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An evaluation of a MSW-to-energy system using Emergy synthesis

Cecilia M.V.B. Almeida*

Graduate Program in Production Engineering,
Paulista University, R. Dr. Bacelar,
1212 CEP 04026 001,
São Paulo, Brazil
E-mail: cmvbag@unip.br
*Corresponding author

Gislaine S. Frimaio

Federal Institute of Education, Science and Technology,
Praça Tiradentes, 416 CEP 37.576-000,
Inconfidentes, Minas Gerais, Brazil
E-mail: gfrimaio@gmail.com

Silvia H. Bonilla

Graduate Program in Production Engineering,
Paulista University, R. Dr. Bacelar,
1212 CEP 04026 001,
São Paulo, Brazil
E-mail: bonilla@unip.br

Carlos C. da Silva

Federal Institute of Education, Science and Technology,
Praça Tiradentes, 416 CEP 37.576-000,
Inconfidentes, Minas Gerais, Brazil
E-mail: cezaradts@gmail.com

Biagio F. Giannetti

Graduate Program in Production Engineering,
Paulista University, R. Dr. Bacelar,
1212 CEP 04026 001, São Paulo, Brazil
E-mail: bonilla@unip.br

Abstract: This paper presents a biophysical understanding of the MSW-to-energy facility located at the São João landfill in São Paulo using Emergy synthesis. Accounting for the material inputs and the biogas accumulation Emergy-based indices are calculated to evaluate the environmental load and sustainability level of the concerned biogas project.

The study was conducted by combining the analysis of transformities, Emergy indicators and the net Emergy yield ratio to establish long-term sustainability and measure global environmental stress. The implementation of a project for environmental compensation in fulfilment of state's requirements was also assessed. The findings reveal that the Emergy investment to the use of biogas is quite low and, therefore, advantageous. Transformities show that the global productivity of the MSW-to-energy plants can compete with traditional plants. The conclusions justify the effort invested in developing MSW-to-energy plants and are relevant for policy makers in a highly sensitive sector to accomplish sustainability goals.

Keywords: Emergy; municipal solid waste; MSW; energy; electricity.

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Biographical notes: Cecilia M.V.B. Almeida is a Researcher of the LaPROMA (Laboratório de Produção e Meio Ambiente) at the Paulista University, in São Paulo, Brazil. She specialises on environmental accounting and on questions related to cleaner production and sustainability indices.

Gislaine S. Frimaio received his MSc at the Laboratório de Produção e Meio Ambiente (LaPROMA) at the Paulista University, in São Paulo, Brazil.

Silvia H. Bonilla is a Researcher of the Laboratório de Produção e Meio Ambiente (LaPROMA) at the Paulista University, in São Paulo, Brazil. She specialises on environmental accounting and on questions related to cleaner production and sustainability indices.

Carlos C. da Silva heads the Federal Institute of Education in Inconfidentes, Minas Gerais, Brazil. He specialises on environmental accounting and on questions related to cleaner energy production.

Biagio F. Giannetti heads the Laboratório de Produção e Meio Ambiente (LaPROMA) at the Paulista University, in São Paulo, Brazil. He specialises on environmental accounting and on questions related to cleaner production and sustainability indices.

1 Introduction

Sao Paulo is a mega-city with more than 10.5 million people using natural resources and emitting greenhouse gases through a variety of activities. The city has the tenth largest gross domestic product (GDP) in the world representing, alone, 12.26% of the total Brazilian GDP (IBGE, 2011), hence, is also a source of greenhouse gases emissions (GHGs) mainly associated with energy use and final disposal of solid waste (landfill emissions). On June 5, 2009, the city enacted an ordinance on Climate Change (City Council Policy on Climate Change, Law No. 14,933), which set a target of 30% reduction in GHGs for Sao Paulo. However, with the implementation of two Biogas plants in São João and Bandeirantes landfills, the city has already managed to reduce about 20% of its emissions (SVMA, 2010). Each of the two thermoelectric plants have a nominal capacity of 20 MW, allowing an annual electricity generation of 340,000 MWh, enough to meet needs of about 800,000 inhabitants (SVMA, 2010). In 2009, 53,884 tons of methane were destroyed by this two municipal landfills, equivalent to 1,131,564 tons of carbon dioxide (SVMA, 2010).

Landfilling is a well known method for disposal of municipal and household solid wastes. Landfill gas is generated by the natural degradation of municipal solid waste (MSW) by anaerobic micro-organisms, and once the gas is produced, large landfills are required to install collection systems at their sites to minimise the release of methane, a major contributor to global climate change. Even supposing that wastes are maintained in an oxygen-free environment and relatively dry conditions, landfill generates significant amounts of landfill gases, typically comprised of roughly 60% v/v methane and 40%v/v carbon dioxide. The presence of methane compels the control of landfill emissions, as it can cause fire and explosions. Also, under the authority of São Paulo's Law No. 14,933, air pollution emissions are regulated in both new and existing MSW landfills, which effectively require the collection and combustion of landfill gases. Though not a renewable resource, landfill gas is in great supply in solid waste management systems and can be used to supply part of a city energy demand. Since landfill gas recovery facilities are located at existing landfills, there are generally fewer obstacles associated with them compared to other wastes-to-energy facilities. In this context, a very popular solution to the landfill gas problem is to collect and use it to produce electricity.

Emergy synthesis, by means of a thermodynamics-based measure, gives an appraisal of the actual environmental cost of any class of resource which is not solely limited to its economic price or energetic content (Pulselli et al., 2008). It assesses all the inputs that supply a system, especially those that are usually neglected by classic economic accounting methods (Odum, 1996). This paper presents a biophysical understanding of the MSW-to-energy facility located at the São João landfill in São Paulo using Emergy synthesis. Accounting for the material inputs and the biogas accumulation Emergy-based indices are calculated to evaluate the environmental load and sustainability level of the concerned biogas project.

1.1 Literature background

Several studies were conducted in order to provide data and understanding on existing solid waste management systems, and to assess the practices and state of these systems (Ogbonna et al., 2007; Khalil and Khan, 2009; Saxena et al., 2010, Weng and Fujiwara, 2011). The environmental performance of existing plants, based on field measured data, were made available by Blengini (2008), who integrated the findings of different investigations from the literature with field measured data in order to obtain a more comprehensive framework representative of several solid waste management systems. Exergy analysis was also practiced for systemically assessing MSW management system in south Beijing (Zhou et al., 2011a). The authors concluded that integration of different technologies (separation, recycle, compost, incineration and landfill) could increase the systematic exergetic efficiency.

Life cycle assessment was widely used to evaluate the environmental performance of solid waste management systems with and without electricity production (Feo and Malvano, 2009; Chaya and Gheewala, 2007; Buttol et al., 2007, Beccali et al., 2001). Liamsanguan and Gheewala (2008) compared landfilling (without energy recovery) and incineration (with energy recovery). Incineration was found to be superior to landfilling, but when methane recovery and electricity production were introduced landfilling reversed to be superior to incineration. Cherubini et al. (2008) applied LCA to the case of MSW management in Rome, with focus on energy and material balance. Indices and indicators of efficiency, effectiveness and environmental impacts, point out important benefits of greenhouse gas emission reduction by waste treatments with energy and material recovery. According to these authors, waste treatments leading to energy recovery provide an energy output that may supply 15% of the Rome electricity consumption (Cherubini et al., 2008). The use of biomass resource for energy in China was investigated by Zhou et al. (2011b). The potential electricity supply of MSW was estimated for the base years 2008, and 2007 as 18,862.6 GWh corresponding to 0.2% of the electricity consumption in 2008.

Emergy analysis was used in researching the recycling processes of MSW (Bastianoni et al., 1999; Marchettini et al., 2007) and demolition waste (Brown and Buranakarn, 2003). Several authors have adopted this environmental accounting methodology to evaluate waste management alternatives (Bjorklund et al., 2001; Niccolucci et al., 2002; Marchettini et al., 2002; Bastianoni et al., 2002). Energies, materials, labours and investments are unified into solar Emergy joules (seJ) to assess systemic efficiency (Marchettini et al., 2007; Lei and Wang, 2008); and to evaluate different systems of biogas and electricity production (Zhou et al., 2010; Ciotola et al., 2011; Jiang et al., 2010). Looking for a correct waste management policy based on the principles of sustainable development, Marchettini et al. (2007) applied Emergy synthesis to evaluate three different waste treatments and conceived an approach capable of assessing strategy of waste management. The evaluation included how much investment is needed for each type of waste management and how much ‘utility’ is extracted from wastes. The system of electricity generation from waste landfill gas was studied by Zhang and Long (2010). These authors divided the system into three different phases: collection, land filling, and disposal of solid and liquid residues. The analysis of the managed landfill showed that the land filling stage requires the greatest Emergy investment while disposal is almost negligible and collection represents about 3% of the total Emergy cost. These results are in agreement with those reported by Lou (2004), who also performed an Emergy analysis of an electric power generation with waste landfill gas in China.

2 Methods

2.1 System description

The São João landfill began its operations in 1992, occupying an area of 80 hectares, of which 50 hectares have been assigned for the disposal of MSW. In the remaining area units were deployed the infrastructure (leachate ponds, biogas burning plant), and the operational support units, such as construction site and administrative buildings (Ecourbis Environmental S.A., 2010).

The landfill site operated 24 hours a day, 365 days a year, and had 120 employees. It ceased its operations in October 2009 with about 29 million tons of MSWs characterised as household waste, non-residential household waste, inert waste, waste of health services (previously treated), remains of furniture, wastes from markets and fairs, and treated sewage sludge (Ecourbis Environmental S.A., 2010).

The São João landfill consists of impermeable liners and caps, and leachate and gas collection systems (IBAM, 2001). In this facility, all waste was first deposited into a discharge area, where it is then compacted and finally covered with a layer of clay and inert materials. This operation allows for the biodegradation of wastes and the formation of a large deposit of biogas. Biogas is collected by a collection system, which consists of a series of wells drilled into the landfill and connected by a piping system. The typical dry composition of the gas is 57% methane, 42% carbon dioxide, 0.5% nitrogen, 0.2% hydrogen, and 0.2% oxygen. A significant number of other compounds are found in trace quantities, including alkanes, aromatics, chlorocarbons, oxygenated compounds, other hydrocarbons and sulphur dioxide. The gas is then burnt to generate electricity. The system is operated by 35 employees and 16 groups of generators totalling 24.64 MW of generating capacity. Part of the energy produced supplies the power generation plant.

In April 2009, the landfill has implemented a project for environmental compensation in fulfilment of requirements made by the State Council on the Environment, as for its installation was necessary to remove native vegetation (Atlantic Forest biome), changing the local landscape (Cruz, 2009). The project, called EcoÍris, occupies an area of 800 m^2 adjacent to the landfill, and produces annually 50,000–80,000 seedlings of native species of São Paulo Plateau's Atlantic forest and vegetables that are distributed to the local community. It consists of a composting system and humus production, which are powered by wastes from street fairs (Ecouribis Environmental S/A, 2010).

2.2 *Emergy synthesis procedure*

The Emergy synthesis was developed by H.T. Odum in the early 1980s. Emergy is defined as the equivalent solar energy directly or indirectly required to generate a product or service. It is denoted by the unit solar Emergy joules (seJ). The transformity (seJ/J), defined as the Emergy per energy unit flow or unit product is used to convert all of the flows involved in the process into this common basis. Each input is not only examined on the basis of its energy content, but is also weighed by its transformity. If an input has a high Emergy content, or high transformity, it means that it requires great work to be produced, and may turn into a limiting factor for the process. The method is used to establish long-term sustainability and measure global environmental stress. After 17 years of operation, the landfill received about 29 million tons of MSW, and was totally filled. This first stage was used to calculate the transformity of the biogas used to produce electricity. As energy recovery occurs over an extended period (about 30 years), due to the kinetics of biogas production, a plant life of 30 years was since this is the estimated time that is required to recover close to 100% of the total biogas production.

The Emergy synthesis procedure (Odum, 1996) consists of four steps:

1 constructing the system diagram

2 building the Emergy analysis table

3 calculating the Emergy indices

4 interpreting results with the use of ternary Emergy diagrams.

Two energy system diagrams were used for the evaluation of the São João landfill. The first diagram was constructed to evaluate the biogas production, and includes the landfill and the EcoÍris project. The second one was used to assess the electricity production plant (Figures 1 and 2).

Figure 1 Energy system diagram of the São João landfill and the EcoÍris project

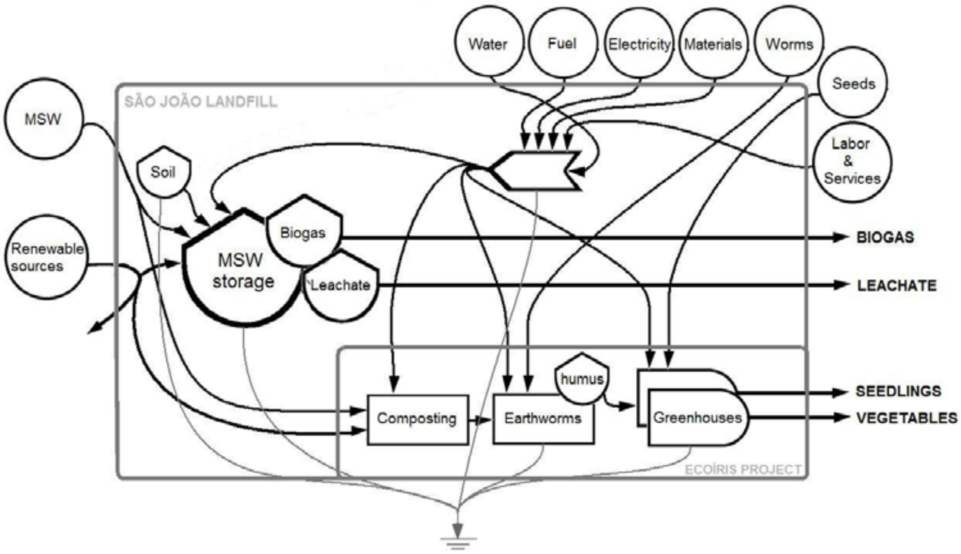
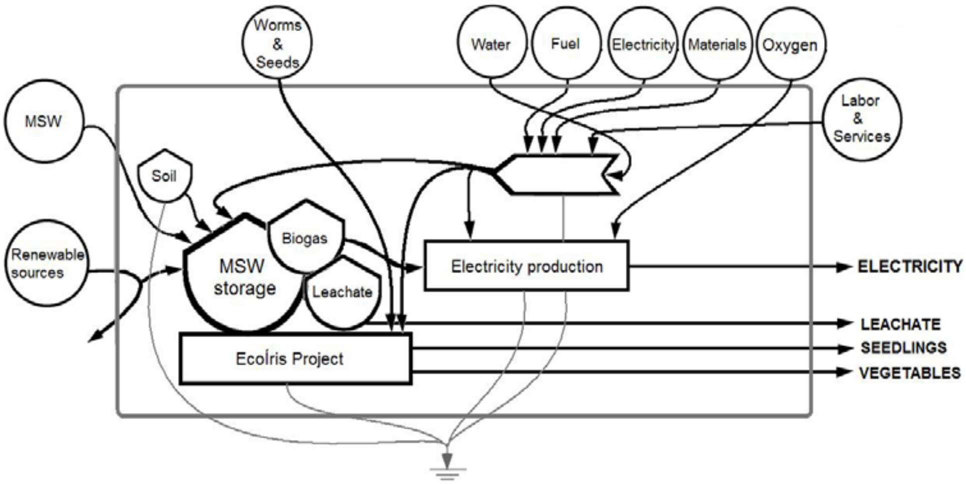


Figure 2 Energy system diagram of the São João landfill and the EcoÍris project including the electricity production plant



Two Emergy synthesis tables were created for this evaluation:

1 biogas production

2 electricity generation powered by waste biogas.

The line items in the Emergy tables include both the implementation phase as well as the inputs required to operate and maintain the systems. In order to convert infrastructure inputs to an annual rate, initial inputs were divided by the lifespan of each input.

Emergy synthesis separates renewable (R) from non-renewable (N) inputs and local (R + N) from external (F) inputs. These distinctions make it possible to define several Emergy-based indicators that can provide decisional support tools, especially to measure global environmental stress (Ulgiati et al., 1994; Brown and McClanahan, 1996; Odum, 1996).

In this paper, three indices (EYR, ELR and ESI), are chosen to evaluate the solid MSW-to energy facility. In particular, EYR is "a measure of the system's net contribution to the economy beyond its own operation" (Odum, 1996). EYR is the ratio between output Emergy and the purchased Emergy (EYR = (N + R + F) / F). The higher the ratio, the higher the relative contribution of the local (renewable and non-renewable) sources of Emergy to the system. This index shows how efficiently the system uses the available local resources. The environmental loading ratio (ELR = (N + F) / R) provides additional information to EYR, expressing the use of renewable resources by the system. The Emergy sustainability index (ESI = EYR / ELR) is measure of the overall sustainability of a production process (Ulgiati and Brown, 1998). Finally, the net Emergy yield ratio was used to match the Emergy of the purchased inputs with the Emergy of the system's products (net Emergy yield ratio = Emergy of the product / F). This ratio allows the comparison the potential benefit of a product made by different production processes.

3 Results and discussion

3.1 The system under study

The energy diagram of the biogas production system is shown in Figure 1. In the diagram, can be observed energy flows that enter the system, and the interactions that occur between system components, and system with the environment. The diagram shown in Figure 2 includes the electricity generation plant.

The Emergy flows of each input and the total Emergy of the São João landfill and the EcoÍris project are shown in Table 1. Emergy values were calculated without services in order to assess only the physical and technological characteristics of the system under investigation. Components that depend on indirect labour and services will vary according to the economic level of the country in which the system operates (Brown and Ulgiati, 2002).

The analysis of the managed landfill (Table 1) shows that among the most significant resources from the economy (F) to the landfill, the waterproofing membrane corresponds to c.a. 27% of the resources used while gravel to c.a. 18% of the total Emergy. This gravel is used to build the percolated liquids drainage system and for the daily covering of the solid waste received. The direct labour has a contribution of about 11% and the Emergy cost of MSW collection contributes with 42% of the landfill total Emergy. This results show that collection should be improved, for example by purchasing new trucks with lower consumption, or optimising the collection frequency.

Table 1 Emergy table of São João landfill site with the environmental compensation project for 2010

Item	*Description*	*Unit*	*Quant. (unit/year)*	*Emergy per unit **(seJ/un.)*	*Emergy (seJ/year)*	*% (seJ/seJ)*
			Implantation phase			
Non-renewable resources						
1	Soil	J	3.62×10^8	2.08×10^5	7.53×10^{13}	<1
Purchased resources						
2	Aluminium	g	2.80×10^4	1.27×10^{10}	3.56×10^{14}	<1
3	Fuel	J	4.26×10^9	1.11×10^5	4.73×10^{14}	<1
4	Earthworms	g	2.71×10^9	2.08×10^5	5.64×10^{14}	<1
5	Wood	g	6.81×10^5	1.48×10^9	1.01×10^{15}	<1
6	Plastic	g	2.28×10^5	9.66×10^9	2.20×10^{15}	<1
7	Steel	g	1.11×10^6	2.77×10^9	3.07×10^{15}	<1
8	Labour	J	7.53×10^8	4.30×10^6	3.24×10^{15}	<1
9	Tiles	g	6.14×10^6	1.20×10^9	7.37×10^{15}	<1
10	Cement	g	3.25×10^6	3.31×10^9	1.08×10^{16}	<1
11	Machinery	g	3.27×10^7	3.00×10^9	9.81×10^{16}	<1
12	Concrete	g	1.58×10^8	2.27×10^9	3.59×10^{17}	1.8
13	Crushed stone	g	2.12×10^9	1.68×10^9	3.56×10^{18}	17.6
14	Waterproofing membrane	g	5.60×10^8	9.66×10^9	5.41×10^{18}	26.8
			Operation phase			
Renewable resources						
15	Sun*	J	6.68×10^{12}	1	6.68×10^{12}	-
16	Evapotranspiration*	J	6.25×10^6	2.59×10^4	1.62×10^{11}	-
17	Rain (chemical)	J	1.12×10^{11}	2.95×10^4	3.31×10^{15}	<1
18	Geothermic energy	J	7.95×10^{11}	1.49×10^4	1.18×10^{16}	<1
Purchased resources						
20	Electricity	J	7.74×10^9	4.52×10^5	3.50×10^{15}	<1
21	Grass	g	9.42×10^6	9.00×10^8	8.48×10^{15}	<1
22	Plastic bags	g	1.11×10^6	9.66×10^9	1.07×10^{16}	<1
23	Seeds	US$	1.59×10^3	1.20×10^{13}	1.91×10^{16}	<1
24	Fuel	J	3.81×10^{12}	1.11×10^5	4.23×10^{17}	<1
25	Labour	J	5.10×10^{11}	4.30×10^6	2.19×10^{18}	10.8
26	MSW (collection)	g	6.35×10^{11}	1.33×10^7	8.45×10^{18}	41.8

Notes: *Not accounted to avoid double-counting; **the values of Emergy per unit used in this table are based on the approximate planetary baseline of 15.83×10^{24} seJ/year.

Source: Odum et al. (2000)

Table 1 Emergy table of São João landfill site with the environmental compensation project for 2010 (continued)

Item	*Description*	*Unit*	*Quant. (unit/year)*	*Emergy per unit **(seJ/un.)*	*Emergy (seJ/year)*	*% (seJ/seJ)*
Total Emergy					2.02×10^{19}	100
	Biogas	J	1.18×10^{15}	1.72×10^{4}		
	Seedlings	unit	7.00×10^{4}	2.89×10^{14}		
			5.60×10^{10}	3.61×10^{8}		
	Vegetables	J	4.12×10^{11}	4.91×10^{7}		

Notes: *Not accounted to avoid double-counting; **the values of Emergy per unit used in this table are based on the approximate planetary baseline of 15.83×10^{24} seJ/year.

Source: Odum et al. (2000)

Table 2 Emergy table of electricity production from waste biogas for 2010

Item	*Description*	*Unit*	*Quant. (un./year)*	*Emergy per unit *(seJ/un.)*	*Emergy (seJ/year)*	*% (seJ/seJ)*
			Implantation phase			
Purchased resources						
1	Galvanised steel	g	8.91×10^{6}	1.81×10^{9}	1.61×10^{16}	<1
2	Machinery	g	1.09×10^{8}	3.00×10^{9}	3.26×10^{17}	<1
3	Ceramic	g	4.20×10^{7}	8.64×10^{9}	3.63×10^{17}	<1
4	Steel	g	2.38×10^{8}	2.77×10^{9}	6.60×10^{17}	<1
5	Labour	J	1.11×10^{12}	4.30×10^{6}	4.77×10^{18}	3
6	Concrete	g	2.25×10^{9}	2.27×10^{9}	5.10×10^{18}	3
			Operation phase			
Renewable resources						
7	O_2 for combustion	g	2.27×10^{12}	5.16×10^{7}	1.17×10^{20}	73
Non-renewable resources						
8	Biogás (CH_4)	J	1.18×10^{15}	1.72×10^{4}	2.02×10^{19}	13
Purchased resources						
9	Electricity	J	3.76×10^{9}	4.52×10^{5}	1.70×10^{15}	<1
10	Water	m^3	3.29×10^{4}	7.75×10^{11}	2.55×10^{16}	<1
11	Fuel	J	2.50×10^{11}	1.11×10^{5}	2.78×10^{16}	<1
12	Labour	J	1.14×10^{10}	4.30×10^{6}	4.88×10^{16}	<1
Total Emergy					1.60×10^{20}	100
	Electricity	kWh	3.40×10^{8}	4.70×10^{11}		
		J	1.22×10^{15}	1.31×10^{5}		
	Seedlings	unit	7.00×10^{4}	2.28×10^{15}		
		J	5.60×10^{10}	2.86×10^{9}		
	Vegetables	J	4.12×10^{11}	3.88×10^{8}		

Note: *The values of Emergy per unit used in this table are based on the approximate planetary baseline of 15.83×10^{24} seJ/year

Source: Odum et al. (2000)

Table 2 shows the Emergy flows of each input and the total Emergy of the electricity production using the biogas (methane) produced in São João landfill. The implantation of the electricity production systems is associated to less than 10% seJ/seJ of the total Emergy, which suggests that the Emergy investment to the use of biogas is quite low and, therefore, worthwhile. The recovered methane and the free oxygen used correspond to 90% of the total Emergy needed for the system operation.

3.2 Exploring the Emergy indicators for the case of electricity production

Emergy indicators are used to evaluate technological processes and their interactions with the environment, and for a given system, are functions of renewable (R), non-renewable and purchased Emergy inflows. The Emergy tables show renewable, non-renewable, and purchased goods from the economy. Indicators in Table 3 are given to evaluate the global performance of both systems.

Table 3 Emergy indicators for the São João landfill with and without electricity production

	Emergy indicators		
	EYR	*ELR*	*ESI*
São João landfill	1.0	367,7	0.0
São João landfill with electricity production	12.9	0.3	50.8

The EYR of landfilling is low and shows that this system has a highest cost and a low benefit. This indicator shows that the cost of electricity production is lower than its benefit, and the biogas recovery is advantageous in Emergy terms. The electricity production system has a lower environmental loading, less than 1.0. As the loading ratio is a measure of matching between the (N + F) fractions and the renewable one, a higher R (oxygen consumption) makes the loading ratio decrease, signalling that the system presents a new balance for the use of the non-renewable fractions and the locally renewable Emergy input. Values of the ESI are given in the last column of Table 3. The ESI is a ratio of the Emergy yield per unit environmental load (EYR/ELR). The electricity production system has a high yield and low environmental load and thus the higher aggregated (economic and ecological) sustainability (Brown and Ulgiati, 2002).

The assessment with the use of Emergy indicators makes clear that the collection and use of biogas for electricity production is advantageous in terms of resource use. It is worthy to attention that the benefits associated to the resource recovery might be added to those associated to the reduction in GHGs, which are not accounted in this study.

The solar transformity of the electricity is calculated as the ratio of the total Emergy inputs to the energy of the electricity output. The work required to produce a good or service can help to understand and to compare the global efficiency of the production process with similar processes (Table 4). The transformity calculated for the São João landfill Site indicates that less Emergy is needed to produce 1 J of electricity than that required by the Chinese one. However, despite of the differences, all results shown in Table 4 are in the same order of magnitude, as expected. Emergy is not a state function and depends on the particular features of each process. Nevertheless, it can be assumed that products that are produced in similar ways will have therefore very similar transformities, as confirmed in Table 4.

Table 4 Transformity of the electricity production at São João landfill compared with values of literature

	Transformity/(seJ/J)	
	São João landfill	*Zhang e Long, 2010*
Electricity	1.31×10^5	2.67×10^5

Note: * The values of Emergy per unit used in this table are based on the approximate planetary baseline of 15.83×10^{24} seJ/year

Source: Odum et al. (2000)

Values of transformities for electricity production using traditional production cycles (hydroelectricity, methane, oil and coal), together with electricity from wind and geothermic heat are compared to the transformity obtained for São João landfill (Table 5). Transformities for hydroelectric and wind were lower, and according to Brown and Ulgiati, (2002), are probably close to the thermodynamic minimum transformity for electricity production cycles. The transformity for electricity generated in the geothermal cycle (2.39×10^5 seJ/J) as well as the transformity of fossil fuel plants (2.62 to 3.14×10^5 seJ/J) are over twice the transformity of the electricity generated in the wind and hydro plants, but all values are of the same order of magnitude of MSW-to-energy plant (Table 4).

Table 5 Transformity of the electricity production at São João landfill compared with values of literature for other electricity production cycles

	Transformity/(seJ/J)*						
	São João landfill	*Wind*	*Geothermal*	*Hydro*	*Methane***	*Oil*	*Coal*
Electricity	*1.31×10^5*	9.90×10^4	2.39×10^5	9.86×10^4	2.69×10^5	3.14×10^5	2.62×10^5

Notes: *Transformities, without services were taken from Brown and Ulgiati (2002). Values were multiplied by 1.68 to compare results using the 15.83 baseline.
** fossil methane fired plant.

It is worth noting that transformities in the same order of magnitude mean that the global productivity of the MSW-to-energy plants can compete with traditional plants to obtain electricity. These plants, designed for energy recovering from MSW offer other benefits, which are not accounted in this analysis: resource savings regarding the energy production, in the case of fossil fuels fired plants, and especially the mitigation of GHGs. This landfill is considered as one of the five largest projects of gases control in the world. The system was recognised by the UN for the Clean Development Mechanism in 2007, and generates 800,000 tons of carbon credits per year (Gasnet, 2010).

3.3 *Exploring the Emergy indicators for the case of the EcoÍris project*

The implementation of the project for environmental compensation in fulfilment of State's requirements does not change the Emergy accounting significantly. The increase of the total Emergy is less than 1% seJ/seJ. However, when the Emergy investment is practically constant, and the the energy recovery is higher (Table 6), the benefits can be evaluated. The project produces annually 50,000–80,000 seedlings of native species of

São Paulo Plateau's Atlantic forest and vegetables that are distributed free to the local community (Ecouribis Environmental S/A, 2010).

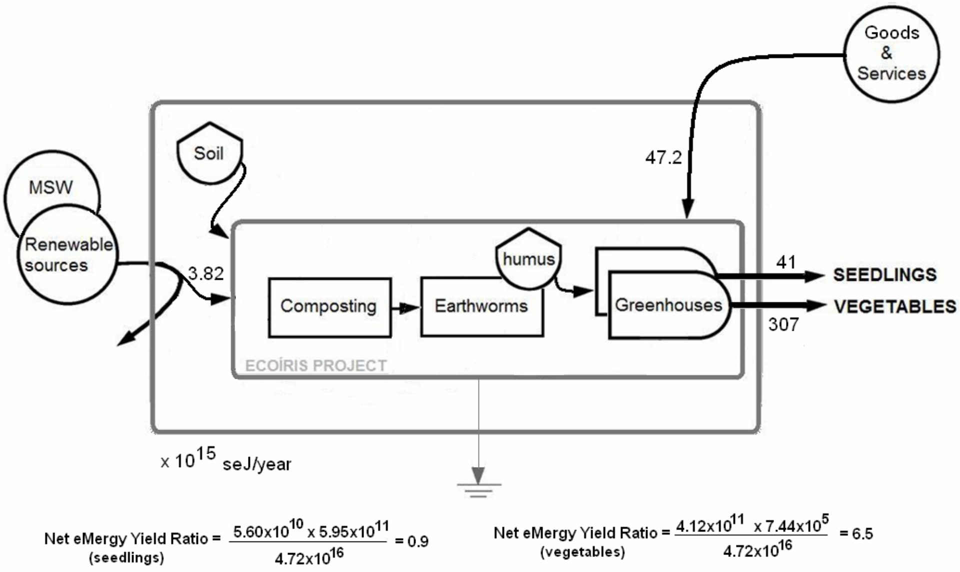
Table 6 Energy recovered by the EcoÍris project

		Landfill	*Landfill + EcoIris*
Emergy invested	seJ/year	2.00×10^{19}	2.02×10^{19}
Energy recovered	J/year		
Seedlings	J/year	-	7.00×10^{4}
Vegetables	J/year	-	4.12×10^{11}
Total	J/year	0	4.12×10^{11}

Considering that the vegetables produced are employed to provide 1/3 of the daily diet of the local community, the value of recovered energy is capable of supplying approximately 90,000 people a year.

An Emergy yield ratio is used to compare the benefits associated to the energy recovered (seedlings and vegetables) by the EcoÍris project (Figure 3). The ratio is defined as the ratio between Emergy benefits and Emergy of purchased inputs (Odum, 1996). The Emergy benefits are those that match the Emergy of the EcoÍris products with others produced by conventional methods. For the seedlings, the Emergy match was done with seedlings for forest restoration (Lu et al., 2011), and the Emergy of vegetables was compared to those produced in an integrated production system for pigs, poultry and vegetables (Ortega et al., 2003).

Figure 3 Emergy analysis of the production of seedlings and vegetables at the EcoÍris Project



$$\text{Net eMergy Yield Ratio (seedlings)} = \frac{5.60\text{x}10^{10} \text{ x } 5.95\text{x}10^{11}}{4.72\text{x}10^{16}} = 0.9$$

$$\text{Net eMergy Yield Ratio (vegetables)} = \frac{4.12\text{x}10^{11} \text{ x } 7.44\text{x}10^{5}}{4.72\text{x}10^{16}} = 6.5$$

Notes: The Emergy per unit of the seedlings (5.95×10^{11} seJ/unit) was taken from Lu et al. (2011) and the transformity of vegetables (7.44×10^{5} seJ/J) from (Ortega et al., 2003). The Emergy table was published in Almeida et al. (2011) and is available on request.

Values shown in Figure 3 clearly show that the production of vegetables, beyond the social benefits to the local community, is also advantageous in Emergy terms, with a net Emergy yield ratio of 6.5. The production of seedlings presents an Emergy yield ratio lower than one, indicating that there is no Emergy yield. However, it is worth to remember that most of the seedlings will be used to support the reforestation projects of two disabled landfills in São Paulo, which are managed by the same company (Santo Amaro and São Mateus landfills). The surplus of seedlings will be directed to environmental education programs in the local community.

4 Conclusions

Emergy synthesis of the electricity production at the São João landfill is comprehensively presented in this study, and some concluding remarks can be summarised:

- Emergy synthesis is a powerful tool that can be successfully used in the understanding of the MSW-to-energy facilities.
- Emergy indicators show that the benefits commonly associated to the reduction in GHGs may be added to those obtained from the correct management of resources. The electricity production at the São João landfill provides a more environmental friendly product because of its demand for low environmental support mainly based on the reclamation/recovery/use of a greenhouse emission.
- The transformity of electricity production from waste landfill gas is lower than transformities of coal, oil, hydroelectricity, wind, geothermic and methane fired plants. The waste biogas demands lower environmental support than electricity production from other production cycles.
- The inclusion of subsystems to produce co-products (vegetables and seedlings) may also improve the whole system, and their products may compete with other production processes regarding their efficiency in resource use.

Policy decisions regarding the use and the choice of technologies to be prioritised for power generation require that decision-makers have the ability to compare net yields, global efficiencies, and environmental competitiveness. The Emergy synthesis was used on the MSW-to-energy system of the São João landfill, which was compared to other production cycles. The results, despite of not statistically significant, may offer a comprehensive method to understand and interfere in waste management systems, contributing to the energy supply chain.

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