Comparative study of landfill gases generation Via bioreactor and traditional design for maximizing the power generation

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Abstract

Landfills are a cheap alternative to municipal solid waste (MSW) disposal at present in upper Egypt where the desert is spread. It is worth mentioning that, After the treatment process, around 20% of MSW will be disposed of in landfills. This paper aims to compare the different types of landfills design, namely traditional and Bioreactor, investigating the amount of gas collected, the period of gas generation, the potential life cycle cost of the landfill, and the usage of landfill area after closure. The data relating to the MSW such as waste generation, waste characterization, and collection efficiency were measured in four Egyptian governorates named Luxor, Aswan, Minya, and Suhag which are in upper Egypt. A commercial software named Land GEM was used to calculate the amount of generated landfill gases (LFG) from each landfill design for each governorate. Furthermore, a mathematical model is established to calculate the power generated from the gas produced in each design. It will be noted that the generation of LFG is the highest for bioreactor design compared to traditional design according to the high level of waste decomposition which leads to a decrease in the period of gas generation and operation cost. Many technologies have been used to produce electricity from LFG before exportation to the grid, such as internal combustion engines (ICEs), turbines, and microturbines according to the production rate of the LFG. For example the amount of methane accumulated in this landfill in the Suhag site (Q = 8415000 m3 / year) for the bioreactor (the maximum power generated from the collected LFG using ICE, turbines, microturbines generator reaches 10 MW, 9MW, and 8.4 design in 2024 respectively, and for the traditional (Q=1143000 m3/ year) and power is 3.2 MW, 2.7MW, 2.9MW, respectively, in 2042.

Keywords: Life cycle assessment, landfill gas, municipal solid waste, anaerobic digestion, biogas, combustion, upgrading

1. Introduction

There are many problems facing the international community, namely the lack of energy resources and environmental pollution resulting from solid waste. This problem also faces developing countries like Egypt. So, all the developing countries turned to the prevailing least expensive ways to dispose of solid waste in the world, especially with the availability of land [1]. Therefore, the landfill is considered one of the common methods that are used to dispose of solid waste in safely way, especially in the absence or the weakness of treatment facilities and the existence of organic matter with high percentages due to the presence of scavengers. The energy policy focuses on developing renewable energy sources, reducing dependence on fossil fuels, and reducing energy consumption. So, the landfill is considered a renewable energy source as it has the potential to be an important source of human methane emissions, it is also a viable source of landfill gas (LFG), which can be used to produce heat and electricity [2,3]. There are two main types of landfills design namely traditional and bioreactor. The traditional landfill is a modern engineering landfill where waste is permitted to decompose into biologically and chemically inert materials in a setting isolated from the environment [4,5]. Traditional landfilling, typically based on anaerobic degradation of waste, use bottom liner, topsoil cover, gas, and leachate collection and treatment systems. Although these technical measures can significantly reduce the uncontrolled release of gas and leachate, potential environmental impacts remain high, and threats to the environment exist far beyond the time frame of a generation. Also, this kind of landfill design doesn't allow the land to be used until after a long period [3,6,7]. Technical measures include bottom liner, leachate collection system, and leachate treatment before discharge to surface water bodies and topsoil cover, gas collection system, flares, and gas utilization for energy recovery and monitoring in all years are required. The latter may be accomplished for electricity or combined heat and power (CHP) generation, depending on the gas generation due to waste decomposition [7,8]. The second design is the bioreactor landfill design which in turn accelerates the degradation of the waste by recirculating the liquid (Leachate) and air to the disposed waste. In addition, the degradation process is microbially enhanced to achieve a faster and more extensive stabilization of waste. When waste breaks down faster, there is a shortened period that greenhouse gases are produced and a quicker turnaround of the land for reuse in the community[7,9,10]. Therefore, the waste will be under controlled conditions for the engineered bioreactor landfills. Moreover, the potential benefits of the bioreactor landfill include increased waste settlement rates and utilization decreased costs for leachate treatment, which improves the economics of gas recovery, and may reduce the post-closure maintenance period [7,9]. Furthermore, the developed bioreactor is established to minimize environmental impacts from landfilling. In bioreactor landfill design, the gas collection by using a piping system contributes significantly to reducing emissions of carbon dioxide and other greenhouse gases that prevent release into the atmosphere which have a good impact on the environment. The calorific value of LFG is significant enough to allow its usage as a fuel in combustion[11]. Thus, the capturing and positive usage of biogas is advantageous in environmental terms and attractive in economic terms [12]. Some bioreactor landfills are called flushing bioreactors which work on recirculating considerable amounts of water together with leachate to flush out soluble waste components in a process called waste irrigation” or ‘‘waste flushing”. The flushing rate typically ranges from 1 to 5 m^3 of total liquids (leachate and external water) per ton of waste landfill [4]. In addition to waste irrigation measures to reduce ammonia/ammonium (NH3/NHþ4) concentrations in leachate are commonly used in flushing bioreactor landfills. Leachate may be nitrified before being recirculated to the waste mass, thereby becoming rich in nitrate (NO_3), providing further oxidation of waste components, and finally leading to the removal of NH3/NHþ4 through the emission of gaseous nitrogen (N2). But the attention will be directed to the problems produced by using landfills. the first problem is the leachate which is a liquid by-product and contains high amounts of pollutants. It is characterized usually by an offensive odor and complex chemical composition. Landfill leachate contains high concentrations of ammonia-nitrogen (NH3-N) content, heavy metals, inorganic salts, and other organic materials. However, landfill leachate may contain other compounds such as sulfide, barium, borate, arsenate, lithium, cobalt, and mercury. If these pollutants are left without proper control and treatment, they can reach the groundwater [13]. So, an effective management process with modern technologies is required for the massive quantities of landfill leachate treatment and the impact of landfill leachate on groundwater quality, especially in developing countries. El-hammam landfill, in Alexandria-Egypt, where a study was conducted on some landfill leachate treatments. Alexandria was choosen as a coastal city with heavy rains, the landfill leachate increased significantly due to the high level of rain in this area [14]. Landfill gas (LFG) is considered the second problem which denotes predominantly greenhouse gas (GHG) consisting mainly of methane and carbon dioxide generate because of the anaerobic biodegradation of municipal solid waste (MSW) in landfills. LFG is formed of methane (CH_4) (50%), carbon dioxide (CO_2) (45%), and other irrelevant elements, such as nitrogen (N2), hydrogen sulfide (H_2S), and nonmethane organic compounds (NMOCs) (5%) [15]. The increase in GHG emissions has changed the global pattern of temperature and posed a threat to the environment and human health. Methane signifies the second most frequently observed greenhouse gas. It has a global warming potential that exceeds that of carbon dioxide (CO_2) by a minimum of 28 times and creates 20% of the global greenhouse gas impact[16]. The LFG is considered one of the major sources that can be used for the generation of electricity instead of fossil fuel depending on the usage of internal combustion generators, turbines, microturbines, fuel cells, combined heat, and other power-producing facilities[17,18]. In this manner, the commercial software named Land GEM is used in a wide range of the world to calculate the amount of collected landfill gases which is considered one of the important software in this direction [17,18].

Finally, as a conclusion for the previous studies in particular in Egypt, there is a lack of studies conducted concerning the design of landfills used to bury municipal solid waste. From this point of view, this work aims to present a comparative study of the common two landfilling technologies which are named traditional landfills with flares and energy recovery and flushing bioreactor landfills compare their environmental performance via a life cycle. This comparison includes the main parameters that affect the landfill performance,i.e. the amount of gas collected, period of gas generation, and potential life cycle cost of the landfill. But due to the topography of Egypt, the study will concern two zones based on the land available for use as a landfill. These zones are Delta and Upper Egypt. Upper Egypt will be concerned with the study of landfills, as it includes huge areas of the desert that can be relied upon for landfills construction. Four governorates in Upper Egypt namely: Minya, Suhag, Luxor, and Aswan will be selected as case studies. Moreover, the climate conditions will be considered in the study, as it is changed from year to year.

2. Methodology

The available area in each governorate, El Minya, Suhag, Luxor, and Aswan, for landfill construction, is (27, 65, 12, and 9) acres respectively. The total generated waste for each governorate will be measured as well as the waste characterization during the field study to estimate the exact waste composition and generation rates. It should be noted that the usage of landfills is suitable in these areas where the climate conditions are characterized by a high temperature almost around the year with a low level of rains. The amount of generated gas will be estimated for the proposed two designs, traditional and bioreactor, to optimize the design to be applied for each governorate[19].

2.1 Volume of accumulated landfill waste

The accumulated volume of landfill waste can be estimated from equation (1).

$$\text{Volume (v)} = \frac{N*P*R*365*F}{\rho} \quad (1)$$

Where

N= effective life of the landfill

P= the Project Population

R = waste acc. rate (kg/per/day)

F= factor for daily soil cover (1.25) assume

ρ =compacted waste density ρ kg/m3

$$\text{Landfill area A}= \frac{Volum}{Depth} \quad (2)$$

By assuming a square site shape, the dimensions of the landfill site will be calculated.

$$\text{Length (l)}= \sqrt{area} \quad (3)$$

2.2 Land Gem Model

This model is used to calculate the rate of generated gases from the designed landfills over time. It is used to calculate landfill CH_4, CO_2, volatile organic compounds, and specific air contaminants. The prototype is based on a first-order decay equation, which calculates the mass of methane produced by dumped MSW in a landfill. It is assumed that biogas production peaks when anaerobic conditions within the MSW confinement are balanced, and subsequently diminishes as the organic waste portion decreases. The Land GEM program was used to predict the methane rate generated at the four potential locations from 2021 to 2041. Equation (4) calculates the amount of LFG biogas that could be created in the year of computation using solid waste projections [19]

2.3 First-order decomposition rate

The first-order decay rate equation used by the Land Gem modeling tool is represented as follows.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} Kkt \left(\frac{Mi}{10}\right) e^{-ktij} \quad (4)$$

Where

Q_{CH_4}= represents the Annual methane generation.

i = One-year time increments,

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

J = 0.1-year time increment (cutting the year into tenth)

K = Methane generation rate ($year^{-1}$)

L_o = Potential methane generation capacity ($m^3 . Mg^{-1}$)

Mi = Mass of waste accepted in the j^{th} year (Mg)

t_{ij} = Age of the j^{th} section of waste mass Mi accepted in the j^{th} year

The higher value of k means that the rate of methane production increases faster and then decomposes over time. Also, the value of k is dependent primarily on the next four factors:

1) Availability of the nutrients for microorganisms that break down the waste to carbon dioxide and methane[20].

2) pH of the waste mass,

3) Moisture content of the waste mass

4) Temperature of the waste mass [21].

Due to the lack of available data for the MSW characteristics in many areas in Egypt especially for the four targeted governorates. The model parameters' default values of k and Lo will be assumed as in Table 1. Because of the high content (59-75%) of organic matter (food waste), the k value could be higher in the four governorates however, it was considered the same as the default value [19].

Table 1: Determine model parameters to run the Land GEM default [22,21].

Parameters	Reference	Unit	Symbol	Rate a traditional landfill	Rate a bioreactor generates landfill
Methane production	Clean Air Regulations (CAA)	year_1	k	0.05	0.7
Potential methane production capacity		m^3/Mg	L0	170	96
Non-methane organic compounds concentration NMOC		ppmv as hexane	-	4000	4000
Methane content		by volume	-	50	50

3. Waste characterizations study and generation rates

A sampling at the source and sampling at the disposal site are the two fundamental ways of determining volumes of municipal solid waste via sampling A waste characterization study's goal must be determined, and the representative nature of waste characterization must be addressed. The data were measured and collected, and studies were carried out in the selected city in four governorates Luxor, Aswan, Minya, and Suhag to calculate the generation rate for each governorate according to ASTM D5231 − 92. (Standard Method for Determining the Composition of Unprocessed Municipal Solid Waste) represents the sampling criteria considered during the sampling period (7 successive days).To define MSW amounts for four governorates in Egypt in this direction, four different cities were chosen within each governorate, and in each city, three different living standards (30 families per level) were selected, which are as follows:

- The lowest standard of living
- Middle-income
- The highest standard of living

The amount of generated waste in all four governorates and the amount per capita per day were calculated for each capita which is equal to 0.6 kg/capita/day. According to the amount of waste generated in each governorate, there is availability to construct one landfill for each of the four governorates in Upper Egypt to be used as a dumpsite. This is regarding the environmental regulation which allows 20 % of waste to be dumped and the reminder value will be directed to the recycling plant. Figure 1 shows the measured average waste generated for the first three years 2021,2022, and 2023 which helps to predict the reminder years' average waste generation. In the year 2024 the waste management program will be applied to each governorate by establishing many recycling plants to decrease the disposed waste by 80%. In addition to that, a study was conducted to analyze samples of the waste as shown in Table 2, and the average efficiency of the waste collection was also calculated which equals an average of 80%.

Table 2: Percentage waste composition in organic waste in 4 governorates in Egypt.

No	Waste components %	El Minya	Suhag	Luxor	Aswan
1	Paper and card	15.75	11	13	4.98
2	Plastic film	6	-	-	8.40
3	Dense plastic	5.25	18	14	5.12
4	Textiles	5.25	1	-	0.09
5	Wood	5.25	1	-	-
6	Combustible	3.50	-	-	-
7	Glass	-	1	2	5.88
8	Organic	59	56	67	75.06
9	Ferrous metal	-	1	4	0.47
10	Fine material<10mm	-	11	-	-

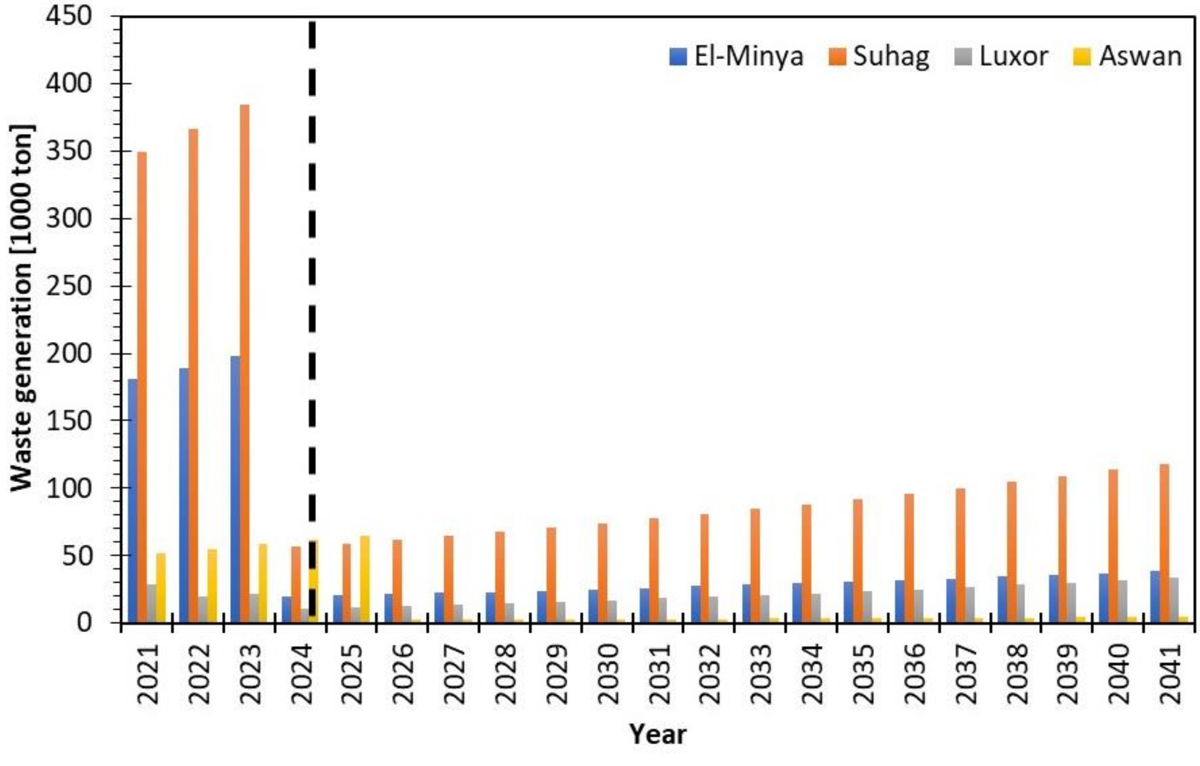


Figure 1: The estimated annual waste disposed for four governorates El Minya, Suhag, Luxor, and Aswan from 2021 to 2041 with a fixed increasing percentage of 10% after the year 2024.

4. Assumptions for the landfill design model

It's assumed for each design of landfill that the period of filling from 2021 to 2041 with a height of the waste inside the cell to be 20 m. The height of the dumped waste is divided into 15m below the sea level due to the land structure and 5 m above the sea level according to governmental regulations. Table 3 shows the opening and closing dates of the landfill, and the amount of waste per year with an annual increase of 10 percent depending on the population rise.

Table 3: Percentage waste composition in 4 governorates in Egypt [23].

Item	ElMinya	Suhag	Luxor	Aswan
Year of landfill opening	2022	2022	2022	2022
Year of landfill closing	2037	2037	2037	2037
Total dumped waste ton /year	181405	349305	28550	52195
Landfill area (acre)	27	65	12	9
High from bottom to top of the cell (m)	20	20	20	20

5. Materials characterization and methods

It is important to know the landfill design parameters such as location, climate, municipal solid waste (MSW) composition shown in Table 2, and characteristics, which affect the landfill design [24]. These parameters affect the landfill biogas generation capacity. First, the characteristic parameters of Egypt's landfills are obtained, and then biogas is estimated based mathematical model by using Land GEM software. second, The landfills' locations are selected by the governorates as shown in Table 4.

Table 4: Dumpsite locations.

No.	Dumpsite	Coordinates
1	Kom Ombo in Aswan,	24°28′00″N 32°57′00″E
2	Armant in Luxor,	25°37′00″N 32°32′00″E
3	ElMinya center in ElMinya,	28.1003°N 30.7582°E

4	Almonshah in Suhag.	26°28′37″N 31°48′13″E

6. Power generation estimates

Energy recovery from waste is a significant approach to minimizing the quantity of electric energy generated using fossil fuels, that is, non-renewable energy sources. But the direct LFG usage results in lower greenhouse gas emissions. The available power output and the energy flow can be calculated based on. (Equations 5,6 and 7). This information is critical for determining the project's overall economic feasibility.

6.1 Power potential estimation from LFG

To determine the power capacity, it is necessary to assess the generation LFG. The design choice depends on the amount of biogas production [22].

$$\text{Available Thermal energy}, E_{th}(\text{kW}) = \dot{m}_{CH_4} \times LHV_{CH_4} \times R \tag{5}$$

$$\text{Generated power (MW)} = \dot{m}_{CH_4} \times LHV_{CH_4} \times \eta \times R \tag{6}$$

The electrical energy (kWh/year) that could be obtained from the methane content of collected landfill gas is estimated as:

$$E\ (\text{MWh/year}) = P_{generated} \times 876 \tag{7}$$

Qc is the average methane collected per annum (m^3/year) and can be obtained as:

$$Q_c = \lambda \times Q_g \tag{8}$$

$$Q_g = \frac{\sum_{i=1}^{n} Q_{LFG}}{n} \tag{9}$$

λ is the average gas collection efficiency for a landfill. Which is in a range from 60 to 95 percent, with a typical average of 75 percent [25][26].

Where,

$\dot{m}_{CH4}$:volume Flow rate of methane (m^3/h)

LHV_{CH4}: Lower heating value of methane = 9.94 (kWh/m^3),[11]

R: Recovery rate of LFG

$P_{generated}$= annual available power (MW), [27]

Q_{LFG} =annual LFG discharge (m^3 /year)

η=conversion efficiency yield (%) is the electrical efficiency of the generating element in transforming thermal energy into electrical energy (ICM, turbine, or micro-turbine)

E =annual available energy (kWh)

6.2 Different technologies for Landfill Gas to Energy

The use of LFG to generate electricity is a viable technique for conserving energy as well as lowering air pollution and greenhouse gas emissions. The production of electrical energy from controlled landfill methane is the most common application of beneficial use as shown in **Error! Reference source not found.**. To measure power capacity, the generation technique used must be evaluated. The technology selection depends on the available biogas flow rate cfm through the study period.

Three proposed technologies can be used in the present study to generate electricity using the generated gases named as follows: -

- gas turbines
- and microturbines
- internal combustion engine ICE.

These technologies are available in a variety of sizes to accommodate diverse biogas potentials, but ICE has a lower cost per kW compared to gas turbines and microturbines. Unfortunately, biogas turbines are often employed for big projects with a high biogas generating flow capability of at least 3 MW and frequently more than 5 MW. Also, some of its benefits include low maintenance needs and great efficiency that grows with growth. The microturbines may be linked in series to offer as much equipment as needed. Micro-turbines do not require extensive biogas treatment since they are resistant to hydrogen sulfide in biogas. **Error! Reference source not found.** describes the features of the three different technologies that can be used to generate electricity from the generated biogas.

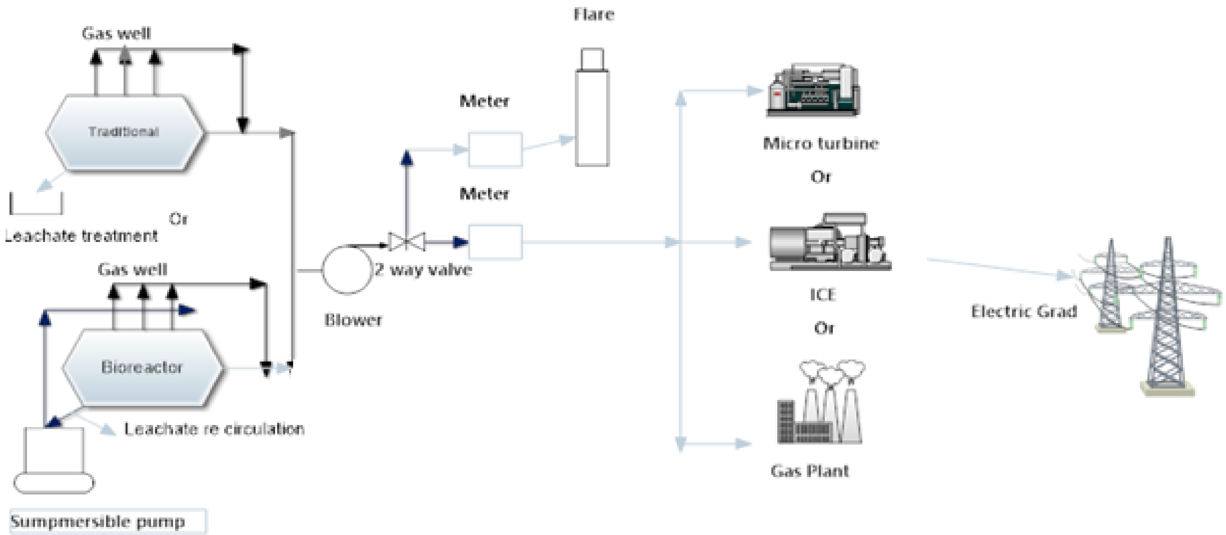


Figure 2: Typical LFG system components.

Table 5: Characteristics and costs associated with LFG energy recovery technologies [28]**.**

Technology	Fuel Flow range cfm: cubic feet per minute	Electrical efficiency (%)	Typical capital costs ($/kW)	Typical Annual O&M Costs ($/kW)
Internal combustion engine **Generated power range (> 800 kW – 3MW)**	(300 – 1100 cfm) Multiple engines can be combined for a larger project	Range (32-45) Assumed (0.33)	$3600	$360
Small internal combustion engine Generated power range (<800 kW)	Rang (204 -234 cfm)	Range (32-45) Assumed (0.33)	$4800	$480
Turbine **Generated power range (3 to 5 MW)**	minimum of 1,300 cfm typically exceeds 2100 cfm	Range (25-40) Assumed (0.28)	$2800	$280
Micro-turbine **Generated power range (30-250) kW**	(20-200 cfm)	Range (26-32) Assumed (0.30)	$ 5600	$392

Source: EPA, 2014

7. Results and discussion

7.1 Landfill gas production

Figure 3. In general, depicts the creation rate for both landfill designs over time. It is possible to deduce that the process of landfill gas generation begins much sooner and is more intensive, i.e., the volume of landfill gas generated is greater and takes less time in the bioreactor landfill than in the traditional landfill.

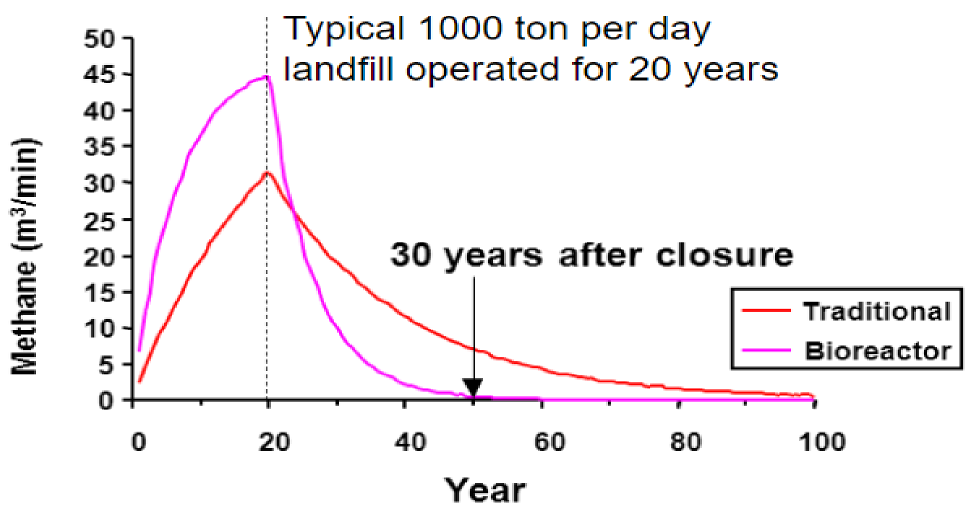


Figure 3: Typical landfill

These results were obtained theoretically using the Land GEM model software when it was applied to the four governments in Egypt (El Minya, Suhag, Luxor, Aswan), for two designed landfills to compare traditional landfill and bioreactors in terms of total gas emissions measured in megagrams per year and period time from open 2021 and closed 2041. This amount of gases was calculated depending on the field waste characterization study for the study area. Figure 4 demonstrates the comparison of the total emissions generated by the bioreactor and traditional designs, methane, carbon dioxide as well as (NMOC) of Egypt (the case study) throughout the years.

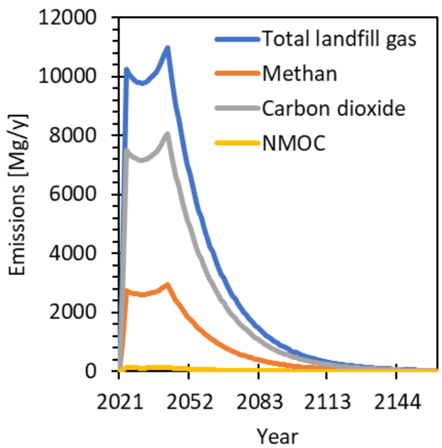
7.1.1 Gas generated from traditional design

Methane is not produced immediately after being disposed of in the landfill, in Figure 4, curve (a) presents the accumulation of gases over years from 2021 to 2107 for the traditional design. It is observed that the gas formation gradually decreased after 2043. Because the production of LFG takes a downward trend since the degradable carbon present in the residue is depleted by bacteria. When the maximum gas formation continued, especially from 2026 to 2041. The maximum values of generated methane are noted at 2042, 2043, 2043, and 2023 for Minya, Suhag, Luxor, and Aswan with values equal to 2933,7623,1433, and 1450 Mg/year respectively as predicted by the Land GEM model, then declined concurrently before finally stopping in 2107. In general, it is possible to divide the organic part of municipal solid waste into rapidly degradable compounds and slowly degradable compounds. Rapidly degradable compounds degrade between three months to five years as shown in Fig.4 (a) from (2021 to 2025), while biodegradable compounds degrade slowly over fifty years or more from (2021 to 2141).

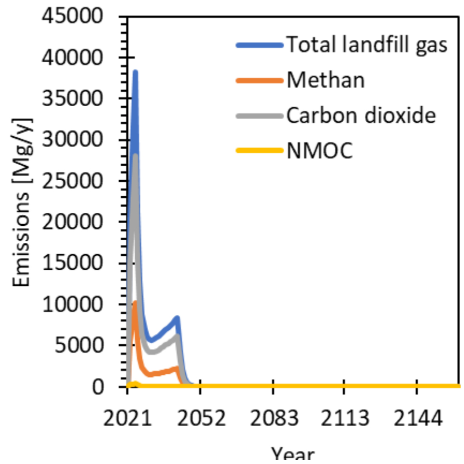
The total amount of gas produced corresponds to the area under the rate curve from (2021 to 2041) which is a constant generation, due to rapidly degradable compounds. From 2041 the gas formation gradually decreased because the available moisture is insufficient to allow the complete conversion of the degradable organic components which takes more time to generate the gas. After 2041 the gas formation gradually will be decreased because the available moisture is under 45 to 60 percent which is insufficient to allow the complete decomposition of the degradable organic components to continue the gas production. Hence, the gas production curve becomes flattened and extends over a longer period. as the same in the rest of the governments.

7.1.2 Gas generated from bioreactor design

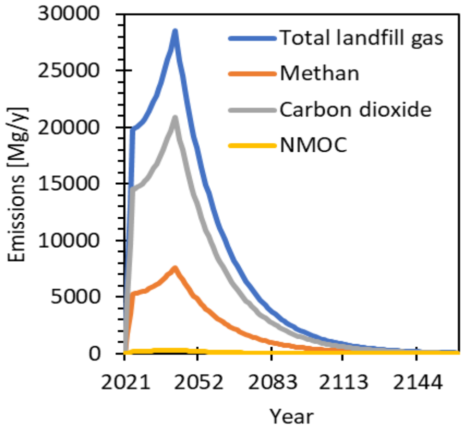
The gas formation gradually decreased after 2024 as shown in Fig.4.b which is indifferent to the traditional design. Methane production peaked in 2024 which equals 10210 Mg /year and declined sharply before finally stopping in 2044. According to the leachate recycling system, the gas production rate will be improved which reduce the time required to stabilize biodegradable organic matter in the landfill. So, the enhancement in biodegradation also speeds up landfill gas production allowing landfill operators to collect methane at a commercially viable level. Therefore, reducing the time where post-closure monitoring and maintenance must be accomplished. Also, waste organic matter will decompose quickly giving the curve a steep first slope, then waste such as wood and cloth will take over and plastic will finally take over and decompose slowly and produce a little methane.



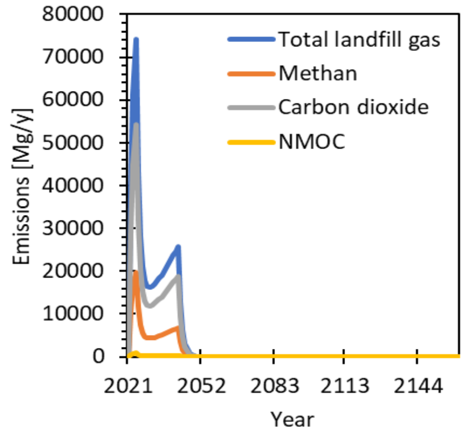
a. The amount of gas emission from traditional design for El Minya governorate.



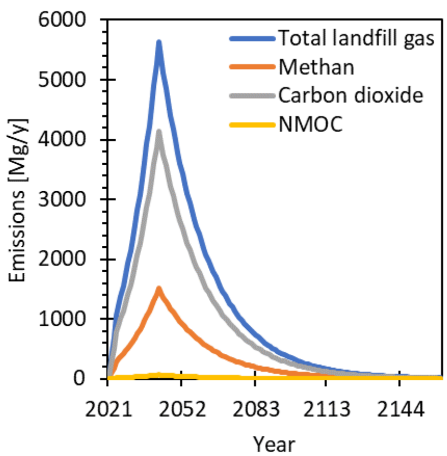
b. The amount of gas emission from bioreactor design for El Minya governorate.



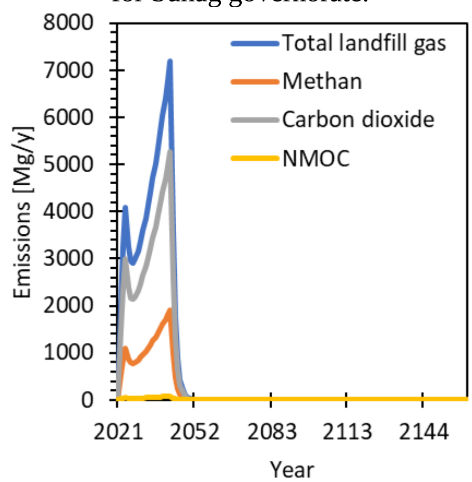
c. The amount of gas emission from traditional design for Suhag governorate.



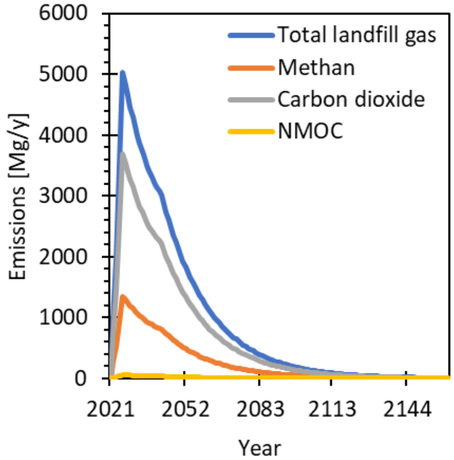
d. The amount of gas emission from bioreactor design for Suhag governorate.



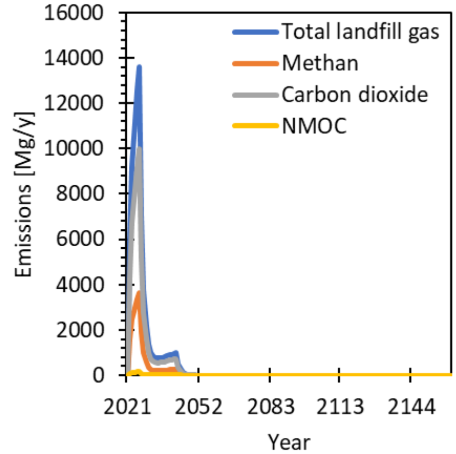
e. The amount of gas emission from traditional design for Luxor governorate.



f. The amount of gas emission from bioreactor design for Luxor governorate.



g. The amount of gas emission from traditional design for Aswan governorate.



h. The amount of gas emission from bioreactor design for Aswan governorate

Figure 4: Comparison between LFG generation for traditional & bioreactor landfill design in four governorates over years.

7.2. Estimation of the generated power

The maximization of the benefits from the generated gases depends on the amount of power generated from the combustion process of these gases by any kind of available technologies like using the followings:-

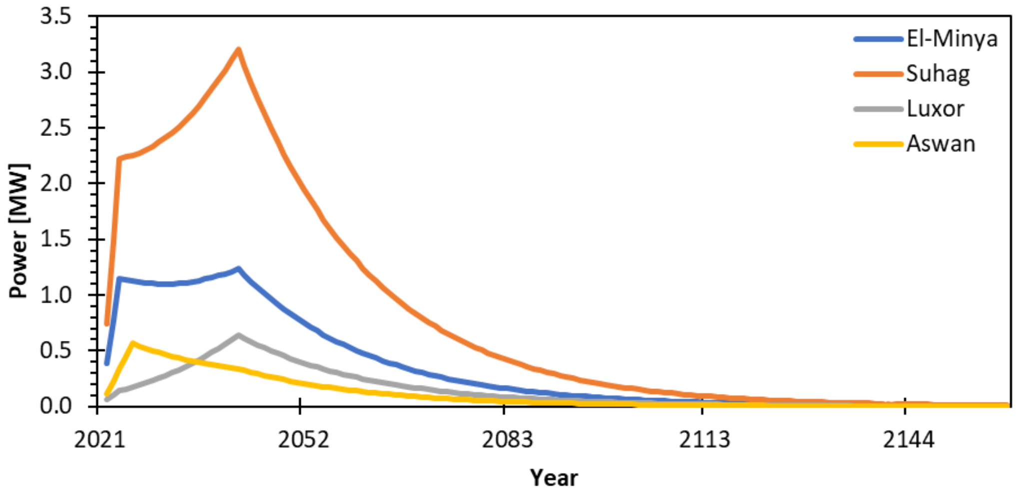
1. An internal combustion engine (scenario 1)
2. Gas turbine (scenario 2)
3. Microturbine (scenario 3)

Equations 2 and 3 will be used to calculate the generated power for each landfill at the four governorates in Egypt from (2021 to 2041) taking into consideration the amount of generated gases, the calorific value of these gases, and the data in table 4.

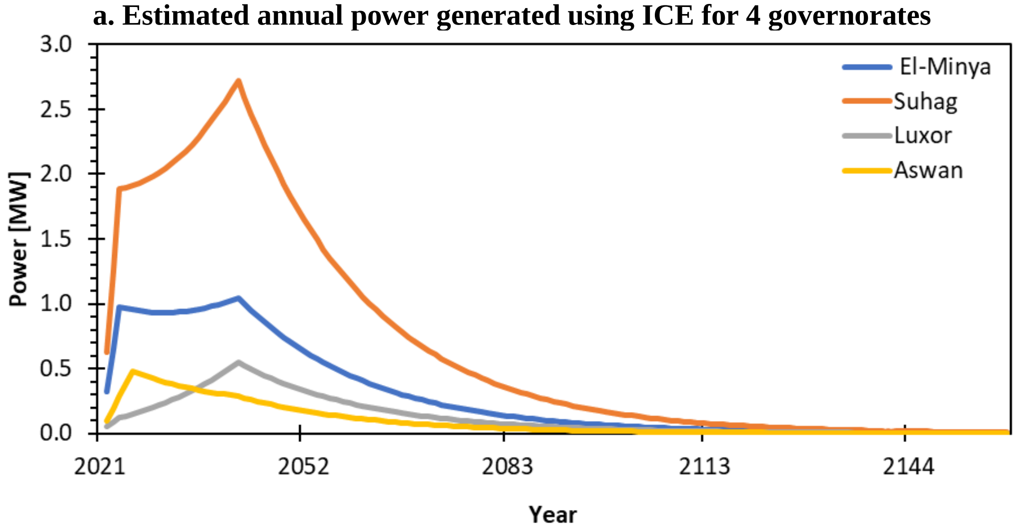
7.2.1 Traditional landfill design annual power production

Figures (5), show the estimated power of each scenario due to the estimated gases for each governorate during the period of the study. In scenario 1, ICE technology can be used in Suhag landfills regarding the average value of Q_{CH4} (equals 400 cfm) which generates the maximum average value of power equal to 2.5 MW in years from 2025 to 2059. ICE cannot be used for EL Minya governorate as the Q_{CH4} is equal to 250 cfm which is under the minimum used value for ICE (Q_{CH4} 300 cfm). In that case, the small internal combustion engine can be used which works with a low level of methane production (1.4 MW in years from 2023 to 2048). But for Luxor and Aswan scenario 1, could not be applicable as the maximum average values of power are 0.5 and 0.54 MW which is not sufficiently related to the mentioned assumption in Table 4. In scenario 2, gas turbines are not applicable in Suhag, Luxor, Minya, and Aswan which produce maximum average values of power equal to 2.8, 1.1, 0.8, and 0.5 MW respectively where the generated gases are not sufficient to run the gas turbine.

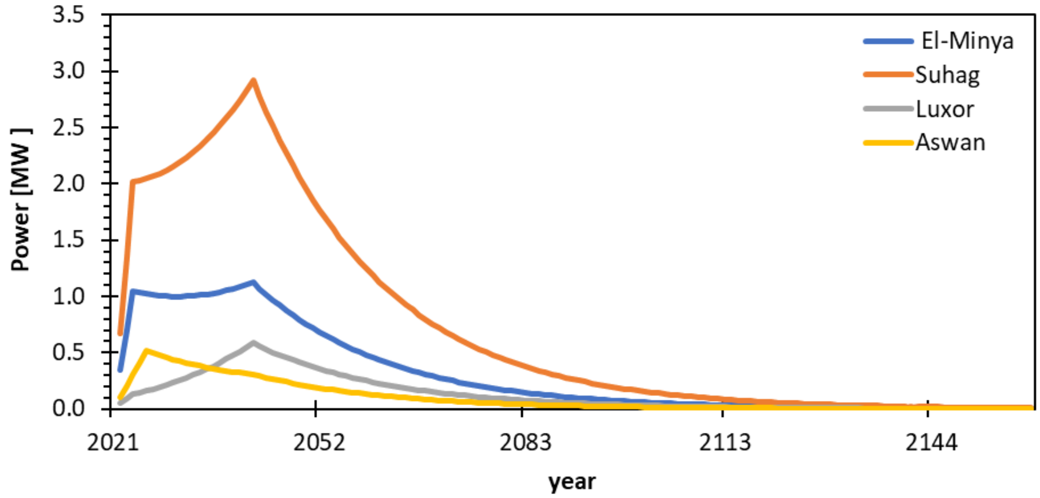
In Scenario 3, a microturbine will be used in the four governorates related to the amount of generated gases that can run the microturbine over a large period from 2022 to 2053.



a. Estimated annual power generated using ICE for 4 governorates



b. Estimated annual power generated using Gas Turbine for 4 governorates

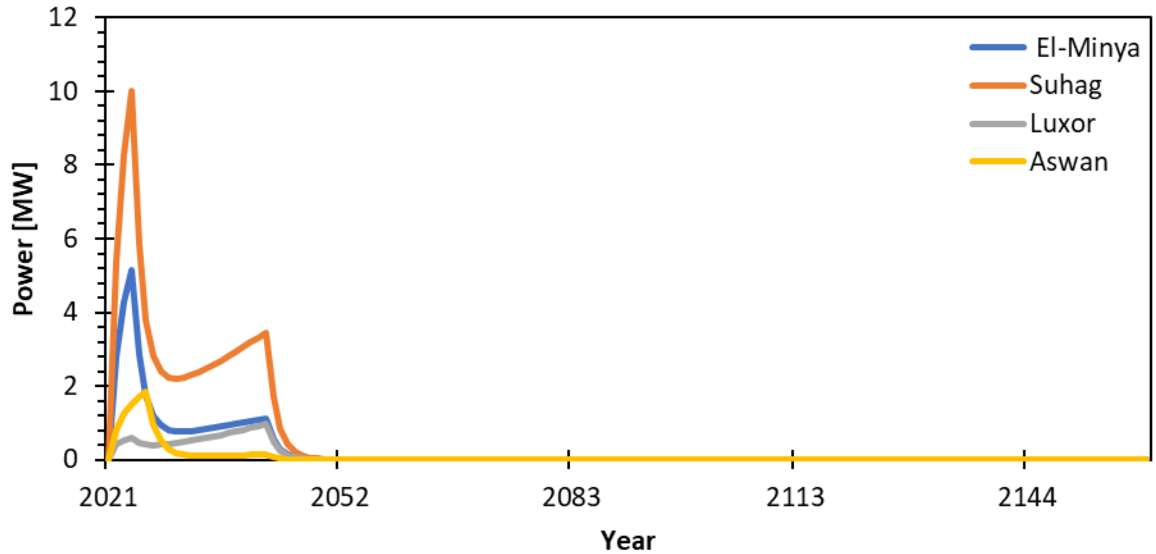


c. Estimated annual power generated using micro Gas Turbine for 4 governorates

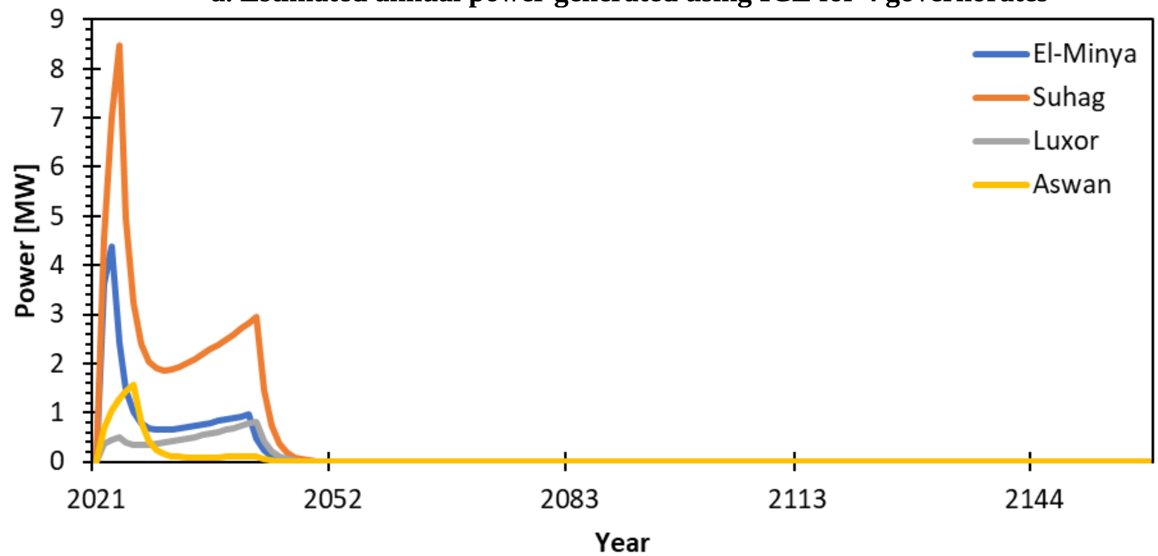
Figure 5: Estimated power generation for a traditional landfill (MW) for different technologies throughout the study.

7.2.2 Bioreactor landfill design

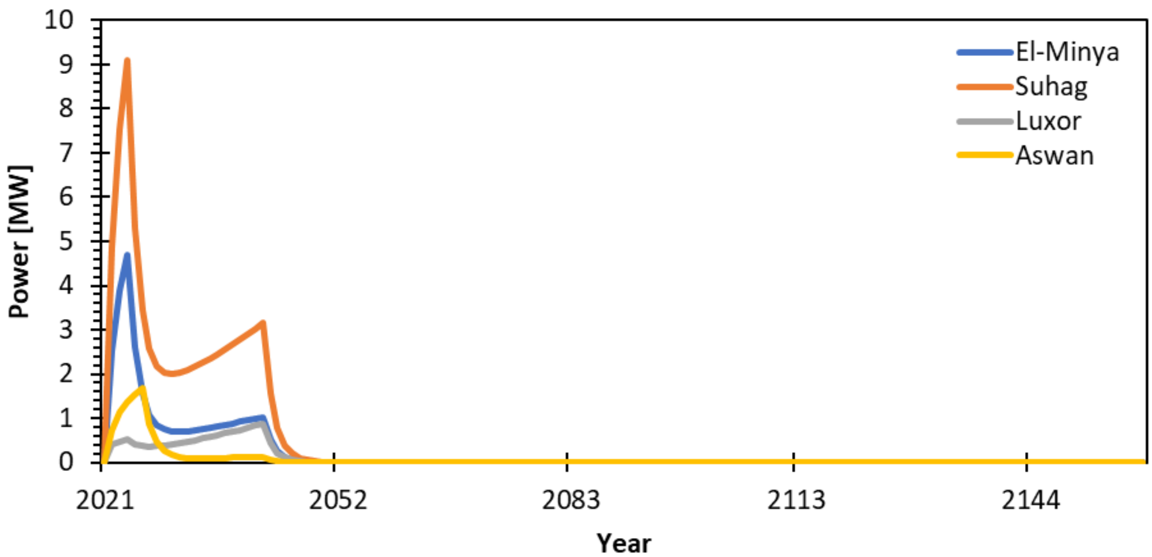
The estimated power produced for each scenario regarding the amount of generated gases in each governorate during the period of the study is illustrated in figure 6. ICE technology is used in Suhag landfills which produced enough gases amount of 600 cfm for ICE operation. It will be noted that the maximum average generated power in scenario 1 reaches 4 MW in the period starting from 2021 and ending in 2042. Unfortunately, the ICE is not adequate because of the low level of gas production in the other three governorates. But for El Minya scenario 1 could not be applicable due to the average Q_{CH4} (equals 159 cfm) which is not sufficiently related to the mentioned assumption in Table 4 also, Luxor and Aswan. In scenario 2, the gas turbine couldn't be applicable in Suhag, El Minya, Luxor, and Aswan landfills because the collected gases are less than the required value. In Scenario 3, a microturbine may be employed in each of the four governorates based on the quantity of generated gases that can be used to operate the microturbine over a long period, from 2021 to 2042. Suhag has a maximum of 9 MW in 2024 and a minimum of 3.2 MW in 2046, whereas El Minya has a maximum of 4.8 MW in 2022 and a minimum of.88 MW in 2042. Luxor has a maximum of.88 MW in 2042 and a minimum of.7 MW in 2027, whereas Aswan has a maximum of 1.6 MW in 2024 and a minimum of.11 MW in 2036.



a. Estimated annual power generated using ICE for 4 governorates



b. Estimated annual power generated using Gas Turbine for 4 governorates



c. Estimated annual power generated using micro Gas Turbine for 4 governorates

Figure 6: Estimated power generation for bioreactor landfill (MW) for different technologies over the period of study.

Table 6: scenarios for four governorates in Egypt for defined tocology are used

No.	Technology	A Bioreactor landfill			
		Aswan	Luxor	El Minya	Suhag
Scenario 1	Internal combustion engine Generated power range (> 800 kW – 3MW)	No	No	No	From (2021 to 2041) used 3 2 used 1 standby (300cfm)
Scenario 2	Turbine Generated power range	No	No	No	No

	(>3 MW)				
Scenario3	Micro-turbine Generated power range (>1 MW)	From (2021 to 2041) used 3 and 1 standby (20cfm)	3 (20cfm) And 1 stand by	3(159cfm) And 1 stand by	4 (600cfm) And 1 stand by
Traditional landfill					
Scenario 1	Internal combustion engine Generated power range (> 800 kw – 3MW)	No	No	No	From (2021 to 2030) used1 from 2031to 2039 used 2 from 2040 to2065 used 1
Scenario 3	Turbine Generated power range (>3 MW	No	No	No	No
Scenario 4	Micro-turbine Generated power range (>1 MW)	a modular multi-unit system			

8. Conclusion

The goal of this study was to calculate the quantity of LFG released from landfills in four Egyptian governorates and, as a result, to assess the power production potential of these emissions. A comparison was made between two distinct landfill designs (traditional and bioreactor). The total LFG emissions in the four landfills were calculated using the Land Gem modeling tool and the IPCC standards since 2006. A waste characterization study's goal must be determined, and the representative nature of waste characterization must be addressed. Studies were carried out in four governorates Luxor, Aswan, Minya, and Suhag.

The data on waste from the four governorates were collected and measured to estimate the generation rate for each governorate. The conclusions can be summarized as follows:

- In Egypt, most landfills are open wet, no traditional landfills are employed, and when they are filled with the waste they are covered with sand after burial and used to create recreational gardens, with the gas not being used.
- To produce methane gas and in consequence to generate power in the case of bioreactor landfills, rapid gas extraction resulted in a shorter landfill age. This permits the land to be utilized once again while maintaining a high environmental system to prevent filtration of groundwater.
- In the Suhag case study, internal combustion engines (ICEs) were chosen for scenario 1 because they are efficient and inexpensive to operate in both traditional and bioreactor landfills.
- El-Minya, small ICE may be employed in a traditional landfill but not in a bioreactor since the QCH4 is insufficient. Luxor and Aswan landfills were studied in both cases.
- Due to inadequate gas volumes in Scenario 2, power plant technology was inapplicable in the four governorates.
- In the case of traditional landfills, a modular multi-unit system might be employed, however, with a bioreactor, one or two micro-turbine units could be used during the 20 years.
- This comparison research provides an extensive example of dealing with waste management in four distinct governorates in Egypt utilizing two different landfill designs. It is possible to infer that a well-designed and managed bioreactor is preferable since it has shorter maintenance and processing time, as well as a larger amount of created gases, which opens the path to reuse the land.

References

[1] T. R. Ayodele, M. A. Alao, and A. S. . Ogunjuyigbe, “Recyclable resources from municipal solid waste: Assessment of its energy, economic and environmental benefits in Nigeria,” *Resour. Conserv. Recycl.*, vol. 134, pp. 165–173, Jul. 2018, doi: 10.1016/j.resconrec.2018.03.017.

[2] V. Strezov and H. H. Cho, “Environmental impact assessment from direct emissions of australian thermal power generation technologies,” *J. Clean. Prod.*, vol. 270, p. 122515, Oct. 2020, doi: 10.1016/j.jclepro.2020.122515.

[3] M. Rasapoor, B. Young, R. Brar, and S. Baroutian, “Improving biogas generation from aged landfill waste using moisture adjustment and neutral red additive – Case study: Hampton Downs’s landfill site,” *Energy Convers. Manag.*, vol. 216, p. 112947, Jul. 2020, doi: 10.1016/j.enconman.2020.112947.

[4] S. Manfredi and T. H. Christensen, “Environmental assessment of solid waste landfilling technologies by means of LCA-modeling,” *Waste Manag.*, vol. 29, no. 1, pp. 32–43, Jan. 2009, doi: 10.1016/j.wasman.2008.02.021.

[5] S. L. Machado, M. F. Carvalho, J.-P. Gourc, O. M. Vilar, and J. C. F. do Nascimento, “Methane generation in tropical landfills: Simplified methods and field results,” *Waste Manag.*, vol. 29, no. 1, pp. 153–161, Jan. 2009, doi: 10.1016/j.wasman.2008.02.017.

[6] I. Madon, D. Drev, and J. Likar, “Long-term risk assessments comparing environmental performance of different types of sanitary landfills,” *Waste Manag.*, vol. 96, pp. 96–107, Aug. 2019, doi: 10.1016/j.wasman.2019.07.001.

[7] J.-F. Ménard, P. Lesage, L. Deschênes, and R. Samson, “Comparative life cycle assessment of two landfill technologies for the treatment of municipal solid waste,” *Int. J. Life Cycle Assess.*, vol. 9, no. 6, pp. 371–378, Nov. 2004, doi: 10.1007/BF02979080.

[8] C. Hadjidimoulas, “Methane Gas Emissions: Methods of Improving the Efficiency of the Biggest Landfill Gas Waste to Energy Project in the Middle East Installed in Amman, Jordan,” *OALib*, vol. 05, no. 08, pp. 1–35, 2018, doi: 10.4236/oalib.1104476.

[9] J. Dong, Y. Tang, A. Nzihou, Y. Chi, E. Weiss-Hortala, and M. Ni, “Life cycle environmental assessment of thermal waste-to-energy technologies and energy–environment–economy model development,” in *Waste-to-Energy*, Elsevier, 2020, pp. 111–151.

[10] M. Warith, “Bioreactor landfills: experimental and field results,” *Waste Manag.*, vol. 22, no. 1, pp. 7–17, Jan. 2002, doi: 10.1016/S0956-053X(01)00014-9.

[11] R. Mambeli Barros, G. L. Tiago Filho, and T. R. da Silva, “The electric energy potential of landfill biogas in Brazil,” *Energy Policy*, vol. 65, pp. 150–164, Feb. 2014, doi: 10.1016/j.enpol.2013.10.028.

[12] A. Johari, S. I. Ahmed, H. Hashim, H. Alkali, and M. Ramli, “Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 2907–2912, Jun. 2012, doi: 10.1016/j.rser.2012.02.005.

[13] R. S. Al-Wasify, M. N. Ali, and S. R. Hamed, “Application of different magnetic intensities for the treatment of landfill leachate in Egypt,” *Cogent Eng.*, vol. 5, no. 1, p. 1436114, Jan. 2018, doi: 10.1080/23311916.2018.1436114.

[14] M. M. Abd El-Salam and G. I. Abu-Zuid, “Impact of landfill leachate on the groundwater quality: A case study in Egypt,” *J. Adv. Res.*, vol. 6, no. 4, pp. 579–586, Jul. 2015, doi: 10.1016/j.jare.2014.02.003.

[15] S. I. Ahmed *et al.*, “Optimal landfill gas utilization for renewable energy production,” *Environ. Prog. Sustain. Energy*, vol. 34, no. 1, pp. 289–296, Jan. 2015, doi: 10.1002/ep.11964.

[16] İ. Şentürk, “Techno-Science,” vol. 3, no. 2, pp. 63–76, 2020.

[17] Q. Aguilar-Virgen, P. Taboada-González, S. Ojeda-Benítez, and S. Cruz-Sotelo, “Power generation with biogas from municipal solid waste: Prediction of gas generation with in situ parameters,” *Renew. Sustain. Energy Rev.*, vol. 30, pp. 412–419, Feb. 2014, doi: 10.1016/j.rser.2013.10.014.

[18] United States Environmental Protection Agency (US EPA), “Landfill Gas Energy,” *U.S Environ. Prot. Agency [Online]*, pp. 1–34, 2012.

[19] M. A. Al-Anbari, M. Y. Thameer, N. Al-Ansari, and S. Knutsson, “Estimation of Domestic Solid Waste Amount and Its Required Landfill Volume in Najaf Governorate, Iraq for the Period 2015-2035,” *Engineering*, vol. 08, no. 06, pp. 339–346, 2016, doi: 10.4236/eng.2016.86031.

[20] B. Purmessur and D. Surroop, “Power generation using landfill gas generated from new cell at the existing landfill site,” *J. Environ. Chem. Eng.*, vol. 7, no. 3, p. 103060, Jun. 2019, doi: 10.1016/j.jece.2019.103060.

[21] U. S. E. P. A. USEPA, “Landfill gas emissions model. United States Environmental Protection Agency, Version 3.02 user’s guide.,” no. May, p. 48, 2005, [Online]. Available: http://www3.epa.gov/ttncatc1/dir1/landgem-v302-guide.pdf.

[22] M. M. Lopes, V. R. M. Cobas, R. M. Barros, E. E. S. Lora, and I. F. S. dos Santos, “Energy potential using landfill biogas and solar photovoltaic system: a case study in Brazil,” *J. Mater. Cycles Waste Manag.*, vol. 21, no. 6, pp. 1587–1601, Nov. 2019, doi: 10.1007/s10163-019-00904-7.

[24] J. N. Meegoda, H. Hettiarachchi, and P. Hettiaratchi, “Landfill Design and Operation,” in *Sustainable Solid Waste Management*, Reston, VA: American Society of Civil Engineers, 2016, pp. 577–604.

[25] T. R. Ayodele, A. S. O. Ogunjuyigbe, and M. A. Alao, “Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria,” *Appl. Energy*, vol. 201, pp. 200–218, Sep. 2017, doi: 10.1016/j.apenergy.2017.05.097.

[26] C. O. Colpan, I. Dincer, and F. Hamdullahpur, “The reduction of greenhouse gas emissions using various thermal systems in a landfill site,” *Int. J. Glob. Warm.*, vol. 1, no. 1/2/3, p. 89, 2009, doi: 10.1504/IJGW.2009.027083.

[27] T. . Ayodele, M. . Alao, and A. S. . Ogunjuyigbe, “Effect of collection efficiency and oxidation factor on greenhouse gas emission and life cycle cost of landfill distributed energy generation,” *Sustain. Cities Soc.*, vol. 52, p. 101821, Jan. 2020, doi: 10.1016/j.scs.2019.101821.

[28] S. H. Budisulistiorini, “Electricity Generation From Landfill Gas,” *J. Presipitasi Media Komun. dan Pengemb. Tek. Lingkung.*, vol. 3, no. 2, pp. 9–15, 2007, doi: 10.14710/presipitasi.v3i2.9-15.