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Municipal solid waste management scenarios for Attica and their greenhouse gas emission impact

Asterios Papageorgiou, Avraam Karagiannidis
Laboratory of Heat Transfer and Environmental Engineering, Department of Mechanical Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece

John R. Barton
School of Civil Engineering, Faculty of Engineering, The University of Leeds, Leeds, UK

Efstratios Kalogirou
SYNERGIA, Greece

Disposal of municipal solid waste in sanitary landfills is still the main waste management method in the Attica region, as in most regions of Greece. Nevertheless, diversion from landfilling is being promoted by regional plans, in which the perspectives of new waste treatment technologies are being evaluated. The present study aimed to assess the greenhouse gas (GHG) emissions impact of different municipal solid waste treatment technologies currently under assessment in the new regional plan for Attica. These technologies are mechanical–biological treatment, mass-burn incineration and mechanical treatment and have been assessed in the context of different scenarios. The present study utilized existing methodologies and emission factors for the quantification of GHG emissions from the waste management process and found that all technologies under assessment could provide GHG emission savings. However, the performance and ranking of these technologies is strongly dependent on the existence of end markets for the waste-derived fuels produced by the mechanical–biological treatment processes. In the absence of these markets the disposal of these fuels would be necessary and thus significant GHG savings would be lost.

Keywords: Municipal solid waste, incineration, mechanical biological treatment, mechanical treatment, Attica

Introduction

Waste management activities and especially disposal of waste in landfills that generates methane (CH_4) contribute to global greenhouse gas (GHG) emissions approximately by 4% (Bogner *et al*. 2007). In Greece, the main method of solid waste management still remains landfilling; apart from this, 22 material recovery facilities (MRF) are in operation for source-segregated recyclables, and two mechanical–biological treatment (MBT) plants processing residual municipal solid waste (MSW) operate currently in Attica and in Chania (Crete), with a further two new MBT plants in Kefalonia and Herakleion (Crete) coming into operation during 2009 (Psomopoulos 2008, HSWMA 2009). Nevertheless increasing environmental concerns, public pressures and the European and Hellenic waste policy and legislation that force diversion from landfill through sustainable waste management, necessitate investments in more new treatment plants for municipal solid waste (MSW), including biological and thermal treatment of MSW. In this context, the 13 regional authorities in Greece have issued their regional plans, in which the need for new MSW treatment facilities is recognized and operationalized (Hellenic Ministry for the Environment, Physical Planning and Public Works 2007).

In Attica Region (i.e. the Greater Athens area) 2 200 000 t MSW (wet weight) were generated in 2008, of which 12% was recycled and 350 000 t were treated in the existing MBT plant at the Liossia site (Eurostat 2009, HSWMA 2009) (Figure 1). Given that the Hellenic waste management policy only recently started to address waste minimization measures such as home composting and 'pay-as-you-throw' (PAYT) schemes, the waste growth is anticipated to remain at present levels into the future (i.e. 1.1% per annum in 2007 – cf. Eurostat 2009) or even to increase. By taking into account the

Corresponding author: Avraam Karagiannidis, Laboratory of Heat Transfer and Environmental Engineering, Department of Mechanical Engineering, Box 483, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece.
E-mail: makis@aix.meng.auth.gr
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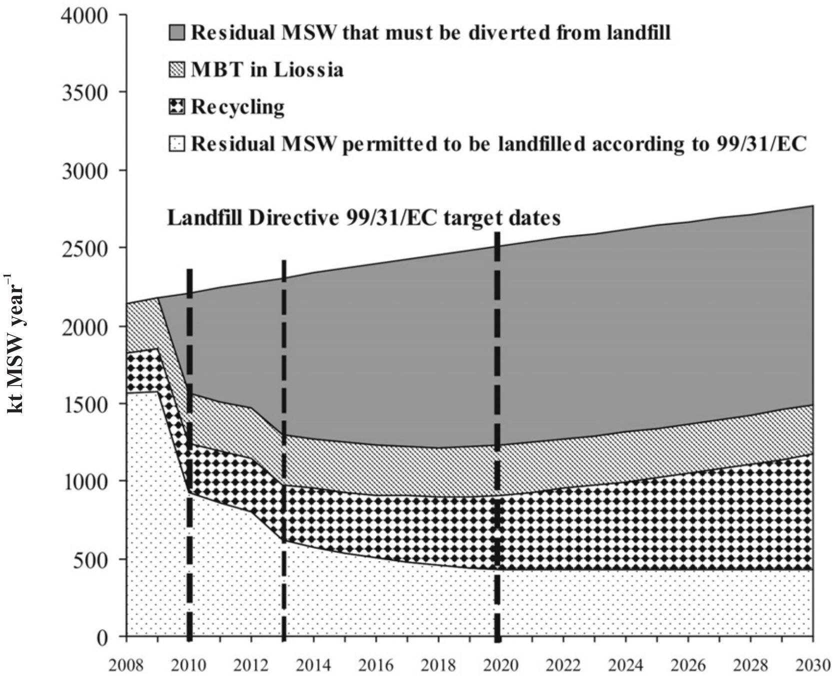

Fig. 1: Foreseen MSW management in Attica until 2030 according to existing facilities.

forecast growth of the population (Eurostat 2009), if waste growth rates remain at present levels, 2 800 000 t MSW will be generated annually by 2030. Even if source segregation is enhanced and consequently recycling rates increase, a significant amount of residual MSW will have to be diverted from landfills in order for the targets of the Landfill Directive 99/31/EC to be met (Figure 1).

Therefore, a new waste management infrastructure is necessary and in the regional plan for Attica a new integrated waste management centre (IWMC) in Liossia in western Attica is proposed, where new plant with a total treatment capacity of 1 100 000 t will be constructed and operated in conjunction with the existing MBT plant, providing a total capacity of 1 450 000 t MSW. Moreover, two other IWMC are proposed in north-east and in south-east Attica with a total annual capacity of 250 000 t. For each of the two IWMC in eastern Attica, MBT plants incorporating anaerobic digestion have been proposed, and various waste management treatment technologies, such as mass-burn incineration (MBI), mechanical treatment (MT) and MBT have been evaluated for the IWMC in west Attica, which is anticipated to be one of the largest IWMC in the world. The aim of the present study was to assess the GHG emission impacts of the proposed technologies for the IWMC in west Attica in the context of different scenarios.

Treatment technologies

MBI with energy recovery is the most common method for recovering value from waste and it is commonly defined as waste-to-energy (WtE). The majority of the WtE plants use moving grate technologies and they are designed to handle large volumes of MSW with or without pre-treatment. Usually, the steam produced from the incineration of waste is used in turbines to generate electricity, while the remaining heat of the process is discarded. In the combined heat and power (CHP) incinerators, the residual heat is recovered and exported to adjacent industrial premises or districts for space heating, hot water supply, industrial heat demand and other duties (Williams 2005).

Mechanical treatment is another technology for treatment of MSW. A MT plant or ‘dirty’ MRF processes mixed residual MSW by contrast to a ‘clean’ MRF that processes source-segregated recyclables. A MBT plant incorporates trammel conveyors and hand picking lines, separators, magnetic separators, eddy current separators, and potentially near infrared detection devices, shredders and baling equipment (AEA 2001). As MT plants receive mixed MSW with high putrescible content they usually recover metals and RDF from the coarse fraction of input material.

MBT is another treatment option for residual MSW. MBT partially processes mixed MSW by mechanically removing some parts of the waste and by biologically treating others. Generally a wide range of MBT plant configurations exist, depending on the various processes that are integrated into MBT and the outputs of the process. The biological process of an MBT plant may either take place prior to or after mechanical treatment of the waste, depending on the outputs of the plant and could be either aerobic composting (in-vessel or tunnel), or anaerobic digestion (AD) or bio-drying (Enviros Consulting Limited 2007). Within this study MBT with aerobic composting is defined as MBT(C), MBT with AD as MBT(AD) and MBT with bio-drying MBT(BioD).

MBT(C) plants incorporate mechanical treatment for recovery of recyclables with aerobic in-vessel composting to minimize the biodegrability of waste and produce a bio-stabilized output. Usually in these plants refuse-derived fuel (RDF) is recovered from the coarse fraction of materials going to the biological process stage (Archer *et al*. 2005).

MBT(AD) plants include mechanical separation with anaerobic digestion to recover recyclables (and potentially RDF) and produce biogas that is usually combusted for energy recovery. Some MBT(AD) plants combine the anaerobic digestion process with post-digestion aerobic composting that further bio-stabilizes the biodegradable content of waste and produces a bio-stabilized output that could be landfilled or used as soil improver (Archer *et al*. 2005).

MBT(BioD) plants utilize bio-drying to drive-off moisture from the waste using the biological activity in an aerobic in-vessel system (boxes). The reduction of moisture and the degradation of a part of the more volatile biodegradable fraction of waste increase its calorific value and produce a solid recovered fuel (SRF) rendering it an option for co-incineration and energy recovery. In MBT(BioD) plants the waste remains in the system usually for a week, by contrast to MBT(C) where the waste remains at least for 3 weeks and hence the bio-drying process does not fully biostabilize the waste. (Archer *et al*. 2005).

In the present paper, the terms RDF and SRF are both utilized. For the moment, there is only the CEN 343 Draft European standard for SRF and the legal definition of the term SRF has not yet been finalized. In general, both terms are used across European countries to describe fuels derived from non-hazardous MSW. Quite often, the terminology used in different countries to describe waste-derived fuels may reflect the desire of the users to have the material treated in a specific way under existing national legislation (Gendebien *et al*. 2003). Within this study, the term SRF is used for fuels derived by MBT(BioD) as these plants are dedicated to the production of these fuels and therefore they are anticipated to amend their production lines, if it is necessary, in order to adjust the SRF attributes to the requirements of the new European Standard. The term RDF is used for fuels derived by MT, MBT(C) and MBT(AD) plants, as these fuels derive from the coarse fraction of waste before biological treatment and their quality will be more difficult to define.

In general there are various options for the utilization of RDF and SRF, such as combustion in WtE plants or pyrolysis or gasification plants for energy recovery, or even co-incineration in cement kilns and power plants, where they substitute fossil fuels; however the market for these fuels is extremely volatile and they quite often end up in landfills, as has happened to the RDF produced by the MBT in Liossia (Tsatsarelis & Karagiannidis 2007).

Methodology

The present study aimed to quantify carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions from waste management activities in the Attica scenarios under assessment. CO_2, CH_4 and N_2O are the major GHG emissions generated by MSW management and of significant interest under the Kyoto Protocol (IPCC 1997, 2006). For the quantification of GHG emissions from the treatment of MSW in each of the scenarios, a validated methodology (Papageorgiou *et al*. 2009) was adopted and emission factors (EFs) were sourced from previous studies that assessed the GHG emissions impact of MSW treatment technologies and were applied in this study after adjustment to the Hellenic MSW composition. It should be mentioned that the performance of the modelled technologies could potentially be different when applied to Greece, however due to lack of data it was not possible to model technology application specific to Greek conditions.

Treatment scenarios

Five scenarios described herein were compiled on the basis of published information on the technologies proposed in the regional plan for Attica and the treatment capacities of the proposed plants. The MSW management system for each of the scenarios is presented in Figure 2. In these scenarios residual MSW is transferred by means a kerbside collection scheme, from households to treatment facilities, via transfer stations.

Scenario 1

A total of 400 000 t of residual MSW are treated in a MBT(C) plant and 700 000 in a WtE. MBT(C) outputs include ferrous and aluminium metals, bio-stabilized output, residues and RDF. Metals are recovered for recycling, whereas the bio-stabilized output and residues are disposed of in a landfill and RDF is used to replace coal in a cement kiln. The bottom ash from the combustion of RDF in the cement kiln is used for the production of clinker. In the WtE plant, the ferrous metals recovered from the bottom ash are sent to a reprocessor for recycling, and the bottom ash and the air pollution control (APC) ash are both landfilled in a sanitary and a hazardous landfill cell, respectively. The WtE plant recovers electricity only with a net electrical efficiency of 22.6% [related to the net calorific value (NCV) of waste], in order to qualify as a recovery operation according to the requirements of the new Directive on Waste (2008/98/EC) (Karagiannidis *et al*. 2009).

Scenario 2

A total of 400 000 t of residual MSW are treated in a MBT(AD) and 700 000 t in a WtE. The MBT(AD) outputs are ferrous and aluminium metals (sent for recycling), residues and bio-stabilized output that are disposed of to landfill, RDF that is used in place of coal in cement kilns, and biogas which is combusted for electricity generation with an efficiency of 37%. It is assumed that 33% of the electricity produced is used in-house for the operation of the plant and 65% is exported to the grid. The WtE plant is similar with that in scenario 1.

Scenario 3

A total of 400 000 t of residual MSW are processed in a MBT(C) (like scenario 1) and 700 000 t in a MBT(BioD). MBT(BioD) outputs are metals sent for recycling, residues

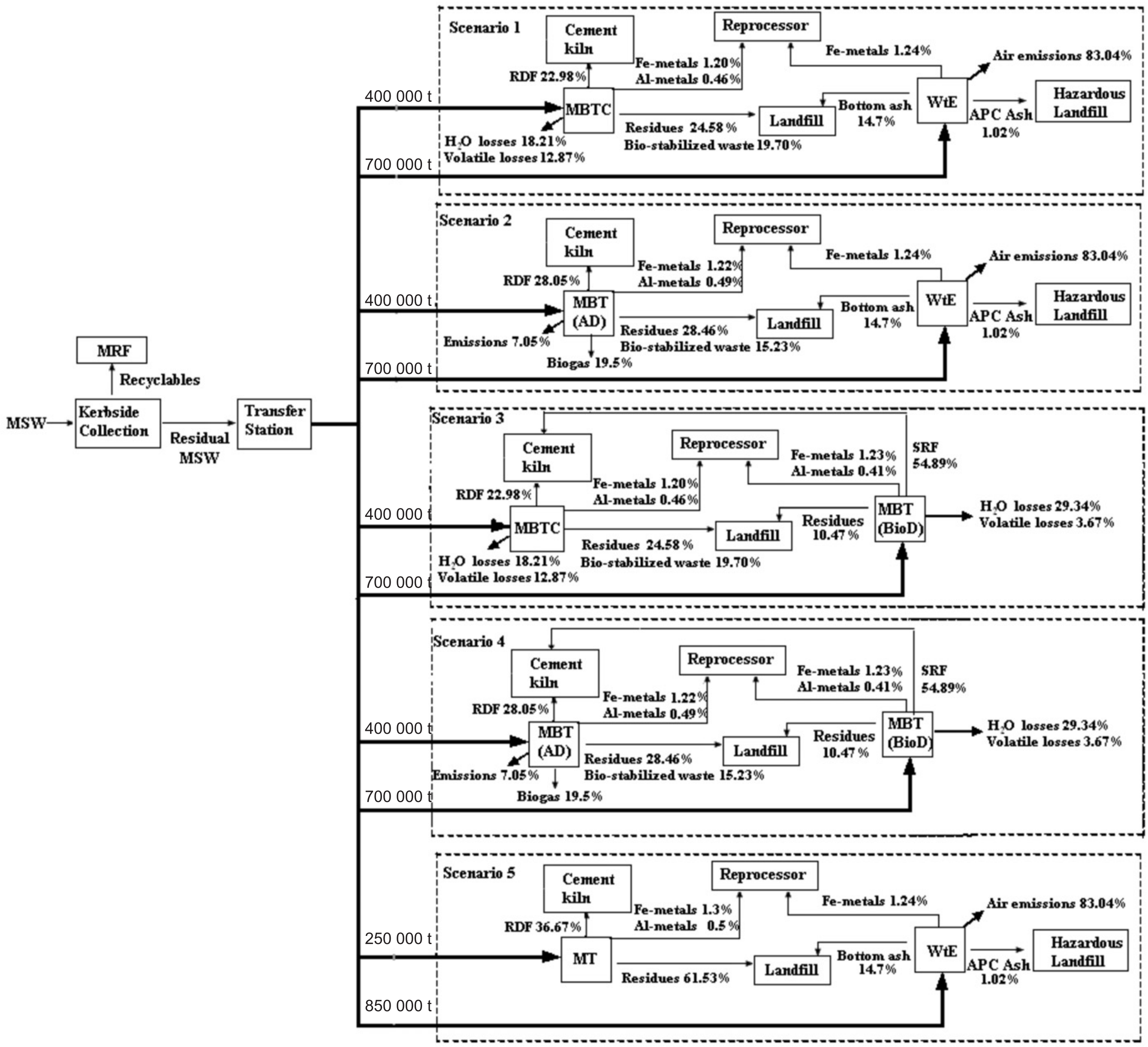

Fig. 2: Waste management scenarios for the IWMC in west Attica.

disposed to landfill and SRF that replaces coal in a cement kiln. Ash from SRF combustion in the cement kiln is included in clinker production.

Scenario 4

A total of 400 000 t of residual MSW are treated in a MBT(AD) (as scenario 2) and 700 000 t in a MBT(BioD) (as scenario 3).

Scenario 5

A total of 250 000 t of residual MSW are processed in a MT plant and 850 000 t in a WtE. The MT outputs are metals sent for recycling, RDF that replaces coal in a cement kiln and residues that are landfilled.

Both SRF and RDF were assumed to replace coal in cement kilns, as this would be the only option for these fuels in Greece as there are no existing WtE plants at the moment, and the coal-powered plants that could potentially combust these fuels are located in northern Greece and the transportation of SRF/RDF from Attica might be very difficult due to logistical constraints. In scenarios 1, 2 and 5, RDF from the MBT(C), MBT(AD) and MT plants could be combusted in the WtE plants instead, but this case was not assessed initially, as the proposed capacities of WtE plants in the regional plan, are only intended for residual MSW and not additional RDF. However, in the case that there is no market for these fuels, WtE plants could combust them after investment to allow capacity extension.

It should be mentioned, that the case of CHP WtE plants was not evaluated as the demand for heat is anticipated to be low due to the current conditions in Attica's waste-derived heat and industrial market and system. CHP WtE plants

Table 1: MSW, packaging waste and residual MSW composition and physical analysis.

	MSW (wet)	Packaging waste (wet)	Residual waste (wet)			Residual waste (dry)		
	Weight (% w/w)	Fraction of packaging waste in MSW (% w/w)	Weight (% w/w)	Moisture (% w/w)	NCV (GJ t^{-1})	Carbon content (%w/w)	Degradable organic carbon (DOC) (%w/w)	Fossil carbon (%w/w)
Category								
Paper and card	29	8.1	26.7	10	14.2	46	46	0
Kitchen and garden waste	40	0	44.2	60	4.5	43	43	0
Plastic	14	6.1	13.9	0	29.3	75	0	100
Other	6	0	6.5	40	7.3	38	19	50
Inerts	3	0	3.3	10	0	0	0	0
Leather, wood, textiles, rubber	2	1.2	2	20	13.6	55	44	20
Glass	3	3	1.4	0	0	0	0	0
Ferrous metals	2.47	2.4	1.4	0	0	0	0	0
Non-ferrous Metals	0.53	0.5	0.6	0	0	0	0	0
Total	100	21.3	100	32.5	10.6	31.5	–	–

would only be beneficial in Greece if they were sited near industries that have a constant demand for heat and steam, but the site of the proposed IWMC at Liossia is far from any industrial sites.

Residual MSW composition

The MSW composition and also the fraction of packaging waste in MSW in Attica are displayed in Table 1 (Technical Chamber of Greece 2006; Eurostat 2009). In this study it was assumed that the treatment plants in each scenario treat residual MSW, after kerbside collection. For the estimation of the future residual MSW composition, it was assumed that the targets set by the Packaging Waste Directive (99/42/EC) would be met and hence 60% w/w of packaging glass, 60% w/w of paper and cardboard, 50% metals w/w, 22,5% w/w plastic and 15% w/w wood would be recycled.

The residual MSW is taken as the input to the waste management system of each scenario and its composition is shown in Table 1. The same table displays the NCV, moisture, carbon and degradable organic carbon (DOC) content of residual MSW, as well as the fossil carbon fraction of total carbon in the residual waste (IPCC 2006, Papageorgiou 2009). Based on the residual MSW composition, mass balances for each of the examined scenarios were compiled and are shown in Figure 2.

Quantification of GHG emissions

In the present study the methodology presented in Papageorgiou *et al*. 2009 was applied for the quantification of GHG emissions from the treatment of residual MSW in each scenario. This methodology proposes a life-cycle perspective for setting model boundaries and utilizes emission factors (EFs) based on life-cycle inventories and methodologies proposed by the Intergovernmental Panel on Climate Change (IPCC 1997, 2006) for emission quantification. In a full life-cycle perspective, biogenic CO_2 emissions are considered neutral to global warming, because they originate from organic matter generated by an equivalent biological uptake of CO_2 during plant growth. Conversely, emissions of CO_2 from combustion of fossil carbon do have a global warming potential because this release is not balanced by a 'recent' uptake of CO_2 (IPCC 2006, Christensen *et al*. 2007).

In this study both direct and indirect GHG emissions generated by direct and indirect activities in the waste management system of each scenario were accounted for (Consonni *et al*. 2005, Liamsanguan & Gheewala 2008). Direct emissions result from activities within the waste management system, namely material and energy flows within the system, whereas indirect emissions take place in systems outside the waste management system, as a result of activities within the latter and occur when materials and energy flow to and from the waste management system (Soderman 2003). The direct and indirect emission impacts that were included in the model are summarized in Table 2.

Direct emission impacts

Direct CO_2 emissions derive from the incineration of fossil carbon in MSW or in RDF and SRF and they were calculated based on the composition of waste, the carbon content and the proportion of fossil carbon of each waste fraction in MSW, according to the methodology proposed by the IPCC (IPCC 2006). N_2O emissions from the combustion of waste and waste-derived fuels were included in the model and the EF 0.02 kg t^{-1} MSW was applied (IPCC 2006).

Moreover CO_2 emissions are generated by the consumption of diesel for the operation of the facilities and the EU EF for diesel consumption was utilized as there is no EF reported for Greece. The EU EF is 3.17 kg CO_2-eq. kg^{-1} diesel and it was taken from the Global Emission Model for Integrated Systems (GEMIS) inventory (GEMIS 2009).

Table 2: Direct and indirect emission impacts included in the model.

Process	Indirect (upstream) impacts	Direct impacts	Indirect (downstream) impacts
MBT(C)	CO_2 emissions associated with electricity provision	1. CO_2 emissions from the combustion of fossil fuels for the treatment of waste. 2. CH_4 and N2O emissions from the composting process 3. CO_2 emissions from the combustion of fossil carbon in RDF 4. CH_4 emissions from landfilling of residues and CO_2 from the consumption of fuels for the operation of landfill -the bio-stabilized output is assumed not to generate methane	1. CO_2 savings from recycling of metals and from substitution of fossil fuels (coal) by RDF in cement kilns
MBT(AD)	Electricity for the operation of plant is provided by the electricity generated by the combustion of biogas	1.CO_2 emissions from the combustion of fossil fuels for the treatment of waste 2. It is assumed that CH_4 from digestion is recovered efficiently and no leakage takes place 3. CO_2 emissions from the combustion of fossil carbon in RDF 4. CH_4 emissions from landfilling of residues and CO_2 from the consumption of fuels for the operation of landfill -the bio-stabilized output is assumed not to generate methane	1. CO_2 savings from electricity substitution by generated electricity from the combustion of biogas 2. CO_2 savings from recycling of metals and substitution of fossil fuels (coal) by RDF in cement kilns.
MBT(BioD)	CO_2 emissions associated with electricity provision	1. CO_2 emissions from the combustion of fossil fuels for the treatment of waste 2. CO_2 emissions from the combustion of fossil carbon in SRF 3. CH_4 emissions from landfilling of residues and CO_2 from the consumption of fuels for the operation of landfill	1. CO_2 savings from recycling of metals and from substitution of fossil fuels (coal) by SRF in cement kilns
WtE	Electricity for the operation of plant is provided by the electricity produced on-site	1. CO_2 from the combustion of fossil fraction of waste and fossil fuels for the treatment of waste 2. N2O emissions from the combustion of waste 3. CO_2 emissions from the consumption of fuels for the operation of landfill where ash is disposed	1. CO_2 savings from electricity substitution and from recycling of ferrous metals recovered from bottom ash
MT	CO_2 emissions associated with electricity provision	1. CO_2 emissions from the combustion of fossil fuels for the treatment of waste 2. CO_2 emissions from the combustion of fossil carbon in RDF 3. CH_4 emissions from landfilling of residues and CO_2 emissions from the consumption of fuels and electricity for the operation of landfill	1. CO_2 savings from recycling of metals and from substitution of fossil fuels (coal) by RDF in cement kilns

CH_4 and N_2O emissions are generated from aerobic composting processes as well and they were included in the model for the MBT(C) plant. For the estimation of these emissions the EFs 1 kg CH_4 t^{-1} MSW and 0.1 kg N_2O t^{-1} MSW were used (IPCC 2006). For the MBT(AD) plant CH_4 emissions due to leakage were assumed to be negligible, while CH_4 and N_2O emissions from bio-drying of MSW were not included in the model as they are anticipated to be very low due to a small duration of the process (1 week) in comparison with aerobic composting processes (3–4 weeks).

Finally for the estimation of CH_4 emissions from landfilling of residues from the treatment processes, the mass balance (Tier 1) method was applied. This method was proposed in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 1997), which assumes that all the methane is released from the waste in the year of disposal. Although this method does not generate estimates as accurate as the first-order decay method (Tier 2) it was preferred in this study as it can give an annual estimate of CH_4 emissions per tonne of waste landfilled, which is necessary for the calculation of overall EFs for the processes assessed in the scenarios. For the Tier 1 method, it was assumed that the landfill where the residues are disposed is an engineered landfill, in which 80% of the landfill gas is captured and flared without energy recovery. The DOC for every fraction of residual waste is presented in Table 1. The methane correction factor (MCF), fraction by volume of CH_4 in landfill gas, oxidation factor and the fraction of DOC dissimilated (DOC_F) were sourced from the more recent *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Indirect emission impacts

For the estimation of indirect emission impacts from electricity provision for the operation of treatment plants information on energy utilization of MSW management systems was sourced from literature (AEA 2001, Fischer 2006). The EF for the average electricity mix in Greece is applied for estimating both the GHG emissions from consumption of electricity in the processes and the GHG emission savings from energy recovery. The EF for the Hellenic electricity mix is estimated to be 0.783 kg CO_2-eq. kW h^{-1} in 2010 according to the GEMIS inventory, which includes data for the whole life-cycle of energy production (fuel extraction, transport, conversion, combustion, distribution) (GEMIS 2009).

In the case of co-incineration of RDF and SRF in a cement kiln, the fuel was assumed to replace coal on an energy equivalent basis (i.e. 1 GJ of RDF/SRF replaces 1 GJ of coal). Hence, the combustion of SRF replaces emissions from the combustion of coal that would generate equivalent energy.

Table 3: EFs for the waste management options in the scenarios (kg CO_2-eq. t^{-1} MSW.

	MT	MBT(C)	MBT(AD)	MBT(BioD)	WtE
Treatment of waste					
Combustion of MSW	–	–	–	–	420.65
Combustion of RDF/SRF	321.07	166.92	261.84	350.44	–
Power use	17.85	39.15	–	62.64	–
Fuel use	2.95	2.54	4.12	2.85	0.37
CH_4 and N_2O emissions from composting	–	26.40	–	–	–
Recycling of metals	–64.31	–59.13	–62.03	–55.46	–5.66
Displaced energy					
Displaced coal in cement kilns	–620.18	–372.66	–434.37	–883.15	–
Displaced electricity	–	–	–97.88	–	–521.55
Disposal of waste					
CH_4 emissions	159.64	43.97	61.90	17.46	
Fuel use	1.80	0.72	1.28	0.32	0.16
Total	–181.18	–152. 09	–265.14	–504.90	–106.03

The NCV of coal used in cement kilns is 24.9 GJ t^{-1} (Papageorgiou 2009) and the EF for the combustion of coal in cement kilns is 93 kg CO_2 TJ^{-1} of fuel (EEA 2007).

Regarding recycling of metals, the EFs for recycling offset of ferrous metals is –434 kg CO_2-eq. t^{-1} and for aluminium metals –11 634 kg CO_2-eq. t^{-1} (Fischer 2006).

In this study carbon sequestration in landfills as well as in soils as a result of application of the bio-stablized output from MBT plants was not included in the model of this study, as it is not considered in the IPCC methodology (IPCC 1997; 2006).

GHG emissions from the use of fossil fuels for transportation of waste, were not included in the model as the proposed site for the new IWMC in western Attica is common for all scenarios and moreover the sanitary landfill where the residues of the processes will be disposed is located near this site. The only differences on GHG emissions could be derived from transportation of waste and materials to various reprocessors, RDF/SRF to cement kilns and APC ash to a hazardous waste landfill. However, the main reprocessors of recyclables in Greece are based near Attica, while there are two cement kilns near Athens that could be potential users of RDF and SRF. Finally, the only hazardous landfill in Greece where APC ash could be disposed of is in Attica (Laurio) as well. Thus the differences on GHG emissions from the transportation of waste and materials via different routes, is estimated to be negligible.

The EFs (kg CO_2-eq. t^{-1} of MSW treated) estimated for all activities involved in the waste management system of every examined scenario, are summarized in Table 3. The EFs of these activities were converted to CO_2-eq. using global warming potentials for a 100-year time frame (IPCC 1996) and all are expressed in the units of kg CO_2-eq. t^{-1} MSW treated.

Results and discussion

From Figure 3, where the results of the analysis are shown, it can be seen that all scenarios under assessment in this study could generate GHG emission savings. Scenarios 3 and 4 are those that performed better, followed by scenarios 2, 1 and 5.

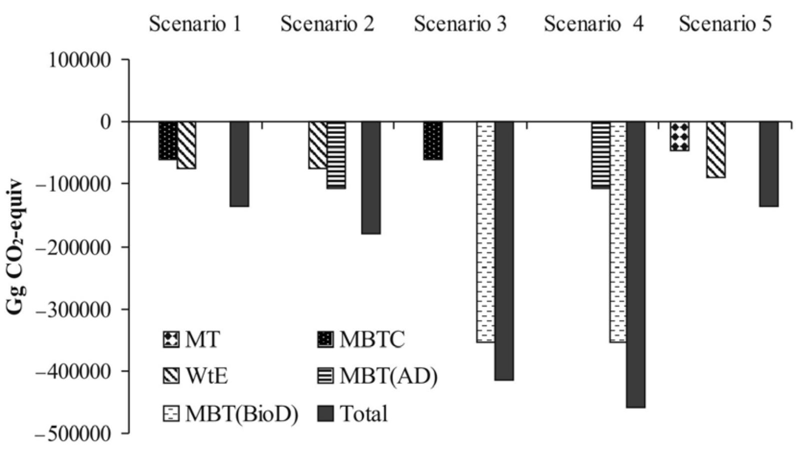

Fig. 3: GHG emissions (kg CO_2-eq.) for all five scenarios.

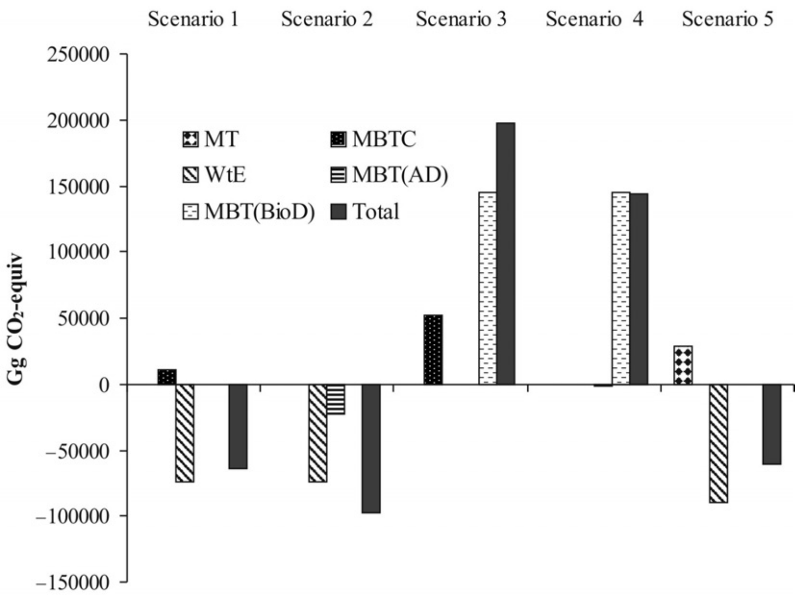

Fig. 4: GHG emissions (kg CO_2-eq.) for the five scenarios with no market for SRF/RDF.

Scenario 3 incorporates MBT(C) with RDF production and MBT(BioD) with SRF production. Both of these fuels were assumed to replace coal in cement kilns, as this would be the only option for these fuels, since there are no WtEs in Greece at the moment. In general the performance of all scenarios and especially scenarios 3 and 4 are strongly dependent on the existence of a final market for the produced RDF and SRF. However, the market for these fuels is extremely volatile and there are many cases where these fuels are disposed of in landfills instead of being utilized for energy recovery. For instance in Attica, the RDF produced from the only existing MBT in the region is landfilled because the agreement for its utilization in a proximate cement kiln in Evoia, has so far failed to be implemented due to public opposition (Tsatsarelis & Karagiannidis 2008). Similarly, in Germany in 2007, almost 7 million tons of SRF were produced but only 3.2 million tons were used as secondary fuel in SRF-dedicated incinerators, coal-fired power plants and cement kilns, and the rest were stored for future use (Schingnitz *et al*. 2008). Therefore, it was deemed to be absolutely necessary to perform a sensitivity analysis on the case where there is no market for these fuels.

Sensitivity analysis on scenarios

The sensitivity analysis aimed to evaluate what would be the GHG emission impact in the case where there is no end market for the produced RDF and SRF from the MT, MBT(C), MBT(BioD) and MBT(AD) plants in the assessed scenarios. In this case the GHG emission savings from the recovery of energy from these fuels should not be taken into account, whereas potential CH_4 production from the degradation of the biodegradable content of these fuels should be assessed, if they are finally disposed of in a landfill. In particular, a MBT(BioD) plant incorporates a bio-drying process, that either does not reduce the biodegradable content of the waste or else reduces only a small amount of it, about 10% (Adani *et al*. 2002, Archer *et al*. 2005) and thus the disposal of SRF in landfill will surely generate CH_4. Moreover, RDF in the MBT(C) and MBT(AD) plants is recovered before the biological process and thus the biodegradation of their organic fraction due to disposal in landfills will generate CH_4 as well. The results of the sensitivity analysis and the GHG emissions from the treatment of MSW in each of the scenarios are displayed in Figure 4. In the sensitivity analysis of the scenarios it was assumed that the WtE facilities in scenarios 1, 2 and 5 will increase their capacity and finally combust the surplus RDF from the MBT(C), MBT(AD) and MT, respectively. On the other hand in scenarios 3 and 4, where no thermal treatment plant is foreseen, it was assumed that the produced RDF and SRF will finally end up in landfill.

From Figure 4 it can be clearly seen how the performance of all scenarios depends strongly on the existence of an end market for the recovered RDF and SRF. Especially scenarios 3 and 4 generate net GHG emissions and thus the treatment of residual MSW in these scenarios, offers no benefit, at least on GHG emission savings. Therefore, in the event that a SRF market does not exist, further aerobic treatment for RDF and SRF will probably be necessary in order to reduce its biodegradable content, since they will be disposed in landfills. On the other hand scenarios 1, 2 and 5 can provide GHG emission savings as they incorporate WtE and MBT(AD) which recover electrical energy for which the demand is constant.

Conclusions

The present study assessed the GHG emission impact of various treatment technologies for the residual MSW in the Attica region in the context of five different waste management scenarios that were compiled according to information from the regional plan for Attica. The study has shown that all scenarios under assessment could save GHG emissions provided that there is an end market for the recovered RDF and SRF. In this case the co-incineration in cement of SRF mainly from MBT(BioD) and RDF from MBT(C), MBT(AD) and MT can generate significant emission savings. However, if these fuels are not utilized and are instead disposed of in landfills, then CH_4 emissions could be generated from the biodegradation of their organic fraction. Therefore it is proposed that decision-makers and planners evaluate the perspectives of these fuels in the Hellenic market and decide on which technology is more beneficial for the treatment of residual MSW in Attica. A superficial planning could result in large amounts of waste-derived fuels disposed of in landfills, which would have adverse GHG emission impact and moreover it would increase the cost of waste management in Attica due to additional disposal costs for RDF and SRF. In this case MBT(AD) or WtE plants are considered better options, as has been shown in the sensitivity analysis, where scenario 2, which incorporates a MBT(AD) plant and a WtE facility, performs best. In general, the conclusions of this study could support an integrated assessment that would examine the additional environmental impacts of MSW treatment technologies and at the same time evaluate their perspectives in the Hellenic market, in this way supporting the decision-makers. It should be also noted here that waste policy and planning in Greece for the moment does not promote waste minimization measures nor pose high recycling targets but instead promotes technologies and plants of large capacity that will treat mixed residual waste. Thus, the potentials for waste minimization measures such as home composting and PAYT schemes in conjunction with new waste treatment plants should be evaluated as well.

Abbreviations

DOC	degradable organic carbon
EF	emission factor
GHG	greenhouse gas
IWMC	integrated waste management centre
MBI	mass-burn incineration
MBT	mechanical–biological treatment
MBT(C)	MBT with composting
MBT(AD)	MBT with AD
MBT(BioD)	MBT with bio-drying
MRF	material recovery facilities
MSW	municipal solid waste
MT	mechanical treatment
NCV	net calorific value
PAYT	pay-as-you-throw
RDF	refuse-derived fuel
SRF	solid recovered fuel
WtE	waste-to-energy

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