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Global warming factors modelled for 40 generic municipal waste management scenarios

Thomas H. Christensen, Federico Simion, Davide Tonini, Jacob Møller
Department of Environmental Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

Global warming factors (kg CO_2-eq.-tonne^{-1} of waste) have been modelled for 40 different municipal waste management scenarios involving a variety of recycling systems (paper, glass, plastic and organics) and residual waste management by landfilling, incineration or mechanical–biological waste treatment. For average European waste composition most waste management scenarios provided negative global warming factors and hence overall savings in greenhouse gas emissions: Scenarios with landfilling saved 0–400, scenarios with incineration saved 200–700, and scenarios with mechanical-biological treatment saved 200–750 kg CO_2-eq. tonne^{-1} municipal waste depending on recycling scheme and energy recovery. Key parameters were the amount of paper recycled (it was assumed that wood made excessive by paper recycling substituted for fossil fuel), the crediting of the waste management system for the amount of energy recovered (hard-coal-based energy was substituted), and binding of biogenic carbon in landfills. Most other processes were of less importance. Rational waste management can provide significant savings in society's emission of greenhouse gas depending on waste composition and efficient utilization of the energy recovered.

Keywords: Global warming factors, greenhouse gas savings, Europe, waste management, environmental performance

Introduction

Climate change and greenhouse gases (GHG) have become significant issues related to waste management in recent years. The Intergovernmental Panel on Climate Change addresses the post-consumer waste sector in their fourth assessments report (Solomon *et al.* 2007), company protocols for GHG accounting are being introduced (e.g. EpE 2007), and life-cycle-assessment modelling of waste management systems suggests that global warming is one of the important potential impacts from waste management (e.g. Kirkeby *et al.* 2006a). Gentil *et al.* (2009) recently presented the various scopes and approached used in waste management in GHG accounting and concluded that the issue is complex and not very transparent. Nevertheless, GHG accounting and carbon foot-printing of waste management has come to stay, since waste management, like other sectors in society, will have to account for their GHG emissions and provide contributions to reach society's targets of reducing them.

Waste management contributes to GHG emissions through its use of energy and fuels, through incineration of waste containing fossil carbon, primarily plastic, and through emission of CH_4 from anaerobic degradation of organic waste. However, waste management also provides savings by producing energy and fuels and by providing recyclable materials as, for example, iron scrap and recovered paper. Reprocessing of recyclables is usually less energy demanding that producing from virgin resources. Finally, biogenic carbon can be bound in landfills and, when compost is applied to land, as sequestered carbon in soils. Bound and sequestered carbon of biogenic origin constitutes a saving with respect to global warming (Christensen *et al.* 2009) and should be assigned a negative global warming potential.

Recently, the GHG issues of the main processes in waste management have been presented (Eistedt *et al.* 2009, Merrild & Christensen 2009, Merrild *et al.* 2009, Larsen *et al.* 2009a, Damgaard *et al.* 2009, Boldrin *et al.* 2009a, Astrup *et al.* 2009a, b, Møller *et al.* 2009, Manfredi *et al.* 2009). Within each main treatment process, the various technologies available add variability to the parameters controlling the GHG emissions, suggesting that a single value of CO_2-equivalents per tonne of waste may not fully represent a technology. However, for many of the technologies it was also demonstrated that the major contributions to GHG were down-stream savings

Corresponding author: Thomas H Christensen, Department of Environmental Engineering, Building 115, Technical University of Denmark, DK-2800 Kongens Lyngby, Denmark.
E-mail: thc@env.dtu.dk

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because of recovered energy and recycled materials. As some waste management technologies are partly complementary and some technologies contribute to treatment trains [e.g. mechanical–biological technologies (MBT)], any comparison of GHG emissions can only be done consistently at a system level; namely when the management schemes using different combinations of technologies all treat the same waste. For this purpose the global warming factor (GWF), which expresses the overall CO_2-equivalents per tonne of waste handled by an integrated system, has been introduced.

The purpose of this study was to model the GWF for a range of municipal solid waste (MSW) management scenarios in a European context. A total of 40 basic waste management scenarios were established representing a variety of recycling schemes and treatment technologies. Modelling of GWF issues was done using the EASEWASTE model (Kirkeby *et al.* 2006b) for 1 tonne of wet municipal waste (European average) entering the alternative management scenarios.

Methodology

Defining the study

The scope of the study was to quantify how much the different feasible management systems for municipal waste contribute to GHG emissions and savings considering up-to-date technologies and systems managing the same average European municipal waste. The significance of waste composition and the type of energy substituted by the energy recovered by waste management was also part of the scope. The technologies considered were generic up-to-date waste management technologies; they do not represent any specific brand or plant, but represent realistic technologies that either are being or could be introduced in Europe today and in the future.

This information may be used in ranking the alternatives and for identifying which parts or technologies in a waste management system are the main factors in the GHG account. The assessment of the importance of the waste composition and the energy substitution on the GHG account may reveal if these issues, which may differ from country to country, significantly affect the ranking of the waste management alternatives and the understanding of which factors are important. The study focuses only on GHG accounts and thus represents only a part of the platform needed for making decisions as to which management system is preferable.

The functional unit used throughout the study is 1 metric tonne of wet waste (1000 kg). An average European municipal waste composition (see later) was used for the main study, but alternative waste compositions were also studied.

System boundaries

The system boundaries of the study are the MSW from the point of collection by the waste management system to final disposal, namely landfilled or exported out of the waste management system. In this study home composting was excluded as it is considered to be a relatively small contribution to the total waste management.

A system expansion was made for the energy sector for electricity, heat and fuels delivered to and from the waste management system and for the recyclables used in the reprocessing industry (glass, plastic, aluminium, ferrous materials and compost products). It was assumed that paper recycling reduces wood demand (from forestry) and that any excess wood is made available as an energy source substituting other sources of fossil energy. This approach tacitly assumes a constant stock of forestry over time (Christensen *et al.* 2009).

Modelling and global warming potentials used

The GWF was modelled by means of EASEWASTE (Kirkeby *et al.* 2006b). This LCA-waste model allows for source separation of waste into different streams and tracks the flows and substances through the treatment schemes until final disposal.

EASEWASTE quantifies all carbon flows as biogenic or fossil and assigns global warming potentials according to Christensen *et al.* (2009).

- Fossil C emitted as CO_2: 1 kg CO_2-eq. kg CO_2^{-1} emitted.
- Fossil C bound in a landfill: 0 kg CO_2-eq. kg C^{-1} bound
- Biogenic C emitted as CO_2: 0 kg CO_2-eq. kg CO_2^{-1} emitted
- Biogenic C bound in landfills or sequestered in soils: –3.67 (44/12) kg CO_2-eq. kg C^{-1} bound

Of the other GHGs, methane and dinitrogenoxide are the main contributors. Their global warming potentials are 25 kg CO_2-eq. kg CH_4^{-1} emitted and 298 kg CO_2-eq. kg N_2O^{-1} emitted, respectively (Solomon *et al.* 2007).

The global warming factor (GWF) expresses in CO_2-equivalents the overall GHG account of the scenario managing 1 tonne of wet municipal waste.

Waste composition

An average European municipal waste composition was used in the study. No standard methodology exists in Europe for defining waste composition (Beigl *et al.* 2008), but several studies have recently estimated the composition of average European municipal solid waste, for example, Kreißig & Stoffregen (2008), Sander (2008) and ETC/RWM (2008), reaching comparable but not identical compositions. The findings of these studies were used to distribute the waste into the 48 material fractions used in EASEWASTE (detailed data not shown here). This high number of material fractions was introduced to be able to establish a range of source-separation schemes and allow for calculation of the composition of the residual waste. The composition used corresponded at the waste source on a wet weight basis to 35% organics, 22% paper and cardboard, 3% textile, 10% plastic, 6% glass, 4% metal, and 20% ‘other’ (see Table 1).

The importance of the waste composition was assessed by modelling selected typical waste management systems with modified waste compositions. An assumed ‘northern European’ waste composition with less organics and more paper,

Table 1: Municipal waste composition: average European used in the study and two modified ('northern European' and 'southern European') waste compositions used for sensitivity analysis.

% ww	Average European MSW (this study)	'Northern European' modified MSW (sensitivity analysis)	'Southern European' modified MSW (sensitivity analysis)
Organic	35	30	47
Paper	22	33	20
Textile	3	4	3
Plastic	10	9	9
Glass	6	4	5
Metal	4	4	5
Other	20	16	11

and an assumed 'southern European' waste composition with more organics and less paper were introduced (see Table 1). The latter two waste compositions are hypothetical and not based on any statistical material, but introduced to induce a change in waste composition on selected management systems.

Energy system

Electricity and heat

The exchange within the energy systems is in terms of both use and recovery of energy. The use is primarily electricity and fuels (diesel and natural gas), and the recovery is primarily electricity, heat and refuse-derived fuel (RDF).

For the waste management systems, coal-based energy was assumed for both the use and the recovery of energy. Coal-based energy is assumed to be the energy marginal in many European countries (Fruergaard *et al.* 2009). As the modelling represents generic scenarios with up-to-date technologies that could be introduced in the years to come and as most countries will face a major challenge in phasing out fossil fuels in order to meet their Kyoto obligations and any further obligations that may exist beyond 2012, this justifies the use of coal as marginal. The values used were 1.03 kg CO_2-eq. kWh^{-1} for electricity and 0.335 kg CO_2-eq. kWh^{-1} for heat based on Fruergaard *et al.* (2009).

Electricity is a regional commodity and marginal electricity may be different in different regions depending on fuel type and production mode. Direct and indirect emissions were included, such that the data encompassed the entire supply chain from exploration and extraction of the fuels over combustion at the energy-producing plants to the final distribution to consumers via the grid. Some loss in transmission and distribution was therefore included as well. In the sensitivity analysis, for selected scenarios representing an interesting range of waste management systems the average European electricity production and electricity production based on brown coal was also modelled. An average EU electricity mix of 0.588 kg CO_2-eq. kWh^{-1} was based on data from the European Reference Life Cycle Data System (ELCD 2009) and also corresponds to electricity based on natural gas. Brown coal-based electricity is the most 'dirty' of all production modes and in the present study was represented by a low-efficiency production corresponding to 1.511 kg CO_2-eq. kWh^{-1}. This was calculated based on European Commission (2003) assuming an efficiency of electricity production of 25% (according to Dones *et al.* (2004), European brown coal electricity production has an efficiency between 23 and 40%.)

Heat is a local commodity and the marginal production technology cannot be determined unless local heat production technologies as well as heat demands are specified. In some cases electricity production and heat production may be linked, although this is generally not the case in Europe. Production of 1 kWh heat was, as mentioned above, calculated to 0.335 kg CO_2-eq. kWh^{-1} representing a fuel mix of fossil and biomass origin. CO_2, CH_4 and N_2O were included in the calculation. Similar values have been used in other reports on waste management in Europe: Kreißig & Stoffregen (2008) applied a value of 0.324 kg CO_2-eq. kWh^{-1}, and in their report Skovgaard *et al.* (2008) used 0.27 kg CO_2-eq. kWh^{-1}. In the sensitivity analysis it was decided to couple the 'dirty' electricity production with a 'dirty' heat production representing combustion of fuel oil in old low-efficiency (60%) boilers with a value of 0.51 kg CO_2-eq. kWh^{-1}.

Fuel combustion

Diesel combustion and natural gas combustion are straightforward in terms of GHG emissions. Values of 3.0 kg CO_2-eq. L^{-1} diesel and 2.5 kg CO_2-eq. N m^{-3} natural gas were used, respectively. These values include the provision as well as the combustion of the fuels (Fruergaard *et al.* 2009).

In some systems the RDF fractions were assumed to substitute directly (1 : 1 based on the energy content of RDF and hard coal) for coal combustion at power plants. In these cases the combustion of coal is avoided corresponding to 115 kg CO_2-eq. GJ^{-1} hard coal substituted by RDF; this value also includes GHG emissions associated with provision of hard coal.

Waste management technologies

The waste management technologies were modelled by means of technologies available in the EASEWASTE-model (www.easewaste.dk). Technologies that were considered up-to-date in terms of their emissions to air, water and soil and in terms of their resource and energy recovery were chosen. These technologies were considered to be realistic and resemble technologies that are being or could be introduced in Europe – they are briefly described below.

Source separation

The sorting efficiencies used to estimate the amounts collected separately at the source reflect optimistic values and assume a high degree of collection at the source and a high level of participation in the recycling schemes. Efficiencies for selected material fractions were set at 65% for paper, 55% for glass and 50% for plastic. For organic waste different sorting efficiencies were assumed depending on the treatment method: 60% if it was composted and 50% in the case of anaerobic digestion. The percentages were calculated based on the recyclable part of each material fraction and not as percentages of the whole material fraction. As an example the sorting efficiency of 65% for paper does not represent 65% of the 22% paper in the average European waste composition (Table 1), but only 65% of the recyclable paper fractions, namely newsprint, magazines, advertisement papers, etc. The actual amounts source separated in the various scenarios are quantified in the scenario tables (see Tables 3–5 below).

Collection

Collection was modelled by its diesel consumption per tonne of waste collected. Five different waste collection technologies taken from Larsen *et al.* (2009b) were used; these technologies consume 3 L diesel tonne^{-1} residual waste, 4 L tonne^{-1} paper, 6 L tonne^{-1} glass and organic waste and 8 L tonne^{-1} plastic waste. Collection of waste is further discussed with respect to GHG issues by Eisted *et al.* (2009).

Transport

Transport was modelled by means of assumed distances and fuel consumptions (L diesel tonne^{-1} km^{-1}) from transport technologies in the EASEWASTE database. The distances assumed ranged from 15 km for transport of residual waste to an incineration plant to 500 km for transport of metal scrap to a recycling plant. Transport of waste is with respect to GHG issues further discussed by Eisted *et al.* (2009).

Recycling

Recycling processes were modelled using data present in the EASEWASTE database. Recycled materials substitute similar products made with virgin material. The environmental benefits from the avoided impacts are credited to the system. Each recycling process was modelled as a combination of two parameters: the material loss in the process (technical substitution) and the market acceptance of the recycled product (marked substitution). Both parameters depend on the fraction recycled. The technical substitution rate was in the range from 85 to 90% whereas the market-related substitution ratio was set at 100% for all fractions but plastic (90%). GHG issues of recycling various waste fractions are described in detail in the literature: paper and cardboard (Merrild *et al.* 2009b), glass (Larsen *et al.* 2009a), metals (Damgaard *et al.* 2009) and plastic (Astrup *et al.* 2009b).

Composting

The composting process was based on data from a tunnel composting plant in Italy. Degradation of the organic material was modelled as a percentage of the volatile solid content in the incoming waste for each material fraction. With respect to GHG, methane and nitrous oxide released from the biofilter were taken into account as well as electricity consumption at the composting plant. The produced compost was assumed used by spreading on farm-land as fertilizer substitute. Credits were obtained from the substituted fertilizer. The composting module in EASEWASTE is further described by Boldrin *et al.* (2009b) and the use of compost on agricultural land is described by Hansen *et al.* (2006). GHG issues of composting and use of compost are described by Boldrin *et al.* (2009a)

Anaerobic digestion

In this study anaerobic digestion was included as an alternative to composting; the only difference being that the anaerobic digestion plant was assumed to accept fewer fractions of organic waste because of the restriction on the quality of the waste for this technology. For example, fractions such as cat litter, pot plants and cut flowers were not accepted as input to the anaerobic digestion plant, whereas these fractions were accepted in the composting process. As a representative technology a one-stage thermophilic wet reactor in the EASEWASTE database was used. The biogas production was modelled as 70% of the methane potential of the waste received. The methane content in the biogas was set at 63% per volume. Electricity consumption and energy spent for running the plant were the main loads of the process since the emissions from the process itself were small. The main output was the electricity production from biogas combustion modelled as a percentage of the energy content in the biogas. An electricity production efficiency of 35% of the energy content of the biogas was assumed. Emissions from biogas combustion, such as methane and nitrous oxide, were taken into account. The heat from the gas combustion was assumed to be used for heating the reactor. The anaerobic digestion module in EASEWASTE is further described by Boldrin *et al.* (2009b). GHG issues of anaerobic digestion and use of digestate are described by Møller *et al.* (2009)

Landfilling

The landfill modules in EASEWASTE simulate all the processes involved in the landfill, namely the degradation of the organic waste and production and release of gas and leachate. The landfill module defines four time periods in which gas and leachate generation, collection and composition are defined depending on the landfill technology used. In the present study a conventional landfill and a bioreactor landfill with leachate recirculation were used to model the disposal of the residual waste. Both bioreactor and conventional landfill were provided with gas and leachate collection systems. Considering the 100 year time frame, the overall life-time gas collection efficiency equals 50% for the conventional landfill and 80% for the bioreactor. A bottom ashes landfill was used for the incineration residue whereas an MBT landfill was used for residues from the mechanical–biological treatment of the waste, neither of them had gas collection systems. Electricity and fuel consumption for running the landfill (compaction, soil movement, extraction and combustion of the gas, leachate treatment, etc.) were included in the inventory. The main output from the system is the electricity production from combustion of biogas. The combustion efficiency was set at 35% of the energy content of the biogas for electricity generation when relevant. No heat recovery was assumed to take place. Biogenic carbon left in the landfill 100 years after disposal was counted as saved GHG emission (Christensen *et al*. 2009). The landfilling module of EASEWASTE is further described by Kirkeby *et al.* (2007) and Manfredi & Christensen (2009). GHG issues of landfilling are described by Manfredi *et al*. (2009)

Incineration

With respect to GHG, incineration was modelled by its consumption of electricity (blowers, electrostatic precipitators, etc.) and fuels (start-up-fuels, transport, etc.), the emissions of CO_2 originating from fossil carbon in the received waste, and the recovery of heat and electricity calculated as percentages of the lower-heating-value (LHV) of the received waste. For electricity 20.7% and for heat 40% were used when relevant. These numbers do not represent the present European average energy recovery for incinerators that according to Kreißig & Stoffregen (2008) is at 48.9% gross production of heat and electricity related to energy input. A more efficient modern incinerator with relatively high electricity production, of a type that is not uncommon in Denmark and Germany, was chosen for the present study. In these countries heat recovery is often much higher than the European average, but as the demand for heat in southern Europe is small 40% was chosen as a realistic target for future incinerators in Europe. Iron scrap was recovered from the bottom ash. It was assumed that the bottom ash was landfilled. The incineration module of EASEWASTE is further described by Riber *et al*. (2008) and the GHG issues of incineration are described by Astrup *et al*. (2009a).

Mechanical–biological treatment

Two types of MBT plants were modelled: a mechanical–biological stabilization (MBS) plant where mechanical treatment is performed after the composting of all incoming waste for a short period and a mechanical–biological pre-treatment (MBP) plant where composting follows after the mechanical treatment. The relevant outputs from these plant are recyclable metals and an RDF fraction with a high calorific value (14–15 GJ tonne^{-1} RDF). The RDF from an MBS plant can be routed to an incinerator. In the case of a MBP plant, the RDF can be used in a coal-based power plant as a direct coal substitute. RDF from MBP plants generally contains fewer pollutants in the form of heavy metals, etc. than RDF produced at MBS plants and is, therefore, better suited for co-combustion at coal-fired power plants. An MBP plant also encompasses a landfill module for the composted fine fraction from the mechanical step whereas in the MBS plant the composted non-recyclable fraction forms the RDF. Basically, operation of both types of plants brings a load to the environment because of the electricity consumption which is relatively high, especially at MBS plants. The MBT plants were modelled by the biotechnology module of EASEWASTE (Boldrin *et al*. 2009a).

Waste management systems

The generic waste management systems were defined around the three main residual waste management options: Landfilling, incineration and MBT. Each of these residual waste treatment technologies were combined with a range of source separation and recycling schemes, ranging from no recycling (as a reference scenario) over paper, glass and plastic recycling to source separation of organics for composting or anaerobic digestion. The latter, however, were not considered very common when MBT was the residual waste treatment technology. In addition the energy recovery from the residual waste treatment technologies was varied, from none to efficient recovery of electricity (landfill gas, incinerator, anaerobic digester, RDF to incinerator) and recovery of both electricity and heat (incinerator, RDF to incinerator). In some systems the RDF was assumed to substitute directly for coal at coal-fired power plants. A total of 40 generic waste management scenarios were modelled. These do not cover all possible and relevant combinations of source-separation schemes and treatment technologies, but hopefully they offer insight into the GWF of the most common waste management systems. Table 2 gives an overview of the different scenarios organized according to residual waste treatment.

The source separation schemes were highly efficient for paper (143 kg), glass (33 kg) and plastic (13 kg) and were considered the same in all systems, whereas the source separation of organics differed for composting (232 kg) and anaerobic digestion (174 kg). The values in parenthesis show the amounts that were source separated per 1000 kg of municipal waste. Metal recovery was also modelled for incineration and MBT plants (13–40 kg).

The mass flows and energy recoveries of the 40 scenarios modelled are shown in Table 3 for the landfill-based scenarios, in Table 4 for the incinerator-based scenarios and in Table 5 for the MBT-based scenarios.

Modelling the 40 generic scenarios involved defining the scenarios, choosing technologies and assessing operational parameters typical for up-to-date waste management technologies. The vast amount of technological data did not allow a systematic investigation of the importance of each technological parameter by means of sensitivity analysis. However, previous experience has indicated that

Table 2: Scenarios organized according to residual waste treatment (Landfill: LAN; incineration: INC; mechanical-biological treatment: MBT).

Scenario	Source separation of paper	Source separation of glass	Source separation of plastic	Source separation of organics	Composting	Anaerobic digestion	Incineration	MBP	MBS	Landfill: conventional	Landfill: bioreactor	Landfill: MBT	Landfill: bottom ash	Energy
LAN1-0	–	–	–	–	–	–	–	–	–	×	–	–	–	LFG: flared
LAN2-0	–	–	–	–	–	–	–	–	–	×	–	–	–	LFG: electricity
LAN3-0	–	–	–	–	–	–	–	–	–	–	×	–	–	LFG: electricity
LAN1-1	×	×	–	–	–	–	–	–	–	×	–	–	–	LFG: flared
LAN2-1	×	×	–	–	–	–	–	–	–	×	–	–	–	LFG: electricity
LAN3-1	×	×	–	–	–	–	–	–	–	–	×	–	–	LFG: electricity
LAN1-2	×	×	×	–	–	–	–	–	–	×	–	–	–	LFG: flared
LAN2-2	×	×	×	–	–	–	–	–	–	×	–	–	–	LFG: electricity
LAN3-2	×	×	×	–	–	–	–	–	–	–	×	–	–	LFG: electricity
LAN1-3	×	×	×	×	×	–	–	–	–	×	–	–	–	LFG: flared
LAN2-3	×	×	×	×	×	–	–	–	–	×	–	–	–	LFG: electricity
LAN3-3	×	×	×	×	×	–	–	–	–	–	×	–	–	LFG: electricity
LAN1-4	×	×	×	×	–	×	–	–	–	×	–	–	–	LFG: flared
LAN2-4	×	×	×	×	–	×	–	–	–	×	–	–	–	LFG: electricity
LAN3-4	×	×	×	×	–	×	–	–	–	–	×	–	–	LFG: electricity
INC1-0	–	–	–	–	–	–	×	–	–	–	–	–	×	Electricity
INC2-0	–	–	–	–	–	–	×	–	–	–	–	–	×	Electricity + heat
INC1-1	×	×	–	–	–	–	×	–	–	–	–	–	×	Electricity
INC2-1	×	×	–	–	–	–	×	–	–	–	–	–	×	Electricity + heat
INC1-2	×	×	×	–	–	–	×	–	–	–	–	–	×	Electricity
INC2-2	×	×	×	–	–	–	×	–	–	–	–	–	×	Electricity + heat
INC1-3	×	×	×	×	×	–	×	–	–	–	–	–	×	Electricity
INC2-3	×	×	×	×	×	–	×	–	–	–	–	–	×	Electricity + heat
INC1-4	×	×	×	×	–	×	×	–	–	–	–	–	×	Electricity
INC2-4	×	×	×	×	–	×	×	–	–	–	–	–	×	Electricity + heat
MBT1-0	–	–	–	–	–	–	–	×	–	–	–	×	–	RDF to coal-fired power plant
MBT2-0	–	–	–	–	–	–	–	×	–	–	–	×	×	RDF to INC w electricity
MBT3-0	–	–	–	–	–	–	–	×	–	–	–	×	×	RDF to INC w electricity + heat
MBT4-0	–	–	–	–	–	–	–	–	×	–	–	–	×	RDF to INC w electricity
MBT5-0	–	–	–	–	–	–	–	–	×	–	–	–	×	RDF to INC w electricity + heat
MBT1-1	×	×	–	–	–	–	–	×	–	–	–	×	–	RDF to coal-fired power plant
MBT2-1	×	×	–	–	–	–	–	×	–	–	–	×	×	RDF to INC w electricity
MBT3-1	×	×	–	–	–	–	–	×	–	–	–	×	×	RDF to INC w electricity + heat
MBT4-1	×	×	–	–	–	–	–	–	×	–	–	–	×	RDF to INC w electricity
MBT5-1	×	×	–	–	–	–	–	–	×	–	–	–	×	RDF to INC w electricity + heat
MBT1-2	×	×	×	–	–	–	–	×	–	–	–	×	–	RDF to coal-fired power plant
MBT2-2	×	×	×	–	–	–	–	×	–	–	–	×	×	RDF to INC w electricity
MBT3-2	×	×	×	–	–	–	–	×	–	–	–	×	×	RDF to INC w electricity + heat
MBT4-2	×	×	×	–	–	–	–	–	×	–	–	–	×	RDF to INC w electricity
MBT5-2	×	×	×	–	–	–	–	–	×	–	–	–	×	RDF to INC w electricity + heat

the waste composition as well as the energy profile plays an even large role in LCA–modelling of waste management systems (Christensen *et al*. 2007) and sensitivity analysis involving two different waste compositions and two different energy profiles were therefore performed, as described later.

Table 3: Mass-flows for landfill-based scenarios per 1000 kg waste.

Scenario – landfill-based	Source separation of paper	Source separation of glass	Source separation of plastic	Source separation of organics	Compost	Anaerobic digestate	Landfill: conventional	Landfill: bioreactor	Energy from digester	Energy from landfill
1000 kg	kg	kg	kg	kg	kg	kg	kg	kg	kWh	kWh
LAN1-0	–	–	–	–	–	–	1000	–	–	–
LAN2-0	–	–	–	–	–	–	1000	–	–	99
LAN3-0	–	–	–	–	–	–	–	1000	–	178
LAN1-1	143	33	–	–	–	–	824	–	–	–
LAN2-1	143	33	–	–	–	–	824	–	–	77
LAN3-1	143	33	–	–	–	–	–	824	–	140
LAN1-2	143	33	13	–	–	–	811	–	–	–
LAN2-2	143	33	13	–	–	–	811	–	–	77
LAN3-2	143	33	13	–	–	–	–	811	–	140
LAN1-3	143	33	13	231	58	–	580	–	–	–
LAN2-3	143	33	13	231	58	–	580	–	–	45
LAN3-3	143	33	13	231	58	–	–	580	–	81
LAN1-4	143	33	13	173	–	609*	638	–	47	–
LAN2-4	143	33	13	173	–	609*	638	–	47	51
LAN3-4	143	33	13	173	–	609*	–	638	47	92

* High water content (95%).

Table 4: Mass-flows for incineration based scenarios per 1000 kg waste.

Scenario – incinerator-based	Source separation of paper	Source separation of glass	Source separation of plastic	Source separation of organics	Compost	Anaerobic digestate	Incineration	Recovery of iron scrap from bottom ash	Landfilling of bottom ash	Electricity from digester	Electricity from incinerator	Heat from incinerator
1000 kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kWh	kWh	kWh
INC1-0	–	–	–	–	–	–	1000	13	165	–	587	
INC2-0	–	–	–	–	–	–	1000	13	165	–	587	1134
INC1-1	143	33	–	–	–	–	824	13	110	–	477	
INC2-1	143	33	–	–	–	–	824	13	110	–	477	921
INC1-2	143	33	13	–	–	–	811	13	109	–	452	
INC2-2	143	33	13	–	–	–	811	13	109	–	452	873
INC1-3	143	33	13	231	58	–	580	13	98	–	396	
INC2-3	143	33	13	231	58	–	580	13	98	–	396	765
INC1-4	143	33	13	173	–	609*	638	13	106	47	410	
INC2-4	143	33	13	173	–	609*	638	13	106	47	410	792

* High water content (95%).

Results and discussion

Generic waste management (40 systems)

Tables 6 to 8 show GWFs for the 40 generic waste management scenarios grouped according to the main management option for residual waste: Landfilling, incineration and mechanical–biological treatment.

All but one of the systems had overall numerically negative GWFs, which means that the waste management scenarios contributed with GHG savings by replacing more polluting technologies outside the waste sector in terms of energy or recyclable materials or by storing biogenic carbon in landfills. It was noticeable that the GHG contributions of waste collection and transport were relatively modest (9–12 kg CO_2-eq. tonne^{-1} and 8–34 kg CO_2-eq. tonne^{-1}, respectively) as were the emissions from composting and anaerobic digestion. Landfills, incinerators and MBT plants have large significant GHG loads, but they also offer major savings in terms of energy recovery and in the case of the landfill also in terms of bind-

Table 5: Mass-flows for MBT based scenarios per 1000 kg waste.

Scenario – MBT-based	Source separation of paper	Source separation of glass	Source separation of plastic	MBP	MBS	Recovery of iron scrap from MBT	Landfilling of MBT waste	RDF to power plant	RDF to incinerator	Landfilling of bottom ash	Electricity from incinerator	Heat from incinerator
1000 kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	kWh	kWh
MBT1-0	–	–	–	1000	–	40	188	530	–	–	–	–
MBT2-0	–	–	–	1000	–	40	188	–	530	61	446	–
MBT3-0	–	–	–	1000	–	40	188	–	530	61	446	863
MBT4-0	–	–	–	–	1000	38	–	–	597	102	518	–
MBT5-0	–	–	–	–	1000	38	–	–	597	102	518	1001
MBT1-1	143	33	–	824	–	40	131	420	–	–	–	–
MBT2-1	143	33	–	824	–	40	131	–	420	37	357	–
MBT3-1	143	33	–	824	–	40	131	–	420	37	357	690
MBT4-1	143	33	–	–	824	38	–	–	437	67	408	–
MBT5-1	143	33	–	–	824	38	–	–	437	67	408	789
MBT1-2	143	33	13	811	–	40	130	400	–	–	–	–
MBT2-2	143	33	13	811	–	40	130	–	400	37	335	–
MBT3-2	143	33	13	811	–	40	130	–	400	37	335	648
MBT4-2	143	33	13	–	811	37	–	–	425	66	386	–
MBT5-2	143	33	13	–	811	37	–		425	66	386	746

ing of biogenic carbon in the landfill. Net savings were substantial for landfills with efficient energy recovery (savings: 100–200 kg CO_2-eq. tonne^{-1}), incinerators (savings: 200–600 kg CO_2-eq. tonne^{-1}), and MBT-plants (savings: 200–600 kg CO_2-eq. tonne^{-1}). Of the recyclables, paper was the most important contributor offering savings of the order of 250 kg CO_2-eq. tonne^{-1} MSW when 143 kg of paper was recycled for each tonne of MSW. The high saving was linked to the assumption that wood no longer required for paper-making because of paper recycling could be used as a fuel, replacing fossil fuels in the energy sector. If this assumption was not made then paper recycling would only have saved 108 CO_2-eq. tonne^{-1} municipal waste. The savings from plastic and glass were minor (8–10 CO_2-eq. tonne^{-1}), whereas the savings from metals may be significant (22–118 CO_2-eq. tonne^{-1}).

Landfill scenarios

Table 6 shows that all the landfill scenarios but one (LAN1-0) had a negative GWF, which means that they all contributed with a saving with respect to GHG. The only exception was waste disposed directly in a conventional landfill equipped with a flare but no energy recovery.

The results also show that for residual waste a bioreactor landfill was better than a conventional landfill with respect to GHG savings. The main difference was the maximized electricity production and the reduction in uncontrolled emissions of CH_4 from the bioreactor landfill.

The best landfill scenario (LAN3-4) involved source separation of paper, glass, plastic and organic waste that was routed to anaerobic digestion where electricity was produced (–485 kg CO_2-eq. tonne^{-1}). In this case only 638 kg of waste was landfilled. Source-separated organic waste for anaerobic digestion contributed with only 10% of GHG savings, because the introduction of anaerobic digestion also caused less energy recovery at the landfill. Anaerobic digestion was a better approach than composting from a GHG perspective because of both the energy recovery from the biogas and the higher savings from using digestate on land (higher fertilizer substitution).

Within the landfill scenarios, the important factors were in decreasing rank: recovery of energy from the landfill, bioreactor instead of conventional landfill, and the introduction of paper recycling schemes. Introduction of anaerobic digestion and use of digestate on land also provided savings in GHG emissions.

It should be underlined that carbon storage was a critical factor which influenced the results significantly by providing savings between 141 and 261 CO_2-eq. tonne^{-1}.

Incineration scenarios

All incineration scenarios (Table 7), without exemptions, showed negative GWF; that is, all incineration scenarios contributed to GHG savings (Table 7). Some incineration scenarios, but not all, offered more savings with respect to GHG than the landfill-based scenarios. The least beneficial incineration scenarios involved incineration with only electricity recovery. This shows that heat recovery – although not always possible – is a critical parameter for the GHG accounting of waste incineration. It should be kept in mind that the high benefit obtained was due to a heat recovery efficiency of 40% of the lower heating value of the waste.

Another important result is that source separation of organic waste did not enhance the GHG savings, when heat

Table 6: Disaggregated GHG emissions (kg CO_2-equivalents/1000 kg of waste) for landfill- based scenarios.

Scenario	Total	Collection	Transport	Recycling of paper	Recycling of glass	Recycling of plastic	Composting plant (total)	Use of compost	Digester (total)	Use of digestate	Landfill: operation	Landfill: gas emissions	Landfill: energy recovery	Landfill: C-binding
LAN1-0	18	9	16	–	–	–	–	–	–	–	22	233	–	–261
LAN2-0	–112	9	16	–	–	–	–	–	–	–	22	232	–129	–261
LAN3-0	–275	9	16	–	–	–	–	–	–	–	21	102	–202	–221
LAN1-1	–207	10	19	–255	–8	–	–	–	–	–	18	183	–	–172
LAN2-1	–309	10	19	–255	–8	–	–	–	–	–	18	183	–102	–172
LAN3-1	–437	10	19	–255	–8	–	–	–	–	–	17	80	–158	–141
LAN1-2	–216	10	19	–255	–8	–10	–	–	–	–	18	183	–	–172
LAN2-2	–318	10	19	–255	–8	–10	–	–	–	–	18	183	–102	–172
LAN3-2	–446	10	19	–255	–8	–10	–	–	–	–	17	80	–158	–141
LAN1-3	–277	12	18	–255	–8	–10	23	–3	–	–	13	106	–	–172
LAN2-3	–335	12	18	–255	–8	–10	23	–3	–	–	12	106	–59	–172
LAN3-3	–396	12	18	–255	–8	–10	23	–3	–	–	12	46	–92	–141
LAN1-4	–318	12	21	–255	–8	–10	–	–	–34	–6	14	120	–	–172
LAN2-4	–385	12	21	–255	–8	–10	–	–	–34	–6	14	120	–67	–172
LAN3-4	–458	12	21	–255	–8	–10	–	–	–34	–6	13	53	–104	–141

Table 7: Disaggregated GHG emissions (kg CO_2-equivalents per 1000 kg of waste) for incineration- based scenarios.

Scenario	Total	Collection	Transport	Recycling of paper	Recycling of glass	Recycling of plastic	Composting plant (total)	Use of compost	Digester (total)	Use of digestate	Incinerator (consumption)	Incinerator: air emissions	Incinerator: scrap iron recovery	Incinerator: bottom ash landfilling	Incinerator: electricity recovery	Incinerator: heat recovery
INC1-0	–239	9	8	–	–	–	–	–	–	–	72	297	–22	2	–606	–
INC2-0	–620	9	8	–	–	–	–	–	–	–	72	297	–22	2	–606	–380
INC1-1	–398	10	12	–255	–8	–	–	–	–	–	59	296	–22	1	–492	–
INC2-1	–707	10	12	–255	–8	–	–	–	–	–	59	296	–22	1	–492	–309
INC1-2	–416	10	13	–255	–8	–10	–	–	–	–	58	263	–22	1	–466	–
INC2-2	–708	10	13	–255	–8	–10	–	–	–	–	58	263	–22	1	–466	–293
INC1-3	–352	12	15	–255	–8	–10	23	–3	–	–	42	262	–22	1	–408	–
INC2-3	–608	12	15	–255	–8	–10	23	–3	–	–	42	262	–22	1	–408	–256
INC1-4	–419	12	17	–255	–8	–10	–	–	–34	–6	46	262	–22	1	–423	–
INC2-4	–684	12	17	–255	–8	–10	–	–	–34	–6	46	262	–22	1	–423	–265

was recovered at the incineration plant. This is in contrast to the findings for the landfill-based scenarios, where source separation and anaerobic digestion was shown to improve the GHG account. As the incinerator with heat recovery had very high total energy recovery efficiency (20.7% for electricity and 40.0% for heat recovered of the LHV), the anaerobic digestion plant, despite having a very high efficiency on the electricity production, did not match the incinerator. Only when the incinerator had limited or no heat recovery, did source separation of organic waste and anaerobic digestion lead to higher GHG savings, but it is important to note that it was assumed that heat from the combustion of the biogas was not recovered.

The best GWF (–708 kg CO_2-eq. tonne^{-1} wet waste) among the incineration scenarios was achieved when source segregation of paper, glass and plastic was combined with incineration including electricity and heat recovery. In particular paper recycling contributed significantly to the GHG savings. This is linked to the fact that the savings from paper recycling processes including alternative use of the saved biomass substituting for fossil fuels were higher than the savings the system would be credited if the paper fraction was incinerated. Plastic recycling seems to a lesser extent to lead to benefits; the savings originate mainly from avoided fossil carbon emissions through the stack of the incinerator. A high level of recycling of paper, glass and plastic is therefore always

Table 8: Disaggregated GHG emissions (kg CO_2-equivalents per 1000 kg of waste) for MBT-based scenarios. Bottom ash disposal (< 1 kg), iron recovery from bottom ash (–1 to –2), MBT landfilling (2–3) and methane emissions from MBT –landfill (4–5) were only included in the total.

Scenario	Total	Collection	Transport	Recycling of paper	Recycling of glass	Recycling of plastic	MBT plant (total)	MBT plant: iron scrap recovery	Power plant: emissions from RDF	Power plant: coal substitution	Incinerator consumption	Incinerator: emissions	Incinerator: electricity recovery	Incinerator: heat recovery	Landfilling: C-binding
MBT1-0	–684	9	34	–	–	–	51	–60	270	–892	–	–	–	–	–101
MBT2-0	–234	9	20	–	–	–	51	–60	–	–	39	261	–460	–	–101
MBT3-0	–523	9	20	–	–	–	51	–60	–	–	39	261	–460	–289	–101
MBT4-0	–190	9	19	–	–	–	125	–118	–	–	43	268	–534	–	–
MBT5-0	–525	9	19	–	–	–	125	–118	–	–	43	268	–534	–335	–
MBT1-1	–757	10	33	–255	–8	–	42	–60	267	–715	–	–	–	–	–74
MBT2-1	–397	10	23	–255	–8	–	42	–60	–	–	30	260	–369	–	–74
MBT3-1	–628	10	23	–255	–8	–	42	–60	–	–	30	260	–369	–231	–74
MBT4-1	–372	10	21	–255	–8	–	103	–118	–	–	31	267	–421		–
MBT5-1	–636	10	21	–255	–8	–	103	–118	–	–	31	267	–421	–264	–
MBT1-2	–752	10	33	–255	–8	–10	41	–60	237	–671	–	–	–	–	–74
MBT2-2	–414	10	23	–255	–8	–10	41	–60	–	–	29	231	–346	–	–74
MBT3-2	–631	10	23	–255	–8	–10	41	–60	–	–	29	231	–346	–217	–74
MBT4-2	–388	10	21	–255	–8	–10	101	–118	–	–	31	238	–399	–	–
MBT5-2	–638	10	21	–255	–8	–10	101	–118	–	–	31	238	–399	–250	–

recommended. Anaerobic digestion was generally better than composting and could improve the GHG account if the incinerator recovered only electricity. It should be kept in mind that incineration of organic waste in this study was considered to be neutral with respect to GHG emissions.

MBT scenarios

All MBT scenarios (Table 8) showed net GHG savings between approximately 200 and 750 kg CO_2-eq. tonne^{-1}. The destination of the RDF fraction was the determining factor for the overall saving. The best scenarios were represented by an MBP plant where the RDF was routed to a coal-based power plant for co-combustion. Here the RDF was directly substituted for coal according to the energy content. Thus the saving was in the burning of coal independent of the efficiency of the coal-based power plant. Only the RDF from the MBP plant would have sufficient quality to substitute directly for coal at the power plant. The MBP scenarios furthermore offer GHG savings from the carbon bound in the landfill by the composted residue.

Source segregation of paper was again a key factor and the combination of paper recycling and RDF co-combustion in power plants gave the best GWF. Material recycling of glass and plastic played a minor role.

Comparison between MBS and MBP plants when routing the RDF to incineration gave different results depending on the type of incinerator used. For the same source segregation upstream and the same energy recovery efficiency at the incinerator, MBS plants seemed to be better with respect to GHG savings if both heat and electricity were recovered at the incinerator. If only electricity was produced MBP plants showed higher savings. Recovery of electricity and heat at the incinerator was higher for the RDF from MBS plants because of the larger amount of RDF produced. MBS plants moreover that recovered aluminium together with iron gave higher saving, as noted under the column ‘metal recovery’ in Table 8. The factor that made the MBS plants less beneficial than the MBP plants (when only electricity was recovered) was the carbon bound in the landfill (present only in MBP scenarios) and the higher electricity consumption for running the MBS plant.

Sensitivity analysis

Sensitivity analyses were made for 27 of the scenarios regarding the waste composition and the energy profile in order to assess the importance of these factors on the GWF of the waste management scenarios. These 27 scenarios were chosen to represent a wide range of GHG savings.

- The MSW composition was changed so that, in addition to the average European MSW composition it aso had what was defined as a ‘northern European’ waste composition with more paper and less kitchen organics and a ‘southern European’ waste composition with less paper and more kitchen organics (see Table 1).
- The energy profile was changed so that, in addition to the coal-based electricity profile, an EU-energy mix, which in terms of CO_2-eq. was close to a natural-gas-based electricity and thus fairly clean, and a brown coal-based electricity, which was considered ‘dirty’, were also introduced. In the latter case also the heat was made more ‘dirty’. The actual values used are shown on Table 9.

Table 9: Sensitivity analysis with respect to variation in waste composition and energy substituted. Units in CO_2-equivalents/1000 kg of waste.

		Changed waste composition		Changed energy substitution	
Scenario	Original values	Northern Europe	Southern Europe	Brown coal	EU mix /gas
Paper:	EU average	More paper	Less paper	EU average	EU average
Organics:	EU average	Less organics	more organics	EU average	EU average
Electricity*:	1.033	1.033	1.033	1.511	0.588
Heat*:	0.335	0. 335	0.335	0.51	0.335
LAN1	18	–73	72	24	12
LAN2	–112	–198	–57	–165	–62
LAN1-3	–277	–390	–171	–267	–285
LAN1-4	–318	–422	–221	–332	–304
LAN3-3	–396	–511	–286	–429	–366
LAN3-1	–437	–542	–338	–505	–373
LAN3-2	–446	–550	–346	–514	–382
LAN3-4	–458	–556	–362	–521	–399
INC1	–239	–289	–212	–488	–8
INC1-3	–352	–437	–265	–517	–199
INC1-1	–398	–472	–327	–600	–211
INC1-2	–416	–487	–343	–606	–239
INC2	–620	–696	–557	–1066	–388
INC2-4	–684	–776	–597	–1016	–504
INC2-1	–707	–794	–620	–1069	–519
INC2-2	–708	–795	–621	–1050	–531
MBT4	–190	–250	–180	–361	–31
MBT2	–234	–284	–213	–410	–70
MBT3	–523	–600	–465	–849	–359
MBT5	–525	–621	–474	–871	–366
MBT3-1	–628	–731	–540	–890	–497
MBT3-2	–631	–734	–543	–875	–509
MBT5-1	–636	–745	–546	–907	–512
MBT5-2	–638	–747	–556	–892	–522
MBT1	–684	–790	–584	–664	–702
MBT1-2	–752	–863	–637	–736	–767
MBT1-1	–757	–869	–641	–740	–772

*kg CO_2·eq kWh^{-1}

Importance of waste composition

The waste composition, as illustrate by the average EU-composition, a 'northern European' waste composition and a 'southern European' MSW composition, significantly affected the GWF of the generic waste management scenarios, typically of the order of 100–200 kg CO_2-eq. $tonne^{-1}$ (The data are shown in Table 9 and plotted in Figure 1). The importance seemed to be greatest for the scenarios with the highest savings.

The rankings of the scenarios were not affected by the waste composition, but consistently the 'northern European' waste gave larger GHG savings than the average EU-waste and the 'southern European' waste. The 'northern European' waste resulted in average in 170 kg CO_2-eq. $tonne^{-1}$ more savings than the 'southern European' waste. This illustrates that regardless of the technology for the residual waste management; paper is a more beneficial waste fraction than kitchen organics seen from the GHG perspective. The recycling of the paper is much more beneficial with respect to GHG than recycling of kitchen organics. It should be remembered that this is to a large extent related to the fact that it was assumed that the wood saved by recycling was used as an alternative fuel substituting for fossil fuel in the energy sector. This clearly shows that although the same waste management scenarios from a GHG perspective may be beneficial in northern as well as in southern Europe – assuming that the energy profiles are identical – the same absolute savings cannot be expected because of differences in waste composition.

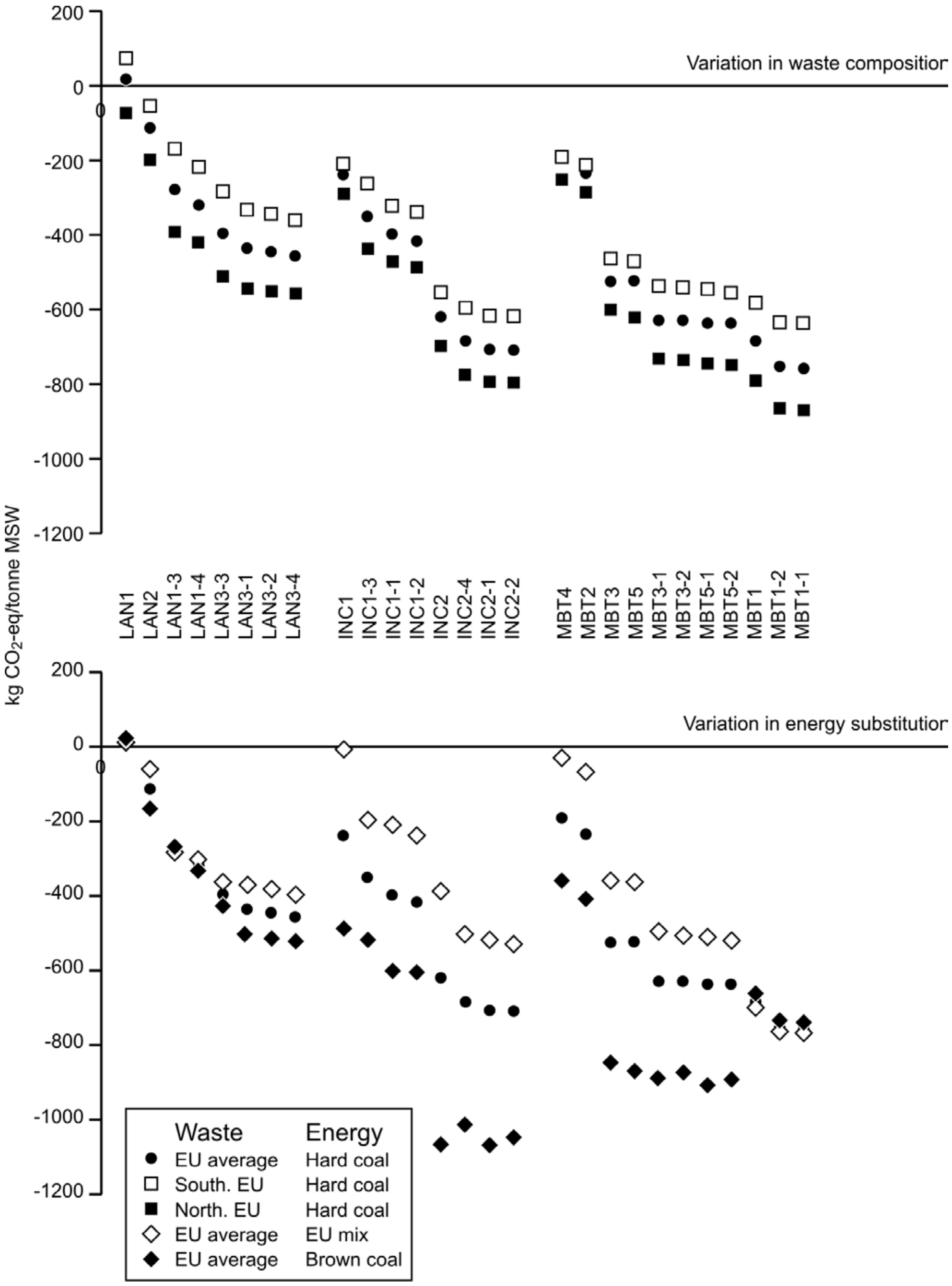

Fig. 1: GHG savings in CO_2-eq. per 1000 kg municipal waste for a range of waste management scenarios organized according to the treatment of the residual waste (landfill, incineration, MBT). The dot represents the basic scenarios and the two other markers for each scenario represent the variation caused by the waste composition and the energy substitution, respectively (see Table 9 for details).

Importance of energy substitution

The type of energy substituted – and to some lesser extent also the type of energy used – significantly affected the GWF of the generic waste management scenarios (the data are shown in Table 9 and plotted in Figure 1). The only exemptions were the landfill scenarios because only little energy was recovered, and the MBT scenarios in which the RDF was routed to a coal-fired power plant, which in all the generic scenarios were substituting for hard coal.

The brown-coal-based electricity is as 'dirty' as it gets but is found in several central European regions and in other parts of the world. For the intensive incineration scenarios, which may save 600–700 kg CO_2-eq. tonne^{-1} municipal waste, substituting brown coal-based electricity instead of hard-coal-based electricity could, when also substituting a more 'dirty' heat production, increase the savings by as much as 50% (250–400 kg CO_2-eq. tonne^{-1}municipal waste). This is also the case for the MBT scenarios where the RDF is burned in incinerators and the substitution takes place via the electricity and heat produced and not by direct avoidance of coal-burning.

EU average electricity is, with respect to GHG emissions, similar to electricity production based on natural gas. This electricity is 'cleaner' than the hard-coal-based electricity that was used in the generic scenarios. Table 9 shows that substituting this 'cleaner' electricity – with no changes in the heat substitution – reduced the savings significantly for the energy-intensive scenarios; typically by 100–200 kg CO_2-eq. tonne^{-1} municipal waste.

Conclusions

Assessing the global warming issues of waste management in terms of potential saving in CO_2 emissions cannot be done on a single technology level, but must be done on a system level in order to ensure comparability: the systems must treat the same waste with respect to amount and composition. The GWF expresses the overall performance on a waste management scenario in terms of CO_2-eq. tonne^{-1} waste managed. GWFs modelled for 40 generic waste management scenarios using various recycling schemes and up-to-date treatment technologies showed that most rational waste management scenarios can lead to substantial savings in CO_2 emissions per tonne municipal waste. Scenarios with landfilling of the residual waste showed savings in the range of 0–400 kg CO_2-eq. tonne^{-1} municipal waste, scenarios with incineration of the residual waste showed savings in the range 200–700 kg CO_2-eq. tonne^{-1} municipal waste, and scenarios with mechanical–biological treatment of the residual waste showed savings in the range 200–750 kg CO_2-eq. tonne^{-1} municipal waste. The estimated savings were affected by the waste composition (average European waste composition), the crediting of the electricity produced in the waste management system (substitution of hard coal-based electricity), the assumption that wood not required for paper-making due to paper recycling would substitute for fossil fuel in the energy sector, and that biogenic carbon bound in the landfill 100 years after its landfilling is a saving with respect to GHG accounting. These factors control the overall results and may each affect the results as much as 200 kg CO_2-eq. tonne^{-1} municipal waste.

The scenario modelling and the sensitivity analysis showed that paper-rich waste which was typical for northern Europe provided a better basis for GHG savings that waste which was rich in kitchen organics as expected to be found in southern Europe. This is independent of how the residual waste was treated. The energy recovery is very significant for the overall outcome of the scenarios and those scenarios with high electricity recovery and high heat recovery – typical for incineration systems – or with direct use of RDF as a coal-substitute in coal-fired power plants, obtained the best GWF, which equates to the most savings. The dirtier the energy substituted the more savings will be obtained in the waste management system.

The GWFs for the 40 generic waste management systems show that waste management, in addition to offering safe and hygienic management of the waste, may also contribute to reducing the GHG emissions in society. The generic scenarios provide insight into which factors are important, but savings provided by a specific system must always be assessed by paying attention to local waste composition and waste management technologies.

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