IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 05, Issue 01 (January. 2015), ||V3|| PP 31-41

Energy potential from treatment of wastes in São Luís- Brazil

Fatima A. Morais Lino[1] Kamal Abdel Radi Ismail[2]
[1]*Department of Energy, Faculty of Mechanical Engineering, State University of Campinas, UNICAMP, CEP 13083-860, Campinas (SP), Brazil. Phone: +55 19 35213376; Fax: +55 19 32893722.*
[2]*Department of Energy, Faculty of Mechanical Engineering, State University of Campinas, UNICAMP, CEP 13083-860, Campinas (SP), Brazil. Phone: +55 19 35213376; Fax: +55 19 32893722.*

Abstract: - Collection and treatment of urban solid waste and domestic sewage are essential sanitary services for the population, but in many countries as Brazil these services are defficient. In São Luís-MA, municipality with more than one million inhabitants are generated about 414 thousands ton/year of municipal solid waste and about 190 million cubic meters of domestic sewage per day. Their collection and treatment have been one of the biggest challenges for municipal administrators. This paper proposes techniques for treatment of municipal solid waste and domestic sewage with energy recovery and minimization of environmental impacts by recycling, biodigestion and incineration. The results show that reuse of 10% of the potential of recyclables can annually generate financial gains of R$ 6 million/year (US$ 2,7 million); the landfill biogas when converted to electricity can be enough for 5.5 thousand homes while MSW is incinerated it can produce electricity sufficient for 24% of the residences of the city. Both biogas of sewage and heat of incineration can generate energy sufficient for 3% of the homes in the municipality. The treated wastewater is sufficient for 45% of the homes in São Luis which has a deficit of 41.7% of homes without to treated water.

Keywords: *domestic sewage, emissions, energy, municipal solid waste, wastewater*

I. INTRODUCTION

Municipal solid waste (MSW) and domestic sewage (DS) are subproducts of human consumption which need to be collected and treated before its final disposition. These activities, which are essential for good quality of life of the population, are still very deficient in most of countries as in Brazil. In this country which is the fifth most populated of the world, of about 200 million inhabitant [1], there are about four thousand dumping sites for MSW while most of the collected DS is discharged without any treatment into water bodies or in open sky.

MSW is composed of organic degradable matter (animal and vegetal left over), non degradable organic matter (plastics) 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 [2, 3]. While the DS is composed of solids and liquid which contain bacteria e microorganisms pathogenic responsible for diseases such as typhoid fever, tetanus, hepatitis, dysentery, leptospirosis and others [4].

In 2008, about 12% of the 5565 the Brazilian municipalities registered cases of leptospirosis resulting in 3% death where the highest indices are in the north and north east regions. In addition cases of leptospirosis are very common in the country [5, 6, 7]. According to the analysis realized by WHO/UNICEF [5] there is a clear relation between precocious basic sanitary conditions, poverty and hospitalization indices which attacks poor area and peripheries of big cities. Adequate treatment of MSW and DS results in better hospitalization indices and better public health in general terms.

São Luis is a Brazilian metropolitan whose indices of collection and treatment of DS are the worst of the country, where less than 10% of DS generated is collected and treated [8] while all collected MSW is deposited in dumps. According to IBGE [9], in 2012 the municipality registered the death of 3613 citizens of which 425 were due to infectious and parasite diseases.

II. LITERATURE REVIEW

2.1 MUNICIPALITY OF SÃO LUIS

São Luis is capital of the state of Maranhão situated in northeast region of Brazil (Figure 1) and is considered as one of the fifteen municipalities most populated among the 5565 Brazilian municipalities. Its territorial area is about 834.79 km² and had a registered population in 2013 of about 1,053,922 inhabitant, 92% of them live in urban areas [8,9].

Figure 1 Localization of the municipality of São Luís (MA).

In 2011, about 413,852 tons of MSW were collected and disposed in dumps. Although the law number 12.305/2010 which established the National Solid Waste Policy (PNRS), determined extinction of dumping sites until august 2014, São Luis like most of the Brazilian municipalities, could not attend this determination [10, 11,12].

MSW collection from 90% of the population is done twice or three times a week while 10% has a daily collection. The municipality in 2011 paid R$ 92.47 (USS 42) for each ton of MSW collected or a total cost of R$ 47,926,313 (US$ 21,784,687) [10]. This sum was not sufficient to cover the costs of collecting all MSW generated and keep the city clean which according to IBGE [8], MSW generated by about 23 thousand homes was not collected and dumped in the streets.

DS treatment and final disposition are also serious problems with severe implications on public health and negative ambient and economic impacts. In all the state of Maranhão the public collection DS grid handles 9.6% of the residences. In São Luis 48.2% of the urban population or 127,408 residences are attended by this public service. About 12.9% of the collected DS is treated which also represents 8% of the total generated by the municipality [12, 13].

Besides collection and treatment of MSW and DS, another essential public service necessary for good life quality of the population is access to treated water. In São Luis treated water is supplied only for 85% of the population with an average of consumption in 2011 of about 196.5 L/inhab./day [13]. Consequently 15% of the population does not have access to treated water in a city which has abundant natural water resources and rivers [8].

Data from IBGE [8] shows that water losses from the water distribution system in São Luis through leaks and distribution grid failures are about 67% which ranks São Luis among the worst four Brazilian cities with respect to water distribution control and service quality. If DS is collected and treated adequately, the recovered wastewater from its treatment can be enough to attend population not connected to water distribution piping system. UN [14], UN-Habitat [15] and UNU/INWEH [16] show that lack of basic sanitation do not only affect poor population in developing countries but also reduce annual GDP (Gross Domestic Product) of the municipalities by 3% to 7%.

2.2 TREATMENT SYSTEMS FOR MSW AND DS

Negative impacts due to inadequate treatment of MSW and DS can be minimized by recycling and biological and thermal treatments where their intrinsic energy content can be exploited, their harmful emissions can be greatly reduced or eliminated, and their drastic impacts on public health can significantly attenuated.

2.3 RECYCLING

In the recycling process solid wastes such as paper, cardboard, plastic, glass and metals are transformed into input to be used for manufacturing new products. The return of recyclables to the production chain reduce the extraction of natural resources (raw material, water and energy), increase the useful life of landfills, reduce emissions to the atmosphere and create jobs and income [17]. Recycling is a practice in developed countries such as Japan, USA, and many European countries where the indices can reach 60%. In developing countries this practice is less explored. In Brazil, for example, the recycling rate is 1.2%.

2.4 BIOLOGICAL TREATMENT OF WASTES

This type of treatment is adequate for organic matter in MSW, and DS where the biogas produced as part of the biological reactions is used as fuel or converted to heat and vapor to produce electricity. Different developed and developing countries have established programs for using biogas as fuel and for generating electricity as in the cases of Slovakia, Egypt, Sweden [18, 19, 20]. The remaining material is usually rich in nutrients and can be used as fertilizer or for soil correction.

2.5 INCINERATION OF WASTES

In the incineration process the heat generated from the combustion of MSW or DS can be converted to vapor and electricity while ash can be used as covering layer for landfills, civil construction and other uses [21]. As a result of technical development, controls and monitoring systems for emissions, incineration became an acceptable practice for treating MSW and DS in many developed countries such as Japan, Sweden, Germany, USA [22, 23, 24]. Although the initial cost of the equipments is relatively high, the resulting energy, ambient, public health and financial benefits are worthy it. Incineration of MSW and DS presents a definite answer and environment correct solution for the safe and final disposition of MSW and DS.

Considering the above information and data the municipality of São Luis also must urgently find adequate solutions for the treatment of MSW and DS as recommended by WHO/UNICEF [5]. In this context, this paper proposes systems for treating and final disposition of MSW and DS. The proposals include reuse 10% of the available recyclables, and treatment of MSW either by biodigestion in landfills, or by incineration. In the case of DS, the proposed treatment processes are either biological or incineration and in both cases wastewater is recovered for reuse.

III. MATERIALS AND METHODS

The available technical data and the simplified models proposed for MSW and DS treatment are presented and discussed.

3.1 MATERIALS

The literature review reveals that thermal, biological treatments and recycling are the most sustainable routes for MSW and DS in São Luís. By adopting adequate public policies, incentives and well planned awareness programs, it is possible to engage the population in separation of recyclable at their residences. The rest of MSW is collected by the municipality public service and deposited in landfills, where the organic matter is biologically digested and produce biogas which is converted to electricity. In this process, the volume of MSW is reduced by about 20 to 25%.

The alternate route, 90% of recyclable and 100% of the organic matter is subjected to thermal treatment (incineration) where the released heat is converted to electricity. The remaining ash is usually a small quantity of about 10% is reused for fabricating bricks and other applications.

In the thermal route, the DS is dewatered and the sludge is incinerated producing heat and electricity. The ash is also reused as in the case of MSW.

In the biological treatment, the DS is dewatered and the wastewater is submitted for further treatment for reuse. The sewage sludge is biodigested producing mainly biogas to be converted to heat and electricity. The parameters and data used in the calculations are presented in Table 1

Table 1 Data used in the calculations

Description	Reference Value	Adopted value	Reference
Biogás production from lanfill (L/kg)	35 - 45	40	[25]
Specific mass of CO_2 (kg/m^3)		1.83	[26]
Emission of MSW incinerated (tCO_2/TJ)	10 - 40	25	[27]
LCV of CH_4 (MJ/m^3)[1]		33.95	[26]
Avoided emissions in recycling (CO_2/ton)		1.971	[28]
Avoided energy in recycling (GJ/ton)		31.629	[28]
Market value of mixed recyclable (R$/ton)		450	[29]
LCV of MSW incinerated (kJ/kg)	5250 – 10,264	6,130	[30]
Auxiliary fuel for incineration LPG (kg/ton)[2]		8.0	[31]
Efficiency of recuperated biogas (%)	50 - 75	75	[27]
LCV of LPG (MJ/kg)	40.05 - 46.05	40.05	[26]
GWP of CH_4	25	25	[32]
Biogas production from sludge (m³/kg)	0.8-1.1	0.95	[33]
Solid fraction in sludge(kg/m^3)	0.1 – 0.3	0.2	[33]
Emissions (kg CO_2/kg LPG)	3.019	3.019	[34]
LCV of biogas from sludge (MJ/m^3)	15 - 25	20	[30]
Heat content of incinerated sludge (MJ/kg)	12.800 - 19.750	16	[33]
Average water consumption (m³/month)	17.1	17.1	[13]
EE consumption (MWh/capita) [3]	0.604	0.604	[31]

(1) Lower calorific value.

(2) Liquefied Petroleum Gas.

(3) Electric energy
Source: Prepared by the authors.

The municipality of São Luís does not have any characterization of its MSW, hence, in the present study the average composition of the Brazilian MSW is adopted. The national average composition of MSW is: 52.5% is organic matter, 24.5% is paper/cardboard, 2.9% is plastic, 1.6% is glass, metal is 2.3% and 16.2% others [35].

3.2 METHODS

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

3.2.1 Recycling and landfilling of MSW with biogás utilization

The amount of recyclables collected selectively is 10%. All organic matter and 90% of recyclables are transported to landfills for biogas collection and electricity production. The biodigestion of the organic matter in MSW can reduce its volume by about 20 to 25% [29].

From the gravimetric analysis 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 from selling the recyclables = 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 the associated emissions. Lino and Ismail [28] calculated using the data from McDougall [36] and from Hekkert [37, 38] the 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. Fig.1 shows a simplified representation for the biological treatment of MSW.

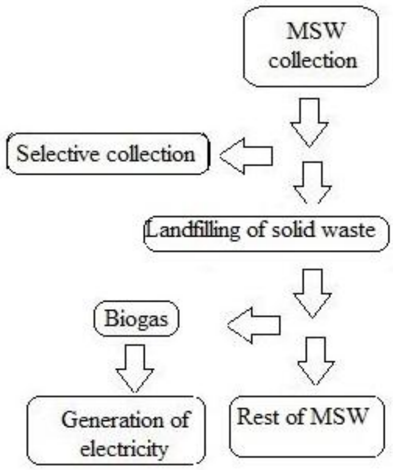

Fig.1 Recycling and biological treatment of MSW.

The avoided energy and emissions due to recycling can be calculated form Equations 3 and 4 as below,

- Avoided energy due to recycling = Avoided energy factor x Recyclable mass (3)
- Avoided emissions due to recycling = Avoided emissions factor x Recyclable mass (4)

Organic wastes are landfilled for biogas generation. 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 the 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. Hence the collected gas can be calculated from Equation 6

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

The generated biogas is mainly 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 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)

3.2.2 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 = ($1-\eta$) x Quantity of generated biogas (10)

Where η is the biogas recuperation efficiency = 75%; GWP of Methane = 25

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

3.2.3 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 (Liquefied Petroleum Gas). Energy generated during the combustion of MSW can be used to generate vapor and electricity. The heat content of the hot exhaust gases is removed in heat exchangers and used for various applications. When it is relatively cold the offensive gases, acids and soot particles are removed and discharged into the ambient without risks. The ash of the incineration process can be used in road paving and civil construction. Fig. 2 shows a simplified flow chart of the thermal route for treating MSW.

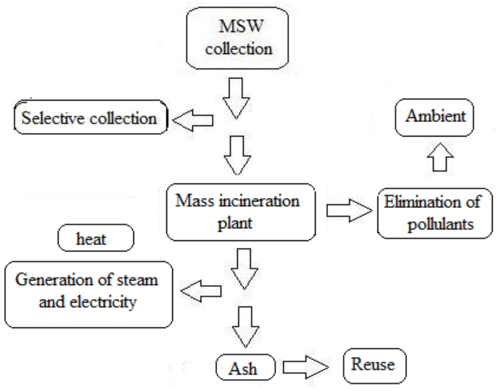

Fig. 2 Incineration of MSW.

As in the previous case, the financial, ambient 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. Equation 13 can be used to determine the amount of heat released by the auxiliary fuel.

- Energy released by the auxiliary fuel = mass of the auxiliary fuel x LCV of the auxiliary fuel (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 in the incineration process = Heat released due to the combustion of MSW – Heat released by the auxiliary fuel (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 prior the combustion gases are allowed to atmosphere. The polluting gases are treated by special techniques depending on the nature of the pollutant gas. The amount of CO_2 generated due to the combustion of both MSW and the auxiliary fuel can be calculated using data (Table 1) and Equations 15 and 16.

- Quantity of CO_2 generated due to the combustion of LPG = Emission factor x mass of LPG (15)
- Quantity of CO_2 generated due to the combustion of MSW = Emission factor x mass of MSW (16)

3.2.4 Biological treatment of sewage sludge

The biogas production depends on the composition of the sludge, specifically its content of biodegradable mass 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 ranging 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 generated from biogas = Energy released by biogas x thermal conversion efficiency (η)(20)

According to the MME [31] 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 [12], the monthly electric energy consumption for a family is 0.6342 x 10^9 J_{el}. The generated electric energy sufficient for a number of residences to be calculated from Equation 21,

- Number of residences = Monthly electric energy generated $\div$ 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. From this equation it is clear that the amount of CO_2 produced is equal to the quantity of combusted 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 7. Figure 3 shows the biological treatment scheme of DS.

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

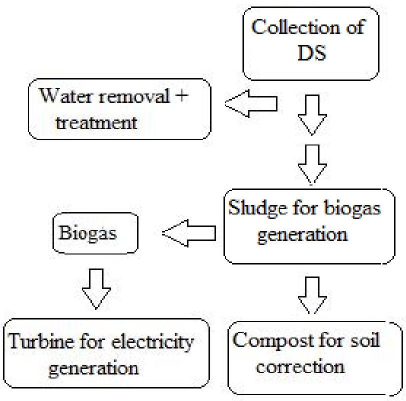

Figure 3 Biological treatment of DS.

Wastewater from dewatering sewage sludge can be treated for reuse. The amount of wastewater possibly 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 23.

- Number of residences which can be attended by the recovered wastewater = Volume of daily recovered wastewater ÷ daily average water consumption of a residence (23)

3.2.5 Thermal treatment of sludge

As in the previous case the collected sewage is dewatered and the separated wastewater is further treated for reuse as in Figure 4. The amount considered for reuse is 50%. The sludge is thickened and pumped to the incineration plant.

The mass of solids in the DS can be determined by using Equation 17. The energy content of the sewage sludge depends on its composition. Auxiliary fuel (LPG) is used to start and maintain incineration. Energy resulting from incineration of sewage sludge can be calculated from Equation 24.

- Energy released by incineration of sewage sludge = Mass of solids x Energy content of sewage sludge (24)

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 25.

- Total amount of consumed LPG = Mass to be incinerated x Rate of consumption of the auxiliary fuel (25)

Energy released by the combustion of LPG can be calculated from Equation 26.

- Energy released by the auxiliary fuel = Mass of auxiliary fuel x LCV of the auxiliary fuel (26)

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 27.

- Net energy released during incineration = Energy released by sewage sludge – Energy released by the auxiliary fuel (27)

  The hot gases can be used to generate steam and electricity with conversion efficiency of about 30%, as in Equation 28.

- Generated electric energy = Net energy released by incineration x Conversion efficiency (28)

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.

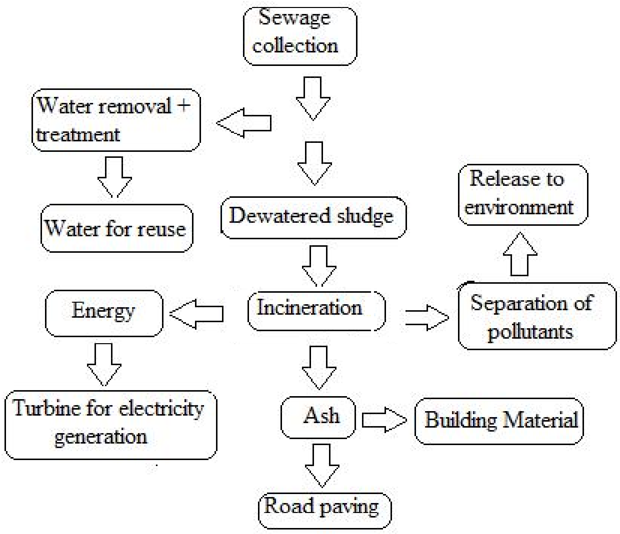

Figure 4 Incineration of DS.

The quantity of CO_2 emitted due to the combustion of LPG and incineration of sewage sludge can be calculated from Equations 29 and 30.

- Emissions of CO_2 from the combustion of LPG = Emission factor x LPG mass (29)
- Emissions of CO_2 from the incineration of sewage sludge = Emission factor x mass of sewage sludge (30)

Total emissions are the sum of the results from Equations 29 and 30. Ash resulting from incineration can be used for road paving, cement industry and other applications.

IV. RESULTS AND DISCUSSION

From the data presented in MCidades [10, 13] one can observe that São Luis benefits nothing of the energy and economic potential of MSW and DS generated in the municipality. The proposed routes for treating MSW and DS are intended to be adequate enough to cope with the actual deficiencies.

4.1 Proposed scenarios for treatment of MSW

4.1.1 Recycling

The results of the proposed scenario of reusing 10% of the recyclables generated by in the municipality of São Luis of about 13 thousand tons per year can generate about R$ 5.8 million/ year (US$ 2,63 million) or about 8 thousand national minimum salaries of R$ 724.00/ month (January 2014). Part of these funds can be used to improve the selective collection service such as educational campaigns, awareness programs, purchase of equipments and upgrading installations. Apart from the financial funds the avoided energy due to reuse of recycled material is about 410 thousand GJ/ year or 34 GJ/ month which is equivalent to energy consumption of 54 thousand homes with energy consumption of about 0.6342 GJ_{el} per month. Additionally, about 25.5 thousand tons CO_2/ year is avoided.

4.1.2 Landfilling

According to the proposed route organic matter in MSW of about 309 thousand tons/year can be deposited in landfill designed to collect biogas. According to the results shown in Table 2, this can produce about 9.3 million cubic meters / year after subtracting 3 million cubic meters / year corresponding to the fugitive biogas. The captured biogas can generate monthly about 3.5 TJ_{el} sufficient for 5600 homes each consuming an average of 0.6342 GJ_{el}/month. Considering the price of electric energy for residential consumers practiced by Campinas (SP) energy distributor, in 2013, as R$ 0.389/kWh, the amount of energy generated from biogas has a monthly value of R$ 382 thousand (US$ 173 thousand). Emissions due to energy production from biogas are about 17 thousand tons CO_2/year or three times less than the emissions due to the fugitive biogas.

4.1.3 Incineration

Incineration of the 77% of MSW of São Luis produces monthly about 12.9 GWh sufficient to meet the demand of 73 thousand homes each consuming the national average of 0.6342 GJel / month. The estimated cost of this energy is about R$ 5 million per month (US$ 2,264 million). Energy released by incineration is about 13 times energy released by landfill while the biogas utilization emissions are one third of that due to incineration but when including the fugitive biogas the total emissions come to about 1.5 the emissions due to incineration as Table 2.

Table 2 Results of proposed scenarios for treating MSW in São Luis (MA)

Description	**Recycling**	
Collected MSW (t/year)	413,852	
Recyclabkes potentially available (t/year)	129,535.7	
Recyclables for sale (t/year)	12,953.57	
Funds from selling recyclables (R$/year)	5,829,105.4	
Avoided energy due to recycling (GJ/year)	409,708.5	
Avoided emissions due to recycling (tCO_2/ year)	25,531.5	
Treatment of MSW	**Landfilling**	**Incineration**
Organic matter for landfilling (t/ year)	308,733.6	
MSW for incineration (t/ year)		318,666
Generated biogas (m^3/ year)	12,349,344	
Collected biogas (m^3/ year)	9,262,008	
Energy form incineration (J/year)		1953.4×10^{12}
Energy from biogas (J/ year)	141.500×10^{12}	
Net energy from incineration (J / year)		1851.3×10^{12}
Electric energy from biogas (Jel / month)	3.538 x 1012	
Electric energy from biogas (GWh per month)	0.983	
Net electric energy from incineration (Jel /month)		46.283 x 1012
Net electric energy from incineration (GWh per month)		12.857
Number of households that can be assisted [1]	5,579	72,887
Emissions (tCO_2/ year)	16,949.48	56.473
Fugitive biogas (m^3 biogas / year)	3,087,336	
Emissions from fugitive biogas ($m3CO_2e$/ year)	36,430,564.8	
Mass of emissions from fugitive biogas (tCO_2e / year)	66,667.93	

(1) Average national consumption of electric energy per residence = 0.6342 GJ_{el} / month.
Source: [2].

4.2 Proposed scenarios for treatment of DS

4.2.1 Biological treatment

The results of the proposed conventional biological treatment route for DS of São Luis (Table 3) shows that it is possible to generate from 38 thousand tons of sewage sludge /day electric energy sufficient for 10.3 thousand homes or 6.5 TJ_{el} / month costing about R$ 700 thousand / month (US$ 316,9 thousand). Emissions generated due to biogas utilization for electric energy production are about 24 thousand tons CO_2/year. The digested organic matter can be used as fertilizer and soil correction.

4.2.2 Incineration of DS

The results of the incineration scenario shows that the 38 thousand tons / day of DS can produce about 5.4 TJ_{el} / month enough for about 8.5 thousand homes, as in Table 3. This amount of energy corresponding to the cost of about R$ 580 thousand per month (US$ 262.6 thousand).

It is possible also to recover about 50% of wastewater which is enough to supply about 135,860 homes with treated water. The ash from incineration can be reused for construction materials, fabrication of bricks and roads paving.

The municipality of São Luis generates daily 850 tons of MSW and 38 tons of DS which need adequate treatment. Adequate treatment will allow energy benefits, reduce atmospheric emissions, protect public health and water resources, create jobs and help in the social inclusion of waste collectors. The amounts of MSW and DS indicated above can be incinerated and relieve the municipality of the waste disposal problems.

Table 3 Results of proposed scenarios for treating DS in São Luis (MA)

Description	Biological treatment	Incineration
Generated domestic sewage (m^3 / day)	190,201.54	190,201.54
Mass of sludge (t/day)	38,040	38,040
Generated biogas gerado (m^3 / day)	36,138.29	
Energy generated from biogas (J/day)	0.72277×10^{12}	.
Energy generated from incineration (J/day)		0.608645×10^{12}
Energy generated from biogas (J/month)	21.683×10^{12}	
Net energy generated from incineration (J/month)		17.8937×10^{12}
Electric energy generated from biogas (J_{el} / month)	$6{,}505 \times 10^{12}$	
Electric energy generated from biogas (GWh / month)	1.807	
Net electric energy from incineration (J_{el} /month)	.	5.368×10^{12}
Net electric energy from incineration (GWh/month)		1.491
Number of homes served by generated elctric energy [1]	10,257	8464
Emissions (tCO_2 / day)	66.133	16.135
Emissions (tCO_2 / year)	24,138.57	5889.2
Treated wastewater for reuse (m^3 /day)	95,101	
Number of homes served by recovered water[2]	135,860	

(1) Considering electric energy consumption as 0.6342 GJ_{el} / month.
(2) Considering the local water consumption per home as 21 m^3/month.
Source: [2].

V. CONCLUSIONS

1. MSW and DS are sources of renewable energy which when adequately managed can increment the energy matrix of the city of São Luis with significant energy contribution, reduction of emissions, enhance its sustainability and its basic sanitation while minimizing the impacts on the soil, air and water.
2. The results show that recycling is an important instrument which helps in sustainability of the municipality and in the social inclusion of poor families while reducing the volume of MSW discarded.
3. The 10% recyclables or 12.9 thousand tons / year if commercialized the financial gain will be around R$ 5.8 million / year (US$ 2,626 million). In the mean time, the substitution of raw material by recyclables can save about 409.7 thousand GJ / year and avoids emitting to the atmosphere 25.5 thousand tons CO_2 / year.
4. Landfilling of organic matter in MSW produce biogas which can generate about 3.5 TJ_{el} /month sufficient for 5.5 thousand homes. This amount of energy results in the release of about 16.9 thousand tons CO_2/ year which when added to the fugitive biogas reaches about 66.6 thousand tons CO_2e/ year.
5. Incineration of MSW of São Luis produces about 46 TJ_{el} /month sufficient for 72.9 thousand homes or 23.9% of the residences of the city and releases about 56.5 thousand tons CO_2 / year to the atmosphere.
6. The biological treatment of DS produces biogas which can generate about 6.51 TJ_{el} / month enough for 10,257 homes or 3.3% of the total number of homes in the municipality. According to Censo 2010 [8] there are about 4,776 homes or 15,187 inhabitant without access to electricity which is an essential public service.

7. The recovered wastewater for reuse is about 95.1 thousand m^3 / day sufficient for 45% of the total number of homes in São Luis and more than the declared deficit of homes without treated water which is about 41.7% [8].
8. As was observed, there are material and energy fluxes between the processes of MSW and DS treatments which can be interchanged and optimized achieving better global control and higher efficiencies if the treatment processes were integrated.
9. In order to achieve these benefits it is important to rethink and plan sanitation projects, establish adequate public policies which can induce the population to adhere to selective collection programs. These actions require high investment in educational and awareness programs. Tax incentives can encourage the private sector to adhere and participate financially in basic sanitary projects.

VI. ACKNOWLEDGEMENTS

The authors wish to thank the CNPQ for the doctorate scholarship for the first author and for the PQ Research Grant for the second author.

REFERENCES

[1] IBGE - Instituto Brasileiro de Geografia e Estatística. Projeção população brasileira: abril de 2014. Available at: http://www.ibge.gov.br/home/

[2] F A M Lino, *Proposta de aproveitamento do potencial energético do resíduo sólido urbano e do esgoto doméstico com minimização dos impactos ambientais*, Doctorate Thesis, State University of Campinas, BR, 2014.

[3] P J Reddy, *Municipal solid waste management: processing, energy recovery, global examples*, BS Publications, India, 2011.

[4] F R Spellman, *Handbook of water and wastewater treatment plant operations* Lewis Publishers CRC Press Company, 2003.

[5] WHO/UNICEF. *Progress on sanitation and drinking-water, Update* World Health Organization and UNICEF, France, 2013.

[6] IBGE, Instituto Brasileiro de Geografia e Estatística, *Atlas de Saneamento*, BR, 2011. http://www.ibge.gov.br/home/estatistica/populacao/atlas_saneamento/default_zip.shtm

[7] MMA, *Módulo específico: licenciamento ambiental de Estações de tratamento de Esgoto e aterros sanitários* Ministério do Meio Ambiente, Brasília, BR, 2009.

[8] IBGE, Instituto Brasileiro de Geografia e Estatística, *Atlas do Censo demográfico 2010*. Rio de Janeiro, BR, 2013.

[9] IBGE, Instituto Brasileiro de Geografia e Estatística Cidades: Maranhão-São Luís morbidadeshospitalares-2012, 2014. http://cidades.ibge.gov.br/xtras/temas.php?lang=&codmun=211130&idtema=114&search=maranhao|sao-luis|morbidades-hospitalares-2012

[10] MCidades, *Diagnóstico dos manejo de resíduo sólido urbano 2011* Ministério das Cidades/SNSA/ SNIS, Brasília, BR, 2013a.

[11] Brasil/ MMA - Ministério do Meio Ambiente, *Política Nacional de Resíduo Sólido 2014*, BR, Available at: http://www.mma.gov.br/cidades-sustentaveis/residuos-solidos/politica-nacional-de-residuos-solidos

[12] IBGE/PNAD, *Síntese dos indicadores 2011* Instituto Brasileiro de Geografia e Estatística- Pesquisa nacional por amostra de domicílios, Rio de Janeiro, 2012.

[13] MCidades, *Diagnóstico dos Serviços de Água e Esgoto 2011* Ministério das Cidades/SNSA/ SNIS, Brasília, BR, 2013b.

[14] UN, *World Economic and Social Survey 2013: Sustainable Development Challenges*. Department of Economic and Social Affair. United Nation: New York, 2013.

[15] UN-HABITAT, *Planning and design for Sustainable urban mobility. Global report on human settlements 2013* United Nation Human Settlements Programme, New York, 2013.

[16] UNU/INWEH, World lacks data on wastewater reuse: rising reuse of wastewater in forecast but world lacks data on a massive potential Resource, United Nations University / Institute for Water, Environment and Health, 2013, http://inweh.unu.edu/rising-reuse-wastewater/

[17] F A M Lino, K. A R Ismail, Alternative treatments for the municipal solid waste and domestic sewage in Campinas, Brazil, *Resources, Conservation and Recycling, vol. 81*, pp. 24– 30, 2013.

[18] I Bodík, M Kubaská, Energy and sustainability of operation of a wastewater treatment plant. *Environment Protection Engineering, vol.39*, no.2, 2013.

[19] M R Ghazy, T Dockhorn, N Dichtl, Economic and environmental assessment of sewage sludge treatment processes application in Egypt, *Fifteenth International Water Technology Conference*, IWTC-15. Alexandria, Egypt, 2011.

[20] G Petersen, *Life Cycle Assessment of four sludge disposal routes* Master Thesis, Environment Systems Analysis, Goteborg, Sweden, 2001.

[21] EC European Commission, *Integrated pollution prevention and control*. Reference document on the best available techniques for waste incineration. 2006.

[22] OECD - Organization for Economic Co-operation and Development. *Total amount generated of municipal waste*, in Factbook Country Statistical profiles 2013 edition/Environmental. OECD. StatExtracts. Available at: http://stats.oecd.org/Index.aspx?DatasetCode=CSP2013.

[23] World Bank. Urban Development Serie. *What a waste: A global review of solid waste management* Hoornweg, D. and Bhada-Tata (authors). World Bank, 15. USA. 2012.

[24] UNSTAT, Environmental indicators. Population connected to wastewater collecting systems, United Nation Statistic Division, 2011, http://unstats.un.org/unsd/environment/wastewater.htm

[25] A Karagiannidis, *Waste to Energy: Opportunities and challenges for developing and transition economies*, editor Avraam Karagiannidis. London: Springer-Verlag; 2012.

[26] J W Rose, J R Cooper, *Technical data on fuels* 7th edition, The British National Committee, London. 1977.

[27] S Monni., R Pipatti, A Lehtilä, I Savolainen, S Syri, *Global climate change mitigation scenarios for solid waste management* VTT publications, 603, ESPOO, 2006.

[28] FAM Lino, KAR Ismail, Analysis of the potential solid waste in Brazil. *Environmental Development*, 4, pp. 105-112, 2012.

[29] CEMPRE – Compromisso Empresarial para Reciclagem. Preço do material reciclável. 2013. Available at: http://www.cempre.org.br/servicos_mercado.php.

[30] W R Niessen, *Combustion and Incineration Processes* 3rd Edition: Marcel Dekker, Inc., New York, USA, 2002.

[31] MME, *Anuário Estatístico de energia elétrica 2012*, Ministério de Minas e Energia, 258p. BR, 2012,. http://www.epe.gov.br/AnuarioEstatisticodeEnergiaEletrica/20120914_1.pdf

[32] IPCC, *Guidelines for National Greenhouse by Gas Inventories*, Intergovernmental Panel on Climate Change, vol.5, Waste, 2006.

[33] I S Turovskiy, P K Mathai, *Wastewater Sludge Processing* John Wiley & Sons, Inc. 2006.

[34] MCT, *Projeto Usina Verde: Incineração de resíduos sólidos urbanos, com carga de composição similar ao RDF, evitando emissão de metano e promovendo geração de eletricidade para autoconsumo* Ministério da Ciência e Tecnologia, Brasília: MCT, 2005, http://www.mct.gov.br/index.php/content/view/581778/.

[35] IPT/Cempre. *Lixo municipal: manual de gerenciamento integrado*. Instituto de Pesquisa Tecnológica & Compromisso Empresarial para Reciclagem. São Paulo, BR: 2000:

[36] F McDougall, P,White M Franke, P Hindle, *Integrad solid waste management: a life cycle inventory*, Blackwell Science published: 2ª ed., USA, 2001.

[37] M P Hekkert, L A J Joosten, E Worrell, Reduction of CO_2 emissions by improved management of material and product use: the case of transport packaging. *Resources, Conservation and Recycling 30* p. 1-27, 2000a.

[38] M P Hekkert, L A J Joosten, E Worrell, Reduction of CO_2 emissions by improved management of material and product use: the case of primary packaging. *Resources, Conservation and Recycling 29*, 33-64 2000b.