LandGEM Biogas Estimation, Energy Potential and Carbon Footprint Assessments of a Controlled Landfill Site. Case of the Controlled Landfill of Mohammedia-Benslimane, Morocco

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ABSTRACT

Landfills throughout the world are contributing to the global warming problem. This is due to the existence of the most important greenhouse gases in landfill gas; namely, methane and carbon dioxide. Methane has a high potential for energy production and by utilizing the proper technology, large amounts of energy can be extracted from it. This paper deals with the estimation of methane emissions from the controlled municipal solid waste landfill of Mohammedia-Benslimane (MB) in Morocco. Methane emissions were calculated using the LandGEM method. In this research, the following parameters were evaluated: the amount of landfilled waste, the characteristics of the landfill and the composition of the landfilled waste, as well as the climatic conditions prevailing in the region. According to the LandGEM model, the total amount of methane generated from approximately 3.663 E+06 kg of municipal solid waste that will be buried of in the MB controlled landfill over 20 years, 2012 to 2032, is 1.76 E+08 m^3. For the year 2020, the estimated electrical energy production in the landfill is 1.78 E+07 kWh. Regarding the carbon footprint for this landfill, the landfilling of household solid waste at the MB landfill has resulted in a production of about 499,238,000 kg CO_2e in 2020 since its opening in 2012, according to the LandGEM model. These huge amounts of greenhouse gas are related to the fact that the waste buried at this landfill is highly organic. By installing an efficient system to capture and flare the biogas generated in this landfill, the management of this landfill is actively contributing to the protection of the environment by mitigating greenhouse gas emissions, particularly methane.

Keywords: municipal solid waste, LandGEM, methane, carbon footprint, greenhouse effect, electrical energy.

INTRODUCTION

In the same way as developing countries, Morocco has experienced a strong growth of the legal population estimated at 33,848,242 inhabitants, with 7,313,806 households (High Commissariat for Planning, RGPH 2014) and a huge industrial boom. Indeed, the improvement in life styles, and changes in production and consumption patterns and the proliferation of peripheral neighborhoods have led to a consequent increase in the volume of household waste produced. The current production of household waste in urban areas in Morocco is 5.38 million tons per year, or an average of

0.76 kg per capita per day, and in rural areas 1.47 million tons per year, or an average of 0.28 kg per capita per day [Saghir et al., 2018]. With population growth, rapid urbanization and changing consumption patterns, the production of household waste in Morocco is increasing. This situation has made the collection, evacuation, disposal and treatment of household and similar waste more difficult. This waste is very often disposed of in uncontrolled landfills [Elmaghnougi et al., 2018], or in black spots and water ways without any treatment or control, which has serious consequences both for public health and the environment as well as for the future of socio-economic

activities in our country. And considering that the patrimonial management of the vital space, the management of the environment and the sustainable development are part of the current concerns of the State, the creation of the controlled dumps turned out to be a major necessity to face this difficult situation. The rate of controlled landfill that was planned in 2019 is 62.63%, this rate should reach 100% in 2022 (Ministry of Energy, Mines and Environment). In fact, a controlled landfill, also known as an engineered landfill, is a place designed for the deposit of waste for a specific period of time while avoiding as much as possible the nuisance to the neighborhoods, caused mainly by the emanation of greenhouse gases (methane) [Abbasi, 2018] and the infiltration of leachate [Chofqi et al., 2004]. From the deposition phase, the waste is subjected to degradation processes related to complex biological and physicochemical reactions [Kumar et al., 2017]. Water seeps through and produces leachate and biogas loaded with organic and mineral substances that generate pollution mainly of organic and metallic type, related to the natural biodegradation of the confined waste and with its anthropogenic components that release many toxic substances into the natural environment. The burial and storage of solid household waste must therefore allow not only an efficient management of the waste but also the good management of the discharges. By opting for this approach, it becomes necessary to think of solutions to control and minimize these releases.

Morocco ratified the Kyoto Protocol on February 16, 2005, and organized the twenty-second COP 22 conference in Marrakech, from November 07 to November 18, 2016. One of the objectives of COP22 is to reduce and develop household waste through the construction of controlled landfills, in order to combat climate change due to greenhouse gas emissions. In this context, it is constantly improving environmental projects of which waste management projects are part. These projects focus on the evolution of controlled landfills into Landfill and recovery Centre in order to reduce greenhouses gas emissions. Indeed, the controlled landfill, although essential, cannot be considered as a sustainable solution of waste management, because important emissions of greenhouse gas persist even after their closure. Therefore, for a sustainable management of household waste, the development of material and energy recovery channels is undoubtedly important, and remains the appropriate solution to save raw materials, reduce the amount of waste to be eliminated and thus limit the extent of controlled landfills and the negative impacts on the environment, as well as create new jobs and generate income.

Household waste in Morocco contains 50–70% organic matter, so landfills in Morocco are one of the sources of biomass. Based on calculations of the energy potential of biomass, it can be deduced that the amount of electricity that can be produced by incinerating household waste in the Rabat region is approximately one hundred giga-watt hours [Naimi et al., 2017].

A recently published research study on the analysis of the economic feasibility and environmental impact of landfill gas on energy technologies in African urban areas (53 countries), showed that converting landfill gas to electricity could reduce global warming potential by 72.2% and increase acid gas emissions by 8.75% to 9.00% in African urban areas in 2012 [Cudjoe et al., 2021]. This study will guide investment and decision-making on the environmental sustainability of energy projects in Africa.

Currently, the choice of waste treatment in the communes of Mohammedia and Benslimane is oriented rather towards burying and flaring of biogas. However, although this management method has the advantage of reducing the negative effects of waste on the environment, it does not allow the potential of this biomass to be exploited in terms of recycling of materials, and alsoin terms of production of an organic amendment by composting and energy production.

The objectives of this study are:
- The use of the LandGEM kinetic model to estimate the amount of methane generated by the anaerobic decomposition of waste buried in the Mohammedia-Benslimane controlled landfill and to make a comparison with the data obtained on this site.
- Assessment of the energy potential of this landfill site
- The contribution of this site to the reduction of the greenhouse effect

MATERIALS AND METHODS

Presentation of the study area

The prefecture of Mohammedia covers an area of 180 km^2 and is located on the Atlantic

coast 25 km north of the city of Casablanca, while the province of Benslimane covers an area of 2,760 km², it is bounded by Skhirat-Temara to the north, Settat to the south, Khmisset to the east and the Atlantic Ocean to the west.

The controlled landfill of Mohammedia-Benslimane was commissioned on February 27/2012, after the closure of the unctrolled landfill of Mesbahiat. It has a capacity of 5 million cubic meters (m³) of waste and will be operated over a period of 20 years (until 2032). It covers an area of 109 hectares, of which the exploited area is 47 hectares. This landfill is located approximately 8 km south east of the center of Beni Yakhlef, 17 km east of the center of Mohammedia, 24 km south west of the center of Benslimane, and 800 m from the provincial road RP 3313 precisely to Beni M'ghit Chaâba El Hamra (ECOMED Group). Figure 1 shows the geographical location of the site.

The controlled landfill of Mohammedia-Benslimane, class I, which has the concept of an anaerobic bioreactor with storage in a controlled cell, is based on an efficient disposal of solid waste to avoid any harm to the environment and human health. Only household and similar wastes, inert wastes and non-hazardous wastes are allowed in the landfill.

The landfill is located on a site designed to accommodate five large landfill cells and five raw leachate ponds. The site also contains a weighbridge to control the admission of waste with their weighing. Its capacity is 60,000 kg and its uncertainty is 20 kg per 1,000 kg, this uncertainty is considered negligible.

For the evacuation of the generated biogas, a drainage network in the closed compartments is installed. At present, after 8 years of operation, the first three landfills are completely filled with household and similar waste, while the fourth one is under operation. The landfill is equipped with two flares to burn the biogas generated by the anaerobic decomposition of the waste. The first flare operates continuously

Figure 1. Geographical location of the Mohammedia-Benslimane landfill

Figure 2. Aerial view of the Mohammedia-Benslimane technical landfill site
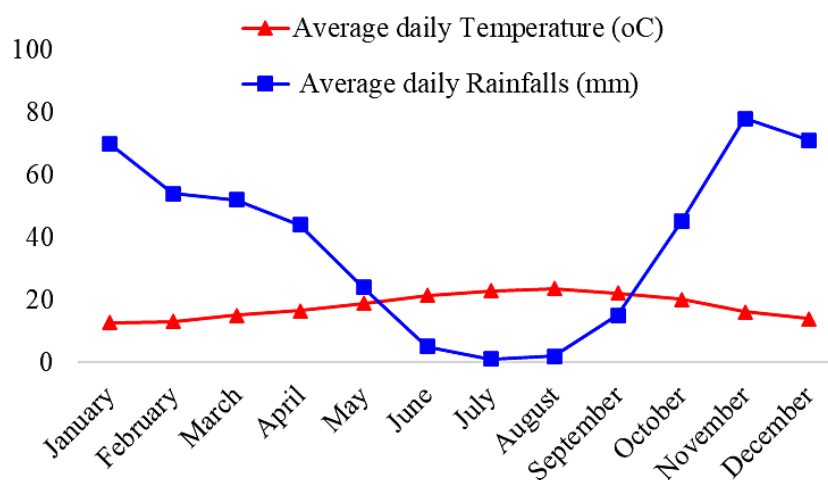
Figure 3. Climate conditions in the Beni Yakhlef region in 2020

(passive), while the second flare operates 3 hours per day (active) and can burn up to 1,000 m³ of methane per hour at a temperature of about 900 °C. The active flare is capable of burning biogas with a methane content between 20 and 70%. The biogas collection system includes a booster that creates a negative suction pressure to draw the collected landfill gas from the landfill waste to the flares.

The biogas flare system has a control panel to operate the flare, display and record data. The flare system also measures the biogas flow rate with a flow meter (Nm³/h) and the gas concentration with a biogas analyzer (CH_4, CO_2, O_2 and H_2S). Data are recorded every hour to monitor the flow rate and quality of the biogas produced by the anaerobic degradation of the landfilled waste.Figure 2 shows an aerial view of the Mohammedia-Benslimane landfill site.

The proximity to the Atlantic Ocean gives the municipality of Beni Yakhlef, where the Mohammedia-Benslimane controlled landfill site is located, a temperate and humid climate with a mild winter and a summer that is cooled by the ocean breezes. Figure 3 shows the climatic conditions of the Mohammedia-Benslimane controlled landfill site. Over the year, the average temperature at Beni Yakhlef is 18 °C and the average rainfall is 461 mm.

The technical landfill site ensures two essential missions which are:
- Burying of solid waste
- The treatment of biogas by flaring to mitigate the greenhouse effect caused by the emission of methane.

The nature and quantity of landfill waste

Since its opening, the site receives household and similar waste, green waste, rubble and sweeping waste from nine local communities of the prefecture of Mohammedia and the province of Benslimane, as well as ordinary industrial waste from various companies in the region (Table 1). The communes of the prefecture of Mohammedia are: the two urban communes (Mohammedia and Ain Arruda), and the four rural communes (Beni Yakhlef, Sidi Moussa El Majdoub, Sidi Moussa Ben Ali and Ech-challalate). As well as the three urban communes of the province of Benslimane: (Benslimane, Bouznika, and El Mansouria).

The quantity of municipal solid waste (MSW) buried in this site from 2012 to 2020 was provided by the ECOMED-Mohammedia group. The amount of MSW from 2021 to 2032 has been extrapolated using the demographic data of the Mohammedia prefecture and the Benslimane province. According to the data from the General Census of Population and Housing (RGPH-2004-2014), the population of the nine communes increased from 410,832 inhabitants in 2004, to 518,840 inhabitants in 2014 spread over

Table 1. Fraction of different types of waste landfilled (ECOMED Group, 2020)

Waste category	Amount of waste (tons)	Percentage by weight (%)
Household waste	162,625	78.34
Household waste	2,564	1.24
OM-Soil-Gravel mixture	7,937	3.82
Gravel	570	0.27
Ordinary industrial waste	33,901	16.33

Table 2. Evaluation of the population of the communes of Mohammedia - Benslimane (RGPH-2004-2014)

Communes	2004		2014	
	Population	Households	Population	Households
Mohammedia	188,619	39,154	208,612	49,974
Ain Harrouda	41,853	8,417	62,420	15,143
Beni Yakhlef	33,112	6,681	48,338	10,827
Ech-Challalate	40,311	7,970	53,503	12,840
Sidi Moussa Al Majdoub	12,412	2,502	20,330	4,917
Sidi Moussa Ben Ali	9,368	1,666	11,445	2,650
Benslimane	45,195	9,430	57,101	13,092
Bouznika	27,028	5,305	37,238	8,488
Manssouria	12,934	2,787	19,853	4,842
Total	410,832	83,912	518,840	122,773

approximately 122,773 households, i.e., an annual growth rate of 2.36% (Table 2). Using the available data for the population and the amount of waste landfilled in the site during the two years 2019 and 2020, the specific daily waste generation regarding this area is 0.75 kg/capita/day.

The landfill of Mohammedia-Benslimane, receives the waste during the opening hours starting from 12 am until 16 pm. The waste stored in the Mohammedia-Benslimane interprovincial controlled landfill is regularly monitored, weighed and the data is archived (500 tons/day). This process has started since the opening of the landfill in 2012. In this study, we used the available data from 2012 to 2020 (ECOMED Group), and then interpolated to 2032, the year the landfill is expected to close.

With data from the RGPH population censuses, from 2004 and 2014, it is possible to elaborate the population growth and/or decrease rate of each community, using geometric progression. The average of per capita waste generation was estimated in the period 2019–2020 (Table 3).

Municipal solid waste produced annually in the future years by each community is simply calculated by multiplying the estimated population amount by the per capita waste production in this region (Table 3). The final amount disposed at Mohammedia-Benslimane Landfill was estimated by the sum of the annual waste produced by each community.

Table 3. Index of municipal waste generation per capita

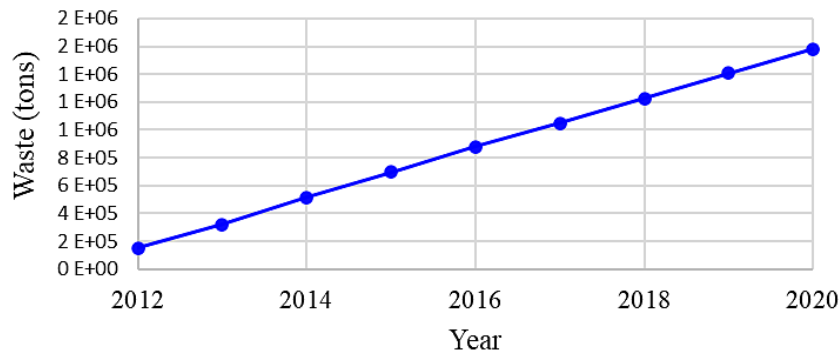| Communes	Per Capita Generation Index (kg/inhabitant/day)	
	Year 2019	Year 2020
Mohammedia	0.997	0.936
Ain Harrouda	0.545	0.501
Beni Yakhlef	0.701	0.689
Ech-Challalate	0.341	0.443
Sidi Moussa Al Majdoub	0.277	0.292
Sidi Moussa Ben Ali	0.150	0.172
Benslimane	0.760	0.728
Bouznika	1.086	1.047
Manssouria	0.954	0.903

Table 4. Amount of waste landfilled from 2012 to 2020 and the projection to 2031

Year	Waste Acceptance (tons/year)	Waste-In-Place (tons)
2012	151,501	0
2013	168,008	151,501
2014	195,617	319,509
2015	182,360	515,126
2016	179,862	697,486
2017	169,854	877,348
2018	178,033	1,047,202
2019	182,983	1,225,235
2020	173,126	1,408,218
2021*	169,288	1,581,344
2022*	173,201	1,750,632
2023*	177,236	1,923,833
2024*	181,395	2,101,069
2025*	185,683	2,282,464
2026*	187,540	2,468,147
2027*	192,007	2,655,687
2028*	196,614	2,847,694
2029*	201,366	3,044,308
2030*	206,269	3,245,674
2031*	211,328	3,451,943
2032*	0	3,663,271

* Projected value

Figure 4. Evolution of landfilled waste by year

Table 4 shows the annual amount of waste landfilled in tons at the Mohammedia-Benslimane landfill from the year 2012 until the year 2020, with the projection made for the 2021 to 2031.

The amount of waste received has increased from approximately 151,501 tons in 2012 to 173,126 tons in 2020. Figure 4 illustrates the evolution of the quantity of waste buried in tons in the site since its opening in 2012. It can be seen that there is a good correlation between the amount of waste landfilled and the year.

Figure 5 shows the monthly amount of waste landfilled for each commune in 2020. It was observed that the urban commune of Mohammedia is the largest producer of waste compared to the other communes. The commune of Mohammedia has the highest population density in this area. It could be observed again, that the average of daily specific waste production concerning the urban communes (0.85 kg/inhabitant/day) is higher than that of the rural communes (0.38 kg/inhabitant/day).

Estimating the carbon footprint of the Mohammedia-Benslimane landfill

Although greenhouse gas emissions are much discussed in developed countries around the world, they are of little concern in developing countries. Carbon dioxide and methane from biodegradation of waste are the only gases considered in this study. Global warming potential (GWP) of 1 and 21 were considered for CO_2 and CH_4 respectively [Kumar et al., 2017, Noor et al., 2013]. The carbon footprint (*CF*) of this landfill was evaluated from the two majority components (CH_4 and CO_2) of the biogas produced and is given by Eq. (1) [Haro et al., 2019]. These biogas components are evaluated using the LandGEM V3.03 (June 2020) first order kinetic model provided by the US Environmental Protection Agency (US.EPA).

$$CF = \left(Q_{CH_4} * \rho_{CH_4} * GWP_{CH_4}\right) + \\ +\left(Q_{CO_2} * \rho_{CO_2} * GWP_{CO_2}\right) \tag{1}$$
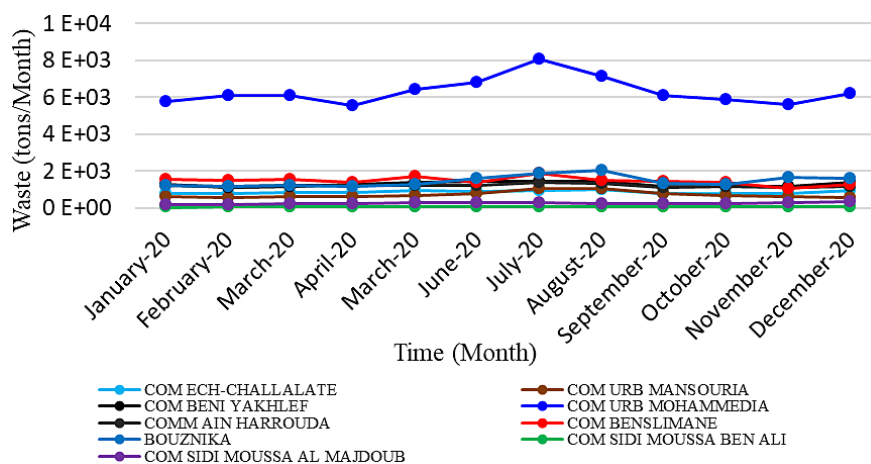
Figure 5. Monthly waste generation in the study area for the year 2020

were:
- CF: Amount of GHGs in tons of carbon dioxide equivalent (tCO$_2$eq).
- Q_{CH_4}: Amount of methane emitted into the atmosphere in (m^3/year).
- ρ_{CH_4}: Density of methane (0.667 kg/m^3).
- GWP_{CH_4}: Global warming potential of methane (GWP = 21).
- Q_{CO_2}: Amount of carbon dioxide emitted into the atmosphere in (m^3/year).
- ρ_{CO_2}: Density of carbon dioxide (1.87 kg/m^3).
- GWP_{CO_2}: Global warming potential of carbon dioxide (GWP = 1).

Estimation of the electrical energy generated by the MB landfill

The production of electrical energy from methane produced by a controlled landfill is a common application and its use is very beneficial. Electricity can be generated by burning methane in a generator set or gas turbine. The potential for generating electrical energy from landfill methane recovery was estimated using Eq. (2) [Ayodele et al., 2017]:

$$E_{elc} = \frac{0.9 * Q_{CH_4} * LHV_{CH_4} * \eta * \lambda}{3.6} \quad (2)$$

The is the amount of methane gas emitted in m^3 from the landfills during the particular year, is the Lower Heating Value of methane and usually taken as 35.8 MJ per m^3 [Saghir et al., 2018], η is the electrical conversion efficiency for the internal combustion engine and usually taken as 35% [Saghir et al., 2018], λ is the collection efficiency of methane from landfills and usually taken as 75 %, 0.9 is the empirical coefficient and 3.6 is the conversion factor from MJ to kWh (Low calorific value : LCV $_{CH4}$ = 9.94 kWh/m^3 at To = 273 K and Po = 1atm).

Landfill gas emissions model (LandGEM)

Description of the LandGEM model

LandGEM is a commonly used model to estimate the amount of landfill gas generation. This model is developed by the Control Technology Center of the American Environmental Protection Agency (US.EPA) for the prediction of gaseous pollutant generation in solid waste landfills. It considers (i) the quantities and characteristics of the landfilled waste over several consecutive years, (ii) the characteristics of the biogas produced and (iii) the meteorological conditions in the study area. It allows the prediction of CH$_4$ and CO$_2$ generation up to 140 years from the first-order decomposition equation [EPA USA, 2008].The CH$_4$ generation Eq. (3) considers increments of one tenth (1/10) of a year in order to increase the accuracy of the estimation process.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0,1}^{1} k * L_0 * \left(\frac{M_i}{10}\right) * e^{-k\, t_{i,j}} \quad (3)$$

were:
- Q_{CH_4}: annual methane generation in the year of the calculation (m^3/year)
- n: define as (year of the calculation) – (initial year of waste acceptance)
- i: is the one -year time increment
- j: is the 0.1 year time increment
- k: methane generation rate (year^{-1})
- L_0: potential methane production capacity (m^3/Mg)
- 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)

To conduct our study, the required inputs for estimating the amount of generated landfill gas are the landfill opening year, the landfill closure year, the annual waste acceptance rates from the opening to the closure year, the potential methane production capacity L$_0$, the methane generation rate k, the methane proportion in the biogas and Nom Methane Organic Compound concentration (NMOC).

LandGEM Model Parameters

In the LandGEM model the degradable organic carbon (DOC) is entered into Eq. (4) to yield the methane generation potential (L$_0$) [Ayodele et al., 2017, Pillai et al., 2018]:

$$L_0 = MCF \text{ x } DOC \text{ x } DOC_f \text{ x } F \text{ x } \frac{16}{12} \quad (4)$$

where: L_0 is the methane generation potential (kg/ton), MCF is the methane correction factor (MCF = 1 for sanitary landfills, 0.4 – 0.8 for waste dumps); DOC is 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).

Table 5. Fraction of different solid waste components

Waste type	A	B	C	D
Pourcentage (*wt* %)	19.4	3.1	75.9	1.6

The degradable organic carbon (DOC) is simply calculated using Eq. (5) and the waste characterization data for the Mohammedia-Benslimane landfill (Table 5).

$$DOC = (0.40 \times A) + (0.17 \times B) + (0.15 \times C) + (0.30 \times D) \qquad (5)$$

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

For the estimation of the methane generation potential [according to Eq. (4)] the following values have been applied: MCF = 1 (managed landfill); DOC = 0.20 kgC/kg-waste; DOC_f = 0.5 and F = 0.6 (*measured in-situ*). Hence, the methane formation potential L_0 = 120 m³/ton (density of methane = 0.667 kg/m³).

In this study, a theoretical k value was calculated using the composition of the disposed waste (Table 4). The k value of the controlled landfill of Mohammedia-Benslimane can be calculated from a weighted average (*wt. fraction* ₍ᵢ₎) of the k of each biodegradable component (k_i) as described in Eq. (6) as follows [Park et al., 2017, Pillai et al., 2018]:

$$k = \sum_{i=1}^{n} (k_i * (wt. fraction_i)) \qquad (6)$$

The IPCC (*Intergovernmental Panel on Climate Change*) lists the k values for food, garden/park, paper/textiles and wood/straw wastes as 0.06 year⁻¹, 0.05 year⁻¹, 0.04 year⁻¹, and 0.02 year⁻¹ respectively. Others wastes, non-biodegradables, were not incorporated into this weighted average. Using the defaults values and the Eq. (6), the k value was calculated as 0.055 year⁻¹ for this controlled landfill site.

RESULTS AND DISCUSSION

The results of this study are presented in four parts: (a) characterization of the biogas produced by the waste in this landfill, (b) estimation of the biogas produced using the Land-GEM model, (c) estimation of the energy potential, and (d) estimation of the global warming potential reduction.

Biogas characterization and evaluation of the methanogenic potential of the CET

The controlled landfill of Mohammedia-Benslimane, Morocco, receives a waste flow of about 500 tons per day, composed of biodegradable and non-biodegradable fractions. The biodegradable organic waste generates, through anaerobic biological decomposition, a biogas mainly composed of carbon dioxide and methane which are greenhouse gases. In-situ analyses of biogas have revealed an average methane content of around 60% by volume. Table 5 shows the results of in-situ measurements in 2020 for CH_4 (% by volume), CO_2 (% by volume) and H_2S (ppm), the biogas volume flow rate (Nm³/h), the biogas pressure (mbar) and the temperature of the biogas combustion reaction in the closed active flare. For biogas recovery, the open fraction of the extractor valve is only 22.45%. The biogas collection is done by a network of horizontal wells.

It should be noted that the values grouped in the table 6 are the averages of all the measurements carried out at the level of the closed active flare inlet and the horizontal capture well present on the cells. Therefore, they correspond to the overall flow of the landfill site. (In-situ monitoring for 76 days in the period 02/2020–05/2020).

The results obtained show constant values of stable proportions of CH_4 and CO_2 of 59.59% and 38.97% respectively were obtained (Fig. 6). These percentages are very close to the average values found in the literature during methanogenesis in anaerobic fermentations: 60% CH_4 and 40% CO_2. Very similar values were obtained for the La Gabarre landfill in Guadeloupe [Plocoste et al., 2016].

Table 6. In-situ measurement results for methane, carbon dioxide, oxygen and hydrogen sulfide, biogas pressure and flow, and temperature of the closed flare system in 2020 (given by the landfill operator)

CH_4 (Vol %)	CO_2 (Vol %)	O_2 (Vol %)	H_2S (ppm)	Biogas flow (Nm³/h)	Pressure (mbar)	T (The closed flare system) (ºC)
59.59	38.97	0.13	1050.4	326	250	1005.5
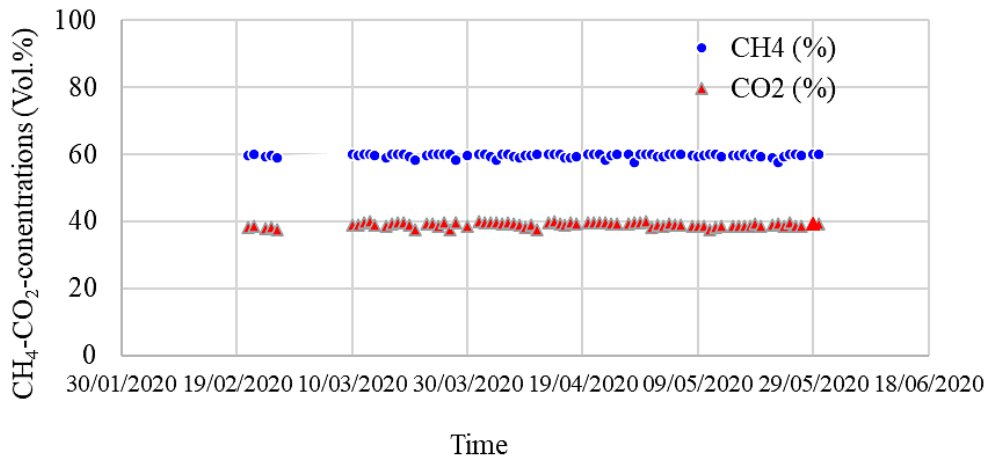
Figure 6. Methane and carbon dioxide concentrations in the gas of the MB landfill site (21/02/2020 to 30/05/2020)

The CH_4/CO_2 ratio close to 1.5 and a very low amount of oxygen ($O_2 < 1\%$), suggests that the landfilled waste is in an advanced state of bio-degradation (*methanogenesis phase*). This result indicates that this landfill of Mohammedia-Benslimane has a great capacity to produce methane, which can be energetically valorized (renewable energy). The quantity of hydrogen sulfide (H_2S) found on the landfill site can be explained by the presence of high levels of food waste.

From the flow and the composition of the biogas (Table 6), we can easily calculate the quantity of biogas generated in 2020. This quantity is given by Eq. (7):

$$Q_{biogas} = \frac{326}{(1 + 0.250)} * 24 *$$

$$* 365 * \frac{1}{0.2245} = 10,176,428 \ m^3$$

(7)

Therefore, in 2020, the annual biogas production is 10,176,428 m^3. At a methane (respectively carbon dioxide) content of 59,59 % (respectively 38,97 %), the annual methane (respectively carbon dioxide) production is reduced to 6,064,133 m^3 (3,965,754 m^3 respectively).

The results obtained by the LandGEM model

In Table 7, we have introduced all the data concerning the controlled landfill of Mohammedia- Benslimane and the parameters necessary for the application of the LandGEM model.

Figures 7a and 7b illustrates the annual landfill gas emissions from Mohammedia-Benslimane controlled landfill from 2012 to 2152.

For the first year of waste deposition in 2012, the model assumes no biogas production. Indeed, the research shows that the methanogenesis stage starts at least 6 months after the waste is deposited. The degradation of the waste depends on several factors: type of waste, moisture in the waste, climatic conditions and the materials covering the waste. To simplify the calculations, the LandGEM kinetic simulation model does not take into account all these parameters to establish the beginning of methanogenesis and considers that after one year, all the criteria are met for the beginning of this stage. According to Figure 7a, we see that it contains two intervals:

Table 7. Parameters for the LandGEM model

Landfill characteristics	
Landfill open year	2012
Landfill Closure Year (with 80-year limit)	2032
Actual Closure Year (without limit)	2032
Have model calculate closure year?	No
Waste Design Capacity (mega grams)	3,542,350
Model parameters	
Methane generation rate, k (per year)	0.055
Potential methane generation capacity, l_o (m^3 methane /mg waste)	120
Nmoc concentration (ppmv as hexane)	4,000
Methane content (%)	60
Gas/pollutants selected	
Gas/pollutant # 1	Total landfill gas
Gas/pollutant # 2	Methane
Gas/pollutant # 3	Carbon dioxide
Gas/pollutant # 4	NMOC

a)

b)
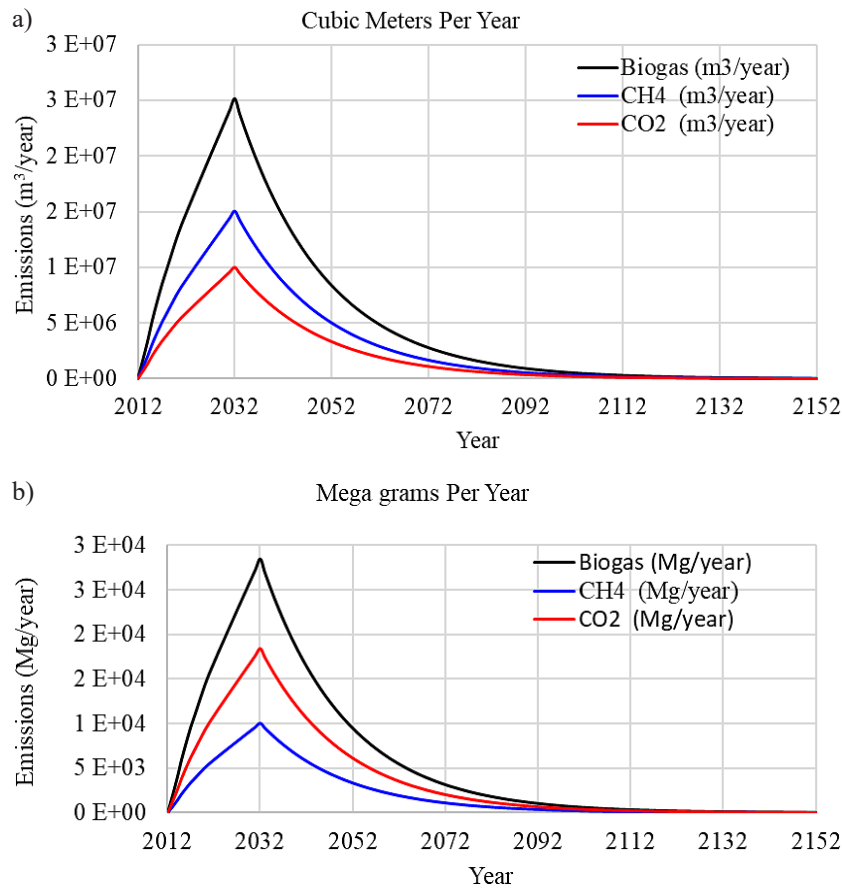
Figure 7. a) Annual estimate of the volume of biogas (m³/year) of Mohammedia-Benslimane controlled landfill; b) Annual estimate of the quantity of biogas (Mg/year) of Mohammedia-Benslimane controlled landfill

- If $2012 \leq t \leq 2032$ the quantity of biogas increases linearly with the years to reach a maximum value of 2.51×10^7 m³/year (28,450.77 Mg). The maximum estimated quantities of CH_4 and CO_2 produced are equal to 1.51×10^7 m³/year (10,056.20 Mg) and 1.00×10^7 m³/year (18,394.56 Mg) respectively.

- If $t > 2032$ the quantity of biogas generation will decrease exponentially after the landfill closure parallel to the decrease of the amount of decomposable matter in the landfill.

The ratio between the annual biogas production estimated by the LandGEM model and that calculated from the parameters measured in 2020 is calculated by Eq. (8):

$$R = \frac{Q_{Biogas-LandGEM}}{Q_{Biogas-Measurements}} =$$

$$= \frac{1.261 \times 10^7}{1.018 \times 10^7} = 1.24 \quad (8)$$

were:

- $Q_{Biogas-LandGEM}$: mean flow of biogas estimated by LandGEM model (m³/year)
- $Q_{Biogas-Measurements}$: mean flow of biogas determined from field measurements (m³/year)

The landfill gas collection system efficiency defined as the ratio of the collected landfill gas quantity relative to the LandGEM estimated LFG production. From these results, it can be concluded that the biogas recovery efficiency is 81% of the landfill for the year 2020. This value is good if considering the EPA regulations for biogas collection and recovery networks, when the recuperation rate of biogas production is defined as being between 75 and 85%.

Several factors can explain this result:

- the biogas recovery area (the three closed cells) is well sealed due to the good coverage of this area by the active (2 mm well protected geomembrane) and passive barriers (clay with a very low permeability of 10^{-9}–10^{-8} m/s).

- the installation of three horizontal well networks under the waste (every 12 meters of waste height there is a collection network) for biogas recovery.

125

Despite the construction cost of these horizontal well networks is higher, they have a higher landfill gas collection rate [Fei et al., 2019].

Estimation of the energy potential Mohammedia-Benslimane landfill

From Eq. (7), we can calculate the annual estimation of electrical energy production by the

Table 8. Annual estimate of electrical energy production by the controlled landfill of Mohammedia-Benslimane

| Year	Annual estimate of the volume of methane produced by the landfill CH_4 (Mm³/year)	Annual estimate of electrical energy production E_{elc} (GWh/year)
2012	0.000	0.000
2013	0.976	2.291
2014	2.005	4.709
2015	3.158	7.415
2016	4.163	9.776
2017	5.098	11.973
2018	5.919	13.900
2019	6.749	15.849
2020	7.566	17.768
2021	8.276	19.435
2022	8.923	20.955
2023	9.561	22.452
2024	10.191	23.931
2025	10.813	25.393
2026	11.430	26.842
2027	12.026	28.242
2028	12.619	29.634
2029	13.210	31.021
2030	13.800	32.406
2031	14.390	33.791
2032	14.980	35.179

Mohammedia-Benslimane controlled landfill. The results of the calculations are collected in Table 8.

From these results gathered in Table 8, we can plot the evolution of the estimated annual production of electrical energy for the landfill of Mohammedia-Benslimane from 2012 to 2032 (Fig. 8).

From this result, it is observed that the estimation of electrical energy production increases with the growth of the amount of methane generated from the controlled landfill. For the year 2032, the estimate of electrical energy production in the landfill will be 35.2 GWh.

Carbon footprint of Mohammedia-Benslimane landfill

Figure 9 shows the evolution of the carbon footprint (CF) over the years of the Mohammedia-Benslimane landfill. The model assumes that there is no biogas production in the first year (2012) of landfilling. The anaerobic fermentation had not yet started. Therefore, biogas production starts in 2013. If the landfill was not equipped with a capture and flare system the contribution to greenhouse gas emissions would have been 115,511 tons CO_2e, 164,945 tons CO_2e, 210,945 tons CO_2e and 210,497 tons CO_2e in 2020, 2025, 2030 respectively and would reach a maximum value of 228,505 tons CO_2e in 2032. This significant contribution to the greenhouse effect is explained by the high organic content of the waste buried in the landfill and the meteorological conditions. After 2032, the contribution will decrease exponentially and will reach zero after 2152, even though more than 100 years after its closure, the landfill will still contribute to greenhouse gas emissions.
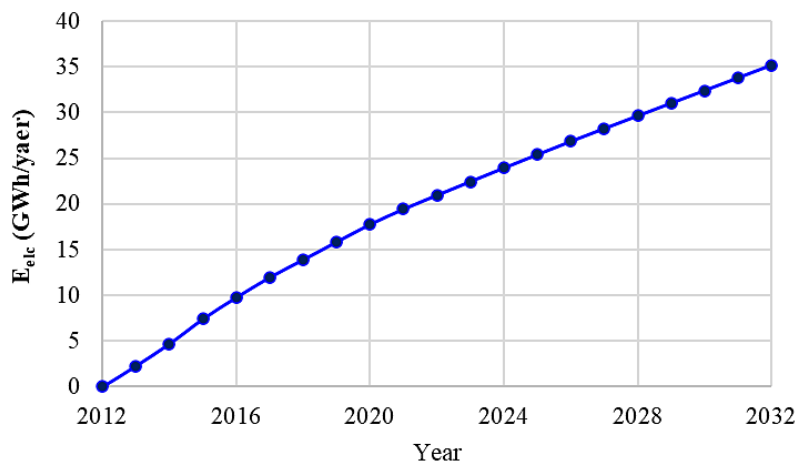
Figure 8. Estimate of the electrical energy generated by the landfill of Mohammedia-Benslimane
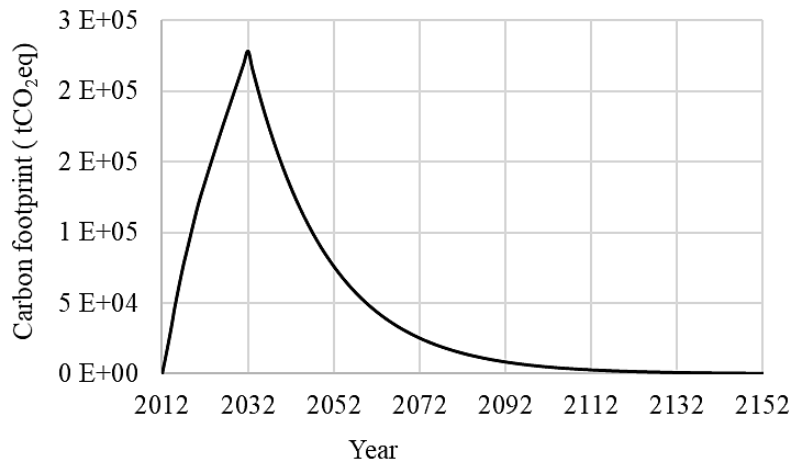
Figure 9. Annual estimate of the quantity of carbon footprint (Mg/year) of Mohammedia-Benslimane landfill

Landfill biogas recovery projects can decrease emissions of greenhouse gases. In the calculation of greenhouse gas reduction by landfill gas recovery we only considered the amount of CH_4 destroyed. Using a global warming potential (GWP) of 21 for methane and estimating that 80% of methane can be captured through the landfill gas collection system and destroyed in flares, with methane reduction efficiency of 90% in closed flare [Tayyeba et al., 2011, Lattanzi et al., 2020], it is possible to observe the difference between the amount of carbon emitted without the installation of flares and the installation of closed flares (Table 9 and Figure 10).

Considering landfill emissions without any use or destruction of methane, there would be a total of 211,180 Mg of carbon equivalent being generated at the peak of gas production. Against with the closed flare system, it is possible to observe a 72% reduction in CO_2e emission.

The total emission reductions achievable from the landfill gas recovery during the 20-year Period, 2012 through 2032, are 1.78×10^6 Mg of CO_2e (Fig. 11).

By installing a very efficient system for capturing and flaring the biogas generated in the controlled landfill of Mohammedia-Benslimane, the managers of this site will actively contribute to the protection of the environment by mitigating greenhouse gas emissions, particularly methane, with an overall reduction of 1.78 E+06 tCO$_2$e, in 2032, when the site will close.

CONCLUSIONS

In this study, the methane generation capacity (L_0) and methane generation rate (k) were determined for the Mohammedia-Benslimane controlled landfill and methane gas emissions were estimated by using the landGEM 3.03 model. The use of methane produced by the anaerobic decomposition of municipal solid waste in the Mohammedia-Benslimane controlled landfill is a good approach to generating electrical energy and protecting the environment through

Table 9. Estimated methane generated annually from 2012 to 2032, with respective CO_2e values in two scenarios (without flare and with the closed flare)

Year	Methane (Mg/year)	CO_2e (Mg/year) without flare	CO_2e (Mg/year) with the closed flare
2012	0	0	0
2013	651	13,668	9,841
2014	1,338	28,094	20,228
2015	2,107	44,239	31,852
2016	2,777	58,323	41,993
2017	3,401	71,429	51,429
2018	3,949	82,930	59,710
2019	4,503	94,554	68,079
2020	5,048	106,002	76,321
2021	5,521	115,948	83,483
2022	5,949	124,933	89,952
2023	6,372	133,811	96,344
2024	6,790	142,597	102,670
2025	7,205	151,305	108,939
2026	7,617	159,949	115,163
2027	8,026	168,542	121,350
2028	8,433	177,097	127,510
2029	8,839	185,626	133,651
2030	9,245	194,142	139,782
2031	9,650	202,657	145,913
2032	10,056	211,180	152,050
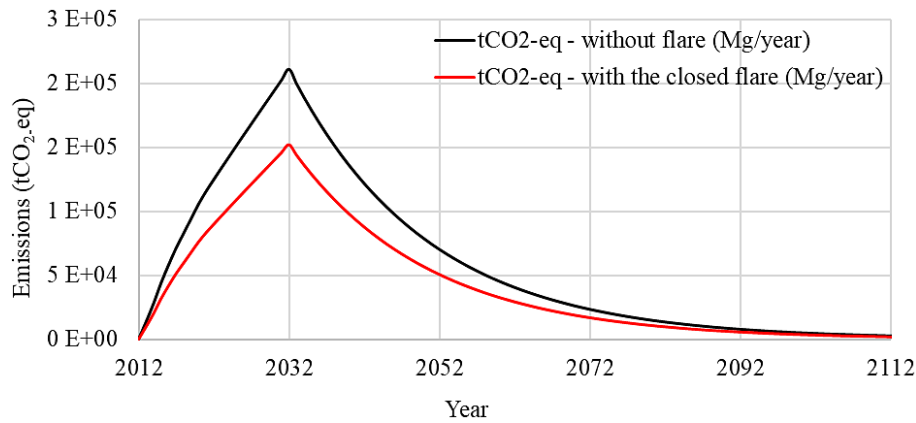
Figure 10. Annual estimate of the quantity of CO_2 (Mg/year) of Mohammedia-Benslimane landfill
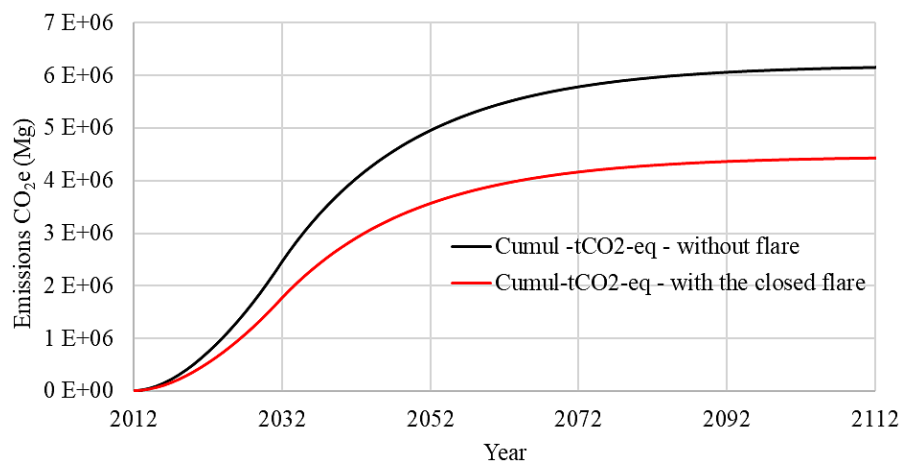
Figure 11. Cumulative sum chart of global warming potential of Mohammedia-Benslimane landfill

greenhouse gas mitigation. As the methane gas is considered as one of the major contributors for the global warming and also a source of green energy, it needs to be sequestered. According to the LandGEM model, the maximum methane production rate is 1.50 E+07 m³/year and is observed during the year 2032 for this controlled Landfill. The year 2032 correspond to the closure year of Mohammedia-Benslimane. The methane gases that will be recovered from the controlled landfill can be converted into energy. We have shown that the estimated electrical energy in this landfill was 35.2 GWh for the year 2032. Therefore, it can be concluded that the Mohammedia-Benslimane landfill is a source for energy production and can be used to move fossil fuels. With the flare system implemented in this controlled landfill of Mohammedia-Benslimane, it is possible to observe a 72% reduction in CO_2e emission. The total emission reductions achievable from the landfill gas recovery during the 20-year Period, 2012 through 2032, are 1.78 E+06 tons of CO_2e.

For the follow-up of this study, it appeared to us very interesting to study the impact of the gases formed at the time of the flaring of the biogas in this site on the potential of acidification, namely the sulfur dioxide (SO_2) and the hydrochloric acid (HCl), and on the other hand to proceed to a desulfurization of the biogas of this site (by decreasing the quantity of hydrogen sulfide (H_2S)) if a unit of production of electric energy will be installed locally for the next years.

Acknowledgements

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