Estimation of landfill gases in Egypt, 1- evaluation and validation of different models

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Abstract. Alexandria landfill site in El Hammam operated by Onyx since 2003 has been used as an Egyptian landfill case study. Methane generation rates have been estimated using three different simulation models namely: LandGEM, E-PLUS, and the 2006 IPCC Waste Model. The models were run using actual waste quantities disposed at this site together with projected waste quantities till the closure of the landfill site. Power consumption becomes economically feasible only if electricity price is increased locally.

1. Introduction

Greenhouse gas emissions are of high worldwide concern due to their serious effect on climate changes. The whole mankind is responsible for its continuation, which is having significant and negative impacts on people health and life style, natural resources specially water, and economic conditions of the whole world [1-7]. The major greenhouse gases (GHGs) are H2O (g), CO2, CH4 and N2O. Their relative appendance in the emissions is H2O (g) (36-70%), CO2 (9-26%), CH4 (4-9%), and N2O (3-7%) plus other trace gases [5]. CO2 and CH4 are the first and second responsible gases for the global warming [8]. The emissions of these gases are caused by both natural and anthropogenic actions.

Since the preindustrial period, the atmospheric concentration of methane has increased from approximately 400 to 700 ppb up to a global average of 1774 ppb till 2005 [6]; the rate of increase is around 0.6-0.8% annually [9]. Among the different anthropogenic resources of greenhouse gases, the gases generated form Municipal Solid Waste, MSW, dumping sites, landfills, are considered the highest growing source. Landfills represent the dominant alternative for municipal solid waste (MSW) disposal in many parts of the world. For example, it is the utilized technology for 54% of MSW generated in US, 95% of MSW generated in Australia while in, almost 100% of MSW generated in South Africa and over 80% of MSW generated in China. In EU (European Union) Member States, waste management policies and the utilization of refused derivative fuel (RDF) produced from MSW in cement industry have resulted in a reduction of MSW sent to landfills from 62% in 1995 to 41% in 2007 [10]. In principle, any place where Municipal Solid Waste, MSW, is dumped or disposed of in large quantities is considered as a bioreactor generating leachate and gases [10]. The bio-reactions in the waste are dependent upon a series of conditions such as moisture content of waste, composition, availability of oxygen “redox potential”, temperature, micro-flora, and compaction rate. Under strict anaerobic conditions, methane and carbon dioxide are often the primary gases generated. When generated in a landfill, this gas is often known as landfill gas, LFG. Landfill gas is an end-product of the decomposition of biodegradable wastes in a landfill site and is itself legally considered to be a
waste. During recent years and due to the extraordinary increase in domestic wastes, landfills have become important methane emission sources [11–13]. Globally, it is estimated that more than 10% of the total anthropogenic methane emissions originate from landfill gases [14]. Moreover, recent results have shown that landfills generate up to 30% of anthropogenic methane in Europe [15]. Although it is well understood and widely accepted that the impact of LFG emissions on global warming is unignorable, still its direct effect on urban communities in the vicinity of the landfill, which are directly exposed to its emissions, is of great concern. The emissions could cause negative effects when migrating offsite, e.g. damage to vegetation or even explosion hazards. Therefore measuring, estimating and controlling of methane emission on landfills is of great importance [11]. Besides, the estimation of LFG amount is an important process to evaluate the possibility of utilizing this gas in an environmental and economical way. Several reports were published in recent years proposing or utilizing different models for such purpose [8,12,14–24]. The landfill sites and LFG management was the topic of different reports trying to propose the optimum performance and management processes for both of the landfills themselves and LFG generated [25–28].

2. Materials and methods

2.1 Landfill Site

The landfill site at El Hammam has been selected as case study as it fulfills the following requirements for commercial recovery of generated LFG. The landfill site should receive at least 200 ton/day of waste, be designed for a minimum total capacity of 2.5 million ton, and have a minimum filling height of 10 meters. Furthermore, the waste should not have been deposited for more than 5 - 10 years before LFG recovery is attempted. El Hamman landfill site could receive a total of 9.424 million tons and its lifetime is expected to extend up to year 2026 as shown in Table 1. The data provided by the landfill management (Onyx Co) Onyx Company shows that 50% of the waste is organic matter. LFG generation is due to biodegradation of organic waste which follows a pattern of five phases, with different micro-organisms involved at each stage.

Table 1. Requirement for LFG recovery project

| Requirement          | Minimum Requirement | El Hammam Landfill Site (Pelt R., 1998) |
|----------------------|---------------------|----------------------------------------|
| Waste Quantity (t/d) | 200                 | 2,600                                  |
| Total capacity (million ton) | 2.5          | 9,424                                  |
| Filling height (m)   | 10                  | 11                                     |
| Operation start date (y) | 5-10               | 5                                      |

Phase 1: Hydrolysis and aerobic degradation by aerobic micro-biota which metabolize a fraction of the organic waste to produce simpler hydrocarbons, water and carbon dioxide, which is an exothermic process.

Phase 2: Hydrolysis and Fermentation (Acidogenic), which is an aerobic process with the development of anaerobic conditions. A fermentation process takes place developing acids in the leachate.

Phase 3: Acetogenic (Acetogenesis) where anaerobic conditions are established and methanogenic conditions emerge. The LFG will start to contain increasing quantities of methane [11].

Phase 4: Methanogenic where methane production is at its highest, with a stable concentration of 40-60% CH4 by volume. At this point, the chemical processes involved are comparatively slow and can take many years to complete.

Phase 5: Oxidation where methane production will begin to decrease and the presence of atmospheric air will reintroduce aerobic conditions. This phase may be reached only after many decades.
2.2 Approach to achieve study objectives

Figure 1 presents the approach followed to achieve the study objectives of selecting the most cost-effective option of energy utilization.

2.3 Estimation of Landfill gases

The emission rate for nonmethane organic compounds, NMOCs, will be estimated using the following simulation models: (1) The United States Environmental Protection Agency (USEPA) Landfill Gas Emission Model (LandGEM– version 3.02) (Pelt R., 1998; U. S. Environmental Protection Agency (EPA), 2005). (2) Energy Project Landfill Gas Utilization Software (E-PLUS- version 1.0) (Weitz M., 2007). (3) 2006 IPCC Waste Model (Environment Canada, 2003; Pelt R., 1998; Weitz M., 2007).

2.3.1 LandGEM model. The LandGEM uses the following first-order decomposition rate equation to estimate annual LFG, methane and NMOC generation rates over a time period. The LandGEM model parameters are:

- Methane generation rate (k);
- Potential methane generation capacity (Lo);
- NMOC concentration in landfill gas. It is a function of the types of waste in the landfill and the extent of the reactions that produce various compounds from the anaerobic decomposition of waste. NMOC concentration is measured in units of parts per million by volume (ppmv) and is used by LandGEM only when NMOC emissions are being estimated. An NMOC concentration of 4,000 ppmv (Clean Air Act) as hexane was used;
Methane content 40% as per landfill data. Although methane production is not affected by the concentration of methane, production of carbon dioxide depends on this value. The model is described by the following equation:

\[ Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0}^{1} k L_0 \left[ \frac{M_i}{10} \right] e^{-ktij} \]  

(1)

\( Q_{CH_4} \): annual methane generation in the year of the calculation (m³/y)
\( i \): 1-year time increment
\( n \): (year of the calculation) - (initial year of waste acceptance)
\( j \): 0.1-year time increment
\( k \): methane generation rate (year⁻¹)
\( L_0 \): potential methane generation capacity (m³/Mg)
\( M_i \): mass of waste accepted in the \( i \)th year (Mg)
\( t_{ij} \): age of the \( j \)th section of waste mass \( M_i \) accepted in the \( i \)th year (decimal years, e.g., 3.2 years)

2.3.1.1 Estimating \( k \). The values of methane generation rate, \( k \), are given in Table 2. Therefore, the location of El Hammam landfill site is considered an arid area as it receives less than 25 inches (635 mm) of rainfall per year. In line with the USEPA (United State Environmental Protection Agency) recommendation, the \( k \) value for our calculation has been selected at 0.02 for arid area.

| Default Type | Landfill Type | \( k \) value (year⁻¹) |
|--------------|--------------|-----------------------|
| CAA (Clean Air Act) | Conventional | 0.05 |
| CAA          | Arid Area    | 0.02 |
| Inventory    | Conventional | 0.04 |
| Inventory    | Arid Area    | 0.02 |
| Inventory    | Wet (Bioreactor) | 0.7 |

2.3.1.2 Estimating \( L_0 \). The Potential Methane Generation Capacity, \( L_0 \), depends only on the type and composition of waste placed in the landfill. The higher the cellulose contents of the waste, the higher the value of \( L_0 \), and was estimated by the following equation to be 105 m³ CH₄/ t waste

\[ L_0 = MCF \times DOC \times DOC_f \times F \times (16/12) \]  

(2)

\( L_0 \): Potential methane generation capacity of the waste (ton CH₄ / ton Waste)
\( MCF \): Methane Correction Factor
\( DOC \) : Degradable organic carbon in the waste (fraction)
\( DOC_f \): Fraction of organic carbon dissimilated (fraction)
\( F \) : Fraction of CH₄ in the landfill gas (fraction)

16/12 : [molecular weight of methane gas to the atomic Weight of carbon]

According to the 2006 IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories, MCF is assumed to be 1 since the landfill is well managed.

Degradable organic fraction (DOC) is based on the composition of the waste. It is estimated from weighted average of the carbon content of various components of the waste stream. Applying the following equation DOC was found to be 0.155

\[ \% \text{DOC (by weight)} = 0.4(A) + 0.17(B) + 0.15(C) + 0.30(D) \]  

(3)

\( A \): is the percent paper and textiles in the waste
\( B \): is the percent garden and park waste, and other non-food organics
\( C \): is the percent food waste
\( D \): is the percent wood and straw waste
2.3.1.3 Estimating CO\textsubscript{2} generation rate. The production of carbon dioxide (Q\textsubscript{CO2}) is calculated from the production of methane (Q\textsubscript{CH4}) and the methane percentage (P\textsubscript{CH4} = 40%) using the following equation:

\[
Q_{CO2} = Q_{CH4} * 60 / 40
\]  

(4)

2.3.2 E-PLUS Model. E-PLUS developed two methods to estimate methane, NMOC and LFG generation rates which are WIP-30 and First Order Decay.

2.3.2.1 WIP-30. The WIP-30 method uses the amount of waste in place over the past 30 years to estimate methane emissions.

The equations for small landfills (≤ 907,000 tons of waste in place) and large landfills (>907,000 tons of waste in place) in arid and non-arid regions are outlined in Table 3.

Table 3. WIP-30 Equations for Arid and Non-Arid Regions.

|                  | Arid Region                        | Non-Arid Region                     |
|------------------|------------------------------------|-------------------------------------|
| **Small Landfills** | CH\text subscript{4} emission = 18.56025 * (5.3253 * 10^{-6} * W) | CH\text subscript{4} emission = 18.56025 * [6.9492 * 10^{-6} * W] |
| **Large Landfills** | CH\text subscript{4} emission = 18.56025 * [8.22 + (3.1298 * 10^{-6} * W)] | CH\text subscript{4} emission = 18.56025 * [8.22 + (5.0259 * 10^{-6} * W)] |

W = waste in place that is less than 30 years old, (106 tons)
Arid environment = Less than 25 inches of precipitation per year
Non-arid environment = More than 25 inches of precipitation per year

2.3.2.2 First Order Decay. The first order decay equation is the following.

\[
Q = Lo \times R \times (e^{-KCt} - e^{-Kt})
\]  

(5)

Q: Methane generated in current year (m\textsuperscript{3}/yr).
Lo: Methane generation potential (m\textsuperscript{3}/Mg of refuse). Default value for arid environment is 2.7228 ft\textsuperscript{3} per pound of refuse or 170 m\textsuperscript{3}CH\textsubscript{4}/Mg of refuse.
R: Average annual waste acceptance rate during active life (Mg/yr).
K: Methane generation rate constant (yr\textsuperscript{-1}). Default value for arid environment is 0.05 yr\textsuperscript{-1}.
C: time since landfill closure (yr)
t: time since landfill opened (yr)

2.3.3 2006 IPCC Waste Model. The 2006 IPCC waste model provides two options for the estimation of CH\textsubscript{4} emissions from MSW, which can be chosen depending on the available activity data.

2.3.3.1 Waste Composition Model \[17,19,24\]. CH\textsubscript{4} is generated as a result of degradation of organic material under anaerobic conditions. Part of the CH\textsubscript{4} generated is oxidized in the cover of the SWDS (Solid Waste Disposal Sites), or can be recovered for energy or flaring. The CH\textsubscript{4} actually emitted from the SWDS will hence be smaller than the amount generated. The CH\textsubscript{4} emissions from waste for a single year can be estimated using the following equation.

\[
CH_4 \text{ Emissions} = [\Sigma x CH_4 \text{ generated} \times T - RT] \times (1 - OXT)
\]  

(6)

CH\textsubscript{4} Emissions: CH\textsubscript{4} emitted in year T, Gg
T: Inventory time
x: Waste category or type/material
RT: CH\textsubscript{4} Recovery in year T, Gg
OXT: Oxidation factor in year T, (fraction)
Methane recovery (R): CH$_4$ generated at SWDS can be recovered and combusted in a flare or energy device. The amount of CH$_4$ which is recovered is expressed as R. The default value for CH$_4$ recovery is (zero) which is used in our calculations.

Oxidation factor (OX): it reflects the amount of CH$_4$ from SWDS that is oxidized in the soil or other material covering the waste. CH$_4$ oxidation is by methanotrophic micro-organisms in cover soils and can range from negligible to 100% of internally produced CH$_4$. The thickness, physical properties and moisture content of cover soils directly affect CH$_4$ oxidation.

One key input to the model is DOC$_m$ (Degradable Organic material in Gg), calculated on the basis of DDOC$_m$ (Decomposable Degradable Organic material in Gg).

The following two equations are used for calculating DDOC$_m$ accumulated and decomposed at the end of year T. k is the reaction constant.

\[(DDOC_m)^a_T = (DDOC_m)^d_T + ((DDOC_m)^a_{T-1} - 1) e^{-k}) \quad (7)\]

Where
- (DDOC$_m$)$_{aT}$: DDOC$_m$ accumulated in the SWDS at the end of year T, Gg
- (DDOC$_m$)$_{dT}$: DDOC$_m$ deposited into the SWDS in year T, Gg
- (DDOC$_m$)$_{aT-1}$: DDOC$_m$ accumulated in the SWDS at the end of year (T-1), Gg
- k: Reaction constant, k = ln(2) / t$_{1/2}$ (y-1)
- t$_{1/2}$: Half-life time (y)

\[(DDOC_m)^d_T = (DDOC_m)^a_{T-1} * (1 - e^{-k}) \quad (8)\]

Generated Methane can then be calculated from the following equation, where F is the fraction of Methane in the generated gas:

\[CH_4 \text{generated}_T = (DDOC_m)^d_T * F * 16/12 \quad (9)\]

The parameters used as input to the model are shown in Table 4.

2.3.3.2 Bulk Waste Model. The only differences in bulk option calculations are the following:

- DOC value for bulk MSW = 0.12 Gg
- Methane generation rate constant (k) = 0.05

Input values are shown in Table 5.

2.4 Comparison between the different models

Table 6 presents a comparison between the different models used.

3. Results and discussion

3.1 Simulation Results for NMOC, LFG and methane generation

The average NMOC emitted from El Hammam landfill is 367 Mg/yr and 740 Mg/yr as calculated by both LandGEM and E-PLUS model, respectively. The maximum value for NMOC emitted during landfill lifetime is 577 Mg/yr and 1,240 Mg/yr as predicted by both LandGEM and E-PLUS models respectively. Figure 2 illustrates the NMOC annual generation rates as predicted by simulation models.

The emission rates for methane and landfill gas have been estimated using the three simulation models and the results are presented in Figure 3. The results show that the total CH$_4$ flow during 2003-2045 ranges between $1.018 \times 10^{10}$ ft$^3$/yr based on the 2006 IPCC bulk option and $2.156 \times 10^{10}$ ft$^3$/yr based on the E-PLUS WIP-30 method. Maximum methane generation rate during 2003-2045 ranges between $4.129 \times 10^{8}$ ft$^3$/yr based on the E-PLUS model – WIP30 calculation method and $7 \times 10^{8}$ ft$^3$/yr based on the 2006 IPCC model – Bulk Option. The average annual methane generation rate during 2003-2045 ranges between $2.367 \times 10^{8}$ ft$^3$/yr based on the 2006 IPCC bulk option and $5.014 \times 10^{8}$ ft$^3$/yr based on the E-PLUS WIP-30 method. Figure 4 represents the results of such simulations.
Table 4. The 2006 IPCC Waste Model Input Parameters, Waste Composition Option.
Table 5. The 2006 IPCC Waste Model Input Parameters; Waste Bulk Option.

| Parameters                          | IPCC default value | Country-specific parameters |
|-------------------------------------|--------------------|-----------------------------|
|                                     | Value              | Reference and remarks       |
| **Country**                         |                    |                             |
|                                     |                    |                             |
| **Region**                          |                    |                             |
|                                     |                    |                             |
| **Starting year**                   | 2003               | 2003                        |
| **DOC (Degradable organic carbon)** |                    |                             |
| **Bulk**, weight fraction, wet basis |                    |                             |
| Bulk MSV                            | 0.12-0.28          | 0.16                        |
| Industrial waste                    | 0-0.54             | 0.15                        |
| Sewage sludge                       | 0.04-0.05          | 0.06                        |
| **DOCf (fraction of DOC dissimilated)** | 0.5               | 0.5                         |
| **Methane generation rate constant (k)** |                |                             |
| **Bulk**, years⁻¹                   | 0.04-0.06          | 0.05                        |
| Industrial waste                    | 0.04-0.06          | 0.05                        |
| Sewage sludge                       | 0.05-0.08          | 0.06                        |
| **Delay time (months)**             |                    | 6                           |
| **Fraction of methane (F) in developed gas** | 0.5               | 0.37                        |
| **Conversion factor, C to CH₄**     | 1.32               | 1.32                        |
| **Oxidation factor (OX)**           | 0                  | 0.1                         |

The 2006 IPCC Waste Model Input Parameters; Waste Bulk Option.
Table 6. Comparison between the different models.

| Parameters/Assumptions | LandGEM | E-PLUS | 2006 IPCC |
|-------------------------|---------|--------|------------|
|                         |         |        | Compositio n | Bulk |
| Rate equation           | 1\textsuperscript{st} Order | 1\textsuperscript{st} Order | Empirica | 1\textsuperscript{st} Order |
| Landfill Closure Year   | 2026    | 2026   | 2026       | 2026   |
| Model Inputs            | K as bulk, Waste Qty per year | K as bulk, Waste Qty per year | DOC and K for waste comp. Waste Qty per capita | DOC and K for bulk waste. Waste Qty per capita |
| Model Outputs           | LFG, CH\textsubscript{4}, CO\textsubscript{2}, NMOC | LFG, CH\textsubscript{4}, NMOC. Environmental Benefits Analysis. Economical Analysis | CH\textsubscript{4} ONLY total and for each waste component | CH\textsubscript{4} ONLY total |
| Comments                | Simple Approach | Simple Approach | Complex | | |

Figure 2. NMOC generation rate using the different models.
3.2 Model validation

The current collection and flaring system in El Hammam landfill site implemented in August 2006 is assumed to have a collection efficiency of 70% [13] with a maximum design inlet LFG flow rate to the flaring system equivalent to 2500 m$^3$/h. This means that approximately 1.104 x 10$^9$ ft$^3$/y is generated at the landfill site assuming the same collection efficiency in order to meet the existing inlet flare design flow rate. We can conclude from the results presented in Graph 4 that all annual LFG
generation rate estimated by simulation models are in coherence with the existing flare design flow rate at 70% collection efficiency except for the over estimated value from the E-PLUS model – WIP30 method (1.323 x 10^9 ft³/y).

Furthermore, the 2006 IPCC model – Bulk Option seems to be under estimating the LFG generation rate. These two methods are also presenting overestimating and underestimating values as well for methane generation rate as illustrated in Figure 5. Consequently, these two methods are suggested to be excluded from further evaluation in order to ensure conservativeness. 2006 IPCC Waste Model. E-PLUS First-Order Decay Method was found to be the more conservative method in assuming the maximum methane generation rate per year over the studied period from 2003-2045.

![Figure 5.](image)

**Figure 5.** top: LFG generation rate and bottom Methane generation rate.

4. Conclusion

Methane generation rates from Alexandria landfill site in El Hammam have been estimated using three different simulation models namely: LandGEM, E-PLUS, and the 2006 IPCC Waste Model. E-PLUS First-Order Decay Method was found to be the more conservative method in assuming the maximum methane generation rate per year over the studied period from 2003-2045. Therefore, this conservative method is suggested for evaluating different energy utilization options.
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