EMERGY SYNTHESIS 4:
Theory and Applications of the Emergy Methodology

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Integrating Geographical Information Systems and Emergy Synthesis: The Case of Urban Waste Management in Potenza, Southern Italy

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ABSTRACT

Evaluation of a managed landfill system in the Province of Potenza (Southern Italy) was performed by jointly applying Geographical Information System (GIS) and emergy synthesis methods. A GIS survey of the whole province was carried out in order to generate a large-scale picture of the waste management system. According to the results of the survey, the municipal landfill of the town of Potenza was identified as the most relevant waste management site in the area and was therefore chosen as a case study. Data provided and structured by GIS were then converted to emergy flows and emergy-based indicators, in order to provide a comprehensive understanding of the demand for environmental support to the whole process. The main product is identified as the provided service of safe disposal of urban solid waste, for which an emergy cost of 1.15E+09 seJ/g was calculated. A co-product landfill biogas was also considered, with a production cost of 1.11E+05 seJ/J. These results, together with other findings from the investigation, will serve as a reference case for a planned GIS-emergy evaluation of other small and large landfill sites in southern Italy.

INTRODUCTION

Despite a large existing consensus on the need for waste reduction, reuse, recycling, and conversion to other useful energy forms, waste disposal in landfill sites is still a very common procedure. Landfills are active sites where waste is stored and the dynamics of its degradation is controlled in order to avoid undesired emissions of chemicals to the atmosphere, underground water bodies, and the soil. Landfill construction and operation is an expensive process from both an economic point of view due to large monetary investments, as well as from a physical point of view due to large material and energy investments. Developed societies generate increasing amounts of complex wastes that require safe disposal and treatment as an imperative task. Landfills are not the most popular strategy for waste management and a large effort is being made for their reduction and conversion to other types of processing facilities. However, neither keeping a landfill active nor converting it into a waste processing plant (for electricity and heat generation) meet the consensus of local populations, due to environmental concerns and high investment costs. Therefore, it is very important to carefully investigate the investment needed for different waste management procedures, as well as the options for a profitable use of waste management products. In this paper we present an assessment of the construction and operation costs of the municipal landfill of Potenza in southern Italy. This assessment provides a reference for future planned investigations of other existing, small and large landfills in southern Italy in order to quantify the energy, material, and financial investments needed and suggest improvements or alternatives, also taking into consideration scale factors and waste composition.
The main releases from a landfill system are biogas and leachate. The greenhouse gas CH₄, which is approximately 25 times more effective than carbon dioxide (Jensen et al., 1997, page 83), represents about 60 percent of landfill biogas, while the remaining 40 percent is mainly CO₂. Leachate is produced when water passes through the waste in the landfill tank. The water may originate from rain, melted snow, or can be produced by the waste itself. As the liquid moves through the landfill, many organic and inorganic compounds are transported, forming the leachate (Figure 1). It moves by gravity to the base of the landfill tank, where it is finally collected (Bagchi, 2004).

Spatially referenced information is a requirement in several administrative and policy tasks pertaining to local, regional, and national government. According to Burrough (1986) and Burrough and McDonnell (1998) a Geographical Information System (GIS) is defined as: “a powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world.” Therefore, a GIS was implemented in order to provide an inventory of the active landfills located in the area by means of a georeferenced database, as well as to explore the potential pollution sources related to their technical characteristics, locations, and environmental features. A GIS survey of the whole province was carried out in order to generate a large-scale picture of the waste management system. Then, the resource and energy flows supporting the Potenza municipal landfill were analyzed by using the emergy synthesis method (Odum, 1988; 1996; Brown and Ulgiati, 2004b) in order to calculate the total emergy investment required by the landfill facility during its life cycle and the energy investment per unit of service provided (i.e., for the safe disposal and treatment of one unit of urban waste). If we consider that about the 20 percent of the worldwide global emission of CH₄ is generated by landfill biogas, which contributes to climate change with a high CO₂ equivalence factor, we understand the additional environmental advantage that could be obtained if produced landfill gas were used for energy cost optimization instead of merely released or burned. Recovering energy from landfill gas (as fuel for vehicles, heat production, or electricity generation) could become an interesting opportunity for both avoiding emissions of greenhouse gases and, at the same time, improving the energy balance of waste management processes.

Figure 1. Managed landfill system: interactions with environment.
MATERIALS AND METHODS

Description of the Investigated System

The Potenza landfill is a multi-tank plant with a total area of about 10 hectares (ha), located in Montegrosso, a village near the town of Potenza, 800 meters above sea level. This plant is managed by the Municipal Agency for Environmental Protection of Potenza (A.C.T.A.), which is also in charge of waste collection. The operating landfill tank has a capacity of about 63,000 m$^3$ and it collects, on average, $2.73 \times 10^{10}$ g of urban waste per year.

Since a complete and optimized waste management system is planned for the whole area, but it is not yet operating, and since, consequently, a sorted waste collection is not yet performed at a significant level, this landfill site collects all kinds of waste material (see percentages in Figure 2 [A.C.T.A. and University of Basilicata, 1999]). This scenario is likely to increase environmental problems in several different ways. First of all, landfilling unsorted waste materials does not allow recycling or reusing existing useful fractions of metals, glass, paper, plastic, and organic matter. Moreover, the organic fraction of waste is contaminated by metals and other chemicals, generating a very polluting leachate, which is dangerous for soil quality, the water table, and agricultural activities.

For these reasons, an optimized waste management system would require a prior sorting of reusable material, then specific treatment of the organic fraction according to its characteristics (e.g., anaerobic digestion, incineration, composting), only allowing landfilling for the disposal of residual untreated waste.

Each landfill tank has a working time of three years (the time needed for it to be filled with waste and covered with clay and other materials), but leachate and biogas still continue to be produced over a period of 30 to 40 years. We must be aware that a landfill is never, and will never, become an inert system. It continues to degrade and release leachate over a very long time frame, after which the landfill should be empty and its content released to the environment in several chemical forms.

In this work we assume 30 years as landfill life cycle, since after this period more than 90 percent of biogas production is carried out, and, consequently, at least part of the necessary safe disposal can be considered accomplished. During the life cycle, leachate is collected from the landfill tank and sent to a special treatment plant in order to minimize environmental pollution, while biogas is collected and burned (or merely released into the atmosphere) very often without any energy recovery (Krzystek et al., 2001; Alfieri et al., 2004). We calculate in this paper the emergy cost (i.e., the

![Figure 2. Analysis of waste materials composition.](image)
environmental support) required to run the landfill as it is, in order to provide a reference process and reference performance for designing future improvements of the waste management process in Potenza by means of preliminary material sorting and technological improvement of the whole system.

**GIS Analysis of Potenza Province and Waste Management Sites**

A GIS analysis was implemented in order to provide an inventory of the active landfills located in Potenza Province (southern Italy), as well as to explore the potential pollution sources related to their technical characteristics, locations, and environmental features. The first step consisted of geo-referencing raster topographic and aerophotographic maps of the whole province. Then, several thematic layers including municipal boundaries, main roads, rivers, landfill sites, contour lines, and quoted points, were vectorized. Next, a first qualitative assessment of the potential environmental load was made by overlaying the vector layers on the thematic maps describing the main environmental features, such as geology, geolithology, permeability, and land use.

The system of managed landfills in the Potenza Province was also investigated by means of a geo-referenced database containing information about waste flows, plant management, and meteorological data.

The availability of well structured and integrated data allow the implementation of an emergy analysis and synthesis of the whole system, thus shedding light on its demand for environmental support, (i.e., the direct and indirect investment of biosphere activity needed for waste management). Such an evaluation offers a picture of the environmental cost and sustainability of the system of waste management in the area and paves the way to its improvement by identifying the most expensive and less efficient steps of the process, as well as by allowing a qualitative and quantitative comparison with alternative options for waste management.

**Emergy Synthesis of the Potenza Landfill**

Based on data provided by the GIS and integrated by other statistical resources, the landfill system was evaluated by means of the emergy synthesis method. The latter is not described in detail in this paper. The interested readers may refer to published literature for more information (Odum, 1988; 1996; Brown and Ulgiati, 2004a, 2004b, among others). The method allows the quantitative assessment of both economic and ecological support on the common basis of solar equivalent energy (i.e., the available solar energy used up directly and indirectly to make a service or product). Natural and economic flows were calculated. Raw values were multiplied by suitable transformity values and converted to emergy units.

The total emergy investment required by the plant over the entire duration of the waste degradation process was estimated and the emergy cost for the safe disposal of unsorted waste (seJ g⁻¹) was calculated in order to provide both a measure of the investment needed for urban waste treatment and a benchmark for future improvement of waste management by means of material sorting and the most suitable designed landfill and technology. The emergy cost (seJ Joule⁻¹) of landfill biogas production was also calculated and compared with the transformity of natural gas and other fossil fuels in order to evaluate the efficiency of the conversion process.

In spite of the fact that the upstream sorting of reusable or recyclable waste materials (glass, aluminium, paper, plastic, etc.) is an unavoidable preliminary step urgently needed as the basis of any kind of future improvements of the whole waste management process, in the investigated case organic matter is still collected and landfilled together with other waste categories. For this reason it was not possible to make any distinct evaluation of the emergy cost of recycled and landfilled waste, as they are delivered together to the same final destination.
Emergy Calculation Procedure

The main steps of the emergy evaluation carried out during this case study were as follows.

1) Identification of the boundaries of the investigated system.

2) Modelling of the landfill system by drawing an emergy systems diagram that takes into consideration both economic and natural resources.

3) Calculation of matter and energy flows supporting the landfill during its life cycle.

4) Conversion of input matter and energy flows into solar emergy Joules (seJ) by using suitable transformities, updated to the new baseline for biosphere (total emergy driving the biosphere: 1.584·10²⁴ seJ year⁻¹; Brown and Ulgiati, 2004b).

5) Balance of the total life cycle emergy investment (seJ life cycle⁻¹).

6) Calculation of the emergy cost for landfill biogas production (seJ Joule⁻¹).

7) Calculation of the emergy cost for safe disposal of one unit of waste (seJ g⁻¹).

The formal description of the matter and energy flows driving the landfill system (Figure 3) was made by using the symbolic energy systems language (Odum, 1996), drawing direct and indirect flows and storages of natural capital, materials, energy, human labor, and other services, according to the data provided by GIS and A.C.T.A. (2003).

The external boundaries in the emergy diagram (Figure 3) correspond to the boundaries of the landfill system. The role of natural capital in the waste degradation processes is highlighted in the emergy diagram, with particular reference to microbial activity. Similar to material recycling in human productive systems, microbial activity provides an ecosystem service in performing a waste degradation process within the detritus food web. While the former is a human-dominated process that requires a cost in terms of energy, materials, and money; the latter is carried out by nature without any further investment except solar energy derived sources.

Figure 3. Potenza municipal landfill: emergy systems diagram.
Aspects of Emergy Algebra in Waste Management

The input flow of waste delivered to the landfill was, by definition, assumed to be bearing zero emergy content. This is because mixed waste is not considered a desired product of human activities, but instead an unavoidable and undesired emission, as is CO₂ and other pollutants (Ulgiati et al., 2005; 2007) generated by human activities. If waste material is not recycled or processed, but just stored in the landfill, there is no reason for assigning it a transformity. On the other hand, if wastes are treated and re-enter a production process as a substitute material or resource, only the emergy invested in the treatment and recycling process should be assigned to the recycled resource. “Recycling has the same role in the human productive system as the detritus chain in natural systems. Both take a high transformity input at the end of its life cycle, break it down to simpler components, and feed them back to lower hierarchical levels. The recycled component then re-enter the same productive cycle through which it had already passed (may be many times)...” (Ulgiati et al., 2005) and therefore it would be double counting to assign it the total emergy previously required for its production from raw material. According to the allocation rules proposed above, only the additional emergy input needed for further processing must be assigned to recycled waste. This implies that, if a sufficiently efficient recycling process exists, secondary materials (derived from wastes) will have lower transformities than the corresponding primary ones, thus highlighting the advantage of recycling. An emergy investment is needed in order to concentrate, process, and convert waste into useful products, or at least in order to achieve a safe disposal. The total emergy invested per unit of waste disposed of and the total emergy invested per unit of useful product generated from the waste can be considered a production cost. As such, it can be used as useful measure of process efficiency and be compared with transformities of the same materials generated by natural cycles.

All the above considerations are applied to the calculation of the emergy cost of production of biogas in the present case study and will be applied to the same calculation of production cost of sorted or recycled material in the next steps of the present investigation.

RESULTS AND DISCUSSION

According to the results of the GIS survey, the municipal landfill of Potenza was identified as one of the most relevant waste management site for the case study to investigate a landfill system by using emergy synthesis method. Over its whole life cycle the landfill requires an economic and energy investment, mainly due to the need for monitoring and dealing with leachate and biogas production, which still continue to be produced after landfill capping.

The economic investment required by the landfill tank during its life cycle accounts for: 5.16×10⁷ Euros for plant realization (10% of the total financial investment), 3.27×10⁶ Euros for management (64% of the total), and 1.31×10⁶ Euros for waste disposal (26% of the total) (Figure 4).

Table 1 and Figure 4 show the total emergy investment (9.41×10¹⁹ seJ life cycle⁻¹) required during the whole landfill life cycle (assumed as 30 years). The total emergy investment accounts for all the flows of matter, energy, and money, as well as waste collection, plant management, natural flows (e.g., solar radiation, kinetic energy in wind, chemical and geopotential energy in rain, geothermal flow), and economic services (Figure 5).

The potential for energy recovery is addressed by calculating the emergy cost required to produce and collect landfill biogas, which resulted in 1.11×10⁴ seJ/J (Table 1). This value was calculated as the ratio between the life cycle emergy investment and the total amount of biogas produced during the life cycle. As illustrated in Figure 6, the emergy cost of landfill biogas is higher than the transformities of other fossil fuels, suggesting that, as expected, nature is, by far, more efficient in converting organic matter into reduced carbon (in wetlands and deep reservoirs) and that there is potential for further improvement of the whole chain in order to imitate nature cycles, optimizing the demand for environmental support (emergy) to biogas generation. Even if the human-driven process shows a lower efficiency compared to nature, the generated biogas could be usefully...
supplied to the upstream steps of the process (transport and electricity generation) thus improving the energy balance of the process itself. As a consequence of both decreased fossil fuel use and decreased mass of residual waste to be disposed of, the whole process would become more sustainable.

Considering a biogas average annual production of $8.20 \cdot 10^5$ m$^3$ year$^{-1}$, a biogas recovery of 60 percent, a conversion rate of 1.8 kWh per m$^3$, and a market average price of 0.15 Euro kWh$^{-1}$, an annual income of 130·10$^3$ Euro could be obtained if the biogas were used for electricity generation. In fact, the needs of Potenza landfill in terms of electricity could be completely fulfilled and the surplus could be sold to the outside market. In so doing, the monetary cost of the electricity power plant could

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{Figure4.png}
\caption{Potenza landfill: life cycle economic investment (Euros life cycle$^{-1}$).}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{Figure5.png}
\caption{Potenza landfill: life cycle emergy investment (seJ life cycle$^{-1}$).}
\end{figure}
Table 1. Emergy flows supporting Potenza landfill life cycle.

<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Unit</th>
<th>Amount (unit/yr)</th>
<th>Emergy Intensity (seJ/unit)</th>
<th>Ref. for Emergy Intens.</th>
<th>Solar Energy (seJ/yr)</th>
<th>Turnover of investment (years)</th>
<th>Life Cycle Emergy Investment (seJ/total life)</th>
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<td>Sun</td>
<td>J/yr</td>
<td>3.86E+09</td>
<td>1.00E+00</td>
<td>[a]</td>
<td>3.86E+09</td>
<td>30</td>
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<td></td>
<td>Wind</td>
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<td>8.80E+10</td>
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<td>[b]</td>
<td>2.21E+14</td>
<td>3</td>
<td>6.62E+14</td>
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<td>Rain, chemical potential</td>
<td>J/yr</td>
<td>1.38E+10</td>
<td>3.05E+04</td>
<td>[b]</td>
<td>4.22E+14</td>
<td>3</td>
<td>1.27E+15</td>
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<td>Rain , geopotential energy</td>
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<td>3.70E+10</td>
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<td>1.95E+15</td>
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<td>Geothermal flow</td>
<td>J/yr</td>
<td>1.73E+10</td>
<td>5.76E+04</td>
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<td>9.99E+14</td>
<td>30</td>
<td>3.00E+16</td>
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<td><strong>Non renewable input to waste collection process</strong></td>
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<tr>
<td></td>
<td>Water</td>
<td>J/yr</td>
<td>4.09E+10</td>
<td>3.05E+06</td>
<td>[c]</td>
<td>1.25E+17</td>
<td>3</td>
<td>3.74E+17</td>
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<td></td>
<td>Zinc in containers</td>
<td>g/yr</td>
<td>6.56E+04</td>
<td>7.54E+12</td>
<td>[g]</td>
<td>4.95E+17</td>
<td>3</td>
<td>1.48E+18</td>
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<td>Plastic in containers</td>
<td>g/yr</td>
<td>2.42E+07</td>
<td>7.21E+09</td>
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<td>1.75E+17</td>
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<td>5.24E+17</td>
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<td>Iron in containers</td>
<td>g/yr</td>
<td>6.77E+06</td>
<td>5.30E+09</td>
<td>[f]</td>
<td>3.59E+16</td>
<td>3</td>
<td>1.08E+17</td>
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<td>Diesel</td>
<td>J/yr</td>
<td>3.56E+12</td>
<td>9.40E+04</td>
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<td>3.35E+17</td>
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<td></td>
<td>Vehicles (steel)</td>
<td>g/yr</td>
<td>1.93E+07</td>
<td>1.12E+10</td>
<td>[d]</td>
<td>2.16E+17</td>
<td>3</td>
<td>6.49E+17</td>
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<td>Vehicles (plastic and tires)</td>
<td>g/yr</td>
<td>2.14E+06</td>
<td>7.21E+09</td>
<td>[d]</td>
<td>1.54E+16</td>
<td>3</td>
<td>4.63E+16</td>
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<td><strong>Non renewable input to plant construction, waste management and processing</strong></td>
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<td></td>
<td>Water</td>
<td>J/yr</td>
<td>2.96E+01</td>
<td>3.05E+06</td>
<td>[c]</td>
<td>9.04E+14</td>
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<td></td>
<td>Material for plant construction (steel)</td>
<td>g</td>
<td>1.23E+07</td>
<td>1.12E+10</td>
<td>[d]</td>
<td>1.38E+17</td>
<td>1</td>
<td>1.38E+17</td>
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<td></td>
<td>Material for plant construction (sedimentary)</td>
<td>g</td>
<td>6.44E+09</td>
<td>1.68E+09</td>
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<td>1.08E+19</td>
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<td>Material for waste daily covering (sedimentary)</td>
<td>g/yr</td>
<td>1.26E+10</td>
<td>1.68E+09</td>
<td>[b]</td>
<td>2.11E+19</td>
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<td>6.32E+19</td>
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<td>Diesel</td>
<td>J/yr</td>
<td>2.99E+12</td>
<td>9.40E+04</td>
<td>[b]</td>
<td>2.81E+17</td>
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<td>8.43E+17</td>
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<td></td>
<td>Electricity</td>
<td>J/yr</td>
<td>6.50E+10</td>
<td>2.51E+05</td>
<td>[c]</td>
<td>1.63E+16</td>
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<td>4.90E+17</td>
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<td></td>
<td>Machinery (steel)</td>
<td>g/yr</td>
<td>1.23E+07</td>
<td>1.12E+10</td>
<td>[d]</td>
<td>1.38E+17</td>
<td>3</td>
<td>4.15E+17</td>
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<tr>
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<td>Machinery (plastic and tires)</td>
<td>g/yr</td>
<td>1.37E+06</td>
<td>7.21E+09</td>
<td>[d]</td>
<td>9.87E+15</td>
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<td>2.96E+16</td>
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<td><strong>Economic services</strong></td>
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<td>Total cost of landfill plant</td>
<td>€</td>
<td>5.16E+05</td>
<td>2.75E+12</td>
<td>[c]</td>
<td>1.42E+18</td>
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<td>Annual cost for management, incl. labor</td>
<td>€/yr</td>
<td>1.09E+06</td>
<td>2.75E+12</td>
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<td>8.99E+18</td>
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<td>Annual cost for disposal</td>
<td>€/yr</td>
<td>4.36E+04</td>
<td>2.75E+12</td>
<td>[c]</td>
<td>1.20E+17</td>
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<td><strong>Landfill Output and Services</strong></td>
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<td></td>
<td>Safe disposal of waste delivered to landfill</td>
<td>g</td>
<td>8.18E+10</td>
<td>1.15E+09</td>
<td>[h]</td>
<td></td>
<td></td>
<td>9.41E+19</td>
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<tr>
<td></td>
<td>Total landfill gas in 30 years (co-product of organic material degradation)</td>
<td>J</td>
<td>5.10E+14</td>
<td>1.11E+05</td>
<td>[i]</td>
<td>5.65E+19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References for Transformities.

[d] Odum and Odum, 1983. [i] This study. Emergy cost per unit of safe disposal (seJ/g).

Notes
1. Working time of landfill is 3 years. Life cycle of waste degradation process is considered 30 years.
2. Turnover of investment (years) = number of investment repeated in 30 years.
3. Life Cycle Emergy Investment (seJ/life cycle) is equal to (solar emergy) x (number of investment in 30 years).
be amortized in only 3.2 years. Emergy-based performance indicators (Brown and Ulgiati, 2004b) would reflect such a recycling strategy. The Emergy Yield Ratio (EYR) would slightly increase, thus indicating a lower use of imported resources. The Environmental Loading Ratio (ELR), instead, would decrease, as a consequence of decreased use of non-renewable input. Finally, the Emergy Sustainability Index (ESI) would also increase due to the combined effect of both EYR and ELR values.

The amount of emergy invested in order to obtain the safe disposal of waste materials by landfill practice is very high and translates into a high value of the cost for safe disposal of one unit of unsorted waste ($1.15 \times 10^9 \text{ seJ g}^{-1}$) (Table 1).

Considering that the lack of sorting of household waste does not allow for recycle; this practice is not sustainable in the long run and calls for urgently needed preliminary sorting before landfilling. Recycling and reuse of materials would provide additional savings of matter, energy, and money to the larger scale system of waste management, as well as to the economic system of Potenza, (a) by providing cheap material to the productive sectors instead of requiring new import from outside, (b) by allowing lower fossil energy expenditure, and finally (c) by requiring a lower environmental support to the whole area and, in particular, to the waste management system. The present values of emergy production costs for safe disposal (an unavoidable service aimed at making city life possible) and for landfill gas generation (aimed at better energy balance) will be used in the future as comparison figures in order to measure any improvement achieved or achievable by means of better waste management and improvement proposals in the area.

**CONCLUSION**

Environmentally sound waste management requires the identification of some thermodynamic properties able to quantify its residual usefulness. Moreover, in order to choose safe and useful landfill sites, proper size, and appropriate technology, policy makers and technicians should be provided with information far exceeding the mere mono-dimensional analysis based only on economic investment. GIS and emergy synthesis methods provide a significant contribution to expand the focus far beyond just the economic point of view.
The emergy cost calculated for landfill biogas resulted into $1.11 \times 10^5$ seJ Joule$^{-1}$ (Table 1), a very high - and expected - value compared to fossil fuels. The use of landfill gas to produce electricity reduces the greenhouse gas emission, at the same time replacing the use of conventional fuels. Landfills are potentially exploitable reservoirs of energy and matter. This requires suitable technical design and proper procedures, aimed at decreasing the energy and emergy demand for safe disposal and for material and energy recovery. Emergy based indicators show the amount of environmental support required by the investigated process, and, at the same time, the distance of technical processes from natural ones providing the same output (materials and energy), thus suggesting the existence of potential for improvement.

REFERENCES


