Considerations on the energetic use of landfill biogas in MSW compactor-collector trucks

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ABSTRACT: In large landfills, the application of a percentage of the generated biogas to supply the fuel demand of a fleet of Municipal Solid Waste (MSW) compactor-collector trucks may replace, with advantage, the use of diesel by the fleet for many years. There are two technologies for landfill biogas to be explored. The first is related to the generation of electric power and its use in electric (or hybrid) trucks and, the second, with the gas production to fuel natural gas vehicles (NGV). The methodology adopted to compare the two modals was based on the biogas transformation into electrical energy equivalent (kWh). Costs related to the replacement of diesel powered trucks by both NGV powered and electric compactor-collector trucks are presented and discussed. The evaluation developed in the present work shows that the option providing the more effective utilization of biogas as energy source was with NGV vehicles, but very close to electric-powered trucks. Taking the Rio de Janeiro landfill (Jardim Gramacho landfill) as an example, the results showed that only 13.3% of the total gas collected in 2012 would be enough to supply the whole fleet of COMLURB (Municipal Urban Cleaning Company of Rio de Janeiro). The use of electrical energy would consume some 14.8% of the total gas collected. Both modes allows the injection of the remaining energetic potential either in an electric supply net or a pipeline gas network, creating new possibilities for commercial exploitation of landfill biogas and, also, a more sustainable MSW collection.

***Keywords** landfill, biogas, MSW collection trucks*

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1. INTRODUCTION

Municipal solid wastes (MSW) are associated with two factors related to greenhouse gas emissions (GHG): (a) the collection system for trucks fueled by fossil fuels, with the generation of large amounts of Carbon dioxide (CO_2) and Nitrogen oxides (NO_X), and (b) landfills, which are the third largest source of anthropogenic Methane (CH_4) emission (Usepa, 2012).

Surveys conducted by Ziegler (2012) comprising 15,700 vehicles throughout Brazil found that garbage transportation is what emits more CO_2 per km run. According to the survey, garbage compacter trucks emit some 1.24 kg/CO_2 per km run. The high CO_2 emission is related to the characteristics of the operation and the use of diesel as fuel. In this activity, to allow garbage collection, the vehicles stop and go continuously. Thus, the trucks often do not pass the second gear, what generates a high fuel consumption.

According to a study by World Bank (2004), the feasibility of collecting and using biogas as a source of energy is normally limited to large and deep landfills (above 1 million ton of waste and depth of more than 15 meters) and for cities with at least 400,000 inhabitants or neighboring municipalities sharing a large landfill.

In Brazil, where the large MSW production causes huge social and environmental impacts, the inclusion of biogas in its energy matrix is a promising alternative. In large centers, the increased waste generation is higher than the population growth; thousands of tons of garbage are dumped daily into landfills or places without any preparation to receive that type of waste.

The country has, in most part of its territory, advantageous conditions to biogas production in landfills all of the year, like temperature and humidity and, mainly, the predominance of organic matter in the solid waste composition. The biogas generated has, as basic feature, a concentration above 30% of CO_2 and 50 to 55% of CH_4, approximately (Ensinas, 2003). Its calorific value is directly related to the amount of Methane in the mixture, which can range from 5,000 to 7,000 kcal/m^3 (Deganutti, 2002).

Considering the energetic potential of the biogas produced in MSW landfills, this paper aims to quantify advantages in the substitution of diesel powered MSW compactor-collector trucks by both NGV and electric powered trucks. Data related to the Metropolitan Landfill of Rio de Janeiro, known as Jardim Gramacho Landfill, and to the collection system employed in the city of Rio de Janeiro were taken as a basis for the quantification procedures herein presented.

2. TECHNICAL ASPECTS

There are some options for reducing GHG emissions by the MSW transport sector. Several cities in the world are taking advantage of their landfill biogas as fuel energy to supply heavy MSW collection vehicles; and there are those, still in an experimental way, employing electric or hybrid vehicles.

In this work, considering the electric modal, it was taken as model a XXL 26t vehicle, with a 16 t waste loading capacity (PVI, 2012). Such truck is equipped with an ion–lithium

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battery that consumes about 170 kWh in an 8 hours round, and has an autonomy of 170 km, enough to collect some 6100t of waste produced daily in a city such as Rio de Janeiro.

As for the use of biogas as NGV, its transformation into electric equivalent energy was introduced in order to provide a comparison with the electric model analyzed. For that it was used a 26t Renault D-Wide truck with a cylinder capacity of 126 m^3 of gas, totaling an average performance of 1.9 km/m^3, with 239.4 km of autonomy (NGVA, 2015).

The Jardim Gramacho (RJ) landfill, despite not receiving waste since 2012, has been taken as a model to test the viability of the hypothesis herein taken and its replication to landfills from other large Brazilian cities. This landfill has a daily biogas production of approximately 480,000 m^3 (Gas Verde, 2012), with a monthly potential of electricity generation of about 20.563.200 kWh.

Based on technical information from Comlurb (2015), the company has 296 compactor-collector trucks in operation. The amount of MSW collected in December 2014 was 184,500 tons and the average mileage traveled by vehicle was 4160 km. To compute such average mileage, total distances were considered, including: garage; operational manager; path collection; transshipment station; back to the path collection; transfer, return to the garage. The actual distance travelled in collection (only in the path travels) in the shift of operation has an average variation of 15% of the total. The average consumption was of 1.6 km/liter of diesel.

3. ESTIMATE OF ELECTRIC POWER PRODUCTION OF THE LANDFILL AND THE FLEET CONSUMPTION

Equations 1 and 2 express the input parameters for the biogas use as electric power, with the preparation of the landfill installations to generate electricity. The first step is to find the electric equivalence of 1 m^3 of biogas;

$$P\left(\frac{kWh}{m3}\right) = \frac{PCI\ x\ 4{,}1868\ KJ}{3600} \qquad [1]$$

where: P = power available in kWh/m^3; PCI = lower calorific power biogas value = 5000 kcal/m^3; 1 kcal = 4.1868 kJ; 3600 = conversion kcal to kWh.

Equation 2 corresponds to a comparative relationship of equivalence of the calorific power value of 1 m^3 biogas with electricity;

$$E\ eq. = \partial\ x\ P\left(\frac{kWh}{m3}\right) \qquad [2]$$

where: ∂ = 0,246 (25% efficiency of electric generator); having as a result: E eq. (1m^3biogás) = 1.428 kWh.

Equation 3 represents the electric power production available in the landfill in 30 days;

$$E = Q\ x\ E\ eq.\ x\ T \qquad [3]$$

where: E = electric power available monthly (kWh); Q = biogas generation (m^3/24 h); E eq. =1,428 kWh; T = 30 days.

Equation 4 shows the values to calculate the fleet consumption with biogas such as electricity. The monthly consumption by 8h round is:

$$Cconsumption\ monthly = F\ x\ Cconsumption\ 8h\ x\ T \qquad [4]$$

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where: Cconsumption 8h = 170 kWh (energy consumption of the electric truck of 16t in a 8h round); F = fleet of 291 compactor-collector trucks 16 t; T = 30 days;

3.1 Estimate of NGV production

The second alternative comes to the use of biogas as NGV, considering its transformation into equivalent electric energy. In this case, landfill facilities are prepared to purify the biogas to NGV. In this case Equations 1 and 2 are used with parameters adapted to work with natural gas: PCI = 9274 kcal/m^3 and ∂ = 0.34 (34% engine efficiency for electric power production with the NGV) having, as a result: E eq.gn (1m^3biogás) = 3.667 kWh.

The supply capacity of the NGV vehicle cylinder is of 126m^3 of gas, and 1m^3 of gas is equivalent to 3.667 kWh, so it will correspond to 462.04 kWh. To supply all fleet, the total amount would be according to:

$$Cconsumption\ 24h = E\ eq.gn \times F \qquad [5]$$

where: Cconsumption 24h= (Power consumption NGV truck 26t); F = fleet of 291 NGV 16t compacter trucks.

As the efficiency of NGV engines is greater than the efficiency of electrically powered vehicles, the volume of 126 m^3 of NGV is enough to serve at least 3 rounds of 8h collection because each vehicle travels some 70 to 80 km / turn (ADEME, 2014).

Table 1 shows a comparison of the equivalent consumption of electric energy in 2 turns of 8h travel of a fleet of compactor trucks and the monthly use of the landfill biogas production in relation to the biogas consumption by a fleet of 291 trucks running with NGV and electricity. Considering the potential of electric energy generation in the landfill, it can be seen in this Table that the consumption by the electric modal is marginally greater than that of the NGV modal.

Table 1. NGV and electrical fleet consumption in relation to biogas electricity production

Modal	Consumption NGV 16h/day, 2 turns/8 h (kWh)	Equivalent electric energy monthly consumed (kWh)	Monthly equivalent electricity used in relation to that produced (%)
NGV	91,176	2,735,280	13,3
Electric	100,640	3,019,200	14,8

4. ECONOMIC ASPECTS

Table 2 shows the landfill biogas production and its consumption by the fleet of 296 trucks, as well as the energy balance and the expected revenue after supplying energy to all the fleet. Average costs were adopted for the NGV and electric power. In Table 2 and in all the following Tables all values are quoted in American Dollars, with exchange rates from European Euros and Brazilian Reais as per those from April 15th, 2015.

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Table 2. Average numbers associated with landfill biogas production and fleet consumption

Activity	Daily	Yearly	Energetic Balance	Revenue (US$)	
				Unit Cost	Total (year)
Landfill biogas production (Nm^3)	480,000	175,200,000	166,248,960	0.654 (m^3)	108,726,820.00
NGV fleet consumption (Nm^3)	126	8,951,040			
Landfill electric production (kWh)	685,440	246,758,400	210,528,000	0.220 (kWh)	46,316,160.00
Electric fleet consumption (kWh)	100,640	36,230,400			

4.1 Operating costs

Unit costs can be aggregated according to the desired analysis, to introduce or expand a collection service. These will represent the final cost for a particular measure. Can be: per kilometer, per ton collected, per person served, etc.

4.1.1 Cost US$/km

Equation 6 shows that to calculate the fuel cost/km, the method is to divide the fuel price (modal) by the performance of the vehicle:

$$Cost\ modal/km = \frac{V}{Perf} \qquad [6]$$

where: V = US$ value of fuel per modal; Perf = modal performance;

The results obtained with expression 6 are shown in Table 3.

Table 3. Average costs associated with the modal performance

Modal	**Unit Costs (US$)**	**Performance**	**Total cost (US$)**
Diesel	1.013/liter	1.60 km/litter *	0.633/km
NGV	0.654/m^3	1.90 km/m^3 **	0.344/km
Electric	0.220/kWh	1 km/1kWh ***	0.220/km

* Comlurb (2015); ** ADEME (2014); ***Electric consumption (PVI, 2012).

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4.1.2 US$/ton/km Cost

For the calculation of ton/km ($US\$\frac{t}{Km}$), Equations 7 to 9 are used:

$$Dtf = F \times Dt \qquad [7]$$

where: F = n vehicles; Dt = total distance monthly travelled per vehicle;

Dividing the total weight collected (monthly) by the total mileage travelled:

$$US\$\frac{t}{Km} = \frac{Pt}{\mathrm{Dtf}} \qquad [8]$$

where: Pt = total waste weight collected monthly by the fleet; Dtf = total distance monthly travelled by the fleet;

With the value obtained by Equation 8, multiply by the value of each modal:

$$\mathrm{US\$}\frac{\mathrm{t}}{\mathrm{modal}} = \mathrm{US\$}\frac{\mathrm{t}}{\mathrm{Km}} \times \mathrm{US\$\ value\ fuel\ modal} \qquad [9]$$

Using the unit costs shown in Table 3 and Equation 9, costs of ton of waste collected by each modal per travelled millage (km) are show in Table 4.

Table 4. Average costs associated with each modal

Modal	Cost (US$ / t / km)
Diesel	0,150
NGV	0,097
Electric energy	0,032

4.1.3 Miscellaneous costs

Table 5 presents costs related to the installation in the landfill of facilities for exploration of gas or electricity and costs of acquisition of new vehicles. An intermediate choice in terms of cost/benefit would be the conversion of existing diesel powered trucks to NGV. Conversion values for that, in Brazil, ranged between US$ 4,950.00 and US$ 8,250.00. The cost of US$ 6,600.00 was herein adopted as an intermediate reference value. The facilities installation costs were based on information related to the Gramacho landfill (Gas Verde, 2012). The costs of new heavy waste collector-compactor trucks refer to average values considering vehicles produced in different countries in the world. Total costs were computed considering a fleet of 296 trucks.

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Table 5. Costs associated with the renovation of the fleets and landfill installations

Description	Unit Value (US$)	Total (US$)
Installations costs landfill	-	122,549,000.00
New electrics vehicles 26 t	265,200.00	78,495,700.00
New NGV vehicles 26 t	200,000.00	59,200,000.00
New diesel vehicles 26 t	181,780.00	53,808,000.00
Conversion of diesel vehicle to NGV	6,600.00	1,953,800.00

4.2 Values saved with diesel replacement

With the use of biogas energy from landfills, significant expenses with mineral diesel and lubricating oil would be avoided, providing annual savings as indicated in Table 6. In this Table, the exchange of lubricating oil was considered to be required at each 10,000 km.

Table 6. Average values associated with oil lubricant and diesel consumption.

Description	Truck Consumption (L/year)	Fleet Consunption (L/year)	Total cost US$ /year
Diesel	31,200	9,235,200	9,355,260.00
Lubricating oil	152	44,992	177,270.00

5. ENVIRONMENTAL ASPECTS

5.1 Quantities of CO_2 and NO_X emissions and noise pollution produced

Taking into consideration CO_2 and NO_X emissions, Table 7 shows the environmental benefits of having both a NGV and an electric powered fleet of trucks as compared to a diesel powered fleet.

Table 7. Pollution emitted by different models of heavy waste collection vehicles

Description	Emission (kg/ km)	Truck Emission (t/year)	Fleet Emission (t/year)
Diesel vehicle(CO_2)	1.24*	61.90	18,323
NGV vehicle (CO_2)	0.55**	27.46	8,126
Electric vehicle (CO_2 and NO_x)	0***	0	0
Diesel vehicle (NO_x)	0,0146****	0.72	216
NGV vehicle (NO_x)	0,0101****	0.5	149

*Ziegler (2012); **ADEME (2014); ***PVI (2012); ****Andre (2007)

A study by Quadros (2004), pointed out that noise pollution is, after air and water pollution, the environmental problem that most affects people. As indicated in Table 8, NGV powered vehicles produce high noise, from 60 to 72 (dB)A, higher than the 55 (dB)A considered to be tolerated by the World Health Organization (WHO – Quadros, 2004) or the 45 (dB)A allowed by PMC (2002) at night. Diesel collector trucks have an even worse performance, as they emit 105 (dB)A of noise, above the limit considered by WHO as capable to promote deafness. Electric powered trucks do not produce any noise. In this case, the only noise that can happen will be caused by the handling of garbage containers.

Table 8. Noise pollution emitted by different vehicles

Noise pollution emitted	**Values**
Vehicle diesel	105 (dB)A *
Vehicle NGV	72 (dB)A **
Vehicle electric	0 (dB)A ***

*Quadros (2004); ** (ADEME, 2014); *** PVI (2012)

5.2 CDM (Clean Development Mechanism)

CDM can be applied both for the landfill itself and to the waste collection system. In the case of CO_2 and NO_X emissions avoided by a waste collection system, CDM can be computed considering an year of waste collecting activity, through the mileage travelled by the electric and NGV vehicles as shown by Equations 10 and 11.

$$Value = Em\ CO_2 \times tCO_2\ eq. \quad [10]$$

where: Em CO_2 = CO_2 annual emissions; tCO_2 eq. = US$ 10. 00 (Monteiro, 2001)

In the case of NO_X, emissions have to be multiplied by 310, which is the value of global potential warming in relation to CO_2.(Felipetto, 2007):

$$Value = Em\ NOx \times 310\ tCO_2\ eq \quad [11]$$

where: $Em\ NO_X$= NO_X annual emissions from fleet vehicles collectors compactors; tNO_X eq = 310 x tCO_2 equivalent =US$ 10.00.

Considering 296 vehicles and 1 year period of time, the revenue associated to the NGV and electric modals are shown in Table 9.

Table 9. Revenue from CDM in 1 year

Description	**Values (US$)**
CDM (CO_2) electric compactor-collector trucks	18,323.00
CDM (CO_2) NGV compactor-collector trucks	10,195.66
CDM (NO_X) electric compactor-collector trucks	66,867.00
CDM (NO_X) NGV compactor-collector trucks	20,612.00

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6. CONCLUSION

In terms of CO_2 and NO_x emissions, NGV-powered vehicles emit less 44.35% and 30.5% than the diesel modal, respectively. The electrical-powered vehicles would be the best choice in this case as they do not emit any CO_2 or NO_x.

With respect to fuel consumption, which was observed in terms of efficiency energy, (km/fuel) the electrical modal obtained a more efficient performance in comparison to the other two modes. It was 25% more economical than diesel and 46% more than NGV. The electric modal provides an extra lubrication oil economy, since it does not have to use it.

The cost of a ton of waste collected by mileage run (US$/t/km) also points out a significant advantage of the electric mode over the diesel modal (55.1%). The NGV achieved about 35.5% reduction on diesel costs.

Finally, the study demonstrates that the biogas production in a large landfill, such as the Jardim Gramacho landfill in Rio de Janeiro, is great enough to supply a 296 fleet of collector trucks 26t, considering both the NGV and the electric modals. Furthermore, taking into account that the required minimum life time of a sanitary landfill is of 10 years, which is the same life-cycle of a lithium-cadmium battery, and that CDM usually run over a 7 year period, it can be demonstrated that the revenue resulting from the sale of either the remaining produced electricity or purified biogas, associated to the CDM surplus and the economy resulting from the maintenance of a fleet of diesel powered trucks, is more than enough to overcome the high costs of new electric or NGV powered trucks.

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