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Life Cycle Assessment of the MBT plant in Ano Liossia, Athens, Greece

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ABSTRACT

The aim of this paper is the application of Life Cycle Assessment to the operation of the MBT facility of Ano Liossia in the region of Attica in Greece. The region of Attica is home to almost half the population of Greece and the management of its waste is a major issue. In order to explicitly analyze the operation of the MBT plant, five scenarios were generated. Actual operation data of the MBT plant for the year 2008 were provided by the region of Attica and the LCA modeling was performed via the SimaPro 5.1 software while impact assessment was performed utilizing the Eco-indicator'99 method.

The results of our analysis indicate that even the current operation of the MBT plant is preferable to landfilling. Among the scenarios of MBT operation, the one with complete utilization of the MBT outputs, i.e. compost, RDF, ferrous and non-ferrous metals, is the one that generates the most environmental gains. Our analysis indicates that the exploitation of RDF via incineration is the key factor towards improving the environmental performance of the MBT plant. Our findings provide a quantitative understanding of the MBT plant. Interpretation of results showed that proper operation of the modern waste management systems can lead to substantial reduction of environmental impacts and savings of resources.

1. Introduction

Life Cycle Assessment (LCA) is a holistic approach that quantifies all environmental burdens and therefore all environmental impacts throughout the life cycle of products or processes (Rebitzer et al., 2004). LCA is not an exact scientific tool, but a science-based assessment methodology for the impacts of a product or system on the environment (Winkler and Bilitewski, 2007). LCA has been utilized for sustainable MSW management since 1995 (Güereca et al., 2006) and thereafter it is increasingly exploited for decision support and strategy-planning in the field. This tendency is expected to be further strengthened by the recently adopted European Waste Framework Directive (2008/98/EU), which requires waste management strategies to be based on Life Cycle Thinking, an approach less structured than LCA but based on the same holistic principle. Recently, Cleary (2009) presented a comprehensive review on the modeling of MSW management systems in terms of LCA while Del Borghi et al. (2009) review different life-cycle approaches in waste management, while a thorough review of recent literature can be found in Abeliotis (2011).

LCA has been mainly used for assessing the impacts of integrated waste management systems of cities and regions and to compare different operating scenarios, although the "best" option still appear to vary depending on the boundary conditions and the modeling assumptions in spite of the significant efforts for standardization (ISO 14040, 2006). For instance, the environmental superiority of waste-to-energy technologies is highlighted by Fruergaard and Astrup (2011), Chen and Christensen (2010), Khoo (2009), Liamsanguan and Gheewala (2008), Wanichpongpan and Gheewala (2007), and Chaya and Gheewala (2007). On the other hand and in various local conditions, several authors demonstrate that the recovery of materials is the preferable environmental option (Miliūtė and Staniškis, 2010; Winkler and Bilitewski, 2007; Mendes et al., 2004; Rodríguez-Iglesias et al., 2003). Where all relevant LCA studies seem to converge is that landfilling is the worst environmental option, among engineered disposal and/or treatment methods (Cherubini et al., 2009; De Feo and Malvano, 2009; Buttol et al., 2007; Banar et al., 2009; Özeler et al., 2006).

Besides the analysis of integrated waste systems, LCA can be also used for the assessment of specific parts of the waste management systems; for example waste collection (Iriarte et al., 2009; Rives et al., 2010) or management of the organic fraction (Güereca et al., 2006; Martínez-Blanco et al., 2010) or focusing on special solid waste streams such as electrical and electronic waste in Switzerland (Hischier et al., 2005) or batteries in Belgium (Briffaerts et al., 2009).

Mechanical biological treatment (MBT) of mixed streams is becoming increasingly popular as a method for treating municipal

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solid waste (Farrell and Jones, 2009). The outputs of MBT plants are: recyclable (mostly metals) and compostable materials, Refuse Derived Fuel (RDF) and a fraction of residuals. Over the last 15 years MBT technologies have established their presence in Europe (Velis et al., 2009) and their role in waste management is predicted to grow for the foreseeable future (Farrell and Jones, 2009). Currently, MBT is one of the technologies with interest to Greece and to other Mediterranean countries (Economopoulos, 2010) as well as to the New EU countries struggling to achieve the strict landfill diversion targets of the European legislation (Lasaridi, 2009).

Based on the aforementioned analysis, the Life Cycle Assessment of MBT plants operation, as a direct material and an indirect energy recovery option is not sufficiently studied and needs further understanding, based on actual operating data of existing plants. Hence, the aim of this study is to quantify the environmental trade-offs associated with the actual operation of a specific MBT plant, based on the annual operation data for the year 2008; to compare the operation of the MBT plant with landfilling; and to compare four different scenarios of MBT plant operation based on the environmental impacts generated utilizing the Life Cycle Assessment methodology. In addition, to the best of our knowledge, the present research is the first application of the LCA approach in MSW management in Greece, a country currently in transition of its waste management paradigm, which has to rapidly move from extensive landfilling to advanced treatment and diversion options (Lasaridi, 2009). Modeling of the system took place in SimaPro 5.1 (Pré Consultants, 2003). SimaPro is a generic LCA tool that is flexible enough to model MSW treatment systems.

2. Description of the MBT plant

The owner and operator of the plant is the Association of Communities and Municipalities of the Attica Region (ACMAR). The plant is located right adjacent to the Western Attica sanitary landfill area. The MBT was designed to treat 25% of the total MSW generation of the Attica region. The MBT plant occupies an area of 52,740 m^2 and has a lifetime of 20 years.

The trucks enter the plant, are weighed and directed to the available position of discharge. The MSW, after unloading, is fed through grabs to hoppers, from where it is dosed to the mechanical sorting plant. The dosed waste undergoes initial screening, for the separation of the dry and wet fractions. The dry fraction undergoes size reduction and the materials with high calorific value are sorted, pressed and baled as high quality RDF. Along with the dry fraction processing line, the ferrous and non-ferrous (aluminum) metals are separated and driven to the corresponding presses for baling. On the other hand, the wet fraction undergoes size reduction and separation for the removal of rejects. Afterwards, the organic fraction is mixed with porosity controlling organic materials, mostly garden trimmings. The mixture is then fed to the composting plant. The rejects generated at the various intermediate stages of mechanical sorting are collected and transferred to the adjacent sanitary landfill.

The homogenized fraction of organic waste and garden trimmings is fed to the composting plant. The compostable material is spread in layers and is aerated in elongated plug-flow vessels, where it remains and is stabilized for several weeks. The propagation and turning of the material in the vessels is accomplished utilizing specially designed equipment. The produced compost undergoes refining. Following refining, it is fed to the maturation area where the material is stacked and remains for 4 weeks, for the completion of the humification processes. Part of the mature compost is packaged and distributed for sale.

In addition to the main MBT plant, pollution control units are operating: a wastewater treatment plant, where the treatment of leachate produced in the various MBT compartments takes place. For the purification of the various air streams, biofilters and scrubbers are used. Bag filters are used for the removal of dust in the air streams.

3. Life Cycle Assessment

There are four steps in an LCA study: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation (ISO 14040, 2006).

3.1. Goal of the study

There were three main objectives in this study: (a) to assess the environmental impacts generated by the current operation of the MBT plant in Ano Liossia, Greece; (b) to compare the operation of the MBT plant to MSW landfilling; and finally (c) to compare the environmental impacts generated by different scenarios of dealing with the products of the MBT plant.

3.1.1. Functional unit

The key function of the MBT plant is the treatment of mixed MSW and the recovery of useful materials (ferrous and non-ferrous metals, RDF, compost). The functional unit serves as the objective yardstick for comparison among systems (ISO 14040, 2006) to which the inputs and outputs of the inventory are related. Cherubini et al. (2009) claim that for waste management the functional unit must be defined in terms of system's input, i.e. the waste. Moreover, Cleary (2009), in its recent review of LCAs, states that the functional units are variants on "tonnes of MSW treated per year". Therefore, in this study, the functional unit is the total mixed MSW fed to the Ano Liossia MBT plant during 2008, i.e. 251,859 tons/year.

3.1.2. System boundaries

The LCA system boundary is the interface between the waste management system and the environment or other product systems. Typically, the life cycle starts once a material or product becomes waste (McDougall et al., 2001). In our case, the start of the life cycle of the waste is the gate of the MBT plant. The end of the life cycle of MSW is when it ceases to be waste by becoming a useful product, residual landfill material or an emission to either air or water (McDougall et al., 2001). Landfill, therefore, is an end of the MSW life cycle. A time horizon of 100 years is taken into account for the calculation of all resulting emissions. The production of useful products

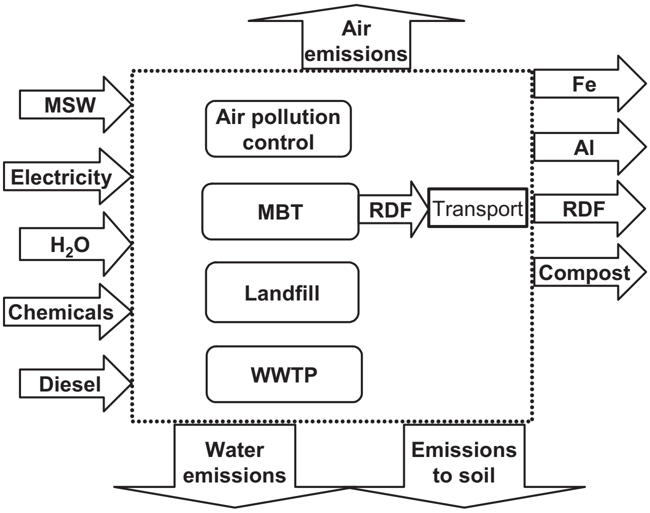

Fig. 1. Boundaries of the main system studied.

resulting from material or energy recovery is also an end of the life cycle of MSW. The main system of the study is the MBT plant. The boundaries of the system are represented graphically by the dotted line in Fig. 1. The system includes (a) the main unit operations of the MBT plant, (b) the wastewater plant for the treatment of the MBT plant leachates, (c) the air emissions control units (strippers and biofilters), (d) transport of materials within the boundaries of the plant, (e) transport of the produced RDF to a cement plant.

Inputs to the system are: mixed MSW, electricity, water, chemicals and transportation fuels. Outputs from the plant are: ferrous and non-ferrous metals, RDF, compost, moisture and residues (solid emissions) in addition to air and water emissions. Note that air and water emissions are accounted for, after the engagement of the pollution control units, i.e. air and water emissions are those that end up in the environment.

MBT plants are multi-output plants. Thus, in order to avoid product allocation, the approach of "system expansion" (Buttol et al., 2007) is engaged. In other words, a useful product derived from the waste system is followed to the point where it can be used. In essence, system expansion implies more information to be gathered (Miliūtė and Staniškis, 2010). In our case, in certain scenarios, we expand our system to include: the RDF utilization in a cement manufacturing plant substitutes the use of brown coal; the compost utilization for soil fertilization substitutes the use of chemical fertilizers; the recycling of metals substitutes the use of virgin raw materials.

The life cycle environmental emissions from the production of capital equipment and infrastructure of the MBT plant, also known as secondary environmental burdens (McDougall et al., 2001), are not included within the present system boundary. Wittmaier et al. (2009) state that experience has shown that for waste treatment plants that have been in operation for many years, the environmental costs of pre- and post-material processing (i.e. the environmental costs resulting from capital equipment and infrastructure) are of minor importance compared with the environmental costs of operating the plant.

3.2. Life cycle inventory

Data for the operation of the MBT plant were provided by the Regional Administration of Attica. The inventory data where then assigned to entries from the SimaPro 5.1 databases.

3.2.1. MSW fed to the MBT plant

As mentioned earlier, the mixed MSW fed to the MBT plant were 251,859 tons/year during 2008. In addition, 7556,200 kg/year of yard trimmings were fed in order to account for porosity control. The percentage composition of the MBT plant inputs and outputs is presented in Table 1. De Feo and Malvano (2009) report results from the MBT plant in Avellino, Italy. Compared to the MBT plant in Ano Liossia, there are similar results reported for the recovery of non ferrous metals and RDF. However the compost percentage in Avellino was double that of the Ano Liossia plant while on the other hand the Ano Liossia plant has double the percentage of the residues ending up in the landfill compared to the Italian plant.

3.2.2. Electricity

In order to account for the electricity consumption of the MBT plant, the actual bills of the Public Power Corporation (PPC) were used. The reference year is 2008. The plant operates for 5 days per week in three shifts, i.e. a year is accounted as 250 days of operation. The total consumption was 10,816 MW.

The mixture of fuels utilized to generate electricity determines the environmental impacts of electricity in each country. Based on the PPC data, the electricity mix in Greece was the following: lignite 51.52%, diesel oil 11.70%, natural gas 15.50%, hydro power 7.70%, other renewables 5.81% and imports 7.77%. Imports were modeled as the average UCPTE electricity mix, from the SimaPro 5.1 database.

Table 1
Composition of input and output streams of the MBT plant.

Input	% w/w	Output	% w/w
Putrescibles	23.80	RDF	39.21
Paper and carton	40.90	Compost	9.84
Leather, wood	2.10	Fe	1.92
Plastic	16.00	Al	0.03
Glass	2.90	Moisture	21.20
Metals	2.10	Residues	27.80
Textiles	3.90	Total	100.00
Inert	2.10	–	–
Other and composites	0.50	–	–
Fines ($d < 10$ mm)	5.60	–	–
Total	100.00	–	–

3.2.3. Water

Water is consumed in the MBT plant for the scrubbers that clean the air from the composting plant as well as for wetting the composting windrows. The underlying assumption is that all of the water, after its utilization, is ending up in the wastewater treatment plant. The water utilized in the MBT plant is 135,000 tons/year.

3.2.4. Chemicals

Chemicals are utilized for scrubbing the air from the composting facility and for odor removal. A 40% w/w solution of H_2SO_4 is utilized in addition to a 12% w/w in active chloride and 0.76% w/w in NaOH solution of NaOCl. These data sum up to an annual consumption of 851,250 kg of NaOCl, 23,793 kg of NaOH and 193,620 kg of H_2SO_4.

3.2.5. Transportation fuels

The fuels utilized for the operation of the utility vehicles (trucks, personnel buses, etc.) within the MBT plant is taken into account. The total diesel oil consumption is 133,333 l/year. The fuels required for the transportation of MSW to the MBT gate is not taken into account.

3.2.6. Outputs

The outputs from the MBT plant are compost, RDF, residues and emissions to water (measured at the exit of the wastewater treatment plant).

3.2.7. Compost

The compost currently produced in the Ano Liossia MBT plant is landfilled due to the lack of suitable markets.

3.2.8. RDF

The RDF produced from the RDF plant has a mean humidity of 27.3% and a lower heating value of 15.5 MJ/kg with a chloride content of 0.4% w/w.

3.3. Impact assessment

The CML 2 baseline 2000 method was used for the life cycle impact assessment. It is a well-established method in the field of MSW LCA, utilized previously by numerous authors (Banar et al., 2009; Hischier et al., 2005; Iriarte et al., 2009; Rives et al., 2010). The six impact categories considered are: abiotic depletion potential (ADP), global warming potential in 100 years horizon (GWP100), acidification potential (AP), eutrophication potential (EP), human toxicity potential (HTP), and photochemical oxidation potential (POP). These are reported to be among the most relevant to MSW management (Cleary, 2009).

4. Scenario development and assumptions

The aim of this paper is to compare on an environmental basis, four different scenarios of the operation of the MBT plant utilizing the LCA methodology. In order to compare the four scenarios in terms of their environmental impacts, a series of qualitative and quantitative data were collected for each scenario. Landfilling is considered as the baseline scenario. Therefore, the analysis of the system is based on a total of five alternative scenarios:

4.1. Baseline scenario (landfilling without any biogas recovery)

The baseline scenario (S0) describes the landfilling of the total MSW without biogas recovery and any prior MSW treatment. In order to quantify the impacts of this scenario, the assumption is that 120 m^3 of biogas (60% v/v CH_4) are produced per ton of MSW landfilled (Obersteiner et al., 2007). The density of CH_4 is taken as 0.68 kg/m^3 (at 15 °C). The land use is estimated based on a density of 1 ton/m^3 of MSW (Obersteiner et al., 2007) in the landfill and a height of 2.5 m. Thus, for 251,859 tons/year an approximate area of 100,000 m^2 is required annually for landfilling. The CO_2 emissions from the landfill are not taken into account since they are biogenic, i.e. they do not derive from fossil fuels. According to Cherubini et al. (2009), in addition to CH_4, other gases released from the landfill are CO, HCl, and HF (emission factors: 13, 65 and 13 mg/m^3 of biogas released). The leachates resulting from the landfill are not taken into account. The baseline scenario is utilized just for the sake of a quick and dirty comparison between landfilling and the operation of the MBT plant.

4.2. Scenario No. 1 (current MBT plant operation)

The first scenario (S1) describes the current operation of the MBT plant. The assessment is based on operational data taken from ACMAR. The data cover a whole year of plant operation, namely year 2008. The land occupation by the MBT plant for scenarios 1–4 is estimated by calculating the amount of materials that end up in the landfill. The rest of the underlying assumptions for scenario 1 are:

- Utilization of 40% of the produced compost for soil fertilization. The utilization of the compost substitutes the use of chemical nitrogen (N) and phosphorus (P) fertilizers.
- Full utilization of the recovered ferrous material (100%). Metal scrap is the material most commonly recovered from material recovery (Consonni et al., 2005). The recovery of iron substitutes the production of new steel. The substitution rate was calculated based on the fact that the production of 1 ton of steel requires 1.19 ton of metal scrap, as reported by Consonni et al. (2005).
- Utilization of the recovered aluminum (85%). The recovery of aluminum substitutes the production of new aluminum.
- Both the produced RDF and the remaining compost are sent to the nearby landfill. Obersteiner et al. (2007) report that after MBT treatment, the biogas generation is 15.6 m^3/ton landfilled and the bulk density of the landfilled material 1.4 ton/m^3.

4.3. Scenario No. 2 (current MBT plant operation + utilization of 100% of the compost)

The second scenario (S2) is based on the current operation of the MBT plant (S1). However, the assumption here is that the whole quantity (100%) of the produced compost is used for soil fertilization. Thus, the material that ends up for landfilling is less, compared to scenario 1. Again, the assumptions for MBT treated material that is landfilled reported by Obersteiner et al. (2007) are utilized. The likelihood of this scenario is quite low due to the fact that an established compost market does not exist in Greece.

4.4. Scenario No. 3 (current MBT plant operation + 55% incineration of the produced RDF in a cement plant)

The third scenario (S3) is also based on the current operation of the MBT plant (S1). However, the alternative here is that part (55%) of the produced RDF is incinerated in a cement plant. The utilization of RDF as a substitute fuel to cement manufacturing plants is well established (Genon and Brizio, 2008; Mokrzycki and Uliasz-Bocheńchyk, 2003; Rotter et al., 2004; Rovira et al., 2010). Since currently no dedicated mixed MSW or RDF incineration facility exists in Greece, the likelihood of this scenario to be implemented in the future is quite high since thermal exploitation of RDF in a cement factory was planed to be the usual mode of operation of the MBT plant in its feasibility study. RDF was supposed to be incinerated in the cement plant in Aliveri, a town approximately 140 km away from Ano Liossia. However, this option was never realized due to the opposition of the local residents. Based on the LHV of the produced RDF presented earlier, the use of the 55% w/w of the RDF substitutes 4821 GJ of coal. The RDF is transported to Aliveri via 28t trucks, which return empty to the MBT plant. The environmental impacts resulting from the transport of RDF are taken into account. However, the emissions resulting from the incineration of RDF in the cement plant are not included in this study since Genon and Brizio (2008) state that it is not easy to distinguish between the contribution of the clinker production process and the contribution of RDF. However, the use of RDF instead of traditional fuels in a cement kiln should not be taken for granted since it could be dangerous in terms of the presence of larger amounts of heavy metals in the waste gas; thus, the quality and the quantity of RDF to be burned should be analyzed in depth (Genon and Brizio, 2008).

4.5. Scenario No. 4 (complete utilization of Fe, Al, compost and RDF)

The fourth and final scenario (S4) describes the complete utilization of the MBT plant products, i.e. 100% utilization of compost as soil fertilizer and 100% incineration of the RDF in Aliveri. Again, the emissions resulting from the cement plant are not taken into account. In terms of product recovery, this scenario is the ideal one, because all MBT products are exploited.

Table 2 sums up the substitution of resources due to the recovery of useful materials from the MBT plant.

5. Results and discussion

This section consists of two parts: at first the input and output flow inventories of the five scenarios are presented; the comparison of the impact assessments follows.

5.1. Main input and output flows

The major input and output flows for the five scenarios are summarized in Table 3. The inputs to the MBT plant are common

Table 2
Substitution of raw materials from recovered MBT materials.

Material recovered from MBT plant	Raw material substituted
RDF	Coal
Compost	Fertilizer (N and P)
Ferrous metals	Steel
Aluminum	Aluminum

for all scenarios but the baseline. In the avoided products section of Table 3, the quantities for the recovered ferrous and non-ferrous metals are identical throughout all four scenarios. The quantities for the recovered compost and RDF shown in Table 3 are based on the respective recovery rates. The emissions to the air are variable among the scenarios due to the different amounts of material landfilled in each one of the scenarios.

5.2. Environmental impact assessment

The current operation of the MBT plant is assessed first; then the operation of the MBT plant is compared to landfilling; finally, the five scenarios are compared in terms of their environmental impact. Table 4 presents the characterization results of the five scenarios in each one of the six impact categories considered. The results in Table 4 are reported on a "per kg of MSW treated" base.

5.2.1. Impact assessment of the current operation of the MBT plant

Fig. 2 presents the characterization results of the current operation of the MBT plant. Percentages above the *x*-axis refer to environmental burdens, while those with negative values refer to environmental gains. The major contributors to the environmental impacts generated by the plant, in order of importance, are the electricity used for the operation of the plant, the diesel consumed for the plant vehicles and the chemicals (sulfuric acid and chlorine) utilized in the air pollution control units of the MBT plant. Electricity consumption contributes to all of the impact categories but eutrophication, while diesel consumption contributes mainly to the eutrophication.

However, the operation of the MBT plant generates also positive environmental outcomes (shown in Fig. 2 as negative numbers below the *x*-axis): the major environmental gains by the operation of the MBT plant result from the recovery of ferrous metals and aluminum, which has a positive impact on all six categories. More specifically the major contribution of ferrous metals recovery is on the reduction of the photochemical oxidation potential while the major contribution of aluminum recovery is on the reduction of the human toxicity potential. The use of compost as P fertilizer contributes positively to the reduction of the eutrophication potential. This finding, i.e. that the recovery of materials improves the environmental performance of an MSW management system, is supported by the findings of other authors too (Banar et al., 2009; Beigl and Salhofer, 2004; Buttol et al., 2007; Güereca et al., 2006; Hischier et al., 2005).

5.2.2. Impact assessment of the operation of the MBT plant vs. landfilling

The next task was to assess the possible environmental benefits that the operation of the MBT plant offers compared to landfilling. Fig. 3 presents the relative characterization results of the operation of the MBT plant vs. landfilling. Again, percentages above the *x*-axis refer to environmental burdens, while those with negative values refer to environmental gains. The three impact categories that the two options can be compared are the global warming potential, the human toxicity potential and the photochemical oxidation potential. In the remaining impact categories, the relative contribution of landfilling is extremely small due to our modeling assumptions. The figure reveals that the operation of the MBT plant

Table 3
Life cycle inventories for the five scenarios.

Flow	Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Baseline scenario
Inputs						
Treated MSW	ton	251,859				251,859
Water	ton	135,000				
Sulfuric acid	kg	193,620				
NAOH	kg	23,793				
Chlorine	kg	102,150				
Diesel	GJ	4821				
Electricity	MW	10,816				
Transport for RDF	tkm	0	0	7,604,051	13,825,548	
Outputs						
Avoided products						
Steel	kg	3,074,400				
Aluminum	kg	99,479				
Fertilizer-N	ton	214	534	214	534	
Fertilizer-P	ton	35	87	35	87	
Coal	GJ	0	0	837,536	1522,792	
Emissions to air						
CH_4	ton	1509	1414	1163	786	12,331
CO	kg	48	45	37	25	393
HCl	kg	240	225	185	125	1965
HF	kg	48	45	37	25	393
Emissions to water						
Dissolved solids	kg	98	91.9	75.5	51.0	
Suspended solids	kg	11	10.3	8.5	5.7	
BOD	kg	5	4.7	3.9	2.6	
COD	kg	51	47.8	39.3	26.6	
N organically bound	kg	15	14.1	11.6	7.8	
Emissions to soil						
Cd	ton	8	21	8	21	
Cr	ton	538	1344	538	1344	
Cu	ton	2601	6503	2601	6503	
Mn	ton	1441	3602	1441	3602	
Pb	ton	671	1677	671	1677	
Zn	ton	4909	12,273	4909	12,273	
Ni	ton	786	1964	786	1964	
Non-material emission						
Landfill area occupation	m^2	67,727	63,479	52,209	35,263	100,744

Table 4
Life cycle characterization results.

Impact	Indicator	Baseline	S1	S2	S3	S4
Abiotic depletion	kg Sb eq.	0	1.51E-4	1.35E-4	2.39E-3	4.48E-3
Acidification	kg SO_2 eq.	0	1.66E-4	1.61E-4	−2.31E-3	−4.35E-3
Eutrophication	kg PO_4^{3-} eq.	0	−8.61E-6	−2.28E-5	−1.15E-4	−2.16E-4
Global warming 100 years	kg CO_2 eq.	1.03	0.15	0.14	−0.214	−0.521
Human toxicity	kg 1,4-DB eq.	4.53E-3	−0.0125	−0.0126	4.26E-4	−0.303
Photochemical oxidation	kg C_2H_2	2.94E-4	3.19E-5	2.94E-5	−7.85E-5	−1.71E-4

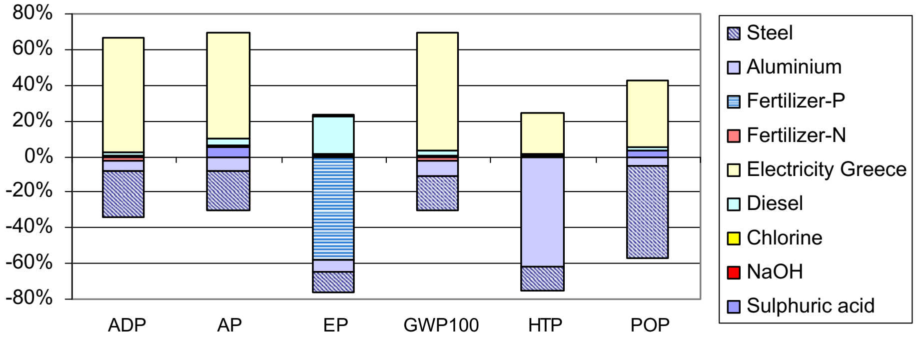

Fig. 2. Characterization results of the current operation of the MBT plant in Attica (% refer to the contribution of each inventory material to the respective impact category, i.e. ADP: abiotic depletion, AP: acidification, EP: eutrophication, GWP100: global warming in a 100 years horizon, HTP: human toxicity, POP: photochemical oxidation).

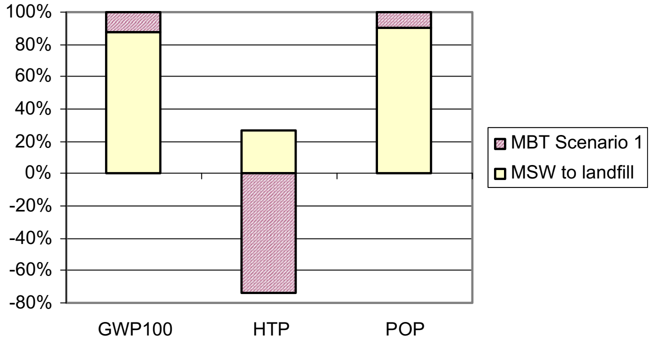

Fig. 3. Characterization results: MBT plant operation vs. landfilling (% refer to the contribution of each scenario to the respective impact category, i.e. GWP100: global warming in a 100 years horizon, HTP: human toxicity, POP: photochemical oxidation).

has a relative positive environmental impact in the human toxicity potential. The operation of the MBT plants is also preferable to landfilling even if we compare its relative impact on global warming potential and photochemical oxidation potential. Landfills are reported to be the worst options when compared to other MSW management systems (Cherubini et al., 2009; Mendes et al., 2004).

5.2.3. Comparison of impact assessments for all five scenarios

The final comparison will be among all five alternative scenarios, i.e. landfilling, the current MBT plant operation, and its three enhancements. Table 4 presents the characterization results of the five scenarios in each one of the six impact categories of considered in our study. The comparative results are analyzed per impact category:

5.2.3.1. Abiotic depletion. Each one of the four scenarios involving the MBT plant has an impact on abiotic depletion. S4 and S3 have the highest impacts on ADP due to consumption of fossil fuels for the transport of RDF to the cement plant. The environmental burdens of transporting the RDF prove to be higher than the credits from the substitution of coal in the cement plant.

5.2.3.2. Acidification. S1 and S2 have the highest impact on acidification due to reduction in the AP achieved by the substitution of coal by the RDF in S4 and S3. The higher the amount of coal substituted, the higher the gains in terms of AP reduction. S2 is better than S1 because of its higher percentage of compost utilization as fertilizer.

5.2.3.3. Eutrophication. It is noteworthy that all four scenarios involving the MBT plant have a positive impact on EP. S4 is the best option, due to the higher substitution of coal by RDF. The burdens set by the RDF transport cannot negate the environmental credits by the coal substitution.

5.2.3.4. Global warming. Landfilling has the highest impact on global warming. The operation of the MBT plant (S1) lowers the GWP100 to almost 15% of the landfill scenario respective value. Moreover, the increase in the percentage of RDF utilized at the cement plant, creates a positive impact on the global warming potential. S4 is the best option in this impact category.

5.2.3.5. Human toxicity. The operation of the MBT plant (S1) lowers the human toxicity potential. Again, the best result is achieved by the S4, i.e. the scenario with the highest utilization of RDF in the cement plant.

5.2.3.6. Photochemical oxidation. Landfilling has the most adverse impact on POP. The operation of the MBT plant (S1) improves the situation. However, the best result is achieved, once more, by S4.

Based on the aforementioned results, the critical factor for the improvement of the environmental performance is the percentage of RDF that is utilized in the cement plant. Exploitation of MSW for energy generation has been found to be a good way to improve the environmental performance of MSW management systems by various other authors, too (Buttol et al., 2007; Cherubini et al., 2009; Papageorgiou et al., 2009; Riber et al., 2008; Rodríguez-Iglesias et al., 2003; Wanichpongpan and Gheewala, 2007; Wittmaier et al., 2009). However, in our modeling we didn't consider the effect of the use of RDF on the cement plant waste gas stream. Genon and Brizio (2008) clearly state that the use of RDF instead of traditional fuels in a cement kiln could be dangerous in terms of the presence of larger amounts of heavy metals in the waste gas. As Rotter et al. (2004) report, quality of the RDF, in terms of its chemical characteristics, is the key issue towards the future success of RDF markets in Europe.

6. Conclusions

The environmental impact of a specific MBT plant has been studied using LCA, based on actual operating data. Five waste treatment scenarios for the residual MSW in the region of Attica, Greece were analyzed. Four of them involved the various alternatives of the utilization of the MBT plant products. The other, the baseline scenario, dealt with the GHG emission impacts generated by landfilling. Taking into account the assumptions and limitations of the study, results indicate that even the current operation of the MBT plant (S1) is preferable to landfilling. Among the scenarios of MBT operation, the one with complete utilization of the MBT material outputs (S4), i.e. compost, RDF, ferrous and non-ferrous metals, is the one that generates the most environmental gains. Moreover, our analysis indicates that the exploitation of RDF in a cement plant is the key factor towards improving the environmental performance of the MBT plant. On the other hand, a key limitation of this study is that a potential emission source (i.e. the cement plant) has not been included due to lack of actual data.

Overall, the findings of the present study clearly demonstrate the environmental benefits that an MBT plant offers compared to landfilling. These environmental benefits result from both the material recovery and the thermal exploitation of the generated RDF. These benefits are strengthened provided that there is an established market for the MBT plant products, which is not the case for the present status of MSW management in Greece. To better benchmark the findings of the current study further work on other specific MBT plants, utilizing different technology options from the wide MBT family would be useful. Moreover, the development of LCA impact indicators better adapted to the Mediterranean conditions (e.g. water scarcity, desertification) could provide a better insight of the life cycle impact of MBT.

References

Abeliotis, K., 2011. Life Cycle Assessment in Municipal Solid Waste Management, Integrated Waste Management, vol. 1. In: Sunil Kumar, (Ed.), ISBN: 978-953-307-469-6, InTech, Available from: <http://www.intechopen.com/articles/show/title/life-cycle-assessment-in-municipal-solid-waste-management>.

Banar, M., Cokaygil, Z., Ozkan, A., 2009. Life cycle assessment of solid waste management options for Eskisehir, Turkey. Waste Management 29, 54–62.

Beigl, P., Salhofer, S., 2004. Comparison of ecological effects and costs of communal waste management systems. Resources, Conservation and Recycling 41, 83–102.

Briffaerts, K., Spirinckx, C., Van der Linden, A., Vrancken, K., 2009. Waste battery treatment options: comparing their environmental performance. Waste Management 29, 2321–2331.

Buttol, P., Masoni, P., Bonoli, A., Goldoni, S., Belladonna, V., Cavazzuti, C., 2007. LCA of integrated MSW management systems: case study of the Bologna District. Waste Management 27, 1059–1070.

Chaya, W., Gheewala, S.H., 2007. Life cycle assessment of MSW-to-energy schemes in Thailand. Journal of Cleaner Production 15, 1463–1468.

Chen, D., Christensen, T.H., 2010. Life-cycle assessment (EASEWASTE) of two municipal solid waste incineration technologies in China. Waste Management and Research 28 (6), 508–519.

Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of waste management strategies: landfilling, sorting plant and incineration. Energy 34, 2116–2123.

Cleary, J., 2009. Life cycle assessments of municipal solid waste management systems: a comparative analysis of selected peer-reviewed literature. Environment International 35, 1256–1266.

Consonni, S., Giugliano, M., Grosso, M., 2005. Alternative strategies for energy recovery from municipal solid waste part B: emission and cost estimates. Waste Management 25, 137–148.

De Feo, G., Malvano, C., 2009. The use of LCA in selecting the best management system. Waste Management 29, 1901–1915.

Del Borghi, A., Gallo, M., Del Borghi, M., 2009. A survey of life cycle approaches in waste management. International Journal of Life Cycle Assessment 14, 597–610.

Economopoulos, A.P., 2010. Technoeconomic aspects of alternative municipal solid wastes treatment methods. Waste Management 30, 707–715.

Farrell, M., Jones, D.L., 2009. Critical evaluation of municipal solid waste composting and potential compost markets. Bioresource Technology 100, 4301–4310.

Fruergaard, T., Astrup, T., 2011. Optimal utilization of waste-to-energy in an LCA perspective. Waste Management 31, 572–582.

Genon, G., Brizio, E., 2008. Perspectives and limits for cement kilns as a destination for RDF. Waste Management 28, 2375–2385.

Güereca, L.P., Gassó, S., Baldasano, J.M., Jiménez-Guerrero, P., 2006. Life cycle assessment of two biowaste management systems for Barcelona, Spain. Resources, Conservation and Recycling 49, 32–48.

Hischier, R., Wäger, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environmental Impact Assessment Review 25, 525–539.

Iriarte, A., Gabarell, X., Rieradevall, J., 2009. LCA of selective waste collection systems in dense urban areas. Waste Management 29, 903–914.

ISO 14040, 2006. Environmental management-life cycle assessment-requirements and guidelines. International Organisation for Standardisation (ISO), Geneva.

Khoo, H.H., 2009. Life cycle impact assessment of various conversion technologies. Waste Management 29, 1892–1900.

Lasaridi, K.E., 2009. Implementing the Landfill Directive in Greece: problems, perspectives and lessons to be learned. The Geographical Journal 175, 261–273.

Liamsanguan, C., Gheewala, S.H., 2008. LCA: a decision support tool for environmental assessment of MSW management systems. Journal of Environmental Management 87, 132–138.

Martínez-Blanco, J., Colón, J., Gabarrell, X., Font, X., Sánchez, A., Artola, A., Rieradevall, J., 2010. The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Management 30, 983–994.

McDougall, F.R., White, P., Franke, M., Hindle, P., 2001. Integrated Waste Management: A Life Cycle Inventory, second ed. Blackwell Science, Oxford, UK.

Mendes, M.R., Aramaki, T., Hanaki, K., 2004. Comparison of the environmental impact of incineration and landfilling in Sao Paulo city as determined by LCA. Resources, Conservation and Recycling 41, 47–63.

Miliūtė, J., Staniškis, J.K., 2010. Application of life-cycle assessment in optimisation of municipal waste management systems: the case of Lithuania. Waste Management and Research 28, 298–308.

Mokrzycki, E., Uliasz-Bocheńchyk, A., 2003. Alternative fuels for the cement industry. Applied Energy 74, 95–100.

Obersteiner, G., Binner, E., Mostbauer, P., Salhofer, S., 2007. Landfill modelling in LCA – A contribution based on empirical data. Waste Management 27, S58–S74.

Özeler, D., Yetis, Ü., Demirer, G.N., 2006. Life cycle assessment of municipal solid waste management methods: Ankara case study. Environment International 32, 405–411.

Papageorgiou, A., Karagiannidis, A., Barton, J.R., Kalogirou, E., 2009. Municipal solid waste management scenarios for Attica and their greenhouse gas emission impact. Waste Management and Research 27, 928–937.

PRé Consultants, 2003. SimaPro 5 Database Manual.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.T., Suh, S., Weidema, B.P., Pennington, A.W., 2004. Life cycle assessment – Part 1: framework, goal and scope definition, inventory analysis, and applications. Environment International 30, 701–720.

Riber, C., Bhander, G.S., Christensen, T.H., 2008. Environmental assessment of waste incineration in a life-cycle-perspective (EASEWASTE). Waste Management and Research 26, 96–103.

Rives, J., Rieradevall, J., Gabarell, X., 2010. LCA comparison of container systems in municipal solid waste management. Waste management 30, 949–957.

Rodríguez-Iglesias, J., Marañón, E., Castrillón, L., Riestra, P., Sastre, H., 2003. Life cycle analysis of municipal solid waste management possibilities in Asturias, Spain. Waste Management and Research 21, 535–548.

Rotter, V.S., Kost, T., Winkler, J., Bilitewski, B., 2004. Material flow analysis of RDF-production processes. Waste Management 24, 1005–1021.

Rovira, J., Mari, M., Nadal, M., Schumacher, M., Domingo, J.L., 2010. Partial replacement of fossil fuel in a cement plant: risk assessment for the population living in the neighborhood. Science of the Total Environment 408, 5372–5380.

Velis, C.A., Longhurst, P.J., Drew, G.H., Smith, R., Pollard, S.J.T., 2009. Biodrying for mechanical-biological treatment of wastes: a review of process science and engineering. Bioresource Technology 100, 2747–2761.

Wanichpongpan, W., Gheewala, S.H., 2007. Life cycle assessment as a decision support tool for landfill gas-to energy projects. Journal of Cleaner Production 15, 1819–1826.

Winkler, J., Bilitewski, B., 2007. Comparative evaluation of life cycle assessment models for solid waste management. Waste Management 27, 1021–1031.

Wittmaier, W., Langer, S., Sawilla, B., 2009. Possibilities and limitations of life cycle assessment (LCA) in the development of waste utilization systems – Applied examples for a region in Northern Germany. Waste Management 29, 1732–1738.