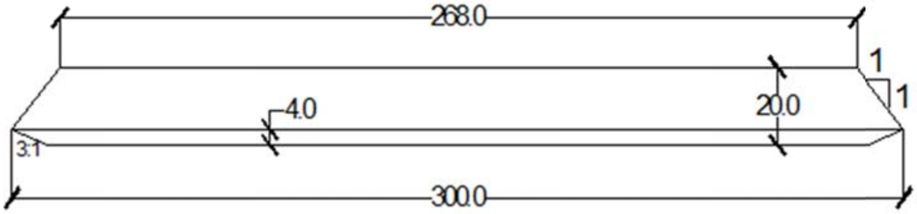

Figure 3.12 Tema Landfill Cross Section

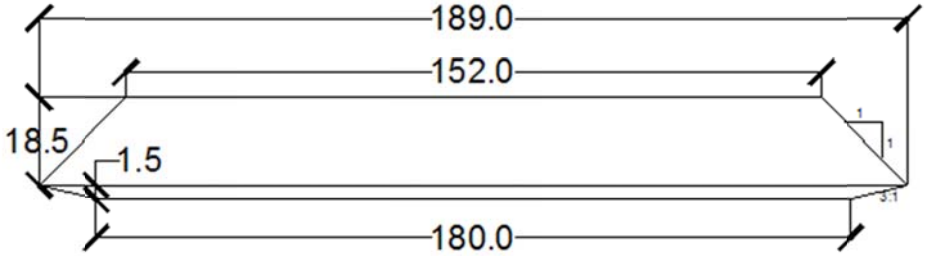

Figure 3.13 Temale Landfill Cross Section

Peak flow rate for the entire landfill is:

$Q_{total} = Q_{well}$ * No. of wells (3.2)

Number of wells needed from flow cautions= Q_{total}/Q_{well}

Wells should be spaced so that their zone of influence overlaps. The spacing between wells are calculated according to

Spacing=(2-O/100)*R (3.3)

Where,

R= radius of influence (e.g. ft)

O=required overlap (which is 27% for corners of equilateral)

LFG velocity in the pipes was calculated according to

$V= Q / A$ (3.4)

Where,

$A=\pi D^2/4$, D= pipe diameter (e.g. ft)

Q=flow in the pipe (e.g. scfm)

Head losses for the system were calculated as the sum of losses incurred due to pulling gas through the waste, within the radius of influence; wall friction losses; valve and fitting losses; and 2 inches negative water column maintained for the system (Bagchi, 2004).

The pressure loss incurred in pulling gas through the waste is calculated according to (USACE, 2008):

$$\Delta P_{well} = \mu\, G_{tot}\, \rho_w\, [R^2 \ln(R/r) + (r^2/2) - (R^2/2)]/(2Ks) \qquad (3.5)$$

where

ΔP_{well} = pressure difference from radius of influence to gas well

R = radius of influence

r = radius of borehole

μ = absolute viscosity of landfill gas

K_s = apparent permeability of waste

ρ_w = density of waste

G_{tot} = total landfill gas production rate = G/(% methane)

3.6 Electricity Generation Potential

Options for use of LFG include direct use, electricity generation, and production of alternate fuels (pipeline quality natural gas and transportation fuels like compressed natural gas or liquefied natural gas). Options for electricity generation include internal combustion (reciprocating) engines, gas turbines, microturbines, and combined heat and power systems (EPA Landfill Methane Outreach Program). Table 3.9 below lists various landfill gas to energy project types and recommended sizes.

Electricity generation potential was estimated using LFG-cost Web, as will be discussed in Chapter 4. Combined heat and power microturbines had the greatest present worth values and shortest payback times, although combined heat and power engines generated more electricity.

Table 3.9 LFG Energy Project Types and Recommended Sizes

(LFG-cost Web, EPA)

LFG Energy Project Type	**Recommended Project Size**
Direct Use (Boiler, Greenhouse, etc.)	Available for any size
Standard Turbine-Generator Sets	Greater than 3 MW
Standard Reciprocating Engine-Generator Sets	800 kW and greater
High Btu Processing Plant	1,000 scfm to 10,000 scfm
Microturbine-Generator Sets	30 kW to 750 kW
Small Reciprocating Engine-Generator Sets	100 kW to 1 MW
Leachate Evaporators	5,000 gallons/day and greater
CHP Reciprocating Engine-Generator Sets	800 kW and greater
CHP Turbine-Generator Sets	Greater than 3 MW
CHP Microturbine-Generator Sets	30 kW to 300 kW

3.7 Estimation of project costs

EPA's LFGcost-Web Model (Version 2.2) was used to obtain an initial economic feasibility analysis for installation of LFG collection and use systems for Tema (conventional and bioreactor) and Temale. Tables 3.10 and 3.11 show required and optional user inputs for each scenario were conducted which varied the following parameters:

- energy project type (all types included in the model were considered),
- the project start year (2015 and 2016), since it is not known when a collection and use system would become operational,
- interest rate (20% and 25%, since rates in Ghana fluctuate between 16 and 25% according to Bank of Ghana),
- down payment (20% and 100%) – 20% is the default, and 100% was tried as a best-case for decreasing the number of years to payback.

- the number of acres - input for Tema as both the actual acres of the landfill and the number of wells estimated to be needed in chapter 4, since LFGcost-Web assumes one well per acre.

Since initially there is no LFG collection system in both landfills, cost analyses were included to cover the cost of a system . Landfill gas collection efficiency was taken as 75%, which is recommended by EPA for LandGEM modeling. The Ghana electricity cost of \$0.15/kWh was taken from Electricity Company of Ghana based on \$1=Ghc3.19.

Although LandGEM provides a default k value of 0.7 for modeling bioreactor landfills , LMOP recommends assigning a k value of 0.3 for bioreactors based on a study conducted by the University of Florida(EPA 2005). IPCC, also recommends k value of 0.4 for rapidly degrading waste & 0.17 for bulk waste for moist and wet climate condition. Therefore a k-value of 0.17 year^{-1} was used for bioreactor landfill cost modeling for both Tema & Temale.

Table 3.10 LFG-cost Web Optional User Inputs

Type Input Required	Input Data			
	Tema	Tema	Temale	Temale
	Con-ventional	Bio-reactor	Con-ventional	Bio-reactor
Year landfill opened	2013	2013	2006	2006
Year of landfill closure	2015	2039	2036	2060
Area of LFG wellfield to supply project (acres) [assumes 1 well/acre]	25 or 44	25 or 44	14	14
Average annual waste acceptance rate (tons/yr)	See Table 3.5	See Table 3.5	See Table 3.7	See Table 3.7

Table 3.10-continued.

LFG energy project type: (D)irect use, (T)urbine, (E)ngine, (H)igh Btu, microtu(R)bine, small en(G)ine, lea(C)hate evaporator, CHP engine (CE), CHP turbine (CT), or CHP microturbine (CM)?	All	All	All	All
Will LFG energy project cost include collection and flaring costs? (Y)es or (N)o	Y	Y	Y	Y
For leachate evaporator projects only: Amount of leachate collected (gal/yr)	N/A	N/A	N/A	N/A
For direct use, high Btu, and CHP projects only:	0	0	0	0
Distance between landfill and direct end use, pipeline or CHP unit (miles)				
For CHP projects only: Distance between CHP unit and hot water/steam user (miles)	0	0	0	0
Year LFG energy project begins operation	2015 or 16	2015 or 16	2015 or 16	2015 or 16

Table 3.11 LFG-cost Web Optional User Inputs

Type of Optional Input	Suggested Default Value	Input Data			
		Tema Conventional	Tema Bioreactor	Temale Conventional	Temale Bioreactor
LFG energy project size: Gas rate = (M)inimum, (A)verage, ma(X)imum, or (D)efined by user (must enter design flow rate below)?	M	X	X	X	X
For user-defined project size only: Design flow rate (ft3/min)	---				
Methane generation rate constant, k (1/yr) [0.04 for typical climates, 0.02 for arid climates, 0.1 for bioreactors or wet landfills]	0.04	0.04	0.17	0.04	0.17
Potential methane generation capacity of waste, L_o (ft^3/ton)	3,204	3,204	3,204	3,204	3,204
Methane content of landfill gas (%)	50%	50%	50%	50%	50%
Landfill gas collection efficiency (%)	85%	75%	75%	75%	75%
Loan lifetime (years)	10	10	10	10	10
Interest rate (%)	8.00%	20%, 25%	20%, 25%	20%, 25%	20%, 25%
Marginal tax rate (%)	35.00%	25%	25%	25%	25%
Discount rate (%)	10.00%	20%, 25%	20%, 25%	20%, 25%	20%, 25%

Table 3.11-continued.

Down payment (%)		20.00%	20% and 100%	20% and 100%	20% and 100%	20% and 100%
Initial year product price:	Landfill gas production ($/million Btu)	$5.00	$5.00	$5.00	$5.00	$5.00
(based on initial year of operation)	Electricity generation ($/kWh)	$0.06	$0.15	$0.15	$0.15	$0.15
	CHP hot water/steam production ($/million Btu)	$7.50	$7.50	$7.50	$7.50	$7.50
	High Btu production ($/million Btu)	$6.50	$6.50	$6.50	$6.50	$6.50

Chapter 4

Results & Discussion

4.1 Moisture content

4.1.1 Tema Landfill

Although food waste is only 27% overall, the landfill's moisture content is fairly high, averaging 43.8% over all samples, ranging from a low of 27% at the industrial working face to a high of 55% at landfill location 1.

A typical average moisture content of waste in place is 25 percent (McBean et al., 1995). For moisture content of about 20% or below, the moisture in the waste is not sufficient to support the biological activity of the methanogenic bacteria. The moisture content of the Tema landfill is high enough to support methane gas production.

4.1.2 Temale Landfill

The average moisture content for this location is only 19.2%, despite the high percent food waste (39%). This is likely due to fires in the landfill that elevate the temperature and thus evaporate moisture. For methane generation, water would need to be added to this landfill.

4.2 Methane Recovery Estimation

4.2.1 Methane Recovery Potential from Tema Landfill

Tema Conventional Operation

Table 4.1 & Figure 4.1 represent potential methane recovery estimates under conventional operation from three models. The inputs used for modeling are shown in Table 3.6.

Table 4.1 Tema Conventional Operation Methane Recovery

Year	IPCC	LandGEM		CLEEN
	SCFM	CAA-(SCFM)	Inv-(SCFM)	SCFM
2013	0	0	0	0
2014	35	191	90	137
2015	67	363	173	254
2016	64	355	170	236
2017	60	338	164	213
2018	56	321	157	192
2019	53	306	151	173
2020	49	291	145	156
2021	46	277	139	141
2022	44	263	134	127
2023	41	250	129	114
2024	38	238	124	103
2025	36	226	119	93
2026	34	215	114	84
2027	32	205	110	75
2028	30	195	105	68
2029	28	185	101	61
2030	27	176	97	55
2031	25	168	93	50
2032	24	160	90	45
2033	22	152	86	40
2034	21	144	83	36
2035	20	137	80	33
2036	19	131	77	30
2037	18	124	74	27
2038	17	118	71	24
2039	16	112	68	22
2040	15	107	65	20
2041	14	102	63	18
2042	13	97	60	16

Table 4.1-continued.

2043	13	92	58	14
2044	12	88	56	13
2045	11	83	53	12
2046	11	79	51	11
2047	10	75	49	9
2048	10	72	47	9
2049	9	68	46	8
2050	9	65	44	7
2051	8	62	42	6
2052	8	59	40	6
2053	7	56	39	5
2054	7	53	37	5
2055	7	51	36	4
2056	6	48	34	4
2057	6	46	33	3
2058	6	43	32	3
2059	5	41	31	3
2060	5	39	29	2

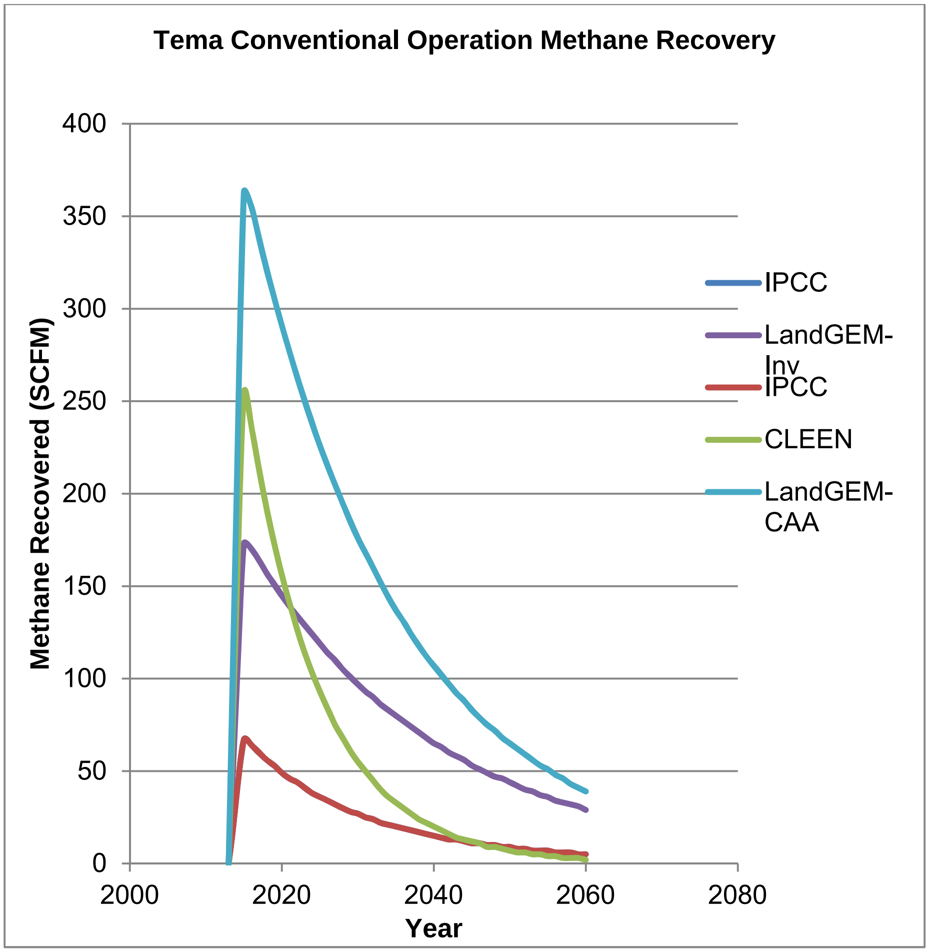

Figure 4.1 Tema Conventional Operation Methane Recovery

LandGEM with CAA defaults (rate constant k and ultimate methane generation Lo) is known to overestimate LFG generation, and represents a worst-case upper bound. For Tema landfill with conventional operation, LandGEM LFG estimates with inventory defaults were used for subsequent cost analyses, estimation of electricity generation potential, and sizing of the LFG collection system.

Tema Bioreactor Operation

As discussed in Chapter 3, two scenarios for bioreactor operation were assumed. In the first scenario, it is assumed that 33% of the landfill waste volume will be recovered every 8 years due to the degradation of organic waste. In the second scenario it is assumed that every eight years the remaining non-degradable waste will be dug out manually; therefore, the entire landfill volume becomes available for waste replacement.

Table 4.2 & Figure 4.2 represent potential methane recovery estimates under bioreactor operation from three models. The inputs used for modeling were shown in Table 3.6.

Table 4.2 Tema Bioreactor Operation Methane Recovery

Year	IPCC (SCFM)		LandGEM(SCFM)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
2013	0	0	0	0
2014	204	204	1150	1150
2015	344	344	1664	1704
2016	265	265	884	884
2017	202	202	439	439
2018	157	157	218	218
2019	126	126	108	108
2020	104	104	54	54
2021	87	87	27	27
2022	75	75	13	13
2023	66	66	7	7
2024	59	59	3	3
2025	188	204	761	1150
2026	147	354	378	1722
2027	119	263	188	855
2028	98	200	93	425
2029	83	156	46	211

Table 4.2-continued.

2030	72	125	23	105
2031	63	103	11	52
2032	56	87	6	26
2033	96	204	253	1150
2034	79	354	126	1722
2035	67	263	62	855
2036	58	200	31	425
2037	51	156	15	211
2038	46	125	8	105
2039	41	103	4	52
2040	38	87	2	26
2041	49	204	84	1150
2042	43	354	42	1722
2043	38	263	21	855
2044	34	200	10	425
2045	30	156	5	211
2046	28	125	3	105
2047	25	103	1	52
2048	23	87	1	26
2049	22	75	0	13
2050	20	66	0	6
2051	19	59	0	3
2052	17	53	0	2
2053	16	48	0	1
2054	15	44	0	0
2055	14	41	0	0
2056	13	37	0	0
2057	12	35	0	0
2058	12	32	0	0
2059	11	30	0	0
2060	10	28	0	0

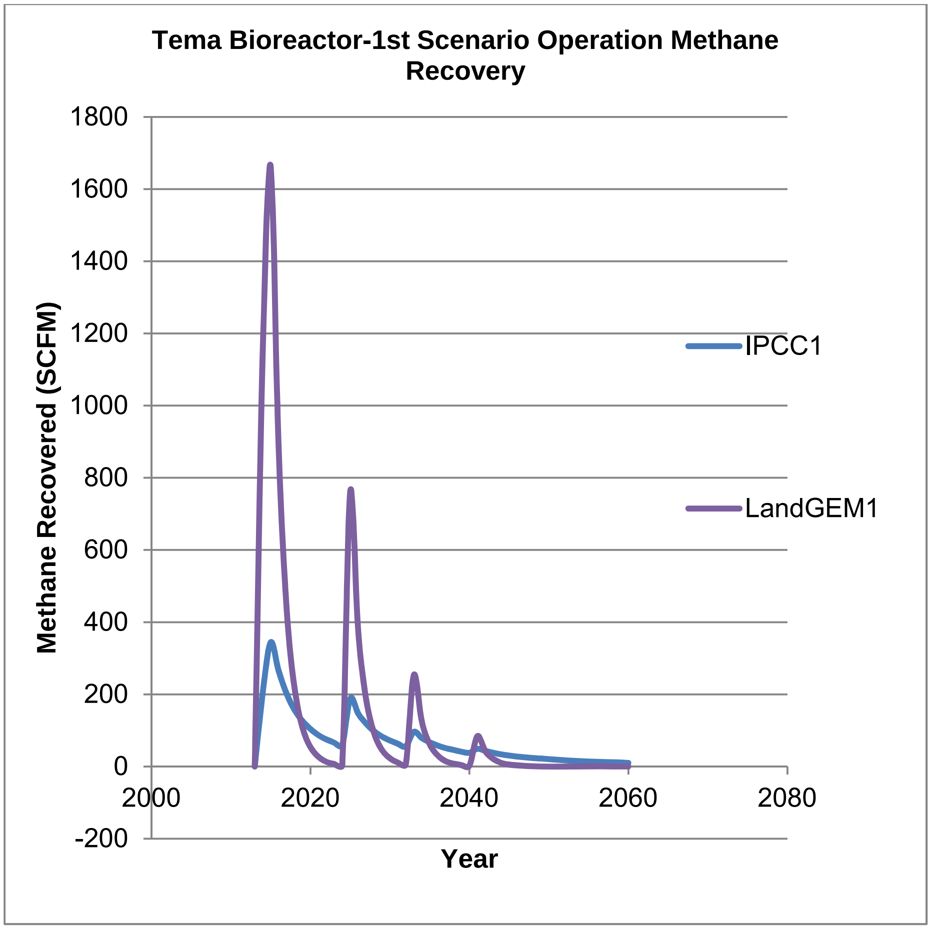

Figure 4.2 Tema Bioreactor-1st Scenario Operation Methane Recovery

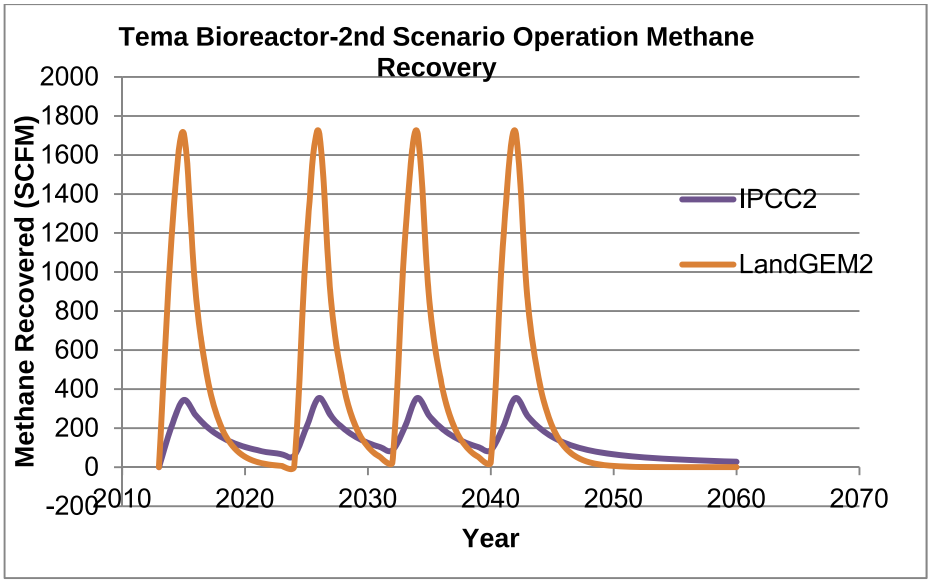

Figure 4.3 Tema Bioreactor-2nd Scenario Operation Methane Recovery

Table 4.3 compares the total amount of methane that can be recovered from Tema landfill until 2060, under conventional and bioreactor operations for IPCC and LandGEM model.

Table 4.3 Methane Recovery from Tema until 2060

	Methane Recovered until 2060 (million SCF)		Methane Recovered until 2060 (million m^3)		Methane Recovered until 2060 (1000 tons)	
	IPCC	**LandGEM**	**IPCC**	**LandGEM**	**IPCC**	**LandGEM**
Conventional	586	2,044[1]	17	58[1]	12	43[1]
Bioreactor 1st Scenario	1,809	3,543	51	100	38	74
Bioreactor 2nd Scenario	3,543	9,606	100	272	74	200

1.LandGEM Inventory

From the results it can be concluded that bioreactor operation substantially increases the gas volume generated. Also, with perpetual landfill operation (2nd scenario) more LFG will be generated in the same life span compared to the first scenario.

4.2.2 Methane Recovery Potential from Temale Landfill

Temale Bioreactor Operation without Waste Addition Methane Recovery

Table 4.4 & Figure 4.4 represent potential methane recovery estimates under conventional operation from three models. Unlike Tema, the conventional (LandGEM Inv.) and bioreactor (IPCC) peak LFG estimates for Temale are similar, due to the substantial rainfall in Temale (43 inches per year), which means that the conventional operation likely has moisture content similar to a bioreactor. Thus, the term “conventional operation” is replaced by “bioreactor operation without waste addition”. The inputs used for modeling are shown in Table 3.8.

Table 4.4 Temale Bioreactor Operation without Waste Addition Methane Recovery

Year	IPCC	LandGEM		CLEEN
	SCFM	Inv-SCFM	CAA-SCFM	SCFM
2006	0	0	0	0
2007	6	5	10	8
2008	10	9	19	16
2009	13	13	28	22
2010	15	17	36	28
2011	17	21	44	34
2012	18	25	52	39
2013	19	29	59	43
2014	20	32	66	47
2015	36	47	98	72
2016	47	62	128	95
2017	56	76	157	116
2018	63	90	184	134
2019	68	103	211	151
2020	72	116	236	166
2021	75	128	259	180

Table 4.4-continued.

2022	78	139	282	193
2023	81	151	303	204
2024	83	161	324	215
2025	85	172	343	224
2026	87	181	361	232
2027	89	191	379	240
2028	90	200	396	247
2029	92	209	411	253
2030	93	217	427	259
2031	94	225	441	264
2032	95	233	455	269
2033	96	241	468	273
2034	97	248	480	277
2035	98	255	492	281
2036	99	261	503	284
2037	100	268	513	287
2038	80	257	488	289
2039	66	247	465	292
2040	56	237	442	294
2041	48	228	420	296
2042	42	219	400	298
2043	38	211	380	299
2044	34	202	362	301
2045	31	194	344	302
2046	28	187	327	303
2047	26	179	311	304
2048	24	172	296	276
2049	22	166	282	250
2050	20	159	268	227
2051	19	153	255	206
2052	18	147	243	186
2053	16	141	231	169
2054	15	136	219	153
2055	14	130	209	139
2056	13	125	199	126

Table 4.4-continued.

2057	12	120	189	114
2058	12	116	180	103
2059	11	111	171	94
2060	10	107	163	85
2061	9	103	155	77
2062	9	98	147	70
2063	8	95	140	63
2064	8	91	133	57
2065	7	87	127	52
2066	7	84	120	47
2067	6	81	115	43
2068	6	77	109	39
2069	5	74	104	35
2070	5	72	99	32
2071	5	69	94	29
2072	4	66	89	26
2073	4	63	85	24
2074	4	61	81	22
2075	4	59	77	20
2076	3	56	73	18
2077	3	54	69	16
2078	3	52	66	15
2079	3	50	63	13
2080	2	48	60	12
2081	2	46	57	11
2082	2	44	54	10
2083	2	43	51	9
2084	2	41	49	8
2085	2	39	47	7

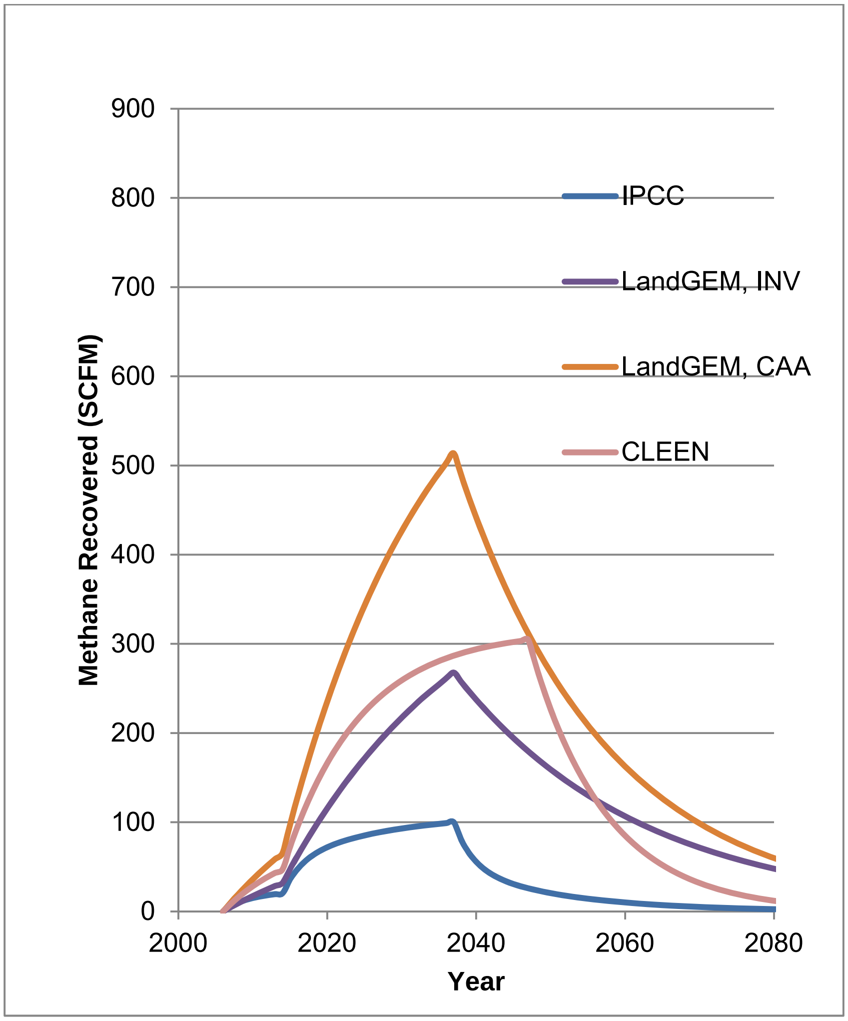

Figure 4.4 Temale Bioreactor Operation without Waste Addition Methane Recovery

Temale Bioreactor Operation with Waste Addition

As discussed earlier unlike Tema, Temale waste acceptance is continued until 2036. Therefore, the perpetual landfill operation is not considered. Table 4.5 & Figure 4.5 represent potential methane recovery estimates under bioreactor operation from three models. The inputs used for modeling are shown in Table 3.8.

Table 4.5 Temale Bioreactor with Waste Addition Operation Methane Recovery

Year	IPCC	LandGEM
	SCFM	SCFM
2006	0	0
2007	14	58
2008	24	88
2009	32	102
2010	38	109
2011	42	113
2012	46	114
2013	49	115
2014	51	116
2015	90	269
2016	119	345
2017	140	383
2018	156	402
2019	169	411
2020	180	416
2021	189	418
2022	196	419
2023	202	420
2024	208	420
2025	301	784
2026	298	671
2027	298	615
2028	299	587
2029	302	573
2030	305	566
2031	308	563
2032	311	561
2033	344	680

Table 4.5-continued.

2034	345	642
2035	346	624
2036	348	614
2037	351	610
2038	302	396
2039	268	289
2040	243	237
2041	235	250
2042	220	225
2043	209	212
2044	200	206
2045	193	203
2046	171	131
2047	154	96
2048	141	78
2049	133	83
2050	124	74
2051	117	70
2052	111	68
2053	106	67
2054	95	43
2055	87	32
2056	80	26
2057	75	27
2058	70	24
2059	66	23
2060	62	22
2061	59	22
2062	53	22
2063	48	22
2064	44	22
2065	40	22
2066	37	22
2067	34	22
2068	32	22

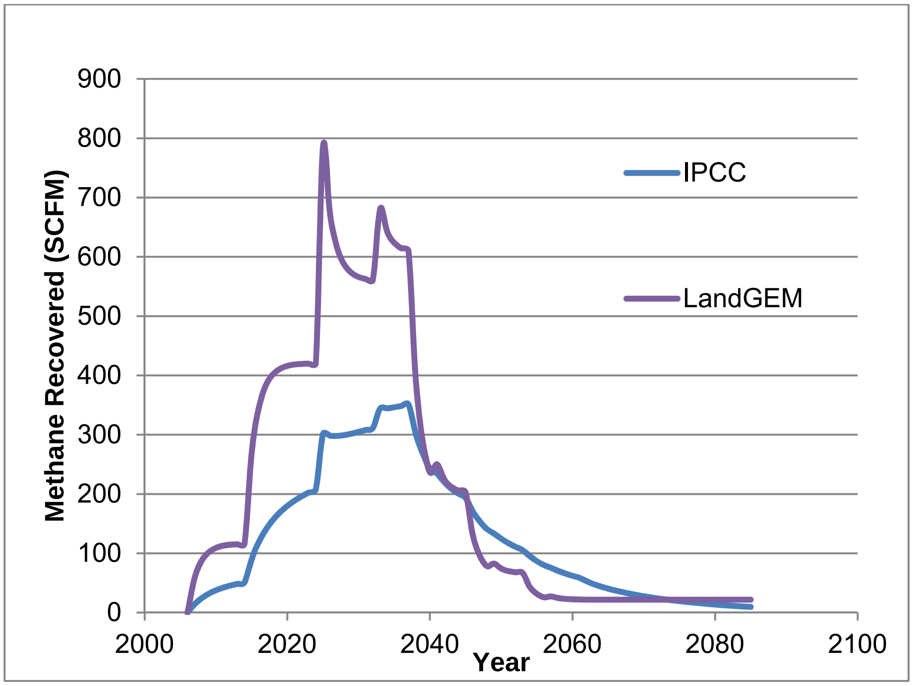

Figure 4.5 Temale Bioreactor Operation with Waste Addition Methane Recovery

Table 4.6 compares the total amount of methane that can be recovered from Temale landfill until 2060, under conventional and bioreactor operations for IPCC and LandGEM model.

Table 4.6 Methane Recovery from Temale Until 2060

	Methane Recovered until 2060 (million SCF)		Methane Recovered until 2060 (million m^3)		Methane Recovered until 2060 (1000 tons)	
	IPCC	**LandGEM**	**IPCC**	**LandGEM**	**IPCC**	**LandGEM**
Conventional	1,391	42,411[1]	39	1201[1]	29	883[1]
Bioreactor	5,026	8,247	142	234	105	172

1.LandGEM Inventory

Same as Tema, bioreactor operation substantially increases LFG generation compared to conventional operation.

4.3 LFG Collection System Design

4.3.1 Flow Used for Design purposes

To size the LFG collection system, we needed to choose among gas estimates provided by the CLEEN, IPCC, and LandGEM models. In preliminary validation of the CLEEN model, LFG data from 2 conventional landfills in two developing countries, Argentina and Brazil, were available. A comparison between LFG modeling results and actual collected methane from landfills are illustrated in Figures 4.6 and 4.7.

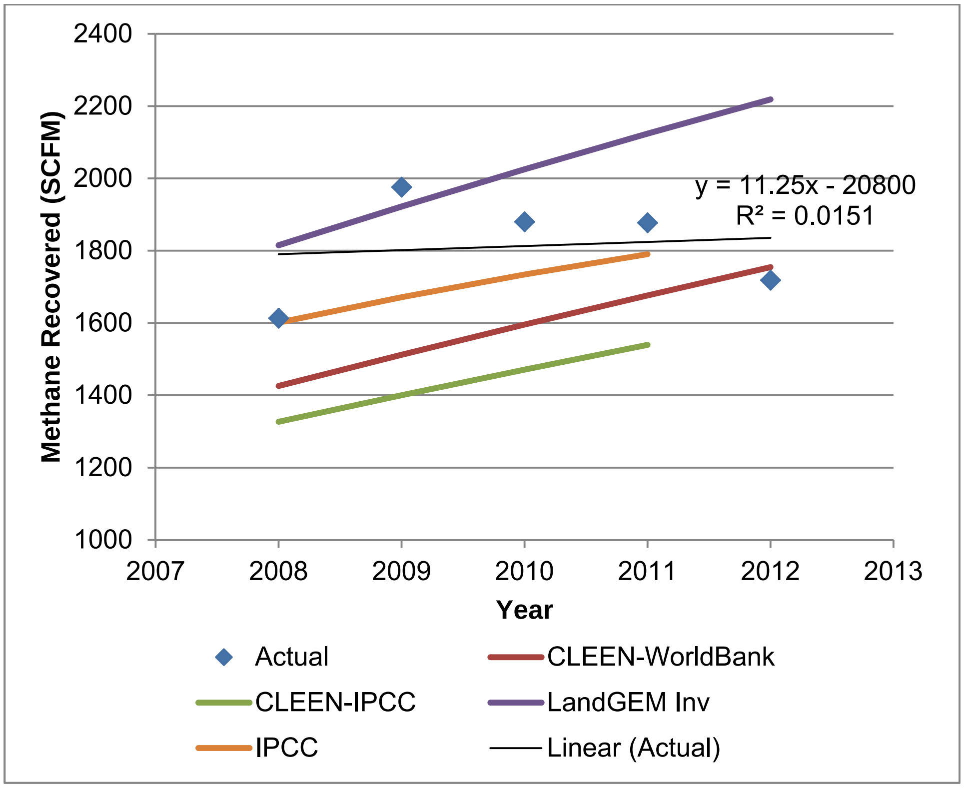

Figure 4.6 Argentina Actual Methane Recovery vs. LFG Modeling Results

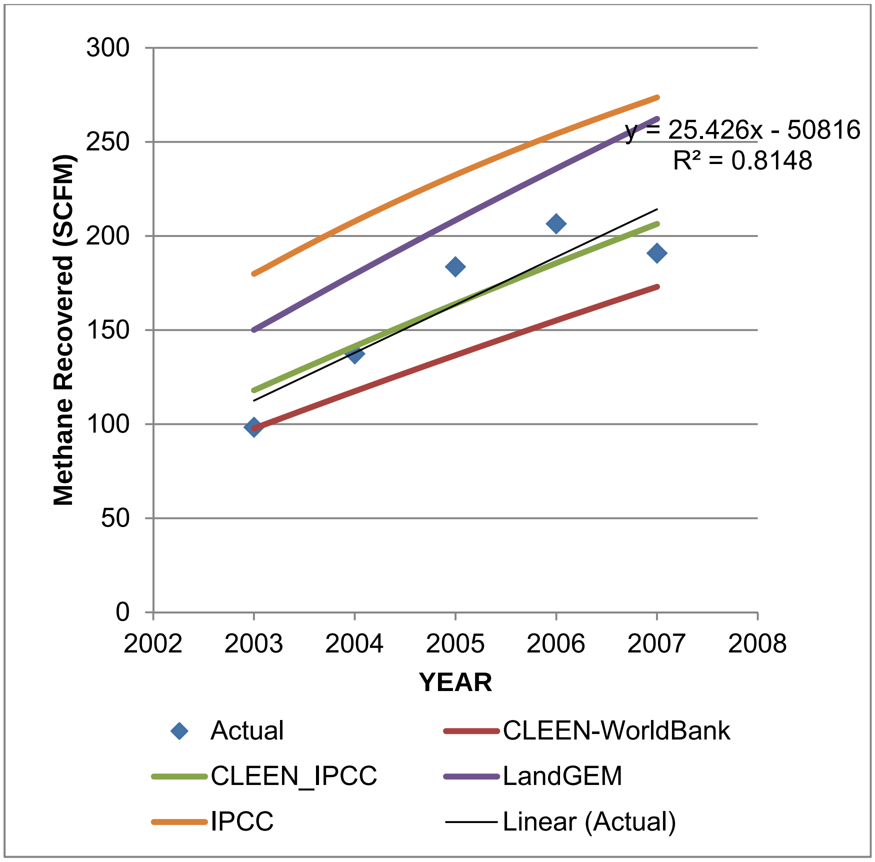

Figure 4.7 Brazil Actual Methane Recovery vs. LFG Modeling Results

For the Argentina landfill, the IPCC model produced LFG estimates closest to the actual, and for Brazil, the CLEEN model produced the closest estimates. However, to be conservative, we wanted to use estimates that exceeded actual. Also, CLEEN model validation is ongoing. Thus for sizing the LFG collection system, the methane recovery peak given by the LandGEM model, with inventory values for k and Lo , was used.

Data from bioreactor landfills was not available for CLEEN validation, thus comparison between model estimates and actual captured LFG was not feasible. Although LandGEM provides a default k value of 0.7 for modeling bioreactor landfills, LMOP recommends assigning a k value of 0.3 for bioreactors based on a study conducted by the University of Florida (EPA, 2005). IPCC, also recommends k value of 0.4 for rapidly degrading waste & 0.17 for bulk waste for moist and wet climate condition which sounds more reasonable. Therefore, results from IPCC were used for LFG collection system sizing for bioreactor operations.

4.3.2 Tema Conventional Operation LFG Collection System Design

A spreadsheet was developed for designing landfill gas collection systems. Table 4.7 shows LFG collection system design values for Tema, conventional landfill operation. Values for waste depth were based on projected filling of cells. Vertical well depth, borehole diameter, and screen depth, and well radius of influence were typical values according to Vesilind et al. (2002) and US Army Corps of Engineers (2008).

The LFG was assumed to be 50% methane, therefore the methane recovery rate (2015 value of 173 scfm) was doubled to give the LFG maximum flow rate (346 scfm). Vertical wells, header, main header & connectors design for Tema conventional operation are summarizes in Tables 4.7,4.8,4.9 & 4.10, respectively.

Table 4.7 LFG Collection Design Values for Vertical Wells for Tema Conventional

Vertical Wells					
	Defaults	SI Unit		US Unit	
Landfill Length		350	m	1148	ft
Landfill Width		300	m	984	ft
Waste Depth		20	m	65.6	ft
Vertical Well Depth		15	m	49.2	ft
Borehole	0.3 to 1 m	0.5	m	1.64	ft
Casing	HDPE or PVC	PVC			
Diameter	min. 100 mm (4 in)	100	mm	4	in
Screen	70%-80% of casing screened	11.25	m	36.9	ft
	Perforated with 15 mm holes spaced every 0.15 to 0.3 m	√			
	Slotted screen with 2.5+ mm slot size				
Gravel Pack	extend min 0.3 m above the end of screen	√			
Seal & Gout	Grout: 1.3 m bentonite plug on top of the gravel - Seal: 0.3 m fine sand between gravel pack and grout	√			
ROI	2 to 2.5 times well depth<50 m	30	m	98.4	ft

Table 4.7-continued.

CH_4 Generation	LandGEM Inv	4.90	m^3/min	173	ft^3/min
LFG Generation	LandGEM Inv	9.80	m^3/min	346	ft^3/min
Waste Density					
Waste Tonnage		912,500	ton		
Waste Volume		2,050,560	m^3	72,432,356	ft^3
CH_4 fraction		0.5			
Q_{well} (LFG)		0.27	m^3/min	9.54	ft^3/min
# Wells needed from flow calculation		36.3		36.3	
# Wells needed from flow calculation, rounded up to nearest whole number		37		37	
Well spacing		52	m	170	ft
# Wells needed from spacing standpoint		44		44	
# of Wells needed (greater #)		44		44	

Table 4.8 LFG Collection Design Values for Header

Header					
# wells connected		11			
Total Flow in Header		2.97	m^3/min	104.93	ft^3/min
#headers		4			
Total Flow Collected - all headers		11.9	m^3/min	419.7	ft^3/min
Header Diameter		15	cm	6	in
Header length		300	m	984	ft
Velocity		2.72	m/sec	8.9	ft/s
Material	HDPE or PVC	PVC			
Slope	2% on landfill in direction of gas flow		2%		2%

Table 4.9 LFG Collection Design Values for Main Header

Main header					
Flow		11.9	m^3/min	419.7	ft^3/min
Header Diameter		25	cm	10	in
Header length		360	m	1180.8	ft
Velocity			3.9 m/s	12.8	ft/s
Slope	2% on landfill in direction of gas flow	2	%	2	%

Table 4.10 LFG Collection Design Values for Connectors

Connectors					
Flow rate		0.27	m^3/min	9.54	ft^3/min
Diameter		100	mm	4	in
Length		22.5	m	73.8	ft
Slope	2% on landfill in direction of gas flow				

Figure 4.8 shows a layout for a landfill gas collection system for the Tema, which includes 4 * 6" diameter headers, each carrying gas flow from 11 vertical wells (44 vertical wells total). Unis are in meters.

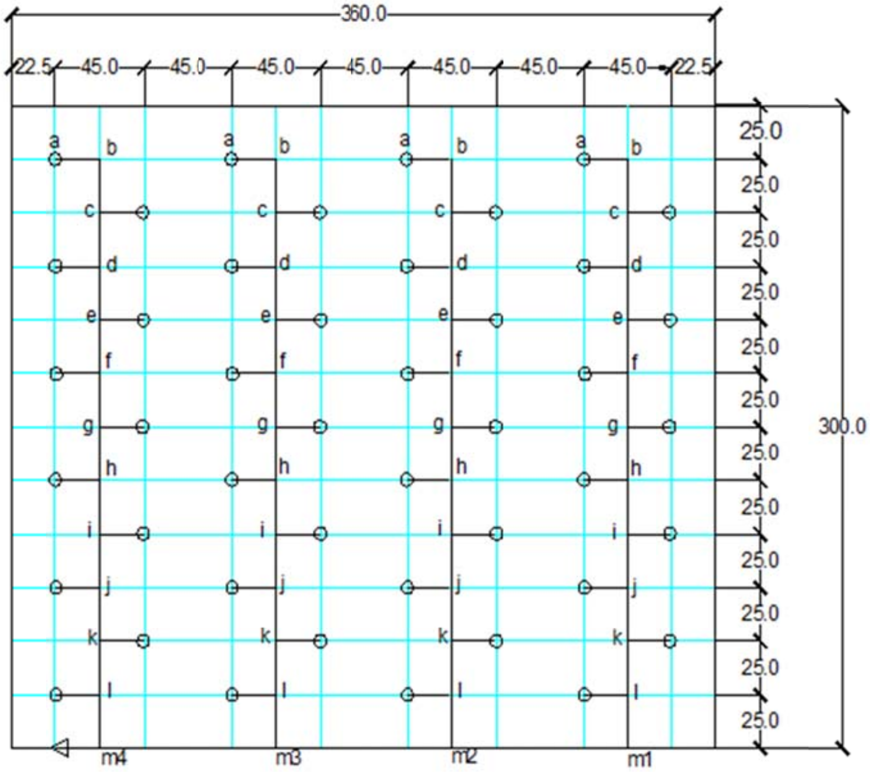

Figure 4.8 Tema LFG Collection Layout

Dividing the total LFG flow rate for the landfill (9.8 m^3/min) by the LFG flow rate per well (0.27 m^3/min) gives 37 for the number of wells needed. However, based on geometry of the landfill, 44 wells are needed, as shown in Figure 4.8, according to Bagchi (2004). The wells are spaced 50 m apart. The larger of the two numbers, 44 wells, is chosen. Since each well has a flow rate of 0.28 m^3/min, the total LFG flow rate that can be collected from landfill would be 0.27 m^3/min * 44 = 11.9 m^3/min.

The main header carries all LFG collected (11.9 m^3/min) to the utilization point. A standard main header diameter of 10” is chosen, which according to the continuity equation (Q = v * A) gives a velocity of 3.9 m/sec. The main header length is determined from the geometry of Figure 4.8.

From Figure 4.8, 4 headers are needed, each carrying gas flow from 11 wells, or ¼ of the total LFG flow rate (2.97 m^3/min). A standard header diameter of 6” is chosen, which according to the continuity equation (Q = v * A) gives a velocity of 2.72 m/sec. The header lengths are determined from the geometry of Figure 4.8.

For each header, 11 connectors are needed to connect the header with each of the 11 gas wells. A standard connector diameter of 4” is chosen, which according to the continuity equation (Q = v * A) gives a velocity of 0.6 m/sec. The connector length is determined from the geometry of Figure 4.8.

Head losses for the system are calculated as the sum of losses incurred due to pulling gas through the waste (Equation 3.5) as show in Table 4.11, within the radius of influence. Pipe wall friction losses and valve & fitting losses are summarized in Tables 4.12 & 4.13 respectively. 2 inches negative water column maintained for the system is also considered (Bagchi, 2004).

Table 4.11 Piping Head Loss Calculation

ROI (ft)	r(Borehole)(ft)	LFG Viscosity (lb.min/ft^2)	K_s (ft^2)	Waste Volume (ft^3)	G_{LFG}(ft^3/min)	ΔP_{well} (lb/ft^2)	in of w.c	# units	Total head lost (in. wc)
98.4	1.64	4.30E-09	1.59E-10	72432356	346	2.25	0.43	44	19.00

Table 4.12 Pipe Wall friction Losses

Unit	Flow (ft^3/min)	Pipe length (ft)	Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/100 ft)	Well head losses (in. wc)	# units	Total head lost (in. wc)
Vertical Well	9.54	49.2	4	109.31	0.01	0.00492	44	0.22
Header	104.93	984	6	534.40	0.1	0.984	4	3.94
Connectors	9.54	73.8	4	109.31	0.01	0.00738	44	0.32
Main Header	419.72	1180.8	10	769.54	0.1	1.1808	1	1.18

Table 4.13 Valve & Fittings

Unit	Flow (ft^3/min)	Equivalent Pipe length (ft)	Equivalent Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/100 ft)	Unit Losses (in. wc)	# units	Total head lost (in. wc)
Globe Valve	9.54	120	4	109.3	0.01	0.012	44	0.528
Tee (branch)	9.54	18	4	109.3	0.01	0.0018	44	0.0792
Tee (run)-Joint c	9.54	3.8	4	109.3	0.01	0.00038	4	0.00152
Tee (run)-Joint d	19.08	3.8	4	218.6	0.035	0.00133	4	0.00532
Tee (run)-Joint e	28.62	3.8	4	327.9	0.08	0.00304	4	0.01216
Tee (run)-Joint f	38.16	3.8	4	437.2	0.13	0.00494	4	0.01976
Tee (run)-Joint g	47.70	3.8	4	546.5	0.2	0.0076	4	0.0304
Tee (run)-Joint h	57.23	3.8	4	655.9	0.3	0.0114	4	0.0456
Tee (run)-Joint i	66.77	3.8	4	765.2	0.35	0.0133	4	0.0532
Tee (run)-Joint j	76.31	3.8	4	874.5	0.5	0.019	4	0.076
Tee (run)-Joint k	85.85	3.8	4	983.8	0.6	0.0228	4	0.0912

Table 4.13-continued.

Tee (run)-Joint l	95.39	3.8	4	1093.1	0.7	0.0266	4	0.1064
Tee (branch)-joint mi	104.93	18	6	534.4	0.1	0.018	4	0.072
Tee (run)-Joint m2	104.93	3.8	6	534.4	0.1	0.0038	1	0.0038
Tee (run)-Joint m3	209.86	3.8	6	1068.8	0.4	0.0152	1	0.0152
Tee (run)-Joint m4	314.79	3.8	6	1603.2	0.7	0.0266	1	0.0266
Total Pressure Loss (in. wc)			27.8					

Therefore, fan must thus be sized to provide a flow rate of 11.9 m^3/min and overcome a head loss of 27.8 inches water column. Table 4.14 shows characteristics of the blower which could be used.

Table 4.14 Blower Characteristics- Tuthill, M-D PLUS, model 3210

Blower Model	Speed (RMP)	Max. Vacuum			
		” Hg	” Water	FLOW(CFM)	BHP
3210	1150	9	128.6	42	3.1
	1759	12	171.4	87	6
	2950	15	214.3	197	12
	3600	15	214.3	270	15

The minimum flow would occur in 2060 which is 60 cfm and maximum flow is 354 cfm. Two blowers in series can be used.

4.3.3 Tema Bioreactor Operation LFG Collection System Design

Tema bioreactor operation scenario, was designed based on the peak LFG flow rate from IPCC model first scenario, which is 19.7 m^3/min. The collection system geometry and number of wells are kept the same as for the conventional operation scenario, as shown in Figure 4.8. Header and connector diameters are also kept the same. However, the gas flow rate doubles, as shown in Table 4.15 resulting in an increase in velocities and wall friction losses in the headers and connectors, as shown in Table 4.16.

Table 4.15 LFG Collection Design Values for Tema Bioreactor

Vertical Well					
	Defaults	SI Unit		US Unit	
Landfill Length		350	m	1148	ft
Landfill Width		300	m	984	ft
Waste Depth		20	m	65.6	ft
Vertical Well Depth		15	m	49.2	ft
Borehole	0.3 to 1 m	0.5	m	1.64	ft
Casing	HDPE or PVC	PVC			
Diameter	min. 100 mm (4 in)	100	mm	4	in
Screen	70%-80% of casing screened	11.25	m	36.9	ft
	Perforated with 15 mm holes spaced every 0.15 to 0.3 m	□			
	Slotted screen with 2.5+ mm slot size				
Gravel Pack	Extend min 0.3 m above the end of screen	□			
Seal & Gout	Grout: 1.3 m bentonite plug on top of the gravel - Seal: 0.3 m fine sand between gravel pack and grout	□			
ROI	2 to 2.5 times well depth<50 m	30	m	98.4	ft

Table 4.15-continued.

CH4 Generation	IPCC	9.74	m^3/min	344	ft3/min
LFG Generation	IPCC	19.48	m^3/min	688	ft3/min
Waste Density					
Waste Tonage		1,345,500	ton		
Waste Volume		2,050,560	m^3	72,432,356	ft^3
CH4 fraction		0.5			
Qwell (LFG)		0.54	m^3/min	18.97	ft^3/min
# Wells needed from flow calculation		36.3		36.3	
# Wells needed from flow calculation, rounded up to nearest whole number		37		37	
Well spacing	50 m used	52	m	170	ft
# Wells needed from spacing standpoint		44		44	
# of Wells needed (greater #)		44		44	

Table 4.15-continued.

Header					
# wells connected		11			
Total Flow in Header		5.91	m^3/min	208.65	ft^3/min
#headers		4			
Total Flow Collected - all headers		23.6	m^3/min	834.6	ft^3/min
Header Diameter		15	cm	6	in
Header length		300	m	984	ft
Velocity		5.40	m/sec	17.7	ft/s
Material	HDPE or PVC	PVC			
Slope	2% on landfill in direction of gas flow		2%		2%

Main header					
Flow		23.6	m^3/min	834.6	ft^3/min
Header Diameter		25	cm	10	in
Header length		360	m	1180.8	ft
Velocity				25.5	ft/s
Slope	2% on landfill in direction of gas flow	2	%	2	%

Table 4.15-continued.

Connectors					
Flow rate		0.54	m^3/min	18.97	ft^3/min
Diameter		100	`1	4	in
Length		22.5	m	73.8	ft
Slope	2% on landfill in direction of gas flow				

Table 4.16 Piping Head Loss Calculations

ROI (ft)	r(Borehole)(ft)	LFG Viscosity (lb.min/ft^2)	Ks (ft^2)	Waste Volume (ft^3)	G_{LFG}(ft^3/min)	ΔP_{well} (lb/ft^2)	in of w.c	# units	Total head lost (in. wc)
98.4	1.64	4.30E-09	1.59E-10	72432356	688	4.47	0.86	44	37.77

Pipe Wall friction Losses								
Unit	Flow (ft^3/min)	Pipe length (ft)	Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/100 ft)	Wellhead losses (in. wc)	# units	Total systel lost (in. wc)
Vertical Well	18.97	49.2	4	217.36	0.035	0.01722	44	0.76
Header	208.65	984	6	1062.63	0.47	4.6248	4	18.50
Connectors	18.97	73.8	4	217.36	0.035	0.02583	44	1.14
Main Header	834.58	1180.8	10	1530.18	0.4	4.7232	1	4.72

Table 4.16-continued.

Valve & Fittings								
Unit	Flow (ft^3/min)	Equivalent Pipe length (ft)	Equivalent Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/100 ft)	Unit Losses (in. wc)	# units	Total head lost (in. wc)
Globe Valve	18.97	120	4	217.4	0.035	0.042	44	1.848
Tee (branch)	18.97	18	4	217.4	0.035	0.0063	44	0.2772
Tee (run)-Joint c	18.97	3.8	4	217.4	0.035	0.00133	4	0.00532
Tee (run)-Joint d	37.94	3.8	4	434.7	0.13	0.00494	4	0.01976
Tee (run)-Joint e	56.90	3.8	4	652.1	0.2	0.0076	4	0.0304
Tee (run)-Joint f	75.87	3.8	4	869.4	0.45	0.0171	4	0.0684
Tee (run)-Joint g	94.84	3.8	4	1086.8	0.7	0.0266	4	0.1064
Tee (run)-Joint h	113.81	3.8	4	1304.1	0.8	0.0304	4	0.1216
Tee (run)-Joint i	132.77	3.8	4	1521.5	1.2	0.0456	4	0.1824
Tee (run)-Joint j	151.74	3.8	4	1738.8	1.5	0.057	4	0.228

Table 4.16-continued.

Tee (run)-Joint k	170.71	3.8	4	1956.2	1.75	0.0665	4	0.266	
Tee (run)-Joint l	189.68	3.8	4	2173.6	2.5	0.095	4	0.38	
Tee (branch)-joint mi	208.65	18	6	1062.6	0.35	0.063	4	0.252	
Tee (run)-Joint m2	208.65	3.8	6	1062.6	0.35	0.0133	1	0.0133	
Tee (run)-Joint m3	417.29	3.8	6	2125.3	1.3	0.0494	1	0.0494	
Tee (run)-Joint m4	625.94	3.8	6	3187.9	3	0.114	1	0.114	

Total Vacuum Needed (in. wc)	68.9

The fan must thus be sized to provide a flow rate of 23.6 m3/min and overcome a head loss of 68.9 inches water column. Table 4.14 shows characteristics of the blower which could be used.

The minimum flow would occur in 2060 which is 20 cfm and maximum flow is 688 cfm. Three blowers in series could be used.

4.3.4 Temale Bioreactor Operation without Waste Addition LFG Collection System Design

Design of the gas collection system for Temale was done in a similar way to that for Tema. Based on geometry of the landfill, only 14 vertical wells are needed, as shown in 4.9, resulting in 2* 6 inches diameter headers, each with 7 4 inches wells connected and a main header of 10 inches diameter. Table 4.17 summarizes the design of different unites of gas collection system for Temale landfill under Bioreactor Operation without Waste Addition operation.

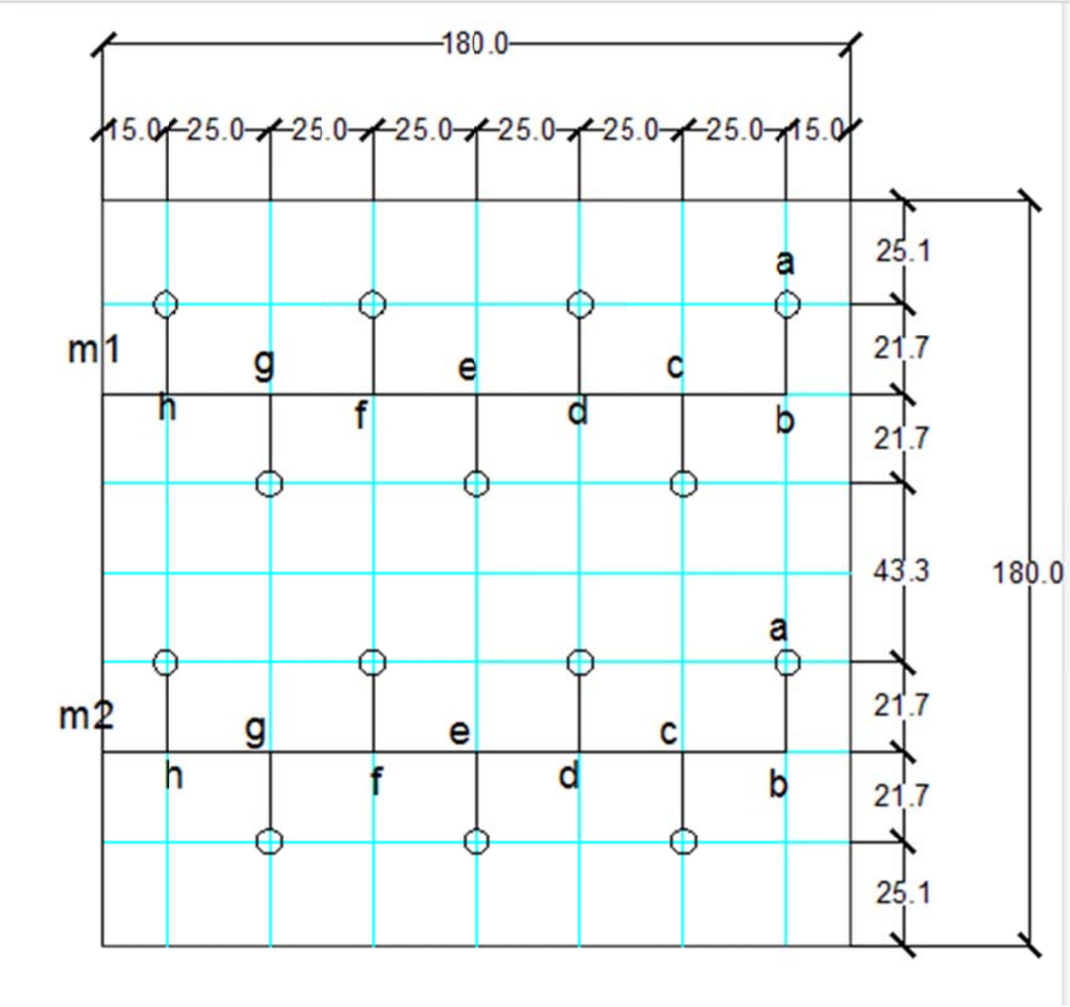

Figure 4.9 Temale LFG Collection Layout

Table 4.17 Temale Gas Collection System Design – Bioreactor Operation without Waste Addition

Parameter	Default Values	SI Unit		US Unit	
Landfill Length		180	m	590.4	ft
Landfill Width		180	m	590.4	ft
Waste Depth		20	m	65.6	ft
Vertical Well Depth		15	m	49.2	ft
Borehole	0.3 to 1 m	0.5	m	1.64	ft
Casing	HDPE or PVC	PVC			
Diameter	min. 100 mm (4 in)	100	mm	4	in
Screen	70%-80% of casing screened	11.25	m	36.9	ft
ROI	2 to 2.5 times well depth<50 m	30	m	98.4	ft
CH4 Generation	LandGEM Inventory	7.58	m^3/min	267.7	ft^3/min
LFG Generation	LandGEM Inventory	15.16	m^3/min	535.4	ft^3/min
Waste Density					
Waste Tonnage		2,116,435	ton		
Waste Volume		617,580	m3	21,814,906	ft3
CH4 fraction		0.5			
Qwell (LFG)		1.39	m^3/min	49.01	ft3/min
# Wells needed from flow calculation		10.9		10.9	
# Wells needed from flow calculation, rounded up to nearest whole number		11		11	
Well spacing	52	used:50	m	170	ft

Table 4.17-continued.

# Wells needed from spacing standpoint		14		14	
		14		14	
Header					
# wells connected		7			
Total Flow in Header		9.71	m^3/min	343.07	ft^3/min
#headers		2			
Total Flow Collected - all headers		19.4	m^3/min	686.1	ft^3/min
Header Diameter		15	cm	6	in
Header length		165	m	541.2	ft
Velocity		8.88	m/sec	29.1	ft/s
Material	HDPE or PVC	PVC			
Slope	2% on landfill in direction of gas flow		2%		2%
Main Header					
Flow		19.4	m^3/min	686.1	ft^3/min
Header Diameter		25	cm	10	in
Header length		150	m	492	ft
Velocity				21.0	ft/s
Slope	2% on landfill in direction of gas flow	2	%	2	%

Table 4.17-continued.

Connectors					
Flow rate		1.39	m^3/min	49.01	ft^3/min
Diameter		100	mm	4	in
Length		21.65	m	71.01	ft
Slope	2% on landfill in direction of gas flow				

Table 4.18 summarizes the head losses in the system

Table 4.18 Temale Gas Collection System Head Losses – Bioreactor Operation without Waste Addition

Piping Head Loss Calculation									
ROI (ft)	R Borehole (ft)	LFG Viscosity (lb.min/ ft^2)	Ks (ft^2)	Waste Volume (ft^3)	G_{LFG} (ft^3/min)	ΔP_{well} (lb/ft^2)	in of w.c	# units	Total system loss (in. wc)
98.4	1.64	4.30E-09	1.59E-10	21,814,906	535.4	11.55	2.22	14	31.05

Pipe Wall Friction Losses								
Unit	Flow (ft3/ min)	Pipe length (ft)	Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/ 100 ft)	Wellhead losses (in. wc)	# units	Total system loss (in. wc)
Vertical Well	49.01	49.2	4	561.62	0.2	0.0984	14	1.38
Header	343.07	541.2	6	1747.25	0.75	4.059	2	8.12
Connectors	49.01	71.0	4	561.62	0.2	0.142	14	1.99
Main Header	686.14	492	10	1258.02	0.275	1.353	1	1.35

Table 4.18-continued.

Valve & Fitting Friction Losses

Unit	Flow (ft^3/min)	Equivalent Pipe length (ft)	Equivalent Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/ 100 ft)	Unit Losses (in. wc)	# units	Total system loss (in. wc)
Globe Valve	49.01	120	4	561.6	0.2	0.24	14	3.36
Tee (branch)	49.01	18	4	561.6	0.2	0.036	7	0.252
Tee (run)-Joint c	49.01	3.8	4	561.6	0.2	0.0076	2	0.0152
Tee (run)-Joint d	98.02	3.8	4	1123.2	0.7	0.0266	2	0.0532
Tee (run)-Joint e	147.03	3.8	4	1684.8	1.5	0.057	2	0.114
Tee (run)-Joint f	196.04	3.8	4	2246.5	2.75	0.1045	2	0.209
Tee (run)-Joint g	245.05	3.8	4	2808.1	4	0.152	2	0.304
Tee (run)-Joint h	294.06	3.8	4	3369.7	6	0.228	2	0.456
Tee (branch)-joint mi	343.07	18	6	1747.2	0.9	0.162	2	0.324
Tee (run)-Joint m2	343.07	3.8	6	1747.2	0.9	0.0342	1	0.0342

Total Vacuum Needed (in. wc)	51.01

The fan must thus be sized to provide a flow rate of 19.4 m^3/min and overcome a head loss of 51 inches water column, as shown in Table 4.14.

The minimum flow would occur in 2085 which is 80 cfm and maximum flow is 535 cfm. Two or three blowers in series can be used.

4.3.5 Temale Bioreactor Operation with Waste Addition LFG Collection System Design

Temale bioreactor operation scenario, was designed based on the peak LFG flow rate from IPCC model, which is 19.9 m^3/min. The collection system geometry and number of wells are kept the same as for the conventional operation scenario, as shown in Figure 4.9. Table 4.19 shows the gas collection system design for Temale bioreactor operation in which header and connector diameters are kept the same as conventional.However, the gas flow rate doubles, as shown in resulting in an increase in velocities and wall friction losses in the headers and connectors, as shown in Table 4.20.

Table 4.19 Temale Gas Collection System Design – Bioreactor Operation with Waste Addition

Vertical Well					
	Defaults	SI Unit		US Unit	
Landfill Length		180	m	590.4	ft
Landfill Width		180	m	590.4	ft
Waste Depth		20	m	65.6	ft
Vertical Well Depth		15	m	49.2	ft
Borehole	0.3 to 1 m	0.5	m	1.64	ft
Casing	HDPE or PVC	PVC			
Diameter	min. 100 mm (4 in)	100	mm	4	in
Screen	70%-80% of casing screened	11.25	m	36.9	ft
	Perforated with 15 mm holes spaced every 0.15 to 0.3 m	☐			
	Slotted screen with 2.5+ mm slot size				
Gravel Pack	extend min 0.3 m above the end of screen	☐			
Seal & Gout	Grout: 1.3 m bentonite plug on top of the gravel - Seal: 0.3 m fine sand between gravel pack and grout	☐			

Table 4.19-continued.

ROI	2 to 2.5 times well depth<50 m	30	m	98.4	ft
CH4 Generation	IPCC	9.94	m^3/min	351	ft^3/min
LFG Generation	IPCC	19.9	m^3/min	702	ft^3/min
Waste Density					
Waste Tonnage		3,143,600	ton		
Waste Volume		617,580	m^3	21,814,906	ft^3
CH4 fraction		0.5			
Qwell (LFG)		1.82	m^3/min	64.26	ft^3/min
# Wells needed from flow calculation		10.9		10.9	
# Wells needed from flow calculation, rounded up to nearest whole number		11		11	
Well spacing	52	used:50	m	170	ft
# Wells needed from spacing standpoint		14		14	
# of Wells needed (greater #)		14		14	

Table 4.19-continued.

Header					
# wells connected		7			
Total Flow in Header		12.73	m^3/min	449.83	ft^3/min
#headers		2			
Total Flow Collected - all headers		25.5	m^3/min	899.7	ft^3/min
Header Diameter		15	cm	6	in
Header length		165	m	541.2	ft
Velocity		11.64	m/sec	38.2	ft/s
Material	HDPE or PVC	PVC			
Slope	2% on landfill in direction of gas flow		2%		2%
Main header					
Flow		25.5	m^3/min	899.7	ft^3/min
Header Diameter		25	cm	10	in
Header length		150	m	492	ft
Velocity				27.5	ft/s
Slope	2% on landfill in direction of gas flow	2	%	2	%

Table 4.19-continued.

Connectors					
Flow rate		1.82	m^3/min	64.26	ft^3/min
Diameter		100	mm	4	in
Length		21.65	m	71.01	ft
Slope	2% on landfill in direction of gas flow				

Table 4.20 Temale Gas Collection System Head Losses – Bioreactor Operation with Waste Addition

ROI (ft)	r(Borehole)(ft)	LFG Viscosity (lb.min/ft^2)	Ks (ft^2)	Waste Volume (ft^3)	G_{LFG} (ft^3/min)	ΔP_{well} (lb/ft^2)	in of w.c	# units
98.4	1.64	4.30E-09	1.59E-10	21814906	702	15.15	2.91	14

Pipe Wall friction Losses

Unit	Flow (ft3/min)	Pipe length (ft)	Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/100 ft)	Well head losses (in. wc)	# units	Total head lost (in. wc)
Vertical Well	64.26	49.2	4	736.37	0.3	0.1476	14	2.07
Header	449.83	541.2	6	2290.94	1.5	8.118	2	16.24
Connectors	64.26	71.01	4	736.37	0.3	0.213036	14	2.98
Main Header	899.65	492	10	1649.48	0.4	1.968	1	1.97

Table 4.20-continued.

Valve & Fittings								
Unit	Flow (ft^3/min)	Equivalent Pipe length (ft)	Equivalent Pipe Diameter (in)	Velocity (ft/min)	Friction Loss (in of w.c/100 ft)	Unit Losses (in. wc)	# units	Total systel lost (in. wc)
Globe Valve	64.26	120	4	736.4	0.3	0.36	14	5.04
Tee (branch)	64.26	18	6	327.3	0.035	0.0063	7	0.0441
Tee (run)-Joint c	64.26	3.8	6	327.3	0.035	0.00133	2	0.00266
Tee (run)-Joint d	128.52	3.8	6	654.6	0.14	0.00532	2	0.01064
Tee (run)-Joint e	192.78	3.8	6	981.8	0.3	0.0114	2	0.0228
Tee (run)-Joint f	257.04	3.8	6	1309.1	0.5	0.019	2	0.038
Tee (run)-Joint g	321.30	3.8	6	1636.4	0.9	0.0342	2	0.0684
Tee (run)-Joint h	385.56	3.8	6	1963.7	1.7	0.0646	2	0.1292
Tee -joint mi	449.83	18	10	824.7	0.12	0.0216	2	0.0432
Tee -Joint m2	449.83	3.8	10	824.7	0.12	0.00456	1	0.00456

Total Pressure Loss (in. wc)	71.37

The fan must thus be sized to provide a flow rate of 25.5 m3/min and overcome a head loss of 71.4 inches water column. Table 14.4 shows characteristics of the blower which could be used.

The minimum flow would occur in 2085 which is 20 cfm and maximum flow is 702 cfm. Three blowers in series can be used.

4.4 Electricity Generation Potential

4.4.1 Tema Landfill

Electricity generation potential was estimated using LFG-cost Web and result are summarized in Table 4.21. Figure 4.10 shows electricity generation vs. time for conventional and bioreactor operations for Tema.

Table 4.21 Electricity Generation Potential for Tema Landfill

	Electricity Potential (million KWh per year)					
Operation	Conventional		Bioreactor 1		Bioreactor 2	
Year	Microturbine	Engine	Microturbine	Engine	Microturbine	Engine
2016	5.1	7.1	17.9	24.9	17.9	24.9
2017	4.9	6.8	15.1	21	15.1	21.0
2018	4.7	6.5	12.7	17.7	12.7	17.7
2019	4.5	6.3	10.7	15	10.7	15.0
2020	4.3	6	9.1	12.6	9.1	12.6
2021	4.2	5.8	7.6	10.7	7.6	10.7
2022	4	5.6	6.4	9	6.4	9.0
2023	3.8	5.3	5.4	7.6	5.4	7.6
2024	3.7	5.1	4.6	6.4	4.6	6.4
2025	3.5	4.9	12.1	16.9	11.4	15.9
2026	3.4	4.7	10.2	14.3	21.1	29.4
2027	3.3	4.6	8.6	12	17.9	24.9
2028	3.1	4.4	7.3	10.1	15.1	21.0
2029	3	4.2	6.1	8.6	12.7	17.7
2030	2.9	4	5.2	7.2	10.7	15.0

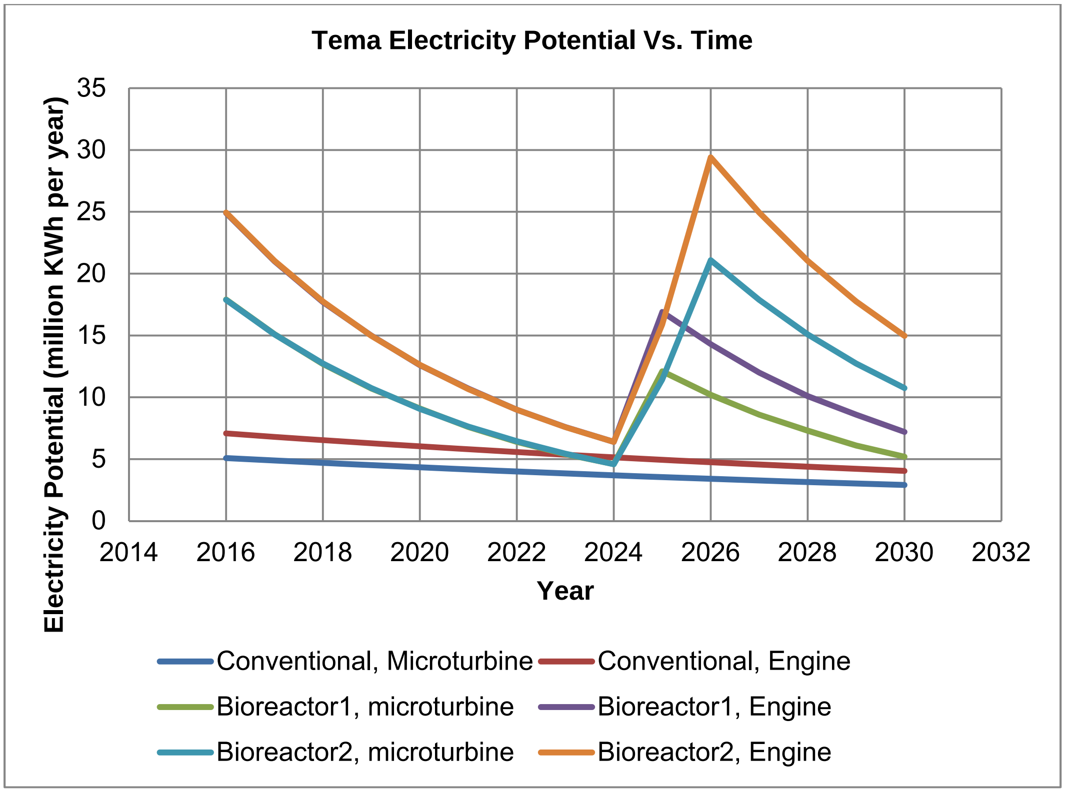

Figure 4.10 Tema Electricity Potential vs. Time

It can be concluded from the results that engines generate more electricity compared to microturbines. Regular turbines, direct use, and leachate evaporation were also examined, but did not have payback periods within 15 years.

Bioreactor operation substantially increases electricity generation potential, as expected. Engine did not have payback period within 15 years in bioreactor second scenario. The second peak in electricity generation for bioreactor operations , which occurs in 2025, is due to addition of new waste made possible by degradation of waste previously placed and perpetual landfill operation. The peak in 2025 for bioreactor second scenario is 2.2 times that of the first scenario, which is due to placing waste to the extent of the entire landfill capacity.

Annual electricity consumption in Ghana is about 2400 kWh per household. Table 4.22 shows number of households to which electricity would be provided based on the minimum and average electricity generation value between 2016 to 2030.

Table 4.22 Number of Households to be Provided with Electricity-Tema

	Conventional		Bioreactor 1		Bioreactor 2	
	Micro-turbine	Engine	Micro-turbine	Engine	Micro-turbine	Engine
Average Electricity Generation Between 2016-2030 (million KWh /yr)	3.9	5.4	9.3	12.9	11.9	16.6
# Households to which electricity would be provided based on Ave. values	1622	2258	3861	5389	4961	6916
Minimum Electricity Generation Between 2016-2030 (million KWh /yr)	2.9	4	4.6	6.4	4.5899	6.4
# Households to which electricity would be provided based on Min. values	1208	1667	1917	2667	1912	2667

4.4.2 Temale Landfill

Table 4.22 and Figure 4.11 represent the annual electricity generation potential for Temale landfill for different project types and landfill operations.

Table 4.23 Electricity Generation Potential for Temale Landfill

	Electricity Potential (million KWh per year)			
Operation	Bioreactor without additional waste placement		Bioreactor with additional waste placement	
Year	CHP microturbine	Engine	CHP microturbine	Engine
2016	1.9	2.6	5.8	8.2
2017	2.3	3.2	7	9.8
2018	2.7	3.7	8	11.2
2019	3.1	4.3	8.9	12.4
2020	3.4	4.8	9.6	13.4
2021	3.8	5.3	10.2	14.2
2022	4.2	5.8	10.7	14.9
2023	4.5	6.3	11.1	15.5
2024	4.8	6.7	11.5	16
2025	5.1	7.1	15.4	21.5
2026	5.4	7.5	15.8	22.1
2027	5.7	7.9	16.1	22.5
2028	6	8.3	16.4	22.9
2029	6.2	8.7	16.7	23.2
2030	6.5	9.0	16.9	23.5

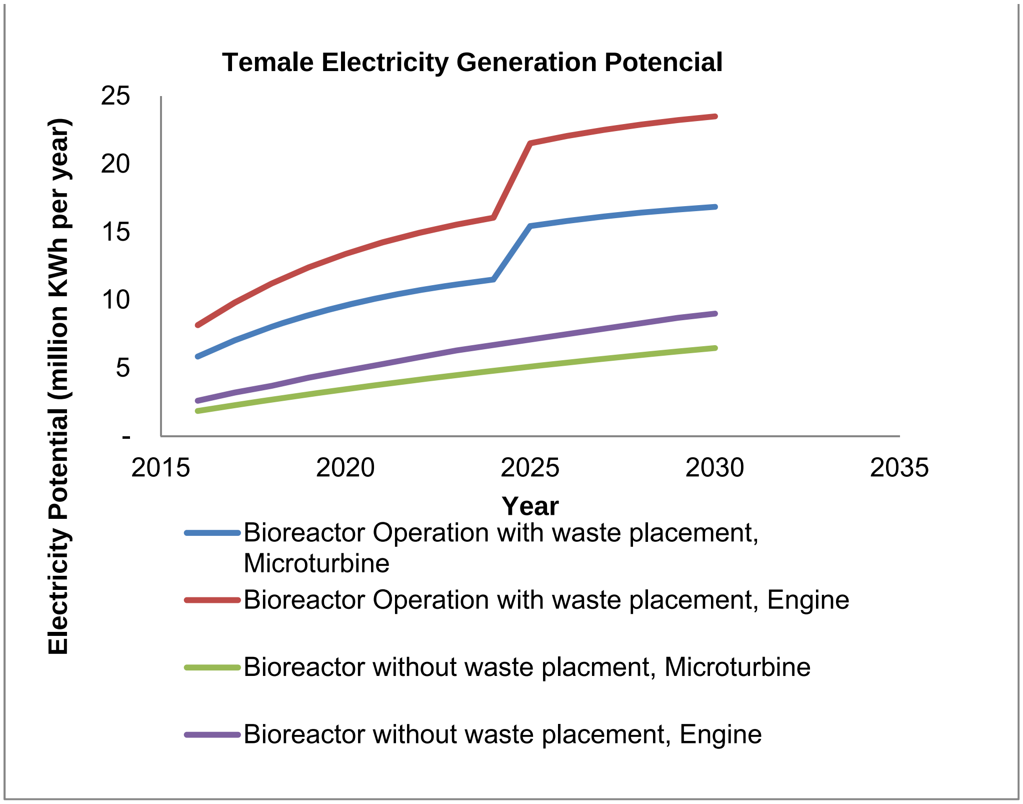

Figure 4.11 Temale Electricity Potential vs Time

Same as Tema, engines generate more electricity compared to microturbines and bioreactor operation substantially increases electricity generation. Engine did not have payback period within 15 years in conventional operation. Unlike Tema, Temale keeps accepting waste continuously within 15 years; thus the electricity potential increases versus time. The jump in electricity generation for bioreactor operation, which occurs in 2024, is due to addition of new waste made possible by degradation of waste.

Annual electricity consumption in Ghana is about 2400 kWh per household. Table 4.24 shows number of households to which electricity would be provided based on the minimum and average electricity generation value between 2016 to 2030.

Table 4.24 Number of Households to be Provided with Electricity-Temale

	Bioreactor without additional waste placement		Bioreactor with additional waste placement	
	CHP microturbine	Engine	CHP microturbine	Engine
Average Electricity Generation Between 2016-2030 (million KWh /yr)	4.4	6.1	12.0	16.8
# Households to which electricity would be provided based on Ave. Value	1822	2533	5003	6981
Minimum Electricity Generation Between 2016-2030 (million KWh /yr)	1.9	2.6	5.8	8.2
# Households to which electricity would be provided based on Min. Value	792	1083	2417	3417

4.5 Estimation of project costs

4.5.1 Tema Landfill

Tables 4.23, 4.24 & 4.25 summarize cost analyses results from LFGcost-WEB model for Tema conventional operation and bioreactor first & second scenarios, respectively. Regular turbines, direct use, and leachate evaporation were also examined, but did not have payback periods within 15 years.

Table 4.25 LFG-cost Web Outputs; Tema Landfill Conventional Operation

Project Type	Start Year	Interest Rate	% Down Pay-ment	No. of Wells	Net average annual electricity produced (kWh)	Average annual CHP hot water/ steam produced (million Btu)	Average methane utilized (MMTCO$_2$E /yr)	Average CO$_2$ from avoided energy generation (MMTCO$_2$E /yr)	Net present value at year of con-struction	Net present value payback year
CHP microturbine	2015	20	100	44	4,043,687	23,487	0.0272	0.0041	$244,465	10
		20	20						$171,281	11
		20	100	25					$601,846	6
		20	20						$537,805	5
		25	100						$207,595	9
		25	20						$107,780	11
	2016	20	100	44	3,894,100	22,587	0.0261	0.0039	$38,241	14
		25	100	25					$124,959	10
		25	20						$24,753	14
		20	100						$497,918	7
		20	20						$433,626	5
CHP Engine	2015	20	20	25	5,638,433	20,022	0.027	0.005	$424,373	7
			100						$512,748	8
	2016	20	20	25	5,429,853	20,023	0.0261	0.0048	$303,346	10
			100						$391,790	9

Table 4.26 LFG-cost Web Outputs; Tema Landfill Bioreactor Operation Scenario 1

LFG Model	Project Type	Start Year	Inter-est Rate	% Down Pay-ment	No. of Wells	Net annual electricity produced (kWh)	CHP hot water/ steam produced (million Btu)	Average methane utilized (MMTCO$_2$E /yr)	Average CO$_2$ from avoided energy generation (MMTCO$_2$E /yr)	Net present value at year of con-struction	Net present value payback year
Land-GEM	CHP micro-turbine	2016	25	20	44	9,235,960	53,567	0.062	0.0094	$1,829,352	2
				100						$2,035,131	3
			20	20						$2,961,194	2
				100						$3,093,222	3
			25	20	25					$2,263,021	2
				100						$2,450,569	3
			20	20						$3,432,568	1
				100						$3,552,899	3
	CHP Engine	2016	20	20	44	12,878,393	48,940	0.062	0.0114	$467,579	11
				100						$720,436	10
IPCC	CHP micro-turbine	2015	20	20	25	4,384,400	25,400	0.0294	0.0045	$237,322	11
				100						$303,870	10
	CHP engine			20		6,113,500	23,200	0.0294	0.0054	$264,100	11
				100						$350,324	10
	Engine			20		12,878,393	N/A	0.0294	0.0054	$168,863	13
				100				0.0294	0.0054	$377,108	11

Table 4.27 LFG-cost Web Outputs; Tema Landfill Bioreactor Operation Scenario 2

LFG Model	Project Type	Start Year	Interest Rate	% Down Payment	No. of Wells	Net average annual electricity produced (kWh)	CHP hot water/ steam produced (million Btu)	Average methane utilized ($MMTCO_2E$/yr)	Average CO_2 from avoided energy generation ($MMTCO_2E$/yr)	Net present value at year of construction	Net present value payback year
IPCC	CHP micro-turbine	2016	25	20	44	12,941,987	75,060	0.087	0.013	$1,872,936	2
			25	100	44					$2,113,415	4
			20	20	44					$3,386,654	2
			20	100	44					$3,540,945	4
			25	20	25					$2,306,604	2
			25	100	25					$2,528,852	4
			20	20	25					$3,858,028	2
			20	100	25					$4,000,622	3
		2015	25	20	44	13,487,340	78,220	0.091	0.014	$2,629,798	2
			25	100	44					$2,867,896	3
			20	20	44					$4,219,994	2
			20	100	44					$4,372,757	3
			25	20	25					$3,057,262	2
			25	100	25					$3,277,310	3
			20	20	25					$4,684,259	1
			20	100	25					$4,825,441	3

Table 4.27-continued.

	CHP Engine	2016	20	100	25	18,046,027	68,573	0.087	0.016	$120,553	15
		2015	20	20	44	18,806,460	71,460	0.091	0.017	$310,103	14
			20	100	44					$637,786	13
			20	20	25					$774,368	12
			20	100	25					$1,090,469	12
	Direct use	2015	25	100	44			0.088	0.011	$57,283	14
			20	20	44					$405,774	7
			20	100	44					$491,589	9
			25	20	25					$357,098	3
			25	100	25					$467,297	6
			20	20	25					$874,509	2
			20	100	25					$945,212	5
		2016	20	20	44			0.084	0.011	$59,131	14
			20	100	44					$163,245	13
			25	20	25					$58,634	13
			25	100	25					$177,315	11
			20	20	25					$551,304	5
			20	100	25					$624,431	8
IPCC	CHP Engine	2015	20	20	44	7,487,520	28,407	0.036	0.007	$104,588	14
			20	100	44					$216,091	12
			25	100	25					$53,149	14
			20	20	25					$568,853	8
			20	100	25					$668,775	8

Table 4.27-continued.

		2016	20	20	44	7,487,520	28,407	0.036	0.007	$67,937	14
			20	100	44					$180,556	13
			25	100	25					$28,508	15
			20	20	25					$539,311	9
			20	100	25					$640,233	9
	CHP Micro-turbine	2015	20	20	44	5,369,793	31,173	0.036	0.005	$173,890	12
			20	100	44					$259,268	11
			25	20	25					$94,261	12
			25	100	25					$209,282	10
			20	20	25					$638,155	6
			20	100	25					$711,952	7
		2016	20	20	44	5,369,793	31,173	0.036	0.005	$153,124	12
			20	100	44					$239,356	11
			25	20	25					$81,965	13
			25	100	25					$198,137	10
			20	20	25					$624,498	6
			20	100	25					$699,033	7

From Tables 4.23, 4.24 and 4.25, LFG-cost Web Outputs for Tema Landfill Conventional Operation, Bioreactor Scenario 1 and 2, the impact of various parameters (project start year, interest rate, percent down payment, number of wells, and project type on net present value and payback time) can be determined:

Impact of project start year: Comparing the 2015 and 2016 start dates, for the same project type (CHP microturbine), interest rate (20%), percent down payment (100%), and number of wells (25), the net present value is greater ($601,846 for conventional and $4,849,158 for bioreactor scenario 2) and payback year equal or lesser for a 2015 start date. This makes sense, since an earlier start-date allows gas generated during 2015 to be captured and utilized for energy production.

Impact of interest rate: Comparing 20% and 25% interest rates for the same project type, the 20% interest rate gives a greater net present value and lesser payback year since it presents less discount on the inflow cash value.

Impact of % down payment: Comparing 20% and 100% down payments for the same project type (CHP microturbine), start date (2015), interest rate (20%) and number of wells (25), the 100% down payment gives a greater net present value, however lesser payback year is achieved by 20% down payment. It is to be expected that a greater down payment would result in a higher net present value. However, payback time is adversely affected by the discount rate. Also a 100% down payment may not be feasible in reality.

Impact of number of wells: Comparing 25 and 44 wells for the same project type (CHP microturbine), start date (2015), interest rate (20%), percent down payment (100%), the net present value is greater and payback year lesser for 25 wells. This makes sense, because the capital cost associated with installing 25 wells is lower.

Impact of project type: Comparing project types (CHP microturbine, CHP engine and Direct use) for the same start date (2015), interest rate (20%), percent down payment (100%) and number of wells (25), the net present value is greater and payback year lesser for the CHP microturbine. The other project types examined did not produce a payback within 15 years. However, as shown in Section 4.4, electricity generation is greater for CHP engines compared to CHP microturbines. Therefore project type shall be determined by the objective of the project and importance of generation of electricity vs. economic benefits.

For bioreactor first scenario, two inputs for LFG generation from two separate models were considered. First model was LandGEM; the LFG-cost WEB estimates LFG generation with the same approach that LandGEM does but with this difference that unlike LandGEM users can enter “k” value in LFG-cost WEB. Second model was IPCC, in which averaged LFG estimates from IPCC over 15 years was used for all of the whole 15 years period in cost analyses. Results conclude that using LandGEM as LFG generation model gives greater net present values and lesser payback years. The reason could be due to the fact that LandGEM model estimates LFG generation annually where in IPCC approach, an average value is considered for the entire period. From this point of view LandGEM model seems more reasonable and IPCC model was not considered for rest of the bioreactor analyses.

Comparing Tema operated as a conventional and bioreactor landfill, the electricity generated is much greater over the 15 year period evaluated and payback times much shorter for the bioreactor landfill, as would be expected. Bioreactor operation causes waste to break down and gas to be generated more quickly, which usually benefits project economics.

Comparing the two scenarios for bioreactor, perpetual landfill (second scenario) has greater net present value and roughly same payback year as first scenario, for the same start date (2016). Perpetual landfill operation, with 2015 as the project start year will have payback periods within 15 years where, first scenario didn't. In perpetual landfill operation, comparing start dates (2015 &2016), 2015 will have greater net present values and lesser payback periods.

4.5.2 Temale Landfill

Tables 4.26 and 4.27 summarize cost analyses results from LFGcost-WEB model for Temale two operations.

Table 4.28 LFG-cost Web Outputs; Temale Landfill Bioreactor Operation without Waste Addition

Project Type	Start Year	Interest Rate	% Down Pay-ment	No. of Wells	Net annual electricity produced (kWh)	CHP hot water/ steam produced (million Btu)	Average methane utilized (MMTCO$_2$E /yr)	Average CO$_2$ from avoided energy generation (MMTCO$_2$E /yr)	Net present value at year of con-struction	Net present value payback year
CHP Microturbine	2016	20	20	14	4,363,340	25,320	0.0293	0.0044	$11,412	15
			100						$122,474	14

Table 4.29 LFG-cost Web Outputs: Temale Landfill Bioreactor Operation with Waste Addition

LFG Model	Project Type	Start Year	Inter-est Rate	% Down Pay-ment	No. of Wells	Net average annual electricity produced (kWh)	CHP hot water/ steam produced (million Btu)	Average methane utilized (MMTCO$_2$E /yr)	Average CO$_2$ from avoided energy generation (MMTCO$_2$E /yr)	Net present value at year of con-struction	Net present value payback year
LandGEM	CHP micro= turbine	2015	25	20	14	11,195,493	64,940	0.075	0.011	$914,415	9
			25	100						$1,103,023	8
			20	20						$2,242,274	6
			20	100						$2,350,581	7
		2016	25	20		12,022,967	69,740	0.081	0.012	$1,351,858	6
			25	100						$1,523,482	7
			20	20						$2,770,780	5
			20	100						$2,880,893	6
	CHP Engine	2015	20	100	14	15,610,753	59,320	0.075	0.014	$131,789	15
		2016	20	20		16,764,560	63,707	0.081	0.015	$309,040	14
			20	100						$620,772	13
	Engine	2016	20	100	14	16,764,560		0.081	0.011	$13,645	15
	Direct Use	2015	20	20	14			0.073	0.010	$131,955	13
			20	100						$231,027	12
		2016	20	20				0.078	0.010	$347,015	11

Table 4.29-continued.

IPCC	Engine	2015	25	100	14	9,249,433		0.045	0.006	$80,106	13
			20	20						$601,856	8
			20	100						$695,440	8
		2016	25	20		9,474,800		0.046	0.006	$50,310	14
			25	100						$197,740	11
			20	20						$725,442	7
			20	100						$820,033	8
	CHP Engine	2015	25	20	14	9,249,433	35,180	0.045	0.008	$326,309	10
			25	100						$495,098	9
			20	20						$1,214,855	6
			20	100						$1,321,249	7
		2016	25	20		9,474,800	36,040	0.046	0.008	$497,981	8
			25	100						$665,575	8
			20	20						$1,398,582	5
			20	100						$1,506,111	6
	CHP micro-turbine	2015	25	20	14	6,633,327	38,467	0.045	0.007	$751,059	5
			25	100						$861,327	6
			20	20						$1,494,886	4
			20	100						$1,565,634	5
		2016	25	20		6,794,947	39,407	0.046	0.007	$903,606	4
			25	100						$1,015,087	5
			20	20						$1,661,655	3
			20	100						$1,733,182	5

The only project type that had payback period within 15 years was microturbine with 2016 as project start date for Temale Bioreactor Operation without Waste Addition operation.

From Table 4.27, LFG-cost Web Outputs for Temale Landfill bioreactor with waste addition operation, the impact of various parameters (project start year, interest rate, percent down payment, number of wells, and project type on net present value and payback time) can be determined:

Impact of project start year: Comparing the 2015 and 2016 start dates, for the same project type (CHP microturbine), interest rate (20%), percent down payment (100%), the net present value is greater ($2,880,893) and payback year equal or lesser for a 2016 start date. This makes sense, because unlike Tema the landfill keeps accepting waste and the LFG generated from waste accumulated in previous years adds up.

Impact of interest rate: Comparing 20% and 25% interest rates for the same project type, the 20% interest rate gives a greater net present value and lesser payback year since it presents less discount on the inflow cash value.

Impact of % down payment: Same as Tema, It is to be expected that a greater down payment would result in a higher net present value. However, payback time is adversely affected by the discount rate. Also a 100% down payment may not be feasible in reality.

Impact of project type: Comparing project types (CHP microturbine, CHP engine and Direct use) for the same start date (2015), interest rate (20%), percent down payment (100%) , the net present value is greater and payback year lesser for the CHP microturbine. The other project types examined did not produce a payback within 15 years. However, as shown in Section 4.4, electricity generation is greater for CHP engines compared to CHP microturbines. Therefore project type shall be determined by the objective of the project and importance of generation of electricity vs. economic benefit.

Comparing Tema operated as a conventional and bioreactor landfill, the electricity generated is much greater over the 15 year period evaluated and payback times much shorter for the bioreactor landfill, as would be expected. Bioreactor operation causes waste to break down and gas to be generated more quickly, which usually benefits project economics.

Same as Tema, comparing Temale operated as a conventional and bioreactor landfill, the electricity generated is much greater over the 15 year period evaluated and payback times much shorter for the bioreactor landfill. Bioreactor operation causes waste to break down and gas to be generated more quickly as well as opening room for new waste placement , which usually benefits project economics.

4.6 Sustainability of LFG Energy Projects for Tema and Temale Landfills

Everything that humans need for their survival and well-being depends, directly or indirectly, on the natural environment . ‘‘Sustainability’’ and ‘‘sustainable” mean to create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations (Federal Register, 2009). The“three pillars” of sustainability are environmental, economic, and social. If any of the pillars is weak, then the system as a whole is not sustainable.

Environment

One of the important goals of sustainability is to reduce the rate of non-renewable resource consumption and to assure that consumption of renewable resources does not exceed their rates of natural regeneration (OECD, 2001).

The LFG to energy project for the two landfills, Tema and Temale, not only reduces GHG emissions directly (capturing methane) but also indirectly with energy offsets. The values of direct and indirect GHG emission reductions for different types of projects are provided in Tables 4.25 to 4.29.

Material flow is an important aspect of sustainability because increasing material consumption requires a greater demand on resources (water, energy, minerals, land, etc.) and larger quantities of pollutants and wastes. With perpetual landfill operation and mining, materials used to make non-degradable waste such as plastics and glasses can be sustained reused. From this stand point, bioreactor perpetual operation is both environmentally and economically sustainable.

As mentioned before, the entire country of Ghana has just 4 landfills. With bioreactor perpetual operation and LFG energy projects, solid waste decomposition can be enhanced and additional waste could be placed in landfills, which sustains a cleaner environment and mitigates the need to build new landfills or expand existing ones.

Economy

The revenue from electricity generation or direct use as summarized in Tables 4.25 to 4.29 makes Tema and Temale LFG energy projects sustainable.

LFG energy projects creates certain job opportunities during the project life cycle which involve engineers, construction firms, equipment vendors, utilities, and end users. From this standpoint, Tema and Temale LFG energy projects are both economically and socially sustainable.

Social

As summarized in Tables 4.22 and 4.24, the LFG to energy projects can provide between 1500 to 7000 households with electricity for each one of the Tema and Temale landfills.

Using LFG, a green power source, can be an effective way for local governments to demonstrate environmental leadership and enhance community awareness of the benefits of clean energy development.

Chapter 5

Conclusions and Recommendations

5.1 Summary

1. LandGEM with inventory inputs estimated peak methane recovery from Tema landfill, conventional operation to be 173 SCFM in 2015. Bioreactor operation first scenario gives 344 SCFM in 2015 based on results from IPCC. Bioreactor with perpetual landfill operation, however, gives 344 SCFM in 2015 and other peaks occur in 2025 (461 scfm), 2033 (506 scfm) and so on as the landfill accepts new waste.
2. The peak methane recovery from Temale landfill will occur in 2037, one year after landfill closure, which is 268 scfm for conventional operation and 351 scfm for bioreactor operation.
3. Bioreactor operation substantially increases the gas volume generated. Also, with perpetual landfill operation (2nd scenario in Tema landfill analyses), more LFG will be generated in the same life span compared to the first scenario.
4. Primary gas collection system design for Tema includes 44 vertical wells (4 inches diameter) which are connected to 4 headers (6 inches diameter) and 1 main header (10 inches diameter). For conventional operation the fan must be sized to provide a flow rate of 11.9 m^3/min and overcome a head loss of 27.8 inches water column. For bioreactor operation, flow is 23.6 m^3/min and head loss is 68.9 inches water column.
5. Primary gas collection system design for Temale includes 14 vertical wells (4 inches diameter each), 2 headers (6 inches each) and one main header (10 inches diameter. The fan must thus be sized to provide a flow rate of 19.4 m^3/min

and overcome a head loss of 51 inches water column for conventional operation and 25.5 m^3/min 71.4 inches water column for bioreactor operation, respectively.

6. For Tema conventional & bioreactor, CHP microturbine & CHP engine have payback back period within 15 years. With perpetual landfill operation (second scenario), direct use is also feasible. Comparing 2015 and 2016, the sooner the operation start year the more income and electricity potential. An engine produces more electricity than a microturbine, but the net present value is much greater with microturbine and payback year is lesser. Bioreactor operation has much greater net present value and lesser payback time than conventional operation. Perpetual landfill operation (second scenario) has greater net present value than first scenario bioreactor operation.
7. For Temale conventional operation CHP micro-turbine was just feasible. With bioreactor operation, CHP microturbine, CHP engine, engine & direct use had payback time within 15 years. Start year 2016 has more revenue than 2015. Starting LFG collection later is more favorable because landfill closure year conventionally is 2036 and there will be more waste accumulated and more LFG will be generated. Same as Tema, bioreactor operation has much greater electricity generation potential and net present value and lesser payback time. From economic stand point (greater net present value and lesser payback period), microturbine, engine & direct use are more favorable, respectively.

5.2 Conclusions

1. Implementation of LFG energy projects for the Tema and Temale landfills is economically feasible due to sufficient LFG generation potential,
2. LFG to energy projects for each of the landfills could provide 1500 to 7000 households with electricity, depending on project type and landfill operation.

3. Bioreactor perpetual operation is the most sustainable operation economically, environmentally and socially.

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5.3 Project Recommendations

Based on the feasibility study presented here, we recommend the following:

- Implementation of the Tema LFG energy system first, based on its greater electricity generation potential and more favorable economics, and Temale later.
- Operation of the Tema landfill as a bioreactor and perpetual landfill, to increase gas production and improve economic benefits.
- Installation of a microturbine at the Tema site operating as a bioreactor and perpetual landfill, to provide estimated average annual power of 13.2 million kWh, with an average payback time of 3 years. Initial capital cost would be $5.1 million, with average O&M costs of around $100,000.

5.4 Recommendations for Future Research

- Performing a more rigorous cost analysis specific to the region for a longer period of time.

Appendix A

Sample Collection Procedure

Preparation before Going to Field:

1. As Safety measures, take safety vests, hard hats, thick rubber gloves, and masks for each person going to the landfill. You might also need safety goggles if the day is supposed to be windy.
2. Take adequate amount of 30 gallon sized heavy duty plastic bags for sample collection. Always take extra bags in case the original ones get ruptured.
3. Take markers and tags for marking the bags after sampling.

During Sample Collection:

1. For your safety, never go within 10 ft. of heavy equipment. Also do not go near open pits, open boreholes and similar things.
2. For sample collection, in Landfill, randomly select a location from the working face of Landfill.
3. Using a backhoe scoop out municipal solid waste (MSW) from that location and spread it on a clean surface.
4. With the help of the backhoe, mix the waste very well so that the trash bags get torn up and the contents get mixed.
5. Using the backhoe quarter the sample.
6. Randomly select a quarter for sampling.
7. Fill 3 numbers of 30 gallon sized plastic bags or buckets with MSW from the selected quarter by grab sampling. Do not select what to take or what not to take. It should be unbiased.
8. Make sure each of the bags/ buckets are filled with at least 30 lbs (approximately 14 kg) of waste.

9. Secure the bags tightly so that no moisture loss can occur after sample collection.
10. Mark each bag for identification.
11. Following the similar procedure, select another random location for collecting next three bags. Repeat as necessary.
12. Sample a minimum of ten bags for one set of testing.

After Sample Collection:

1. Bring the collected samples to the laboratory.
2. If it is not possible to do all necessary tests within 1 day, you will need to store the samples below 38^{O} F (4^{O}C) in environmental growth chamber to preserve the initial properties.

Appendix B

Procedure for Determining Physical Composition

Background:

Municipal solid waste (MSW), also known as refuse trash, or garbage, refers to just about anything that are thrown away from residential, commercial, and institutional sources. It may not contain any hazardous, industrial, or construction & demolition wastes.

Percentages of waste within individual categories are important information for planning solid waste management programs. These include evaluation of recycling programs, quantification of degree of success of exclusion of banned items from waste stream, quality of waste to be used as feedstock to an incinerator, quantification of organics to evaluate biogas possibilities, etc.

The average nationwide physical composition of solid waste for the year 2007, as evaluated by U. S. Environmental Protection Agency (USEPA, 2008) is as follows: Paper (31%), Plastics (12%), Food scraps (12.7%), Rubber, leather & textile (7.9%), wood (6.6%), Yard trimmings (13.2%), Metals (8.4%), Glass (4.9%), Others (3.3%).

Apparatus Required:

- Large 10 ft. x 10 ft. Plastic Sheet
- Weighing Machine (Minimum 50 lbs. Capacity; Precision 0.005 lb.
- 1 Large Metal Bowl

Test Methodology:

1. On a Large Plastic sheet, empty one whole bag of MSW.
2. Manually sort the waste into different categories. The following ten categories are recommended: Paper, Plastic, Food Waste, Wood & Yard Waste, Textiles, Styrofoam & Sponge, Metals, Glass, Construction &

Demolition debris, and Others. Any type of paper including office paper, cardboard packaging, tissue, newspaper, disposable paper plates, etc should be sorted as ‘Paper’. PET bottles, soft plastic such as polyethylene, food wrappers, hard plastic toys, and also latex gloves and other rubbers can be sorted in the ‘Plastic’ category. ‘Wood & Yard waste’ category may contain branches, leaves, grass, garden trimmings, and also broken pieces of wood. Dresses, jeans, any fabrics and leather goods, cotton, wipes, etc. come under ‘Textiles’ group. All types of sponges, foams, insulation, to go boxes, etc should be sorted as ‘Styrofoam & Sponges’. Usually asbestos boards, chalk pieces, broken plaster, brick & stone chips, ceramic tiles etc come under ‘Construction & Demolition Waste’ Category. The ‘Others’ category accommodates soils, materials too small to manually sort, and all other small things which cannot fit into any other category.

3. Measure the weight of waste in each category separately and record them.

Appendix C

Procedure for Determining Moisture Content

Background:

Moisture Content is the quantity of water contained in a material on a volumetric or gravimetric basis.

Moisture content of MSW is highly important information when the landfill is operated as a bioreactor (enhanced leachate recirculation landfill). The value determines the expected level of decomposition and gas generation. Also it determines the additional amount of moisture to be recirculated to attain the optimum moisture content. The moisture content of municipal solid waste is also useful information for estimating heat content, landfill sizing and transport requirements.

For solid waste, moisture content is more commonly expressed as the percentage of wet weight of material.

- Apparatus Required:
- Large Metal Bowls
- Weighing Machine (Minimum 50 lbs Capacity; Precision 0.005 lb)
- Oven

Test Methodology:

1. Start the oven and set the temperature at 105 ^{O}C (221 ^{O}F).
2. Measure the Weight of the empty containers.
3. Before starting sorting, take out minimum 2 lbs. of waste by grabbing and without bias and put them in a bowl. Measure the weight.
4. Put the bowls in the oven at 105 ^{O}C and dry the wastes for 24 hrs.
5. After 18-24 hrs. measure the dry weights and calculate moisture content.

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