

Emergy assessment of an integrated municipal solid waste management

N. Marchettini^{1,3}, R. Ridolfi^{1,3}, E. B. P. Tiezzi^{2,3}

¹*Department of Chemical and Biosystems Sciences and Technology, Siena University, Italy*

²*Department of Mathematics and Informatics, Siena University, Italy*

³*A.R.C.A (Associazione Ricerca Consulenza Ambientale) Onlus*

Abstract

The debate on waste management is becoming one of the most important issues as human needs and activities have overloaded the assimilative capacity of the biosphere. Recent Italian law on solid waste management strongly recommended an increase in material recycling and energy recovery, and it only allows the landfilling disposal for inert materials and residues from recovery and recycling. A correct waste management policy should be based on the principles of sustainable development, according to which garbage is not regarded as waste but rather as a potential resource. This requires the establishment of an integrated waste management plan, considering all the available technologies.

In this context, we applied the emergy analysis to evaluate the whole strategy of the waste management in an Italian district, considering the alternatives of treatment adopted. Particularly, we calculated the total emergy investment, considering the contribution of each input necessary to collect and treat urban waste, highlighting the critical phases. We evaluate how much investment is needed for this type of waste management and how much “utility” is extracted from them. This analysis permitted us to assess the sustainability and the efficiency of the waste management strategy and the possible developments to improve the management strategy according to the type of waste collected and to the type of local resource demanding.

1 Introduction

In a world of ever increasing awareness, a sustainable approach to waste disposal has captured the attention of many politicians and researchers. The waste produced by humanity overloads the absorption capacity of the environment. This means that we must look for systems to dispose efficiently, as well as with low pollution. Waste can be defined as “entropy refuse”, but this does not mean that waste could not be partially reused. In any case, energy and resources need to be used to recover energy and materials from wastes. The recovery will be more advantageous, if the fraction recoverable is greater than the investment. It is important to say that waste disposal always requires economic and resource investment and only the reduction of waste production should be pursued for the final solution of the problem.

A waste management compatible with the environment is possible through energy saving from the waste, while reusing and recycling the initial waste. The environmental aspects of different waste treatment methods are, therefore, not only determined by the properties of the management option, but also by the product that can be replaced as in the energy produced from waste combustion or biogas combustion.

The most common types of waste disposal are incineration, composting and managed landfilling. The latter is the most popular choice; in Italy 74.4% of the wastes produced are disposed in landfills, the 7.2% are burnt in incinerators and only the rest are recycled. Nowadays, it is no more possible to see landfill as a first step of disposal, but it must be seen as the final step of a waste management, after the materials and energy have been recovered. In this article, a waste management of Municipal Solid Waste (MSW) of an Italian district is analysed. The aim of the study is to create a valid evaluation method for a waste management system. We want to propose some useful indices for evaluating the whole system and also each single phase.

In this context, we apply the emergy analysis [1,2], a thermodynamic analysis that evaluates the resources, goods and services of the system with a same unity, the quantity of solar energy necessary (also indirectly) to obtain them.

We evaluate the emergy investment necessary to treat the waste, in terms of consumption of energy and resources during the cycle of management of the waste. We, therefore, evaluate what is necessary to collect the rubbish, to treat it in a landfill or in a fluid bed boiler and the consumptions necessary for the final disposal of residue from landfilling and incineration. As our aim is to create an evaluation method of waste management we normalised the emergy investment for g of MSW. Evaluating the emergy investment of the different options of management permits us to calculate the emergy investment for the integrated waste management.

2 Description of the system

The waste management system, we analysed, is located in the Ravenna district in the center of Italy. The main options to manage solid waste, are landfilling and incineration by a fluid bed boiler. Composting is present in the system but it is not so important because of the low mass of waste treated. The waste management system is modelled using the energy system symbols [2] (figure 1). The system is composed of a managed landfill of 1st category (it can only receive MSW), a landfill of 2nd category (it can only receive hazardous and special waste), a plant for selection of the MSW and for the Refuse Derived Fuel (RDF) production and a fluid bed boiler.

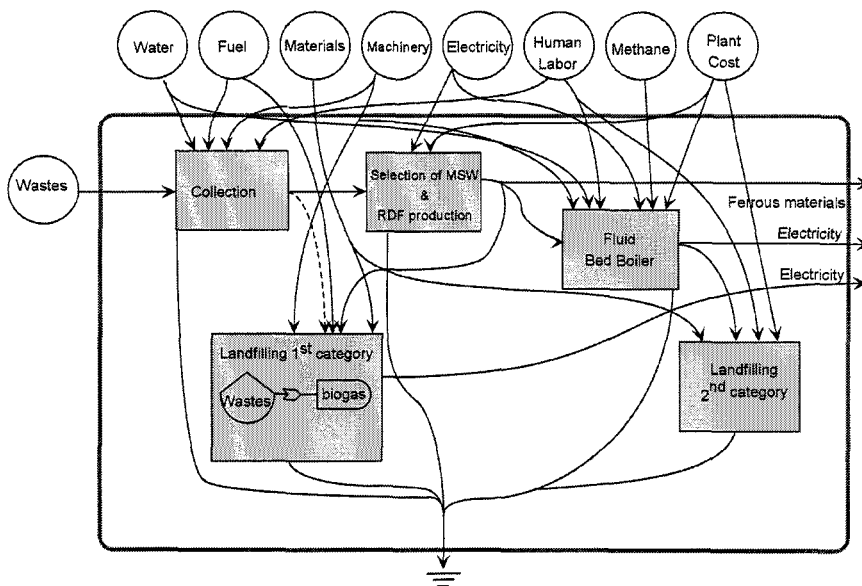


Figure 1: Energy diagram of the Waste Management System

The managed landfill has a system of biogas recovery with a catching efficiency of 65% of the total biogas produced; the remaining 35% goes into the atmosphere. The plant received 170,000 t of waste in the 2000. The fluid bed boiler, fed with RDF, actually is in the starting phase, the first data are relative to the 2000 experimentation. The plant is fed by MSW and by a small fraction of other waste. The MSW is firstly selected and treated in order to produce RDF. Fluid bed boiler has received about 20,000 t of RDF. According to analysis made by the Ravenna district management, RDF is generally formed by the more combustible fraction, like plastics and wooden residues. The residues of this process are mainly formed by the organic and inert fraction and are directed to the landfill of 1st category. As showed in figure 1, the waste collected partially goes to the managed landfill (dashed line) and partially goes to the selection plant. According to the Italian laws, in the near future the wastes of this district

will be submitted to selection before being treated in the landfill or in the fluid bed boiler.

3 Method

In this context, we applied the emergy analysis [1,2] to convert to a common unit (the equivalent solar energy) and to compare inputs of different origin, such as human labor, trucks, fuels, chemicals, plant cost and so on. Solar emergy is the solar energy directly or indirectly necessary to obtain a product or a flux of energy in a process; it is an extensive quantity and its unit is the solar emergy joule (sej). To convert inputs and other kind of flows into the solar equivalent, it is necessary to know the solar transformity, which is the emergy necessary to obtain one unit of product. Unlike the emergy, transformity is an intensive quantity and usually measured in sej/J.

In this article we considered zero the emergy of the waste, because a commodity, once become waste, has no longer the characteristics that it had when it was produced, even if its emergy content really is not zero, this good has lost its quality. We evaluated the total emergy investment, considering the contribution of each input necessary to collect and treat urban garbage.

We divided each management in different phases: trash collection, specific treatment of waste (fluid bed boiler or managed landfill) and chemical disposal of solid and liquid residues from plants. For each of these phases we accounted the emergy value and we divided it by the amount of waste collected in order to evaluate the Emergy Investment (EI). In this way it was possible to evaluate the "critical step" which needs the highest investment in terms of emergy inflow.

Finally we calculated the emergy investment per g of waste necessary to produce 1 MWh of electricity in order to measure and compare the efficiency of the two plants. The sum of the emergy investment of each phase gives us the total EI necessary for the management chosen.

4 Results

Landfill received 170,000 t of waste in 2000 and at this rate of collection will be totally filled in 3 years. As energy recovery in a managed landfill occurs over a long time, because of low kinetic of biogas production, it is necessary to consider the operational time of the plant when an emergy analysis is performed. In fact there is a delay between the waste disposal and biogas recovery. In order to account the annual emergy investment required to manage the landfill, we supposed a plant life-time equal to 12 years, because it is the time necessary for the recovery of 80% of the total biogas production. Therefore, we considered the annual emergy investment equal to the emergy value per number of times that such investment is repeated in the plant life-time, divided to 12 years. Table 1 summarizes the emergy analysis of the managed landfill and contains an additional column for the number of times that an investment is repeated

The first phase of landfilling and incineration is the collection, the detailed analysis of which is only reported in Table 1 with the analysis of managed landfilling. The emergy investment obtained represents the transformity of the collection and it is reported with this value in the other tables where it is present.

Table 1: Energy analysis of a managed landfilling

Item	Amount	Solar Transformity	Ref. Tr.	Solar Energy	Number of investment in 12 years	Solar Energy Investment [#]
	<i>Units/yr</i>	<i>sej/unit</i>		<i>sej/yr</i>		<i>sej/g MSW</i>
MSW collected	1.15x10¹¹g					
COLLECTION						
1 Human labour	6.39x10 ¹⁰ J	7.38x10 ⁰⁶	[6]	4.71x10 ¹⁷	3	1.02x10 ⁰⁶
2 Fuels	2.33x10 ¹³ J	1.21x10 ⁰⁵	[7]	2.82x10 ¹⁸	3	6.13x10 ⁰⁶
3 Machinery	3.84x10 ⁰⁶ g	6.70x10 ⁰⁹	[5]	2.57x10 ¹⁶	3	5.59x10 ⁰⁴
4 Water	4.10x10 ⁰⁹ g	2.03x10 ⁰⁵	[6]	8.33x10 ¹⁴	3	1.81x10 ⁰³
						7.21x10⁰⁶
TREATMENT (MANAGED LANDFILLING)						
MSW collected	8.46x10 ¹⁰ g					
MSW from others	5.50x10 ¹⁰ g					
Refuses from RDF production	3.05x10 ¹⁰ g					
5 MSW in landfill	1.70x10¹¹g					
6 Refuses from RDF production	3.05x10 ¹⁰ g	3.69x10 ⁰⁷	[*]	1.12x10 ¹⁸	1	6.60x10 ⁰⁶
7 Plant cost	1.85x10 ⁰⁶ €	1.40x10 ¹²	[7]	2.59x10 ¹⁸	1	1.27x10 ⁰⁶
8 Materials for construction	1.53x10 ¹¹ g	1.00x10 ⁰⁹	[3]	1.53x10 ²⁰	1	7.49x10 ⁰⁷
9 Human labour	4.37x10 ⁰⁹ J	7.38x10 ⁰⁶	[5]	3.22x10 ¹⁶	3	4.74x10 ⁰⁴
10 Materials for management	4.11x10 ¹⁰ g	1.00x10 ⁰⁹	[3]	4.11x10 ¹⁹	3	6.04x10 ⁰⁷
11 Trucks for management	6.83x10 ⁰⁷ g	6.70x10 ⁰⁹	[4]	4.58x10 ¹⁷	3	6.73x10 ⁰⁵
12 Machinery	2.16x10 ⁰⁷ g	6.70x10 ⁰⁹	[4]	1.45x10 ¹⁷	1	7.09x10 ⁰⁴
13 Fuels	7.13x10 ¹² J	1.21x10 ⁰⁵	[6]	8.62x10 ¹⁷	3	1.27x10 ⁰⁶
14 Electricity	8.10x10 ¹¹ J	1.48x10 ⁰⁵	[7]	1.20x10 ¹⁷	12	7.05x10 ⁰⁵
						1.46x10⁰⁸
DISPOSAL (Leachate treatment)						
15 Chemicals	7.20x10 ⁰⁷ g	3.80x10 ⁰⁸	[3]	2.74x10 ¹⁶	12	1.61x10 ⁰⁵
16 Electricity	3.46x10 ¹¹ J	1.48x10 ⁰⁵	[7]	5.11x10 ¹⁶	12	3.01x10 ⁰⁵
						4.62x10⁰⁵
Power production				5.91x10 ⁰³ MWh		
Phase 1: MSW COLLECTION (sums of 1 to 4)				7.21x10 ⁰⁶ Sej/g MSW		4.69%
Phase 2: TREATMENT (sum of 5 to 14)				1.46x10 ⁰⁸ Sej/g MSW		95.01%
Phase 3: DISPOSAL (sum of 15 to 16)				4.62x10 ⁰⁵ Sej/g MSW		0.30%
Total solar energy investment				1.54x10 ⁰⁸ Sej/g MSW		
Energy Investment per Mwh of power production				2.60x10 ⁰⁴ Sej/MWh/g MSW		

[#] Solar investment is equal to (solar energy) x (number of investment in 12 years)/12.

The analysis of managed landfilling (table 1) shows that the treatment phase requires the higher energy investment (95.01%) while disposal is almost negligible (0.30%) and collection represents only the (4.69%) of the total energy cost. The use of materials has the greatest energy cost and this belong to the fact that a landfill needs great quantity of clay and other materials necessary for its construction and for the daily cover of solid waste received. In Table 2 we calculate the energy investment for the treatment of a waste in a landfill of 2nd category. This value represents the energy cost necessary to dispose residues from fluid bed boiler incineration and it is, therefore, essential to calculate the disposal phase of this management.

Table 2: Energy analysis of a landfill (2nd category)

Item	Amount	Solar Transformity	Ref Tr.	Solar Energy	Solar Energy Investment
	<i>Units/yr</i>	<i>sej/unit</i>		<i>sej/yr</i>	<i>sej/gMSW</i>
COLLECTION					
1 Waste collected	3.20x10 ⁰⁹ g	7.21x10 ⁰⁶	[*]	2.31x10 ¹⁶	7.21x10⁰⁶
TREATMENT					
2 Human labor	7.33x10 ⁰⁸ J	7.38x10 ⁰⁶	[5]	5.41x10 ¹⁵	1.69x10 ⁰⁶
3 Machinery	3.42x10 ⁰⁷ g	6.70x10 ⁰⁹	[4]	2.29x10 ¹⁷	7.17x10 ⁰⁷
4 Diesel	8.14x10 ¹⁰ J	1.21x10 ⁰⁵	[6]	9.85x10 ¹⁵	3.08x10 ⁰⁶
5 Materials	6.40x10 ⁰⁸ g	1.00x10 ⁰⁹	[3]	6.40x10 ¹⁷	2.00x10 ⁰⁸
6 Plant cost	1.37x10 ⁰⁵ €	1.40x10 ¹²	[7]	1.91x10 ¹⁷	5.98x10 ⁰⁷
					3.36x10⁰⁸
DISPOSAL (Leachate treatment)					
7 Chemicals	1.58x10 ⁰⁷ g	3.80x10 ⁰⁸	[3]	5.99x10 ¹⁵	1.87x10 ⁰⁶
8 Electricity	7.56x10 ¹⁰ J	1.48x10 ⁰⁵	[7]	1.12x10 ¹⁶	3.50x10 ⁰⁶
					5.37x10⁰⁶
Phase 1: MSW COLLECTION (item 1)				7.21x10 ⁰⁶ sej/gMSW	
Phase 2: TREATMENT (sum of 2 to 6)				3.36x10 ⁰⁸ sej/gMSW	
Phase 3: DISPOSAL (sum of 7 to 8)				5.37x10 ⁰⁶ sej/gMSW	
Total solar energy investment		3.49x10 ⁰⁸ sej/g			
Legend:					
[*] This study			[5] Ulgiati S., et al. 1994		
[2] Odum H.T.1992			[6] Tiezzi E., et al. 2002		
[3] Odum 1996			[7] Tiezzi E., et al. 2001		
[4] Luchi and Ulgiati, 2000					

The analysis of incineration by a fluid bed boiler (table 3) shows that, like landfilling, the higher energy investment is due to the treatment phase (66.64%), even if it does not have the same importance as in landfilling. In fact, RDF production and disposal have not a negligible value, but together represent about the 30% of the total energy cost. The plant cost and the electricity consumption are the main input to the system; the first one is due to the need for the high

technology of the fluid bed boiler while the electricity use is necessary for the correct functioning of the plant.

Table 3: Energy analysis of a Fluid bed combustion

Item	Amount	Solar	Ref.	Solar	Solar Energy
	<i>Units/yr</i>	<i>Transformity</i>	<i>Tr.</i>	<i>Emergy</i>	<i>Investment</i>
		<i>sej/unit</i>		<i>sej/yr</i>	<i>sej/g MSW</i>
MSW collected	5.14x10 ¹⁰ g				
Other waste collected	1.03x10 ⁰⁹ g				
COLLECTION					
1 MSW collected	5.14x10 ¹⁰ g	7.21x10 ⁰⁶	[*]	3.71x10 ¹⁷	7.07x10 ⁰⁶
2 Other waste collected	1.03x10 ⁰⁹ g	7.21x10 ⁰⁶	[*]	7.45x10 ¹⁵	1.42x10 ⁰⁵
					7.21x10⁰⁶
RDF PRODUCTION					
3 Human labour	2.08x10 ⁰⁹ J	7.38x10 ⁰⁶	[5]	1.53x10 ¹⁶	2.98x10 ⁰⁵
4 Electricity	7.16x10 ¹² J	1.48x10 ⁰⁵	[7]	1.06x10 ¹⁸	2.06x10 ⁰⁷
5 Plant cost	5.85x10 ⁰⁵ €	1.40x10 ¹²	[7]	8.19x10 ¹⁷	1.59x10 ⁰⁷
					3.69x10⁰⁷
TREATMENT (FLUID BED BOILER)					
6 Human labor	3.82x10 ⁰⁹ J	7.38x10 ⁰⁶	[5]	2.82x10 ¹⁶	5.37x10 ⁰⁵
7 Methane	7.60x10 ¹² J	4.80x10 ⁰⁴	[4]	3.65x10 ¹⁷	6.96x10 ⁰⁶
8 Electricity	1.91x10 ¹³ J	1.48x10 ⁰⁵	[7]	2.83x10 ¹⁸	5.40x10 ⁰⁷
9 Plant cost	3.00x10 ⁰⁶ €	1.40x10 ¹²	[7]	4.20x10 ¹⁸	8.00x10 ⁰⁷
10 Water	3.23x10 ¹⁰ g	1.25x10 ⁰⁶	[5]	4.03x10 ¹⁶	7.69x10 ⁰⁵
					1.42x10⁰⁸
DISPOSAL (treatment of fumes & residues)					
11 Chemicals	1.27x10 ⁰⁹ g	3.08x10 ⁰⁸	[3]	3.91x10 ¹⁷	7.47x10 ⁰⁶
12 Residues 2 nd category	2.95x10 ⁰⁹ g	3.49x10 ⁰⁸	[*]	1.03x10 ¹⁸	1.97x10 ⁰⁷
					2.71x10⁰⁷
Power production		1.26x10 ⁰⁴ MWh			
Phase 1: MSW COLLECTION (sum of 1 to 2)		7.21x10 ⁰⁶ sej/g			3.38%
Phase 2: RDF PRODUCTION (sum of 3 to 5)		3.69x10 ⁰⁷ sej/g			17.27%
Phase 3: TREATMENT (sum of the items 6 to 10)		1.42x10 ⁰⁸ sej/g			66.64%
Phase 4: DISPOSAL (sum of the items 11 to 12)		2.71x10 ⁰⁷ sej/g			12.70%
Total solar emergy investment		2.13x10⁰⁸ sej/g			
Emergy Investment per 1 MWh of power production		1.69x10⁰⁴ sej/g/MWh			

In Table 4 the total EI and the total EI per MWh of electricity produced are summarised for a managed landfilling and for a fluid bed boiler incineration.

Table 4: Comparison between Managed landfill and Fluid bed boiler incineration

	Managed landfill	Fluid bed boiler incineration	Waste Management System
EI (sej/MSW)	1.60×10^{08}	2.13×10^{08}	1.68×10^{08}
EI per electricity (sej/MSW/MWh)	2.54×10^{04}	1.69×10^{04}	2.39×10^{04}

The EI per electricity produced has a lower value for the fluid bed boiler than for managed landfill. This means that the latter process of energy recovery is less efficient than the first one. On the other hand, the landfilling requires a low investment per g of treated waste. The greater investment for incineration is not only due to the no potentially full functioning of the plant, but it results from the investment necessary to select the MSW and to treat the fraction selected in order to produce RDF. Moreover, the treatment of the fumes and the residues from the fluid bed boiler (disposal) needs a higher investment than managed landfilling.

The emergy investment of the waste management system is a weighted average between the two values calculated for landfill and incineration. The future plan of directing the whole quantity of waste in the selection plant and consequently in the RDF production will bring a decrease in the value of the emergy investment divided for the electricity produced because of the use of a more efficient energy recovery system. On the other hand it will bring an increase in the EI for a MSW. A possible solution to reduce EI and so the consumptions of energy and resources is to adopt a waste management option less emergy demanding than landfilling and incineration such as high quality composting production. This possibility is also supported either from the fact that agricultural activities are very important in the Province of Ravenna or from the fact that residues from the RDF production are mainly composed by the organic fraction. Hence, the individual collection of the organic fraction permits to recover a greater amount of material from MSW and to reduce the amount of waste in landfill.

5 Conclusion

In this paper we demonstrated with the emergy investment divided by the electricity produced, that the choice of the policy-makers of pursuing an energy recovery from a Fluid Bed Boiler is coherent with our results; on the other hand, this type of recovery, brings together an increase in emergy investment. Considering the fact that residues from RDF are mainly composed of organic fraction. It can be advantageous to collect the organic fraction individually and producing high quality compost. In this way we should have a waste management system that is able to recover more energy and more material using fewer resources than the actual system.

The proposed method of waste accounting permits us to have an holistic view for the assessment of a waste management system. The waste production, the emergy investment and the emergy investment for energy or material recovery could form a set of useful indices to evaluate the sustainability of a waste management system.

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