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Life cycle assessment of municipal waste management options

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ABSTRACT

To date, landfilling remains the most common waste management practice in Greece in spite of enforced regulations aiming at increasing recycling, pre-selection of waste and energy and material recovery. In this study, selected alternative scenarios aiming at minimizing the unused material fraction to be disposed of in landfills are analyzed, using the life cycle assessment methodology. The methodology was applied in the case of municipal solid waste (MSW) management in Athens and Thessaloniki, with a special focus on energy and material balance, including potential global and local scale airborne emissions. Results are given in the form of indices efficiency, effectiveness, environmental and public health impacts. Material flow accounting, gross energy requirement, emergy intensity, emission and release intensity and morbidity or mortality indicators have been used to support the comparative assessment. However, not all options are equally benign to the local environment and to the health of the local population, since both the former and the latter are still affected by non-negligible local emissions. With regard to public health impacts, adverse effects on respiratory health, congenital malformations, low birth weight and cancer incidence were estimated. A significant and not intuitive result is the fact that life cycle analysis produces different conclusions than a simple environmental impact assessment based only on estimated or measured emissions. Taking into account the overall life cycle of both the waste streams and of the technological systems and facilities envisaged alters the relative attractiveness of the solutions considered.

1. Introduction

Over the last twenty years global consumption of products and natural resources has been rapidly increasing and the amount of waste generated by mankind has raised significant concerns over the associated burden on environmental degradation and human health. However, the conventional notion of waste is ill-defined. In a sustainable society waste should be thought of as raw materials, which can be utilized for use in other economic sectors (Allenby and Richards, 1994; Berry and Rondinelli, 1998). In a sustainable future, waste disposal methods would be transformed to ensure an ecological balance with the intention that this vital resource does not harm the environment or human health.

Despite the high rate of technological progress in the field of waste management, people living close to waste disposal and treatment sites can be exposed to potentially harmful substances. The lack of precise exposure to waste emissions and the difficulty to interpret and compare the related health effects, as well as the quantification of environmental risks among the various waste management options remains a controversial issue that has been highlighted in a number of studies (Bocca et al., 2016; Kuehn et al., 2007; Mattiello et al., 2013; Russi et al., 2008). Multiple waste treatment options aiming at zero waste have been brought forward recently; yet, cost-effective solid waste management still remains a great challenge for environmental decision-makers (Marshall and Farahbakhsh, 2013).

Greece currently faces several significant changes regarding municipal solid waste (MSW) management. Over the last twenty years, Greek national government and city authorities alike have not kept at pace with their European counterparts. In contrast to the current trends in MSW management in European Union member states, landfilling remains the dominant waste management options in Greece (Buclet and Godard, 2013). In the EU-27 38% of urban waste goes to sanitary

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landfills, 20% is incinerated, 24% is recycled and 18% is used for composting. The respective values in Greece are as follows: 81% of urban waste goes to sanitary landfills, 18% is recycled and 1% is used for production of compost (Sarigiannis, 2015).

European and national waste legislation, public pressure and awareness of the adverse impacts of municipal waste on environmental and human health are expected to create the impetus for change in Greece as well. This leads to the need for an overhaul of urban waste management in the country introducing sustainable integrated treatments capable of managing the municipal waste stream complexity. Such management strategies should be based on advanced treatment processes and technologies reinforced by recycling, pre-selection of waste, energy and material recovery. The conclusions of the study presented herein are highly relevant for EU Member States other than Greece, such as the Czech Republic, Slovakia, Cyprus, Latvia, Lithuania, Croatia, Romania, Bulgaria. All of these countries are characterized by enhanced waste streams ending up in landfills (from 83% to 100% of total).

Life cycle assessment (LCA) can been used as a key analytical tool by environmental decision makers. In particular, LCA is applied to evaluate products and processes with regard to their environmental burden during their life starting from raw material acquisition to production/process implementation, use and disposal (IOFS, 2006; Rebitzer et al., 2004). Methodologically, LCA consists of goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle interpretation according to ISO 14040 (IOFS, 2006). In particular over the last ten years, LCA has been extensively used in studies related to MSW management to evaluate and assess waste treatment systems (Björklund and Finnveden, 2005; Den Boer et al., 2007; Emery et al., 2007; Koroneos and Nanaki, 2012; Pires et al., 2011; Zaman, 2010). None of these studies, however, have considered the exposome, i.e. the integrated exposure of humans to chemical and biological releases emanating from the waste management system in a life cycle perspective. This is the gap that the methodological extension of LCA proposed in this paper comes to fill in, namely, to couple life cycle analysis with exposome-based health impact assessment in addition to the conventional life cycle impact assessment aspects.

LCA has been applied to different urban solid waste management strategies of large municipalities and variations in the examined waste stream, aiming at the comparison of different technologies (Banar et al., 2009; Cherubini et al., 2009). Moreover, LCA has been also used for the evaluation of single processes of selected scenarios of urban areas (Iriarte et al., 2009; Scipioni et al., 2009). Last but not least, LCA has been carried out in analyzing energy demands and emission on different subsequent of MSW treatments (Montejo et al., 2013; Rigamonti et al., 2009). Finally, assessment of the health impacts of waste management option is of great importance, considering the continuously growing body of evidence related to the health effects associated to waste disposal (Giusti, 2009; Porta et al., 2009; Rushton, 2003).

In the present study, LCA is carried out aiming at assessing municipal solid waste management options in the two largest cities of Greece, namely Athens and Thessaloniki. Towards this aim, the most significant variables are examined, by considering energy and material balances, including potential global and local scale airborne emissions, groundwater and soil releases. In addition, the overall analysis evaluates the impacts related to the investigated scenarios, based on state-of-the-art waste treatment techniques and compares them with the current waste disposal facilities. The aforementioned comparative assessment framework is enchanted taking advantage of indicators related to flow accounting, gross energy requirement, emergy intensity, airborne emissions release intensity and the associated morbidity and mortality. Finally, the study aims at the enhancement of integrated waste management treatment approaches that minimize the material fraction disposed of in landfills. A major advantage of this study is that human exposure and the related health impact is introduced in the decision-making process for the comprehensive evaluation of the waste management options.

2. Methodology

2.1. Description of study area

The present study focuses on integrated strategies for municipal solid waste management in two areas:

- Ombriokastro Kerateas – covering the needs of Athens and mainly the waste produced by the eastern Attica region.
- Central part of the greater Thessaloniki metropolitan area.

The area of Ombriokastro Kerateas is claimed to be the most appropriate site for the disposal and administration of the waste streams produced in Eastern Attica according to the latest studies undertaken by the Organisation for Planning and Environmental Protection of Athens (OPEPA, 2009), Ombriokastro borders with the industrial zone of Eastern Attica and is 7 km far from the city of Keratea. The average amount of municipal solid waste is equal to 125.5 ktn/yr, which corresponds to 376,000 out of the 4,500,000 inhabitants of the whole Attica region (Hellenic Statistical Authority, 2008). The composition of the waste in eastern Attica varies. It includes organics, paper, plastic, metal, and other material. The average transportation distance of the MSW is 19 km.

The MSW generated in the city of Thessaloniki is 121 ktn/yr and corresponds to 364,000 inhabitants (Hellenic Statistical Authority, 2008). The composition of waste in Thessaloniki is like the one in Athens with some differences based on different intensity of seasonal activities such as tourism. The average transportation distance of the MSW is 25 km.

2.2. Description of management scenarios

In this study, integrated waste management strategies have been analyzed instead of just exploring the life cycle impacts of single technologies. Our objective is not to intercompare single management options and/or technologies, but rather to assess integrated waste management strategies that are deemed to be plausible for the large urban centers in Greece. Thus, the management scenarios studied and intercompared in this study are as follows (Fig. 1a–d):

- Scenario 1: In this case, all the waste generated from the cities directly go to landfill without any pre-treatment or pre-sorting. There is no recovery of material or energy (Fig. 1a).
- Scenario 2: Waste with no pre-treatment goes to landfill with collection of the biogas produced in situ for the use of energy generation (Fig. 1b).
- Scenario 3: Waste is pre-treated and pre-sorted into biodegradable and non-biodegradable material for further anaerobic digestion and composting. Residues end in landfill. Plastic, paper and ferrous material are recycled (Fig. 1c).
- Scenario 4: Waste without any pre-treatment or pre-sorting goes directly for combustion to the incinerator for electricity production (Fig. 1d).

Clearly, more scenarios integrating different technological options are available in theory or based on current European and International practice. However, the choice of the four scenarios analyzed herein was based on (a) pragmatic solutions that could be practical in Greece now; and (b) on the opportunity to demonstrate the life cycle impact of clearly contrasting options, thereby attempting to shed light in all aspects of current waste management in Greece avoiding to introduce any kind of bias and allowing actual field data to drive our results.

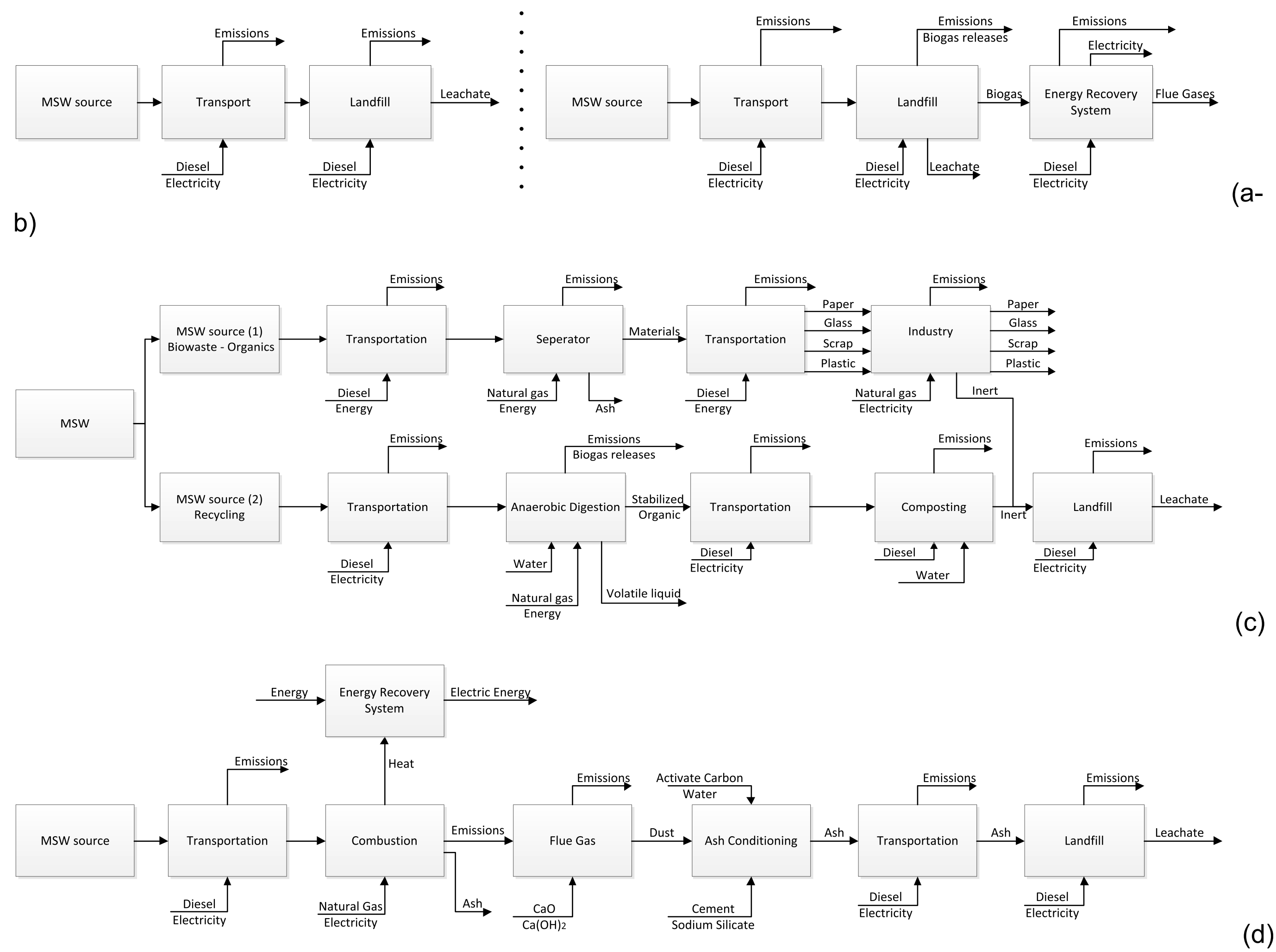

Fig. 1. Flowchart of technological scenarios 1–4 (Fig. 1a–d).

2.3. Lifecycle analysis methodology

Life cycle assessment is a system analysis tool used to describe the environmental impacts of products and processes while assessing the material and energy flows throughout their lifetime. The basic phases of an LCA include collection of the data on all environmental interventions in the unit processes (inventory phase), conversion of inventory data into environmental effects (impact assessment phase) and interpretation of the results in relation to the objectives of the study (Finnveden et al., 2000).

The methodological framework applied to the waste management system analysis given herein is an extended life cycle analysis, as various aspects should be taken into consideration. LCA is time and data intensive; thus, system boundaries need to be drawn carefully to include all relevant processes and procedures. This implies that all inflows should be found in the system boundary between the environment and the technosphere and all the outflows should be traced where emissions leave the technosphere (Crank, 1975). Two are the most significant categories of LCA for municipal solid waste management: the upstream method, which studies the amount of resources utilized per unit of product and the downstream method that focuses on the fate of system emissions (Sundvist, 1999). The functional unit (FU), i.e. the metric of the system operation against which environmental missions/releases and impacts of an LCA are reckoned is the most important factor to perform a good comparison among the studied scenarios. In the case of LCA of MSW the functional unit is the fixed quantity of waste generated which contains combustible, recyclable and biodegradable material (Clift et al., 2000). We chose not to use more sophisticated FUs, such as the potential of the waste as combustible or as recyclable and biodegradable material in order to avoid introducing bias towards specific waste management options in the intercomparison analysis.

According to ISO 14040 in comparative studies such as this one, it is necessary to evaluate the systems before analyzing the results. Systems are only compared using the same functional units and similar methodological considerations including performance, system boundaries, data quality, allocation procedures, decision rules on evaluating inputs and outputs and impact assessment.

In order to have a more comprehensive picture at different scales of MSW management, further studies are essential for more developed LCA-approaches which will integrate health, socio-economic and environmental aspects (Ulgiati et al., 2007). Suitable approaches applicable at different scales (local, regional, global) are selected and designed in such a way as to complement each other. Therefore, each approach will provide information for different scales and their integration will supply an overall picture of the system. The choice of the set of the approaches used is very important. The integrated methodology for waste management assessment used herein will be further analyzed (Ulgiati et al., 2007) in the sections below.

2.3.1. Functional unit

The functional unit for all four scenarios to derive the Life Cycle Analysis is a unit mass of the waste generated in the two largest cities of

Greece.

Fig. 2 presents the consistent elements of the MSW of Athens and Thessaloniki respectively.

2.3.2. System boundaries

The LCA system boundary consists of the interface between the waste management system and the environment. The process of the LCA begins once a product becomes waste and ends when it is no longer a waste but a useful product or as a residual landfilling material or an emission to the air or water (Abeliotis et al., 2012). Energy recovered from waste is considered a useful product as well. A timeframe of 20 years is taken into account for the present study. The boundaries of the systems are graphically shown in the schemes depicted in Fig. 1. The main input of the system is mixed MSW. Waste collection in both cities is based on heavy duty diesel-fueled trucks.

Scenario 1: The waste is un-pre-sorted from bins located at the sidewalks or roadside of the cities. Once disposed into the landfill, waste undergoes decomposition under anaerobic conditions releasing landfill gas. In this scenario that gas is not collected. The gas consists of CH_4, CO_2 and small amounts of H_2S, HCl, HF. Mercury and cadmium, which are the most volatile of the heavy metals, are also released to the atmosphere. Significant attention is given to leachate emissions as it can damage the underground water. The residues of scenarios 2, 3 and 4 go to landfills, therefore the airborne emissions and the leachate emissions of landfilling are evaluated in detail.

Scenario 2: As in Scenario1 the mixed waste is disposed in landfills. In this scenario though the biogas released naturally from landfilling is collected by pipes, treated and used to produce electricity. It is estimated that 50% of the total biogas is used whereas the remaining biogas fraction is either released to the atmosphere or burnt in flares. The emissions released during biogas combustion in flares are CO, NO_2, HCl, HF and dioxins. The biogas is burnt in turbines in order to produce 2.43E+08 kWh of electricity per year (Cherubini et al., 2008). The total energy content of the collected biogas is expected to be 3.12E+09 MJ.

Scenario 3: MSW is separated at the sorting plant where waste is pretreated and pre-sorted into biodegradable and non-biodegradable fraction. The biodegradable material consists mainly of kitchen garbage and the non-biodegradable material such as plastics, paper, cardboard, wood and other material. The biodegradable fraction goes through anaerobic digestion process to produce biogas and a soil conditioning material. Biogas contains 50–65% CH_4, 35–50% CO_2 and 200–4000 vpm H_2S. Chemicals such as N and P are added to maintain pH and supply nutrients. The digestate product which remains as the residue inside the reactor undergoes a composting process to produce a well stabilized compost product with a fraction of C/N equal to 15–18. The remaining residues of a compost process are disposed of to landfills. The inorganic fraction which includes paper, plastic, glass and ferrous metals is delivered to recycling processes.

Scenario 4: The MSW collected is directly delivered to an incinerator plant to be burnt for electricity production. No pretreatment was carried out. The bottom ashes and the residues of the flue gas treatment are sent to landfills.

2.3.3. Environmental impacts

The impact distribution procedure applied in this study was consequential LCA, i.e. our analysis focused on assessing the full share of the activities that are expected to change when the different waste management scenarios considered are implemented. The reason for this choice was because the main purpose of this study was to deliver ready-to-use tools that couple exposome and life cycle analyses into an integrated assessment system that can be used for decision support.

The LCA developed herein considers the environmental and health impacts of both waste treatment and processing technologies considered in the four technological scenarios laid out above and all up- and downstream processes around the main technological options assessed. The impacts of upstream and downstream processes are accounted for using data from state-of-the-art LC databases such as Eco-Invent, GEMIS 4.2 and SimaPro 9.1. The respective impact factors relevant for different upstream (energy carriers, raw materials, auxiliary streams, transport mode of the waste streams through the system) and downstream processes (recycling, composting, incineration, anaerobic digestion, use of waste as SRF/RDF in energy-consuming industry such as cement plants) have been chosen to be representative of general markets so as to render the assessment widely usable. In cases such as transport mode and means for waste streams country-specific data have been used, taking into account the most recent data found in the databases mentioned above.

2.3.3.1. Material flow accounting. Material input and output flows cause serious environmental problems. Consequently, quality assessment and quantification of the process material input-output (products, co-products, emissions) are essential (Ščasný et al., 2003). The environmental disturbance which is provoked by the material flow removal from its previous ecosystem pathways can be evaluated by the quantitative method derived by Material Intensity Factors (Material Input Per service units) (Cherubini et al., 2008). MI factors for processes and substances were estimated by Ritthoff et al. (2002) and were used in the present study. The analysis method used to evaluate environmental disruption is called Material Intensity Analysis (MIA). All input material of the system belongs in 4 categories namely, abiotic matter, biotic matter, water and air. Each input quantity of the material (i.e. concrete, diesel, HDPE etc.) entering the system is multiplied by the Material

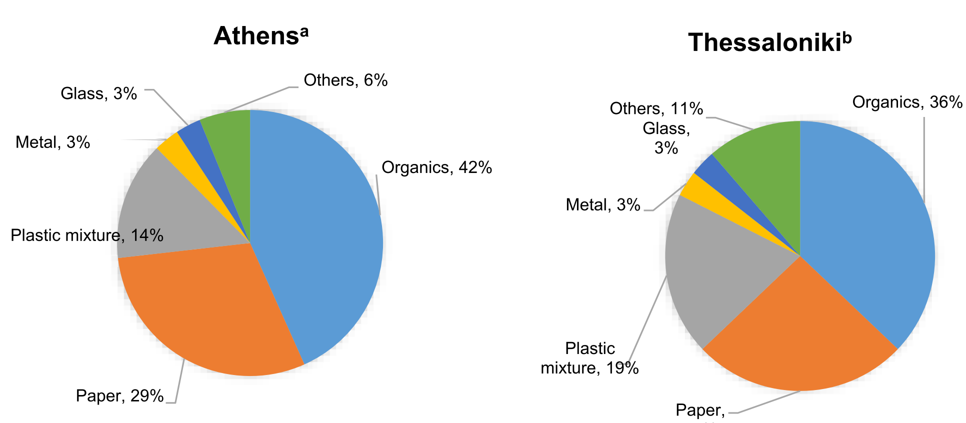

Fig. 2. Composition of waste in cities [a]: information taken by HSWMA (2011), [b]: information taken by Chatziangelou (2007) (the values of the figures are presented in Table S 1).

Intensity Factor of the input material respectively (g/unit) in order to provide the Material Input of the system (Ballesteros-Gómez et al., 2009). The resulting Material Inputs are separately summed based on the environmental compartment in which they belong (abiotic, biotic, water and air) (Ritthoff et al., 2002).

2.3.3.2. Gross energy requirement (GER). Energy Analysis is the tool to identify the gross energy (fossil and fossil equivalent energy) required directly or indirectly to allow the analyzed system to produce a specified good or service. G.E.R is expressed in energy units per physical unit of good or service. G.E.R concerns those goods that demand the consumption of fossil fuels and fossil equivalent resources for their production (Franzese et al., 2009). The Energy Analysis method focuses on the machinery, the assets and the fuel and electricity applied in the process in terms of the oil equivalent energy which is vital for their production (Herendeen, 2004). Therefore, the raw amount of the input is multiplied by an oil equivalent factor (g/unit). The total commercial energy requirement of one unit of output in terms of equivalent Joules of petroleum oil is called Gross Energy Requirement (Cherubini et al., 2008).

2.3.3.3. Emergy accounting. Emergy synthesis uses broader spatial and time frames and accounts for both natural and economic resources. In so doing, it takes into consideration different forms of energy, materials, human labor and economic services on a common basis by converting them into equivalents of only one form of energy (wind kinetic energy, solar radiation or rain evapotranspired) (Franzese et al., 2009). According to Marchettini et al. (2006) emergy analysis can provide decisional support tool as it can distinguish renewable from non-renewable inputs and local from external inputs providing decision makers with emergy-based indicators. Emergy accounting is a way to investigate the environmental support to a process and to study the interactions between the ecosystem and human activities. All energy inputs are accounted for in terms of their solar emergy which is the total amount of solar available energy (exergy) directly or indirectly required to make a product or support a given flow and measured in solar equivalent Joules (seJ) (Jorgensen et al., 2004). The solar transformity defined as emergy per unit flow or unit product is required so as to convert all processes flows into this common energy basis (Marchettini et al., 2006). The total emergy is the sum of local and external emergy inputs. The interpretation of the previous statement is that the higher the ratio the higher the relative contribution of the local sources of emergy in the system (Ulgiati et al., 2007). The total emergy requirement indicates the total environmental service by the analyzed human activity. It is necessary to quantify the energy and materials saved from different waste management options while using the same unit of measure for energy, money and material costs (Marchettini et al., 2006).

2.3.4. Direct health impacts

The health impacts from direct emissions/releases of toxicants into the environment from the waste treatment technologies considered in the integrated management scenarios analyzed in this study were estimated. We focused on long-term mortality and morbidity including carcinogenicity considering the excess risk over forty years (a mean interval depicting the period after first exposure for the average population). All impacts of the LCA considered in this work are estimated over the same time period in order to render all impacts intercomparable, accounting for the impact related to infrastructure interventions.

The assessment of the health effects due to the operation of landfills and incinerators, was based on the study previously carried out by Forastiere et al. (2011). Due to multiple environmental pressures related to the operation of these SWM options (Porta et al., 2009), a hybrid methodology was followed; For assessing the health risks imposed by the operation of the incinerators, the excess risk values reported by Elliott et al. (2009) of cancer for incinerators, as well as the effect of long term mortality due to PM and NO_2 inhalation exposure were employed. For landfills, the health impact indicators employed were congenital malformations and low birth weights (Porta et al., 2009). Finally, in order to be able to compare the different type of health impacts related to the available waste management options, the all related health impacts were translated into disability adjusted life years (DALYs).

In the study carried out by Elliott et al. (2009), cancer incidence between 1974 and 1987 among over 14 million people living near 72 solid waste incinerator plants in Great Britain were studied. The excess risk estimate for living within 3 km of an incinerator for all cancers combined was 3.5%. The use of an overall indicator of cancer risk, has the advantage that incorporates the combined effect of multiple pollutants, pathways and routes of exposure related to the multimedia contamination of the wider area caused by the operation of the incinerator.

The basic formula to compute the number of cancer cases attributable to an incinerator is:

$$AC = Rate_{unex} \cdot ER \cdot Pop_{exp}$$

where $\boldsymbol{AC}$ is the attributable cancer incidence, $\boldsymbol{Rate_{unex}}$ is the background incidence rate in the general population, $\boldsymbol{ER}$ is the excess risk in the exposed population (relative risk - 1) and $\boldsymbol{Pop_{exp}}$ is number of exposed people. Forastiere et al. (2011) assumed that the excess risk is not constant over time, but varies for a specific individual of the population at a given age and specific time as a function of various characteristics, such as level of cumulative exposure, latency since first exposure and latency since cessation of exposure (related to the operation of the incinerator). Therefore a theoretical model of cancer occurrence was assumed and they imputed the varying excess risk around different incinerators, as a function of the different characteristics of the plant and of the nearby population (Forastiere et al., 2011). Background specific cancer incidence data for Greece, were retrieved from the study carried out by Ferlay et al. (2010).

Linear and no-threshold exposure-response functions related to the long-term effects on mortality from PM_{10} and NO_2 have been derived from the extensive existing reviews of epidemiological and toxicological data (Ferrer et al., 2011). The following values were used:

RR = 1.06 (95% CI = 1.03–1.09) increase in mortality for 10 $\mu g/m^3$ PM_{10}

RR = 1.06 (95% CI = 1.04–1.08) increase in mortality for 10 $\mu g/m^3$ NO_2

Attributable mortality risk was expressed in Years of Life Lost as done by Miller and Hurley (2003), assuming constant future birth rates, constant hazard rates over time and immediate mortality effects after change in population-weighted exposure (no lag).

Critical component for the estimation of attributable mortality is population exposure, which in turn is based on the calculation of ambient air concentrations for a range of 3 km around the incinerator. For this purpose, the Industrial Source Complex - Short Term regulatory air dispersion model (ISCST3) was employed. The latter is a steady-state Gaussian plume model developed and recommended by USEPA for use to assess pollution concentration and/or deposition flux on receptors from a wide variety of sources. The model, which is described in the User's Guide for the Industrial Source Complex (ISC3) Dispersion Models (USEPA, 1995), has the ability to calculate airborne and deposition pollutant concentrations from one or more point, area or volume sources based on hourly meteorological data. It has the capability of calculating pollutant concentrations at locations where the plume from the exhaust stack is affected by the aerodynamic wakes and eddies (downwash) produced by nearby structures. The model can calculate airborne concentrations (at ground and elevated height locations) and deposition levels (at ground locations). Incinerator plume and stack parameters were obtained by the study of Morselli et al. (2008), while meteorological parameters for the two sites of interest were retrieved from Hellas Weather (2008).

In the national study conducted by Elliott et al. (2001) on 9565 landfill sites in Great Britain, operational at some time between 1982 and 1997, statistically significant increased risks were found for all congenital malformations and low and very low birth weight in residents within 2 km of the sites, relative risk being for congenital anomalies equal to 1.02 (99% CI = 1.01–1.03) and 1.06 (99% CI = 1.052–1.062) for low birth weight. The formula to calculate the cases of malformation and babies of low birth weight attributable to residence near landfills is the same as for cancer incidence, where incidence should be changed with prevalence at birth and the number exposed are newborns. Prevalence of congenital malformations at birth in Greece, was given by Brilakis et al. (2007), found equal to 5.5%, while background rate of low birth weight was obtained by Tsimbos and Verropoulou (2011), found equal to 10.5%. For landfills it was assumed that the emissions will last up to 30 (an assumption supported by the available knowledge that landfilled biodegradable waste starts to emit biogas a few years after deposit and continues to do so for several decades) and the health effects, in terms of congenital anomalies and low birth weight, are constant throughout this period.

Overall population data regarding population age stratification nearby the sites of interest, birth and death rates were retrieved from the Hellenic Statistical Authority (EL.STAT, 2011).

Damage factors were derived from the extensive burden of disease and health statistics provided by Lopez and Murray (1998) on a world level for 1990. Applying equal weightings for the importance of 1 y of life lost for all ages and no discounting for future damages, ***DALYe*** is the sum of years of life lost (***YLLe***) and years of life disabled (***YLDe***) caused by disease type ***e***:

$$DALYe = YLLe + YLDe$$

The average values for all cancer types and all non-cancer (congenital anomalies) endpoints of interest were obtained from Huijbregts et al. (2005), while uncertainties for the calculations followed the approach of Hofstetter (1998), where it was assumed that the YLL estimate of every disease has an uncertainty factor of 1.4, and the YLD estimate of every disease an uncertainty factor of 2 (Table 1).

3. Results and discussion

3.1. Material flow analysis

Table 2 represents the main products of the MSW for all the scenarios taken for the mass flow analysis method for the 4 systems taken by Cherubini et al. (2008), Economopoulos (2010), HSWMA (2011) and the municipality of Athens and Thessaloniki.

Table 1
Population data for the areas of interest.

Athens						
Population (distance from the site)	147 (1 km)		519 (2 km)		1365 (3 km)	
	M	F	M	F	M	F
0–1	0.6	0.7	2.2	2.4	5.8	6.2
0–14	9.5	10.1	33.4	35.6	87.9	93.6
15–44	33.2	35.3	117.1	124.7	308.0	328.0
45–64	17.3	18.4	61.1	65.1	160.8	171.3
>65	10.6	11.3	37.4	39.9	98.4	104.8
Thessaloniki						
Population (distance from the site)	**2 (1 km)**		**43 (2 km)**		**227 (3 km)**	
	M	**F**	**M**	**F**	**M**	**F**
0–1	0.0	0.0	0.2	0.2	1.1	1.1
0–14	0.1	0.1	3.1	3.2	16.2	16.7
15–44	0.4	0.5	9.4	9.7	49.8	51.4
45–64	0.2	0.2	5.1	5.3	26.9	27.8
>65	0.2	0.2	3.4	3.5	17.7	18.3

For the material flow accounting method the material intensities were obtained from the study of Ritthoff et al. (2002). Data for scenario1,2 and 4 were taken from Cherubini et al. (2008) in order to account for the mass balance. For scenario 3 the data were taken from Economopoulos (2010). Demonstrates the abiotic material intensity of products (minerals, soil, fuel etc.). The abiotic matter indicates the amount which is degraded or diverted so as to provide a product/service measured in $g_{ab}/unit_{prod}$. The figure indicates that 0.10 g of abiotic materials is used up for Scenario 3. It is therefore noted that 0.010 g of abiotic material is required for the disposal of 1 g waste. Similar results are observed for the other waste management options. The results verify that scenario 3 consumes less abiotic matter. It is important to notice at this point that more evolved technologies such as scenario 3 for waste management demand less amount of abiotic matter.

3.2. Gross energy analysis

The gross energy requirement of the four technological scenarios considered herein was estimated using the GEMIS 4.7 database. Waste collection is included in the all partial processes.

Fig. 3 indicates that the disposal of 1 g of waste in scenario 1, 1198 J is required. Similar analysis estimated the requirement for the other scenarios. It is clear that scenario 3 requires more than twice the energy needed for scenarios 2 and 4. Waste is a renewable material and can replace an equivalent amount of fossil fuels as it releases significant amounts of energy. As underlined by Cherubini et al. (2008) this can be explained by the fact that in scenario 3 a separation of the waste into organic and non-organic takes place. This is of great significance for the production of high quality biogas and electricity.

3.3. Emergy analysis

In this paper emergy analysis is applied as a decision making tool for the evaluation of the different options for waste management of the present project. The characteristics and the main processes of landfilling, incineration and anaerobic digestion/composting are presented in the following tables. The solar transformities utilized for the calculations are taken by a study carried out by Marchettini et al. (2006).

Landfill processes (scenarios 1 and 2) are divided into 3 basic parts as indicated in Table 3. MSW collection phase of both cities has an emergy of 1.62E+07 seL/g MSW for Athens and 2.34E+07 for Thessaloniki. This can be explained of the fuel needed during the transportation of the waste. The estimation of the emergy in the treatment phase indicates that there is a big contribution of the building of the plant due to the high amounts of clay used for its construction. The third process is the disposal phase, which contains the collection and the treatment of leachate. The treatment phase in contrast to the other phases requires the greatest emergy investment. As mentioned above, this is due to the clay and other material used for the construction and the covering of the landfill in a daily base.

The results of the emergy analysis of the first part excluding the further recycling treatment of inorganic waste of the scenario 3 are illustrated in Table 4. The emergy investment for both cities was estimated to be approximately 2E+7seJ/g MSW. The collection phase requires high emergy investment because of the significant inputs which are the fuel consumption and the costs of human labor. The electricity of the plant and the management cost required for the treatment phase demand a high eMergy investment as shown in the Table 4.

The emergy investment for the incineration plant is high at the disposal phase and the treatment phase of the residues after the combustion of the waste. This is due to the fact that the emergy costs of landfilling are high, as mentioned by the previous technological scenarios previously. One of the most important inputs as presented in table is the collection phase due to the extensive fuel consumption. In terms of electricity and plant costs the waste treatment phase requires a high emergy investment. Table 5 shows the emergy investment for the

Table 2
Input flows for the four waste management scenarios: the amounts are normalized per g waste.

Input flow (per g of waste)	Unit	Collection	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Water	g	3.00E-01				
Natural gas	g	8.08E-05				1.00E-05
Electricity	kWh	6.28E-07	9.63E-07	5.31E-07	8.89E-06	6.68E-05
Diesel	g	5.65E-03	6.24E-04	6.24E-04	3.79E-04	1.57E-04
Plastics (black sacks)	g	3.75E-04				
Paper and cardboard	g	6.55E-04				
Chemicals	g	7.74E-05				
Lubricants	g	1.76E-05				
MSW containers (steel)	g	1.43E-03				
MSW containers (HDPE)	g	1.23E-03				
Trucks	g	2.42E-02				
Light duty vehicles	g	5.00E-05				
HDPE (pipes)	g		1.25E-04	1.25E-04		
HDPE (landfill walls)	g		6.06E-05	6.06E-05	9.83E-06	1.33E-05
Clay (landfill walls)	g		4.47E-02	4.47E-02	7.26E-03	9.80E-03
Concrete (B25)	g				6.83E-03	6.87E-04
Steel	g			4.20E-07	1.77E-03	5.62E-04
PVC reactors (H2S removal)	g			1.45E-08		
Iron sponge (H2S removal)	g			4.89E-07		
Copper cables	g				1.76E-05	
Polyethylene film	g				1.60E-04	
Urea (NH2CONH2)	g				1.20E-03	3.00E-03
Activated carbon	g					2.50E-03
Ca(OH)2	g					3.20E-03
CaO	g				1.34E-02	2.50E-02
Cement	g				7.25E-04	1.35E-02
Sodium silicate	g				8.05E-04	1.50E-03
Useful output						
Electricity: gross net	kWh			8.05E-05	8.33E-05	6.67E-04
Upgraded biogas	j				8.30E+01	
Compostable matter	g				3.70E-01	
Ferrous metals	g				2.00E-02	
Aluminium	g				1.00E-02	
Glass	g				3.00E-01	
Paper	g				0.00E+00	
Plastics	g				3.00E-01	
Waste to landfill						
Untreated waste	g		1	1		
Heavy wastes	g				3.73E-02	
Ashes	g				1.20E-01	3.20E-01

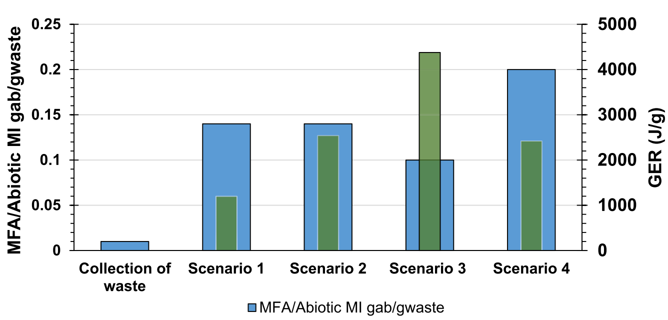

Fig. 3. Indicators according to the material flow accounting method and to the gross energy requirement method (details are presented in Table S 2 and Table S 3).

incineration plant.

The solar emergy investment is used as an indicator to compare the systems. Fig. 4 shows the total solar emergy investments. It proves that scenario 3 is the least emergy demanding whereas landfilling requires the highest emergy investment per gram of waste. Incineration also demands higher emergy investment per gram of waste than composting.

3.4. Global and local air emissions

Each technological scenario and the corresponding waste collection process has different environmental impacts at the global scale as follows:

(a) global warming potential expressed in terms of CO_2 equivalent,
(b) acidification potential expressed in terms of SO_2 equivalent,
(c) tropospheric ozone precursor potential.

The global air emission impacts are presented in Fig. 5. The results are related to the emissions of air pollutants and environmental stressors emitted through the whole life cycle of the waste streams considered in the study. They show that the global warming potential of incineration is very high due to the combustion of inorganic residues. The cities have comparable results as the waste composition produced is similar and the annual waste capacity is almost the same. Moreover, GWP is found to be high in landfill scenario 2. This is due to the fact that scenarios 3 and 4 deliver their residues, ashes and burnt inorganic material, which do not decompose and cannot result in further organic emissions. Scenario 3 has the smallest greenhouse gas effect and acidification potential and these results underline the need of exploring further biological treatment of waste in Greece.

Fig. 6 depicts the local airborne emissions of the four waste treatment methods. The calculations were done using up- and downstream process data from the GEMIS 4.2 database for 1 g of waste. Scenario 3 still has the lowest emissions values for the majority of chemicals studied.

3.5. Health impacts due to incinerators and landfills

Fig. 7 shows the estimated number of additional cancer incident cases for the sites of interest, for a period of 40 years. The annual number

Table 3
Emergy investment for landfilling scenarios.

Item	Unit	Amount (Units/year)	Solar transformity (sej/unit)	Solar emergy investment in Athens (sej/g MSW)	Solar emergy investment in Thessaloniki (sej/g MSW)
MSW collected in Athens	g	1.26E+11			
MSW collected in Thessaloniki	g	1.21E+11			
Human Labor	J	6.39E + 10	7.38E+6	3.74E+06	3.90E+06
Fuels	J	2.33E + 13	6.60E+4	1.22E+07	1.27E+07
Machinery	g	3.84E + 06	6.70E+9	2.04E+05	2.13E+05
Water	g	4.10E + 09	2.03E+5	6.61E+03	2.17E+08
Total emergy investment for collection phase				1.62E+07	2.34E+08
Treatment phase					
Plant costs	€	5.52E+05	1.59E+12	6.99E+06	7.25E+06
Materials for construction	g	3.93E + 10	1.00E+9	3.13E+08	3.25E+08
Human labor	J	4.37E + 09	7.38E+6	2.57E+05	2.66E+05
Materials for management	g	4.11E+ 10	1.00E+9	3.27E+08	3.40E+08
Trucks for management	g	6.83E + 07	6.70E+9	3.65E+06	3.79E+06
Machinery	g	6.44E + 06	6.70E+9	3.44E+05	3.57E+05
Fuels	J	7.13E + 12	6.60E+4	3.75E+06	3.88E+06
Electricity	J	9.67E + 12	1.48E+5	1.14E+07	1.18E+07
Total emergy investment for treatment phase				6.64E+08	6.92E+08
Disposal(leachate treatment)					
Chemical	g	8.59E + 08	3.80E+08	2.59E+06	2.70E+06
Electricity	J	4.12E + 12	1.48E+05	4.84E+06	5.04E+06
Total emergy investment for disposal phase				7.43E+06	7.74E+06
Total solar emergy investment of the system				6.88E+08	9.33E+08

Table 4
Emergy Investment of anaerobic digestion and composting.

Item	Unit	Amount (Units/year)	Solar transformity (sej/unit)	Solar eMergy investment in Athens (sej/g MSW)	Solar eMergy investment in Thessaloniki (sej/g MSW)
Organic MSW in Athens	g	5.27E+10			
Organic MSW in Thessaloniki	g	4.37E+10			
MSW collection					
Containers	g	7.88E+06	3.00E+09	4.48E+05	5.40E+05
Trucks (steel)	g	8.31E+06	6.70E+09	1.06E+06	1.27E+06
Human labor	J	5.32E+09	7.38E+06	7.46E+05	8.99E+05
Fuels	J	4.12E+12	6.60E+04	5.16E+06	6.22E+06
Washing cost		7.12E+04	1.59E+12	2.14E+06	2.59E+06
Total emergy investment for collection				9.56E+06	1.15E+07
Treatment (composting)					
Electricity	J	1.19E+12	1.48E+05	3.34E+06	4.03E+06
Fuels	J	5.73E+11	6.60E+04	7.17E+05	8.65E+05
Liquid oxygen	g	1.03E+07	3.80E+08	7.42E+04	8.95E+04
Microorganisms		1.19E+04	1.59E+12	3.59E+05	4.32E+05
Human labor	J	3.06E+09	7.38E+06	4.29E+05	5.17E+05
Plant cost		6.26E+04	1.59E+12	1.89E+06	2.27E+06
Machinery		4.02E+04	1.59E+12	1.21E+06	1.46E+06
Management cost		7.44E+04	1.59E+12	2.24E+06	2.70E+06
Total emergy investment for treatment				1.03E+07	1.24E+07
Disposal					
14 leachate treatment		3.10E+04	1.59E+12	9.33E+05	1.13E+06
Total solar emergy investment of the system				2.07E+07	2.50E+07

of cases due to current exposure increases and reaches maximum after 20 years of operation due to the latency since first exposure and then declines to almost after 40 years from the initiation of operation. However, the number of additional cancer cases is minimal (less than one case expected), due to the very low population density (especially in Thessaloniki) around the incineration site.

Fig. 8 shows the total number of Years of Life Lost, in the two sites, attributable to exposure to PM_{10} and NO_2 from incinerators. In general, the overall impact is mostly attributed to the presence of NO_2. Overall, the maximum impact of incinerators for the overall population is 5.22 years for Athens and 4.71 for Thessaloniki.

Fig. 9 presents the health effects of landfills in the two sites as annual cases and 30-year incidence of congenital malformations and newborns of low birth weight. It is expected that less than a case of birth defects for all the entire life cycle of the landfill is expected in the worst case, again due to the low population density.

It must be noted that the method applied herein for cancer and birth defects, deals with health outcomes that are related to aggregate (multiple pathways and routes) and cumulative (multiple compounds) exposure, without to do a compound by compound analysis. This is in line with the recently coined risk assessment concept in the frame of real life risks simulations (Taghizadeh et al., 2019; Tsatsakis et al., 2016,

Table 5
Emergy investment for incineration plant.

Item	Unit	Amount (g/year)	Solar transformity (sej/unit)	Solar eMergy investment for Athens (sej/g MSW)	Solar eMergy investment in Thessaloniki (sej/g MSW)
MSW collected in Athens	g	1.26E+11			
MSW collected in Thessaloniki	g	1.21E+11			
MSW collection					
Human labor	J	5.65E+10	7.38E+06	3.32E+06	3.45E+06
Fuels	J	1.07E+13	6.60E+04	5.65E+06	5.86E+06
Machinery	g	6.08E+07	6.70E+09	3.24E+06	3.36E+06
Total emergy investment collection				1.22E+07	1.27E+07
Treatment (incineration)					
Fuels	J	7.40E+12	6.60E+04	3.89E+06	4.03E+06
Natural gas	J	1.11E+12	4.80E+04	4.24E+05	4.40E+05
Electricity	J	3.24E+13	1.48E+05	3.82E+07	3.97E+07
Human labor	J	4.65E+10	7.38E+06	2.73E+06	2.83E+06
Plant cost		1.16E+06	1.59E+12	1.47E+07	1.53E+07
Water	g	3.62E+11	2.03E+05	5.86E+05	6.07E+05
Chemicals	g	2.23E+09	3.80E+08	6.74E+06	6.99E+06
Total emergy investment for treatment				6.74E+07	6.99E+07
Disposal of ashes treatment/managed landfill					
Water	g	1.57E+09	2.03E+05	2.53E+03	2.64E+03
Electricity	J	6.67E+10	1.48E+05	7.84E+04	8.17E+04
Materials	g	1.05E+09	1.00E+09	8.33E+06	8.68E+06
Lubricants	J	1.03E+10	6.60E+04	5.37E+03	5.60E+03
Fuels	J	3.86E+11	6.60E+04	2.02E+05	2.11E+05
Materials	g	8.45E+08	1.00E+09	6.71E+06	6.98E+06
Construction	g	2.91E+10	2.39E+08	5.53E+07	5.76E+07
Total emergy investment for managed landfilled				7.06E+07	7.36E+07
Total solar emergy investment of the systems				1.50E+08	1.56E+08

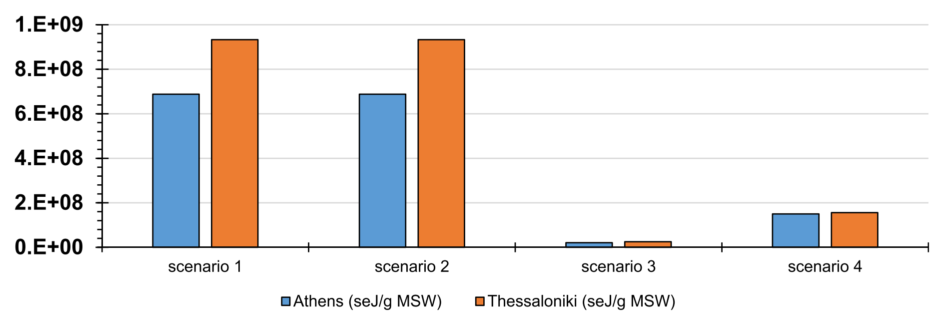

Fig. 4. Total emergy investment per gram of waste for the Athens and Thessaloniki (the values of the figures are presented in Table S 5).

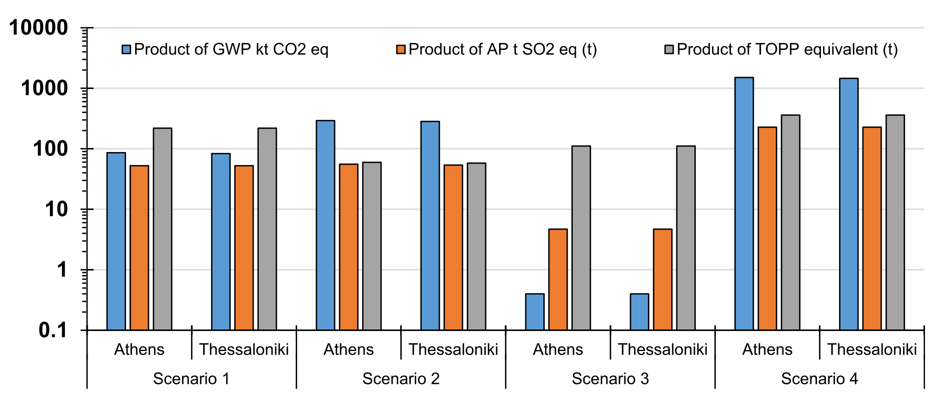

Fig. 5. Environmental impact categories of the examined scenarios (details are presented in Table S 4) (product of GWP denotes the result of the LCA for all scenarios examined with regard to global warming potential; product of AP is the result with regard to acidification potential; and product of TOPP equivalent refers to the potential emissions of tropospheric ozone precursors).

2017, 2019a), accounting for health effects resulting from long-term low level exposure (Kostoff et al., 2018), including hormesis (Docea et al., 2019; Tsatsakis et al., 2019b).

In order to be able to compare the health impacts associated with the major waste management options presented above, all the respective impacts estimated for 30 years of operation, were translated into DALYs.

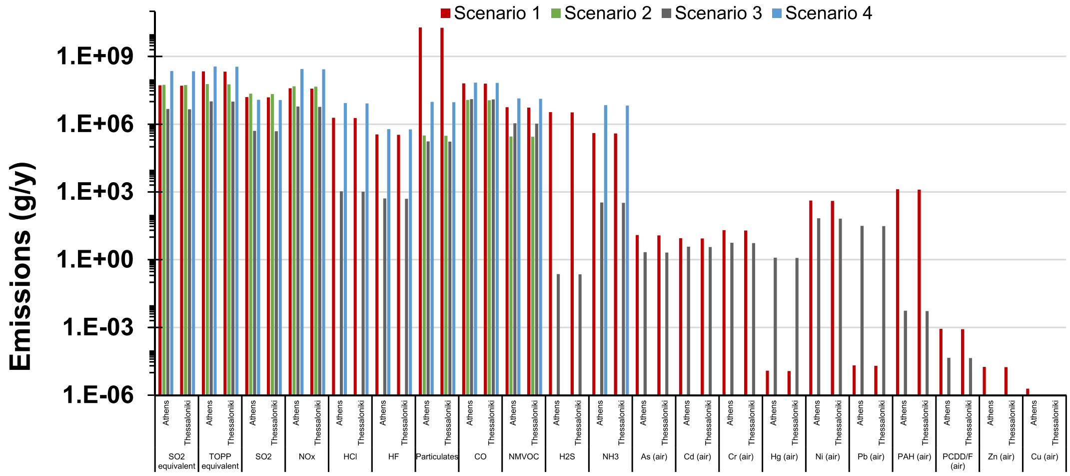

Fig. 6. Airborne emissions at the local scale in Athens and Thessaloniki (details are presented in TableS 6 and Table S 7).

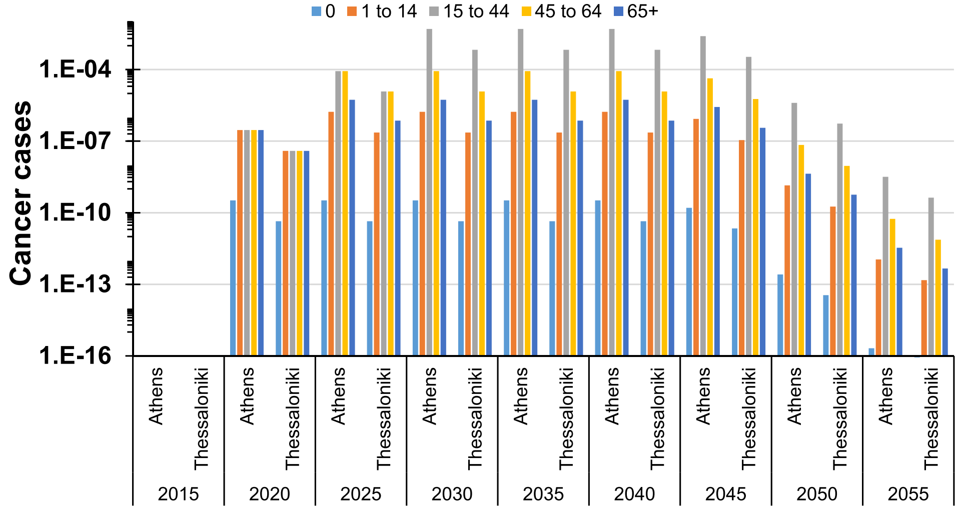

Fig. 7. Cancer expected cases for an incinerator operating for 30 years (2015–2045).

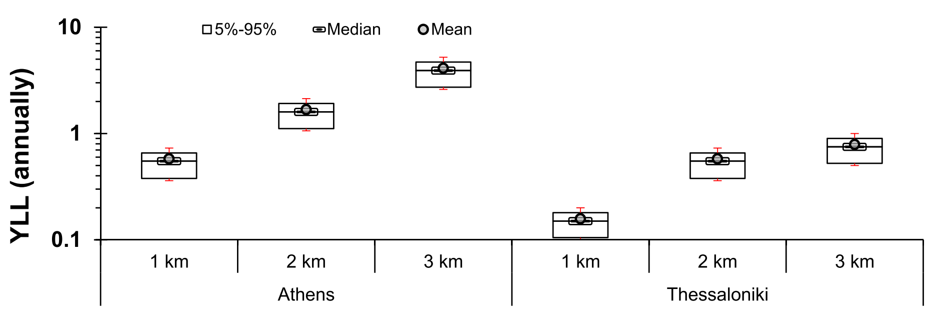

Fig. 8. Years of Life Lost due to the presence of incinerator (annually).

The respective results are presented in Fig. 10. Expressing all the health impact related results with a common metric (DALYs) revealed that landfilling is the waste management option with the higher impact in terms of health effects.

4. Conclusions

The life cycle impact of collection and different waste disposal strategies in eastern Attica and Thessaloniki such as landfilling with and without landfill biogas exploitation, biogas and compost via anaerobic digestion and composting, and waste incineration, was performed by means of a multi-method multi-scale approach. The results of the assessment based on selected impact indicators lead to the following conclusions:

Material flow accounting. The disposal of 1 g of waste requires the production of ca. 0.14 g of further waste as abiotic matter (the four scenarios analyzed range from 0.1 for anaerobic digestion to 0.2 g for incineration). This underlines the need for waste prevention and reduction systems before waste streams reach the processing plants or the landfill in order to minimize the generation of additional waste. It

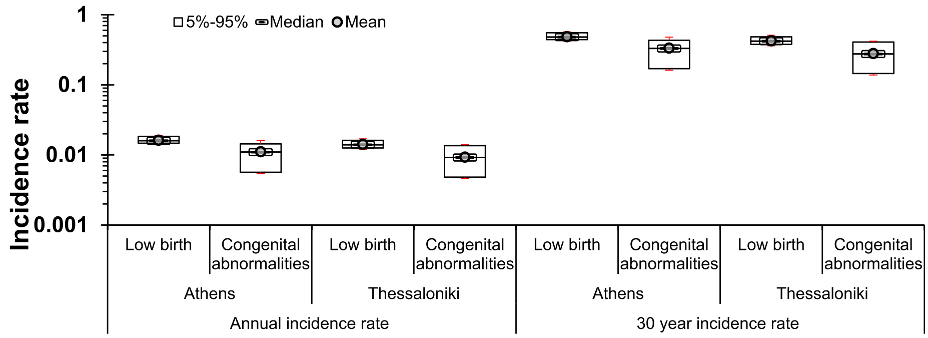

Fig. 9. Birth defects due to use of landfill.

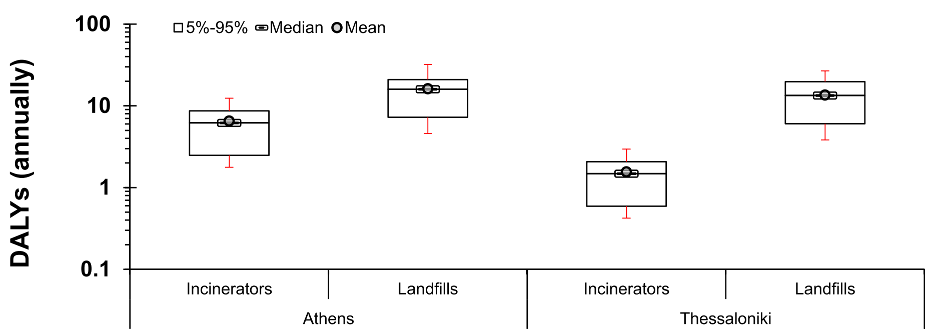

Fig. 10. DALYs associated to the different waste management options in Athens and Thessaloniki.

should be noted that none of the scenarios considered avoid the use of landfilling of the residues, even though anaerobic digestion seems to reduce the need for landfilling significantly.

Gross energy requirement. Anaerobic digestion (primarily) and incineration have the highest gross energy requirement. In general, technological scenarios succeeding in minimizing the amount of residual waste directed to the landfill require more energy when compared to baseline landfilling. However, these systems can provide a consistent energy output that can be used for power or heat generation, offsetting partially the increased energy demand.

Emergy synthesis. Comparative assessment of emergy synthesis for the four scenarios shows that anaerobic digestion is the least emergy demanding, whereas landfilling requires the highest emergy investment per g of waste. Incineration also demands higher emergy investment per g of waste than composting. The overall emergy demand for all options is some 20% higher in Thessaloniki than in eastern Attica. This is due to differences in waste composition, which make some technological options more prone to the need for enhanced environmental support.

Global and local emissions into the air. Incineration is the most polluting waste management option (concerning GWP, AP and TOPP) at the global scale, followed closely by landfilling without recovery and use of the biogas produced. Anaerobic digestion is the best option in terms of GWP and AP. However, when it comes to TOPP, it is landfilling with biogas and energy recovery that comes out at the top. With regard to local air emissions, landfilling with no biogas recovery is by far the worst waste management option. It is particularly bad when considering pollutants such as particulate matter and PAHs, which have been associated with adverse health impacts.

Health impacts. The main adverse health effects considered herein were pre-mature mortality (estimated in terms of years of life lost in the population of the two urban areas), decreased birth rate and increased incidence of congenital anomalies in neonates. Incineration was primarily linked with pre-mature mortality, resulting in ca. 4–5 years of life lost in the populations of eastern Attica and Thessaloniki. Landfilling without biogas recovery did not show a very high incidence of reproductive health problems, mostly due to the relatively low population density in the vicinity of the landfill sites in both urban areas considered. However, comparing the DALYs from the investigated waste management options and accounting that, most of the congenital anomalies have an impact for the whole lifespan, the overall DALYs were almost twice than the ones estimated for incineration. Overall, the health impact assessment findings underline the need for well-studied land use planning when considering the siting of new landfills or waste incineration plants.

Coupling all the indicators above, this multi-method and multi-scale analysis showed that landfilling with no biogas recovery (the most common option in waste management currently in Greece) is the worst management option. Results also show that a sorting plant coupled with power and biogas production using anaerobic digestion could well be the best option for waste management, despite the non-negligible local emissions, especially considering tropospheric ozone precursors. Furthermore, both in the case of anaerobic digestion and in the case of incineration, a non-negligible amount of energy becomes available, in spite of a slight increase in the fossil fuel energy input, while waste residues sent to landfills are minimized and rendered inert.

Finally, it should be noted that none of the scenarios succeeds in doing away with landfills. Thus, waste prevention policies and active recycling coupled with innovative ways of using the bottom and fly ash or the anaerobic digestion residues currently driven to the landfill would need to be put in place to ensure a truly optimized sustainable urban waste management system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.110307.

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