An estimation of bio-methane and energy project potentials of municipal solid waste using landfill gas emission and cost models

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Abstract

Purpose – The purpose of the study is to analyse municipal solid waste (MSW) disposed of in Jimeta-Yola metropolis for landfill gas (LFG), methane and project viability potential.

Design/methodology/approach – The data was collected daily from landfills for four weeks. About 7,329.55 Mg/year of waste was analysed. These waste were separated into bio-degradable components i.e. paper and textile (263.66 Mg), non-food organic (681.45 Mg), wood and straw (189.50 Mg) and food and kitchen waste (1797.20 Mg). Non-degradable components include plastics, polythene bags, metals, sand, stones, cans etc. (4397.73 Mg). The component's characteristics such as a number of samples, weight, volume, landfill age etc. were measured. The waste, methane (CH4) and energy potential were also analysed using LFG energy cost model.

Findings – The landfills received 15 Gg/year of MSW and emit 0.31 Gg/year of LFG having CH4 content of 82.95 Mg in 2016. These can produce 33.78 GWh of heat energy equivalent to 10.14 GWh of electricity analytically. Therefore, between 2016 and 2022, about 2.24 Gg CH4 and 5201.32 MWh of electricity were wasted. Henceforth, proper management of these waste substances can produce 186.4 Gg CH4 which will generate 432.52 GWh of electricity. The most economically viable project is an electricity project generating 418 kW/year at a sale price of $1.14/kWh (58.38/kWh) and a payback period of 11 years.

Practical implications – Raw LFG collected can be used in heating brick kilns, boilers, furnaces and greenhouses. When treated, the LFG can produce renewable natural gas (RNG), which is used in energy generation and various domestic, vehicle and industrial applications.

Social implications – The analytical energy generation can provide gross revenue of ₦19.46bn at an average of ₦192.71million/year. Using Landfill Gas Emissions Model (LandGEM) model, the gross and net revenue will be $0.42m and $0.28m yearly, respectively. The project can provide jobs and economic boost to the immediate community through associated ripple effect.

Originality/value – The research is a pre-feasibility study for LFG to gas or electricity projects in Jimeta-Yola. The study contributed to the body of knowledge as a source of literature for further studies locally and globally.

Keywords Electrical energy, Methane, Landfill gas, LandGEM model, Thermal energy

Paper type Research paper

1. Introduction

Landfill gas (LFG) is a natural by-product of the decomposition of organic material in anaerobic (without oxygen) conditions in landfills containing municipal solid waste (MSW) (Pearse *et al.*, 2020; EPA, 2021a). LFG contains roughly 50–55% CH_4 and 45–50% carbon dioxide (CO_2). It also contains less than 1% non-methane organic compounds (NMOCs) and a trace of inorganic compounds (Romero *et al.*, 2020; EPA, 2021a; Pant and Rai, 2021). CH_4 is a

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potent greenhouse gas (GHG) that is 28–36 times more effective at trapping heat in the atmosphere than CO_2 as reported in Singh *et al.* (2018) and EPA (2021a). MSW is the second major source of LFG after ruminant livestock with global emissions of about 94,000 Gg of CH_4 per year (Sohoo *et al.*, 2021). Pant and Rai (2021) and Precci Lopes *et al.* (2022) reported that the concept of generating CH_4 from more methanogenic bacteria natural process is gaining interest in recent years. These gases are an environmental burden which has to be controlled. However, the liability of LFG can be converted into assets, as it can be used for domestic and industrial applications, and for energy generation (Sohoo *et al.*, 2021).

To reduce these GHG emissions from MSW, different waste treatment technologies have been developed. These include waste composting technology reported by Sohoo *et al.* (2021) and Sanchez (2022), and LFG energy projects reported in EPA (2021a, c) and Huang and Fooladi (2021). The incineration process was also reported in Moharir *et al.* (2019), Gupta *et al.* (2022) and Sohoo *et al.* (2021). Anaerobic digestion is another important process of methane generation from MSW as reported by Caillet *et al.* (2019), Romero *et al.* (2020), Surendran and Shanmugam (2021) and Zhou *et al.* (2022). Al-Saadi and Nageswara Rao (2016), reported studies conducted on CH_4 generation from anaerobic digestion of water waste. The use of organic solid waste such as food, garden and animal manure for CH_4 generation was also reported by Pant and Rai (2021), Lucio Silva *et al.* (2021) and Wang *et al.* (2022). Jin *et al.* (2022) and Zhou *et al.* (2022) reported significant CH_4 generation from sludge waste. Therefore, several studies show that MSW can emit a significant quantity of LFG containing high calorific value CH_4 when subjected to anaerobic digestion.

According to Zuberi and Ali (2015), Sarptas (2016) and Sohoo *et al.* (2021), the energy content of LFG's CH_4 varies depending on the gas quality and generation process. The CH_4 heat content is approximately 26.882 MJ/m^3 or 37.50 MJ/kg and has a density of 0.717 kg/m^3. Islam *et al.* (2012) and Dzene *et al.* (2016) found that when 0.028 m^3 of biogas was burned, it yields about 2.52 kcal of heat energy per % CH_4 composition. If biogas is composed of 60% CH_4, it will yield 5,400 kcal/m^3. Therefore, the gas generated from biodigestion of MSW is a potential source of energy and revenue for landfill owners, local community and government.

LFG are usually purified using modern technology and converted to renewable natural gas (RNG). After this treatment, the RNG can be converted to electricity by a number of techniques which depend on RNG heat content and technology options. The conversion efficiency of 25–30% are usually obtained using gas, steam and micro turbines. While 28–40% are obtained, when internal combustion (IC) engines are used (Sarptas, 2016; EPA, 2021a, b). The use of LFG for generating energy (heat or electricity) is a promising approach both in terms of conserving valuable resources, reducing air pollution and reducing GHG emissions. It also helps in reducing air-borne and water-borne diseases, its associated climate change impact and the quantity of energy produced using fossil fuels and results in generating sustainable revenue (EPA, 2021a, c). According to Dzene *et al.* (2016) and Sohoo *et al.* (2021), an accurate estimation of CH_4 is important for the conduction of life cycle assessment (LCA) of waste to energy (WtE) pathways of landfills.

The importance of reducing GHG emission and air pollution from the decomposition of different organic components of waste had occupied most of the gathering around the world. The availability of un-managed and un-controlled dumpsites in Nigerian cities and communities has made the study significant. Current trend of benefiting from these resources is by converting the MSW into harnessable LFG. This is then purified to obtain RNG which can further be used for electricity generation, domestic and industrial applications. Therefore, there is a need for exploring various methods of estimating and harnessing these valuable resources. The aim of this study is to determine LFG, CH_4 and energy generation potentials of the studied landfills in the Jimeta metropolis using LFG emission model and also to determine the economic viability of the project using the LFG cost model.

2. Methodology

2.1 Waste location and data collection

The landfills are located along Jimeta bypass between *Doubeli* junction and Jimeta bridge in Yola North LGA in Adamawa State, Nigeria. The banned on non-official landfills usage by the authority in the town increases the volume of waste generated at the studied landfills. Thus, almost 50% of MSW from the city are taken to these sites, the remaining are found in drainages, smaller official and non-official landfills and others are taken to farms as manure (Orisakwa and Bakari, 2013). Specifically, the wastes are mainly generated from *Anguwan tana*, *Zango*, *Shunko* and *Doubeli* communities of *Limawa* and *Doubeli* ward and some parts of *Jimeta*. The study considered four landfills tagged landfill A, B, C and D. The types of wastes in the study area were composed of commercial, street, market and domestic wastes which were brought in a wheel barrow, buckets, polythene bags, pickup, etc.

A drum container of 0.2271 m^3 was used for daily waste collection. The waste disposed of was collected for seven days at each landfill and a total of 43 drums of MSW was obtained. The MSW collected daily was separated into five components, namely, (a) paper and textile and (b) garden, park and non-food organic waste (GPNFW). Other major components were (c) food and kitchen waste, (d) wood and straw and (e) others (i.e. plastics, polythene bags, metals, sand, small stones, cans, batteries, etc.). The weight of these compositions was measured in kilograms using weighing balance. Detailed process was described in IPCC (2006a) and Usman *et al.* (2022a, b). The average study area, the landfills, samples and MSW characteristics for the landfills considered were shown in Supplementary Table (Table S1).

2.2 LandGEM model

Landfill Gas Emissions Model (LandGEM) version 3.03 is a Microsoft Excel-based software for estimating LFG, CH_4 and CO_2 content of MSW. It is developed by the United State (US) Environmental Protection Agency (EPA) and landfill methane outreach program (LMOP). The software uses the first-order decay (FOD) rate equation. It also provides a relatively simple approach to estimating LFG emissions. Model defaults are developed based on empirical data from US landfills but field test data can also be used in place of model defaults data (EPA, 2020, 2021a).

LandGEM assumes that CH_4 generation is at its peak shortly after initial waste placement (after a short time lag while anaerobic conditions are established in the landfill). These will increase up to the time shortly after the landfill is closed. The model also assumes that the rate of landfill CH_4 generation will decrease exponentially as organic materials are consumed by bacteria (EPA, 2021a; IPCC, 2015). The description of this model can be seen in EPA (2020) and EPA (2021a). The model was used in reports of CPE (2010) and EESI (2017) and previous studies by Fallahizadeh *et al.* (2019), Dimiskovska *et al.* (2019) and Dimiskovska and Berisha (2021). Equation (1) shows the FOD model used in LandGEM version 3.03.

$$Q_{CH_4} = \sum_{t=1}^{n} \sum_{j=0.1}^{1} kL_0 \left[\frac{M_i}{10}\right] \left(e^{-kt_{ij}}\right) \tag{1}$$

where Q_{CH4} = annual CH_4 generation, i = 1-year time increment, n = (year of the calculation) − (initial year of waste acceptance), j = 0.1-year time increment, k = CH_4 generation rate (year^{-1}), L_0 = potential CH_4 generation capacity (m^3/Mg), M_i = mass of waste accepted in the ith year (Mg), t_{ij} = age of the jth section of waste mass M_i accepted in the ith year.

2.2.1 LandGEM model inputs. There are only three major variables of the FOD equation that are of greater importance when using LandGEM (i.e. M_i, L_0 and k) as can be seen from the introduction page shown in Supplementary File (Figure S1).

2.2.1.1 Annual waste disposal (M_i). This is the primary determinant of LFG generation in FOD-based model. The model does not adjust annual waste disposal estimates to account for waste composition. The adjustments are typically handled by adjusting L_0 value (EPA, 2020, 2021a).

2.2.1.2 Potential methane generation capacity (L_0). This describes the total quantity of CH_4 potentially produced by a metric ton of waste as it decays. EPA determined that the appropriate values for L_0 range from 56.6 to 198.2 m^3/Mg of waste. L_0 depends almost entirely on the type of waste present in the landfill, moisture and the dry and wet organic contents of the waste. LandGEM sets L_0 to a default value of 170 m^3/Mg to represent a conventional landfill (EPA, 2020, 2021a).

2.2.1.3 Methane generation rate constant (k). This describes the rate at which waste placed in a landfill decays to produce LFG. The k value is expressed in 1/year or yr^{-1}. At higher values of k, the CH_4 generation at a landfill increases more rapidly (as long as the landfill is still receiving waste). The generation declines more quickly after the landfill closes. The value of k is strongly a function of moisture content, nutrients for CH_4-generating bacteria, pH value and internal temperature of the landfill (30–60°C) (EPA, 2020, 2021a).

2.2.2 LandGEM model outputs. After the model inputs are entered, emission estimates can be viewed in tabular format on the "RESULTS" worksheet. The results include annual waste inputs data, waste-in-place and estimates of total LFG, CH_4, CO_2 and NMOC generation. The results also may be viewed graphically on the "GRAPHS" worksheet, which plots emission estimates by year (EPA, 2020, 2021a).

2.2.3 Model limitations. LandGEM is considered a screening tool, i.e. the better the input data, the better the estimates. Often, there are limitations with the available data regarding waste quantity and composition, variation in design and operating practices over time. Changes can occur over time and impact the emissions potential and landfill operation such as operating under wet conditions or other liquid additions. These changes will result in generating more gas at a faster rate (EPA, 2020, 2021a).

Accurate estimates for LFG recovery are critical to the proper design and financial success of LFG energy projects. LFG modelling requires proper consideration of factors that produce errors within a model. These are eliminated by using appropriate inputs to avoid significantly overestimating the amount of recoverable LFG. Factors affecting the accuracy of LFG recovery projections include as reported in EPA (2020, 2021a, b):

(1) In-accurate assumptions about variables such as organic content, future disposal rates, site closure dates, wellfield buildout, expansion schedules or collection efficiencies can result in large errors in predicting future gas recovery.

(2) Limited or poor-quality disposal data. A significant model error can be introduced if good disposal data are not available.

(3) Poor-quality flow data or inaccurate estimates of collection efficiency used for model calibration. Model calibration requires both accurate estimates of collection efficiency and good-quality flow data that are representative of long-term average recovery.

(4) A typical waste composition is often not available to determine if the unusual waste composition is a cause of model inaccuracy. However, the risk can be minimized by introducing sample collection procedures to better determine waste composition.

(5) Limitations due to the structure: for example, LandGEM cannot accommodate changes in k or L_0 values in the same model run. Changing landfill conditions that cannot be modelled as a result of this limitation include the application of liquids to existing waste, variations in waste composition over time and installation of a geo-membrane cover.

2.3 LFG applications options

The goal of an LFG energy project is to convert LFG into a useful form of energy (EPA, 2020, 2021a). The most common LFG applications include:

(1) Energy production: This includes electrical energy and combined heat and power (CHP) application. LFG extracted from the landfill is converted to electricity and the heat losses at the combustion chamber are collected for producing low-pressure steam (EPA, 2020, 2021a).

(2) Direct use of gas: Treated LFG is used as a direct source of fuel for heating greenhouses, firing brick kilns and providing fuel to chemical and automobile manufacturing businesses (EPA, 2020, 2021a).

(3) Upgrade to RNG: LFG is cleaned to produce the equivalent of natural gas which are usually compressed natural gas (CNG) or liquefied natural gas (LNG) (EPA, 2020, 2021a).

2.4 LFG-energy generation potential

There are several facilities using LFG as fuel for power production which includes gas engines, gas turbines and steam turbines. Among the gas engines, internal combustion engines occupy the market due to their low cost and high electrical efficiency (η_{el} = 30–40%). Even greater efficiencies are achieved in CHP applications. In CHP, waste heat is recovered from the engine cooling system to make hot water or from the engine exhaust to make low-pressure steam (Surroop and Mohee, 2011; EPA, 2021a). Simple-cycle gas turbines can typically achieve efficiencies of η_{el} = 20–28% at full load. However, these efficiencies drop substantially at partial load. Combined-cycle or CHP configurations can boost system efficiency to approximately 40%. For microturbines, the efficiency can also increase with the increase in turbine size (EPA, 2021a).

According to Surroop and Mohee (2011), Sarptas (2016) and Sohoo *et al.* (2021), gross thermal energy potential can be calculated based on the quantity of CH_4 and its heat content using equations (2) and (3). The net electrical energy potential can be calculated using equation (4) as reported by Surroop and Mohee (2011) and Sohoo *et al.* (2021). The economic viability between energy or RNG projects was determined using LFGCost-Web version 3.5 model (EPA, 2021a, b).

$$EP_{th} = \eta_{gc} \times EC \times G_t \tag{2}$$

$$EP_{th}(Wh) = EP_{th}(J) * Th_c \tag{3}$$

$$EP_{el} = EP_{th}(kWh) \times \eta_{el} \tag{4}$$

where EP_{th} is the thermal energy potential (kWh or kJ); η_{gc} is the gas collection efficiency; EC is the energy content (i.e. LHV) (kJ/m^3 or kJ/kg); G_t is the volume or mass of CH_4 identified by LFG modelling (kg or m^3); Th_c is the thermal energy conversion factor (275 Wh/J); EP_{el} is the electrical energy potential and η_{el} is the electrical conversion efficiency.

3. Results and discussion

3.1 Waste and methane potential

The values of the various factors and initial data for the landfills analyses and CH_4 recovery computation using LandGEM model are given in Table 1. Table S1 shows the array of waste and associated LFG potential of the landfills from 2015 to 2130 (expected the closing year of 2065). Figure 1 shows the variation of LFG, CH_4, CO_2 and NMOC over the years in Mg/year and the corresponding value in m^3/year is shown in Figure S2. Figure 2 shows a comparison between CH_4 potentials using IPCC default (Usman *et al.*, 2022a), IPCC FOD (Usman *et al.*, 2022b) and current study LandGEM models.

It is to be noted that the LandGEM model was designed based on empirical data from the US landfills; therefore, there are some limitations which must be expected from the results of

Table 1. Characteristics and model parameters for LandGEM model

Landfill characteristics and model parameters	Description
Landfill Open Year	2015
Landfill Closure Year (with 80-year limit)	2065
Actual Closure Year (without limit)	2065
Waste Design Capacity	Mega-grams
CH_4 Generation Rate, k	0.050 $year^{-1}$
Potential CH4 Generation Capacity, L_0	170 m^3/Mg
NMOC Concentration	4,000 ppmv as hexane
CH4 Content	50% by volume

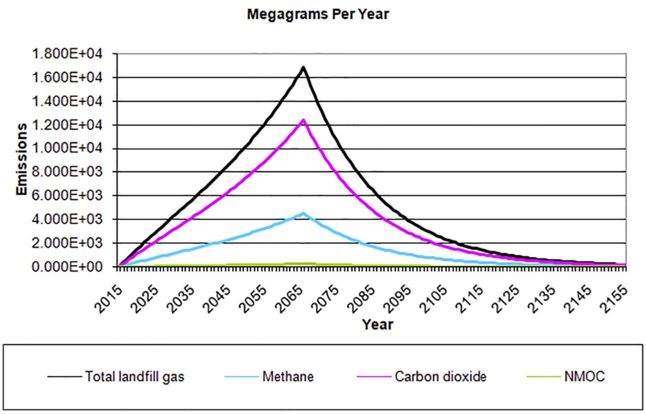

Figure 1. Variation of total LFG, CH_4, CO_2 and NMOC in Mg/yr

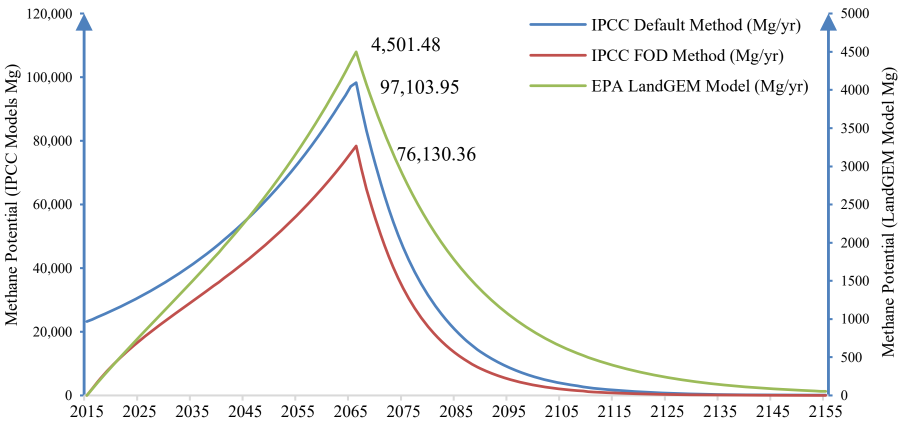

Figure 2. Comparison between CH_4 generating potential using various models

the model on Nigerian landfills. As expected, it could be observed from the results that the quantity of available gas in the sites, i.e. 310.64 Mg of LFG in 2016 will increases with time, reaching a maximum of 16.85 Gg of LFG in the year 2066. This LFG has a CH_4 content of 82.95 and 4501.48 Mg in 2016 and 2065, respectively. The available gas decreases exponentially with time to 196.81 Mg of LFG in 2165 which has about 52.57 Mg of CH_4. From 2016 to 2022, the economy loses about 8.39 Gg of LFG having 2.24 Gg of CH_4 which is emitted into the atmosphere increasing climate change impact. Furthermore, proper management of the landfill will yield about 697.86 Gg of LFG containing 186.41 Gg of CH_4 as can be seen in Figure 3. Cai *et al.* (2014) reported 700 Mg to 10 Gg when studying waste from different cities in China. Jigar *et al.* (2014) reported 7.11 Gg in 2003 to 9.98 Gg in 2012 when studying waste in Addis Ababa, Ethiopia. CPE (2010) studied different waste in *Afufunra* waste in Ibadan, Nigeria, and reported an increase from 30.92 Mg in 1998 to 500.69 Mg in 2014 and the emission reduces to 291.78 Mg in 2032. Similar variations are obtained in the same study while considering *Mpape*, *Ajakanja* and *Awotan* waste. Pearse *et al.* (2020) and Sohoo *et al.* (2021) reported similar results.

From Figure 2, the comparison show that IPCC model generate highest CH_4 gas of about 97 Gg of CH_4 in 2066 followed by IPCC FOD model with about 76 Gg. These models generate about 15–20 times, respectively, more than the generation using LandGEM model with about 5 Gg of CH_4. FOD method produces better estimates of annual emissions, as it takes into account the time factors of the degradation process and produces annual emission estimates that reflect these processes (IPCC, 2006b, c). The improvement from the IPCC model to the FOD model include the consideration of more important accurate variable leading to a lower quantity of CH_4 generation. The LandGEM is also an improve version of all the previously developed FOD models around the world which uses more specific data rather than estimates and assumptions. These reduce the uncertainties associated with IPCC default and IPCC FOD models as reported in IPCC (2006b, c) and IPCC (2015). Sarptas (2016), Singh *et al.* (2018), Trapani *et al.* (2018), Dimiskovska *et al.* (2019) and Romero *et al.* (2020) explore different models and found similar variations. The differences in trends with time are caused by the different estimation theories of the LFG models used in the previous studies.

3.2 LFG energy potential

3.2.1 Analytical LFG energy potential. The CH_4 generated can be used to compute the heat and electrical potentials using relations in equations (2)–(4). Standard IC engines with 30%

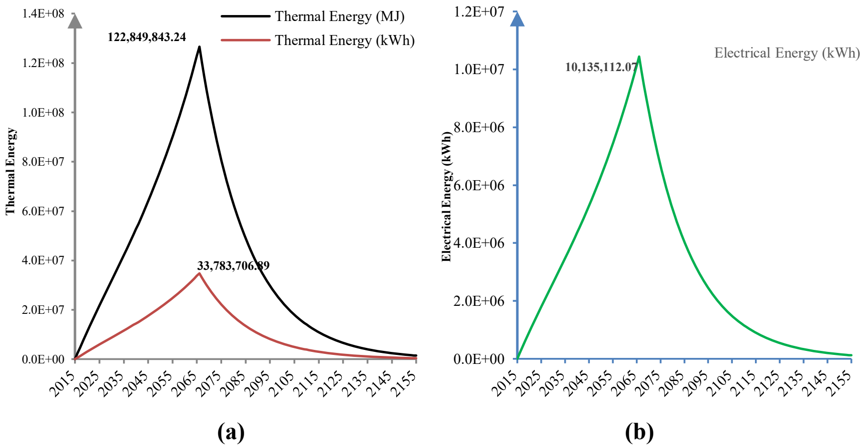

Figure 3. Variation of analytical (a) thermal energy potential (b) electrical energy potential

conversion efficiency together with a CH_4 heat content of 37.50 MJ/kg, density of 0.717 kg/m^3 and 75% gas collection efficiency were considered in this study. Using these parameters, thermal and electrical energy potentials were determined and plotted in Figure 3. These analyses were also reported by Surroop and Mohee (2011), Zuberi and Ali (2015), Sarptas (2016) and Sohoo *et al.* (2021). The comparison between the energy potential of previous studies by Usman *et al.* (2022a) using the IPCC default model and Usman *et al.* (2022b) using the IPCC FOD model with that of the current study using the EPA LandGEM model was shown in Figure S3.

The computation and result in Figure 3 and Figure S3 show that the LFG from the studied MSW is capable of generating up to 2.33 TJ of heat which is equivalent to 641.76 MWh of heat energy. This heat energy is capable of generating 192.53 MWh of electricity in 2016. From 2016 to 2022, the quantity of energy wasted was about 63.046 TJ equivalent to 5201.32 MWh of electricity with an average of 743.05 MWh/year (84.82 kW).

Furthermore, from 2023 onward, the landfills will continue to emit LFG with high CH_4 content and other harmful and carcinogenic polluting gases. These further anaerobic biodegradation process will emit about 697.86 Gg of LFG which contain 186.41 Gg of CH_4 between 2022 and 2122. This gas is capable of generating a total of 5242.70 TJ of heat which is equivalent to 432.52 GWh of electricity using a standard IC engine set. This has an average energy generation of 4282.40 MWh/year (i.e. 488.86 kW/year). If this large quantity of energy can be collected and connected to the grid, it can provide gross revenue of ₦19.46bn. An average of ₦192.71m can be generated every year excluding indirect and induced ripple effects. The results and variation of energy generation from LFG of this study were supported by studies of Surroop and Mohee (2011) and Cabaraban and Paclijan (2015). Similar results and variations were reported in Idehai and Akujieze (2015), Mustafa *et al.* (2016), Sarptas (2016), EESI (2017), Singh *et al.* (2018), Trapani *et al.* (2018) and Sohoo *et al.* (2021).

3.2.2 LFGCost-web model analysis. Evaluating the economic feasibility of an LFG energy project is an essential step and should be completed before preparing a system design, entering into contracts or purchasing materials and equipment. The process for evaluating project alternatives and financing options is discussed by highlighting the typical capital and operation and maintenance (O&M) costs and other influential factors. The influential factors include potential revenue streams, financial incentives and funding opportunities, preliminary financial evaluations and project financing options (EPA, 2021a, b, c). The basic inputs variables, LFG project types and recommended project size for use in the LFGCost-Web model are shown in Table S3.

The cost estimate generated by the LFGCost-Web model includes all the cost associated with the project. In addition to equipment and installation cost, the model also considers costs associated with engineering, design, site surveys, administration, preparations, permits, etc. The uncertainty associated with these cost estimates is ±30–50%. The cost and economic variables such as construction and operation cost and NPV are based on actual or nominal rates. This includes the effect of inflation and the year the project is constructed, started operation and NPV were computed (EPA, 2021b, c). The results of the analyses for LFG application in RNG and standard turbine electricity projects are shown in Tables 2 and 3, respectively.

From Table 2, the RNG project is capable of generating 87.5 M-ft^3/year (2.48 M-m^3/year) equivalent to 166.47 ft^3/min (4.71 m^3/min). The project had an average capital cost of $8,635,144.00 (₦3,608Million) and an annual operating cost of $375,413.00 which are higher than expected. This project also provides higher positive internal rate of return (IRR) of up to 7% and 10% at RNG price of $1.53/kg (₦638.01/kg) and $1.77/kg (₦738.09/kg), respectively. This product price range is higher than the current LNG utility purchase price. The projects had a reasonable payback period of 13 years at a gas price of ₦638.01/kg which is less than the

Type of output		Output data per million BTU*			
Product cost		$23 ($1.07/kg)	$28 ($1.30/kg)	$33 ($1.53/kg)	38 ($1.77/kg)
Design project size (ft^3/min LFG)		179	179	179	179
Average project size for projects not generating electricity	million ft^3/year	87.50	87.50	87.50	87.50
	m^3/year	2.48	2.48	2.48	2.48
	(ft^3/min)	166.47	166.47	166.47	166.47
	m^3/min	4.71	4.71	4.71	4.71
Total construction capital cost ($)		$8,635,144	$8,635,144	$8,635,144	$8,635,144
Annual operational costs ($/year)		$375,413	$375,413	$375,413	$375,413
Internal rate of return (IRR) (%)		0%	5%	7%	10%
Net present value (NPV) ($)		($2,339,374)	($151,014)	$1,298,528	$2,735,616
Payback period**		None	None	13	11

Note(s): *; 1GGE = 2.567 and 1 kg = 46,452BTU or 1BTU = 2.15 E-5 kg or 1mil. BTU = 21.53 kg
**; None = no return on investment or no payback in LFG energy project lifetime

Table 2. Summary of economic analysis for RNG project

Type of output	Output data in ($/kWh)			
Product cost	$0.105	$0.120	$0.140	$0.160
Design project size (ft^3/min LFG)	179	179	179	179
Electricity generating capacity (kW)	418	418	418	418
Electricity generating capacity (kWh/yr.)	2,996,962	2,996,962	2,996,962	2,996,962
Total construction capital cost ($)	$2,027,769	$2,027,769	$2,027,769	$2,027,769
Annual operation costs ($/year)	$130,594	$133,417	$137,180	$140,943
Internal rate of return (%)	0%	4%	8%	12%
Net present value ($)	($505,224)	($118,536)	$397,047	$912,630
Payback period**	None	None	11	9

Note(s): **; None = no return on investment or no payback in LFG energy project lifetime

Table 3. Summary of economic analysis for standard turbine project

project life of 15 years. At this price, the project may be viable if not because of the higher capital cost of $8,635,144.00 (₦3,608Million) and annual operating cost of $375,413.00.

The results in Table 3 using 75% gas collection efficiency show power generation of about 418 kW and net of 2,996,962.00kWh/year from the studied landfills. The viability can be seen from the positive IRR and NPV at a maximum electricity cost of about $0.14/KWh and $0.160/KWh. Even though at a lower electricity cost of $0.105 to 0.120/KWh, the project yields positive NPV of about $505,224.00 and $118,536.00 but the IRR are 0% and 4% and there is no payback period. At a slightly higher price of $0.140 (₦58.38/kWh) and $1.160 (₦66.72/kWh), the project yielded an IRR of 8% and 12% with a positive NPV of about $397,047.00 and $912,630.00 and a payback period of 11 and 9 years, respectively. This plant is estimated to require only $2,027,769.00 in capital cost and $137,180.00 and $140,943.00 as annual operating costs at the stated payback periods, respectively. The minimum electricity cost for the most viable energy project is $0.14/KWh (₦58.38/kWh) which is within the local energy utility purchase price with a minimum operating cost of $137,180.00.

Comparing the two projects, the electricity project in Tables 2 and 3 is the most economically viable. This is due to the RNG project's higher capital cost of $8,635,144.00 (₦3,608Million), operating cost of $375,413.00 (₦156.55Million) and a gas sale price of $1.53/kg (₦638.01/kg). At the viable electricity sale price, the project will yield a gross revenue of $419,574.68 and net revenue of $282,394.68 every year. The result obtained from economic analyses of RNG and standard turbine projects was in conformity with results in CPE (2010) and Huang and Fooladi (2021). Analyses performed using LFGcost-Web are considered preliminary and should be used for guidance only. A detailed final feasibility assessment should be conducted by qualified landfill gas and industrial project professionals. This must be done prior to preparing a system design, initiating construction, purchasing materials or entering into agreements to provide or purchase energy from an LFG energy project (EPA, 2021a, b, c).

4. Conclusion

The following conclusion was made from the research conducted.

(1) The landfills have the potential of receiving an average of about 33,358.83 Mg/year of waste. Anaerobic biodegradation process on these waste will emit a total of 697.86 Gg of LFG which contain 186.41 Gg of CH_4 from 2022 to 2122.

(2) The waste can generate an average of about 6,909.55 Mg/year of LFG which contain about 1845.61 Mg/year of CH_4, 5063.93 Mg/year of CO_2 and 79.33 Mg/year of NMOC from 2022 to 2122 if the landfills are closed around 2065.

(3) Analytically, the studied MSW as well as the LFG and CH_4 is capable of generating up to 2.33 TJ equivalent to 641.76 MWh of heat energy. Therefore, 192.53 MWh of electricity will be generated in 2016 alone.

(4) From 2016 to 2022, about 63.046 TJ equivalent to 17,337.74 MWh of heat energy was already wasted. These can generate about 5201.32 MWh of electricity with an average of 743.05 MWh/year (84.82 kW).

(5) Further LFG collection can produce a total of 5242.70 TJ which is equivalent to 1441.74 GWh of heat. This enormous heat can be converted to 432.52 GWh of electricity using a standard IC engine set. These will have an average energy generation of 4282.40 MWh/year (i.e. 488.86 kW/year).

(6) Connecting the electricity generated to the national grid, it can provide gross revenue of ₦19.46bn. An average of ₦192.71 million can be generated every year excluding indirect and induced ripple effects.

(7) The viability cannot be achieved with the RNG project as the capital cost of $8,635,144.00 (₦3,608Million) is higher than expected when compared to the electricity project. In addition, the project has a lower IRR of 10% and a higher payback period of 13 years at a $1.5/kg gas price.

(8) As compared to local utility purchase and sale price, the economic viability can be achieved at an electricity price of $0.140 (₦58.38/kWh). Even though the project yielded a lower IRR of 8% with a positive NPV of about $397,047.00 and a lower PBP of 11 years.

(9) The viable electricity project using LandGEM model will generate 418 kW (2996.96kWh) which will yield a gross revenue of $419,574.68 and net revenue of $282,394.68 every year.

(10) The project will help the environment by avoiding the emission of a large quantity of CH_4 a potent GHG to the atmosphere thereby mitigating climate change impact.

(11) The project will also reduce the release of polluted air and water to the immediate community thereby reducing airborne and water-borne diseases.

(12) Additional jobs and economic boosts can also be created for the immediate community and provide revenue to state and national governments.

(13) Based on the results obtained, a future study can be conducted to determine the economic viability of establishing LFG to the energy industry in the study area.

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Supplementary Material

The supplementary material is available online for this article.

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