Waste-To-Energy Assessment of Solid Waste in the Centre Region of Portugal

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EXECUTIVE SUMMARY

This study is a contribution to the development of a sustainable solid waste management system in the Centre Region of Portugal, in order to explore its waste-to-energy potential. In order to accomplish, it was made an inventory of the amount of municipal and industrial solid waste produced, giving special attention to waste with high-energy potential. It was concluded that the region produces about 3200kton/year, of which 1000kton/year with high potential for incineration. In this work, it was defined and located a set of waste management infrastructures and the transport effort was estimated. Using a mass and energy flow model (Umberto v5.5), the environmental impact assessment was calculated for a set of scenarios of waste management.

It was considered three management scenarios for municipal waste: scenario 1, which represents the current situation, where the majority of the waste is landfilled, scenario 2, where the PERSU II model is represented and scenario 3, which represents an alternative model, giving emphasis to incineration and separation of biowaste. For industrial waste it was defined two scenarios: scenario #1, which represents the current situation, where all the waste is landfilled and scenario #2 where the waste of high calorific value was separated and incinerated with energy recovery, and the waste that remain is landfilled. The main results reported in the study are related with energy use and production and environment assessment. Considering electric energy production, it was concluded that the scenarios where incineration occurs, are those that present greatest amounts of electricity produced, registering the lower direct fuel consumption in transport. Concerning the environmental impact, it was possible to conclude that the scenarios with large extension of landfilling globally present lower emissions.

INTRODUCTION

Waste management constitutes an environmental, social and economic challenge for all countries. The need to reduce waste production and to ensure their sustainable management has become a matter of citizenship.

The current economic system in Portugal is characterized by a high production of industrial and municipal wastes. Usually, this waste is attributed to a negative economic value, because their use is not economically viable, due to the low cost of raw material. Therefore, the majority of this waste is landfilled, causing pollution, with no recovery, as it could be used drawing the energy content that some of these wastes can offer. [1]

The choice between different alternative procedures must fall within the scope of a concept of integrated waste management that point to the use of different treatment processes according to the nature and status of the waste at their segregation. [2]

Strategies for waste management obey to a hierarchy of priorities based on the prevention (reduce, reuse and repair), followed by recovery (material recycling, biological treatment or thermochemical treatment) and, finally, disposal. [3]

The main purpose of this study was identification of opportunities for a strategy of integrated management of municipal and non-hazardous industrial waste, using the centre region of Portugal as a case study. This strategy of integrated waste management has been developed in order to
improve technical solutions for handling all these wastes, as compared to the current destination controlled landfill, through the assessment environmental impacts methodologies. The approach to waste management should occur in terms of sustainability, since it must allow a more holistic approach than the previous one, based purely on an environmental perspective.

**METHODOLOGY**

**Database**
The methodology used for this work was, initially, the identification and characterization of the subject area of study and research the inventory of municipal and industrial waste produced in the Central Region namely the quantities, types and location by municipality. [4]

Taking into account the main interest of the work on the evaluation of waste potential for energy production, a next stage has been defined in order to find different management scenarios, which were identified for the necessary infrastructure management and quantified the effort to collect and transport. [4]

In a final stage it was conducted a final evaluation for different scenarios based on the computer application Umberto either in the form of an inventory of emissions to the environment or the use of resources. Finally, it were calculated some indicators of environmental impact associated with each scenario, using the Leiden methodology in the Life Cycle Assessment (LCA). [4]

The information required for the study was gathered from various sources on a municipal level. In some cases this information was obtained by estimation from other information. This information has been structured in a database in a Microsoft Excel document and has been subject to treatment in order to insert data in the application Umberto. From the results of life cycle inventory (LCI) it were calculated indicators of environmental impact (LCIA) with the help of the Microsoft Office Tool, Excel. [4]

**Management Scenarios**
The municipal waste management was considered under different scenarios, and developed from the different waste management operation, namely collection, transport, recycling, composting, incineration and landfill. For industrial waste it was considered collection, transport, and disposal by incineration and landfill. [4]

Thus, for municipal waste it has been identified three scenarios:
- Scenario 1 - Current situation (material recycling (8.7%), organic recycling (1.2%) and disposal in landfills (90.1%));
- Scenario 2 – PERSU II Strategy, 2016 (material (18%) and organic (18%) recycling, from mechanical-biological treatment results the sorting of waste for material recycling (6%), organic recycling (18%), refuse derived fuel (RDF) production (18%) and disposal in landfills (10%));
- Scenario 3 – Proposed/alternative strategy (material recycling (20%) and organic recycling (household composting (7%) and municipal composting (18%)), incineration (55%) and landfill (waste resulting from other processes).

For industrial waste two scenarios were considered:
- Scenario # 1 - Current situation where all the waste is landfilled;
- Scenario # 2 – Proposed strategy, applied to the non hazardous industrial waste (NHIW), where the waste with interest to energy recovery are treated by incineration (24.5%) and the other NHIW are landfilled).

**LCA Applied to Waste Management**
Life Cycle Assessment is a methodology that allows the compilation of input and output flows, and the evaluation of potential environmental impacts associated to a product/process in all its life cycle ("from cradle to grave") since the extraction of raw material until the final deposition in the environment. [5]
By using this tool applied to waste management it is possible to estimate the main environmental impacts associated to waste management operations, giving special attention to comparative assessment of different management alternatives (scenarios) to the final destination of waste. [6] According to ISO 14040, this tool has four phases: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation.

**Umberto Software (educational version)**

Umberto is an environmental management tool that allows Life Cycle Assessment material and energy flow analyses in calculating the inventory of emissions, without need for a detailed description of the material input. [7]

In this case study, material flow networks were designed for each scenario. Those networks represent a material flow management system and several processes (collection and transport, the sorting plant, composting plant, incineration plant and landfill). Where it was possible, all parameters have been properly modified for each case, according to its needs.

After the input of all material (waste), it was possible with the calculation tool of the application, to obtain the inventory of emissions and energy (inputs and output of solid waste, emissions to the water, emissions to the air, fuel consumption and generated energy in the process).

**INVENTORY ANALYSES**

**Waste Production in the Central Region**

**Municipal Solid Waste (MSW)**

The central region considered in the case of study for MSW consists of 79 municipalities. The whole region has an approximate area of 23,725 km², which is occupied by about 1,791,773 inhabitants, producing about 700,000 tonnes of MSW per year (data for 2006). The information of the produced MSW quantities was obtained in the Web sites in each management system of the respective municipality. [4]

This information was not differentiated in waste from separate collection and waste from the undifferentiated collection. To this study, the information in question was relevant, so a methodology was defined, in which it was considered that the percentage of undifferentiated MSW and MSW from separate collection is equal in the entire country. [4]

**Non-Hazardous Industrial Waste (NHIW)**

For NHIW, the central region considered consists of 77 counties. From information provided by the CCDRC (Committee for Coordination and Regional Development of the centre region) it was selected the waste with high calorific value, with interest to energy recovery, by selecting appropriate waste from the European List of Wastes (ELW). From the selection, resulted a final quantity of waste for treatment of about 656,000 tonnes per year from 2,582,000 tonnes/year (data for 2005) which are currently sent to two landfills located in the same region. [4]

**Estimative of the Distance of Waste Transport**

In this work it was necessary to estimate the distances of collection and transport of the waste. For this purpose, it was defined a method of calculation, taking into account the location of the treatment and disposal infrastructure that serves each municipality, the quantities of waste produced (yearly basis) taking into account the carrying capacity of vehicles used for collection and transport.

In the transport of MSW it was considered that it can be made by a transfer station "high transport" or directly to final destination "low transport".

In Umberto software, in addition to other factors, the type of vehicle is characterized by the quantity of waste that it carries. In this study was considered a volume capacity of 15m³ for the transport of MSW separated collection, undifferentiated MSW to transfer station and of industrial waste. To transport undifferentiated MSW from transfer station to their final destination, a volume capacity of
40 m³ was considered. To obtain the quantities of waste that each vehicle carries, calculations were made according to their volumetric densities. [4]

Separate Collection of MSW

Through information provided in the ERSUC website (management system), about the distance travelled to collect one tonne of recyclable waste in each city belonging to this municipal system, it was calculated an indicator of the distance travelled to collect recyclable waste in any city in the region under study. There were considered the real distances from each city to their sorting plants. [4], [8]

Initially, it was necessary to calculate a representative ratio of distance travelled for collection of recyclable component in all municipalities of ERSUC (R_{ij(ERSUC)}), by the equation:

$$R_{ij(ERSUC)} = \frac{\sum (d_{ij} S_{ij(ERSUC)})}{\sum (d_{ij} S_{ij(ERSUC)})}$$

(1)

To find the representative (or equivalent) distance travelled to transport each component of recyclable waste for one journey that represent any municipality (d_{m,i}), it was developed the following equation:

$$d_{m,i} = \frac{\sum d_{ij} R_{ij(ERSUC)} S_{ij}}{\sum S_{ij}}$$

(2)

Separate Collection of Organic Waste

For scenario 2 it was assumed that the organic waste collection in urban areas has the same parameters as the glass collection, since this is the component that can have the nearest volume density of organic waste. Organic waste is sent to the four existing composting plants.

For scenario 3, where municipal composting is considered, there were used assumptions from previous studies and there were admitted two types of installation for municipal composting: composting A, capacity to 2500 tonnes biowastes/year and composting B, capacity to 5000 tonnes biowastes/year. [4], [9]

For cities with a very low organic waste production, it was considered that its waste is sent to the closest municipal composting plant. For municipalities with production exceeding 5000 tonnes/year it was admitted the existence of two composting plants in the same municipality.

In what concerns the distances to collect and transport waste for municipal composting, it was admitted a distance of collection and transport of 29 km/journey to cities with a capitation upper than 3.10^{-4} kg/inhab.day, based on another study (Lopes, M. 2008). For other counties, it was considered a distance of 35 km/journey. [10]

To find a representative distance to organic waste transport of the municipal composting facility, it was used the following equation:

$$d_{CM,j} = \frac{\sum \frac{LER_{i,j} d_{m,c}}{v}}{\sum \frac{LER_{i,j} S_{ij}}{v}}$$

(3)

Undifferentiated Collection

For the undifferentiated MSW, the distance travelled on each trip (d_{m,i}) to their transport is given by:
Industrial Waste
In industrial waste, it was not considered any way of collecting, and the average distance by journey (\(d_{\text{RINP},j}\)) to transport is given by:

\[
d_{m,j} = \frac{\sum (d_j + d_{1,j}) - \frac{1}{v} \sum \text{LER}_{i,j,l}}{\frac{1}{v} \sum \text{LER}_{i,j,l}}
\]  

(4)

Conditions of Recovery
The waste recovery includes the separation of waste in material recovery facilities (MRF) for recycling and recovery made in the central organic composting plants. These operations were only considered for MSW. The resulting products from the separation at the sorting plants are sent to recycling industries.

It was considered that waste for home composting goes out of the study area, being the municipal or centralized composting made in a closed and independent system. [10]

In centralized composting considered in scenario 2, where organic waste is from the mechanical treatment of undifferentiated waste collected, it is assumed that the resulting product may be contaminated (with heavy metals, for example), which is then sent to landfill.

Conditions of Disposal
The waste disposal includes the co-incineration of industrial and municipal waste and landfilling in specific landfills. The impact assessment was made for each type of waste.

The incineration plant considered in this case study is equipped with a firing grate and mass-burning. Incineration is made with energy recovery (electricity + heat), resulting emissions to the air and to the water, and solid waste sent to landfill. [10]

For MSW it was considered an average LCV (Lower Calorific Value) of the residue of about 12 MJ/kg and a water content of 21%. For NHIW it was considered a waste with a LCV of 18.5 MJ/kg and a water content of 15%. [4]

The two main emission paths of landfill disposal are seepage (comes from both the water intake via the solid waste and from rainfall precipitation on the landfill site) and landfill gas (results from anaerobic degradation of organic material and consists of a whole series of trace elements as well as of carbon dioxide and methane). The landfill gas collected can either be torched or used in an engine to obtain energy. [11]

RESULTS
Collecting and Transporting Effort
Tables 1 and 2 show the estimated values for the equivalent distance of collecting and transporting effort waste on each trip and for each production process.
Table 1 – Travelled distance for MSW transport in each trip [km]

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>30</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Paper/Cardboard</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Metal and plastic</td>
<td>174</td>
<td>173</td>
<td>166</td>
</tr>
<tr>
<td>Organic matter</td>
<td>-</td>
<td>50</td>
<td>33</td>
</tr>
<tr>
<td>County-TS TS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Separated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With TS</td>
<td>32</td>
<td>35</td>
<td>32</td>
</tr>
<tr>
<td>No TS</td>
<td>44</td>
<td>35</td>
<td>86</td>
</tr>
<tr>
<td>With TS</td>
<td>32</td>
<td>95</td>
<td>88</td>
</tr>
<tr>
<td>No TS</td>
<td>44</td>
<td>99</td>
<td>88</td>
</tr>
<tr>
<td>County-TS TS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Travelled distance for NHIW transport in each trip [km]

<table>
<thead>
<tr>
<th>Non-Hazardous Industrial Waste</th>
<th>Scenario #1</th>
<th>Scenario #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>89</td>
<td>89</td>
</tr>
<tr>
<td>Incineration</td>
<td>-</td>
<td>64</td>
</tr>
</tbody>
</table>

Umberto software application in the case study
For each scenario a network was developed in the application Umberto. An example of a network obtained with the application can be seen in Figure 1.

Figure 1 – Network obtained to scenario #2 of NHIW

For each scenario, the Umberto application made the calculations based in a set of predefined processes belonging to the datasets of its restricted database (education application). The values obtained in terms of fuel consumed (Figure 2), electricity (Figure 3), waste and products generated (Figure 4), volume of landfill occupied (Figure 5), emissions to the water (Table 3) and emissions to the air (these will be discussed in sub-section below).

Figure 2 – Consumed fuels in management processes in each scenario of MSW and NHIW
### Table 3 – Annually emissions to the water in the different scenarios of MSW and NHIW

<table>
<thead>
<tr>
<th>Emissions to the Water</th>
<th>MSW</th>
<th></th>
<th></th>
<th>NHIW</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1</td>
<td>Scenario 2</td>
<td>Scenario 3</td>
<td>Scenario #1</td>
<td>Scenario #2</td>
<td></td>
</tr>
<tr>
<td>Arsenic (As) [kg]</td>
<td>9.76</td>
<td>2.72</td>
<td>1.04</td>
<td>39.17</td>
<td>29.43</td>
<td></td>
</tr>
<tr>
<td>Cadmium (Cd) [kg]</td>
<td>1.02</td>
<td>0.29</td>
<td>0.11</td>
<td>4.12</td>
<td>3.09</td>
<td></td>
</tr>
<tr>
<td>Chromium (Cr) [kg]</td>
<td>18.32</td>
<td>5.10</td>
<td>1.95</td>
<td>73.57</td>
<td>55.28</td>
<td></td>
</tr>
<tr>
<td>Lead (Pb) [kg]</td>
<td>6.67</td>
<td>1.86</td>
<td>0.71</td>
<td>26.80</td>
<td>20.14</td>
<td></td>
</tr>
<tr>
<td>Mercury (Hg) [kg]</td>
<td>0.58</td>
<td>0.16</td>
<td>0.06</td>
<td>2.31</td>
<td>1.74</td>
<td></td>
</tr>
<tr>
<td>Ammonium (NH₄⁺) [tonnes]</td>
<td>125.60</td>
<td>35.02</td>
<td>13.99</td>
<td>504.10</td>
<td>379.00</td>
<td></td>
</tr>
<tr>
<td>Nitrate (NO₃⁻) [tonnes]</td>
<td>4.27</td>
<td>1.99</td>
<td>8.90</td>
<td>14.80</td>
<td>11.00</td>
<td></td>
</tr>
<tr>
<td>Nitrogen Compounds [tonnes]</td>
<td>51.40</td>
<td>14.30</td>
<td>5.46</td>
<td>206.30</td>
<td>154.00</td>
<td></td>
</tr>
<tr>
<td>Phosphorous Compounds [tonnes]</td>
<td>5.04</td>
<td>1.40</td>
<td>0.54</td>
<td>20.20</td>
<td>15.20</td>
<td></td>
</tr>
<tr>
<td>PCB [kg]</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (BOD₅) [tonnes]</td>
<td>58.40</td>
<td>18.18</td>
<td>12.40</td>
<td>232.90</td>
<td>175.00</td>
<td></td>
</tr>
<tr>
<td>Chemical Oxygen Demand (COD) [tonnes]</td>
<td>165.30</td>
<td>58.19</td>
<td>56.70</td>
<td>653.20</td>
<td>490.00</td>
<td></td>
</tr>
<tr>
<td>Total [tonnes]</td>
<td>410.05</td>
<td>129.10</td>
<td>97.99</td>
<td>1631.65</td>
<td>1224.31</td>
<td></td>
</tr>
</tbody>
</table>
Classification of Pollutants in Impact Categories

In this study three impact categories were considered, Global Warming Potential (GWP), Human Toxicity (HT) and Aquatic Ecotoxicity (ECA), in which the pollutants were aggregated according to Leiden Methodology, these given by Equations 6 to 8. [12],[13]

\[
GWP = \sum_{i} f(GWP_i) E_i, \quad i = \text{CO}_2, \text{N}_2\text{O, CH}_4 \quad \text{(Eq. 6)}
\]

\[
HT = \sum_i f(HCA_i) E_{i, \text{air}} + \sum_i f(HCW_i) E_{i, \text{water}}
\]

\[
i = \text{NH}_4, \text{C}_6\text{H}_6, \text{Ni, CO, SO}_x, \text{H}_2\text{S, NO}_x
\]

\[
ECA = \sum_i f(ECA_i) E_i, \quad i = \text{C}_6\text{H}_6, \text{Cd, Pb, Hg, PCB, Cu, Zn} \quad \text{(Eq. 8)}
\]

The results obtained about each impact category can be observed on Figures 6 to 8.

Figure 6 – Contribution of each substance involved in Global Warming Potential in each scenario of MSW and NHIW

Figure 7 – Contribution of each substance involved in Human Toxicity in each scenario of MSW and NHIW
DISCUSSION AND CONCLUSION

Throughout the entire work, the main limitation was in obtaining disaggregated data, particularly in the quantities of separated waste at source, the amounts of industrial waste and each ELW code for each municipality, in consumption energy of the equipment and installation, and the distances travelled for the operations of collection and transport. It can be seen that currently (scenario 1), in the central region under study, the landfill takes precedence over the technology of recovery, with rates of deposition of around 90%. This shows a little oriented management policy less oriented for the prevention and recovery and clearly directed the disposal to landfill. Being the Directive 1999/31/EC about the disposal of organic waste in landfills and outlines targets for the reduction of 65% by year 2016, this scenario for treatment of municipal waste is unacceptable in the future. This study shows that scenario 3, with 45% of separate collection, including 25% of organic waste collection and the remaining 55% of waste from the indiscriminate collection to be incinerated, meets the goals outlined by the European Directive mentioned above. It is assumed that the targets about recycling used in this scenario may be too optimistic, because it involves the correct separation of waste at source, and for that is essential the citizen participation. By the results obtained from Umberto software, was possible to conclude that the scenario of mechanical-biological treatment of municipal waste (scenario 2) shows larger quantities of fuel consumed. On it turns, to industrial waste, the scenario that represents the current situation, where all waste is disposed in landfill, has the largest quantity of fuel consumed. It is important to note that scenario 3 of MSW and scenario #2 of NHIW which makes use of incineration with energy recovery, has the greatest production of electricity. It was found that scenarios where the disposal in landfills prevails, are those where there is a greater amount of final solid waste produced, translated into a greater volume of landfill occupied. Therefore, these scenarios are also showing greater amounts of net emissions of seepage water from landfills. Regarding the assessment of environmental impacts it is possible to conclude that the scenarios with lower environmental impacts are those where prevails the landfilling. This is curious given that the policies for waste management points to the need to reduce the quantities of waste disposed in landfill. During the exercise test of application Umberto for the study was evident lack of flexibility, difficulty in adjusting the tool databases to the case study. These drawbacks are certainly related with the licence restrictions of the software. All these reasons have conditioned the results and its accuracy, but it seems a powerful tool with many potential for future use.

NOMENCLATURE

\[ d_{CM,j} \] – Representative distance travelled to transport organic waste

Figure 6 – Contribution of each substance involved in Aquatic Ecotoxicity in each scenario of MSW and NHIW
for municipal composting in any county [km.journey⁻¹]

\( d_j \) – Distance from county to sorting plant [km]

\( d_{ji} \) – Distance travelled to collect one tonne of recyclable waste \( i \) in county \( j \) at ERSUC [km.tonne⁻¹]

\( d_{m,C} \) – Distance from county \( j \) to composting plant [km.journey⁻¹]

\( d_{m,i} \) – Distance travelled to collect of each component \( i \) in any county \( j \) [km]

\( d_{ij} \) – Distance travelled to transport one tonne of waste in county \( j \) [km.tonne⁻¹]

\( d_{RINP,j} \) – Distance travelled to transport NHIW in county \( j \) [km]

\( LER_{i,j,1} \) – Amount of undifferentiated waste in county \( j \) [tonnes.year⁻¹]

\( LER_{i,j,3} \) – Amount of biowaste produced in county \( j \) [tonnes bw.year⁻¹]

\( R_{INP,j} \) – Amount of non-hazardous industrial waste produced in the central Region in each county \( j \) [tonnes/year.city j]

\( S_{ij} \) – Amount of recyclable waste \( i \) in county \( j \) [tonnes.year⁻¹]

\( S_{ij(ERSUC)} \) – Amount of recyclable waste \( i \) in county \( j \) on ERSUC [tonnes.year⁻¹]

\( v \) – Capacity of the collection vehicle [tonnes]

REFERENCES

[8] www.ERSUC.pt