Potential energetic integration of municipal landfill effluents

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Abstract. *The work reported in this paper estimates mass and energy balances for municipal landfill gaseous and liquid effluents in order to verify the possibility of an energetic integration of the landfill effluents. The objective is to quantify if the amount of released heat by landfill gas (LFG) combustion is sufficient to evaporate the landfill leachate (LFL). A 1st order Intergovernmental Panel on Climate Change (IPCC) model is used to simulate biogas production and its uncertainties, and a modified water balance method is used to quantify leachate production and its uncertainties. Data from Guajuviras landfill, in Canoas – RS – Brazil is used to propose two case scenario for the energy integration: one where combustion and evaporation processes are ideal and another which they are closer to reality, both analyzed for a twenty years period. Energy integration is assessed in these scenarios via two metrics: Energy Surplus (ES) and Energy Ratio (ER). Results show that there would always be enough energy released from biogas to evaporate landfill leachate, and that tendency still can be supported if the uncertainties are taken into consideration. Mass and energy balances indicate that no more than 30% of the biogas released energy by combustion is enough to evaporate the leachate. Engineering systems are not proposed in the present study, but results indicate the possibility of an energy integrated system based on cogeneration.*

***Keywords**: landfill gas. landfill leachate, landfill energy integration, landfill effluent modeling*

1. NOMENCLATURE

BF	Biodegradable fraction in SW [-]
CH_{4g}	Mass of generated methane for the inventory year (Gg)
Cm	Maximum value of CH_4 produced per tonne of waste (Nm³ CH4/ t_{SW})
DDOCm	Degradable organic carbon (Gg)
ER	Energy ratio (%)
ES	Energy Surplus (MWh)
F	LFG volumetric fraction (Dimensionless)
Fr	Biodegradable fraction in SW [-]
HHV	High heating value (MJ/kg)
h	Enthalpy (kJ/kg)
k	Reaction rate constant (year-1)
LFG	Landfill gas (Nm3/h)
LFL	Landfill leachate (Ml/Year)
LHV	Low heating value (MJ/kg)
MSW	Municipal solid waste
MW	Molecular weight (kg/kmol)
P	Precipitation (mm H_2O/month)
PET	Evapotranspiration potential (mm H_2O/month)
R	Surface runoff (mm H_2O/month)
SC	Correction area strategy (m^2)
T	Temperature (°C)
U	Uncertainty
WB	Water Balance
WBM	Water Budget Method
Xi	Model parameter

Greek simbols

η	System efficiency
ρ	Density (kg/m^3)

Subscript and superscripts

a	Annual
C	Extraction
CH_2	Methylene
CH_4	Methane
CO_2	Carbon dioxide
env	Environmental
evap	Evaporation
MO	Model output
Out	Out
R	Recovered

2. INTRODUCTION

Waste disposal became a major issue worldwide due to our way of living, even though there are efforts towards the reduction of its rate of production concerning actions of reuse and recycling. An important amount of municipal solid waste (MSW) is thrown away in landfills, which is a less expensive option for final disposal for developing countries. (Renou et al, 2008).

Municipal landfill (ML) operation is an exclusive operation as it immobilizes the area itself and its vicinities, which are usually under a weaker social and economic position (Reno, 2016). Moreover, MLs produce harmful gases and liquid effluents referred as landfill gas – LFG and leachate – LFL, respectively.

MLs are the world's third major source of anthropogenic methane emissions (Global Methane Initiative, 2012). ML gas can be taken as a 50/50 mixture of methane and carbon dioxide followed by some trace species. As a general solution, LFG is flare burned to mitigate its greenhouse hazard without energetic recovery that could be achieved with motogenerators or by thermal conversion. Motogenerators based on reciprocating engines can overcome a reduction on their endurance when running with unpurified LFG due to the presence of siloxane (H_2S) associated to high contents of moisture. H_2S displays an important corrosive potential and is harmful to human health at concentrations higher than 100 ppm. Besides, that solid deposition over cylinder surface reduces the useful chamber volume followed by an increase on the design pressure ratio (Metcalf and Edy, 2016). It is worth noticing that LFG thermal energy is expected to be part of advanced MSW strategies (Economopoulos, 2012.

LFL comes from interaction between rainwater percolation and organic matter decomposition, and is usually treated on biologic facilities with associated operational costs and transport risks. Evaporation processes based on mechanical, chemical or thermal procedures become an alternative option as they can be performed on-site.

The municipal landfill main proposal is to give a final ending to waste. Its effluents are undesirable byproducts that must be controlled and mitigated even if the related processes generate operational costs. Energetic integrated landfills can become an alternative to mitigate effluent hazards by combining the biogas heat release to leachate reduction. Brazil is the third country in MSW generation with 215.297 tons per day (ABRELPE, 2014) and the national MSW policy establishes a target number of 311 MW (MMA, 2012) for energy recovery from LFG.

The goal of this study is to perform mass and energy balances for the main landfill effluents in order to assess the technical feasibility of their energy integration. LFG thermal release is used as source for leachate evaporation. Meteorological forecast are part of the input data for LFG and LFL production models together with waste mass disposal and its characterization. In these models, prediction uncertainties are also addressed.

3. EFFLUENT PRODUCTION

3.1 Landfill gas (LFG) and landfill leachate models (LFL) (Patiño et al, 2015)

The IPCC 1st order model (IPCC. 2006) was chosen to estimate the average annual landfill gas volumetric flow rate recovered over a given year *T*- $LFG_{a,T}$ (Nm^3/h). LFG is thus given by:

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

where ρ_{CO2} and ρ_{CH4} are the CO_2 and CH_4 densities (kg/m³) at standard temperature and pressure (0°C and 101.325 kPa). MW_{CO2} and MW_{CH4} are the molecular weights of CO_2 and CH_4 (kg/kmol). F_{CH4} is the LFG methane volumetric fraction and Δh_{year} is the number of hours per year (8760 h). The recovered average annual volumetric flow rate $LFG^R_{a,T}$ (Nm^3/h) based on the extraction system efficiency η_c is given by:

$$LFG_{aT}^{R} = \eta_c \, LFG_{aT} \quad (2)$$

The IPCC model depends on two parameters: the degradable organic carbon *DDOCm* (Gg) for a specific waste component i, and the reaction rate constant k (year^{-1}), which is a half-life value defined as the necessary time for the mass of available organic matter to decay to half of its initial value.

Precipitation is the basis of 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, 1975; Tchobanoglous, 2002). It allows for the determination of LFL 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) gives the water balance WB as follows

$$WB = P - PET - R \quad (3)$$

where P is the local precipitation on statistical basis. PET is the evapotranspiration potential given either by the Penman-Monteith's equation (FAO, 2016) or on statistical basis, and R is the surface runoff estimated by empirical correlations, expressed in millimeters of monthly accumulated H_2O.

3.2 Uncertainty estimation

Data from the Guajuviras landfill were chosen as input to the IPCC model (IPCC, 2006). This landfill is located in Canoas, a 300 thousand inhabitants town in south Brazil and was initially created as an open dump for municipal solid waste disposal. It became a landfill after January 1996 and finally closed in December 2011. With a landfilling area of 81,000 m², topsoil intermediate and bottom layers made of 0.6 m compacted clay, it received more than a million tons of solid waste along its lifetime operation.The solid waste gravimetric composition, assumed to be similar to the one from the neighbor city Porto Alegre due to the lack of information on the original site, is: 57.27% organic matter; 26.8% inert; 11.62% paper/cardboard; 3.86% textiles; 0.45% wood in wet basis (PMPA, 2013). The extraction system efficiency η_c was taken as 70% (Amini et al., 2012).

The uncertainty u_{MO} associated to the model output is calculated by the propagation expression (Cabral, 2004).

$$u_{MO}^2 = \sum_{i=1}^{n} \left[\frac{\partial MO}{\partial x_i}\right]^2 ux_i^{\,2} + 2\sum_{i=1}^{n-1} \sum_{j\neq i}^{n} \frac{\partial MO}{\partial x_i}\frac{\partial MO}{\partial x_j} u_i u_j \, u_{ij} \quad (4)$$

where x_i stands for the model parameters and u_{xi} their associated uncertainties. The index j refers to the cross product.

3.3 Effluent estimation

Guajuviras LFG production and its uncertainties propagation are displayed in Figure 1.

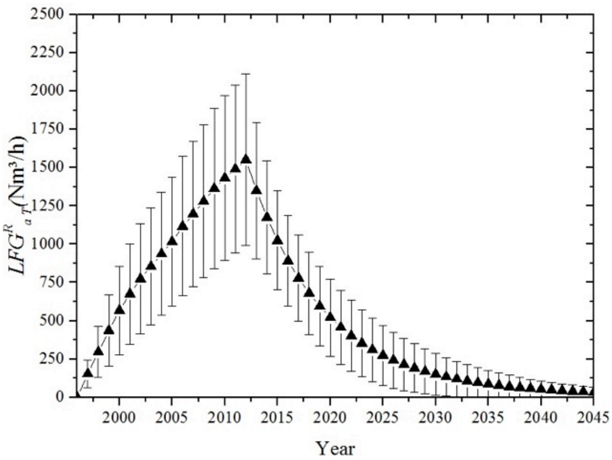

Figure 1: Recovered average annual landfill gas volumetric flow rate recovered LFG^{R}_{aT} (Nm^3/h) with 70% extraction system efficiency η_c and its combined uncertainty.

The LFG pick was predicted to happen around the year 2012, when actually the waste disposal was ceased. From that point on, an expected decay of its production was estimated, until the extinction of the landfill activities, in 2045. The uncertainty increased in absolute value together with the LFG production, and reached its maximum around the year of 2012. Input parameters and its uncertainties are presented in the Table 1, for unitary standard deviation.

Table 1. IPCC input data and correspondent uncertainties (Patiño et al., 2015)

	k		*BF*		*Cm*		*Fr*	
Waste	Average	u_k	Average	u_{BF}	Average	u_{Cm}	Average	u_{Fr}
Paper/Paperboard	6.00E-02	1.00E-02	4.27E-01	9.15E-02	4.22E+02	1.47E+01	1.16E-01	3.49E-02
Organic matter	1.50E-01	8.50E-02	6.40E-01	6.00E-02	5.74E+02	9.76E+01	5.73E-01	1.72E-01
Wood	3.00E-02	1.00E-02	3.09E-01	2.15E-01	4.86E+02	1.61E+00	4.50E-03	1.35E-03
Textile	6.00E-02	1.00E-02	6.00E-02	1.00E-02	6.00E-02	1.00E-02	3.86E-02	1.16E-02

The accumulated leachate volume on annual basis *LFL* (Ml/year) and its combined uncertainty propagation are displayed at Figure 2.

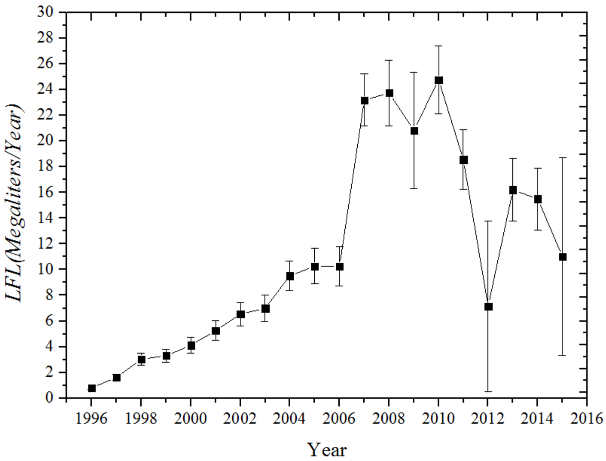

Figure 2: Estimated value of leachate volume LFL (Ml/year) and its combined uncertainty.

The WBM model considers a fixed amount of surface area, and is therefore more suitable to closed landfills. In order to take into account the progressive increase of that surface area, an annual correction strategy SC_a was implemented, ranging from zero to its maximum value in 2012, given by:

$$SC_a = \frac{SW\ mass_a}{Landfill\ total\ surface\ area} \tag{5}$$

After that correction, the model predicted a steady increase on LFL production until 2011, with a special increment on 2006 and 2007 due to higher local precipitation. LFL production for 2012 was particularly lower, decreasing from 18.55 Ml to 7.35 Ml, as the result of the La Niña climatic phenomenon, the most severe drought over 60 years of data collection.

LFL uncertainty was calculated based on data displayed in Table 2, with +/-10% input dispersion.

Table 2: Water balance model parameters and their relative bias. Data from 2007 (LFL = 23.17 Ml/year)

	LFL 2007 (Ml/year)	
Input	Min	Max
	-10%	10%
P	22.61	31.93
PET	26.72	22.20

4. ENERGY BALANCE

Landfill gas and liquid streams are displayed in Figure 3, together with some possible energy integration.

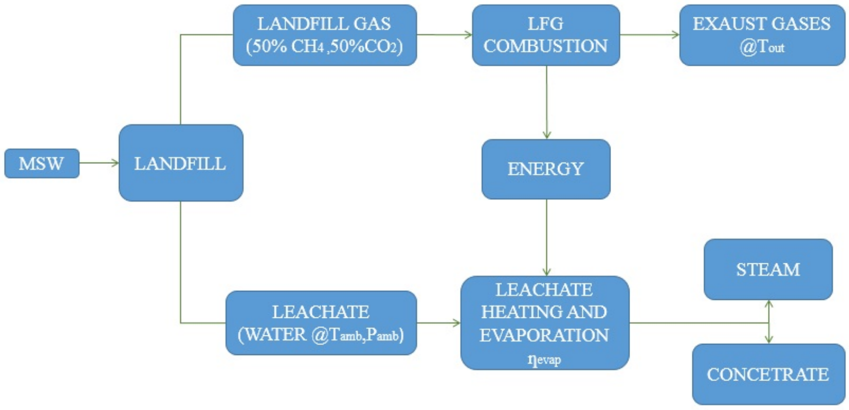

Figure 3: Energy integration scheme considering LFG burning for LFL evaporation.

Both effluents cannot be released to the environment without previous treatment and the basic idea behind this scheme was to recover the thermal energy from LFG burning to treat LFL effluents, based on an energetic balance with the assumptions presented in Table 3. Two operational conditions were taken into account, summarized in Table 4.

Table 3: Modeling assumptions for landfill gas and leachate (LFG and LFL) energetic integration

Landfill GAS - LFG	Landfill LEACHATE - LFL
Available at environmental conditions (P_{env}= 1 atm; T_{env}= 25 °C)	Basically composed by water at environmental conditions (P_{env}= 1 atm ; T_{env}= 25 °C)
50% methane (CH_4) and 50% carbon dioxide (CO_2) in volume basis	Phase chance enthalpy Δh_{pc}= 2256 kJ/kg (P=1atm ;T=100 ºC)
LHV = 13.362 MJ/kg and HHV = 14.834 MJ/kg (Turns, 2000)	Evaporation enthalpy Δh_{evap}= 2571 kJ/kg (P=1 atm ; from T_{env} to T=100 ºC)

Table 4: Ideal and Real process conditions

Condition	LFG flue gas output temperature	LFL evaporation efficiency
Ideal	$T_{out} = T_{env}$	100 %
Real	T_{out} = 150 °C	80 %

These parameters are in accordance to Schroeder (2013), which highlighted the process dependence with biogas flue gas temperature and flow rate. The specific energy of 2850 kJ/m^3 for LFL evaporation was reported by Birchler (1994), which led to a LFL evaporation efficiency of 90% if compared to the evaporation enthalpy Δh_{evap} presented in Table 3. In order to be more conservative, this efficiency was taken as 80%, as declared in Table 4.

Two performance indicators were used to assess the landfill energy balance: the annual energy surplus *ES* and the annual energy ratio *ER*, given by:

$$ES_a = Q_{LFG,a} - Q_{LFL,a} \tag{6}$$

$$ER_a(\%) = 100\frac{Q_{LFL,a}}{Q_{LFG,a}} \tag{7}$$

These two indicators were based on the annual accumulative heat Q_a, for a given year *a*, in MWh. A positive value of the annual *ES* means that the energy released by LFG combustion is sufficient to evaporate LFL, but that parameter can eventually assume negative values as well. *ER* is always positive, and will be as small as the greater is the LFG surplus after the LFL evaporation process.

5. RESULTS AND DISCUSSION

5.1 Energetic potential

Figure 4 displays the amount of heat released by LFG combustion in simultaneous to the evaporation heat of LFL for the ideal condition, presented in Table 4.

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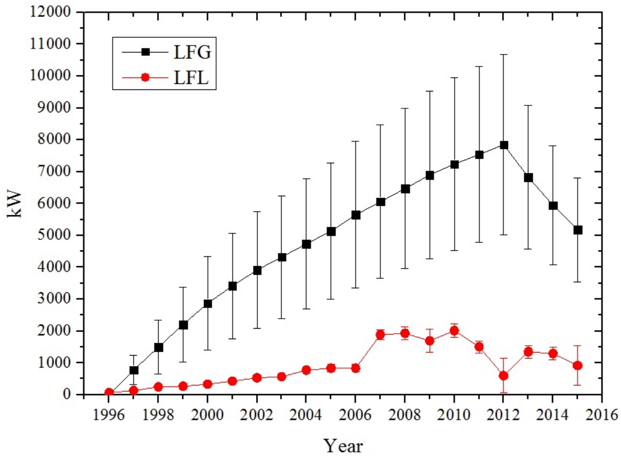

Figure 4: LFG and LFL energy potential conversion of effluents and its uncertainties.

According to the ideal assumption, there is enough energy released by LFG combustion to perform LFL evaporation, which enables the energetic integration of these two streams.

The energy surplus ES given by Equation (6) is plotted on Figure 5 for both the ideal and real conditions declared in Table 4.

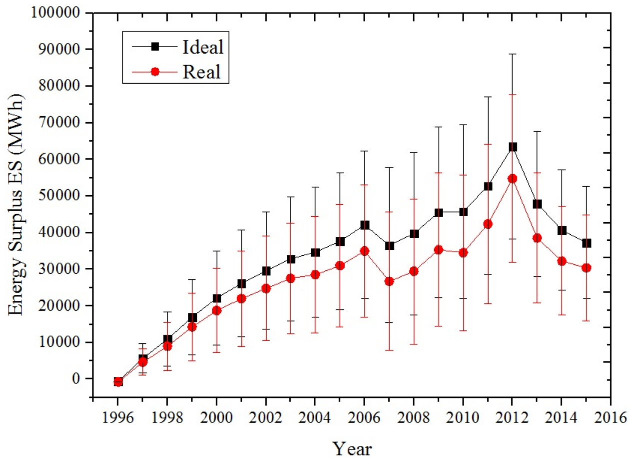

Figure 5: Annual energy surplus ES for the ideal and real conditions

Both curves display the same tendency along time, and the real case was slightly lower, as expected. The volumetric production of LFL was variable and displayed some important differences from year to year, according to the rain regime (Figure 2), but that behavior was attenuated due to the imbalance in favor of the energy released by LFG combustion, expressed by the energy surplus ES. As the rain index value for 2012 was abnormally low, ES_{2012} reached the higher value along the historic series.

The accumulated and average ES values are displayed in Table 5, followed by their uncertainties.

Table 5: Accumulated and average values of Energy Surplus ES over a20-year period of assessment

Condition	Accumulated ES (GWh)	Average ES (GWh)
Ideal	668.266 ± 330.137	33.413 ± 16.507
Real	539.255 ± 296.471	26.963 ± 14.824

Nominal results were in accordance with the behavior previously presented, but it is worth to discuss the role of their associated uncertainties, with reached around 50% for both cases and conditions.

The same period was assessed by the aid of the energy ratio ER given by Equation (7), and displayed in Figure 6.

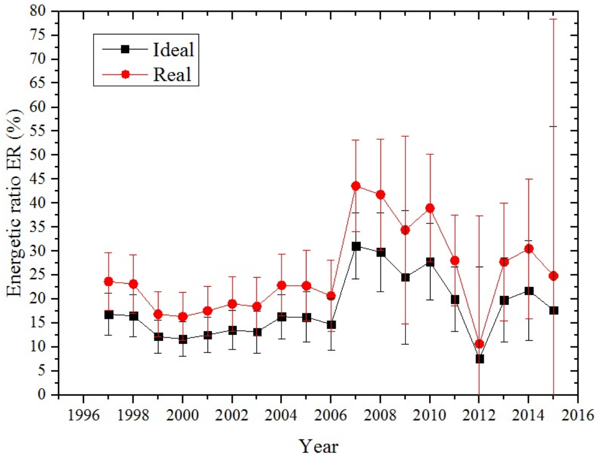

Figure 6: Annual energy ratio ER for the ideal and real conditions

Energy ratio ER indicates that approximately 20% of the energy released by LFG combustion could accomplish LFL evaporation, from the beginning of the landfill operation until year 2006, followed by some important variations from year to year. Although these differences were important, reaching twice the average value for the begging period, there was always an energy surplus in favor of LFG. The design of an energy integrated system should be flexible enough to take into account that behavior, considering also the uncertainties of the simulated results.

The average ER calculated for 20 year period displayed a value of 19.26 ± 9.10% for the ideal condition and of 26.98 ± 12.75% for the real one. On both conditions, the average values were below 1/3 of the landfill gas energetic potential, pointing out that there would be room for cogeneration systems. Once more, uncertainties were large, reaching almost half of the average values.

5.2 Sensibility analysis

ES and ER showed to be sensitive towards the flue gases output temperature, as displayed in Figure 7.

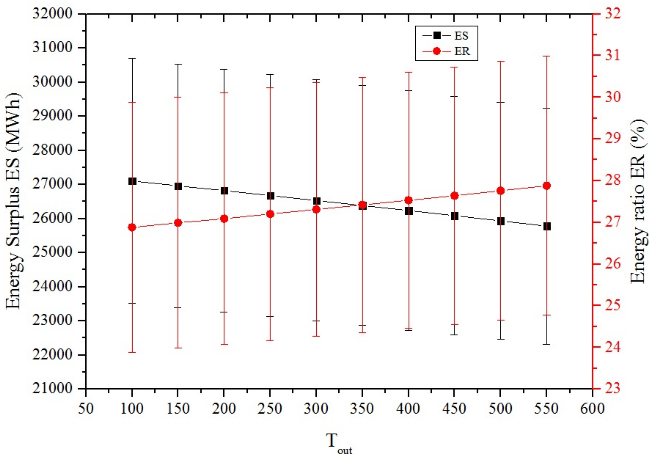

Figure 7: Average values of Energetic surplus ES and energy ratio ER
as function of biogas flue gases output temperatures T_{out} (η_{evap}=80%)

Values were calculated for a constant evaporation efficiency of 80%, and 20 years long period of analysis. ES and ER showed a near linear and inverse behavior as a function of T_{out}, but anyway the system displayed its best performance whenever the output flue gas temperature diminished. The same behavior is presented in Figure 8, that shows ES and ER as a function of the evaporation efficiency η_{evap}, for a constant value of the flue gases output temperature T_{out} of 150 ^{o}C.

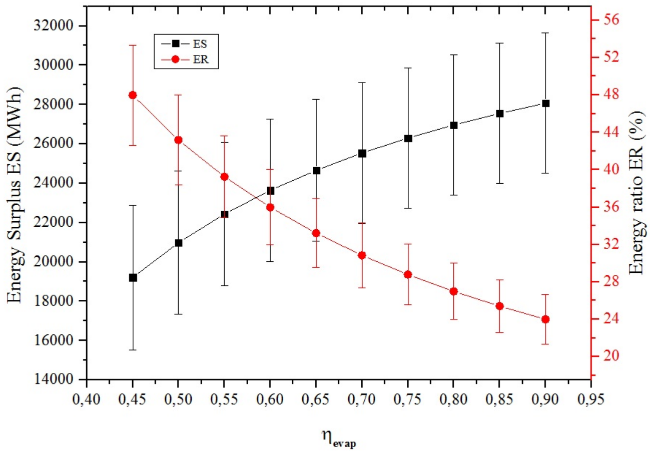

Figure 8: Average values of Energetic surplus ES and energy ratio ER as a function of evaporation efficiency η_{evap} (T_{out}=150 °C)

As showed in Figure 8, there is a consistent and considerable overall gain whenever the evaporation efficiency is improved.

6. CONCLUSIONS

Landfill gas and liquid effluents were predicted for an already closed MSW facility in south Brazil with the aid of a 1st order IPCC model and a modified water balance method, respectively. Simulated results were used to perform mass and energy balances, with associated values of propagated uncertainties for each of them, on a 68% reliability basis. Energy integration was proposed based on the recovery of the released heat from biogas combustion to evaporate landfill leachate.

Results were assessed by observing two proposed metrics: the Energy Surplus ES and the Energy Ratio ER, considering an ideal process of combustion and evaporation, followed by a more realistic one, throughout a 20 years long period. Results showed that there would always be enough energy from landfill biogas to evaporate landfill leachate, and that tendency still can be supported if the uncertainties were taken into consideration. Mass and energy balances indicated that no more than 30% of the biogas energy released by combustion would be enough to evaporate the leachate.

Engineering systems were not proposed in the present study, but results indicated the possibility of an energy integrated system based on cogeneration.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

ABRELPE. Brazilian Association of Public Cleaning Companies and Special Waste (in Portuguese) http://www.abrelpe.org.br/panorama_apresentacao.cfm

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

Birchler, R. D., "Landfill Leachate Treatment by Evaporation", ASCE, Journal of Environmental Engineering Vol 120, No 5, 1994

Cabral, P., 2004. Erro e incerteza nas medições. Departamento de Física. Instituto Superior de Engenharia do Porto. www.peb.ufrj.br/cursos/ErrosIncertezas.pdf (accessed in June, 2015)

Economopoulos, A., 2012. Planning tools and procedures for rational municipal solid wastes management. in: Waste to Energy: Opportunities and Challenges for Developing and Transition Economies. Springer

Fenn, D. G., Hanley, K.I., Degeare, T. V. 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, 1975

Global Methane Initiative. 2012. Basic concepts of integrated solid waste management. in: International Best Practices Guide for Landfill Gas Energy Projects

IPCC. 2006. Guidelines for National Greenhouse Gas Inventories. Volume 5: Waste. www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html (accessed in June, 2015)

Metcalf, L., Edy, Harrison P. Tratamento de efluentes e recuperação de recursos.McGraw-Hill, New York, 5nd edition, 2015

MMA, 2012. National policy for solid waste. (http://www.mma.gov.br/pol%C3%ADtica-de-res%C3%ADduos-s%C3%B3lidos) (in Portuguese)

Patiño, A. Berchon, L. Schneider, P. Thomazoni, A. Saffer, M. Uncertainty assessment of models for landfill biogas production. 23rd ABCM International Congress of Mechanical Engineering.

PMPA, 2013. Integrated municipal plan for solid waste management (in Portuguese) http://www2.portoalegre.rs.gov.br/dmlu/default.php?p_secao=161 (accessed in June, 2015)

Reno. J.. 2016. The Anthropologist in the Landfill.http://www.theatlantic.com/business/archive/2016/03/landfill-anthropologist/476121/ (assessed march 2016)

Renou.S., Givaudan. J.G., Poulain.S., Dirassouyan. F., Moulin. P.. 2008. Landfill leachate treatment: Review and opportunity. J. Hazard. Mater. 150. 468–493. doi:10.1016/j.jhazmat.2007.09.077

Schroeder, D. F., Leachate evaporation by waste heat of municipal landfill biogas driven motogenerator. UFRGS, 2013 (http://hdl.handle.net/10183/79792) (in Portuguese)

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

The ETo Calculator. Reference Manual Version 3.2 September, 2012. Food and Agriculture Organization of the United Nations Land and Water Division FAO. (accessed in Janeiro, 2016)

Turns, S. R. An introduction to combustion, concepts and aplications. Propulsion engineering research center and department of mechanical and nuclear engineering. The Pennsylvania State University. McGrraw-Hill, New York, 2nd edition, 2000.

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