Energy potential and alternative usages of biogas and sludge from UASB reactors: Case study of *Laboreaux* sewage treatment plant

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31 **ABSTRACT**

32 This work assesses the potential of using energy from the biogas and sludge generated in
33 UASB reactors at the *Laboreaux* Sewage Treatment Plant (STP). Two scenarios were
34 considered: (i) priority use of biogas for the thermal drying of dehydrated sludge and the use
35 of the excess biogas for electricity generation in an internal combustion engine (ICE); and (ii)
36 priority use of biogas for electricity generation and the use of the heat of the engine exhaust
37 gases for the thermal drying of the sludge. Scenario 1 showed that the electricity generated is
38 able to supply 22.2% of the STP power demand, but the thermal drying process enables a
39 greater reduction or even elimination of the final volume of sludge to be disposed of. In
40 Scenario 2, the electricity generated is able to supply 57.6% of the STP power demand;
41 however, the heat in the exhaust gases is not enough to dry the total amount of dehydrated
42 sludge.

43 **Keywords:** biogas, energy recovery, sludge, wastewater treatment, UASB reactors.

44

45 **INTRODUCTION**

46 The increase in the number of domestic sewage treatment plants using upflow anaerobic
47 sludge blanket (UASB) reactors has expanded the generation of biogas and sludge, which are
48 byproducts of such a treatment process.

49 With respect to the sludge, before developing studies and evaluating the compatibility of
50 alternatives for its processing and final destination, it is necessary to analyze the
51 characteristics of the sewage to be treated and its treatment technologies, sludge production
52 rates, environmental legislation and the types of soil and regional agriculture in order to

propose alternatives for disposal in agreement with environmental, technical and economic criteria (Fernandes *et al.*, 2001).

In general, the choice of the final destination for the sludge takes into consideration only alternatives which are locally available in the treatment units. The main alternatives for the final destination of the sludge, in 2005, for the 27 countries of the European Union (EU), were agricultural use (41%), incineration (19%), sanitary landfill (17%), composting (12%) and other applications (11%) (EU, 2011). This scenario has been changing in recent years, and the use of thermal processes in the management of sewage treatment plant (STP) sludge for energy purposes is estimated to double by 2020, in the oldest countries of the EU, corresponding to a index of 37% among the forms of final destination (Kelessidis and Stasinakis, 2012). The sludge, usually characterized as the type of residue that can be sent to landfills, may become an energy source after dehydration, demonstrating the change of paradigm regarding its final destination (Courtaud *et al.*, 2010). This scenario points to the tendency of using sludge to produce energy for STPs, even though studies in this area are still not very widespread (De Sena *et al.*, 2007).

According to Stasta *et al.* (2006), the increase in sludge thermal treatment in STPs is evident in European countries. The study and choice of more advantageous alternatives from the viewpoint of sludge management can guarantee the energy self-sufficiency of a STP, in addition to the possibility of exporting the excess electricity to the distribution network, depending on studies about the quality of the energy produced (Houdková *et al.*, 2008). Fonts *et al.* (2009) point out that the lower calorific value (LCV) of the anaerobically digested and dry sludge, with moisture of 5.3%, is 7.7 MJ.kg^{-1} .

A similar tendency is observed for the management of the biogas produced in a STP, with respect to its use for energy purposes. The biogas from anaerobic reactors treating domestic sewage presents concentrations of methane (CH_4) from 70% to 80%, nitrogen (N_2) from 10%

to 25% and carbon dioxide (CO₂) from 5% to 10%, whereas the high N₂ levels are due to the N₂ dissolved in the influent sewage prior to entering the reactors (Noyola *et al.*, 2006). The calorific values of the CH₄ and of the biogas with 60% of CH₄ are 35.9 MJ.Nm⁻³ and 21.5 MJ.Nm⁻³, respectively. In its composition, the biogas can also contain hydrogen sulfide (H₂S) (1,000 to 2,000 ppm), which is corrosive to the materials of thermal equipment such as boilers, pipes and engines. According to Holm-Nielsen *et al.* (2009), biogas containing H₂S concentrations above 300–500 ppm may cause damage following the use of energy conversion techniques.

The energy use of biogas is still incipient in Brazil, where most sanitary landfills and sewage treatment plants only collect and burn the biogas produced, without making use of its energy potential. One of the main advantages of producing energy in STPs is the fact that such energy can be consumed at the plant, without the need of a distribution network (Tsagarakis, 2007). In addition, the anaerobic digestion of domestic sewage sludge usually produces enough biogas to meet the energy demand required for the plant operation (Metcalf and Eddy, 2003).

For Salomon and Lora (2009), the main advantages of electric energy production from biogas are: (i) decentralized energy generation near the consumer source; (ii) possibility of additional profit due to energy production and commercialization, depending on the rules of the regulatory system of the electricity market; (iii) reduction of consumption from an external energy supply; (iv) potential use in processes for the cogeneration of electricity and heat; and (v) reduction of the emissions of CH₄, a greenhouse gas. Considering the concerns towards the minimization of fossil fuel consumption and the increasing costs and energy demands for sewage treatment, aiming at the satisfaction of increasingly strict quality standards for its final effluent, we highlight the importance of the current discussion with respect to design and operation, in order to maximize energy efficiency and reduce treatment costs (Metcalf and

Eddy, 2003). In this context, the objective of this paper is to contribute to the assessment of the energy potential of biogas and dehydrated sludge, and of alternatives for the energetic use of these byproducts at a domestic sewage treatment plant.

METHODS

Study area

The study was developed at the *Laboreaux* STP in Itabira, which is in the Brazilian state of Minas Gerais. The STP was designed to serve a future population of 123,000 inhabitants (313 L.s^{-1}) by 2029 (final stage). The first stage, which is currently operating, was designed for a population of 70,000 people (170 L.s^{-1}). During the study period, the mean observed flow was approximately 80 L.s^{-1} .

The STP consists of pretreatment units (screens and grit chambers) and anaerobic and aerobic biological treatment units, in sequence (UASB reactors followed by trickling filters and secondary clarifiers). Table 1 presents the main characteristics of the *Laboreaux* STP.

The biogas produced in the UASB reactors is currently burned in a flare. The sludge from the secondary clarifiers is returned to the UASB reactors, where it is thickened and stabilized; then it follows to the dehydration step in a filter press, and is finally disposed of in the sanitary landfill of Itabira city. There are four drying beds in the plant, with a total area of 600 m^2 , which are used in case of operational problems with the filter press. Figure 1 shows a general view of the units at the *Laboreaux* STP. Figure 2 presents a flowchart of the stages of the sludge and biogas management in the STP.

Table 1: Main characteristics of the *Laboreaux* STP.

Characteristics	UASB reactors	Trickling filters	Secondary clarifiers
Population (inhab.)*		70,000 (123,000)	
Flow ($\text{m}^3.\text{s}^{-1}$)*		0.170 (0.313)	
Number of units*	8 (16)	2 (4)	2 (4)
Type	Rectangular	Circular	Circular
Dimensions (m)	21.7×6.2	$D = 22.5$	$D = 20.0$

Area (m ²)	134.5	397.6	314.0
Useful depth (m)	4.5	2.5	3.0
Useful volume (m ³)	605.4	994.0	942.0
Sludge dehydration		Filter press	

* Design values in parenthesis refer to the end of plan.

Figure 1: Overall view of the *Laboreaux* STP units.

Figure 2: Schematic flowchart of the stages related to the sludge and biogas management system in the *Laboreaux* STP.

Sludge characterization

The monitoring of the sludge production was carried out from October 2010 to October 2011. The sludge was quantified by weighing the transportation truck after loading each dehydrated sludge storage bucket, before shipping it to the sanitary landfill. The sampling campaigns for characterization were performed from April 2011 to June 2012, every two weeks, and consisted of the collection of three small dehydrated sludge plates from the filter press, which

were macerated and mixed for the analyses of moisture, higher calorific value (HCV) and elemental and immediate composition. All analyses were performed in triplicate.

The moisture determination was carried out according to the *Standard Methods for the Examination of Water and Wastewater* (APHA/AWWA/WEF, 1998); the elemental composition was determined using a Perkin Elmer 2400 Series II CHNS/O elemental analyzer, and the immediate composition (fixed solids, volatile solids and ash) was determined based on the Brazilian Norm – NBR 8112 (ABNT, 2006). The actual HCV of the sludge, dry basis (d.b.), was determined in laboratory using a calorimetric adiabatic pump (Parr 2081). The theoretical HCV and LCV were determined by Dulong's equation and by Cortez *et al.* (2008), respectively, as shown in Table 2.

Table 2: Calculation procedure for determining the theoretical HCV and LCV of the sludge from the *Laboreaux* STP.

Parcels	Equations	Observations
Theoretical HCV	$PCS_s = [337,3 \times C + 1.418,9 \times (H - O/8) + 93,1 \times S + 23,3 \times N] / 1.000$	HCV = High calorific value, (MJ.kg ⁻¹), d.b. C = % of carbon in the material, d.b. H = % of hydrogen in the material, d.b. O = % of oxygen in the material, d.b. S = % of sulfur in the material, d.b. N = % of N ₂ in the material, d.b.
Theoretical LCV	$PCI_t = [(PCS_s - \lambda \times (r + 0,09 \times H_s)) \times (100 - W_t) / 100]$ $r = \frac{W_t}{(100 - W_t)}$	LCV _t = Lower calorific value (MJ.kg ⁻¹), m.b. HCV _s = Higher calorific value (MJ.kg ⁻¹), m.b. r = Solids content and dehydrated sludge moisture ratio H = Hydrogen content (%), d.b. W _t = Solids content in the dehydrated sludge (%), m.b.

d.b: dry basis; m.b.: moist basis (real moisture of the sample after collection). The elemental composition data are presented as % of mass.

Biogas characterization

The volumetric biogas production was carried out on a daily basis, also from October 2010 to October 2011. The measurements were performed using a mass flow meter (Sierra - model 640S-FRQ-2734) positioned in the gas line prior to the flare. The measured biogas flow was considered at standard atmospheric pressure (1 bar) and mean ambient temperature (25 °C).

In the same period, biogas samples were collected in duplicate using plastic syringes equipped with three-way valves, at a point prior to the flare. The biogas characterization, aimed at verifying its energy potential, was performed by chromatography (Perkin Elmer TCD detector

using helium as carrier gas at a flow rate of 17 mL/min and a carbowax packed column) and the percentages of CH₄ and CO₂ in the gas mixture were determined. The biogas composition was analyzed, on average, twice a month.

Energy balance at the *Laboreaux* STP

Using data from the STP operation and biogas and sludge characterization, we determined the unit relationships of CH₄, biogas and energy production in the UASB reactors. The energy balance calculations correspond to the difference between the energy demand of the plant and the energy potential of the biogas and sludge byproducts. The **energy demand** is related to the power consumption in the plant necessary to maintain the treatment system operation, especially the sewage pumping stations (SPS), operation of the filter press, power supply for laboratory equipment and lighting. The **energy potential** is associated with the maximum energy that could be generated from the biogas. The dehydrated sludge from the filter press was considered inappropriate for energy purposes (due to excessive moisture content); in order to make it a potentially viable fuel option, we propose its drying to a moisture content of 10%.

Energy demand in the *Laboreaux* STP

Nearly the entire energy demand at the *Laboreaux* STP is dedicated to operation of two pumping stations (SPS-1 and SPS-2) at the entrance of the treatment plant. The first SPS pumps the raw sewage from the medium-size bar screening to the grit chamber. The second SPS pumps the pretreated sewage to the flow distribution box, which feeds eight UASB reactors. Table 3 summarizes the main design characteristics of SPS-1 and SPS-2.

Table 3: Main characteristics of the SPSs at the *Laboreaux* STP.

Characteristics	SPS-1	SPS-2
No. of pumps	04	04
Type	Self-priming	Self-priming
Model	Gresco X-T 10	Gresco X-T 10
Speed rotation (rpm)	950–1,000	1,075–1,130

Manometric height (m)	9.8	15.4
Installed power (kW)	89.5	111.8

The energy demand in the *Laboreaux* STP was determined from the consumption data provided by the Autonomous Service of Water and Wastewater – SAAE Itabira, for the period of October 2010 to October 2011, considering all energy uses at the STP (lighting; administration and laboratory consumption; operation of the filter press, pumps and other equipments), as shown in Figure 3. The mean power consumption at the STP during that period was 1,586 kWh.d⁻¹ (5,709 MJ.d⁻¹).

Figure 3: Energy demand at the *Laboreaux* STP from October 2010 to October 2011.

Energy potential of the *Laboreaux* STP byproducts

The energy potential of the *Laboreaux* STP corresponds to the sum of the energy potential of the byproducts obtained from the sewage treatment: sludge and biogas. Table 4 shows the parcels and respective equations for calculation of the STP energy potential.

Table 4: Procedure for the calculation of the total energy potential of the *Laboreaux* STP.

Parcels	Equations	Observations
Energy potential of the STP byproducts	$EP_{Total} = EP_{Biogas} + EP_{Sludge}$	EP _{Total} = Total energy potential (MJ.d ⁻¹) EP _{Biogas} = Biogas energy potential (MJ.d ⁻¹) EP _{Sludge} = Sludge energy potential (MJ.d ⁻¹)
Biogas energy potential	$EP_{Biogas} = Q_{Biogas} \times C_{CH4} \times E_{CH4}$	Q _{Biogas} = Measured biogas production (Nm ³ .d ⁻¹) C _{CH4} = CH ₄ concentration in the biogas (%) E _{CH4} = LCV of CH ₄ combustion (35.9 MJ.Nm ⁻³)
Sludge energy potential	$EP_{Sludge} = P_{Sludge} \times LCV_s$	P _{Sludge} = Dehydrated sludge production (kg.d ⁻¹) LCV _s = LCV of sludge (MJ.kg ⁻¹), m.b.

Integrated proposal for energy recovery using sludge and biogas

Two scenarios of energy use/recovery using both sludge and biogas were considered in this study, as shown in Figure 4. Table 5 presents the input data used for both scenarios, in order to determine the mass and energy balances.

- **Scenario 1:** priority use of biogas in a combustion chamber to generate heat for the thermal drying of the dehydrated sludge; the excess biogas is used for the generation of electricity in an internal combustion engine (ICE).
- **Scenario 2:** priority use of biogas in an ICE for the generation of electricity; the heat of the exhaust gases is used for the thermal drying of the sludge.

Figure 4: Scenarios for energy recovery using the *Laboreaux* STP byproducts. (a) scenario 1; (b) scenario 2.

Table 5: Input data for the assessment of the energy recovery scenarios using the byproducts from the *Laboreaux* STP.

Item	Value	Item	Value
Dehydrated sludge (filter press)		Biogas (UASB reactors)	

Production (kg.d ⁻¹)	3,759	Total flow (m ³ .d ⁻¹)	390.1
Moisture (%)	58.7	CH ₄ (%)	78.2
HCV, MJ.kg ⁻¹	8.7	CO ₂ (%)	6.7
LCV, MJ.kg ⁻¹	2.0	Other constituents (%)	15.1
Energy potential (MJ.d ⁻¹)	7,518	Volumetric energy potential (MJ.m ⁻³) ^a	28.1
		Energy potential (MJ.d ⁻¹)	15,284
Characteristics of the equipment ¹		Characteristics of the <i>Laboreaux</i> STP	
Electric efficiency of the ICE (%)	30	Electricity demand (MJ.d ⁻¹)	5,709
Heat of the exhaust gases (%) ^c	25		
Efficiency of the biogas thermal dryer (%) ^b	80		
Efficiency of the exhaust gas dryer (%) ^b	85		
Sludge moisture after drying (%)	10.0		

¹ Values considered from technical manuals of the equipment. ^a Calculated considering 35.9 MJ.Nm⁻³ (Noyola *et al.*, 2006) and the CH₄ composition. ^b Global efficiency of the equipment to evaporate the water, considering losses by radiation and convection. ^c Relationship between the heat in the exhaust gases and the total fuel energy (biogas) consumed by the ICE, according to Arteaga (2010).

CHEMCAD® software was used as a tool to simulate the combustion processes (direct burning of the biogas in a combustion chamber and in an ICE). For both scenarios, the biogas combustion was considered adiabatic, with complete oxidation of CH₄ and an Oxygen excess of 5% ($\lambda = 1.05$). Other data considered in the simulations are presented in Table 6.

Table 6: Characteristics of the biogas burning process in a dryer (scenario 1) and in an ICE (scenarios 1 and 2). In scenario 2, the dryer uses the residual heat of the exhaust gases from the ICE.

Data	Unit	Value			
		Scenario 1		Scenario 2	
Biogas		Dryer	ICE 1	Dryer	ICE 2
Flow (for T = 25 °C and P = 1 bar)	m ³ .d ⁻¹	240	150.1	-	390.1
CH ₄ fraction	%	-	78	-	78
Air					
Flow (for $\lambda = 1.05$, T = 25 °C and P = 1 bar)	m ³ .d ⁻¹	3.14	3.83	-	6.97
O ₂ fraction	%	21	21	-	21
N ₂ fraction	%	79	79	-	79
Burning conditions					
Temperature of the combustion gases ^a	°C	900	-	-	-
Temperature of the exhaust gases from the ICE	°C	-	500	500 ^b	500
Temperature after heat exchanges in the dryer	°C	105	-	105	-
Excess air (λ)	fraction	1.05	1.05	-	1.05

^a Temperature calculated considering the biogas combustion and heat generated in the resulting gases, used for drying. ^b In scenario 2, the ICE exhaust gases (500 °C) feed the dryer.

RESULTS AND DISCUSSION

Biogas potential energy

Table 7 presents the descriptive statistics of flow and chemical oxygen demand (COD) data from the influent raw sewage, and composition and flow data from the biogas produced in the UASB reactors, obtained during the monitoring period.

Table 7: Descriptive statistics of influent raw sewage flow data and COD, and biogas production at the *Laboreaux* STP, from October 2010 to October 2011.

Statistics	Sewage flow (m ³ .d ⁻¹)	Influent COD concentration (mg.L ⁻¹)	Biogas flow (m ³ .d ⁻¹)	Biogas composition (%)*		
				CH ₄	CO ₂	Others
Mean	6,750.6	537.7	390.1	78.2	6.7	15.1
Number of data	396	110	396	22	22	22
Median	6,526.6	553.0	432.5	79.4	6.8	13.1
σ	1,195.7	49.8	165.2	2.7	1.3	3.7

σ: standard deviation with respect to the mean value. * percent in volume.

During the monitoring period, the influent sewage flow presented a mean value of 6,751 m³.d⁻¹ (78 L.s⁻¹) and the mean biogas volumetric production in the UASB reactors was 390.1 Nm³.d⁻¹. The biogas mean composition in this period was 78.2% of CH₄, 6.7% of CO₂ and a mixture of other constituents of 15.1%. The CH₄ concentration (78.2%) was within the range reported by Noyola (2006), of 70 to 80%. From these characteristics, we estimate an energy potential in the order of 10,962 MJ.d⁻¹.

Unit relationships and fitting of real data to theoretical values

The unit relationships of CH₄, biogas and energy production for the *Laboreaux* STP were calculated, based on the monitoring data, to provide the basis for the assessment of the most viable alternative for biogas energy conversion (Table 9). The unit relationship ranges predicted by the model of Lobato (2012) are also presented in Table 9.

Table 8: Unit relationships of CH₄, biogas and energy production in the UASB reactors of *Laboreaux* STP.

Unit relationships	Units	Values	
		Measured	Simulated*
CH ₄ volume per volume of treated sewage	m ³ CH ₄ .m ⁻³ treated sewage	0.06	0.07–0.14
CH ₄ volume per COD removed	m ³ CH ₄ /kgCOD _{removed}	0.17	0.11–0.19
Biogas volume per volume of treated sewage	m ³ biogas.m ⁻³ treated sewage	0.07	0.06–0.10
Biogas volume per COD removed	m ³ biogas/kgCOD _{removed}	0.21	0.16–0.24
Energy production potential per volume of treated sewage	MJ.m ⁻³ treated sewage	2.0	1.5–2.9
Energy production potential per COD removed	MJ/kgCOD _{removed}	6.0	4.1–7.0

246	Energy production potential per volume of biogas produced	MJ.m ⁻³ biogas	28.1	25.1–28.7
247	* Range indicated by Lobato <i>et al.</i> (2012).			

248 The unit relationships calculated for the *Laboreaux* STP are within the ranges estimated by
249 Lobato *et al.* (2012), who developed a model for the mass balance of COD conversion and for
250 the potential of energy recovery in UASB reactors treating domestic sewage. This model
251 considered all parcels involved in the anaerobic digestion, including eventual losses, such as:
252 (i) parcel of the initial COD which is converted into CH₄, present in the biogas; (ii) parcel of
253 the initial COD converted into CH₄ that escapes, dissolved in the anaerobic reactor effluent
254 and along with the residual gas (losses); (iii) parcel of the COD used for sulfate reduction;
255 (iv) parcel of the COD which is converted into sludge; and (v) parcel of the COD which
256 remains in the final effluent.

257 Sludge energy potential

258 As previously explained, the sludge produced in the *Laboreaux* is dehydrated in a filter press
259 and then disposed in a sanitary landfill. Over the monitoring period, the filter press operated
260 for 226 days and produced 849.5 tons of dehydrated sludge. For calculation purposes, the
261 parcel of dehydrated sludge on the drying bed was not considered due to operational problems
262 with the filter press in March 2011.

263 Table 10 presents the descriptive statistics for the characterization of the sludge produced in
264 the dewatering unit (filter press). Complementarily, the box plot graphs (Figures 5 and 6)
265 present the variability of the composition of pressed sludge. It is possible to identify an energy
266 potential in the order of 7,518 MJ.d⁻¹ for the material with 58.7% of moisture content.

267 **Table 9:** Descriptive statistics of characterization of the dehydrated sludge from the *Laboreaux* .

Statistics	Immediate composition % in mass (d.b.)			Moisture %	Calorific value (MJ.kg ⁻¹)				Elemental composition, % in mass (d.b.)				
	Volatile	Ash	Fixed		Theoretical		Real		C	H	N	O*	Ash**
					HCV (d.b.)	LCV (m.b.)	HCV (d.b.)	LCV (m.b.)					
Mean	42.9	53.3	3.8	58.7	7.4	1.7	8.7	2.0	19.8	3.6	2.1	20.5	54.0
Number of data	31	31	31	29	27	27	26	24	19	19	19	19	19
Mean	43.7	53.3	3.6	58.2	7.4	1.5	8.6	1.9	19.6	3.5	2.0	20.0	53.9
σ	4.0	3.1	1.9	5.9	0.9	1.4	1.2	0.8	1.6	0.3	0.5	2.0	3.2

268 *Determined by difference. ** Considering the measured data of ash for the days when the elemental composition
 269 characterization was carried out.

Figure 5: Immediate composition of the dehydrated sludge (filter press), d. b.

Figure 6: Elemental composition of the dehydrated sludge (filter press), d. b.

270 Compared with other types of biological sludge, the C and N₂ values observed are below
 271 those obtained in the sludge characterization reported by Groß (2008) and Fonts *et al.* (2009);
 272 however, the H level is high when compared to the results obtained by Groß (2008), Fonts *et*
 273 *al.* (2009), Courtland *et al.* (2010) and Dogru *et al.* (2002).

274 As for other types of biomass, the C (43.0%) and H (7.8%) values of the sludge characterized
 275 in this study, as fuel basis (disregarding the ash), were below those found for eucalyptus (C =
 276 49.3%; H = 5.9%), rice husk (C = 53.7%; H = 5.8%), and sugarcane bagasse (C = 49.3%; H =
 277 5.9%), as reported by Jenkins (1990) cited in Cortez *et al.* (2008).

278 The van Krevelen diagram, developed for the analysis of the carbonification level of different
 279 fuel types (van Krevelen and Schuyer, 1957), evaluates the energetic properties of the fuels
 280 free from water and ash. Figure 8 shows that the H/C relation is compatible with the
 281 dehydrated sludge characterization carried out by other researchers, whereas the O/C ratio is
 282 significantly higher. One possible explanation is the fact that the UASB reactor at the
 283 *Laboreaux* STP receives secondary sludge from the trickling filters (aerobic units). Such
 284 sludge presents characteristics similar to those reported by Judex *et al.* (2012) for the STP of
 285 Balingen (Germany), which promotes the energy recovery of sludge and biogas considering
 286 the cogeneration of energy in an ICE, by mixing the biogas from anaerobic digestion with the
 287 syngas produced from sludge gasification.

Figure 7: HCVs and LCVs, theoretical and real, for the filter pressed sludge of the *Laboreaux* STP.

(A) Dogru *et al.* (2002); (B) Houdkova (2008); (C) Courtland *et al.* (2010); (D) Groß *et al.* (2008); (E) Fontes *et al.* (2009); (F) Judex *et al.* (2012).

Figure 8: Correlation of the atomic ratios of H/C and O/C for the filter pressed sludge of the *Laboreaux* STP, compared to other authors.

Regarding the results of the sludge energy potential, in general, the values obtained in the lab are slightly higher than those estimated by the Dulong's equation (Figure 7). The LCV_{real} (m.b.) of the *Laboreaux* STP sludge (2.0 MJ.kg^{-1} at 58.7% of moisture content) is lower than that reported by Fontes *et al.* (2009) (7.7 MJ.kg^{-1} at 5.3% of moisture content), which shows the influence of the drying on the calorific value.

Considering a final moisture of 10% and H content of 3.6%, the LCV_{real} (m.b.) of the dry sludge would correspond to 4.5 MJ.kg^{-1} . This would be the energetic value of the sludge for use in thermal generation (boilers, heaters etc.) or thermoelectric plants. However, the dry sludge can be directed to commercial or local/regional industrial users as a substitute to firewood or coal. In this case, even if there is no financial return, the energetic destination of the sludge represents savings, since it will not need to be transported and disposed in a landfill.

Alternatives for the energy use of biogas and sludge

Scenario 1 – priority use of biogas for thermal drying of the sludge

The main objective in this scenario is to promote the thermal drying of the sludge using biogas as a heat source, and the use of the excess biogas to generate electricity for the STP.

Figure 9 presents the mass and energy balances for Scenario 1. It is possible to observe that the evaporation process demands 61.5% of the biogas flow produced in the STP, and the remaining 38.5% is used to generate electricity. Table 11 presents the energy balance for the scenario assessed, as well as relevant data of input and output conditions of the process.

Figure 9: Mass and energy balances for the use of biogas for the thermal drying of the sludge dehydrated in the *Laboreaux* STP – scenario 1.

Considering the total biogas energy potential ($4,218 \text{ MJ.d}^{-1}$) and a conversion yield of 30% by the power generator, the generated electric energy ($1,265 \text{ MJ.d}^{-1}$) is enough to supply 22.2% of the plant energy demand ($5,709 \text{ MJ.d}^{-1}$). The heat produced by the ICE can eventually satisfy other uses, but such a scenario was not considered in the proposed conception.

Table 10: Mass and energy balances for scenario 1.

Item	Initial products			Losses (MJ.d ⁻¹)	Final products		
	Flux	Calorific value	Energy potential (MJ.d ⁻¹)		Flux	Calorific value	Energy potential (MJ.d ⁻¹)
Products received from the STP							
Sludge (58.7% moisture)	3,759 kg.d ⁻¹	2.0 MJ.kg ⁻¹	7,518	-	-	-	-
Biogas	390.1 m ³ .d ⁻¹	28.1MJ.m ⁻³	10,962	-	-	-	-
Subtotal	-	-	18,480	-	-	-	-
Balance in the ICE							
Biogas consumed	150.1 m ³ .d ⁻¹	28.1 MJ.m ⁻³	4,218	-	-	-	-
Generated electric energy (η = 30%)	-	-	-	-	-	-	1,265*
Losses in the system ^a	-	-	-	2,952	-	-	-
Subtotal	-	-	4,218	2,952	-	-	1,265*

<i>Balance in the sludge thermal dryer</i>							
Biogas consumed	240.0 m ³ .d ⁻¹	28.1 MJ.m ⁻³	6,744	-	-	-	-
Fed dehydrated sludge	3,759 kg.d ⁻¹	2.0 MJ.kg ⁻¹	7,518	-	-	-	-
Final dry sludge (10% moist)	-	-	-	-	1,725 kg.d ⁻¹	4.36 MJ.kg ⁻¹	7,519 ^{*c}
Water evaporation ($\eta = 80\%$)	-	-	-	5,411 ^d	-	-	-
Losses in the system ^b	-	-	-	1,074 ^e	-	-	-
Residual heat from the drying	-	-	-	259 ^c	-	-	-
<i>Subtotal</i>	-	-	14,262	6,744	-	-	7,519^{*c}
TOTAL	-	-	18,480	9,696	-	-	8,784[*]

321 * Energy available for use at the plant or elsewhere. ^a Losses by convection/radiation and residual heat contained in the
322 exhaust gases. ^b Losses due to insufficiency of and residual heat in the exhaust gases in the combustion chamber. ^c Value
323 calculated by difference. ^d Considering the specific heat of the sludge as 0.385 kcal.kg⁻¹/°C⁻¹, of the water vapor as
324 2.1 kcal.kg⁻¹/°C⁻¹ and heat of vaporization of water as 540 kcal.kg⁻¹ to promote the thermal drying of the sludge from 57.8%
325 to 10% of moisture content. ^{d + e} Value calculated by CHEMCAD®.

326 The sludge with 10% of moisture content can be considered a potential fuel, however its use
327 requires additional mechanical processing (pelletizing, briquetting). Since the demand for
328 thermal energy in the STP is small, and the thermoelectric generation from dry sludge is not
329 economically attractive, we consider that the best energetic use for this byproduct would be
330 its supply to potential consumers of such type of fuel. Even though it generates little or no
331 income (in case it is donated), its destination as a byproduct represents savings in the STP
332 operation, due to reductions in costs of transport and final disposal in sanitary landfills.
333 Considering the dry sludge (10% of moisture content), the mass of material produced in the
334 dryer would be 1,725 kg.d⁻¹, with an equivalent LCV (m.b.) of 4.36MJ.kg⁻¹. This sludge
335 could provide 7,519 MJ.d⁻¹ in case it was used by a third party, which completely eliminates
336 the amount of final effluent destined for a sanitary landfill. Table 12 presents the detail of the
337 mass balance in the thermal drying of the sludge considering the burning of 240 m³.d⁻¹ of
338 biogas in the combustion chamber.

339 **Table 11:** Mass balance for the thermal drying through biogas combustion – scenario 1.

Component	Input (kg.d ⁻¹)	Output (kg.d ⁻¹)
Sludge	3,759	1,725
Biogas (CH ₄ and CO ₂)	237 ^b	-
Evaporated water	-	2,034 ^a
Air (O ₂ and N ₂)	567 ^b	31 ^b
Exhaust gases (CO ₂ , O ₂ , H ₂ O and	-	773 ^b
TOTAL	4,563	4,563

340 ^a Value calculated for the removal of water from 58.7% to 10% of moisture. ^b Value calculated by
341 CHEMCAD®.

342 **Scenario 2 – priority use of biogas for electricity generation**

The main objective in scenario 2 (Figure 10) is to produce electricity for the STP using all biogas produced in the UASB reactors, and then using the heat of the ICE exhaust gases for the thermal drying of the dehydrated sludge. Table 13 presents the details of the mass and energy balances. In this scenario, there is potential to generate $3,289 \text{ MJ.d}^{-1}$ of electricity, which corresponds to a supply of 57.6% of the STP demand.

Considering that the energy in terms of heat contained in the exhaust gases ($2,000 \text{ MJ.d}^{-1}$) is not sufficient to evaporate all water from the dehydrated sludge ($3,759 \text{ kg.d}^{-1}$) and achieve the final moisture content of 10%, two alternatives were assessed: alternative 1 - thermal drying of all sludge until a minimum possible moisture level; and alternative 2 - thermal drying of a fraction of the sludge until 10% moisture content is achieved, and then sending the remaining dehydrated material (moisture content of 58.7%) to the sanitary landfill.

For alternative 1, the minimum possible moisture content is 52.7%, and this level was considered too high for the energy use of the sludge. Therefore, in this alternative, the dryer promotes the reduction of both mass and volume of the sludge destined for the landfill.

For alternative 2, the dryer is able to process 937 kg.d^{-1} of dehydrated sludge (24.9% of the amount produced in the filter press), and generates 430 kg.d^{-1} of dry sludge with 10% moisture content, that can be used as fuel. The remainder of the sludge ($2,822 \text{ kg.d}^{-1}$) is destined for the landfill.

Therefore, in terms of mass, alternative 1 corresponds to a reduction of 13.5% in the mass of sludge destined for the landfill; for alternative 2, such reduction is of 24.9%. Considering the specific masses of $1,020 \text{ kg.m}^{-3}$ and $1,050 \text{ kg.m}^{-3}$ for the sludge moisture levels of 58.7% and 52.7%, respectively, there is a volume reduction of 15.9% for Alternative 1 and 24.9% for alternative 2. The volume reduction is important due to the costs of transport and final disposal, which are proportional to mass and volume.

Figure 10: Mass and energy balances for the energy use of biogas for electricity generation, followed by the thermal drying of the sludge using exhaust gases at the *Laboreaux* STP – scenario 2.

Table 12: Mass and energy balances for scenario 2.

Item	Initial products			Losses (MJ.d ⁻¹)	Final products		
	Flux	Calorific value	Energy potential (MJ.d ⁻¹)		Flux	Calorific value	Energy potential (MJ.d ⁻¹)
<i>Products received from the STP</i>							
Sludge (58.7% moisture)	3,759 kg.d ⁻¹	2.0 MJ.kg ⁻¹	7,518	-	-	-	-
Biogas	390.1 m ³ .d ⁻¹	28.1MJ.m ⁻³	10,962	-	-	-	-
<i>Subtotal</i>	-	-	18,480	-	-	-	-
<i>Balance in the ICE</i>							
Biogas consumed	390.1 m ³ .d ⁻¹	28.1 MJ.m ⁻³	10,962	-	-	-	
Generated electric energy (η = 30%)	-	-	-	-	-	-	3,289*
Residual heat in the exhaust gases	-	-	-	7,673 ^a	-	-	-
<i>Subtotal</i>	-	-	10,962	7,673	-	-	3,289*
<i>Balance in the sludge dryer using gases from the ICE – alternative 1</i>							
Processed dehydrated sludge	3,759 kg.d ⁻¹	2.0 MJ.kg ⁻¹	7,518	-	-	-	-
Final sludge (52.7% moisture) ^b	-	-	-	-	3,252 kg.d ⁻¹	2.31	7,518*
Water evaporation (η = 80%)	-	-	-	1,700 ^c	-	-	-
Losses due to inefficiency of the dryer	-	-	-	300 ^c	-	-	-
Losses in the exhaust gases	-	-	-	5,673	-	-	-
<i>Subtotal</i>	-	-	7,518	7,673	-	-	-
TOTAL	-	-	18,480	7,673	-	-	10,807*
<i>Balance in the sludge dryer using gases from the ICE – alternative 2</i>							
Processed dehydrated sludge	3,759 kg.d ⁻¹	2.0 MJ.kg ⁻¹	7,518	-	-	-	-
Sludge sent to landfill (58.7%) ^b	-	-	-	-	2,822 kg.d ⁻¹	2.0	5,644
Energetic sludge (10% moisture)	-	-	-	-	430 kg.d ⁻¹	4.36 MJ.kg ⁻¹	1,874 ^{c*}
Water evaporation (η = 80%)	-	-	-	1,700 ^c	-	-	-
Losses due to inefficiency of the dryer	-	-	-	300 ^c	-	-	-

Losses in the exhaust gases	-	-	-	5,673	-	-	-
Subtotal	-	-	7,518	7,673	-	-	7,518*
TOTAL	-	-	18,480	7,673	-	-	10,807*

377 * Energy available for use at the plant. ^a The residual heat in the ICE gases will be used as energy source for sludge
378 drying. ^b The sludge at 52.7% moisture was considered as rejected (destined for the landfill). ^c Considering the specific heat
379 of the sludge as 0.385 kcal.kg⁻¹/°C⁻¹, of the water vapor as 2.1 kcal.kg⁻¹/°C⁻¹ and heat of water vaporization as 540
380 kcal.kg⁻¹. ^d Value calculated by CHEMCAD®. ^e The sludge with 52.7% of moisture content was not considered for energy
381 uses and should be destined for the landfill. The drying has the objective of reducing sludge mass and volume. ^f Value
382 calculated by difference.

383 Comparison of scenarios

384 Table 15 summarizes the energy balance for both scenarios. The results show that scenario 1
385 presents a better performance of drying and conversion of sludge into an energetic byproduct,
386 and can completely eliminate the generation of rejected material to be disposed in the landfill.
387 On the other hand, it presents a lower percentage of electric energy supply. The final decision
388 on which scenario is most attractive must be made after an economic analysis (analysis of the
389 investment required for each configuration as well as the earned returns), which is beyond the
390 scope of this study.

391 **Table 13:** Energy use scenarios for the *Laboreaux* STP.

Items	Current situation	Scenario 1	Scenario 2	
			Alternative	Alternative
Sludge/reject generation for disposal in landfill (kg.d ⁻¹)	3,759	-	3,252	2,822
Reduction of reject compared to current situation (%),	-	100	13.5	24.9
Biofuel dry sludge generation (10% moisture) (kg.d ⁻¹)	-	1,725	-	430
Generated electricity (MJ.d ⁻¹)	-	1,265	3,289	3,289
Electricity supply for the STP (%)	-	22.2	57.6	57.6

393 CONCLUSIONS

394 The systematic characterization of production and calorific value of the biogas and sludge
395 produced in the *Laboreaux* STP, in Itabira, Minas Gerais, enabled the development of mass
396 and energy balances which demonstrate the potential of using these sewage treatment
397 byproducts as a renewable energy source, especially for the STP itself.

398 The sludge dehydrated in a filter press, if submitted to drying to improve its calorific value,
399 can be used as fuel to supply other consumers in the region, as a substitute for firewood or

coal. The biogas can be used at the STP. Scenario 1 presented in this study considers the use of biogas for the thermal drying of sludge up to a final moisture content of 10%, using the excess biogas to generate electricity in ICEs. Scenario 2 presented the total use of biogas for electricity generation and the amount of exhaust gases from the engine necessary to dry the sludge to the minimum possible moisture content.

The first scenario stands out due to the elimination of the need to send the sludge to the landfill, whereas the second scenario presents a high potential for electricity generation to supply the STP.

In general, the study of alternatives for the energy use of sewage treatment byproducts must take into account the needs and the reality of the plants. The mass and energy balances are essential for economic feasibility studies of energy use projects that can be considered technically viable for each STP, individually.

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