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PREDICTION OF LANDFILL GAS AND LEACHATE GENERATION FOR ENERGETIC RECOVERY

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Abstract. *The growing concern on efficient environmental solutions allied with recent changes in the Brazilian policy concerning the management of municipal solid waste MSW and landfills enables an opportunity to investigate the energy recovery and abatement of landfills emissions. The present work explores separated models for the prediction of landfill gas generation and for the leachate production, based on a 1st order decomposition model and on the water budget method, respectively. The model outputs allow for the quantification of landfill gas to energy LFGTE potential, and thereafter an energetic analysis of the potential electric generation or, alternatively, for leachate evaporation. Results show that for more conservative scenarios it is possible to generate 492 kW with 3 motogenerators for a 4 years long period, and about 2.6 MW, with 16 motogenerators, during 3 years of operation. Landfill gas combustion can evaporate around 10% of the maximum volume of produced leachate along 20 years, for the conservative scenario, and 50% along 17 years or 90% during 5 to 9 years, for the optimistic scenario. Results for leachate production showed 7 to 10% deviation when compared to actual data from the Guajuviras landfill (Canoas, Brazil).*

Keywords: *landfill gas to energy, LFGTE, municipal solid waste, landfill energetic modeling*

1. INTRODUCTION

The Brazil's National Solid Waste Policy – PNRS, from 2010, has established limits and targets concerning the collection, treatment and final destination of solid waste – SW (MMA, 2013). That policy aims to change some old management practices by forbidding urban waste disposal on dumps and establishing appropriate biogas effluent collection and control on landfills.

ABRELPE (2012) pointed out that approximately 90% of SW generated in 2011 in Brazil is collected, and from that amount only 58% are sent to landfills, which correspond nearly 105,000 SW tons/ year.

Landfills as final destination of SW remains widely accepted in many countries due to its economic advantages (Renou *et al.*, 2008). The two major landfill effluents are gas emissions, called landfill gas – LFG, and a liquid stream called leachate. LFG is a mixture of methane with other gases as a result of a biodegradation process. Its burning without any energy recovery is a common practice to mitigate its potential greenhouse gas effects. According to IPCC (2006) landfills are responsible to 3 – 4% of the global greenhouse gas emissions. Leachate is a liquid effluent with organic load that cannot be sent to the environment without a proper treatment.

Although landfill be a final deposition site for solid waste, its effluents can be considered as renewable sources. LFG can be burnt on heaters, boilers and combustion engines with heat or electrical conversion. Leachate is usually sent to urban effluent treatment units, where different technologies are employed to neutralize its pollutant content. Its residual organic content suits to be burned and offers again a possibility for energy conversion.

Landfill design and operation conceived for energy recovery relies on the knowledge of these two effluents. In the present work, gas and leachate production for a Brazilian landfill facility are to be estimated by well-known models feed with real data, taken from the Guajuviras municipal landfill, at Canoas, South Brazil. Thereafter, an assessment is carried out identifying the energy recovery potential through LFG use.

2. LANDFILL OUTPUTS

Landfills are usually modeled as biochemical reactors, where waste and water are the major inputs, generating LFG and leachate (Machado *et al.*, 2009). LFG is a biogas generated by chemical and biological processes (Amini *et al.*, 2012) and depends on waste constitution and age, together with the landfill and environmental conditions. Its production is mainly a result or consequence of the waste composition and its biological status, i.e., if it is already organically degraded, what is its moisture content, age of waste, pH and temperature (Machado *et al*., 2009).

In regard to waste composition, different residues will display individual rates of decomposition and potential for methane generation. Wastes like food, nappies and sewage sludge will show higher rates of decomposition. Moderately

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and slowly decomposable organic content like wood, paper, garden and park waste, textiles and other materials will present lower rates of decomposition. Plastics, glasses, metals, concrete and similar ones are considered as inert (Machado ***et al.***, 2009; IPCC, 2006). Table 1 displays LFG general composition and it is clear that it is acceptable to that it can be considered as a major mixture of CH_4 and CO_2.

Table 1. Landfill gas composition in dry volume basis at methanogenesis phase (Tchobanoglous and Kreith, 2002).

Component	Volumetric percentual	Characteristic	Value
Methane	45 - 60	Moisture content	Saturated
Carbon dioxide	40 - 60	Specific Gravity	1.02 - 1.06
Nitrogen	2 - 5	Temperature, °C	37 - 72
Oxygen/Ammonia	0.1-1.0	High heating value, kJ/Nm³	17,700 - 20,500
Sulfides, disulfides, mecaptans, etc.	0 -1.0		
Hydrogen/ Carbon monoxide	0 - 0.2		
Trace constituents	0.01 - 0.6		

The LFG mechanism of formation was thought to occur in more or less five sequential phases (Tchobanoglous and Kreith, 2002), and it is displayed in Figure 1.

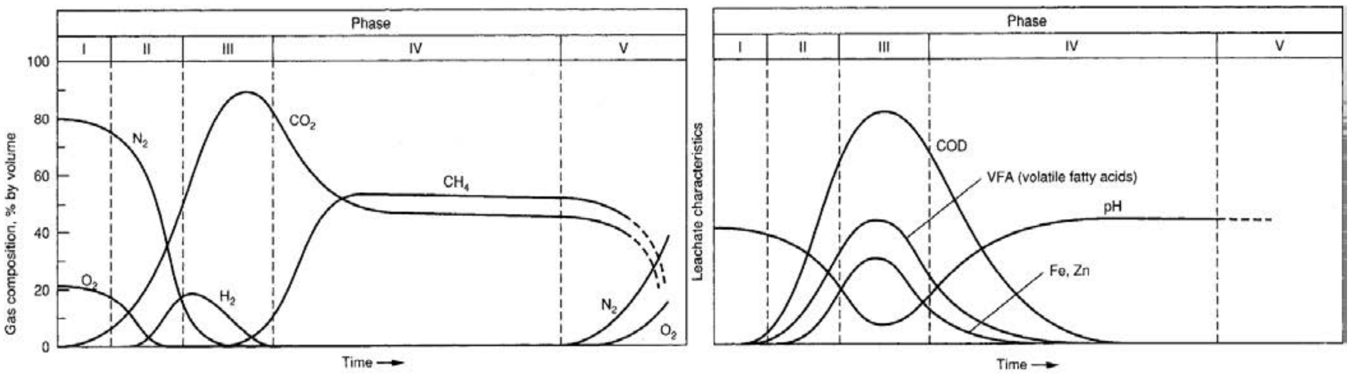

Figure 1. Qualitative time behavior of landfill gas (left) and leachate (right) (Tchobanoglous and Kreith, 2002).

The first phase is an initial adjustment, where the waste placed in landfill undergoes aerobic bacterial decomposition, due to the presence of air trapped within the landfill. The second one is the beginning of an anaerobic process, after the depletion of the O_2 content. The third step is described as the acid phase, with acceleration of bacterial production, started at previous phase, with a significant production of organic acids and a smaller amount of H_2. The fourth step is called the methanogenesis phase, when a group of microorganism converts acetic acid and H_2 into CH_4 and CO_2. At the fifth phase, the LFG generation rate diminishes significantly, since the major part of the biodegradable organic material has been consumed. Methane concentration grows at phase IV, when gas emissions to the atmosphere must be monitored and controlled, and LFG could also be converted into thermal or electrical energy.

Leachate may be defined as a percolated stream composed by water from external sources, such as rainfall, waste water content and liquid produced from the biochemical processes and, if any (Tchobanoglous and Kreith, 2002). Renou ***et al.*** (2008) points out that a liquid effluent can be described by two factors, its volumetric flow rate and its composition.

Table 2. Characterization of the leachate composition (Adapted from Tchobanoglous and Kreith, 2002).

	New landfill (less than 2 years)	Mature Landfill (greather than 10 years)
Constituent	Range (mg/L)	Range (mg/L)
BOD_5 (biochemical oxygen demand)	2,000 - 30,000	100 - 200
TOC (total organic carbon)	1,500 - 20,000	80 - 160
COD (chemical oxygen demand)	3,000 - 60,000	100 - 500
Total suspended solids	200 - 2,000	100 - 400
Organic nitrogen	10 – 800	80 - 120
Ammonia nitrogen	10 – 800	20 - 40
Total iron	50 - 1,200	20 - 200
pH (*dimensionless)	4.5 - 7.5 *	6.6 - 7.5 *

In situ leachate sampling allow for the estimation of the actual phase of a given site, according to Fig. 1, which can range from young to mature. That same figure indicates that the maximum chemical oxygen demand –COD and volatile fatty acids – VFA levels are achieved at phase III, when media is mostly acid.

Beside waste characteristics and internal processes, aspects as climatic and hydrogeological conditions, site operations and management must be considered for leachate generation (El-Fadel ***et al.***, 2002).

ISSN 2176-5480

3. LANDFILL GAS EMISSIONS MODELING

The simplest models for LFG generation presented in the literature are of zero, first and second-orders, based on empirical data (Amini *et al.*, 2012). Results depend strongly on the quality and accuracy of the input data (gas generation parameters) and on the approximation of the model assumptions to the landfill real conditions, such as the waste decomposition rate and anaerobic conditions. Besides all, CH_4 production rate is proportional to the amount of organic matter that can decompose under anaerobic conditions.

First order models from USEPA (2005) and IPCC (2006) are widely used, based on the gas prediction at the landfill methanogenesis phase. The first model is based on the methane generation potential L_0 (m³ CH_4/ ton of SW), and the second one on the decomposable degradable organic carbon $DDOC_m$ (Gg of organic carbon) (Machado ***et al.***, 2009).

Based on data from five inactivated landfills, Amini ***et al.*** (2012) compared the actual collected LFG to the predicted one by first-order model, and concluded that it was able to represent gas generation after 10 years of landfill closure within a range of uncertainty of ±9% to ±18%. A different result was found by Oonk and Boom (1995), who analyzed the LFG prediction given by zero, first and second order models (multi-phase) for 22 landfills in the Netherlands, and concluded that the second order model performed the best, but they depend on a detailed characterization of site gas generation parameters.

3.1 IPCC (2006) first-order decaiment model

The rate of LFG production is predicted by a 1st order kinetic model (Eq. (1)), where the generation rate of the decomposable degradable organic carbon $DDOC_m$ (Gg of organic carbon) decays exponentially with time.

$$\frac{d[DDOC_m]}{dt} = -k(DDOC_m) \tag{1}$$

where k is the reaction rate constant (year^{-1}). $DDOC_m$ is defined as

$$DDOC_m = W\ DOC\ DOC_f\ MCF \tag{2}$$

where DOC is the organic carbon content in respect to the solid waste total amount (Gg of organic carbon/Gg of total SW), W is the total waste mass (Gg), DOC_f indicates the fraction of DOC that is supposed to undergo anaerobic reactions (dimensionless), and MCF is the methane correction factor (dimensionless). This last one takes into account the disposing practices in solid waste sites, and ranges from 0.4, for unmanaged sites, to 1, for controlled landfills.

Equation (2) can be rewritten for a specific waste component i as,

$$(DDOC_m)_i = (W\ FR_i)\ DOC_i\ DOC_f\ MCF \tag{3}$$

where FR_i is the fraction of each component in the total waste mass (Gg of waste component i/Gg of total SW). The integration of Eq. (1) leads to the expression of the decomposable degradable organic carbon as a function of time, as:

$$DDOC_m(t) = DDOC_m(0)\,(e^{-k\,t}) \tag{4}$$

where $DDOC_m(0)$ is the initial value of $DDOC_m$ (Gg of organic carbon) and t is the time (years).

In order to evaluate LFG generation, IPCC (2006) alternatively rewrites Eq. (4) for $DDOC_{m\,dec,i}$, which is the amount of $DDOC_m$ present in the landfill that is decomposed at end of one year of site operation for a specific waste component, as presented by Eq. (5),

$$(DDOC_{m\,dec})_i = \left((DDOC_{m\,0})_i + (DDOC_{m\,a})_i\right)\left(1 - e^{-k_i}\right) \tag{5}$$

where $DDOC_{m\,0}$ is the $DDOC_m$ value of the mass disposed in the first day of the analysis year (Gg of organic carbon), if any, $DDOC_{ma}$ (Gg of organic carbon) is the residual amount of $DDOC_m$ that was not decomposed in previous years (for the first year of landfill operation is null).

In the present work, the mass of generated methane CH_{4g} (Gg) was determined for a specific waste as,

$$CH_{4g} = F_{CH_4} MW_{Ratio} \sum_{i=1}^{z} (DDOC_{m\,dec})_i \tag{6}$$

where F_{CH4} is the volume fraction of methane in final LFG and MW_{Ratio} is the molecular weight ratio of CH_4 to C, and z is the number of waste components.

Finally, the average volumetric flow rate of LFG on annual basis LFG_a (Nm³/h) is given by,

$$LFG_a = \left(\frac{CH_{4g}}{\Delta h_{year}\,10^6}\right)\left[\frac{1}{{}_{CH_4}} + \left(\frac{MW_{CO_2}}{MW_{CH_4}}\,\frac{1}{{}_{CO_2}}\right)\left(\frac{1-F_{CH_4}}{F_{CH_4}}\right)\right] \tag{7}$$

where ρ_{CH_4} and ρ_{CO_2} are CH_4 and CO_2 densities (kg/m³) in STPC (0°C and 101,325 kPa), MW_{CO_2} and MW_{CH_4} are the molecular weights of CO_2 and CH_4 (kg/kmol) and Δh_{year} is the total hours in one year (8,760 h).

Thus, LFG_a determination is only possible when is available the historical data of disposed SW of landfill, the gravimetric SW composition and the gas generation parameters – k and $DDOC_m$. Gas generation parameters may be obtained by distinct methodologies, as theoretical prediction, laboratory essays and from best fit analysis for LFG recovery in real landfills (Machado *et al.*, 2009).

3.2 Methodologies for gas generation parameters determination

REACTION RATE CONSTANT – k

Table 3 presents values for k obtained from technical literature. In the presented work, the determination of k relies on: landfill climate zone classification presented in IPCC (2006), landfill climatologic data, annual accumulated precipitation and mean annual temperature.

Table 3.Values of reaction rate constant k from USEPA (2005) and IPCC (2006).

Author	Author's Classification	k (year^{-1})					
		Paper/Cardboard	Food Waste	Garden Waste	Wood	Textiles	Bulk
USEPA (2005)	Inventory Conventional	-	-	-	-	-	0.05
	Inventory Wet	-	-	-	-	-	0.7
	Inventory Arid	-	-	-	-	-	0.02
IPCC(2006)	Wet Temperate	0.05 - 0.07	0.1 - 0.2	0.06 - 0.1	0.02 - 0.04	0.05 - 0.07	0.08 - 0.1
	Moist and Wet Tropical	0.06 - 0.085	0.17 - 0.7	0.15 - 0.2	0.03 - 0.05	0.06 - 0.085	0.15 - 0.2

DECOMPOSABLE DEGRADABLE ORGANIC CARBON – $DDOC_m$

Two strategies are accepted for $DDOC_m$ determination. In Strategy 1, $DDOC_m$ is estimated after the values of DOC_i suggested by IPCC (2006) (Tab. 4) and then introduced in Eq. (3), together with the available historical data of disposed SW and its gravimetric composition.

Table 4. Suggested values for the decomposable organic matter DOC_i according to waste component (IPCC, 2006).

MSW component	Dry matter content in % of wet weight	DOC_i content in % wet waste		DOC_i content in % dry waste	
	Default	Default	Range	Default	Range
Paper/cardboard	90	40	36 - 45	44	40 - 50
Textiles	80	24	20 - 40	30	25 -50
Food waste	40	15	8 - 20	38	20 - 50
Wood	85	43	39 - 46	50	46 - 54
Garden and Park waste	40	20	18 - 22	49	45 - 55
Nappies	40	24	18 - 32	60	44 - 80
Rubber and Leather	84	39	39	47	47
Inert (Metal/Glass/Other inert)	100	-	-	-	-

In Strategy 2, adapted from Machado *et al.* (2009), DOC_i is estimated after the values of BF_i, the biodegradable fraction in SW (dimensionless) and $C_{m\,i}$, the maximum value of methane produced by a certain amount of waste (Nm³ CH_4/ ton of SW). The organic carbon content DOC_i is given by:

$$DOC_i = \frac{{}_{CH_4}}{F_{CH_4} MW_{Ratio}}\left(\frac{BF_i}{(1+w)}\,\frac{C_{m\,i}}{10^3}\right) \tag{8}$$

where w is the water content in percentage of volume, if any. Equation (8) can be used either for a specific waste material or for bulk waste.

The $C_{m\,i}$ value is determined by quantification of the methane stoichiometric coefficient [$4a+b-2c-3d$] presented in reaction described by Eq. (9), where $C_aH_bO_cN_d$, is the waste chemical composition,

ISSN 2176-5480

$$C_aH_bO_cN_d + \frac{[4a-b-2c+3d]H_2O}{4} \rightarrow \frac{[4a+b-2c-3d]CH_4}{8} + \frac{[4a-b+2c+3d]CO_2}{8} + [d]NH_3 \quad (9)$$

requiring some bulk or specific analysis (Tchobanoglous and Kreith, 2002; Barlaz **et al.**, 1997; Machado **et al.**, 2009).

As for the other parameter,

$$BF_i = BMP_i / C_{m\,i} \quad (10)$$

where BMP_i is the biochemical methane potential, obtained experimentally, also measured in Nm³ of CH_4/ ton of SW. Collected values for BF_i and $C_{m\,i}$ from several authors are shown in Tab. 5.

Table 5.Values of biodegradable waste fraction ***BF*** and maximum produced methane C_m for waste components.

	Author	Paper	Cardboard	Food Waste	Garden Waste	Wood	Textiles
BF (dimensionless)	Tchobanoglous *et al.* (1993)	0.44	0.38	0.58	0.45	0.61	0.4
	Barlaz *et al.* (1997)	0.19-0.56	0.39	0.7	0.34-0.7	0.14	-
	Harries *et al.* (2001)	0.3-0.4	0.44	-	0.2-0.51	0.3-0.33	0.17-0.25
	Lobo (2003)	0.4	0.64	0.64	0.35	0.17	0.32
C_m *(Nm³CH₄ / Mg SW component i) dry basis*	Cho *et al.* (2012)	-	410	643	-	487	509
	Tchobanoglous *et al.* (1993)	418.51	438.7	505.01	481.72	484.72	573.87

Both strategies can be used for DOC_i estimation and feed Eq. (3) in order to calculate $(DDOC_m)_i$. Calculation continues with Eq. (5) for $DDOC_{m\,dec,i}$, allowing for the determination, through Eq. (6), of the generate methane mass CH_{4g}. LFG is finally expressed by Eq. (7), and the flow rate of methane can be evaluated by knowing F_{CH4}, the volume fraction of methane in final LFG.

4. LANDFILL LEACHATE MODELS

Precipitation is on the basis of the leachate volumetric flow rate estimation. Generally, it represents the main source of moisture in the landfill, and by consequence the source for leachate production. A possible approach is given by the water budget method WBM, presented in different ways by several authors (Fenn *et al.*, 1975; Tchobanoglous and Kreith, 2002). It allows for the determination of landfill generated leachate by quantifying the change in landfill moisture storage through a mass balance between the main source of incoming water (precipitation; snow; initial moisture in the SW; initial moisture in the covering material; infiltration from underground water sources; leachate recirculation etc.) and exiting soil moisture (emissions for the environment; leachate to collection system; saturated water vapor within LFG; lost in formation of LFG)

The method proposed by Fenn **et al.** (1975) relies on the fact that the main source of moisture comes from the precipitation over the landfill area. Equation (11) accounts for the water balance ***WB*** for the soil moisture determination on the landfill cover layer, given by:

$$WB = P - PET - R \quad (11)$$

where P is the local precipitation on statistical basis, ***PET*** is the potential evapotranspiration given either by the Thornthwaite's potential evapotranspiration equation (Fenn **et al.**, 1975) or on statistical basis and R is the runoff estimated by empirical correlations, expressed in mm of monthly accumulated H_2O. The balance given by that equation will be compared to the soil field capacity, and indicates whereas water will percolate down into the SW, by respecting the following criteria:

$WB < 0$ reduction of soil moisture content on the cover layer, and therefore no percolation.

$WB > 0$ water recharge of the cover layer, which allows for water percolation if this amount approaches the soil field capacity.

WB in Eq. (11) will be then replaced by ***PERC***, the amount of water that percolates through the cover layer, whenever the soil moisture of the cover layer reaches its field capacity. Equation (11) is only valid under the assumptions presented in Tab. 6. ***PERC*** is first evaluated on month basis along the annual period of analysis, allowing for the calculation of the accumulated annual percolate – $PERC_a$, and furthermore the annual estimated leachate $L_{estimated}$ (liters per year), as shown in Fig. 2, for a given landfill surface area.

Table 6. Simplifying assumptions for WBM proposed by Fenn *et al.* (1975).

1	The cover soil must have 0.6 m of height, with a slope of 2 to 4 % over the surface area
2	Cover area are placed instantaneously in the time period that is beginning the computation. Which implies that the percolation before this time period will not be estimated
3	Only precipitation and soil moisture are considered as source of the possible percolate
4	Hydraulic properties of the soil and the waste are constant in the time and space
5	The moisture addition is only occur when the trench is closed
6	The surface area of the landfill is much higher than its depth, which implies that the flow is preferential in the vertical direction

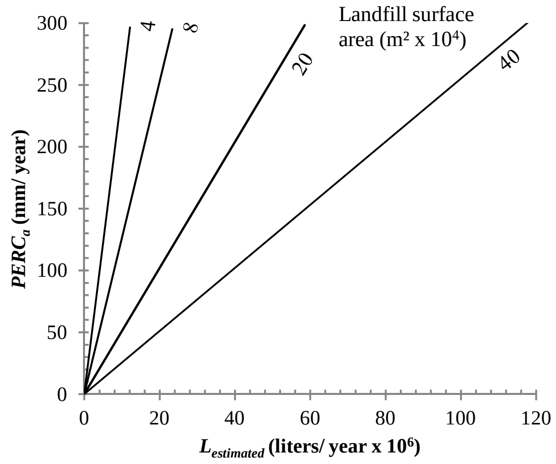

Figure 2. Annual estimated leachate quantities – $L_{estimated}$ (Fenn *et al.*, 1975).

5. THE GUAJUVIRAS LANDFILL – A CASE STUDY

The Guajuviras landfill is located in Canoas, at the metropolitan region of Porto Alegre, Brazil. Initially created as a waste dump, it became a landfill after January, 1996 and was finally turned down in December, 2011. Its topsoil, intermediate and bottom layers are made of 0.6 m compacted clay. With an approximate area of 100,000 m² the landfilling method can be considered as an area method.

Next table presents the landfill historical SW charges, as informed by the city waste service. Some industrial waste was probably added to the charge, but it wasn`t take into account. Results for LFG generation will though be conservative.

Table 7. Historical of MSW disposed at the Guajuviras landfill.

Year	1996	1997	1998	1999	2000	2001	2002	2003
SW in ton	48,896.03	51,732.87	56,913.31	60,146.37	58,231.67	59,916.16	58,087.28	61,782.26
Year	2004	2005	2006	2007	2008	2009	2010	2011
SW in ton	64,471.73	74,372.59	72,576.69	75,952.07	79,993.90	78,278.46	78,066.87	81,594.67

The SW gravimetric composition was taken as similar to the one from the neighbor town of Porto Alegre, based on DMLU (2012) due to the lack of information on the actual landfill. Table 8 shows the approximated gravimetric composition for the Guajuviras Landfill.

Table 8. Guajuviras landfill solid waste gravimetric composition.

% Composition (in wet basis)						
Paper/ Cardboard	Food Waste	Garden Waste	Wood	Textiles	Rejects	Inert
11.62%	45.8%	11.4%	0.45%	3.86%	5.31%	26.98%

Although the available data do not distinguish food from garden waste, an assumption is made in the present work, based on the MSW composition of Brazilian cities, and 80% of this bulk amount was considered as food waste. Rejects on Tab. 8 stand for general residues, organic or not, as nappies, and 50 % of this amount were considered as degradable, due to the lack of better information. Despite knowing that SW gravimetric composition varies with time, this condition was not considered.

A passive LFG collection system is installed on the landfill, composed by 35 cylindrical drains with flaring burners at the top, avoiding eventual damages due to pressure overloads. Leachate is captured by a drainage net and storage by an impermeable lagoon, which plays the role of a reservoir, and finally transported to a wastewater treatment plant. Table 9 presents the monthly leachate volume transferred out from the landfill.

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Table 9. Historical data from 2011 and 2012 for the recovered leachate L_{actual} (m³).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2011	1,518	1,496	1,628	1,562	1,650	1,430	1,848	5495	8,225	4,532	4,036	1,848	35,268
2012	2,420	2,144	2,562	2,152	1,760	1,540	2,845	2,292	1,742	1,180	757	2,040	23,434

5.1 Landfill Gas Prediction

DECOMPOSABLE DEGRADABLE ORGANIC CARBON – $DDOC_m$

The decomposable degradable organic carbon $DDOC_m$ on Eq. (2) was estimated by both strategies 1 and 2, presented on section 3.2, starting with DOC_i calculation. A new parameter is commonly introduced to express $DDOC_m$, called the methane generation potential L_{0i}, Eq. (12), given in Nm³/ ton of SW, as a function of DOC_i.

$$L_{0i} = DOC_i\ DOC_f\ MCF\ \left(F_{CH_4}\ MW_{Ratio}\right)\left({}^{CH_4}\!\big/_{10^3} \right) \tag{12}$$

where DOC_i appears as the main parameter of interest. Table 10 presents L_{0i} values calculated for maximum and minimum values of the input data for strategies 1 (Tab. 3) and 2 (Tab. 5).

Table 10. Estimated L_0 for the landfilled solid waste (Nm³CH$_4$/ton of SW).

	Strategy 1			Strategy 2			Deviation (%)	
Waste Component	*Lo max*	*Lo min*	*Lo max/ Lo min*	*Lo max*	*Lo min*	*Lo max/ Lo min*	*Lo max dev*	*Lo min dev*
Paper/cardboard	209.2	167.4	1.2	255.2	70.8	3.6	22%	58%
Textiles	186	93	2.0	191.3	72.1	2.7	3%	22%
Food waste	93	37.2	2.5	281.3	183.1	1.5	203%	394%
Wood	213.9	181.3	1.2	258.3	59	4.4	20%	63%
Garden and Park waste	102.3	83.7	1.2	210.8	60.2	3.5	106%	28%
Nappies	148.8	83.7	1.8	-[a]	-[a]	-	-	-

[a] not available values
L_0 *dev* (%) = 100 (*Strategy 1- Strategy 2*)/ *Strategy 1*

L_{0i} estimation for both strategies consider DOC_f = 0.5 (recommended by IPCC, 2006), MCF = 1 (for managed landfill), F_{CH4} = 0.5 (considered volumetric fraction of LFG) and w as presented in Tab. 4.

Results for strategy 1 show L_0 ***max*** values 1.2 to 2.5 times greater than L_0 ***min***. For strategy 2, L_0 ***max*** is 1.5 to 4.4 times greater than L_0 ***min***, indicating that variation between maximum and minimum values for strategy 2 is bigger than for strategy 1. This can be explained due to the fact that BF_i and $C_{m\,i}$ were collected from different sources.

L_0 ***max*** values from both strategies display deviations ranging from 3 to 203%, while L_0 ***min*** presents deviations in the order of 22 to 394%. According to Cho ***et al***., 2012, this behavior is due to the experimental methodology employed to calculate BF_i and $C_{m\,i}$ in Eq. (10), that delivers higher L_{0i} values when compared to other experimental methodologies (e.g. lysimiter experiment).

It becomes evident that determining the parameter that relates the produced methane by a certain amount of SW mass $(DDOC_m)_i$ plays a fundamental role in first order models.

REACTION RATE CONSTANT – k

Determination of k values depends upon landfill's climate zone definition. There is no collection of meteorological data in the landfill, so it was adopted data from the nearest meteorological station, which is located in Porto Alegre. The accumulated precipitation is higher than 1,000 mm and mean annual temperature is around 20 °C (INMET, 2013).Therefore, LFG prediction was performed with mean k values, for each waste component, from wet temperate (k_{wt}) and moist and wet (k_{mw}) climate zones (Tab. 3).

Table 3 shows that k_{mw} values for the same SW component are greater than k_{wt}. Therefore, it is expected a higher LFG_a production in the early years for assessments with k_{mw} values compared to those with k_{wt}. Also is expected an opposite behavior of LFG_a towards the last years of the assessed period due to model's exponential behavior.

LFG generation approaches

Once defined the gas generation parameters, the assessment of LFG generation is evaluated for a forty years long period, starting with the landfill's operation (1996 – 2036). Two approaches were proposed in order to analyze LFG_a behavior, by calculating the mean landfill gas before landfill closure LFG_{mB} and after landfill closure LFG_{mA}.

Approach 1: In this first approach, the set of Eq. (5) to Eq. (7) was calculated with the maximum and minimum values of $(DDOC_m)_i$ obtained by the strategy 1, along with mean values of kwt and kmw, producing four curves of LFG_a, for a 40 years long period.

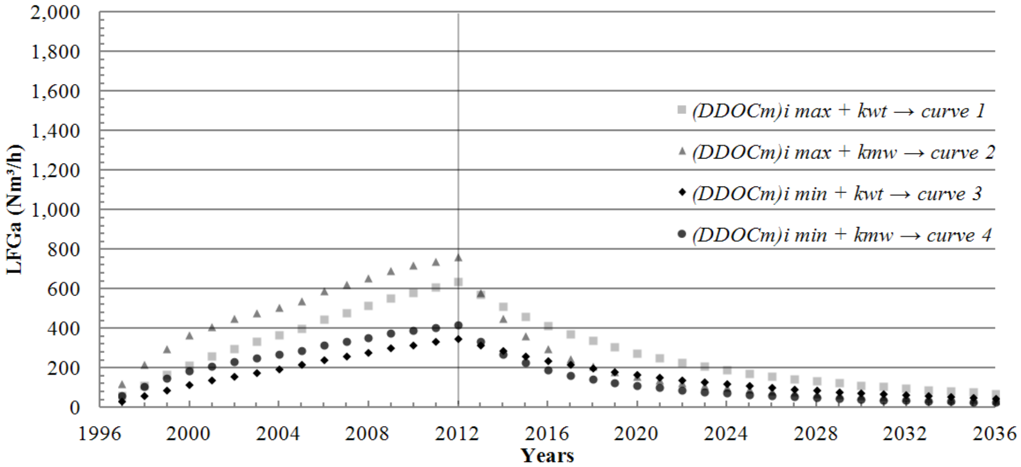

Figure 3. Annual landfill gas generation LFG_a estimation - Approach 1.

The LFG_{mB} rate for SW obtained with the maximum value $(DDOC_m)_i$ with k_{mw} is around 511 Nm³/h, 27% higher than the same value of LFG_{mB} for k_{wt}. The same behavior was observed when LFG_{mB} was calculated for the minimum value of $(DDOC_m)_i$ with k_{mw}, giving approximately 272 Nm³/h, a result 26% greater than the one obtained with k_{wt}. This trend was inverted for the period after landfill closure, in respect to the change on the rate constant.

Approach 2: Results for approach 2 followed the same methodology of calculation employed to the first approach, but with maximum and minimum $(DDOC_m)_i$ values obtained from data from strategy 2. LFG_a results are displayed in Fig. 4.

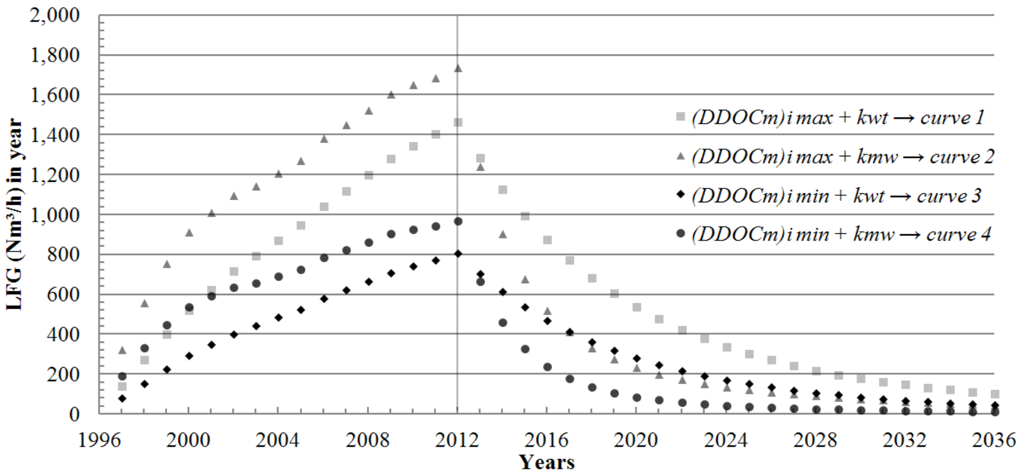

Figure 4. Annual landfill gas generation LFG_a estimation - Approach 2.

A similar behavior to the first approach is observed, but with higher magnitudes of LFG_a. The LFG_{mB} rate with the maximum value $(DDOC_m)_i$ with k_{mw} is around 1205 Nm³/h, 27% higher than the same value of LFG_{mB} for k_{wt}. Although absolute values were slightly different, the deviation for in this case for both approaches was very much the same. The same behavior was observed when LFG_{mB} was calculated for the minimum value of $(DDOC_m)_i$ with k_{mw}, giving approximately 689 Nm³/h, a result 29% greater than the one obtained with k_{wt}. As on the prior approach, this behavior was inverted for the period after landfill closure, in respect to the change on the rate constant.

Results for approach 2 were 1.1 to 4 times higher than those for approach 1 for the same application, due to:

1) Approach 2 employs maximum $(DDOC_m)_i$ values that were higher than those for approach 1 (Tab. 10).
2) L_0 *min* value for food waste component obtained with strategy 2, which is even higher than approach 1 L_0 *max* for the same component, composes 45.8% of total disposed SW, leading to higher LFG_a values for approach 2.

For both approaches, LFG_a curves showed a positive inclination before reaching its peak, due to the increase in the available organic matter by the continuum waste disposal. After the first year of the landfill closure, the exponential behavior is observed. Simulations with k_{mw} indicate a high consummation of available organic matter in the first years

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of the landfill. Also, the behavior after landfill closure indicates that LFG will be produced in significant amounts for a longer period.

LFG_a production in respect to different values of the rate constant, keeping all other conditions and modeling unchanged, showed that k_{mw} can lead to a 3 to 5% higher value of LFG_a, in respect to k_{wt}.

5.2 Landfill leachate prediction

Results for the amount of water that percolates through the landfill cover layer ***PERC*** are displayed on the two right hand columns in Tab. 11, calculated by the water budget method WBM (Eq. (11)) for years 2011 and 2012 on mean statistical basis – data collected from INMET (2013).

In the present work, maximum and minimum values of ***PERC*** were evaluated and displayed on the two left hand columns on the same table. They were obtained by combining the largest values of the local precipitation ***P*** to the minimum values of the potential evapotranspiration ***PET*** (maximum percolation), as well as the minimum values of ***PERC*** were obtained on the other way round of the same combination of parameters. The largest and minimum values of ***P*** and ***PET*** were obtained by statistical analysis from INMET (2013), with a confidence interval of 95%.

For every result, null ***PERC*** values can indicate loss in the soil moisture content, maintenance of the same value of previous month or insufficient precipitation to reach soil field capacity, and thus, the percolation.

Then the annual estimated leachate $L_{estimated}$ was determined based on the calculation of the accumulated annual percolate $PERC_a$ and with the landfill surface area, as shown in Fig. 2. Leachate prediction for 2011 and 2012 was of approximately 33,000 m³ and 22,000 m³, respectively (Tab. 11, bottom line). A deviation of 7 to 10% was observed when compared to the actual collected leachate of 35,268 m³ and 23,434 m³ for the same years, as displayed in Tab. 9.

Table 11. Percolated water through the landfill cover layer ***PERC*** (mm) and leachate estimation $L_{estimated}$ (m^3) with the water budget method WBM.

	Minimum Percolation					Maximum Percolation					2012					2011				
	PERC	*Soil Moisture*[b]	*PET*[a]	*R*	*P*[a]	*PERC*	*Soil Moisture*[b]	*PET*[a]	*R*	*P*[a]	*PERC*	*Soil Moisture*[b]	*PET*[a]	*R*	*P*[a]	*PERC*	*Soil Moisture*[b]	*PET*[a]	*R*	*P*[a]
Jan	0	89	146	14	84	0	133	133	24	140	0	149	139	29	166	0	112	156	23	136
Feb	0	70	133	15	89	0	135	108	23	133	0	123	143	24	140	0	96	122	21	120
May	0	50	118	14	80	0	115	109	20	118	0	115	111	21	123	0	74	107	14	83
Apr	0	39	78	9	55	4	150	69	22	131	0	111	70	13	77	0	143	74	30	173
Mar	0	55	52	14	82	96	150	43	29	167	0	92	58	5	36	0	138	46	9	50
Jun	0	80	36	13	74	123	150	29	32	184	0	89	34	4	32	50	150	29	19	110
Jul	0	122	38	17	98	120	150	26	30	177	59	150	28	25	145	159	150	28	39	226
Aug	1	150	51	16	96	110	150	35	30	175	110	150	64	16	94	114	150	37	31	182
Sep	38	150	60	20	119	121	150	49	35	205	121	150	61	47	274	0	143	51	9	53
Oct	0	123	89	12	72	69	150	75	30	173	69	150	94	21	121	15	150	81	21	124
Nov	0	87	107	12	69	27	150	93	25	146	0	84	107	3	26	0	82	102	2	14
Dec	0	130	141	38	223	93	150	123	45	261	27	95	152	34	196	0	49	119	9	52
	$L_{estimated,min}$=3,800 m³					$L_{estimated,max}$=73,500 m³					$L_{estimated-2012}$=22,000 m³ $L_{actual-2012}$=23,434 m³					$L_{estimated-2011}$=33,000 m³ $L_{actual-2011}$=35,268 m³				

[a] values obtained from INMET, 2013
[b] values obtained for clay soil data from Fenn *et al.*, 1975

The maximum estimated percolation produces around 73,500 m³ of leachate ($L_{estimated,max}$) and minimum estimated percolation ($L_{estimated,min}$) was found to be about 3,800 m³. This indicates that even for minimum percolation, the landfill will generate leachate. The actual collected values were found to be within the estimated maximum and minimum ones.

5.3 Landfill energy recovery

The energy recovery in this paper is based on two concepts. The first converts LFG into electricity with the aid of an internal combustion reciprocating engine (ICE) coupled to a electrical generator, hereby called motogenerator. The second concept is based on the available thermal energy that comes out from the burning of LFG and evaluates its potential to evaporate landfill leachate ***L***. Both analysis considered the biogas low heating value LHV of 18 MJ/ Nm³, with 50% CH_4 content in volume, and approximate the leachate to pure water, a reasonable modeling assumption for mature landfills (Penteado ***et al.***, 2012; Spokas ***et al***., 2006).

For electricity conversion (first concept), data from a specific engine fueled by natural gas (Scania SGI 12A Gas Genset) were taken to estimate LFG performance.

Table 12. Motogenerator electrical output power and conversion efficiency for natural gas (from datasheet*) and LFG (estimated)

Electrical nominal output power with Natural Gas	Natural Gas to electricity conversion efficiency	Estimated output power with LFG	Estimated LFG to electricity conversion efficiency
204 kW	38.1%	164 kW	30-32%

* Scania SGI 12A Gas Genset datasheet

The mean loss in the electricity conversion efficiency reported by Gewald *et al.* (2012) was approximately 17%, based on values for similar applications, and this reduction was adopted in the present work to calculate both the output power and system efficiency.

The assessment of the potential electricity conversion was performed by taken the most optimistic (maximum LFG production) and more conservative (minimum LFG production) values obtained by approaches 1 and 2, previously presented on section (5.1). The maximum LFG_a values were estimated for approach 2, Fig. 4, for gas generation parameters $(DDOC_m)_i$ *max* + k_{wt} and $(DDOC_m)_i$ *max* + k_{mw}, corresponding to curves 1 and 2, respectively. The minimum LFG_a values were estimated for approach 1, Fig. 3, for gas generation parameters $(DDOC_m)_i$ *min* + k_{wt} and $(DDOC_m)_i$ *min* + k_{mw}, corresponding to curves 3 and 4, respectively.

Annual landfill gas generation LFG_a values were converted to annual available thermal power (kW), based on the biogas low heating value LHV, and results are displayed on Fig. 5. Each of the individual hatched areas is equivalent to the energy demand of a motogenerator, presented on Tab. 12. i.e., the available thermal power area corresponds to the electrical output power.

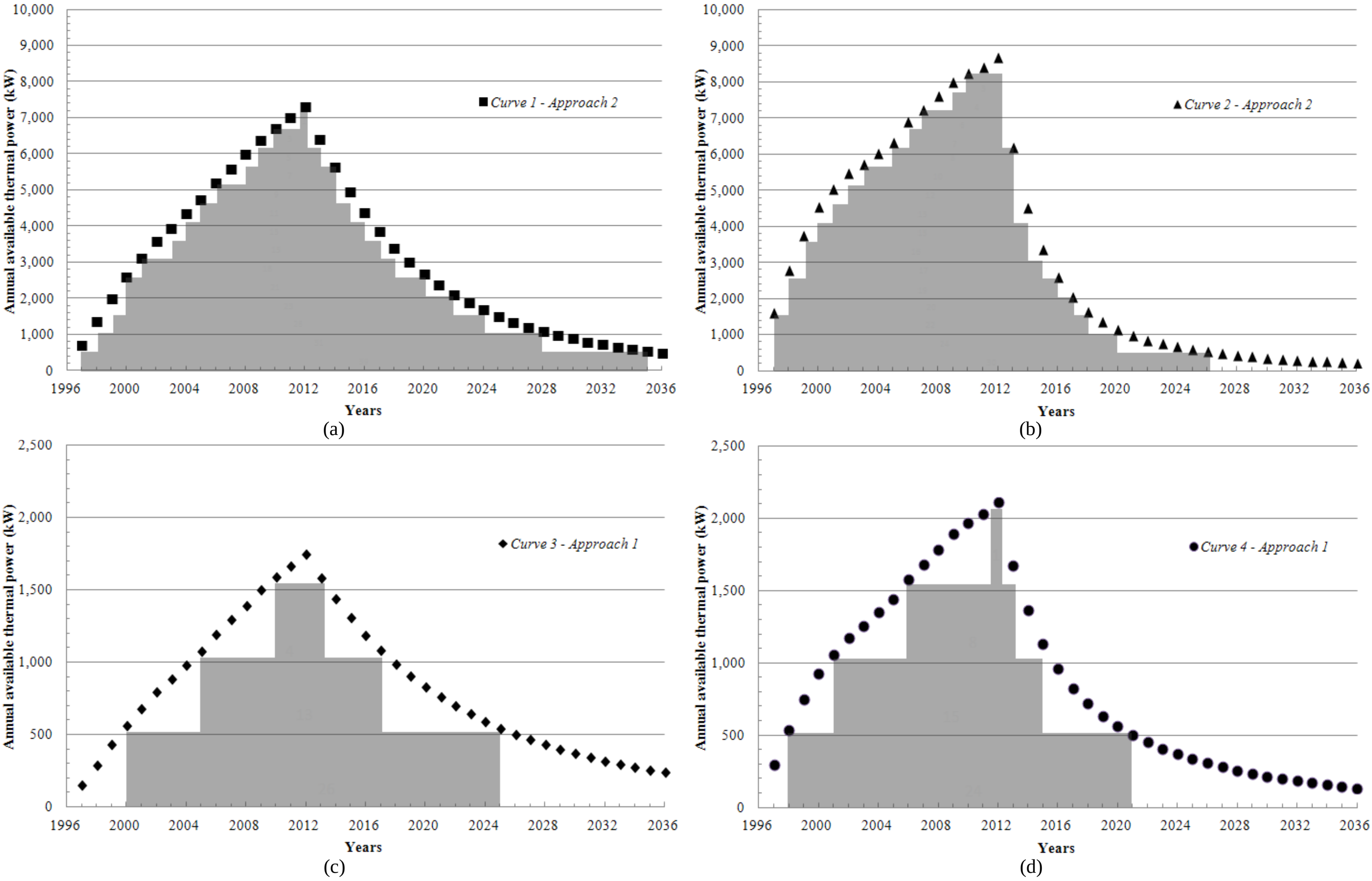

Figure 5. Annual available thermal power: (a) Approach 2 curve 1[$(DDOC_m)_i$ *max* + k_{wt}]; (b) Approach 2 curve 2 [$(DDOC_m)_i$ *max* + k_{mw}]; (c) Approach 1 curve 3 [$(DDOC_m)_i$ *min* + k_{wt}]; (d) Approach 1 curve 4 [$(DDOC_m)_i$ *min* + k_{mw}]

The potential electrical conversion for the optimistic assessments ranges from 318.9 to 324.7 GWh, Fig. 5(a) and 5(b) respectively, for the landfill time life operation. When comparing both options, the first one estimates a longer operational time. Similar behavior is observed for the conservative case, in which the potential electrical conversion varies from 61.8 to 69 GWh, Fig. 5(c) and 5 (d), respectively, however for a shorter landfill time life operation.

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The electricity production (kW) after the landfill closure (2013 – 2036) was estimated for quadrennial periods, presented in Tab. 13.

Table 13. Potential electricity generation (kW) after landfill closure.

Assessment	Years						
	2013 -2016	2017 - 2020	2021 - 2024	2025 - 2028	2029 - 2032	2033 - 2036	Total
Curve 1 - Approach 2	6,560	3,772	2,296	1,312	656	492	15,088
Curve 2 - Approach 2	5,084	1,804	656	328	0	0	7,872
Curve 3 - Approach 1	1,476	820	656	164	0	0	3,116
Curve 4 - Approach 1	1,312	656	164	0	0	0	2,132

Results for potential electrical generation after landfill closure show that the assessments based on the same $(DDOC_m)_i$ and smaller k values (k_{wt}) displayed higher values than the ones calculated for higher k values (k_{mw}).

The leachate evaporation by heat released from LFG burning (second concept) can be assessed directly from the annual available thermal energy, in GJ/ year. The evaporation heat rate was calculated from an energy balance, considering latent and sensible heat, and that energy demand is related to the available thermal energy, shown in Fig. 6.

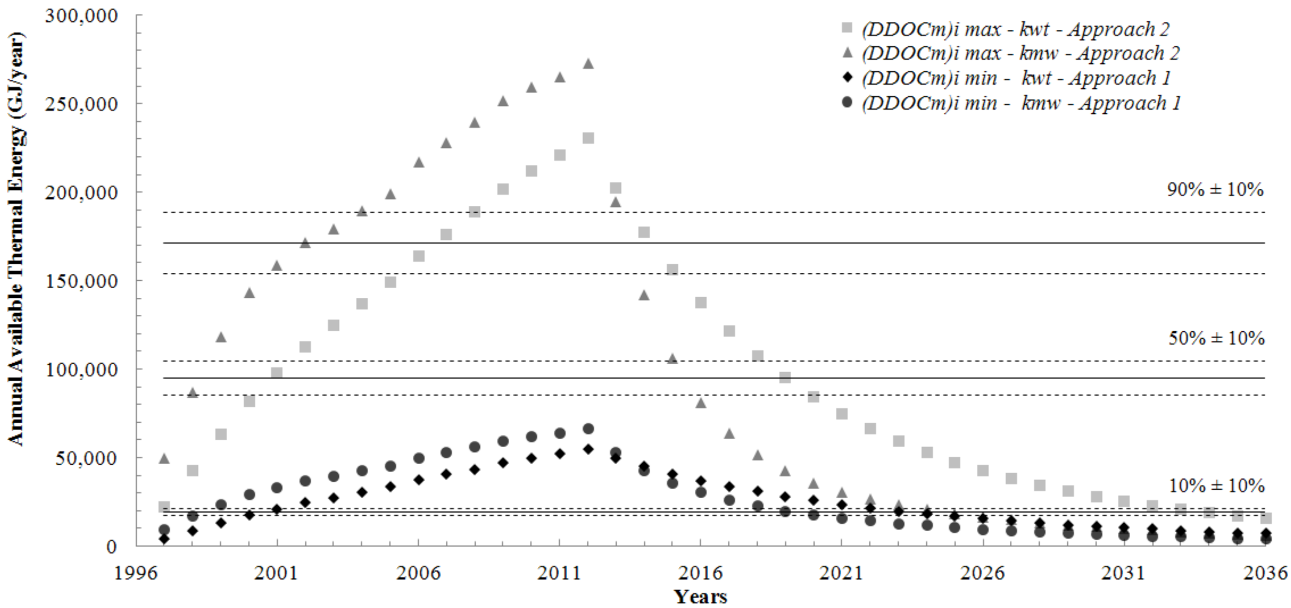

Figure 6. Annual available thermal energy for leachate evaporation.

The maximum estimed leachate $L_{estimated,max}$ of 73,500 m³, calculated for the maximum percolation year, was taken as a reference for the evaporation process. From this maximum amount, three possible cases where assessed: 90%, 50% and 10%, with a 10 % associated uncertainty. Results from all these estimated cases can point out that evaporation of small amounts of leachate can be performed for many operational years, or for a small period if the amount is close to the maximum possible value. The operational period for this exposed situation can range from 5 or 9 years, for 90% $L_{estimated,max}$ to more than 20 years for 10% $L_{estimated,max}$. This wide range of possible duration or expectation for the coupled operation of LFG burning and leachate evaporation introduces an uncertainty factor that makes landfill energy recovery and system design very hard to be evaluated.

6. CONCLUSIONS

The assessment carried out in this study allowed to identify the importance of the proper determination of gas generation parameters to estimate LFG generation, which is critical for decision making in projects with LFG utilization. The $(DDOC_m)_i$ indicates the potential of a certain SW amount to produces methane and influences on the magnitude of calculated LFG_a. This can be seen in calculated LFG_a values with approach 2, which was 4 times bigger than the one obtained with approach 1, where the SW gravimetric composition also plays a fundamental role in LFG_a prediction. The reaction rate constant k is associated to the methane potential conversion, and LFG_a production calculated for the same $(DDOC_m)_i$ but for different values of k, showed a 3 to 5% difference.

Energy recovery from LFG for conservative configurations, considering low electricity production, showed the possibility of generation of 492 kW with 3 motogenerators for a 4 years long period. When considering the more optimistic prediction, this value can reach 2.6 MW, with 16 motogenerators during 3 years of operation.

Leachate production obtained with the WBM method showed good agreement with actual recovered material, with a 7 to 10% deviation. Leachate evaporation was also assessed; pointing out that the system is able to perform the evaporation of 10% of the maximum produced volume during approximately 20 years, for a more conservative scenario, in contrast to 50% along 17 years or 90% during 5 to 9 years, for more optimistic scenarios. In general, leachate evaporation can be considered as an option for energy integration in landfills.

Further work must be done to reduce the uncertainties or the range of the predicted results in order to give more reliable information for economical assessment. Efforts must be done to landfill $(DDOC_m)_i$ determination based on the correct DOC_i values, actual gravimetric composition and its time variation as well the LFG volumetric composition. It is also suggested investigate LFG collection efficiency.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Amini, H. R., Reinhart, D. R., Mackie, K. R., 2012. “Determination of first-order landfill gas modeling parameters and uncertainties”. *Waste Management*, Vol. 32, p. 305-316.

ABRELPE, 2012. “Brazilian Atlas of GHG Emissions and Energy Potential in Solid Waste Disposal” (in portuguese). Brazilian Association of Companies of Public Cleaning and Special Rejects, Brazil.

Barlaz, M.A., Eleazer, W.E., Odle, W.S., Qian, X., Wang, Y-S, 1997. “Biodegrative analysis of municipal solid waste in laboratory-scale landfills”. EPA-600/SR-97/071, US Environmental Protection Agency.

Cho, H. S., Moon, H. S., Kim, J. Y., 2012. “Effect of quantity and composition of waste on the prediction of annual methane potential from landfills”. *Bioresource technology*, Vol. 109, p. 86-92.

El-Fadel, M., Bou-Zeid, E., Chahine, W., Alayli, B., 2002. “Temporal variation of leachate quality from pre-sorted and baled municipal solid waste with high organic and moisture content”. *Waste Management*, Vol. 22, p. 269-282.

Fenn, D. G., Hanley, K.I., Degeare, T. V., 1975. Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites”. U.S. Environmental Protection Agency, EPA 530/SW-168, p. 1–10.

Gewald, D., Siokos, K., Karellas, S., Spliethoff, H., 2012. “Waste heat recovery from a landfill gas-fired power plant”. *Renewable and Susteinable Energy Reviews*, Vol. 16, p. 1779-1789.

Harries, C.R., Cross, C.J., Smith, R., 2001. “ Development of biochemical methane potential (BMP) test and application to testing of mucipal solid waste samples”. In *Procedings of Eight International Waste Management and Landfill Symposium*. Cagliari, Italy, pp. 579-588.

INMET, 2013. “Metereological data of Porto Alegre” *National Institute of Metereology*. 20 Apr. 2013 <http://www.inmet.gov.br/portal/>.

IPCC, 2006. *Guidelines for National Greenhouse Gas Inventories: Intergovernmental Panel on Climate Change*. Vol. 5, Waste, IGES, Japan.

Lobo, AG.C., 2003. *Moduelo 2: A tool to be used to evaluate municipal solid waste landfills contamination* (in Spanish). Ph.D. thesis, University of Cantabria, Spain.

Machado, S.L., Carvalho, M. F., Gourc, J. P., Vilar, O.M., Nascimento, J. C. F., 2009. “Methane generation potential in tropical landfills: simplified methods and field results”. *Waste Management*, Vol. 29, p. 153-161.

MMA, 2013. “Brazil’s Solid Waste Policy” (in Portuguese). Environment Ministery. June, 2013 <www.mma.gov.br/política-de-resíduos-sólidos>.

DMLU, 2012. “Porto Alegre Municipal Plan for Integrated Solid Waste Management” (in Portuguese). Municipal Department of Urban Cleaning. October 2012, Porto Alegre, Brazil.

Oonk, H., Boom, T., 1995. “Validation of landfill gas formation models”. *Climate Change Research: Evaluation and Policy Implications*, p; 597 – 602.

Penteado, R., Cavalli, M., Magnano, E., Chiampo, F., 2012. “Application of the IPCC model to a Brazilian landfill: First results”. *Energy Policy*, Vol. 42, p. 551-556.

Renou, S., Givaudan, J. G., Poulain, S., Dirassouyan, F., Moulin, P., 2008. “Landfill leachate treatment: Review and opportunity”. *Journal of Hazardous Materials*, Vol.150, p. 468-493.

Spokas, K., Bogner, J., Chanton, J. P., Morcet, M., Aran, C.,Graff, C., Moreau-le Golvan,Y., Hebe, I., 2006. “Methane mass balance at three landfill sites: what is the efficiency of capture by gas collection systems?”. *Waste Management*, Vol. 26, p. 516-525.

Tchobanoglous, G., Theisen, H., Vigil, S., 1993. *Integrated Solid Waste Management*. McGraw-Hill, New York, USA.

Tchobanoglous, G., Kreith, F., 2002. *Handbook of Solid Waste Management*. McGraw-Hill, New York, 2nd edition.

US EPA, 2005. *Landfill gas emissions model (LandGem) version 3.02 User’s Guide*. EPA-600/R05/047, May 2005, US Environmental Protection Agency.

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