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Evaluation of the Energy Capacity of the Controlled Landfill from Mohamedia Benslimane by Three Theoretical Methods – Land Gem, IPCC, and TNO

Ahlam Idrissi Oukili[1*], Mostafa Chhiba[1]

[1] Laboratory of Radiation-Material and Instrumentation, Faculty of Science and Technology of Settat, Hassan First University of Settat, Km 3.5, Road to Casablanca, 26000, Settat, Morocco

* Corresponding author's e-mail: ahlamidrissioukili@yahoo.fr

ABSTRACT

The objective of this study was to estimate the content of methane produced and generated by the anaerobic biodegradation of the main organic fraction of municipal solid waste from the controlled landfill of Mohammedia-Benslimane (Morocco) by three theoretical models, based on the first order decay equation: LandGEM, IPCC and TNO. To carry out this study, the quantities of solid waste buried in this landfill since its inauguration in 2012 were used and the composition of the biogas in-situ in 2020 and 2021was determined. The quantities of waste that will be buried in this landfill from 2022 to 2032 were estimated by projection.The results of the analysis of the biogas generated in this controlled landfill in 2020–2021 indicate that it is composed of 59.59% CH_4, 38.9% CO_2, and 0.14% O_2. This result indicates that the waste is in a stable methanogenesis phase. The results obtained by using the three methodologies show that the total volume of CH_4 generated during the period 2012–2021 was 32.59 Mm^3 according to the IPCC model, 20.95 Mm^3 according to the LandGEM model and 20.96 Mm^3 according to the TNO model. The total volume of CH_4 that will be produced during the period 2022–2032 has been projected to 107.48 Mm^3 by the IPCC model, to 76.84 Mm^3 by the LandGEM model, while the total volume of CH_4 projected under the TNO method will be 67.67 Mm^3. The maximum methane production will reach a value of 12.07 Mm^3, 9.46 Mm^3 and 7.82 Mm^3 for the IPCC, LandGEM and TNO models, respectively. In 2021, the volume of methane estimated by the three models is higher than that on-site measurement by a factor of 3.5(IPCC), 2.4 (LandGEM) and 2.3 (TNO). The results clearly indicate that the three models over predict methane generations when compared to the on-site generations. According to the LandGEM methodology, the electricity estimated will reach a maximum value of 33 GWh/year in 2032.The efficient use of methane generated by this controlled landfill as a source of electrical energy in the upcoming years can be an option for the sustainable management of waste.

Keywords:controlled landfill, municipal solid waste, biogas, first order decay model, electrical energy.

INTRODUCTION

In the last decade, Morocco has a strong growth in the legal population which was estimated at 33,848,242 inhabitants following the statistical of the High Commission for Planning (RGPH) during 2014, and also the industrial expansion is increasing. Indeed, the improvement of lifestyles of Moroccan citizens and the proliferation of outlying neighborhoods around the largecities have led to an increase in the quantity of household and similar waste.

The management of municipal solid waste has become a major problem in modern society. Total national waste production is 6.98 million tons per year, including 5.5 million tons in urban areas, and can reach 9.3 million tons in 2030 [El-Ajraoui et al., 2019]. Good planning for the management of household solid waste (MSW) not only solves the problems of disposal of this waste, but also generates revenue for society. Management strategies depend primarily on the chemical composition of the waste and may include: recycling, composting, heat treatment, anaerobic digestion and landfilling. It should be noted that landfill is considered to be the least expensive and most adopted way to treat waste (80% of the world practices) [Kumar and Sharma., 2014].

Uncontrolled landfills do not have landfill gas monitoring and recovery, leachate collection, base coating, compaction, and waste cover systems. By adopting the Sanitary Landfill concept, the problems of leachate contamination of groundwater increased greenhouse gas emissions, fire and hazard explosion, risks to human health, and sanitary problems can be avoided, while additional revenues can be generated from the production of landfill gas.

Since the Moroccan state ratified the Kyoto Protocolon 16th February 2005, it has continued to improve environmental projects, including those of municipal solid waste management. These projects concern the construction of controlled landfills and their evolution into landfills and recovery centers, and the rehabilitation of old uncontrolled landfills, in order to fight against the potential risks of environmental degradation.

Cudjoe et al., conducted a study on a project in urban Africa, about the economic feasibility and environmental impact analysis of a landfill gas to energy conversion [Cudjoe and Han., 2021]. They showed on the one hand that a project to convert landfill gas into energy for Morocco has a positive net present value; on the other hand, they reported that on average a landfill gas to electricity conversion project could reduce the global warming potential with 72.2% but could lead to an 8.9% increase in acid gas emissions (SO_2 and HCl). It should be noted that methane has a warming potential 21 times that CO_2 [Noor et al., 2013].

For example, in the city of Fez (Morocco), the biogas produced by the anaerobic decomposition of solid waste buried in the controlled landfill is converted into electrical energy [Saghir et al., 2018]. To counter the nuisances induced by biogas and specifically methane, the Bikarane landfill in Greater Agadir (Morocco) was rehabilitated by installing an active degassing system. In this landfill, biogas is converted into thermal energy whose objective is to treat by forced evaporation leachates from the new controlled landfill of Agadir (Tamellast) [El-Ajraouiet al., 2019].

Mohammedia-Benslimane Intercommunal Controlled Landfill was selected as an appropriate case study, as it receives waste from nine municipalities (Waste Accepted Rate = 182 500 Mg/year). It is worth noting that the biogas generated in this landfill is regularly monitored by analyzing its quality, and by measuring its composition and volume flow. This biogas is destroyed by flaring at a temperature above 900 °C to reduce its negative impact on the environment, but this type of management does not allow exploiting the potential of this biogas in the production of thermal energy or electrical energy.

In a previous study, the authors used the LandGEM model to estimate the methanogenic and energetic potentials as well as the evaluation of the carbon footprint of Mohammedia-Benslimane controlled landfill [Oukili et al., 2022]. The purpose of this study is to estimate the biogas generated in this controlled landfill by three theoretical models (LandGEM, IPCC and TNO), widely described in the literature, and to predict its potential energy if a landfill biogas-to-electricity project is installed in the upcoming years.

MATERIAL AND METHODS

Study area

The total surface of the controlled landfill of Mohammadia-Benslimane is 109 ha. The area reserved for burial is 47 ha. It has a capacity of 5 million cubic meters and was inaugurated on 27th February 2012. The landfill is situated at 800 meters from Provincial Road RP 3313, 8 km southeast of the of Beni Yakhlef center, 24 km southwest of Benslimane and 17 km east of Mohammedia (Fig. 1). During the year, in Beni Yakhlef, the average of precipitation and temperature is 461 mm and 18 °C, respectively.

Municipal solid waste characterization

The landfill receives a total of 500 tons/day of municipal solid waste (MSW). The landfill area is divided into five cells, used for MSW disposal, and it is expected to operate for 20 years (to 2032). The landfill was sequentially implemented cell by cell. Four cells were put into operation, totaling 13.33 hectares: Cell 1 (3.92 ha), Cell 2 (3.37 ha), and Cell 3 (2.38 ha) are closed. Cell 4 has an area of 3.68 hectares and is currently active, whereas the fifth cell with an area of 4.02 hectares is not yet operational. The total buried MSW was 2 million tons in 2021. The Annual MSW quantities are presented in Figure 2.

Figure 1. Geographic location of the studied area

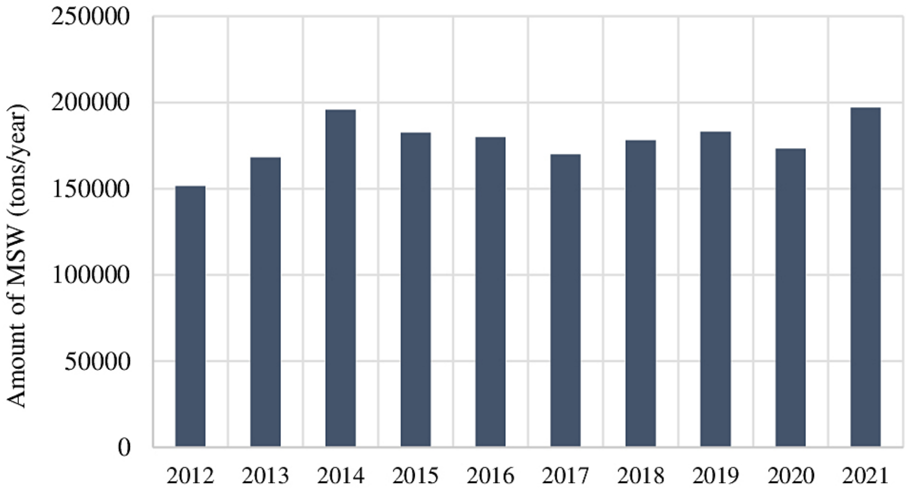

Figure 2. Annual amount of MSW received and buried at Landfill (2012–2021)

Since 2012, the controlled landfill has receivedseveral waste categories from nine local communities of the province of Benslimane and the region of Mohammedia (Table 1). The Mohammedia' communes are: the two urban communes (Mohammedia (Moh-C) and Ain Harrouda (Ah-C), and four rural communes particularly Sidi Moussa Ben Ali (SmBea-C), Sidi Moussa AlMajdoub (SmAlm-C), Ech-chaellalete (Ech-C) and (Beni Yakhlef (Bey-C). The three urban communes of Benslimane are: Mansouria (Mans-C), Bouznika (Boz-C) and (Benslimane (Bes-C).

It can be seen that the largest fraction of household waste is found in waste buried in the Mohammedia-Benslimane landfill (79%). A study conducted at this landfill in 2016 (ECOMED), revealed that the organic fraction (composed mainly of food waste) is the largest in municipal solid waste leaking into this controlled landfill (60.81%), followed by plastics (13.09%), textiles and sanitary textiles (12.21%), paper and cardboard (8.08%), ceramic glass-scrap (1.70%), others (1.58%), metals (1.36%) and wood (1.20%).

Table 1. Different categories of waste buried at years 2020 and 2021 in the studied regions (ECOMED)

Categories of waste	Annual amount of MSW (ton/year)		Average percentage (%)
	Year 2020	Year 2021	
Household waste	162,625	183,984	79.00
Green waste	2,564	4,316	1.57
Household waste - soil-gravel mixture	7,937	8,616	3.77
Gravel	570	630	0.27
Ordinary industrial waste	33,901	33,620	15.39

The amount of municipal solid waste (MSW) buried at this site from 2012 to 2021 was provided by the ECOMED group. That from 2022 to 2031 was extrapolated using the demographic data of these nine municipalities. The General Census of Population and Habitat (RGPH-2004-2014) mentioned that the population of the regions studied increased from 410, 832 inhabitants in 2004 to 518, 840 inhabitants in 2014 with an annual growth rate of 2.36%.

On the basis of the available data on the quantity of waste buried in this landfill and the population, during the three years 2019, 2020 and 2021, it was possible to estimate a weighted average value of the specific production of waste per day for this area (0.883 kg/inhabitant/day). It should be noted that this daily production represents only a fraction of the waste landfilled and not all the waste generated by the population in this area. On the basis of this value, it was possible to estimate the annual amount of waste that will be landfilled from 2022 to 2031, as well as the total amount of waste that will be in place at this landfill in 2032 (4.06 E+6 tons). A total waste quantity very close to that estimated by the specific daily production (0.883 kg/inhabitant/day) was obtained using the average annual growth rate of solid waste buried from 2012 to 2021 (2.96%). This average annual growth rate was calculated using the exponential model (Eq. 1) [Mavridis and Voudrias., 2021]:

$$P_n = P_o\left(1 + \frac{\tau}{100}\right)^n \tag{1}$$

where: P_n – MSW production in year n, 2012 (151,501 Mg/y);
P_o – MSW production in base year, 2021 (196,916 Mg/y);
τ – annual rate of change (2.96%);
n – number of years (n = 9).

Table 2. Quantities of solid waste landfilled from 2012 to 2021 and their estimation from 2022 to 2032

Year	Waste disposal per year (Mg/year)	Accumulated disposed waste (Mg)
2012	151,501	151,501
2013	168,008	319,509
2014	195,617	515,126
2015	182,360	697,486
2016	179,862	877,348
2017	169,854	1,047,202
2018	178,033	1,225,235
2019	182,983	1,408,218
2020	173,126	1,581,344
2021	196,916	1,778,260
2022*	204,055	1,982,315
2023*	209,360	2,191,675
2024*	214,841	2,406,516
2025*	220,505	2,627,021
2026*	222,710	2,849,731
2027*	228,620	3,078,351
2028*	234,729	3,313,080
2029*	241,043	3,554,123
2030*	247,570	3,801,693
2031*	254,318	4,056,011
2032	0	4,056,011

* Projected values.

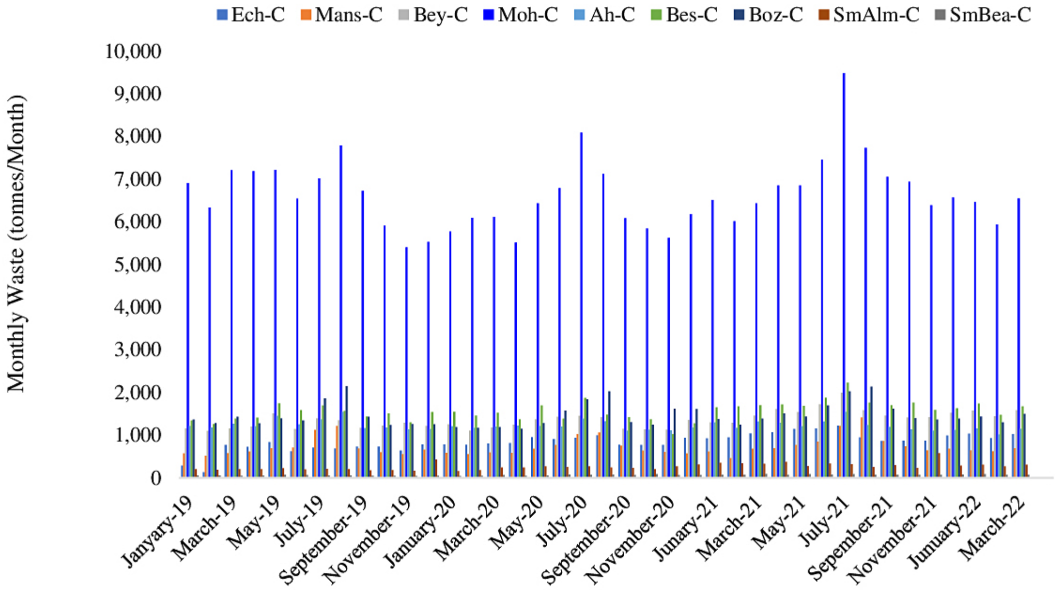

Figure 3. Monthly MSW received at Landfill (January 2019-March 2022)

The waste received in the landfill is regularly checked, weighed and the data are registered (average about 500 tons/day). This process has been ongoing since the opening of the landfill in 2012. In this study, the data available from 2012 to 2021 (ECOMED) was used and then projected to 2032, i.e. the year planned for the closure of the landfill. Table 2 shows the annual amount of waste landfilled in tons at the Mohammedia-Benslimane controlled landfill from 2012 to 2021.

On the basis of the amount of municipal solid waste landfilled for each month and in each municipality in this area from January 2019 to March 2022 (ECOMED), it has been remarked that the urban municipality of Mohammedia (Moh-C) is the main producer of household waste;it is larger compared with other municipalities (Fig. 3) since it has the highest population density. In addition, an increase in waste produced was observed during the summer period of each year (June, July, and August) in all the regions.

Estimation of methane generation using different methods (FOD)

To estimate the generation of biogas from the controlled landfill, the first-order models used were the Landfill Gas Emissions model LandGEM [EPA USA 2008], the Intergovernmental Panel on Climate Change model IPCC [IPCC 2006] and the TNO model [Kumar and Samadder., 2017].

Model of LandGEM

To estimate the amount of landfill gas generation using a first order equation (Eq. 2), the LandGEM model is usually used.

The control technology center of the American Environmental Protection Agency (US.EPA) has developed this model for the prediction of gaseous pollutant generation by decomposition solid waste.

It considers (i) the characteristics and content of the buried waste during consecutive years, (ii) the characteristics of the biogas produced and (iii) particularly the meteorological conditions in the studied regions. It allows predicting of CH_4 and CO_2 quantities that will beproduced up to 140 years from the first-order decomposition equation [EPA USA 2008]. In order to increase the accuracy of the estimation process, the CH_4 generation equation (Eq. 2) considers increments of one tenth (1/10) of a year.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} k * L_0 * \left(\frac{M_i}{10}\right) * e^{-kt_{i,j}} \quad (2)$$

where: Q_{CH_4} – annual methane generation the calculated year (m^3 $year^{-1}$);
i – is the one year time increment;
n – defines as (year of the calculation) – (initial year of waste acceptance);
j – the 0.1 year time increment;
L_0 – potential methane production capacity (m^3/Mg);
k – methane generation rate ($year^{-1}$);
M_i – mass of waste accepted in the ith year (Mg);
$t_{i,j}$ – age of the jth section of waste mass Mi accepted in the ith year (decimal years, e.g., 3.2 years).

To conduct thestudy, the required inputs for estimating the amount of generated landfill gas are both the landfill opening and closure year, the annual waste acceptance rates from the opening to the closure year, the methane generation rate k (1/year), the potential generation of methane L_0 (m^3CH_4/ton-waste) and the methane proportion in the biogas and Nom Methane Organic Compound concentration (NMOC).

Methane generation potential (L_0) depends on the type and composition of waste buried in the landfill. Thewaste with higher cellulose content would have higher methane generation potential, while the waste having lignin content have lower L_0 value [Kumar and Sharma., 2014]. The methane generation rate k depends on four factors: moisture content, availability of the nutrients for bacteria, temperature and the pH of buried waste.

The model contains two sets of default parameters, Inventory defaults and CAA defaults (Table 3) [Krause et al., 2016].The inventory defaults are based on the emission factors in EPA's Compilation of Air Pollutant Emission Factors (AP-42). The CAA defaults are based on the USA federal regulations for MSW landfills laid out by the Clean Air Act (CAA). LandGEM model uses the following first-order decay equation (Eq. 2) to estimate the methane generation rates over a specified time period.

The degradable organic carbon (DOC) is entered into equation 3 to yield the methane generation potential (L_0) [Ayodele et al., 2017; Pillai and Riverol., 2018; Atabi et al., 2014]:

Table 3. Default values for methane generation potential (L_0) and rate (k)

Default type	Landfill type	L_0(m^3/Mg)	k ($year^{-1}$)
CCA	Conventional (rainfall >25 in/year)	170	0.05
CCA	Arid area (rainfall < 25 in/year)	170	0.02
Inventory	Conventional (rainfall >25 in/year)	100	0.04
Inventory	Arid area (rainfall < 25 in/year)	100	0.02
Inventory	Wet (bioreactor)	96	0.70

$$L_0 = MCF * DOC * DOC_f * F * \left(\frac{16}{12}\right) \quad (3)$$

where: L_0 – the methane generation potential (kg CH_4/Mg-waste);
MCF – the methane correction factor (MCF = 1 for sanitary landfills, 0.4 – 0.8 for waste dumps);
DOC – the degradable organic yielded on of methane in landfill gas (0.5 default), and 16/12 is the stoichiometric factor (the ratio of the molecular mass of methane to carbon ($M(CH_4)/M(C) = 16/12$);
F – fraction of methane in biogas (%v).

The degradable organic carbon (DOC) is simply calculated using equation 4 and the waste characterization data for this landfill (Table 4).

$$\mathrm{DOC} = (0.40 * \mathrm{A}) + (0.17 * \mathrm{B}) + \\ +(0.15 * \mathrm{C}) + (0.30 * \mathrm{D}) \quad (4)$$

For the estimation of the methane generation potential [according to Eq. 4] the following values have been applied: MCF = 1 (managed landfill); DOC = 0.2015 kgC/kg-waste; DOC_f = 0.50 and F = 0.60 (*on-site measurement*). Hence, the methane formation potential L_0 = 120 m^3/ton (*density of methane* = 0.667 kg/m^3).

It should be noted that several published scientific papers on the estimation of biogas emissions from landfills, the researchers used equation 5 to calculate the value of the constant k (methane generation rate) [Plocoste and Koaly., 2016; Kale and Gökçek., 2020; Kumar and Sharma., 2014]:

Table 4. Percentage of different solid waste components

Waste type	A	B	C	D
Percentage (%)	19.4	3.1	75.9	1.6

Note: A – fraction of municipal solid waste (MSW) that is paper and textiles, B – fraction of MSW that is garden or park waste, C – fraction of MSW that is food waste, D – fraction of MSW that is wood or straw waste.

$$k\ (year^{-1}) = (3.2 * 10^{-5} * X) + 0.01 \quad (5)$$

where: X – represents the average annual precipitation (in mm) of the area where the landfill is located.

In this study, the parameters that were used for methane estimation by the LandGEM model are:

- methane generation potential: L_0 = 120 m^3/Mg;
- methane decay rate: k = 0.024 $year^{-1}$;
- fraction of methane in biogas: F = 0.60 (*on-site measurement*);
- IPCC model (first order decay (FOD)).

IPCC first order decay method model is based on three main equations (Eq. 6, Eq. 7 and Eq. 8, with its parameters described in Table 5 [IPCC 2006; Ghosh et al., 2019].

$$DDOC_{maT} = DDOC_{mdT} + \left(DDOC_{md(T-1)} * e^{-k}\right) (6)$$

$$DDOC_{mdecompT} = DDOC_{ma(T-1)} * (1 - e^{-k}) \quad (7)$$

$$CH_{4_{generatedT}} = DDOC_{mdecompT} * F * \left(\frac{16}{12}\right) (8)$$

Taking into account the climatic conditions in the region where this controlled landfill is located, the following default methane generation rate values were used [IPCC 2006]: $k_{Foodwaste}$ = 0.06 $year^{-1}$, k_{Paper} = 0.04 $year^{-1}$, $k_{Textiles}$ = 0.04 $year^{-1}$, $k_{Hygiene\ nappies}$ = 0.05 $year^{-1}$ and k_{Wood}= 0.02 $year^{-1}$.

Table 5. IPCC model parameters

Parameter	Description
T	Inventory year
$DDOC_{maT}$	DOC mass accumulated at the end of year T (Gg =10^9 g)
$DDOC_{mdT}$	DOC mass deposited year T (Gg)
$DDOC_{md(T-1)}$	DOC mass deposited in year T-1 (Gg)
k	Decay constant
$DDOC_{mdecompT}$	DOC mass decomposed in year T (Gg)
$DDOC_{ma(T-1)}$	DOC mass accumulated at the end of year T-1 (Gg)

Methane generation potential depends on the type and the composition of waste buried in the landfill. The waste composition in 2016 (ECOMED) was used in this study as the input for the IPCC method. The following default values of DOC fraction of degradable organic carbon (*weight fraction, wet basis*) were used in this study: $DOC_{Foodwaste} = 0.15$, $DOC_{Paper\ waste} = 0.40$, $DOC_{Textiles\ waste} = 0.24$, $DOC_{Hygiene\ nappieswaste} = 0.24$ and $DOC_{Wood\ waste} = 0.43$.

Methane correction factor (MCF) and fraction of DOC dissimilated (DOC_f) were chosen at 1 and 0.50 respectively. Fraction of methane CH_4 (*volume fraction*) in biogas produced in this landfill was F = 0.60 (*on-site measurement*).

TNO model

Although the TNO model was developed for the waste characteristics of the Netherlands, it can be used for landfill gas estimation for other countries, as it has less relative mistake (22%) between the observed and calculated values. The TNO model equation (Eq. 9) [Kumar and Samadder, 2017]:

$$\alpha_t = \varsigma * 1.87 * A * C_0 * k_1 * e^{-k_1 * t} \tag{9}$$

where: α_t – landfill gas production at a given time (m^3/year);
ς – dissimilation factor 0.58;
1.87 – conversion factor;
A – amount of waste (in ton);
C_0 – amount of organic carbon in waste (kg of C/ton of waste);
k_1 – degradation rate constant ($year^{-1}$);
t – time elapsed since depositing (year).

To estimate the methane generated by the TNO model, the same parameters as the LandGEM modelwere used.

Estimation of electrical energy

The electrical energy produced from methane generated in the landfill is a common application and its use is very beneficial. Electricity can be generated by burning in a generator or gas turbine the methane. The equation (Eq.10) [Saghir et al., 2018] was used to estimate the potential for electric power generation from landfill methane recovery.

$$E_{elc} = LCV * r_{elc} * Q_{CH_4} \tag{10}$$

where: E_{elc} – annual production of electricity in (kWh/year);
LCV – lower calorific value of methane (9.94 kWh/m^3);
Q_{CH_4} – annual methane generation in the year generated by anaerobic decomposition in Landfill in (m^3/year);
r_{elc} – efficiency of the facility producing electricity from methane generated by anaerobic decomposition in Landfill (35%).

RESULTS AND DISCUSSION

The results of the conductedstudy are presented in three parts:

- characterization of the produced biogas;
- estimating the methane's amount produced using three models: LandGEM, IPCC, and TNO;
- estimating the electrical energy potential of this controlled landfill.

Characterization of landfill biogas

The Mohammedia-Benslimane controlled landfill receives about 500 tons of waste per day, composed of biodegradable and non-biodegradable fractions. The carbon dioxide $CO_2$and methane CH_4 which are greenhouse gases, are the main products of biodegradable organic waste through anaerobic decomposition. At this site, the biogas analyses showed the average methane content of around 60% by volume. Table 6 gives the results of measures taken in 2020 and 2021. It is worth noting that

Table 6. Biogas quality at the controlled landfill (ECOMED)

Year		CH_4 (% vol)	CO_2 (% vol)	O_2 (% vol)	Flow of biogas (Nm^3/h)	$T_{(enclosed\ flare)}$ (°C)
2020	February	59.48	38.10	0.18	326.8	994.8
	March	59.64	39.02	0.11	315.7	1041.2
	April	59.57	39.37	0.11	329.1	1009.5
	Jun	59.60	38.68	0.14	317.9	1013.4
	Average	59.59	38.97	0.13	326.2	1005.5
2021	July	59.72	38.94	0.14	314.9	1015.6

(76 days – February-March-April and May 2020; 25 days – July 2021)

the open fraction of the extraction of biogases valve is only 22.5%. The biogas is collected by a network of horizontal wells up to the flaring system to undergo the combustion reaction at a temperature above 900 °C.

According to the results presented in Table 6, there is no significant variation in the composition of biogas overtime during the period 2020–2021, as the recorded values are very close. The value of the combustion temperature in the enclosed flare shows that the biogas is burned more efficiently to produce CO_2, H_2O and other pollutants in very small amounts. Since CH_4 methane has a global warming potential (GWP) of 21 more than CO_2, capturing and destroying it by flaring contributes to a significant reduction in the greenhouse effect. The enclosed flare burns biogas with an average flow rate of 320 Nm^3/h (337.6 m^3/h). The average percentage of methane measured is 59.66%, so the flare burns 201.4 m^3 of methane per hour, or 302 kg of CH_4. The global warming potential (GWP) of this mass of CH_4 when released to the atmosphere is:

$$302\ \text{kg}\ CH_4 \times 21 = 6342\ \text{kg eq}CO_2$$

During the complete combustion of the biogas flare (Eq. (11)):

$$CH4(g) + 2\ O2(g) \rightarrow CO2(g) + 2\ H2O(g) \quad (11)$$

$$302\ \text{kg}\ CH_4 \times 44/16 = 830.5\ \text{kg eq}CO_2$$

Either a reduction of 5511.5 kg eqCO_2 per hour or a reduction of 48.28 Gg eqCO_2 per year is achieved.

It can be concluded that the flaring system with active degassing, installed at this controlled landfill, will contribute to a reduction of emissions of 482.8 Gg eqCO_2 from 2022 to 2032. The percentages of CH_4 and CO_2 are in accordance to the values mentioned in literature during the methanogenesis phase anaerobic decomposition of the organic fraction of the waste: 60% CH_4 and 40% CO_2 (Williams., 2005). Similar results have been reported in the literature [Plocoste and Koaly, 2016]. The CH_4/CO_2 ratio value of 1.53 and the very low amount of O_2 dioxygen (< 1% by volume) in biogas indicate that landfill waste is in an advanced and stable biodegradation state (maturation), and that the degassing system and waste cover layers are sealed. It can be concluded that this controlled landfill has a large capacity to produce methane, which could be upgraded for the production of electrical energy.

It The concentration measured of hydrogen sulfide H_2S (1102 ppm in July 2021) at the landfill can be explained by the anaerobic decomposition of high levels of protein-rich food waste, especially amino acids (cysteine HS-CH_2-CH(NH_2)-COOH and methionine CH_3-S-CH_2-CH-CH(NH_2)-COOH)), and reduction of sulfate ions by Bacteria (BSR) [Ko et al., 2015].

It should be noted that during the methanogenesis stage, more H_2S is produced. Sulfur compounds are one of the dominant chemical groups in landfill gas and H_2S hydrogen sulfide alone accounts for almost 90%, and its concentration in biogas from municipal solid waste landfills can be as high as 2340 ppm [Kim et al., 2005]. Low concentrations were measured in closed or old landfills, while the active landfills were responsible for the higher concentrations [(Duan et al., 2021)]. For example, the average concentration of H_2S in landfill gas from the rehabilitated landfill in Agadir is 16 ppm [El-Ajraoui et al., 2019]. It should be noted that H_2S in biogas is destroyed by combustion in the flares by the following chemical reaction: (Eq. 12):

$$H2S(g) + 1.5\ O2 \rightarrow SO2(g) + H2O(g) \quad (12)$$

Estimating the methanogenic potential of the controlled landfill

For the first year 2012, there was no biogas production. The models suppose that the anaerobic decomposition stage begins at least 6 months after the landfill of the waste. Several factors are responsible of the degradation of waste: climatic conditions, type of waste, moisture in the waste and the materials that cover the waste.

The quantities of CH_4 methane produced by the decomposition of the organic fraction of municipal solid waste buried in this controlled landfill over the period 2012-2032 (2032 is the year planned for closure of this site) are presented in Table 7. The results obtained show that the total volume of CH_4 generated during the period 2012–2021 was 32.59 Mm^3 according to the IPCC model, 20.95 Mm^3 according to the LandGEM model and 20.96 Mm^3 according to the TNO model. The total volume of CH_4 that will be produced during the 2022-2032 period has been projected to 107.48 Mm^3 by the IPCC model, 76.84 Mm^3 by the LandGEM model, while the total volume of CH_4 projected by the TNO method will be 67.67 Mm^3. It wasfound that the annual estimated amount of methane (m^3 CH_4/year) by the three models increases with the years and reaches a maximum value in 2032 (Fig. 4), which is the year expected for the closure of the site. The maximum methane production will reach a value of 12.07 Mm^3, 9.46 Mm^3 and 7.82 Mm^3 for the IPCC model, LandGEM model and TNO model, respectively. In 2021, the volume of methane estimated by the three models is higher than that on-site measurement by a factor of 3.5 (IPCC model), 2.4 (landGEM model) and 2.3 (TNO model). The results obtained with the models LandGEM and TNO were almost similar during the period 2012–2032.However, the IPCC model yields values differ markedly from those obtained by the LandGEM and TNO models. This difference can probably be explained by the fact that the k value used for the LandGEM and TNO models is low (0.024 year^{-1}) compared to the k default values used for the IPCC model. This result clearly indicates that the three models over predict methane generations when compared to the on-site generations. After 2032, methane production decreases exponentially over time, as the site will

Table 7. Predicted methane estimation from the landfill from 2012 to 2032 IPCC, TNO LandGEM

Year	Methane generated CH$_4$ (m^3/year)			
	IPCC	LandGEM	TNO	On-site measurement
2012	0	0	0	
2013	721,671	431,646	461,091	
2014	1,484,555	900,087	949,361	
2015	2,338,675	1,436,080	1,494,303	
2016	3,085,027	1,921,592	1,975,321	
2017	3,780,570	2,388,474	2,425,777	
2018	4,392,243	2,815,769	2,826,744	
2019	5,011,118	3,256,234	3,228,883	
2020	5,621,476	3,700,358	3,623,095	1,807,696
2021	6,153,265	4,105,865	3,972,035	1,741,155
2022	6,770,911	4,569,537	4360,728	
2023	7,390,629	5,042,553	4,745,842	
2024	8,003,605	5,519,466	5,122,639	
2025	8,611,063	6,000,686	5491,402	
2026	9,214,193	6,486,632	5,852,413	
2027	9,796,773	6,967,336	6,198,009	
2028	10,377,553	7,453,479	6,536472	
2029	10,957,601	7,945,499	6,868,061	
2030	11,537,953	8,443,840	7,193,026	
2031	12,119,630	8,948,960	7,511,612	
2032	12,703,636	9,461,327	7,824,059	

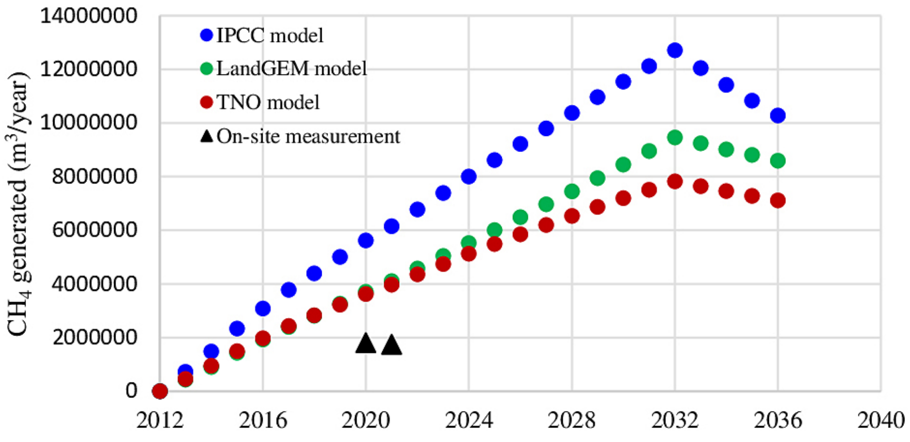

Figure 4. Comparison of modeled (IPCC, LandGEM and TNO) and on-site measurement methane flow at landfill

no longer be powered by waste sources of biodegradable organic matter. It should be noted that this result is in good agreement with the literal value [Kumar and Sharma, 2014].

The difference between the estimated amount of methane by the three theoretical models and that measured on the site can be explained by the fact that the opening of the valve of the biogas extractor (PID) is only 22.5%. It worth noting that theoretical models for estimating landfill gas may overestimate or underestimate the amount of biogas relative to that measured on the site.

A literature review of landfill biogas estimation models has shown that many researchers around the world have applied the LandGEM model. Indeed, this model gives current and future projections of the greenhouse gas (GHG) emission potential, in particular methane, and has the ability to estimate emissions of more than 46 gaseous pollutants such as organic and inorganic sulfur compounds, in particular H_2S. If landfill-specific data are available, the resulting estimates will be more accurate. The LandGEM model is easily accessible and free of charge and was chosen to be applied to the estimation of the energy potential.

Energy potential estimation in this controlled landfill

The result of the annual estimation of the energy potential of this controlled landfill to produce electrical energy as a function of time is represented by Figure 5. It should be noted that the estimated values of methane by LandGEM model were used.

According to Figure 5, electrical energy differs in two different ways depending on the time:

- When 2012 ≤ t ≤ 2032: the estimated electric energy increases linearly over the years to reach a maximum value of 33 GWh/year in 2032 (Eq. 13) (year planned for the closure of the landfill).

$$E_{elc} = 1.6347 * t - 3289.1 \left(\frac{GWh}{year}\right) \quad (13)$$

where: t – year.

- When t ≥ 2032: the estimated electrical energy follows an exponential decrease as a function of time (Eq. 14). This growth is done with a slow rate.

$$E_{elc} = 5 * 10^{22} * e^{-(0.024*t)} \left(\frac{GWh}{year}\right) \quad (14)$$

where: t – year.

These values show that the non-use of biogas produced in this landfill, as is the case in several Moroccan landfills, will lead to a great economic loss.

CONCLUSIONS

In this study, at the Mohammedia-Benslimane controlled landfill, LandGEM, IPCC and TNO models were used to estimate annual generation of methane. Its volumes estimated by LandGEM and TNO are similar but larger than those measured on site. The IPCC model significantly overestimated methane generation. In general, when default parameters are used, the volumes of

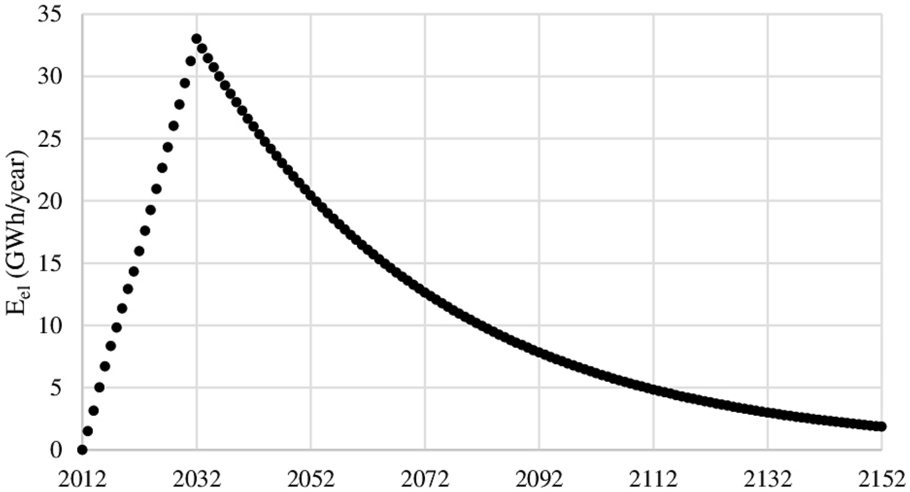

Figure 5. Annual estimated of electrical energy generation by methane produced at Landfill

methane estimated by the theoretical models are larger than those measured on site.The composition of biogas, measured on-site, showed that the municipal solid waste buried in this landfill is in a stable methanogenic phase. It is clear from the results that the potential for methane generation is significant.

For the continuation of this research, a socio-economic study on the feasibility and the profitability of a future project of installation of a power plantwill be carried out. The objectives of this project are the valorization of the biogas produced in this controlled waste for the production of electric energy and the protection of the environment by reducing the greenhouse effect.

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