Integrated solid waste management and energy production - a life cycle assessment approach: the case study of the city of Thessaloniki

Christopher J. Koroneos a,*, Evanthia A. Nanaki b

a Interdisciplinary Postgraduate Program, ‘Environment and Development’, School of Rural and Surveying Engineering, National Technical University of Athens, Iroon Polytechniou 9, Zografou 157 80, Athens, Greece
b University of Western Macedonia, Department of Mechanical Engineering, Mpakola & Sialvera, Kozani 50100, Greece

Abstract

Innovative strategies are needed to deal with the waste we produce today to prevent it from causing problems for future generations. As waste management issues gain public awareness, concern has risen about the appropriateness of various disposal methods. The objective of this work is the environmental assessment of different municipal solid waste treatment strategies for the city of Thessaloniki, within the methodological frameworks of Life Cycle Assessment (LCA) and the Integrated Solid Waste Management strategy, taking into account social, environmental and economic effects. The waste management methods in this study include: landfill of all waste fractions, recycling of paper, and anaerobic digestion of food waste in a biological treatment plant. The waste fractions considered are the total amount of food, paper and plastic waste produced in Thessaloniki during the period of one year. Environmental impacts are decreased when the solid waste management methods include some kind of recovery from waste. The results of this work indicate that paper recycling and anaerobic digestion of food waste is preferable compared to landfilling. It is also shown that landfilling of food waste utilizing the biocells method is more attractive than anaerobic digestion in a separate plant; nevertheless, energy recovery is about 45% lower.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

During the past decades environmentally sound waste management was recognized by most countries as an issue of major concern. Waste management is an important factor in ensuring both human health and environmental protection. Waste generation in EU is estimated at about 1.3 billion tones per year. This includes, waste from manufacturing (427 million tones), from energy production and water supply (127 million tones), from the construction sector (510 million tones) and municipal waste (241 million tones). Between 1998 and 2002, hazardous waste generation increased by 13% to reach 58.4 million tones. Both GDP and municipal waste grew by 19% between 1995 and 2003 (European Commission, 2003).

Sustainability governs the general direction of waste management and forms the basis for the hierarchy of waste management options in EU policy. The hierarchy, which consists of Prevention/Mitigation, Materials Recovery, Energy Recovery and Landfill, was first introduced in the Waste Framework Directive (European Commission, 1975; European Commission, 1989; European Commission, 1991) and constitutes a component of all relevant waste directives. At national level, the legal framework includes the Joint Ministerial Decision 50910/2727/2003 concerning the scheduling and permission status of the landfill sites selection (Joint Ministerial Decision 50910/2727/2003) and the Joint Ministerial Decision 29407/3508/2002 defining mainly the technical specifications for the landfill construction and operation, as well as the environmental targets to be achieved (Joint Ministerial Decision 29407/3508/2002). In order to implement these European requirements, it is of great importance the existence of a sustainable waste management approach that will lead to effective environmental and economic solutions, and it will evaluate on the best approach for the combination of collection, processing and disposal systems that will best serve the present and future needs of a particular community. It is obvious that a sustainable waste management approach should be efficient in terms of environmental protection, social acceptability as well as efficiency in terms of economic viability.

The methodology of Life Cycle Assessment is very useful on showing paths that could possibly decrease the environmental impacts caused by the waste management process. LCA originates...
from “net energy analysis” studies, first published in the 1970s (Boustead, 1972; Hannon, 1972; Sundström, 1973). These studies took into consideration only energy use over the life cycle of a product or a process. Later studies included wastes and emissions (Lundolm and Sundström, 1985; Boustead, 1989); nevertheless, none of them went further than the quantification of materials and energy use. As a result the Society of Environmental Toxicology and Chemistry and the International Organization for Standardization (ISO 14040, 1997; ISO 14041, 1998; ISO 14042, 2000a; ISO 14043, 2000b) developed in the 1990s a complete LCA methodology. In 2006, standard ISO 14040 was revised (ISO 14040, 2006) and a new standard ISO 14044 (ISO 14044, 2006) was presented. Formal changes include the reduced number of standards, the reduced number of annexes and the reduced number of pages that contain all the requirements. All these changes are intended to increase the readability and accessibility of the standards. The two new standards, ISO 14040 and ISO 14044, reconfirm the validity of the main technical content of the previous standards. Errors and inconsistencies were removed and the readability was improved (Finkbeiner et al., 2006). Further details on the current state–of–the–art of the LCA methodology can be found on the publications pages of the European Platform of Life Cycle Assessment or the UNEP/SETAC Life Cycle Initiative (UNEP, 2010; European Commission, 2010).

As far as integrated solid waste management systems are concerned, they incorporate all the policies, programs and technologies that are necessary to manage the waste streams. The mix and emphasis of approaches that are taken, generally varies from region–to–region and depends on local conditions (UNEP, 2005). A number of studies have been published during the past decade, investigating the usefulness of LCA methodology in sustainable waste management (Finnveden et al., 1995; Liamsanguan and Gheewala, 2012; Moberg et al., 2005; Reich, 2005). The concept of Integrated Solid Waste Management (ISWM) can be defined in various ways, but generally it is considered as an optimized waste management system in which environmentally and economically best solution for each individual case is sought (Sundqvist, 1999; McDougall and Hruska, 2000).

An LCA regarding the assessment of different waste management scenarios has been carried out in the city of Thessaloniki. The methods of treatment considered in this work include landfill of all waste fractions, anaerobic biological treatment of food waste, and recycling of paper. Emphasis has been given to air emissions and water pollution caused by landfilling, since it is one of the most common and environmentally hazardous “treatment method”.

The objective of this study is to analyze the environmental impacts caused by waste management methods and to compare alternative scenarios regarding these methods, providing a case study from the Greek sector. It should be noted that not all environmental impacts have been analyzed in this study (odors, noise, thermal pollution and radiation were not included). The impact categories of total energy usage as well as contribution to the global warming effect were taken into consideration. These two categories have a significant environmental impact and are factors that have been thoroughly investigated in the LCA as their results are considered highly credible. In addition, the impact categories of human toxicityology and eutrophication/acidification as well as the land use were also included and analyzed in a sensitivity analysis scenario.

2. Description of the geographic area under study

Thessaloniki is the second largest city in Greece located in the northern part of the country. The population in the greater Thessaloniki area is about one million with a high density of inhabitation in most of the peripheral municipalities. The whole area is served by a sanitary landfill operated by the Association of Local Authorities of Greater Thessaloniki for the last 14 years.

The functional unit used is the treatment of municipal solid waste collected during one year in Thessaloniki. It is noted that the solid waste life cycle stages of waste collection and transportation have not been included in this study.

The fractions of municipal solid waste included in the study are the total amount of food waste, paper, and plastic collected during the period of one year. The amounts of these waste fractions are based on 2004 data, whereas their average composition is based on 1998 data, since the effect of change in time is insignificant. These three waste fractions account for 74% of the total waste produced in Thessaloniki and due to their physical and chemical properties, various treatment methods could be utilized to avoid the hazards they create (Papachristou et al., 2002).

Greece’s electric energy system was taken into consideration in order to analyze the corresponding air emissions corresponding to electricity used that is produced by the use of non renewable resources such as lignite. It should be mentioned that for each process related with energy recovery, the corresponding amounts of air emissions and non renewable resource use are considered as avoided environmental impacts; whereas other avoided environmental impacts associated with paper recycling, use the anaerobic digestion residue as a fertilizer and heat production from methane flaring are not. Air emissions and non renewable energy sources use that correspond to the production and usage of 1 MJ of electricity from lignite based power plants are listed in Tables 1 and 2. The same methodology has been applied also for the avoided environmental impacts systems. Fig. 1 presents a simplified flow chart of all the systems analyzed in this study.

The total amount of municipal solid waste of Thessaloniki that are sent to the landfill located on the outskirts of the city in a place called Tagarades, during the last two decades, is presented in Fig. 2. The quantity and the composition of the municipal solid waste of Thessaloniki (Table 3), indicate that the amounts of paper, food waste and plastics make up two thirds of the total waste. A decrease of the compostable organic is observed, whereas recyclable materials present an increase. This can be attributed to the rise of the standard of living and the change of consumption habits, during the last decade.

3. Waste treatment methods

In this work the waste treatment methods that have been considered and are used in setting up the various scenarios include, landfill, biological treatment, and paper recycling.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>[Kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>3.91E-03</td>
</tr>
<tr>
<td>Lignite</td>
<td>1.20E-01</td>
</tr>
<tr>
<td>Natural gas</td>
<td>1.72E-04</td>
</tr>
<tr>
<td>Diesel</td>
<td>3.75E-03</td>
</tr>
<tr>
<td>Heavy oil</td>
<td>1.93E-02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 1 Air emissions that arise from the production and usage of 1 MJ of electricity from lignite based power plants.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air emission</td>
</tr>
<tr>
<td>Kg/[MJ]</td>
</tr>
<tr>
<td>Air emission</td>
</tr>
</tbody>
</table>
has been estimated that the CH4 produced at solid waste disposal sites contributes approximately 3–4% to the annual global anthropogenic greenhouse gas emissions (Intergovernmental Panel on Climate Change (IPCC), 2001). Furthermore, disposal sites also produce biogenic carbon dioxide (CO2) and non-methane volatile organic compounds (NMVOCs) as well as smaller amounts of nitrous oxide (N2O), nitrogen oxides (NOx) and carbon monoxide. For this reason it is significant to examine the landfill emissions and their impact on a very distant time frame.

The composition of leachate was calculated based on first order differential rate equations (Qasim and Chiang, 1994; Lu et al., 1984). Those equations provide adequate information concerning the leachate behavior for landfills of age up to 30 years. The average value of leachate composition was used for the 0–20 year’s time frame and the value of the 30th year was used as the average value for the 0–21 year’s time frame (Table 5).

The methane emissions, carbon dioxide emissions and ammonia emissions of the landfill can be estimated using the general equation (Eq. (1)), which describes the anaerobic transformation as a consequence of the microbial processes that occur in the landfill:

$$C_4H_8O_4N_4 + xH_2O \rightarrow \psi CH_4 + z CO_2 + d NH_3$$

(1)

where, $x = (4a - b - 2c + 3d)/4$; $\psi = (4a + b - 2c - 3d)/8$; $z = (4a - b + 2c + 3d)/8$ (Tchobanoglous et al., 1993).

During the energy recovery process, 30% of the energy is utilized as electricity, 60% as heat and 10% is lost. The assumption concerning energy recovery depends on each scenario. Electricity use of the plant is 31 MJ/ton of food waste, heat consumption is 495 MJ/ton of food waste and energy production is 3743 MJ/ton of food waste. The distribution of energy produced from the energy recovery process is as follows: 30% of the energy is utilised as electricity, 60% as heat (which also provides the heat needed by the plant) and 10% is lost.

The elementary composition of the three waste fractions was used in order to calculate the total mass per substance and the waste fraction that is buried in the landfill. The degradation factors of Table 4 were used in order to calculate the total amount of carbon that is emitted, along with the corresponding amounts of H, O, N, that were the input to the general anaerobic transformation equation (Table 6). A mass balance concept was used in order to estimate the solid waste emissions separately for each waste fraction.

### Table 3

<table>
<thead>
<tr>
<th>Waste fractions</th>
<th>Quantity (tones/year)</th>
<th>Share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper (mixed)</td>
<td>175,260</td>
<td>26.66</td>
</tr>
<tr>
<td>Food waste</td>
<td>159,960</td>
<td>29.21</td>
</tr>
<tr>
<td>Plastics (mixed)</td>
<td>107,400</td>
<td>17.9</td>
</tr>
<tr>
<td>Leather, wood, clothes, rubber</td>
<td>54,780</td>
<td>9.13</td>
</tr>
<tr>
<td>Glass</td>
<td>21,660</td>
<td>3.61</td>
</tr>
<tr>
<td>Metals</td>
<td>20,400</td>
<td>3.4</td>
</tr>
<tr>
<td>Aluminum</td>
<td>6180</td>
<td>1.03</td>
</tr>
<tr>
<td>Other</td>
<td>54,360</td>
<td>9.06</td>
</tr>
<tr>
<td>Total</td>
<td>600,000</td>
<td>100</td>
</tr>
</tbody>
</table>
3.2. Biological treatment

Anaerobic digestion of organic waste expedites the natural decomposition of organic material without oxygen, by maintaining the temperature, moisture content and pH close to their optimum values.

In this study, food waste is supplied to the anaerobic treatment plant operating under wet and mesophilic conditions, and it transforms it into biogas. The produced biogas is then collected and flared. The digestion residue is used as a low-grade fertilizer replacing N and P fertilizer (based on its nutrient content) which otherwise would be produced from the fertilizer industry. The nutrient content of the digestion residue is 7.6 Kg nitrogen and 1.1 Kg phosphorus per ton of food waste.

Emission factors during the process of biogas flaring and energy recovery are presented in Table 7. The same emission factors are used in order to estimate the emissions of the biogas flaring process at the landfill model (Finnveden et al., 2005). It is noticed that the food waste content on heavy metals (Pb, Cd, Hg, Cu, Cr, Ni and Zn) was used, in order to estimate the emissions to soil caused when applying the anaerobic digestion residue as a fertilizer.

### 3.3. Paper recycling

Paper can be classified in different categories depending on its quality and the presence of impurities. Paper originating from commingled waste has for example low commercial value due to a big amount of impurities, such as plastic films that cause problems to the paper recycling equipment, organics attached that cause high moisture levels as well as small metal pieces like paper clips.

Paper is considered as the fastest developing market for recycled products. In this study, paper recycling includes newspaper (70%), books and magazines (30%) and it is based on a closed loop system. In addition to the recycled fibre from the waste paper fractions, 16% of the pulp is thermo mechanical pulp from wood.
Table 8
Overview of the systems studied regarding the flow of the different waste fractions across the different waste treatment methods.

<table>
<thead>
<tr>
<th>Waste treatment strategies</th>
<th>Landfill</th>
<th>Recycling</th>
<th>Anaerobic digestion in a plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>System 1</td>
<td>100% for all waste fractions</td>
<td>–</td>
<td>50% for food waste</td>
</tr>
<tr>
<td>System 2</td>
<td>50% for food waste, 100% for plastic and paper</td>
<td>–</td>
<td>50% for food waste</td>
</tr>
<tr>
<td>System 3</td>
<td>30% for paper, 100% for plastics and food waste</td>
<td>–</td>
<td>50% for food waste</td>
</tr>
<tr>
<td>System 4</td>
<td>30% for paper</td>
<td>–</td>
<td>50% for food waste</td>
</tr>
</tbody>
</table>

4. Municipal solid waste management strategies

In order to compare and define the advantages and disadvantages of the strategies used on municipal solid waste management systems, various municipal waste management strategies have been investigated. The variations of these strategies are based on the differences of the waste flows included in this study (food, paper, plastic) as compared to the different waste management methods (landfill, recycling, anaerobic digestion in a plant). Short descriptions regarding the system under study are listed in Table 8. For each of these strategies, a base scenario has been defined. The latter enables the specification of the parameters of each solid waste management strategy that have a significant effect on the results of the environmental impact analysis. Most of the parameters are involved with the landfill site.

4.1. Base scenario

In the area of landfill, 50% of biogas and 80% of leachate produced is collected. From the energy produced by the anaerobic treatment of sludge and from the landfill area, 30% is converted to electricity, 60% to thermal energy and 10% is lost to the environment. The same happens to the energy produced from the anaerobic digestion of food waste on a plant, which accepts the 50% of food waste (systems 2 and 4). Paper recycling (systems 3 and 4) amounts to 30% and comes from newspapers and magazines.

4.2. Scenario A

It is assumed that biogas and leachate produced in the landfill is not utilized. This results to the release of all polluting substances to the natural environment.

4.3. Scenario B

Collected biogas gets burned without any capturing of energy. This results to significant decreases of methane levels and other organic pollutants without any energy gains.

4.4. Scenario C

The utilization of the thermal energy produced from the burning of biogas is not possible. The energy gained does not replace thermal energy from heating oil but only electrical energy coming from the power station at the rate of 30%. The remaining 70% are energy losses to the environment.

4.5. Scenario “biocells”

The use of biocells permits better use of biogas (up to 65%) and leachate collection (up to 90%). Furthermore, it provides the ability to efficiently utilize the remains of the anaerobic decomposition process by converting them into low-grade fertilizer. This can be attributed to a separation mechanism, which is enforced prior to the burning, allowing the waste to be buried into groups of organic and non-organic substances, while land mounting does not occur on a daily basis. This results to decreased land usage, while the emission of pollutants appear to be also reduced. Nevertheless this final disposal method can increase the levels of odors as well as the energy required to mechanically separate the waste.

4.6. Scenario “natural gas”

In this scenario the heat gained from the burning of biogas is considered to replace the corresponding amount of heat produced from natural gas.

4.7. Scenario “land use”

In this scenario, the impact category land use is added in order to define how much the inclusion of this impact category affects the overall results of the life cycle impact assessment. The method used to estimate the area needed to landfill each waste fraction is based on calculating the volume of certain amount of each landfill fraction using typical values of density and compression ratios during landfill process. Table 9 presents an overview of the scenarios studied regarding biogas collection-utilization, leachate collection, avoided systems and impact categories.

Table 9
Overview of the scenarios studied regarding biogas collection-utilization, leachate collection, avoided systems and impact categories included.

<table>
<thead>
<tr>
<th>Biogas collection from landfill site:</th>
<th>Scenario A</th>
<th>Scenario B</th>
<th>Scenario C</th>
<th>Scenario “land use”</th>
<th>Basic scenario</th>
<th>Scenario “natural gas”</th>
<th>Scenario “biocells”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas from landfill site utilized as electricity:</td>
<td>0%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Leachate collection from landfill site:</td>
<td>0%</td>
<td>0%</td>
<td>30% of collected</td>
<td>30% of collected</td>
<td>30% of collected</td>
<td>30% of collected</td>
<td>63%</td>
</tr>
<tr>
<td>Heat recovery from landfill biogas replaces:</td>
<td>No heat recovery</td>
<td>No heat recovery</td>
<td>No heat recovery</td>
<td>Yes</td>
<td>No</td>
<td>Heat from oil</td>
<td>80%</td>
</tr>
<tr>
<td>Land use at landfill site impact category:</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Biogas from anaerobic digestion plant utilized as electricity:</td>
<td>Heat from oil</td>
<td>Heat from oil</td>
<td>No heat recovery</td>
<td>Heat from oil</td>
<td>Heat from oil</td>
<td>Heat from natural gas</td>
<td>60%</td>
</tr>
<tr>
<td>Heat recovery from anaerobic digestion plant replaces:</td>
<td>Heat from oil</td>
<td>Heat from oil</td>
<td>No heat recovery</td>
<td>Heat from oil</td>
<td>Heat from oil</td>
<td>Heat from natural gas</td>
<td>60%</td>
</tr>
<tr>
<td>Biogas utilized as heat: (both landfill site and plant)</td>
<td>60%</td>
<td>60%</td>
<td>No heat recovery</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
<td>60%</td>
</tr>
</tbody>
</table>
The results of the environmental impact analysis as well as the sensitivity analysis have been conducted for the overall amounts of the municipal solid waste fractions (Table 1).

### 5. Environmental impact assessment - results

The eco-indicator method 99 (Goedkoop and Spriensma, 2000) was used in order to quantify the potential impacts of the above mentioned alternative waste management strategies. The following impact categories have been considered: total energy, global warming (GW), the environmental impacts to resources, ecosystems quality, human health, the combined effect of eutrophication/acidiﬁcation (EA) and human toxicology (HT).

The classification and the weighed damage factors (WDF) of the emissions to the corresponding impact categories are listed in Table 10.

The weighed damage factors and the mass balance of the emissions of each scenario as well as the sensitivity analysis scenario are used, in order to determine the corresponding potential contribution across the different impact categories. The impact assessment calculations were performed using SIMA PRO 5 (SIMA PRO 5). The program includes the following data bases: BUWAL 250 (Brand et al., 1998), IDEMAT database (Remmerswaal, 1996) as well as PRE 4 database. All the results are presented per total amount of food, paper and plastic waste, in order to fulfill the functional unit. The results of impact assessment analysis are presented analytically in Fig. 3–19.

The total energy use for each one of the sensitivity scenarios of system 1 is presented in Fig. 3. It is noticed that the biocells scenario uses the highest amount of energy. The contribution to global warming for each of the sensitivity analysis scenario of system 1 (Fig. 4) shows that scenario A has the worst performance. Fig. 5 presents the total environmental impacts for each one of the sensitivity analysis scenarios of system 1 (method eco-indicator 99, total weighted results, single score). In this case also scenario A has the worst performance. The total energy use for each one of the sensitivity analysis scenarios of system 2 is shown on Fig. 6. In this case, the biocell scenario has the highest use of energy, as it was also noticed in system 1. The contribution to global warming for each one of the sensitivity analysis scenarios of system 2 (Fig. 7) presents the same behavior as that of system 1; scenario A has the worst performance. Fig. 8 presents the total environmental impacts for each one of the sensitivity analysis scenarios of system 2 (method eco-indicator 99, total weighted results, single score). Based on the above the conclusion is reached that scenario A has by far the worst performance with scenario B following. Fig. 9 presents the total energy use of the sensitivity analysis scenarios of system 3.
which presents great similarities with systems 1 and 2, regarding the upper end of energy use. Nevertheless, the scenario with the lowest energy use is that of scenario A.

The contribution to global warming and the total environmental impacts (method eco-indicator 99, total weighted results, single score).

**Fig. 6.** Total energy use for each one of the sensitivity analysis scenarios of system 2.

**Fig. 7.** Contribution to global warning for each one of the sensitivity analysis scenarios of system 2.

**Fig. 8.** Total environmental impacts for each one of the sensitivity analysis scenarios of system 2. (Method eco-indicator 99, total weighted results, single score).

**Fig. 9.** Total energy use for each one of the sensitivity analysis scenarios of system 3.

**Fig. 10.** Contribution to global warning for each one of the sensitivity analysis scenarios of system 3.

**Fig. 11.** Total environmental impacts for each one of the sensitivity analysis scenarios of system 3. (Method eco-indicator 99, total weighted results, single score).
score) for each one of the sensitivity analysis scenarios of system 3 (Figs. 10 and 11) are similar to systems 1 and 2. Fig. 12 through 14 include the equivalent analysis of system 4, which follows a similar pattern except for the contribution to global warming for each one of the sensitivity analysis scenarios (Fig. 13) as a credit is given for the first four scenarios.

The comparison of the total energy use for each one of the four systems is shown in Fig. 15. The bars stand for the average value of the sensitivity analysis scenarios of each system. System 1 uses the lowest amount of energy. The contribution to global warming for

![Fig. 12. Total energy use for each one of the sensitivity analysis scenarios of system 4.](image1)

![Fig. 13. Contribution to global warming for each one of the sensitivity analysis scenarios of system 4.](image2)

![Fig. 14. Total environmental impacts for each one of the sensitivity analysis scenarios of system 4 (method eco-indicator 99, total weighted results, single score).](image3)

![Fig. 15. Total energy use for each one of the four systems. The bars represent the average value of the sensitivity analysis scenarios of each system.](image4)

![Fig. 16. Contribution to global warming for each one of the four systems. The bars represent the average value of the sensitivity analysis scenarios of each system.](image5)

![Fig. 17. Contribution to the combined eutrophication/acidification impact category for each one of the four systems. The bars represent the average value of the sensitivity analysis scenarios of each system.](image6)
Solid waste management is one of the many challenges that communities face. While the overall quantities of waste are generally increasing, it is becoming increasingly difficult to site new facilities to manage their waste. Waste minimization and recycling/reuse policies have been introduced to reduce the amount of waste generated, and increasingly, alternative waste management strategies have been identified to reduce the environmental impacts of waste management.

Based on the findings of Fig. 19, it becomes obvious that there is a significant decrease of environmental impacts when the solid waste management methods include some kind of recovery from waste. It is well known that paper recycling and anaerobic digestion of food waste is preferable compared to landfilling and this was clearly illustrated on the results of the present study (Eriksson et al., 2005). Despite the fact that landfilling food waste according to the biocells method may be more attractive than anaerobic digestion in a plant, costs are much less and energy recovery is about 45% lower.

Based on the above, it is obvious that a new environmental policy is needed so that planning for solid waste management should be performed aiming at achieving the desirable sustainable development. Policies focusing on energy and material recovery from solid waste, as shown on (ISO 14043, 2000b; ISO 14040, 2006; ISO 14044, 2006; Finkbeiner et al., 2006; UNEP, 2010), lead not only to a significant decrease of greenhouse gases, but also have significant environmental benefits (e.g. use of fossil fuels, ecosystem quality). Nevertheless, it should be pointed out that there is a very high sensitivity of the results due to the assumptions made about the origin of the energy that is replaced from biogas utilization.

According to the main assumptions made in this work, electricity production is based on lignite and this remains constant in all scenarios, since lignite is the primary energy carrier in Greece. For this reason, electricity production from biogas (that accounts for the 30% of energy recovery from biogas) is assumed to replace part of the electricity based on lignite. On the other hand, heat production from biogas (60% of the total amount of energy recovery from biogas) in scenarios A, B, “biocells” and “basic”, replaces thermal energy from oil. In the scenario of “natural gas”, it replaces thermal energy from natural gas and in scenario C it replaces no thermal energy at all. When the heat from natural gas (instead of the heat from oil) is replaced by heat coming from biogas, a small increase in the impact categories of human health and ecosystem quality is noticed, while the impact category of non renewable resources is positively influenced. In scenario C where no heat from biogas is utilized, it does not seem to effect significantly the results except for systems 2 and 4 where an anaerobic digestion plant is present, leading to the increase of heat energy recovery (even though the difference is very small).

Parameters regarding the landfill site seem to have a significant effect on the overall results. Another very important issue is the fact that the environmental impacts of all systems under study are maximized in the case of uncontrolled waste disposal site (no biogas and leachate control). Although parameters regarding biogas and leachate treatment have a considerable effect on the results, the inclusion of land use as an impact category only gave an insignificant increase of 6–16% (depending on the system) on ecosystem quality impact category.

7. Conclusions

The presented study is considered crucial for the sustainability decision making process regarding different solid waste management strategies at any level (technology developers, system managers, public authorities, etc). In this context, the application of LCA methodology is of great importance as it helps in optimizing the different waste flow fractions optimization using various treatment methods, in order to minimize the environmental impacts. However, two basic disadvantages of LCA (difficulties on defying the system in order to make a holistic approach, and the lack of appropriate data) are becoming more obvious when applying LCA to the field of waste management. It is obvious that the most important pitfall stems from the complexity of waste management systems in conjunction with the lack of reliable and harmonized data, which limit the applicability of the results. When discussing solid waste management strategies it would be interesting to see how the inclusion of other electricity sources (e.g. from renewable sources instead of lignite based power plants)
would affect the results. Additionally, a more detailed study could contain some other relevant waste treatment methods like incineration, composting, recycling of plastic and aluminum and of course the process of waste collection and transfer. That would give a holistic approach to the problem of municipal solid waste management.

It is interesting to note that the presented application of LCA should be taken into consideration along with the objectives of an Integrated Solid Waste Management Plan. As far as Greece is concerned, the objectives of an Integrated Solid Waste Management Plan include actions such as the selective collection at source and recycling of municipal wastes, the creation of modern, sanitary landfills, equipped with sorting and recycling plants, the construction of suitable transfer station networks, the pause in operation of uncontrolled dumps, followed by rehabilitation projects, the development of an integrated public communication strategy, in the context of the common effort for tackling the waste management problem (Varelidis and Skordilis, 2001).

References


Sweden.


Joint Ministerial Decision 50910/2727/2003, Measures and Terms for the Handling of Solid Waste, National and Regional Planning (in Greek).


Remmerswaal, H., 1996. IDEMAT Database. IDEMAT Database Faculty of Industrial Design Engineering, Delft University of Technology, Netherlands.

SIMA PRO 5: www.pre.nl/simapro.


Intergovernmental Panel on Climate Change (IPCC), 2001. Climate Change 2001. UNEP & WMO.