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Emergy Evaluation of Domestic Wastewater Treatments: The Role of Energy and Materials Consumption and Carbon Emissions

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Abstract

Technologies for domestic wastewater treatment systems can be planned and constructed to use locally available materials lessening the need for resupply materials and to fit the local conditions. However, most plans for wastewater treatment systems do not consider the renewable support required to dilute plants' emissions. Solutions for mitigating environmental impacts and achieve sustainable environments with low carbon depend on the accounting for the available local resources and the environmental services required for diluting emissions. Two example applications of domestic wastewater treatment metabolism are discussed using sustainability indicators and inputs to the greenhouse gas emissions calculation. The analysis compares upstream and downstream environmental investments and may be used to advise public policies for sustainable regional and urban development.

1 Introduction

The continuous increase of human population, with consequent escalate of the pollution menace and the simultaneous pressure on the environment require more inclusive and efficient environmental protection systems. Sewage treatment facilities are vital for sustainable urban development acting as a technological reaction to the increase of pollution caused by human-controlled interferences in the water cycle (Chen et al., 2014). Thus, development for sustainable wastewater systems requires a wide-ranging understanding and assessment of the integrated wastewater systems with the regional characteristics.

In recent years, noteworthy improvements occurred in sewage treatment technologies (Donatello and Cheeseman, 2013; Krüger and Adam, 2015), which are built with increased efficiency and functionality. Nonetheless, wastewater treatments also consume large quantities of energy and materials that have to be cautiously accounted for when estimating their environmental efficiency. In the modus operandi of removing contaminants and discharging cleaner water, wastewater treatments consume resources and trigger environ-

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mental emissions during its life span (Risch et al., 2015; Vehlow, 2015).

The activated sludge system is the most used in Brazil, and biodigestion is often chosen as a feasible alternative to small isolated communities. On one hand, both systems use different amounts of materials and energy for their implementation and operation. On the other hand, both systems generate air pollutants such as methane, which must be maintained at levels that do not compromise the environmental health of the surrounding ecosystems (El-Fadel and Massoud, 2001). Part of these emissions can be mitigated with human intervention, but also depends on the environment that provides dissipation or degradation services. Both treatment systems analyzed delivery water of the same quality and both treat domestic wastewater. The novelty of our study is to evaluate and compare the environmental costs of the treatment systems, which are commonly disregarded in traditional evaluations of wastewater treatment systems.

The most used assessment methods for systems operation are based on an analysis of energy and material flows, in this manner tracking inputs, storages, transformations, and outputs (Zhang, 2013). Emergy synthesis associates sustainability with maximizing renewable resource use and was widely used to improve current approaches that target creating built environments that contribute to a sustainable rapport between the geobiosphere and the human activities (Mellino et al., 2015; Arbault et al., 2014; Dong et al., 2013). This method accounts for resources/energy consumption and carbon emission by waste water treatments in terms of a combination of practice and input/output analyses with a course of action that covers manpower material, equipment, and energy inputs (Shao et al., 2014a). A stimulating array of innovative research on sewage treatment options and their assessment using emergy synthesis is available in the literature (Wang and Chen, 2015). Natural wetlands required a large amount of land area, and also need an assortment of resources that must purchased to accomplish the strict society`s rules for wastewater treatment. Nelson et al. (2001) showed that measured up to conventional sewage treatment, wetland treatment systems require less purchased materials, are less energy dependent and involve simpler maintenance. They also provided a list of additional benefits including fiber from plants, the maintenance of biodiversity, and esthetic landscape improvement for the neighboring area. Geber and Björklund (2002) uses emergy synthesis to analyze the need of resources in three different wastewater treatment systems: conventional three-step treatment, standard mechanical and chemical treatment matched with a constructed wetland, and a natural wetland treatment. They observed that, in Sweden, it was not possible to substitute purchased inputs by natural ones. Björklund et al. (2001) examined the requirement of environmental resources for wastewater treatment in Sweden using emergy synthesis. The study also included an estimation of the emergy quantity connected with the wastewater production. These authors concluded that the Swedish municipal wastewater treatment systems were principally supported by fossil energy. Their analysis also indicated that, in terms of resource use, it would be more efficient to purchase the electricity directly from the distribution net than producing it via in-plant sludge biodigestion. Considering the cold climate in a small Swedish town, Grönlund et al. (2004) evaluated the wastewater treatment sustainability with microalgae confronting the emergy results and socio-ecological principles. They compared the results to those of Geber and Björklund (2002) and found that, in emergy terms, the algae treatment requires fewer resources than the other alternatives.

Considering that recirculation of nutrients or production of cost-effectively viable products from the by-products of the treatment would strongly influence the sustainability, Siracusa and La Rosa (2006) proposed the construction of a wetland on a Sicilian wastewater treatment plant. The proposed design provides the option of recycling clean water reducing the pressure on the local environment and also results in savings by reducing electricity consumption. The emergy synthesis allowed a quantitative assessment of the environmental savings due to water reuse. assessed in Italy. A first round assessment of the environmental costs of a wastewater treatment plant located along the Ligurian coast (Vassallo et al., 2009) showed that the released water was still loaded with substances that have to be absorbed by the receiving natural medium. The environmental services used for absorbing this burden, conventionally regarded as free, are reckoned as an additional cost in the total emergy requirements of the water purification process.

Zhang et al. (2010) applied emergy synthesis to evaluate two alternatives for the Chinese Mingjingtan sewage treatment plant and their results pointed out the environmental pressure of the sewage treatment subsystem with reclaimed water reuse subsystem and aerobic compost production is smaller than that of the sewage treatment system that discharges treated water and landfills sludge, even if its economic results are poorer. The authors proposed methods to help operators and guide policy-makers and designers to improve the performance of the sewage treatment. Moss et al. (2014) assessed the sustainability of small-scale anaerobic digestion systems introducing an emergy efficiency index and an adjusted yield ratio. A human sanitation system in Haiti and a dairy manure system in the US were investigated using emergy synthesis to determine their relative sustainability. The emergy efficiency index and an adjusted yield ratio were confronted with traditional indices to evaluate the effect of accounting methodology and waste source on digester sustainability.

Chen and Chen (2013) called attention to the fact that systems of wastewater treatment are progressively being planned for the recuperation of energy and chemicals in addition to waste stream discarding. These authors assessed a typical domestic wastewater treatment system combining biogas use and sludge processing in regard to the energy production and emission mitigation. Their results showed that biogas and sludge reuse compensates the cost of plant's installation and operation. Shao et al. (2013) compared a constructed wetland, a cyclic activated sludge plant and a system combining conventional treatment system and constructed wetland. The on-site direct energy, which accounts for only 30–40% of the total, is revealed to be less important than the indirect energy. In regard to environmental benefits, the ecological engineering of the conventional wastewater treatment was found less favorable than the constructed wetland. Shao et al. (2014) assembled a comprehensive framework to analyze the natural resources and environmental emissions of wastewater treatment. The framework combines process and input–output analyzes supplying a set of indicators to support for optimal decision-making among different wastewater treatment technologies.

Most studies found in the literature focus on the use of resources, natural or not, to implement and operate domestic wastewater treatment plants. A cross-sectional analysis makes clear that the use of energy and resources depend not only on the type of treatment, but also to the local geographic and climatic conditions. Local conditions determine the energy requirement (Nelson et al., 2001; Shao et al., 2013), the availability of direct and indirect area (Björklund et al., 2001; Geber and Björklund, 2002), and the treatment time. There is also a great concern regarding the additional benefits that each treatment may return to the society (Chen and Chen, 2013; Huang et al., 2013), such as energy and money savings (Zhang et al., 2010, Shao et al., 2014; Boithias et al., 2014), in helping policy-makers and guiding designers and operators to choose the most suitable treatment. However, environmental services to dilute or mitigate the air emissions of each treatment are only considered in cases where their burden is verified (Ulgiati and Brown, 2002). Thus, it is important to develop and combine the system-based tools and metrics in order to evaluate the complete water service system based not only on the concept of resource/energy management (Xue et al., 2015), but also considering the carrying capacity of the system's neighborhood.

The aim of this study was to analyze two different wastewater treatment systems commonly used in Brazil in regard to:

- the use of resources: investigating to what extent each treatment depends on resources provided by their surroundings and on ecosystem services.
- the environmental costs: in terms of the emissions to the air that have to be absorbed or dissipated by the surrounding natural system.

Since this nature's work uses the biosphere cycles and processes and free environmental services, an analysis of the environmental area required to dilute, absorb and process the unwanted emissions without trigering major effects in the environment was also performed. The work done by nature to dissipate these emissions is computed as a further cost in the wastewater treatment systems total emergy budget. This integrated approach including upstream and downstream requirements may help municipalities to build an environmentally sound sewage management system accordingly to treatment demands and the carrying capacity of the surrounding areas.

2 Methods

Emergy synthesis has been used to quantify all inputs to a system by translating them to solar energy equivalents. The method allows direct comparison of the miscellaneous inputs of human labor, renewable energies and purchased goods needed to build and maintain any kind of system, including domestic wastewater treatment systems. This methodology, proposed by Odum (1996), is capable of evaluating the exploitation of resources by a system accounting for the available energy that is required (directly or indirectly) to obtain a good or service. Departing from energy system diagram (please see detailed information about their construction in Odum, 1996), tables of the actual flows of materials, labor and energy are constructed, and the different units of each flow are multiplied by unit emergy values (UEVs, sej/unit) or transformities (sej/J) converting them to solar emergy. The UEV relates to the emergy quantity required to produce one unit of output (sej/unit). GP is the inverse of UEV (unit/sej) and is a measure of efficiency. When using emergy synthesis to calculate the efficiency of a system we include human labor and renewable energies along with the common inputs used to account for efficiency and thus it is called global productivity (GP).

The energy inflows are classified into renewable (R), non-renewable (N) and the flows feedback by the economic system (F). The renewable input (R_2) made available by the local and surrounding ecosystems for the dilution and the abatement of plant emissions (Ulgiati and Brown, 2002), account for the environmental services necessary to drive the dilution of air emissions. The kinetic energy was used in order to quantify the quantity of air needed to dilute local emissions in to the average concentration of the atmosphere. The emergy value to achieve concentration levels comparable to the biosphere average values was calculated as the kinetic energy of the mass of air for dilution dilution, using typical values for wind speed in the region, according to Equations 1 and 2.

$$m = d \text{ x } (W/c) \tag{1}$$

$$R_2 = \tfrac{1}{2}\, m \text{ x } v^2 \text{ x } \mathrm{UEV}_{(\mathrm{wind})} \tag{2}$$

where d is air density, 1.23 g/dm^3; W is the annual total of a particular emission from the plant, c is the background concentration, and v the wind speed (4 m/s). When multiplied by the wind transformity (UEV), R_2 gives a measure of the environmental service that is essential to dilute the treatment plants emissions. The persistence of each pollutant is a phenomenon that occurs in a large scale (outside the boundaries of the systems in analysis), and was considered in the calculation of the A_{RE} (re-irradiation area), which accounts for the support of the larger system required by each treatment system.

2.1. Emergy indices for evaluating the performance of the treatment systems

Traditional emergy indices are used to assess the treatment systems' performance regarding the use of resources for their implementation and operation. These traditional indices were complemented by the environmental sustainability index proposed by Brown and Ulgiati (2002) (Table 1).

Table 1. Emergy indices calculated with and without computing the environmental services.

Indices	Equation	Description
EYR	*without environmental services:* = Y/(F) where: Y = R + N +F *with environmental services:* = Y/(F+R_2) where: $Y_{(ES)}$ = R + R_2 + N +F	The emergy yield ratio confronts the total emergy (Y) and the emergy of inputs provided by the economy (F). It provides information on the aptitude of the process to exploit local resources, whether renewable or not.
ELR	*without environmental services:* = (N + F) / R *with environmental services:* = (N + F+R_2) / R	The environmental loading ratio reports on the balance between non-renewable and purchased and the renewable emergy inputs to a system. It compares the investment of nonrenewables compared to available local renewable emergy.
ESI	*without environmental services:* = EYR / ELR *with environmental services:* = $EYR_{(ES)}$ / $ELR_{(ES)}$	The emergy sustainability index is a combined measure of yield and loading, implying that sustainability requires high yield and low environmental load.

where: R: renewable flows; R_2: renewable flows for dilute pollutants; N: non-renewable flows, and F: feedback from the economy or purchased resources. ES points out to the inclusion of environmental services.

To facilitate interpretation and communication of the results and help decision-making (Gasparatos et al., 2008), the emergy ternary diagram (Fig. 1) is used to visually represent the systems under study, with and without accounting for the environmental services (Almeida et al., 2007; Giannetti et al., 2006). This graphic tool include lines that indicate constant values of the ESI. These lines connect the N apex to the RF axis establishing sustainability regions within the diagram.

The sustainability regions are very useful to categorize and compare the sustainability of sytems (Fig. 1). Further information about the diagnostic properties of ternary diagrams can be found in (Almeida et al., 2007; Giannetti et al., 2015; Agostinho et al., 2013).

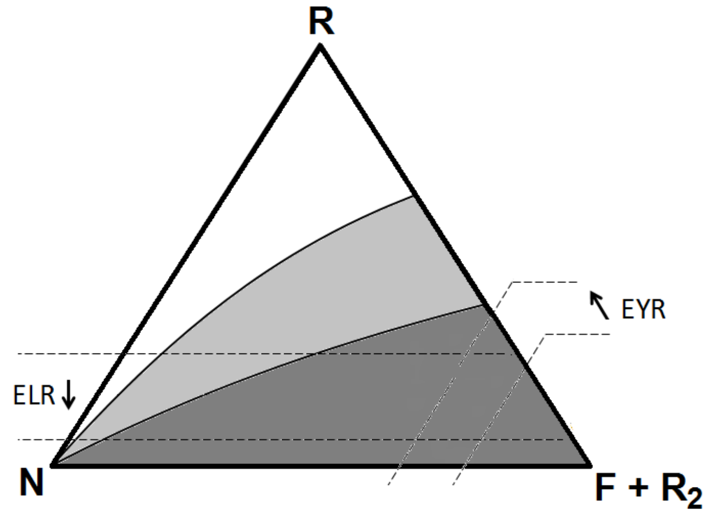

Fig.1. Ternary emergy diagram with the sustainability lines (N apex → RF axis). The region (ESI > 5, white) indicates systems that should be sustainable for long term; the region (1 < ESI < 5, grey) encloses medium-term sustainable systems, and the region (ESI < 1, dark grey) includes systems that are not sustainable. R_2 is accounted as an environmental cost, since it is inflicted on the environment and the region. The dashed lines show how the emergy indices (EYR and ELR) vary within the diagram.

The ternary diagram has been successfully used to determine the evaluation emergy from materials selection systems for soft drinks packages (Almeida et al., 2010a); to identify improvements in water management of bus-washing stations (Almeida et al., 2010b), to determine thesuitable production model for a coffee plantation (Giannetti et al., 2011a), to evaluate of a MSW-to-energy system (Almeida et al., 2012) and a reverse logistics network for steel recycling (Giannetti et al., 2013). All these studies illustrate the robustness of the triangular diagram for determining the best systems when environmentally analyzed by emergy accounting.

2.2. Evaluating the carrying capacity of the surrounding areas

After comparing the domestic wastewater plants by means of emergy indicators, a meticulous analysis of the environmental area to supply resources for implementation and maintenance and to dilute the undesired air emissions was performed, considering the upstream and the downstream environmental services. The emergy results were converted into area units to facilitate the understanding by the general public since the estimation of this indirect area may enhance planning and policy making regarding domestic wastewater plants location. Several methods found in the literature were applied and confronted: the modified Ecological footprint proposed by Zhao et al. (2004); the Support Renewable Area (Brown and Ulgiati, 2001) and the S_A introduced by the same authors in 2002; and the area of re-irradiation (A_{RE}) that accounts for the emergy associated to the labor of nature to re-balance the system, and the residence time of pollutants in the atmosphere (Tiezzi et al., 1995). Equations are shown in Table 2.

Table 2. The requirement for carrying capacity, computing the upstream and the downstream environmental services.

Indices	Equation	Description
EF_M	$(N + F + R_2) / (Y_{Brazil}/A_{Brazil})$	The modified Ecological Footprint (EF_M) converts the emergy inputs (N+F) into area units by dividing them by the quotient of Y_{Brazil}/A_{Brazil} (Zhao et al., 2004). where, Y_{Brazil} is the emergy of the country and A_{Brazil} its total area.
SA_r	$(F + N + R_2) / (R_{Brazil}/A_{Brazil})$	The Support Renewable Area (SA_r) reflects the necessary area to substitute the economic and the non-renewable flows by renewable ones in the region where the system is inserted. It is obtained by dividing (N+F) by (R_{Brazil}/A_{Brazil}), which is the density of renewable emergy of the country (Brown and Ulgiati, 2001)
S_A	$R_2/(R_{Earth}/A_{Earth})$	The environmental services (R_2) are divided by the area of land needed to balance the emissions released by the systems (Geber and Björklund, 2002). R_{Earth} is the average flux of renewable emergy per year per unit area of the Earth (A_{Earth}).
A_{RE}	$E_R / (Y_{Earth}/A_{Earth})$ where: $E_R = Y - E_i \times T_r$	Re-irradiation area: this approach uses the emergy of total heat (E_i) reflected towards the surface of the planet from additional pollutants - over all its residence time in the atmosphere - multiplied by their transformities (Tiezzi et al., 1995). The emergy of this process (E_R) is converted into area by dividing E_R by the quotient (Y_{Earth}/A_{Earth}).

2.3. Systems Description

The activated sludge treatment was adopted in Brazil in the 60s and is one of the most widely used methods in the country. The plant is located in Guaratingueta, São Paulo and is managed by the Municipal Water and Wastewater Autonomous Sanitation. The plant produces an annual volume of 504,576 m^3 of clean water serving a population of 9,985 inhabitants.

The Activated Sludge system uses tanks for aeration and sedimentation. During agitation, the sludge absorbs colloidal and suspended materials present. The wastewater goes through aeration and agitation, becomes flaky and accumulates a large amount of aerobic bacteria, protozoa, and metazoan, which oxidize the organic matter present in the wastewater. A Hi-Cone system discharges the mixture in a tank for agitation and circulation. The aeration process lasts 8 hours and consumes from 3 to 10 liters of air to achieve a BOD of 100 mg/L. The aerated "wastewater-sludge" mixture goes to a decanter, from where the liquid portion is removed. Part of the decanted sludge (13% in weight) returns to the aeration tank while the remaining 87% is dried outdoors and sent to the municipal landfill.

The biodigestion wastewater treatment plant is located in Petrópolis, Rio de Janeiro and is managed by the Independence Community. The wastewater treatment is performed by biodigestion by collection and storage of effluent in a digester in which the biogas is stored. Methanogenic bacteria convert the nutrients in the effluent into biogas (a mixture of methane, sulfur dioxide and CO_2). The biodigester tank has a conical shaped bottom to store the sand that may be contained in the sludge. Complete digestion takes place in 24 discharging clean water and biofertilizer. The biogas is used to generate energy for community use. The liquid portion of the digested effluent passes through a filter and is released into a water body. This system produces an annual volume of 30,275 m^3 of clean water obtained from the sewage produced by 600 residential inhabitants.

3 Results

Figures 2 and 3 show the energy systems diagrams of the activated sludge and the biodigestion treatment plants. In regard to the emissions, the carbon dioxide and the methane emitted by the activated sludge treatment are released into the atmosphere (Fig. 2). In the biodigestion treatment, the biogas is collected and distributed to the community being released, after burning as carbon dioxide (Fig. 3).

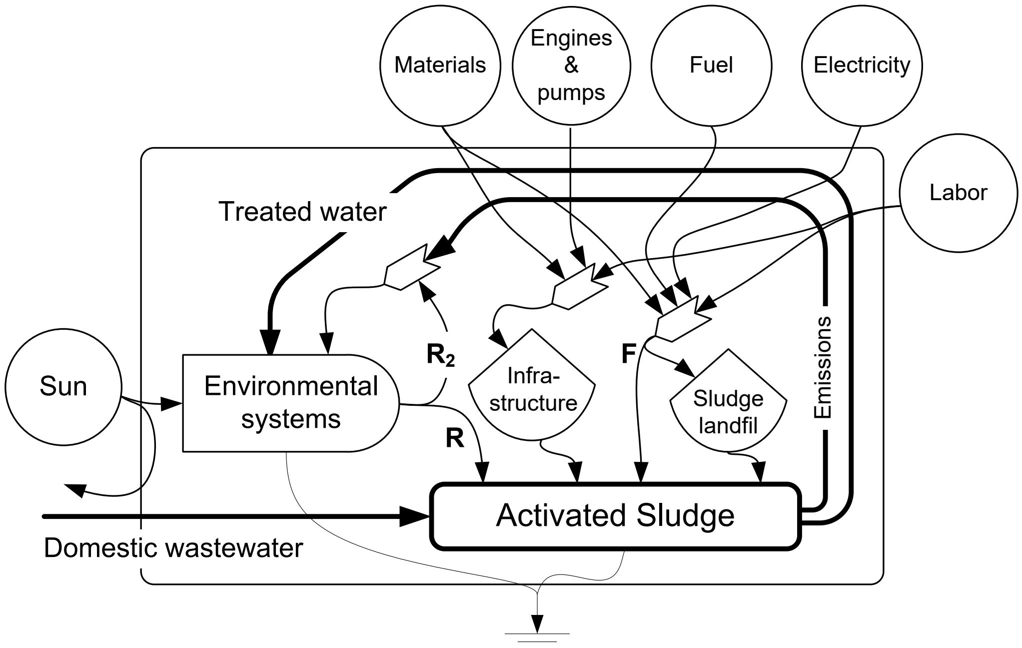

Fig. 2. Energy system diagrams of the activated sludge treatment system. Nature dilutes and/or recycles emissions (carbon dioxide and methane) through the renewable emergy investment, R_2.

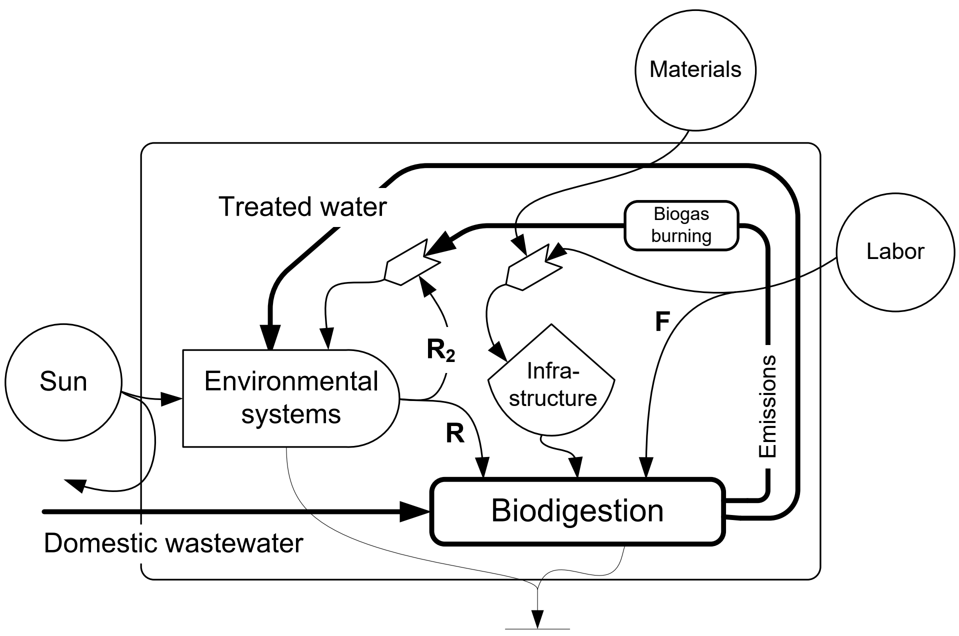

Fig. 3. Energy system diagram of the biodigestion treatment system. Biogas is burned, and carbon dioxide emissions are recycled and/or diluted by renewable emergy investment provided by nature, R_2.

Tables 3 and 4 show both systems treating approximately 10,000 inhabitants and producing 50 m^3 of sewage *per capta*. Resource use was discriminated according to the demands of the construction and operating phases, and those required to dilute emissions. Without considering the environmental services, the main contributions to the activated sludge treatment are electricity (28% sej/sej) and labor (17% sej/sej), followed by concrete used in the plant construction (11% sej/sej) and the landfill fraction used to dispose the sludge (Table 3). The biodigester is less resource intensive with 44% of its total emergy is related to the work done by employees (Table 4). If applied on a large scale for spread populated areas, biodigester would use the same amount of emergy of the activated sludge system (about 6.8 x10 16 sej/year) in the construction phase, but would require 1/5 of resources of conventional sewage treatment during the operational phase.

Once the annual direct emissions to atmosphere due to the systems operation were calculated, it was possible to estimate the environmental services considered necessary to treat these emissions in emergy terms. Tables 3 and 4 show the R_2 flows required by both systems. These flows represent the environmental costs for pollutant dilution and account for 27% of the total emergy of the activated sludge system, and less than 1% sej/sej of the biodigestion one. For the same output of treated water, the emergy invested to dilute emissions from the activated sludge system is about 60,000 times larger than that of the biodigester underscoring the higher environmental cost of the conventional system.

Table 3. Emergy Evaluation for Treatment with Activated Sludge with and without accounting for the environmental services (ES). Detailed calculations of the required carrying capacity of the domestic wastewater treatments are available in Supplementary material, Appendix A.

	Description	Unit	Class [a]	Value (un/year)	UEV[b] (sej/un)	Emergy (sej/year)	Refs.	% without ES (sej/sej)	% with ES (sej/sej)
	Upstream emergy investment								
	Plant construction phase								
1	Concrete	g	F	3.56×10^{7}	1.54×10^{9}	5.48×10^{16}	(a)	11	8
2	Engines and Pumps (steel)	g	F	5.40×10^{4}	4.10×10^{9}	2.21×10^{14}	(b)	<1	<1
3	Labor	J	F	1.43×10^{8}	4.30×10^{6}	6.15×10^{14}	(c)	<1	<1
4	Steel	g	F	3.50×10^{6}	2.77×10^{9}	9.70×10^{15}	(a)	2	1
5	Cooper	g	F	2.77×10^{3}	2.00×10^{9}	5.54×10^{12}	(d)	<1	<1
6	Soil use	J	N	1.05×10^{11}	2.21×10^{4}	2.32×10^{15}	(e)	<1	<1
	Plant operating phase								
	Non renewables								
7	Diesel for sludge transport	J	F	3.50×10^{11}	6.60×10^{4}	2.31×10^{16}	(d)	5	4
8	Electricity	J	F	8.07×10^{11}	1.65×10^{5}	1.33×10^{17}	(d)	28	20
9	Labor	J	F	1.92×10^{10}	4.30×10^{6}	8.26×10^{16}	(c)	17	13
10	Landfill for sludge	g	N	1.23×10^{9}	3.79×10^{7}	4.66×10^{16}	(a)	10	7
	Renewables								
11	Sun [c]	J	R	7.03×10^{9}	1.00	7.03×10^{9}	(d)	-	-
12	Evaporation [c]	g	R	2.02×10^{8}	1.45×10^{5}	2.93×10^{13}	(f)	-	-
13	Precipitation	g	R	6.18×10^{8}	1.57×10^{5}	9.70×10^{13}	(f)	<1	<1
14	Oxygen for combustion processes	g	R	2.72×10^{7}	5.16×10^{7}	1.40×10^{15}	(g)	<1	<1
15	Oxygen for aeration processes	g	R	2.40×10^{9}	5.16×10^{7}	1.24×10^{17}	(g)	26	19
	Total Emergy without ES	m^3		5.05×10^{5}	9.47×10^{11}	4.78×10^{17}		100	-
	Downstream emergy investment								
	Environmental services								
16	Wind's kinetic energy for CO_2 dilution	J	R_2	5.69×10^{11}	1.50×10^{3}	8.54×10^{14}	(d)	-	<1
17	Wind's kinetic energy for CH_4 dilution	J	R_2	1.18×10^{14}	1.50×10^{3}	1.77×10^{17}	(d)	-	27
	Total Emergy with ES	m^3		5.05×10^{5}	1.30×10^{12}	6.56×10^{17}		-	100

[a] R: local/free renewable resources. N: local/free non-renewable resources. F: purchased resources or feedback from the economy and R_2: global/free renewable resource for dilute pollutants.

[b] Unit Emergy Values (UEV) refer to the 15.83 x 10^{24} sej/year baseline (Odum et al., 2000). The baseline is reference value on which all the unit emergy values (UEVs) are based upon. It is calculated by the sum of all renewable energies that feed the planet (win, sun, tide and geothermal energies.

[(c)] Not accounted to avoid double-counting (Odum, 1996).

References: (a) Brown and Buranakarn, 2003; (b) Geber and Björklund, 2002; (c) Bonilla et al., 2010; (d) Brown and Ulgiati, 2002; (e) Romitelli, 2000; (f) Odum, 1996; (g) Ulgiati and Brown, 2002.

Table 4. Emergy Evaluation of the Biodigestion Treatment with and without accounting for the environmental services (ES). Detailed calculations of the required carrying capacity of the domestic wastewater treatments are available in Supplementary material, Appendix A.

	Description	Unit	Class [(a)]	Value (un/year)	UEV[(b)] (sej/un)	Emergy (sej/year)	Refs.	% without ES (sej/sej)	% with ES (sej/sej)
	Upstream emergy investment								
	Plant construction phase								
1	Concrete	g	F	$3.50x10^7$	$1.54x10^9$	$5.39x10^{16}$	(a)	31	40
2	Brick	g	F	$3.17x10^6$	$2.52x10^9$	$7.98x10^{15}$	(b)	6	26
3	Labor	J	F	$6.20x10^8$	$4.30x10^6$	$2.67x10^{15}$	(c)	2	2
4	Plastic	g	F	$4.13x10^3$	$5.87x10^9$	$2.43x10^{13}$	(b)	<1	<1
5	Soil Use	J	N	$7.15x10^{10}$	$2.21x10^4$	$1.58x10^{15}$	(e)	<1	<1
6	Steel	g	F	$6.33x10^5$	$2.77x10^9$	$1.75x10^{15}$	(a)	<1	<1
	Plant operating phase								
	Non renewables								
7	Labor	J	F	$1.37x10^{10}$	$4.30x10^6$	$5.91x10^{16}$	(c)	44	44
	Renewables								
8	Sun	J	R	$1.45x10^{10}$	1.00	$1.45x10^{10}$	(f)	-	-
9	Geothermal Heat	J	R	$1.80x10^9$	$2.55x10^4$	$4.59x10^{13}$	(f)	<1	<1
10	Oxygen for combustion processes	g	R	$1.22x10^8$	$5.16x10^7$	$6.28x10^{15}$	(d)	5	5
	Total Emergy without ES	m^3		$5.05x10^5$	$2.64x10^{11}$	$1.33x10^{17}$		100	-
	Downstream emergy investment								
	Environmental services								
1	Wind's kinetic energy	J	R_2	$1.82x10^{09}$	$1.50x10^3$	$2.73x10^{12}$	(g)	-	<1
	Total Emergy with ES	m^3		$5.05x10^{05}$	$2.64x10^{11}$	$1.33x10^{17}$		-	100

[a] R: local/free renewable resources. N: local/free non-renewable resources. F: purchased resources or feedback from the economy and R_2: global/free renewable resource for dilute pollutants.

[b] Unit Emergy Values (UEV) refer to the 15.83×10^{24} sej/year baseline (Odum et al., 2000). The baseline is reference value on which all the unit emergy values (UEVs) are based upon. It is calculated by the sum of all renewable energies that feed the planet (win, sun, tide and geothermal energies.

[(c)] Not accounted to avoid double-counting (Odum, 1996).

References: (a) Brown and Buranakarn, 2003; (b) Geber and Björklund, 2002; (c) Bonilla et al., 2010; (d) Brown and Ulgiati, 2002; (e) Romitelli, 2000; (f) Odum, 1996; (g) Ulgiati and Brown, 2002.

The UEV value of the treated water from the activated sludge treatment is 5 times as high as the biodigester reflecting both the higher use of resources in the operational phase and the use of environmental services to dilute emissions (Tables 3 and 4). The efficiency of each treatment, verified by the emergy invested to treat one cubic meter of sewage (UEV), shows that the most appropriate treatment choice is the biodigestion solution, considering the emergy investments required both upstream and downstream.

3.1. Emergy indices

Figure 4 positions the treatment systems within the ternary diagram in terms of their relative usage of renewable, nonrenewable and economic resources, without considering the downstream environmental services.

Results are compared with those found in the literature (Nelson et al., 2001, Geber and Björklund, 2002; Grönlund et al., 2004; Vassalo et al., 2009). All systems are located in the lower part of the diagram (dark grey region), and the position of the biodigestion system is one of the lowest, highlighting the lack of renewable fluxes feeding the treatment process. However, the biodigestion operates anaerobically, and the best performance of the activated sludge system is due to the use of oxygen (a renewable resource) to the aeration of sewage (Table 3). In fact, the oxygen to aeration has only been included in recent emergy evaluations (Vassalo et al., 2009) in contrast to previous assessments shown in Fig. 5. The latest and more accurate analysis recognize that the environment contributes to each system providing an upstream investment (included only in the systems 1 and 2, Fig. 4), also called environmental services of provision (Tsonkova et al., 2015), which are natural driving energies essential to operate the system (Giannetti et al., 2011b).

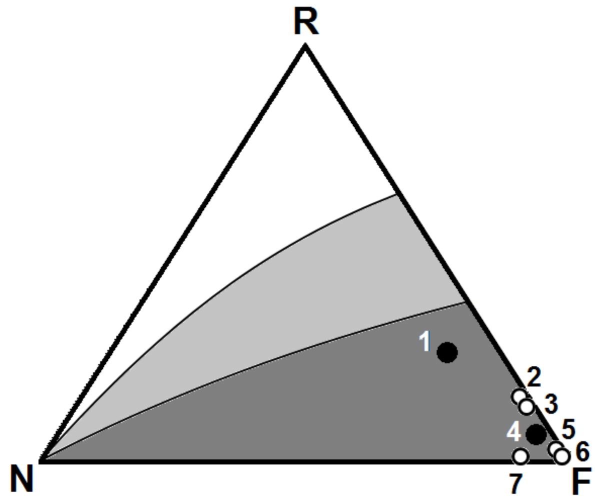

Fig. 4. Ternary diagram of the domestic wastewater treatments (black) studied compared to data found in the literature (white) without including the downstream environmental services. Where: 1 represents the activated sludge treatment system; 2 data from Vassalo et al., 2009 including oxygen for aeration; 3 data from Grönlund et al., 2004; and 4 the biodigestion system, 5 and 6 data from (Geber and Björklund, 2002), and 7 data from (Nelson et al., 2001). ESI > 5 (white) indicates systems that should be sustainable for long term; the region (1 < ESI < 5, grey) encloses medium-term sustainable systems, and the region (ESI < 1, dark grey) includes systems that are not sustainable.

It is noteworthy that the emissions from each treatment plant also require additional environmental services, required downstream, outside the plants' borders, and beyond the time scale of the plant, as these environmental services (R_2) do not treat the emissions at the same quickness of the sewage treatment plants. Figure 5 shows the ternary diagram for both systems with and without considering the downstream environmental services. The ratio EYR measures the capacity to provide clean water with a lower relative investment in purchased resources, which is accomplished by the activated sludge treatment system. The ELR values are also favorable to this system indicating a lower stress to the environment. Thus, in an upstream evaluation restricted to the combination of resources (R, N and F) used to implement and operate systems, the activated sludge treatment system may be recommended.

The dimension of each circle is proportional to the emergy of each system to treat 1 m^3 of sewage and shows that, in spite of the better imbalance among the upstream fluxes, the activated sludge system uses much more emergy to treat the same amount of water (Fig. 5). Thus, a more complete evaluation could confront the efficiency in the resource usage represented by the global productivity (Bonilla et al., 2010) of each treatment system with the use of ESI index, which assess if a system puts forward a profitable contribution to the customer (high EYR) with a low environmental demand (low ELR). The areas defined by ESI x GP of both systems are not so different (Fig. 6), but the confrontation makes clear that the activated sludge system (ESI x GP =2.47 x 10^{-13} m^3/sej) operates consuming more local and free resources in relation to those provided by the economy, but is less efficient than the biodigestion (ESI x GP =2.06 x 10^{-13} m^3/sej).

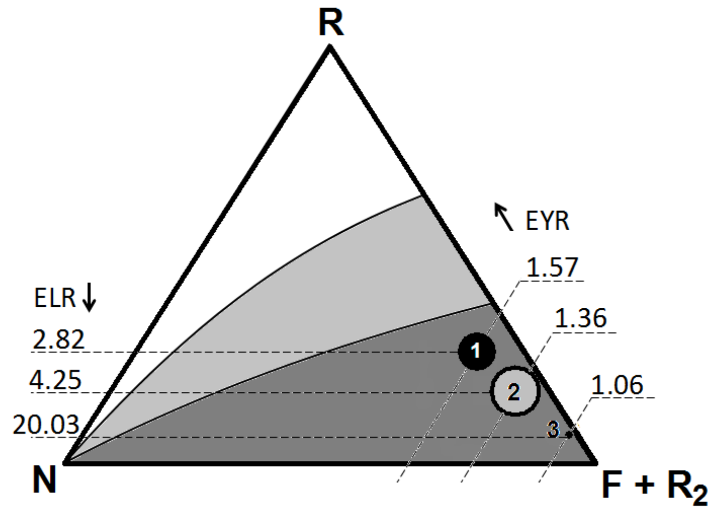

Fig. 5. Emergy indices and the ternary diagram of the domestic wastewater treatments, with and without accounting for the environmental services (ES), R_2 is the renewable emergy investment to dilute emissions to air, where: 1 represents the activated sludge treatment system without including the environmental services; 2 the activated sludge treatment system with environmental services; and 3 the biodigestion system with and without including the environmental services.The dimension of each circle is proportional to the emergy of each system to treat $1m^3$ of sewage.

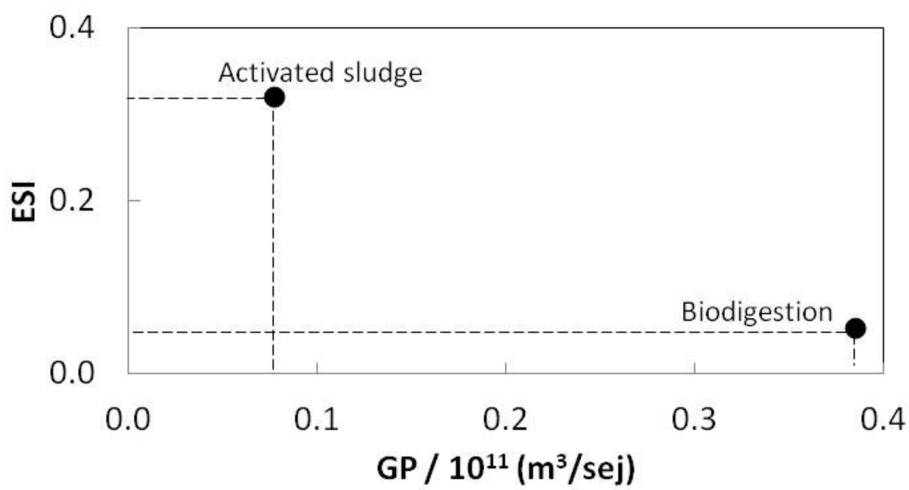

Fig. 6. ESI (Emergy Sustainability Index) versus GP (global productivity) for the treatment systems considering both the upstream and downstream requirements for environmental services, where GP is 1/UEV (unit emergy value).

3.2. Evaluating the area required to resources supply and pollutants dilution

Even fixing activities, such as domestic wastewater treatments, require resources and release pollutants, and potentially cause hazardous increases in environmental loading. The necessary carrying capacity to support these systems accounts for the free work of the nature in supplying these resources and diluting processes' emissions. Environmental services are required to dilute these emissions, and consequently, the systems occupy a larger area than the direct plant area. If a proper support area is not available, or if it overlaps the supporting areas of other processes, the fixing activity causes additional stress to the local environment and population. Thus, a wastewater treatment with the lowest support area requirements would be beneficial in areas with high activity density. Otherwise, a wastewater treatment with high support area requirements may be applicable in less populated areas. Table 5 shows the support areas calculated for both wastewater treatments.

Table 5. The requirement of carrying capacity for the domestic wastewater treatments computing the upstream and downstream environmental services. Area values are referred to 1 m^3 of treated wastewater. Detailed calculations of the re-irradiation area are available in Supplementary material, Appendix B.

	Activated Sludge (m^2/m^3)	Biodigester (m^2/m^3)
Direct Area	0.0027	0.0018
Modified Ecological Footprint (E_{FM})	1.1615	0.2778
Support Area (S_A)	11.3465	0.0002
Support Renewable Area (SA_r)	2.6360	0.6858
Re-irradiation Area (A_{RE})	90693.1	220.1

As expected, depending on the method used to calculate these areas (Table 2), different results are obtained, but clearly the carrying capacity required by the activated sludge treatment is higher than that of the biodigestion system independently the considerations made in the area calculations. As expected, the area associated with the labor of nature to re-balance the system accounting for the residence time of pollutants in the environment (A_{RE}) is much higher than those calculated considering only the environmental services for pollutant dilution. As the activated sludge system releases methane, which has a residence time of 19 times that of CO_2 in the atmosphere, the support area calculated to treat 1 m^3 of water using this system is about 400 times higher that that required the biodigestion one, which releases only CO_2. The environmental services considered necessary to cope with the biodigestion system emissions can be regarded as negligible, in contrast to those required to dilute the emissions of the activated sludge system.

4 Conclusions

Understanding the extension of the support required for each treatment may improve planning and policies and decision-making regarding the plant location. The result of the performance of the domestic wastewater treatment shows that although these systems have been designed to help the environment to deal with the waste of human activities, both still impose an additional charge of environmental stress to the environment. Thus, in the case of choosing between one treatment or another, it is worth considering the extent of the imposed extra environmental load, and if there is an environmental support area available for their downstream demands.

A qualitative summary encompassing the results obtained by calculating the emergy indices and the required carrying capacity for both systems is shown in Table 6.

The decision on adopting either the activated sludge or the biodigestion system, with information supplied by the emergy indices or the required carrying capacity evaluation, can be made with a better assessment of the actual role of direct inputs and the repeatedly neglected environmental inputs. Even if both systems have advantages and disadvantages, knowing about the emergy expenses of environmental services that are necessary to deal with the emissions may support choices. Sometimes a treatment that appears more feasible or more advantageous when emissions are not considered may show a lower large-scale performance and for that reason turn out to be less attractive when costs to deal with emissions dilution or mitigation are taken into account.

Considering space and time scales of existing environmental services may direct policies concerning the suitable balance between ecological storages and populated areas, the locating of large-scale population areas, and other regulations and planning policies.

The amount of emergy invested in fixing activities, such as wastewater treatment, may consider the environmental services, which must be quantified resulting to evaluate the kind of treatment that can be acceptable in a given area. Thereby, decisions can move away from individual scale toward a broader scale, which consider that every activity occurs in a larger area.

Table 6. Summary of the main results from the domestic wastewater treatments investigated. Where: worst evaluation (gray), and the best outcome (white). The signals + and - give an idea of the magnitude of the differences among the results.

		Activated Sludge		Biodigester
		Upstream evaluation		
EYR	++	To operate appropriates more resources of nature, and the relative contribution of resources to the economy is less	-	Operates anaerobically, and uses labor as the main input, ensuring the provision of jobs for people in the region.
ELR	+	Employs more renewable resources in the operation phase	- - - - -	Employs fewer renewable resources in the operation phase
ESI x GP	--	Operates consuming more local and free resources in relation to those provided by the economy	+	Is more efficient, operates consuming fewer resources to provide clean water
		Downstream evaluation		
A_D	+	1,340 m²	-	9,130 m²
EF_M	- - - -	Higher total nonrenewable emergy inputs (N+F)	+	Lower total nonrenewable emergy inputs (N+F)
SA_r	- -	Higher area to substitute the economic and the non-renewable flows by renewable ones	+	Lower regional area to replace the economic and the non-renewable flows by renewable ones
S_A	----	Higher area to balance the total emissions released.	+	Lower area to balance the total emissions released.
A_{RE}	**10 x (----)**	Higher area/time to balance the total emissions released.	+	Lower area/time to balance the total emissions released.

where: EYR: emergy yield ratio; ELR: environmental loading ratio; ESI: emergy sustainability index, EF_M: modified Ecological Footprint; SA_r: Support Renewable Area; S_A: Support Area; and A_{RE}: Re-irradiation area.

Decisions with reference to trade-offs between the resources and carrying capacity requirements are expedited using emergy assessments. The emergy invested in domestic wastewater treatments using both technologies (activated sludge and biodigestion) is no longer available for other processes (natural or not). Additionally, the environmental services used to dilute the emissions of both systems are no longer available to other systems, imposing a limit to the requirement of support area and environment for other systems. Requirement of carrying capacity may become a restrictive issue to human activities, and may be used to advise policies to cope with the call for environmental support to diverse activities.

The advantages of assessing the domestic wastewater treatment metabolism framework as a tool for public policies are that it: (1) clearly recognizes the system's boundaries; (2) quantifies and categorizes inputs and outputs to the systems; (3) uses a hierarchical way to handle evaluation and decision making; (4) comprises decomposable elements for regional assessment; (5) is an flexible approach to solutions and their related investments integrating biophysical science and technology; and (6) directs policies and technology results towards sustainability targets.

While there is much interest in the science of domestic wastewater treatments, hard work is still essential to get it set up in the practices of planning, design and management. Research on resource flows for regional development needs to become mainstream practice, and requires the planning of wastewater treatments not only designed to attend the community and to become much more restrained in energy and material flows, but also respecting the carrying capacity of the surrounding environment and of the region.

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Appendix A

Table A-01. Support Renewable Area (SA_r)

Activated Sludge

$(F+N+R_2) = 3.53X10^{17}$ sej/year

$$SA_r = \frac{(F+N+R_2)sej/year}{R_{Brasil}\,{}^{sej}/_{year}\,/\,A_{Brasil}m^2}$$

$$SA_r = \frac{3.53x10^{17}sej/year}{1.93x10^{24}\,{}^{sej}/_{year}\,/\,8.55x10^{12}m^2} = 1.56x10^6m^2$$

$$SA_r = \frac{1.56x10^6m^2}{50{,}4576\ m^3} = 3.09\frac{m^2}{m^3}$$

Biodigester

$(F+N+R_2) = 2.372x10^{16}$ sej/year

$$SA_r = \frac{2.372x10^{16}sej/year}{1.93x10^{24}\,{}^{sej}/_{year}\,/\,8.55x10^{12}m^2} = 1.05x10^5m^2$$

$$SA_r = \frac{1.05x10^5m^2}{30{,}275\ m^3} = 3.47\frac{m^2}{m^3}$$

Table A-02. Direct and Indirect Area

Activated Sludge

A_D = 1,344 m² = $1.34x10^3$ m²

A_D = 1,344 m² / 504.576 m^3 = 2.7 x 10^{-3} m^2 of area per m^3 of treated effluent.

A_I = ($3.04x10^{17}$sej x 1.344 m²)/$1.25x10^{17}$sej = $3.27x10^3$ m²

A_I = $3.27x10^3$ m²/504,576 m³ = $6.48x10^{-3}$ m² of area by m³ of effluent

Biodigester

A_D = 54.76 m² = 5.48x10 m²

A_D = 54.76 m² / 30.275 m^3 = 1.8 x 10^{-3} m^2 of area by m^3 of treated effluent

A_I = ($2.37x10^{16}$ sej x 54.76 m²)/($3.79x10^{14}$ sej)= $3.42x10^3$ m²

A_I = $3.42x10^3$ m²/30.275 m³ = $1.13x10^{-1}$ m² of area by m³ of effluent

Appendix B

Table B-01. Support Renewable Area (SA_r)

Activated Sludge

$(F+N+R_2) = 5.31x10^{17}$ sej/year

$$\frac{5.31x10^{17} sej/year}{1.93x10^{24} \frac{sej}{\frac{year}{8.55x10^{12} m^2}}} = 2.35x10^6 m^2$$

$$AS_r = \frac{2.35x10^6 m^2}{504{,}576\ m^3} = 4.66 \frac{m^2}{m^3}$$

Biodigester

$(F+N+R_2) = 2.372x10^{16}$ sej/year

$$AS_r = \frac{2.372x10^{16} sej/year}{1.93x10^{24} \frac{sej}{\frac{year}{8.55x10^{12} m^2}}} = 1.05x10^5 m^2$$

$$AS_r = \frac{1.05x10^5 m^2}{30{,}275\ m^3} = 3.47 \frac{m^2}{m^3}$$

Table B-02. Direct and Indirect Area

Biodigester

$A_D = 54.76\ m^2 = 5.48x10\ m^2$

$A_D = 54.76\ m^2 / 30.275\ m^3 = 1.8 \times 10^{-3}\ m^2$ of area by m^3 de treated effluent

$A_I = (2.37x10^{16}$ sej x $54.76\ m^2)/(3.79x10^{14}$ sej$) = 3.42x10^3\ m^2$

$A_I = 3.42x10^3\ m^2/30.275\ m^3 = 1.13x10^{-1}\ m^2$ of area by m^3 de effluent

Activated Sludge

$A_D = 1.344\ m^2 = 1.34x10^3\ m^2$

$A_D = 1.344\ m^2 / 504.576\ m^3 = 2.7 \times 10^{-3}\ m^2$ of area per m^3 of treated effluent

$A_I = (4.82x10^{17}$sej x $1.344\ m^2)/1.25x10^{17}$sej $= 5.18x10^3\ m^2$

$A_I = 5.18x10^3\ m^2/504.576\ m^3 = 1.03x10^{-2}\ m^2$ of area by m^3 of effluent

Table B-03. Support Area

Activated Sludge

Wind's Kinetic Energy

Pollutants Emission (CH_4) = $2.58x10^4$ kg

Natural concentration =1,745ppt ($1.75x10^{-9}$ kg/kg of air) (IPCC, p. 244)

Wind's Kinetic Energy = 1/2 x pollutant/natural concentration*(wind speed)^2

Wind's Kinetic Energy = 1/2 x $2.58x10^4/1.75x10^{-9}$ kg x $4^2\ m^2/s^2 = 1.18x10^{14}$J

Pollutants Emission (CO_2) = $1.06x10^2$ kg

Natural concentration =367 ppm ($3.67x10^{-4}$ kg/kg of air (IPCC, 1996. p. 185)

Wind's Kinetic Energy = 1/2 x pollutant/natural concentration*(wind speed)^2

Wind's Kinetic Energy = 1/2 x $1.06x10^2/3.67x10^{-4}$ kg x 4^2 m/s = $2.31x10^6$ J

$R_2 = (1.18x10^{14} + 2.31x10^6)$J x $1.50x10^3$ sej/J = $1.77x10^{17}$ sej

S_A = 1.77x10^{17}sej/1.83x10^{10}sej/m^2 = 9.67x10^{6}m²
S_A = 9.67 x 10^6 m²/504,576m³ = 19.2 m²/m³

Biodigester
Wind's Kinetic Energy
Pollutants Emission (CO_2) = 5.02x10^3 kg
Natural concentration =367 ppm (3.67x10^{-4} kg/kg of air (IPCC, 1996. p. 185)
Wind's Kinetic Energy = 1/2 x pollutant/natural concentration*(wind speed)^2
Wind's Kinetic Energy = 1/2 x 5.02x10^3/3.67x10^{-4} kg x 4² m²/s² = 1.09x10^8 J
R_2 = 1.09x10^8 J x 1.50x10^3 sej/J = 1.64x10^{11} sej
S_A = 1.64x10^{11}sej/1.83x10^{10}sej/m² = 8.96 m²
S_A = 8.96m²/30,275m³ = 2.96x10^{-4} m²/m³

Table B-04. Emergy re-irradiated Indicator
The transformities of CH_4 and CO_2 used this work was calculated by studied systems emission.

CH_4 and CO_2 Transformities.
CH_4 Transformity = (6.56x10^{17} sej)/(25,834.29 kg x 5.57 x 10^{7}J/kg) = 4.56x10^5 sej/J
Activated Sludge CO_2Transformity = (6.56x10^{16} sej)/(2.41x10^{7g} x 44mol/g x 2.53x10^{4}J/mol) = 2.45x10^{4}sej/J
(Biodigester emergy, Methane prodution and ΔG CO_2)
Biodigester CO_2Transformity = (2.41x10^{16} sej)/(5.018.750g x 44mol/g x 2.53x10^{4}J/mol) = 4.31x10^{3}sej/J
(biodigester emergy. methane production and ΔG CO_2)

$$\Delta G\ CO_2 = -nRT = \frac{8,314J}{K \square mol} x 298 K x \ln 367 x 10^6 = \frac{2,471.57J}{mol} x(1.021) = 2.53x10^4\ J/mol$$

Activated Sludge
Methane emergy = 25,834.29 kg x 5.57x10^7 J/kg x 4.56 x 10^5 sej/J= 6.56 x 10^{17} sej
Irradiated energy = 4.4 W.year.m^{-2}x10^{-15}.g^{-1} x 25,834.29 kg x 10^3 g/kg x 5.1x10^{14}m² x 3.15 x 10^7 sec/year = 1.83 10^{15} J
Irradiated emergy = 1.83 10^{15} J x 4.56 x 10^5 sej/J = 8.34 x 10^{20} sej
CO_2 Emergy = 2.41x10^{7}g x 44mol/g x 2.53x10^{4}J/mol x 2.45x10^{4}sej/J=6.56 10^{17}sej
Irradiated Energy = 0.42 W.year.m^{-2}x10^{-15}.g^{-1} x 2.41x10^{7}g x 5.1x10^{14}m² x 3.15x10^{7}sec/year = 1.63 10^{14} J
Irradiated Emergy: 1.63 10^{14} J x 2.45x10^4 sej/J = 3.98 x 10^{18} sej
Irradiated Emergy Total= 8.34 x 10^{20} sej + 3.98 x 10^{18} sej = 8.38 x 10^{20} sej
re-irradiate Emergy = system's emergy – irradiated emergy
Re-irradiated Emergy = 6.56 x 10^{17}sej – 8.38 x 10^{20} sej = -8.38 x 10^{20} sej
A_{RE} = (8.38 X10^{20} sej)/(1.83x10^{10}sej/m^2) = 4.58X10^{10} m²
A_{RE} = (4.58X10^{10} m²)/(504.576 m³) = 9.08x10^4 m²/m³

Biodgester
CO_2 Emergy: 5,018,750g x 44mol/g x 2.53x10^4 J/mol x 4.31x10^{3}sej/J = 2.41 10^{16} sej
Irradiated Energy: 0.42 W.year.m^{-2}x10^{-15}.g^{-1} x 5,018,750g x 5.1x10^{14}m² x 3.15x10^{7}sec/year = 3.39 10^{13} J
Irradiated Emergy: 3.39 10^{13} J x 4.31x10^3 sej/J = 1.46 x 10^{17} sej
Re-irradiated Emergy = 2.41 x 10^{16}sej – 1.46 x 10^{17} sej = -1.22 x 10^{17} sej
A_{RE} = (1.22x10^{17} sej)/(1.83x10^{10}sej/m^2) = 6.67X10^6 m²
A_{RE} = (6.67x10^{10} m²)/(30.275 m³) = 2.20x10^2 m²/m³

Supplementary Materials

Table 3 calculation Memorial - Emergy Evaluation of Activated Sludge Wastewater Treatment Plant.

Note **Plant construction**

1 **Concrete** (Depreciation in 25 years (life) – THOMSON, 2004)
Volume $=335.98\ m^3$
Standardized mass = $(335.98\ m^3)x(2.65x10^6 g/m^3)/(25\ years)$
$= 3.56x10^7$ g/year

2 **Engines and Pumps** (Depreciation in 10 years (life) – THOMSON, 2004)
Mass $=5.40x10^5$ g
Standardized mass = $(5.40x10^5$ g)/(10 years)
$=5.40x10^4$g/year

3 **Labor** (Depreciation in 25 years (life) – THOMSON, 2004)
Concrete Total =1,961.28 m^2
Daily requirement of human metabolism
$=3.00x10^3$ kcal/day by men
Energy Total $=\{[(1{,}961.28\ m^2)x(3.5\ h/m^2)]/(24\ h/d)\}x(3.00x10^3\ kcal/d)x(4{,}186\ J/kcal)/25$ years
$=3.59x10^9$ J/ (25years)
$=1.43x10^8$ J/year

4a **Steel** (Depreciation in 10 years (life) – THOMSON, 2004)
Mass $=3.18x10^7$g
Standardized mass $=(3.18x10^7$g)/(10 years)
$=3.18x10^6$ g/year

4b **S10 mass (Steel)** (Depreciation in 5 years (life) – THOMSON, 2004)
Mass $=1.61x10^6$g
Standardized mass $=(1.61x10^6$g)/(5 years)
$=3.21x10^5$ g/year
Total steel mass $=3.18x10^6$ g/year + $3.21x10^5$ g/year = $3.50x10^6$ g/year

5 **Cooper** (Depreciation in 10 years (life) – THOMSON, 2004)
Mass $=2.77x10^4$ g
Standardized mass $=(2.77x10^4$ g)/(10 years)
$=2.77x10^3$ g/year

6 **Soil use** (eucalyptus values per hectare, kcal/g of eucalyptus and the area in hectare, was taken from Romitelli, 2000)
Area Total =1,344 m^2 or $1.34x10^{-1}$ ha
Conversion kg of
Eucaliptus p/ hectare $=(5.40x10^6$ kg/year)/135 ha = $4.00x10^4$ kg/ha x year
Total Energy =(area ha)x(kg of eucaliptus p/ ha)x(g/kg)x(kcal/g)x(J/kcal)
Total Energy $=(0.134ha)x(4.00x10^4kg/ha\ x\ year)x(1.00x10^3g/kg)x(4.68kcal/g)x\ (4{,}186J/kcal)$
$=1.05x10^{11}$ J/year
*Considering that the soil no longer produces eucalyptus biomass in the period.

Plant operating phase

7 **Diesel for sludge transport**
Freight's Total = (sludge mass)/(S10 capacity)

Freight's Diesel = freight x 8 liters (trip of 80 km round trip, acoording SAEEG, and consume of 1 liter per 10 km)
Freight's Total =(1,226,842 kg/year)/(1.065 kg/trip) = 1,152 trips/year
Freight's Diesel = 1,152 trips/year x 8 liters = 9,216 liters/year
Total Energy = 9,216 L/year x 0.85 kg/L x 10,667 kcal/kg x 4,186 J/kcal (diesel density, according MMA, 2005. PCI according NATURA, 2005)
Total Energy = 3.50×10^{11} J/year

8 **Electricity** (according SAAEG)
Total use =614.5 kWh/day in 365 days/year
Total Energy =(614.5 kWh/day)x(365 day/year)x(3.6×10^{6} J/kWh)
=8.07×10^{11} J/year

9 **Labor**
Total =5 men, monday through friday. 02 men saturday and sunday
Daily requirement of human metabolism =3.00×10^{3} kcal/day per man
Total Energy =[(265 days/year)x(3.00×10^{3} kcal/day)x(4186 J/kcal)x(5men)]+[(100 day) x (3.00×10^{3} kcal/day)x(4,186 J/kcal)x(2men)]
=1.92×10^{10} J/year

10 **Landfill for sludge**
Sludge mass =2.4% effluent + (precipitation – evaporation) thickener
Standardized mass = 1.23×10^{9} g/year

11 **Sun** (CRESESB. 2005)
Field of the tanks =418 m²
Average insolation =4.67 kWh/m².year
Energy =(418 m²)x(4.67 kWh/m².year)x(3.6×10^{6} J/kWh)
=7.03×10^{9} J/year

12 **Evaporation** (APASC, 2005)
Field of the tanks =418 m²
Average Evaporation=485mm/year
Total Mass =(418 m²)x(485mm/year)x(1.00×10^{-3}m/mm)x(1.00×10^{6}g/m³)
=2.02×10^{8} g/year

13 **Precipitation** (CPTEC. 2005)
Field of the tanks =418 m²
Average Precipitation=1476mm/year
Total Mass =(418 m²)x(1.476mm/year)x(1.00×10^{-3}m/mm)x(1.00×10^{6}g/m³)
=6.18×10^{8} g/year

14 **O2 for combustuion processes**
O2 mass = mol quantity x Molar Mass
O2 mass = 850,618.18 mol x 32 g/mol
O2 mass = 2.72×10^{7} g/year

15 **O2 for aeration processes**
DBO reduction = 251.7 mg/litro x 504,576,000 liters/year
Ar Volume =7 liters/mg each 100 mg/liter of DBO

Total Mass =[(251.7 mg/L)x(504,576,000 liters/year)x(7/100 L/mg)]x(0.21/22.4 liters) x (28.84g/mol)

=2.40×10^9 g/year

16 Wind's kinetic energy for CO_2 dilution

Emission Pollutants (CO_2)= 2.61×10^7 kg

Natural Concentration =367 ppm (3.67×10^{-4} kg/kg of air (IPCC, 1996. p. 185)

Kinetic energy of wind = 1/2x pollutant/natural concentration x (Wind speed)^2

Kinetic energy of wind = 1/2 x 2.61×10^7(kg/year)/3.67×10^{-4} kg/kg x (4 m/s)^2 = 5.69×10^{11} J/year

17 **Wind's kinetic energy for CH_4 dilution**

Emission Pollutants (CH_4)= 2.58×10^4 kg/year

Natural Concentration =1745ppt (1.75×10^{-9} kg/kg of air) (IPCC, 1996. p. 244)

Kinetic energy of wind = 1/2 x pollutant/natural concentration x (Wind speed)^2

Kinetic energy of wind = 1/2 x 2.58×10^4(kg/year)/1.75×10^{-9} kg/kg x (4 m/s)^2

= 1.18×10^{14} (kg.m^2/s^2.year) = 1.18×10^{14} J/year

Table 4 calculation Memorial. Emergy Evaluation of the Biodigestion Treatment with and without accounting for the environmental services (ES).

Note **Plant construction**

1 **Concrete** (Depreciation in 25 years (life) – THOMSON, 2004)

Standardized mass =[(mass of cement)+(gravel 1 mass)+(gravel 2 mass)+(sand mass)+(iron 0.20 mass)+(iron 0.25 mass ferro)+(wire mass)+(water mass)]/(25 years)

Standardized mass =(3,985,500+25,380,000+10,848,000+12,105,000+96,100+64,384+3,900+154,529)g/25years

=52.527.034g/25years

=2.10×10^6 g/year

2 **Brick** (Depreciation in 25 years (life) – THOMSON, 2004)

Mass =[(quant. Of bricks)x(unity mass)]/years

Standardized mass =[4,308x1,100g]/25years

=1.90×10^5 g/year

3 **Mão de Obra** (Deprecation in 25 years (life) – THOMSON, 2004)

Total of days =18.49 dias x 4 men (according ONG OIA)

Daily requirement of human metabolism =3.00×10^3 kcal/day per man

Energy Total =(18.49 days)x(4 men)x(3.00×10^3 kcal/d)x(4186 J/kcal) = 9.29×10^8 J/ (25years)

=3.72×10^7 J/year

4 **Plastic** (Depreciation in 25 years (life) – THOMSON, 2004)

Mass =[(mts Tubes x mass)+(quant.pieces 90 x mass)+(quant.pieces 45xmass)]/years

Standardized mass =[(7m x 600g)/m+(4pc x 350g)/pç+(2pc x 300g)/pc]/(25 years)

=2.48×10^2 g/year

5 **Soil Use (**eucalyptus values per hectare, kcal/g of eucalyptus and the area in hectare, was taken from Romitelli, 2000)

Total Area =54.76 m² or 0.005476 ha

Conversion kg of

Eucaliptus p/ hectare=(5.40×10^6 kg/year)/135 ha = 4.00×10^4 kg/ha x year

Total Energy =(area ha)x(kg of eucaliptus p/ ha)x(g/kg)x(kcal/g)x(J/kcal)

Total Energy =(0.005476 ha)x(4.00×10^4 kg/ha x year)x(1.00×10^3 g/kg)x(4.68 kcal/g) x (4186J/kcal)

=4.29×10^9 J/year

6 **Steel** (Depreciation in 10 years (life) – THOMSON, 2004)

Mass =3.8×10^5g

Total Mass =(3.8×10^5g)/(10 years)

=3.8×10^4 g/year

Plant operating phase

7 **Labor**

Total =1 man Monday through Friday, 01 man Saturday and Sunday

Daily requirement of human metabolism =3.00×10^3 kcal/day per man

Energy Total =[(265 days/year)x(3.00×10^3 kcal/day)x(4186 J/kcal)x(1man)] +[(100 days) x (3.00×10^3 kcal/day)x(4186 J/kcal)x(1man)]

=4.58×10^9 J/year

8 **Sun**

Area =54.76 m²
Average Insolation =4.41 kWh/m².year (CRESESB, 2005)
Energy =(54.76 m²)x(4.41 kWh/m².year)x($3.6x10^6$ J/kWh)
=$8.69x10^8$ J/year

9 **Geothermal Heat**
Area =bottom area (12.56m²) + side area (37.68m²)
Geothermal flux =68 mJ/s.m².year (GOMES and HAMZA, 2003)
Energy =(50.24 m²)x(68 mJ/s.m².year)x($1.00x10^{-3}$J/mJ)x($3.6x10^3$ s/h)x (24h/day)x(365 day/year)
= $1.08x10^8$ J/year

10 **Oxygen for combustion processes**
O_2 for burn 2,555 m³ of CH4= 5,110 m³ per year
Annual Mass = (5,110 m³/year)x(1/22.4 mol/L)x(32g/mol)x(1,000 L/m³)
=$7.30x10^6$ g/year

11 **Wind's kinetic energy**
Pollutants Emission (CO_2)= $5.02x10^3$ kg/year
Natural Concentration=367 ppm ($3.67x10^{-4}$ kg/kg of air (IPCC, 1996. p. 185)
Wind's kinetic energy = 1/2 x pollutants/natural concentration x (Wind speed)²
Wind's kinetic energy = 1/2 x $5.02x10^3$(kg/year)/$3.67x10^{-4}$ kg x $(4m/s)^2$
= $1.09x10^8$ (kg.m²/s².year) = $1.09x10^8$J/year