Assessment of the energy potential from urban wastes of Belem city, Brazil: case study

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Abstract
Dumping municipal solid waste and domestic sewage is common practice in most developing countries offering risks to public health and to the ecosystem. In Belem, Brazil, which is an important metropolis, this is a serious problem. As a contribution, this paper proposes treatment of municipal solid waste and domestic sewage by recycling, landfilling and incineration. The results show that recycling 10% of the recyclables potentially available generates funds of about R$ 5.5 million/year in addition to saving energy and avoiding emissions. Electric energy from incineration and landfilling of urban solid waste is sufficient for the consumption of 72,000 and 5000 homes, respectively while incineration and biological treatment of sewage sludge produce energy enough for 10,000 and 8000 homes, respectively, and recover 50% of waste water for reuse. Finally, treatment of municipal solid waste and domestic sewage can ensure for the municipality energy, economic benefits, and healthy environment for its inhabitants.

Keywords: Municipal solid waste; Domestic sewage; Energy; wastewater; treatment

1 Introduction

The increase of the population in the urban centers has unleashed a series of negative, ambient, energetic and economic impact, some of which are associated with the inadequate management of municipal solid waste (MSW) and domestic sewage (DS). The final disposition of the sub products of human consumption not only represents eminent risks to public health but also interferes in the equilibrium between man and nature.

MSW is composed of organic degradable matter (animal and vegetable left over), non degradable organic matter (plastic) and inorganic matter (glass and metal). During the biological degradation of organic matter, liquid effluents are produced which causes serious contamination in soil and underground water resources. In addition, the site attracts insects, rats and other disease vectors (Lino, 2014). While the DS is composed of solid and liquid which contain bacteria e microorganisms pathogenics responsible for diseases such as typhoid fever, tetanus, hepatitis, dysentery, leptospirosis and others (Spellman, 2003).

Report from UN-HABITAT (2013) shows that the lack of basic sanitation not only affects poor populations in developing countries but also reduces Gross Domestic Product (GDP) of the municipalities by 3% a 7%.

Collection and treatment of MSW and DS as well as treated water provision are essential public services under the sole responsibility of the local governments and considered as a human right. Nevertheless, the World Health Organization alerts that about 2.6 billion person in the world do not have neither collection nor treatment of MSW and DS, of these about 780 million have no treated water (WHO/UNICEF, 2013).

In Brazil about 124 million inhabitants do not have treatment of their DS (IBGE, 2013). The country uses about four thousand dumping sites (open sky or closed sites) to dispose of MSW while the water bodies receive untreated sewage. About 30.5% of the municipalities extract water for treatment for population consumption, recreation, irrigation and aquaculture from the same water bodies (IBGE, 2011, MCidades, 2013a).

Specifically in Belem, capital of the state of Para and one of the important Brazilian metropolis, about 18% of the population does not have access to treated water. The municipality is included among the ten municipalities which present the highest hospitalization percent because of diarrhea caused by the inadequate sanitary services affecting principally children up to five years old. The number of hospitalization of the municipality of 985 people per 100.000 inhabitants surpasses the national average which is 600 inhabitants. (IBGE, 2011, 2012, 2013; MCidades, 2013a).

With the objective of changing this scenario, the National Policy for Solid Waste was created and regulated by the law 12.305/2010, which establishes MSW treatment by recycling, biodigestion and incineration. Among other actions, this law determines the closure of dumping sites, increases the recycling index to 20%, apply the principle of producer responsibility and the inclusion of waste collectors in the selective collection programs of the municipalities (BRASIL/MMA, 2014).

The treatment methods proposed in the Brazilian law are applied in other countries as Germany, Sweden, United Kingdom, Japan and Canada. These methods not only minimize the environmental impacts but also allow reuse the energy and financial potential contained in MSW and DS (Unstat, 2011).

Considering the huge amounts of MSW and DS generated in Belem municipality of about 389,000 t/year and 71 million m³/year, respectively (MCidades, 2013a; b), wasted benefits and the environmental and public health impacts, this paper presents two scenarios for MSW treatments based upon recycling and biodigestion and recycling and incineration and two scenarios for treatment of DS based upon biodigestion and incineration. The objective is to demonstrate to the public administrators the wasted energy, economic and ambient potential of MSW and DS which can be reverted to additional benefits and complement to energy and treated water demands.

2. Literature review

2.1 Treatment systems of MSW

MSW treatment is defined as the processes, units and procedures which change the physics, chemical or biological characteristics of waste and result in minimizing its risks to public health and environment quality (CONAMA, 2012). The principle methods for MSW treatment includes recycling, landfilling with or without biogas recovery and incineration with or without heat utilization. Studies on waste composition in many developing countries indicate the intrinsic high potential of recycling due to the presence of big quantities of recyclables in the MSW stream (Pariatamby and Fauziah, 2014).

Recycling

Solid waste as paper/ cardboard, plastic, glass and metal can be transformed via recycling into inputs for manufacturing new products. The reuse results in benefits such as water, energy and raw material preservation as well as prolonging the landfill useful life and creates jobs and income (Lino, 2014). OECD (2013) shows that some countries recycle and compost more than 50% of their MSW as Germany (63%), Austria (62%), Netherland and Korea (61%), Belgium (57%) and Switzerland (50%).

Countries such as Singapore, Japan and Korea have rigorous regulation and have active participation from public and private sectors. Recycling practice eventually became more of a habit rather than an approach regulated by the authorities. In 2012, Singapore recycled 60% (ZeroWasteSG, 2013). However, in many developing countries recycling is practiced more for financial reasons and in many cities in Asia and the Pacific region, recycling has become the source of income to the poor and underprivileged population (Pariatamby and Fauziah, 2014).

Landfills

Landfill is considered as a method of deposition of MSW in soil without impacting public health and environment, where engineering principles are used to confine the solid waste in the smallest possible area and reduce its volume to the minimum possible, covering with a layer of soil at the end of each day (ABNT, 1992). Although landfilling is a well known method, in 2011 countries as Denmark, Switzerland, Netherland, Belgium, Austria and Japan landfilled less than 4% of their MSW (OECD, 2013).

Biodigestion/ Incineration

Biodigestion is biological degradation of the organic matter (confined in the landfill) by bacteria multiplication in oxygen rich or poor ambient producing gases and digested organic matter. In the absence of oxygen these bacteria produce biogas composed basically of methane and carbon dioxide.

Incineration is defined as the combustion of solid and liquid wastes in pollution and emission controlled incineration plants. The combustion process reduce the volume and weight of MSW by about 90% and 75%, respectively, eliminate pathogens, destruct potentially damaging substances and yet produce heat which can be transformed to electric energy (WEF, 2009; EC, 2006). Countries as Germany, Japan and USA incinerate raw and selected MSW. In Germany in 2005/2006, incineration produced about 6 TWh of electricity and 17 TWh of heat sufficient for the electricity needs of Berlin City. In the last three decades Germany expanded its incineration capacity and recycling to ensure a correct destination of MSW instead of landfilling. In the twenty seven European countries, energy production from MSW incineration in ten years increased by about 140%. In 2010, the contribution of incineration in Germany was 29%, in France was 16% and in Italy and Netherland was 10% for each (EEA, 2013).

2.2 Treatment systems of DS

After collection the DS is sent to treatment station where it is subjected to a series of operations according to the level of required treatment and are identified as preliminary, primary, secondary and tertiary. Beside the primary sludge which is organic solid, in the subsequent treatment processes the secondary sludge which is organic material of biological origin and the tertiary sludge produced by chemical precipitation (IPCC, 2006; Spellman, 2003).

An investigation realized by COPASA (2013) showed that the biological treatment of DS of a million inhabitants in the state of Minas Gerais generated 13.0 GWh/year in 2012 and only in January 2013, the average generated energy is of about 19.0 MWh.

Biodigestion/ Incineration

Where by the secondary sludge in the reactor and in the absence of oxygen and under constant temperature is transformed into biogas and digested sludge which can be used for soil correction or incinerated together with MSW for heat and electricity generation. The biogas after cleaning and drying can be combusted to produce heat to be transformed into electric energy. In countries as Slovakia, Egypt and Switzerland, the biogas is used for electricity generation to supply energy for the treatment plant itself (Bodik & Kubaská, 2013).

The incineration of combustible elements in the dehydrated sludge at temperatures between 420 to 500 ^{o}C in the presence of oxygen producing carbon dioxide, water vapor, ash and heat. The heat produced can be used to generate electricity and eliminates DS offensive impacts (IPCC, 2006; EC, 2006; Turovskiy and Mathai, 2006).

As the literature review, MSW and DS have financial and energy potential which is generally well used in developed countries while in developing and poor countries, these potential benefits are wasted with subsequent negative impacts to the population and to the environment.

2.3 Municipality of Belem

Belem is the capital of the state of Para (PA) situated in the North of Brazil as in Fig.1, occupies an area of 1,059,406 km², population of 1,393,399 inhabitant in 2010, has a population density of 1,315.26 inhab./km² and is considered as one the 15 big municipalities in the country (IBGE, 2013). Official data (MCidades, 2013b) shows that in 2011 Belem collected 388,643 t/year of MSW from 97% of the urban areas. According to official records, accumulated MSW in the streets covers 35,471 homes or 142,606 inhabitants.

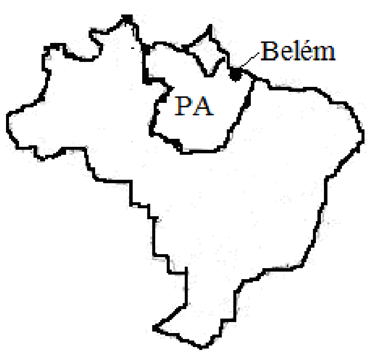


Figure 1. Localization of the municipality of Belem (PA).

About 600 tons per year of recyclables were collected selectively by waste pickers helped by the municipality authorities in 2011 while the rest of collected MSW was deposited in Aura landfill (dump) where informal waste pickers work daily recovering recyclables to sell for survival. For the MSW collection service and its final deposition, the municipality paid R$ 77.31/t or US$35 (MCidades, 2013b).

With respect to the DS, in Belem only 6.4% of the population (8.1% homes) has their DS collected and only 1.6% of the DS is treated (MCidades, 2013a). According to the IBGE (2013), part of DS discharged freely in the streets affects directly about 466,435 inhabitants. In addition, volume of treated water is about 455,255 m³/ day, sufficient to attend the needs of about 82% of the population (IBGE, 2011). The average water consumption in Belem in 2011 was 140L/inhab./day (MCidades, 2013a).

As can be observed, the basic sanitation services in the municipality of Belem are precarious and do not meet the needs of the population, although they are services guaranteed by the Federal Constitution of 1988. Majority of Brazilian municipalities are facing same or similar situation. For a populous country like Brazil with developing economy and vast natural resources, a firm and strong political must be established to adequately prioritize basic sanitation issues.

3 Materials and Methods

The composition of solid waste used in the calculations of Belem is the same as the national average. Organic matter = 52.5 %; paper/cardboard = 24.5 %; plastics = 2.9 %; glass = 1.6%; metal = 2.3%; others = 16.2 % (IPT/Cempre, 2000).

Data in Table 1 was used to calculate the energy, economic and emissions from the thermal and biological treatments of MSW and DS from the municipality of Belem.

Table 1 Technical data used in the calculations

Description	Reference Value	Adopted value	Reference
Biogas production from landfill (L/kg)	35 - 45	40	Karagiannidis (2012)
Specific mass of CO_2 (kg/m^3)		1.83	Rose & Cooper (1977)
Emissions of incinerated MSW (tCO_2 /TJ)	10 - 40	25	Monni et al. (2006)
LCV of CH_4 (MJ/m^3)[1]		33.95	Rose & Cooper (1977)
Avoided emissions due to recycling (CO_2/t)		1.971	Lino and Ismail (2012)
Avoided energy due to recycling (GJ/t)		31.629	Lino and Ismail (2012)
Market value of mixed recyclable (R$/t)		450	Cempre (2013)
LCV of incinerated MSW (kJ/kg)	5.250 – 10.264	6.130	Niessen (2002)
Auxiliary fuel for incineration LPG (kg/t)[2]		8.0	Brasil/MCT (2005)
Biogas recuperation efficiency (%)	50 - 75	75	Monni et al. (2006)
LCV of LPG (MJ/kg)	40.05 - 46.05	40.05	Rose & Cooper (1977)
GWP of CH_4	25	25	IPCC (2006)
Biogas production from sludge (m³/kg)	0.8-1.1	0.95	Turovskiy and Mathai (2006)
Solid fraction in sludge(kg/m^3)	0.1 – 0.3	0.2	Turovskiy and Mathai (2006)
Emissions due to LPG (kg CO_2/kg LPG)		3.019	Brasil/MCT (2005)
LCV of biogas from sludge (MJ/m^3)	15 - 25	20	Niessen (2002)
Heat content of incinerated sludge (MJ/kg)	12.80 - 19.75	16	Turovskiy and Mathai (2006)
Water consumption (m³/month)[3]		17.1	MCidades (2013a)
EE consumption (MWh/capita)[4]		0.604	BRASIL/MME (2013)

(1) Lower calorific value, (2) Liquefied Petroleum Gas, (3) Per average brazilian residence; (4) Electric energy

Source: Elaborated by the authors.

3.1 Methods

This section presents the simplified diagrams of the proposed routes of MSW and DS treatment, the respective explanations and equations used in the calculations.

3.2 Municipal solid waste
3.2.1 Recycling and landfilling of MSW

The amount of recyclables collected selectively for reuse is 10%. Organic matter and the rest of recyclables not reused are transported to landfills for biogas collection and utilization for heat and electricity production. The biodigestion of the organic matter can reduce its volume by about 20 to 25% (MCT, 2005).

From the gravimetric characterization of MSW it is possible to determine the amount of recyclables from equation 1

- *Quantity of recyclables = Recyclables fraction x Collected MSW* (1)

The financial gain from commercializing the recyclables is obtained from equation 2.

- *- Financial gain = Price of recyclables U$ / t x quantity of recyclables* (2)

The return of the recyclables to the production chain eliminates the necessity of energy to process raw material e consequently avoids associated emissions. Lino and Ismail (2012) calculated by using the data from McDougall et al. (2001) and from Hekkert et al. (2000), the total energy savings per ton of recyclable mix (Table 1). The same procedure is used to calculate the amount of avoided CO_2 due the reuse of the recyclables.

The energy and emissions avoided due to recycling can be calculated by the equations 3 and 4

- *Avoided energy = Avoided energy factor x Recyclable mass* (3)

- *Avoided emissions = Avoided emissions factor x Recyclable mass* (4)

The rest or 90% of MSW is transported to landfill. The rate of biogas production depends on MSW composition, ambient conditions, humidity and the average pH value. The average quantity of biogas production can be calculated from equation 5 as

- *Quantity of generated biogas =*
  Rate of biogas production x biodegradable mass in MSW (5)

The generated biogas is collected, cleaned and forwarded for utilization or for energy generation. It is important to mention that not all the biogas generated is collected, some of it escapes because of the porous structure of the landfill. Hence the recuperation efficiency may vary and, in the present work the value of 75% was used. The collected gas can be calculated from equation 6

- *Collected biogas = Recuperation efficiency x volume of generated biogas* (6)

The generated biogas is principally composed of CH_4 and CO_2 and small quantities of other gases. In the present study a composition of biogas of 45% CH_4 and 55% CO_2 is adopted. The energy contained in the collected biogas can be calculated by using the lower calorific value (LCV) of the methane or by using an average value for the biogas of the generated composition. Equation 7 can be used to calculate the energy content of the collected biogas.

- *Energy content of the collected biogas = mass of collected biogas x LCV of the biogas* (7)

Calculations of emissions

The combustion of CH_4 produces the same quantity of CO_2 according to equation 8

- $CH_4 + 2O_2 = CO_2 + 2H_2O$ (8)

Hence the quantity of CO_2 generated due to the combustion of collected biogas is equal to quantity of collected biogas or

- *CO_2 generated from the combustion of collected biogas = quantity of collected biogas* (9)

The calculations of the fugitive biogas and the equivalent emissions (CO_2e) can be calculated from equations 10 and 11

- *Quantity of fugitive biogas = (1-η) x Quantity of generated biogas* (10)

where η is the biogas recuperation efficiency = 75% and GWP of methane = 25.

- *Equivalent CO_2e of CH_4 = GWP x CH_4 quantity* (11)

3.2.2 Incineration of MSW

Subtracting 10% of the recyclables, the rest of MSW is directed to the mass incineration plant where it is burnt with the help of auxiliary fuel, considered here as LPG. Energy generated during the combustion of MSW can be used to generate vapor and electricity and the energy in the hot flue gases can be recovered to heat the admission air for the boilers or other applications. When it is relatively cold is admitted for removal of offensive gases, acids and soot particles after which it is discharged into the ambient. The ash of the incineration process can be recycled or used in road paving and civil construction etc.

As in the previous case, the financial, environmental and energy gains can be calculated from equations 1 to 4.

The mass of MSW sent for incineration is the mass of collected MSW minus the mass of commercialized recyclables (10%). The heat released during incineration depends upon the heat content of MSW and can be calculated from equation 12

- *Heat released during incineration = Mass of MSW incinerated x Heat content of MSW* (12)

Normally, the auxiliary fuel is used to start incineration and to maintain the temperature in the furnace. The auxiliary fuel can be any type of fuel whose characteristics and consumption for the type of MSW are known from experimental operation. In the present work LPG is used. equation 13 can be used to determine the amount of heat released by the auxiliary fuel.

- *Energy released = mass of the LPG x LCV of the LPG* (13)

The net heat released in the incineration process is the difference between the heat released by incineration of MSW and the heat released due to the combustion of the auxiliary fuel as in equation 14

- *Net heat released = Heat released in combustion of MSW –*
  Heat released by the LPG (14)

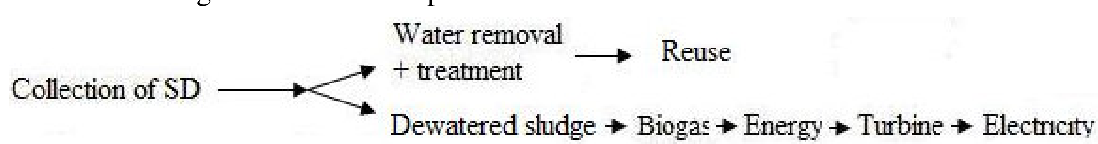
This energy will be converted to electricity with a conversion efficiency of about 30%. As a result of the combustion of the different biomass and plastics in MSW, tremendous amounts of pollutants gases needs to be removed before the combustion gases are allowed to atmosphere. The polluting gases are treated by special techniques depending on your nature. The amount of CO_2 generated due to the combustion of both MSW and the auxiliary fuel can be calculated using data (Table 1) as in equations 15 and 16.

- *Quantity of CO2 generated due to the combustion of LPG =*
  Emission factor x mass of LPG (15)
- *Quantity of CO2 generated due to the combustion of MSW =*
  Emission factor x mass of MSW (16)

3.3 Sewage domestic treatment

3.3.1 Biological treatment of sewage sludge

The biogas production depends on the composition of the sludge, specifically its biodegradable mass content and the rigid control of the operational conditions.



Rate of biogas production from sewage sludge, according to Table 1, has an average value of 0.2 kg/m^3. The biodegradable solid mass can be calculated from equation 17.

- *Biodegradable solid mass in the sludge =*
  Solid fraction in sludge x Volume of treated sludge (17)

Biogas generated from sludge biodigestion can be calculated from equation 18.

- *Volume of generated biogas =*
  Production rate of biogas x Biodegradable solid mass (18)

The quantity of released heat depends on the calorific value of biogas which varies from 15 to 25 MJ/m^3. The biogas generated can be combusted to produce heat and generate electricity. The quantity of released heat can be calculated from Equation 19.

- *Energy released by biogas = Volume of biogas x LCV of biogas* (19)

The electric energy generated from the biogas can be calculated by multiplication of the result of equation 19 by the thermal conversion efficiency (η), assumed here as 30%,

- *Electric energy = Energy released by biogas x thermal conversion efficiency (η)* (20)

According to the Brasil/MME (2013) the energy consumption per capita in 2012 was 0.604 MWh which corresponds to 0.1812 x 10^9 J_{el}. Consider that a typical Brazilian family is composed of 3.5 members, the monthly electric energy consumption for a family is 0.6342×10^9 J_{el}. The generated electric energy for a number of residences is calculated from equation 21,

- *Number of residences = Monthly electric energy generated ÷ average residential consumption* (21)

Emissions released during the combustion of biogas can be calculated by equations 22 and 23 where equation 22 represents the chemical reaction formula for CH_4. Hence the total amount of CO_2 released is equal to the sum of amount of collected CH_4 and CO_2 originally present in the biogas. The emissions can be calculated from equation 23

- $CH_4 + 2O_2 = CO_2 + 2H_2O$ (22)
- *CO_2 emissions due to the combustion of collected biogas = Quantity of collected biogas* (23)

Wastewater from dewatering sewage sludge can be treated for reuse. The amount of wastewater recoverable is assumed to be 50% of the consumed water. Hence by knowing the average water consumption of a typical family it is possible to estimate the number of residences which can be attended by the recovered water from equation 24.

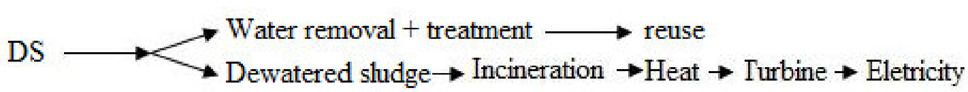
- *Number of residences attended by the recovered water = Volume of daily recovered water ÷ daily average water consumption of a residence* (24)

The biodigested material can be used for soil correction or treated further for use as fertilizer.

3.3.2 Thermal treatment of sludge

As in the previous case the collected sewage is dewatered and the separated wastewater is further treated for reuse. The amount considered for reuse is 50%. The sludge is thickened and pumped to the incineration plant.

The mass of solids in the sewage sludge can be determined by using Equation 17. The energy content



of the sewage sludge depends on its composition. Normally there is a need for auxiliary fuel to start and maintain incineration and in the present case LPG was used. Energy resulting from incineration of sewage sludge can be calculated from equation 25.

- *Energy released = Mass of solids x Energy content of sludge* (25)

Knowing the rate of consumption of LPG during the incineration process per ton of sewage sludge (usually determined experimentally) the total amount of consumed LPG is calculated from equation 26.

- *Total of LPG consumed = Mass to be incinerated x Rate of consumption of LPG* (26)

Energy released by the combustion of LPG can be calculated from equation 27.

- *Energy released by LPG = Mass of LPG x LCV of the LPG* (27)

The net amount of energy released during the incineration process is the difference between energy released by the incinerated material and energy released by the auxiliary fuel as in equation 28.

- *Net energy released = Energy released by sludge – Energy released by the auxiliary fuel* (28)

The hot gases can be used to generate steam and electricity with conversion efficiency of about 30%, as in equation 29.

- *Generated electric energy = Net energy released by incineration x Conversion efficiency* (29)

The combustion gases after leaving the boiler still have thermal energy which can be recovered for heating combustion air, produce hot water and drying sewage sludge to improve the overall thermal efficiency of the system. The relatively cold gases are cleaned and the pollutants are removed before releasing to the atmosphere.

Emissions resulting from incineration of sludge and the combustion of LPG can be calculated from the emissions factors presented in Table 1.

The quantity of CO_2 emitted due to the combustion of LPG and incineration of sewage sludge can be calculated from equations 30 and 31.

- *Emissions of CO_2 from the combustion of LPG = Emission factor x LPG mass* (30)

- *Emissions of CO_2 from the incineration of sludge = Emission factor x mass of sludge* (31)

Total emissions are the sum of the results from equations 30 and 31. The ash resulting from incineration can be reused for road paving, cement industry and other applications.

4 Results and discussion

4.1 Proposed treatment for MSW

The models used for the evaluation of the proposed treatment routes are presented in section 3.2 with the respective equations and the results shown in Table 2.

Recycling

The results of recycling 10% (or 12 thousands t/year) of the available recyclable potential in the city of Belem corresponds to 7.6 thousand national minimum salary of R$ 724.00 or US$ 327.75. Parte of these funds can be destined to educational programs to enhance the population adhesion to recycling while the other part can be invested in equipments. These actions can increase the recycling index of the city and promote the social inclusion by creating jobs and income.

Besides the financial gains from introducing 10% of the available recyclables in the production chain, additional benefits as avoided energy sufficient for 50.5 thousand homes and avoided emissions.

Landfilling

Landfilling of about 290 thousand t/year of organic matter with possibility of energy recuperation, as in Table 2, can produce biogas after subtracting the quantity of the fugitive biogas. The biogas effectively collected when converted to electric energy is sufficient for 5.2 thousand brazilian homes. Considering the billing price of electric energy of the municipality as R$ 0.478/kWh, the electricity from biogas of 923,000 kWh, one can find that monthly total financial gain is R$ 441,000 (US$ 199,000). Emissions due to landfilling are about 16 thousand tCO2e/year. Again the energy and avoided emissions can be used to formulate pro-ambient sanitation projects to capture financial funds.

Incineração

In the incineration scenario about 77% of Belem MSW is to incinerated to produce electric energy sufficient for 72 thousand homes each consuming 0.6342 GJ_{el} / month at a total of about
R$ 6 million/month (US$ 2.7 million/ month).

Energy and emissions produced from incineration are about fourteen times and three times, respectively, that from landfill biogas, but when summing the fugitive biogas, the emissions due to landfilling are almost double that of incineration. Table 2 shows the results of the two scenarios for the treatment of MSW of Belem City.

Table 2 Results from proposed scenarios for treatment of Belem´s MSW

Description	**Recycling**	
Collected MSW (t/year)	388,643	
Potential of available recyclables (t/year)	121,645.26	
Recyclables for sale (t/year)	12,164.53	
Funds from selling recyclables (R$ / year)	5,474,037	
Avoided energy due to recycling (GJ / year)	384,751.92	
Avoided emissions due to recycling (tCO_2 / year)	23,976.29	
Treatment of MSW	**Landfilling with biogas recovery**	**Incineration**
Organic matter for landfilling (t / year)	289,927.68	
MSW for incineration (t / year)		,
Biogas production (m^3/year)	11,597,107	
Collected biogas (m^3/year)	8,697,830.34	
Fugitive biogas (m^3 /year)	2,899,276.78	
Energy from incineration (J/year)		1834.43×10^{12}
Energy from biogas (J/year)	132.88×10^{12}	
Net energy from incineration (J_{el} /month)		45.86×10^{12}
Net energy from incineration (GWh/month)		12.739
Electric energy from biogas (J_{el} /month)	$3{,}322 \times 10^{12}$	.
Electric energy from biogas (GWh/month)	0.923	
Possible attended number of homes[1]	5238	72,312
Emissions (tCO_2/ year)	15,917.03	45,867.98
Emissions due to fugitive biogas (tCO_2e /year)	62,606.98	

(1) National average electric energy consumption per residence as 0.6342 GJ_{el} / month.

4.2 Proposed treatment of DS

The models used for the evaluation of the proposed treatment routes were presented in section 3.3 with the respective equations and the results shown in Table 3 for the proposed scenarios.

Biodigestion and Incineration

The results presented in Table 3 shows that the biological treatment of DS sludge produces electricity sufficient for 10,400 homes. The total cost of this energy is about R$ 878,000/ month (US$ 397,000 / month).

The result of incineration of Belem's sewage sludge shows electric energy produced corresponds to the consumption of 8600 homes and costs R$ 725,000 (US$ 328,000). Comparing the two proposed routes for DS treatment (Biodigestion and incineration) the amount of energy produced by both routes is of the same order, but the difference is in the associated CO_2 emissions which in the case of biodigestion route emissions are more than three times that of incineration. Recovered wastewater from treatment of DS at the rate of

50% is enough for demands of the 150,000 homes not connected to public network. Table 3 shows the results of the treatment routes proposed for handling DS of Belem city.

Table 3 Results of the proposed scenarios for treatment of Belem´s DS

Description	Biological treatment of DS with energy recovery	Incineration
Generated DS (m^3 / day)	193,406.5	193,406.5
Mass of sludge for biodigestion (t /day)	38.681	
Produced biogas (m^3/day)	36,747.24	
Mass of sludge for incineration (t /day)		38.681
Energy from biogas (J/day)	0.734945×10^{12}	.
Energy from incineration (J/day)		0.6189×10^{12}
Energy from biogas (J/month)	22.048×10^{12}	
Energy from incineration (J/month)		18.567×10^{12}
Electric energy from biogas (J_{el} /month)	6.615×10^{12}	
Electric energy from biogas (GWh/month)	1.837	
Net electric energy from incineration (J_{el} /month)		5.4586×10^{12}
Net electric energy from incineration (GWh/montl		1.516
Possible number of attended homes[1]	10431	8607
Emissions (tCO_2 /year)	24,545.3	5,988.4
Recovered water for reuse (m^3 / month)	2,901,098	2,901,098
Possible number of attended homes [2]	193,406	193,406

(1) Average consumption of electric energy per residence = 0.6342 GJ_{el} / month.

(2) Average water consumption per month of 15 m^3 /residence.

As can be observed, the treatment of MSW and DS in Belem is alarming since it presents serious risks to public health and impairs the environment. Adequate treatment of both offers a number of benefits, among which, creation of job and income, electricity generation which can reduce the demand for new hydroelectric plants and relief of water bodies from launched wastes. The volume of recovered waterwaste which can be reused reducing costs of treatment and extending these public services to regions not attended while contributing to the sustainability of the city.

5. Conclusions

The results show that the proposed scenarios can produce favorable environmental impacts such as reduction of emissions and of contamination of soil and water resources, more energy generation, saving raw materials and treatment of wastewater for reuse.

1. The funds generated from commercializing 10% of the available potential in MSW of Belem together with avoided energy and emissions due to recycling are important contributions to minimize the social problems by creating jobs and income. In addition, the municipality can invest part of the generated funds in awareness programs to encourage separation of waste in households and update infrastructure for processing recyclables. While landfilling of MSW produces biogas and its conversion into electricity can supplement the Brazilian energy matrix by an additional renewable energy source.
2. MSW incineration scenario produces sufficient electricity for 17% of the municipality homes, and ash that can be reused.
3. Incineration of DS sludge also presents good results, produces energy sufficient for 2% of the residences

in Belem while the recuperated wastewater is enough for nearly 45% of the municipality homes.

4. The municipal expenditure with treatment of MSW in 2011 if accumulated over ten years there will be enough money for acquiring an incineration plant of capacity of 1000 t/day which can incinerate both MSW and DS of the Belem city.

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