Resources, Conservation and Recycling 54 (2010) 793–801

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Comparison of carbon emissions associated with municipal solid waste management in Germany and the UK

S. Mühle[a,b], I. Balsam[b], C.R. Cheeseman[a,*]

[a] Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK
[b] Department of Processing and Recycling, RWTH Aachen University, D-52062 Aachen, Germany

ARTICLE INFO

Article history:
Received 12 October 2009
Accepted 16 December 2009

Keywords:
Waste management
Greenhouse gas emissions
Recycling
Landfill
Energy from waste

ABSTRACT

The systems used to manage municipal solid waste (MSW) in Germany and the UK have been compared on the basis of carbon equivalent emissions. The legislative background to MSW management in Germany emphasises recycling and recovery, while the UK continues to rely on much higher levels of landfill, relatively low use (~9%) of energy from waste (EfW), with currently about 34% recycling and composting. Analysis indicates that the carbon emissions associated with current MSW management in the UK is approximately five times higher than that for Germany. UK management of MSW is calculated to produce 175 kg CO_2 equivalents/t, while MSW in Germany generates 34 kg CO_2 equivalents/t. These results show the benefits of German initiatives in waste management introduced over the past 20 years. To put these figures into perspective, the difference in CO_2 emissions would be approximately equivalent to removing 1.2 million cars from roads in England and Wales. The potential for the UK to achieve the Waste Management Strategy targets through increased recycling/separation and landfill legislation is discussed.

1. Introduction

The systems used to manage municipal solid waste (MSW) in Germany and the UK are very different despite the fact that both countries generate comparable amounts of MSW per capita per year, both operate under European law, the standard of living in both countries is similar, and citizens of both countries have comparable economic status and lifestyle. In 2007, 564 kg of MSW was generated per capita in Germany compared to 572 kg in the UK. The average MSW generation per capita in the EU (15 member states) was slightly less at 562 kg per capita (Eurostat, 2009a). There is little difference in per capita waste generation between the two countries and both generate waste at marginally above the EU average.

MSW composition data for Germany and the UK is given in Fig. 1 (BMU, 2006; Defra, 2007). This was obtained from different studies and the categories used to define waste composition in the two countries are not identical. Although this makes direct comparison difficult, the data demonstrates that MSW in the two countries is broadly similar in composition.

Despite the per capita quantity and composition of MSW in Germany and the UK being similar, the treatment and disposal methods applied are very different. Germany has one of the highest recycling rates in Europe and also extracts significant energy from residual waste via combustion in mass burn energy from waste (EfW) facilities. In Germany, EfW is normally referred to as waste to energy (WtE). In contrast, the UK remains highly dependent on landfill, although recycling has increased significantly over the last few years. Fig. 2 illustrates the situation in 2007 for both countries and the EU (15) average. Germany recycled more than 60% of MSW, EfW was used to treat ~30%, while only ~1% was landfilled. The UK recycled approximately 30% of MSW, EfW (WtE) was used to treat ~10% while ~55% of total MSW was landfilled. This is slightly less recycling, but significantly more landfill than the EU (15) average. The objective of this research was to compare the MSW systems in Germany and the UK in terms of their carbon equivalent emissions.

2. Legislation and targets in the EU, Germany and UK

Germany and the UK are both subject to European Union (EU) targets for waste management and both countries have aligned their legislation accordingly. While the UK aims to achieve the EU targets, Germany has set more stringent targets.

The EU objectives for MSW management were enacted in the Sixth Action Programme for the Environment and the Directive on Landfill of Waste (European Union, 1999). The Sixth Action Programme for the Environment gives guidelines on the improvement in the general legal framework, the prevention of negative waste

* Corresponding author. Tel.: +44 207 594 5971; fax: +44 207 823 8401.
E-mail addresses: c.cheeseman@ic.ac.uk, c.cheeseman@ic.ac.uk
(C.R. Cheeseman).

0921-3449/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.resconrec.2009.12.009

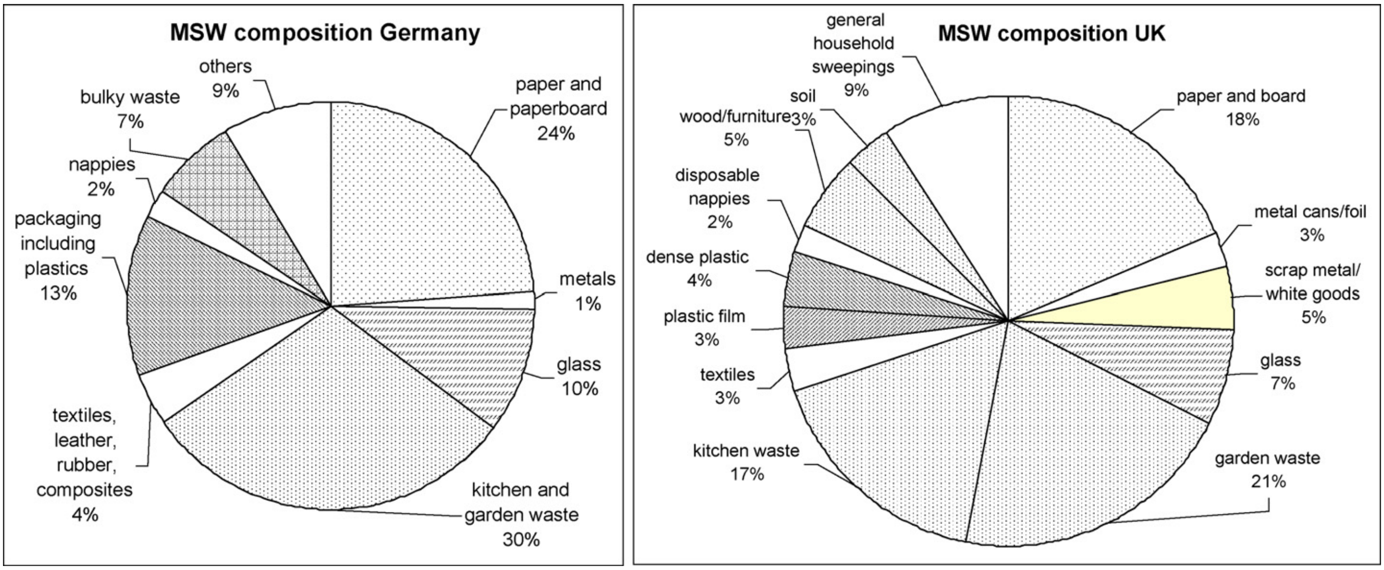

Fig. 1. Comparison of MSW composition in Germany and the UK (BMU, 2006; Defra, 2007).

impacts and promotion of waste recycling. The Directive on Landfill of Waste is intended to prevent or reduce the adverse effects of landfill of waste on the environment. European objectives for waste management are:

20% reduction in waste disposal by 2010 and 50% reduction by 2050 compared to 2000;
20% reduction in hazardous waste generation by 2020 and 50% by 2050 compared to 2000;
75% of biodegradable MSW going to landfill by 2006, 50% by 2009 and 35% by 2016 compared to a 1995 baseline.

Targets for MSW management in England are outlined in the Waste Strategy for England 2007 (Defra, 2007). The objective is to emphasise waste recycling and reuse, meet the Landfill Directive diversion targets for biodegradable MSW and maximise environmental benefits by using a mix of technologies to recycle resources and recover energy from residual waste. The following targets have been set compared to a 2005 baseline:

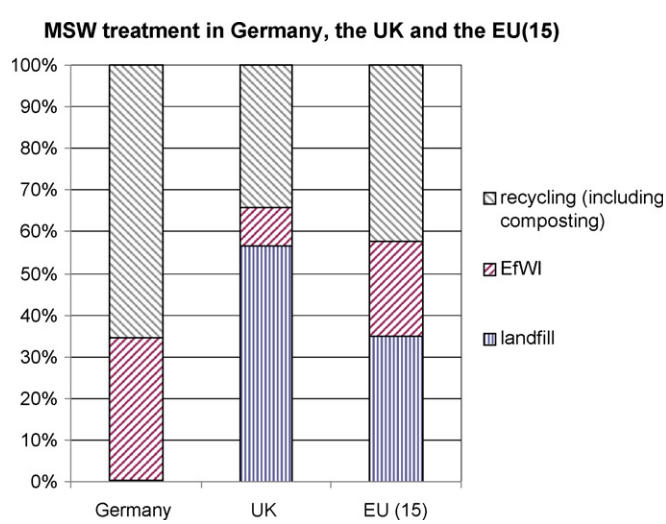

Fig. 2. MSW management in Germany, the UK (2007) and the EU (15 member states) (Eurostat, 2009b).

Household waste after reuse, recycling and composting to be reduced by 29% by 2010, 35% by 2015 and 45% by 2020;
household waste reuse, recycling and composting to be at 40% by 2010, 45% by 2015 and 50% by 2020;
recovery targets for MSW are 53% by 2010, 67% by 2015 and 75% by 2020.

Germany aims to further develop and expand treatment methods in order to recover MSW in an environmentally friendly manner, with the aim of completely recovering MSW by 2020. The aim is to eliminate all landfill of recoverable MSW (Verbüchelen et al., 2005). As a result, disposal will not be practiced and only recycling and recovery will be allowed (BMU, 2009).

2.1. German legislative schemes

The three relevant legislative schemes are (i) the refund systems, (ii) the separated curbside collection and (iii) landfills. These define the disposal and recycling routes of materials through the MSW management system in Germany.

There are two refund systems, one for glass and plastic bottles which are reused or recycled, and one for plastic bottles and cans which are recycled. Mineral water, beer and soft drinks have to be sold in refund option packaging. Only juice, nectar, wine, milk and dietary refreshment drinks are not affected by the refund obligation. The amount of reuse and recycling of beverage packaging is demanded by the "Ordinance on the avoidance and recovery of packaging wastes" (Verpackungsverordnung), which was enacted in 1998 (BMU, 1998). This aims to achieve use of 80% of reusable and environmentally friendly non-reusable beverage packaging of the total. In 2006 the proportion of reusable and environmentally friendly non-reusable beverage packaging was 59.7%, of which 55.5% was reusable plastic and glass bottles and 44.5% was non-reusable plastic bottles and cans. The target of 80% for recyclable and reusable bottles and cans has therefore not been met. In fact, the proportion has decreased since 2003 when the refund system for recyclable bottles and cans was introduced (GVM, 2008). The effects of the "Ordinance on the avoidance and recovery of packaging wastes" will be reviewed by January 2010.

Separated curbside collection was introduced in the early 1990s in Germany. Since then all German citizens are obliged under the "Act for promoting closed substance cycle waste management and ensuring environmentally compatible waste disposal"

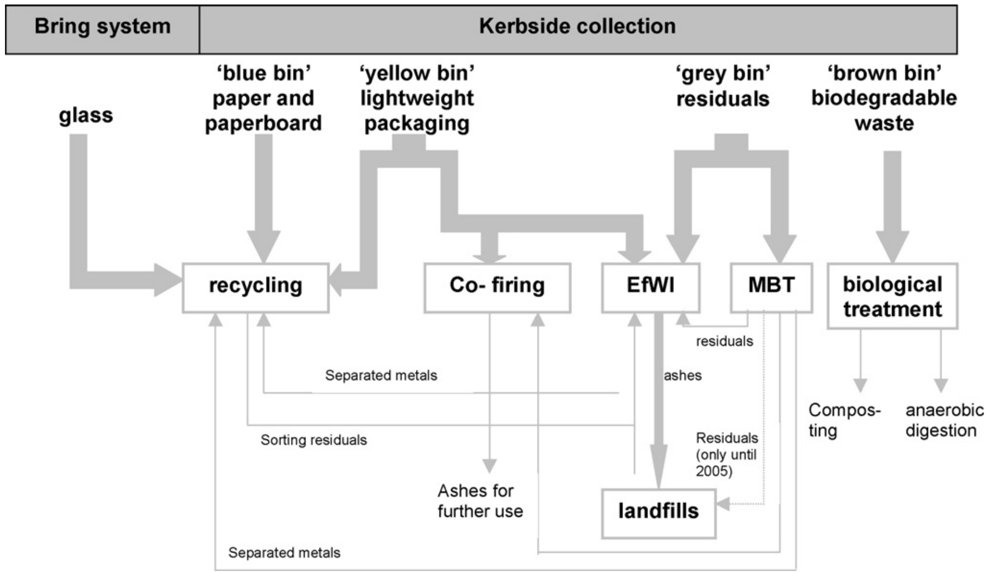

Fig. 3. Illustration of the present German MSW management system since the tightened waste acceptance criteria for landfill sites came into force in 2005 (Dehoust et al., 2005).

(Kreislaufwirtschafts- und Abfallgesetz) to separate their MSW. This is to allow use of the best treatment for each waste fraction and make the maximum amount of MSW available for recycling (BMU, 1994). Collection is organized by local authorities and while the exact details may differ slightly, the MSW is usually separated into four bins for paper and paperboard, biodegradable kitchen and garden waste, lightweight packaging (plastic foils and wrappings, beverage cartons, cans, spray bottles and aluminum dishes) and residual waste. Glass is also collected using a bring system. In 2006, the recycling rates for the separately collected MSW materials were: glass 100%, paper and paperboard 99%, biodegradable waste 100% and lightweight packaging 78.5% (BMU, 2009).

Landfilling of recoverable MSW has been restricted in Germany since 2005 by the commencement of the "Technical instructions on municipal solid waste" (Technische Anleitung für Siedlungsabfälle) (BMU, 1993). Furthermore, the restrictions on MSW going to landfill were tightened with the effect that landfill of non-pretreated MSW is now practically impossible. The aim of this law was to reduce the amount of waste going to landfill in order to minimise the emissions from landfill to air, soil and groundwater. In 2006, only 4 kg per capita of MSW was landfilled, compared to 104 kg per capita in 2004 and 225 kg per capita in 1996 (Eurostat, 2009b). At present the main wastes being landfilled are inert residual ashes from EfW and co-firing facilities.

2.2. MSW disposal in Germany

Fig. 3 shows the different disposal routes for MSW in Germany that have resulted from the legislative framework since 2005 (Dehoust et al., 2005). 'Blue bin', 'yellow bin', 'brown bin' and 'grey bin' refer to typical bin colours used for specific waste fractions. Most Federal regions in Germany use blue bins for paper, yellow bins for recyclables, grey bins for residuals and brown/green bins for biowaste. A notable difference to conventional MSW management is that landfill is not a primary treatment and is only applied as a secondary treatment.

2.3. MSW disposal in the UK

MSW management and disposal varies significantly across different regions of the UK. In some parts of the country only one bin is distributed to householders, although different types of waste separation systems have been introduced in recent years by many local authorities. There are also extensive 'bring' systems available at civic amenity waste/recycling sites and collection systems for mixed recyclables. No single system currently predominates.

Although reliance on landfill for MSW disposal has decreased over the last few years, it is still the major disposal method, with 64% of UK MSW typically sent to landfill (Eurostat, 2009b). Since 2001 the proportion of UK MSW going to landfill has fallen by ~15% (Defra, 2009) and consequently, the amount of MSW being treated by composting and material recovery facilities (MRF) has significantly increased. In 1996 only 6% of MSW was recycled or composted, but this had increased to 26% by 2006. In 2007, 34% of the total MSW was recycled or composted with 9% treated by EfW. The amount of MSW generated has also changed in recent years and is now marginally decreasing, with the amount of MSW generated in 2005/2006 about 3% lower than in 2004/2005 (Defra, 2009).

3. Methodologies to evaluate the carbon footprint of MSW management

The carbon footprint is used to assess the contribution of anthropogenic processes to the greenhouse effect and indicates the sustainability and environmental impact of a process. Two different methodologies from Germany and the UK have been assessed in order to determine the most appropriate methodology for comparing MSW management systems.

Three relevant greenhouse gases (GHG) have been taken into account for the carbon footprint calculations. These were carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The distinction between fossil and regenerative CH_4 emissions should be borne in mind as the global warming potential is different. Furthermore, regenerative CO_2 emissions are regarded as greenhouse effect neutral because the CO_2 was previously taken from the atmosphere and incorporated in plants, and therefore this generates no net increase.

In order to make emissions of the different gases comparable, global warming potentials (GWPs) were used. These express the global warming potential for each GHG compared to CO_2. The overall carbon footprint is calculated as CO_2 equivalent emissions. The GWPs for the relevant greenhouse gases used were: CO_2 1, CH_4

(fossil) 21, CH_4 (regenerative) 18.5 and N_2O 310 (Houghton, 1996). These values are valid for up to 100 years, as the waste may remain active depending on the chosen treatment option over this time period.

3.1. UK methodology

The Department for Environment Food and Rural Affairs (Defra) has assessed the carbon footprint of UK wastes in the report 'Carbon Balances and Energy Impacts of the Management of UK Wastes' (Fisher et al., 2006). This included a macro-level investigation of carbon flows for predominant waste materials. The aim of the study was to examine the benefits and impacts of different waste management processes, assess alternatives for processing waste and identify where potential benefits lie. For this study fifteen representative waste fractions were examined. These were paper/card, kitchen/food waste, green waste, agricultural crop waste, manure slurry, other organics, wood, dense plastic, textiles, ferrous metals, non-ferrous metals, silt/soil, minerals/aggregates and miscellaneous combustibles. The study included waste materials from all sources and did not concentrate on post-consumer wastes.

Four different core scenarios were defined. A baseline scenario (state of the art), a high resource recovery scenario, a high energy recovery scenario and a combined recovery (both resource and energy recovery) were analysed over the period between 2005 and 2031. These core scenarios covered the whole waste management process, starting from collection of the waste and ending with processing or disposal. The carbon balances were calculated for each material and each core scenario. Instead of using one representative GWP, a minimum and maximum impact for each scenario was evaluated so that the range of GWP data found in the literature could be taken into account. This range results from different energy and resource recovery efficiencies and from the variety of products and qualities which are produced.

The waste management options included were recycling and reuse, windrow composting, in-vessel composting, anaerobic digestion, mechanical biological treatment (MBT), combustion, landfill, land spread/recovery/reclamation and disposal at sea. It was identified that the major flows of carbon and therefore GHG and energy resulted from:

- Use of fuel and energy in processing;
- transportation of waste to and from sites (including collection);
- direct releases from waste materials on processing or disposal in landfill;
- avoidance of GHG emissions or energy elsewhere in the economy;
- sequestration of carbon in landfill and soil.

The net GHG emissions were calculated based on the findings above as follows:

(1) Ancillary impact factors were sourced from published lifecycle inventory databases;
(2) ancillary inputs (e.g. tonnes of diesel) and direct emissions associated with the management of wastes were determined for each treatment process and waste material;
(3) avoided burdens (e.g. tonnes of material separated for recycling, kWh electricity recovered) were calculated;
(4) ancillary impacts, direct process emissions and avoided burdens were combined and multiplied by process throughputs to give total net GHG emissions and energy demand.

The results for each year were combined with time-lagged landfill impacts, allowing for a gas release over 100 years in order to generate annual GHG emissions.

3.2. German methodology

As part of a lifecycle analysis the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) assessed the carbon footprint of German MSW management (IFEU, 2005). The aim of the study was to evaluate the overall performance of German MSW management with special regard to sustainability. Therefore, amongst other factors the GHG emissions and sinks for the years 1990, 2001 and 2005 were calculated.

As with the UK methodology the German analysis covered the whole MSW management process. However, the analysis focused on post-consumer waste and instead of choosing representative materials included the whole MSW fraction.

A material flow analysis was conducted based on the amount of MSW generated, collected and treated, which examined the management routes for each waste fraction. Six general process steps were considered. These were collection, sorting and conditioning, recovery or recycling, disposal, use of secondary products (for example energy) and equivalent processes.

As there are emissions, energy consumption and additives used for each process, the expenditure for each process and for each waste fraction was evaluated. An equivalent process is a process that substitutes a conventional process and this includes recycling and EfW. The MSW treatment options considered were EfW, landfill, composting and anaerobic digestion, recycling and refuse derived fuel (RDF). The equivalent processes include use of energy derived from fossil resources and generation of primary products (fertilizer, glass, fibres for paper and paperboard production), and these are used to determine the avoided burdens. Consequently, the GWP for each process and equivalent process were calculated using the aggregation method:

$$\mathrm{GWP} = \Sigma(m_i \times \mathrm{GWP}_i)$$

where m_i is the mass of climate relevant gases emitted and GWP_i is the related global warming potential.

The prefix convention is to regard the GWP from processes as positive and those from equivalent processes as negative. Finally, an overall balance for all GHG emissions from processes and equivalent processes and therefore the carbon emissions for German MSW management was calculated.

3.3. Implemented methodology

Both the UK and German studies use the same methodology to calculate the carbon footprint by comparison of the net emissions with the net avoided burdens. This has been applied to 1 t of representatively managed MSW for both countries. All possible future emissions are accounted for in the year in which the MSW is managed. This is not necessarily the year when the emissions occur, but this is necessary to keep the calculations for both countries comparable. However, there is disagreement in the literature about what an avoided burden is. According to the two reports referenced above, energy generation and resource saving will be considered as avoided burdens. Furthermore, the calculations are based on the three most important GHGs, carbon dioxide, regenerative methane, fossil methane and nitrous oxide, and the period under consideration is 100 years.

Finally, these methodologies show differences in the choice of materials. In the following carbon footprint analysis, the whole MSW generated will be reviewed in as much detail as possible from the data available. Treatment methods taken into account are EfW, landfill, mechanical biological treatment (MBT), in-vessel and in-windrow composting, anaerobic digestion and recycling of glass, paper, plastics, bulky waste and ferrous and non-ferrous metals. Other recycled materials are not considered because of the insignif-

Table 1
Breakdown of MSW by management option for Germany, England, Wales, Northern Ireland, Scotland and UK total.

Management option	Germany (2005)		UK total		England (2005/2006)		Wales (2005/2006)[a]		Northern Ireland (2005/2006)		Scotland (2006/2007)[b]	
	Amount [1000 t]	Percentage%	Amount [1000 t]	Percentage%	Amount [1000 t]	Percentage%	Amount [1000 t]	Percentage%	Amount [1000 t]	Percentage%	Amount [1000 t]	Percentage%
Energy from waste incineration	13.420	26.9%	2.958	8.6%	2.859	10.3%	2	0.1%	–	–	96.7	2.7%
Co-firing	2.093	4.2%	9.7	0.0%	N.A.[c]	N.A.[c]	9.7	0.5%	–	–	–	–
Recycling glass	3.172	6.4%	912.4	2.7%	760	2.7%	47.9	2.6%	13.1	1.2%	91.4	2.6%
Recycling paper	7.600	15.3%	1.877	5.5%	1.475	5.3%	104.4	5.7%	65.6	6.2%	231.8	6.5%
Recycling lightweight packaging	2.122	4.3%	–	–	–	–	–	–	–	–	–	–
Recycling co-mingled	–	–	864	2.5%	860	3.1%	–	–	4	0.4%	–	–
Recycling plastic	N.A.[d]	N.A.[d]	33.5	0.1%	N.A.	N.A.	13.7	0.8%	7.7	0.7%	12.1	0.3%
Recycling bulky waste	1.000	2.0%	113.1	0.3%	N.A.	N.A.	40.2	2.2%	16.5	1.6%	56.4	1.6%
Recycling ferrous metals	309.9	0.6%	623.6	1.8%	532[e]	1.9%[e]	23.9	1.3%	15.4[e]	1.5%[e]	52.3	1.5%
Recycling non-ferrous metals	12.8	0.0%	1.088	0%	N.A.[e]	N.A.[e]	0.4	0.0%	N.A.[e]	N.A.[e]	0.7	0.0%
Recycling others	2.480	5.0%	985.5	2.9%	730	2.6%	52.6	2.9%	24.8	2.3%	178.1	5.0%
Total recycling	15.386	30.9%	5.358	11.2%	4.357	15.7%	283.0	14.1%	147.1	13.9%	570.5	16.0%
Landfill	3.791	7.6	22.474	65.6%	17.873	64.5%	1.389	75.8%	813.5	76.7%	2.398	67.1%
MBT	6.221	12.5	145.5	0.4%	N.A.	N.A.	12.5	0.7%	–	–	133	3.7%
In-windrow composting	–	–	3.083	8.9%	2.439	8.8%	137	7.5%	100.5	9.5%	361.1	10.1%
In-vessel composting	7.604	15.3%	–	–	–	–	–	–	–	–	–	–
Anaerobic digestion	N.A.	N.A.	3.4	0.0%	N.A.	N.A.	–	–	–	–	3.4	0.1%
Other treatment	–	–	205	0.6%	195	0.7%	–	–	–	–	10	0.3%
Total	49.825	100%	34.243	100%	27.723	100%	1.833	100%	1.061.12	100%	3.573	100%

[a] Recycling data, 2006/2007.
[b] Composting, anaerobic digestion, EfW and MBT data from 2007/2008.
[c] Co-firing is included in EfW (England only).
[d] Plastic is included in lightweight packaging.
[e] If type of metal is not specified, metal is considered to be ferrous metal.

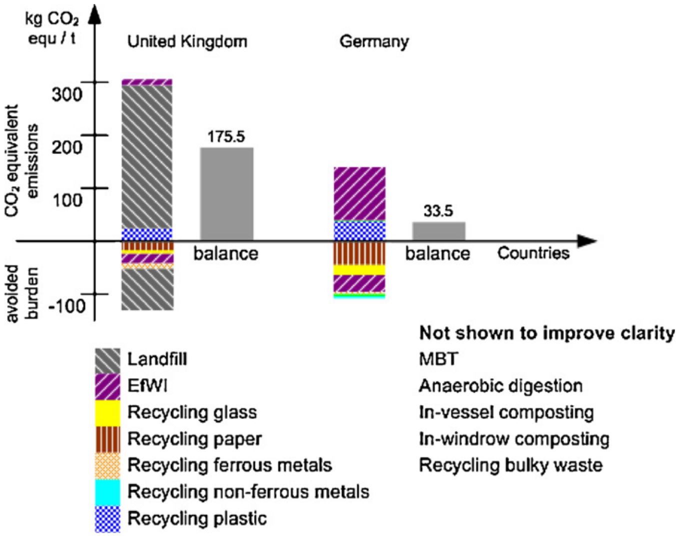

Fig. 4. Comparison of the carbon equivalent emissions from MSW management in the UK and Germany.

icant amounts generated. Furthermore, transport is not included in the comparison as it will be approximately equivalent for both countries. The comparison of the carbon emissions is based on the following assumptions:

- Co-firing is included in EfW;
- although the landfill ban for recyclable MSW came into effect on 1st June 2005, all MSW brought to landfill in Germany will be considered to comply with the new regulation;
- all UK composting is considered to be in-windrow composting, while all composting in Germany is considered to be in-vessel composting due to more stringent emission regulations;
- net energy generation is assumed for EfW, anaerobic digestion and landfills;
- all co-mingled materials and all lightweight packaging is accounted as plastics;
- bulky waste is assumed to be predominantly wood material;
- a fugitive release of landfill gas (LFG) of 22% is assumed in both countries as there is agreement in the literature that about 78% of LFG is the maximum amount that can be captured;
- all EfW is assumed to generate energy;
- 30% of the energy from EfW is considered to be used for electricity generation and 70% for heat generation;
- reuse of ash from EfW and co-firing, soil conditioner made from compost, treated effluent from anaerobic digestion and fuels derived from MBT are not considered to contribute to the avoided burden in order to simplify the model.

4. Carbon footprint calculation

The methodology described has been applied to the MSW data in Table 1 which shows the quantities and proportions of MSW treated in 2005/2006 in Germany and the UK. The proportions of MSW were used to model a typical management mix for 1 t of MSW. The carbon footprint is calculated for this representative 1 t of MSW in Table 2. The amount of MSW treated by each method was multiplied by the specific GWP and if available the avoided burdens. Finally, the GHG emissions and avoided burdens were added together. In this respect, the sign convention was that all GHG emissions are positive, while all avoided burdens are negative. Results are illustrated in Fig. 4, but the emissions from MBT, anaerobic digestion, in-vessel composting, in-windrow composting and recycling bulky waste were not included as emissions from these sources are not comparable on the same scale, and are negligible in comparison to the emissions from other treatment methods.

It is important to note that the GWPs and avoided burdens for landfill and EfW are different in Germany and the UK. As discussed earlier, it was assumed that only inert material is landfilled in Germany which affects the generation of landfill gas. The GWP and avoided burden are modeled based on the maximum legally permitted total organic carbon (TOC) content of 1%, with further details given in Appendix A.

From a representative 1 t of UK MSW, 656.3 kg goes to landfill and produces carbon emissions of 272.7 kg CO_2 equivalents (equ). In Germany 76 kg are landfilled and this emits 2.5 kg CO_2 equ. Furthermore, the GWP from EfW in Germany and the UK are significantly different. In the UK, the specific GWP for EfW is 132 kg CO_2 equ/t, while the German figure is 321 kg CO_2 equ/t. From 1 t of UK MSW 86.4 kg is combusted/incinerated and this causes carbon emissions of 11.4 kg CO_2 equ compared to Germany where 311 kg/t is incinerated causing carbon emissions of 99.8 kg CO_2 equ. This difference is due to the proportion of biogenic carbon. The proportion of biogenic material incinerated in Germany is 66.6%, while in the UK it is 85.0% (Porteous, 2001; Beckmann et al., 2005). The lower biogenic content of the material going to EfW in Germany results from the source sorting scheme described earlier.

According to the applied model 129.1 kg/t of MSW are recycled or composted in the UK and this causes carbon emissions of −11.6 kg CO_2 equ. Therefore, for each 129.1 kg of MSW recycled, 11.6 kg CO_2 equ are saved compared to the use of virgin materials. In Germany 286.5 kg/t are recycled and this saves −51.9 kg CO_2 equ.

The avoided burden of EfW, landfills and anaerobic digestion is due to energy generation and substitution of conventional energy sources. Consequently, the avoided burden was modeled on the basis of the energy generation mix for each country and the average net energy generation of the treatment method. The detailed derivations can be found in Appendix A. The differences in the MSW composition treated by EfW again cause different amounts of net energy to be generated due to the differences in calorific values which are 5800 kJ/kg (Beckmann et al., 2005) in Germany and 10,600 kJ/kg in the UK (Porteous, 1997). The avoided burden for energy generation by EfW is −210.1 kg CO_2 equ/t in the UK and −108.3 kg CO_2 equ/t in Germany. Consequently, −18.2 kg CO_2 equ can be saved in the UK compared to −33.7 kg CO_2 equ in Germany. Furthermore, the energy generated from landfill gas in Germany is significantly lower than in the UK due to the lower total organic carbon (TOC) content. The UK saves −79.4 kg CO_2 equ by energy generation from landfill gas accounting for an avoided burden of −121 kg CO_2 equ/t, with 656.3 kg/t of MSW going to landfill. Only −3.8 kg CO_2 equ can be saved in Germany with an avoided burden of −50.5 kg CO_2 equ/t, with just 76 kg/t of MSW being landfilled. Unfortunately, it is not possible to compare the avoided burdens for anaerobic digestion due to a lack of reliable German data.

5. Discussion

The results presented in Fig. 4, expressed in kg of CO_2 equivalent per tonne of MSW, illustrate that the net carbon emissions associated with the management of MSW in the UK is about five times greater than that of Germany. The factors that contribute to this result are the amount of MSW that is recycled, the amount and composition of MSW landfilled and the amount and composition of MSW treated by EfW. The most important factor with regard to GHG emissions is the mitigation of the biogenic content in landfilled MSW. The GWP of a tonne of MSW landfilled in Germany is approximately 16% the value of 1 t of MSW in the UK. However, it has to be considered that the value for net energy generation from landfill gas in conventional landfills is based on the experiences

Table 2
Calculation of the carbon footprint based on proportions of management options determined in Table 1 for a representative 1 t of MSW in Germany and the UK.

Treatment method	UK			Germany		
	Specific GWP [kg CO_2 equ/t]	kg in 1 t MSW	Carbon footprint [kg CO_2 equ]	Specific GWP [kg CO_2 equ/t]	kg in 1 t MSW	Carbon footprint [kg CO_2 equ]
EfW	132[a]	86.4	11.4	321	311	99.8
Landfill[b]	415.1	656.3	272.5	32.6	76	2.5
MBT	7.6	4.3	0	7.6	125	1.0
Anaerobic digestion	4.1	0.1	0	4.1	N.A.	N.A.
In-vessel composting	3.4	0	0	3.4	153	0.5
In-windrow composting	5.8	88.7	0.5	5.8	0	0
Treatment method	Avoided burden [kg CO_2 equ/t]	kg in 1 t MSW	Carbon footprint [kg CO_2 equ]	Avoided burden [kg CO_2 equ/t]	kg in 1 t MSW	Carbon footprint [kg CO_2 equ]
Recycling glass	−300	26.6	−8	−300	64	−19.2
Recycling paper	−280	54.8	−15.3	−280	153	−42.8
Recycling ferrous metals	−580	18.2	−10.6	−580	6.2	−3.6
Recycling non-ferrous metals	−12.300	0	0	−12.300	0.3	−3.7
Recycling plastic	850	26.2	22.3	850	43	36.6
Recycling bulky waste	1.2	3.3	0	1.2	20	0
Energy generation EfW[b]	−210.1	86.4	−18.2	−108.3	311	−33.7
Energy generation landfill[b]	−120.97	656.3	−79.4	−50.5	76	−3.8
Energy generation anaerobic digestion[b]	−83.5	0.1	0	−80	N.A.	N.A.
Other treatment (not included in the calculation)	N.A.	35.1	N.A.	N.A.	48.5	N.A.
Sum carbon footprint MSW management [kg CO_2 equ/t]	175.3			33.5		

[a] N_2O not included.
[b] See Appendix A.

of one landfill and generally this value depends on many different parameters including gas generation rate, MSW composition, efficiency of pumps and engines. Furthermore, the GWP of inert landfills in Germany was extrapolated from conventional landfills and is a rather generous approximation as it was assumed that the total TOC content reacts to form methane and carbon dioxide. For conventional landfills it is noted that typically only about 50% of the biogenic material degrades to landfill gas. It can be expected that the real value for the GWP of German MSW that is landfilled is likely to be lower than the value presented here. Furthermore, it can be seen that alternative treatment for biodegradable wastes, such as composting, MBT and anaerobic digestion contribute significantly less to the carbon footprint than conventional landfill, even without taking into account the products which can be derived from these processes are useful substitutes for fossil fuels. Additionally, the results illustrate that each of the recycling options is more beneficial than landfill with the exception of plastic recycling. In particular, the recycling of ferrous and non-ferrous metals is shown to be extremely beneficial. One disadvantage of increased recycling and composting rate is the decreased energy yield from EfW plants. A typical UK EfW plant generates 500 kWh of electricity per tonne of MSW while it is only about 263 kWh/t in Germany.

In order to put the differences in CO_2 emissions from waste management systems into perspective the data has been compared to emissions associated with transport by car. Given that an average car produces ~167.2 g CO_2 equ/km and the average car is estimated to drive about 20,000 km/year, cars typically produce 3344 kg CO_2 equ/year. Assuming there is approximately 28.5 million tones of MSW generated per year in England and Wales, the figure of 175 kg CO_2 equ/t calculated for emissions from MSW gives a total of 4.98×10^6 t/year CO_2 equ per year. This is equivalent to ~1.49 million cars. Applying the German CO_2 equivalents per tonne of MSW gives 0.969×10^6 t/year, which is equivalent to ~0.29 million cars. Therefore the difference in CO_2 equ emissions between the German and UK waste management systems would be approximately equal to removing 1.2 million cars from the roads in England and Wales.

Both Germany and the UK have drafted ambitious targets for future MSW management. Germany aims to recover all MSW by 2020 at the latest, and to prohibit surface disposal of recoverable MSW. The UK aims to recycle and compost 40% of MSW by 2010. The positive effects that promoting recycling and recovery has on the carbon footprint of MSW management systems is demonstrated in the earlier analysis.

However, the progress of Germany and the UK towards achieving improved MSW management and reducing waste related GHG emissions is different. Germany is closer to realising a sustainable and environmental friendly MSW management system and this has resulted from significant developments made over the last 20 years.

The legislation introduced in Germany in the period since the 1990s has had positive effects of obligatory source separation and the ban on landfill of recoverable. Source separation is environmentally beneficial because it generates large amounts of homogenous recyclable material. However, the quality and homogeneity of the collected material can be problematic as the system relies on public participation. Alternatively, a mechanically operated separation system can be implemented.

The stringent requirements for MSW going to landfill has forced local authorities to promote more environmental friendly alternatives such as EfW, composting, anaerobic digestion and MBT. Germany implemented both recycling and a landfill ban for recoverable material by forcing stakeholders to participate using legislation. However, the same effects could be achieved using more flexible, incentive driven strategies. For example, increasing landfill tax, financial incentives for households separating recyclables and local authorities which encourage recycling and recovery could be employed.

The results of this comparison illustrate that further promotion of recyclables separation and stringent landfill legislation are necessary to enable the UK to achieve their MSW management targets. This would have an extremely positive effect on associated carbon emissions and lead to a more sustainable and environmental friendly system.

The data presented here is partially based on assumptions and approximations. Therefore, the results could be improved by obtaining more detailed MSW data, especially with regard to recycling. A more representative value for the energy generation from landfill gas in conventional landfills would be beneficial. In addition, the methane generation from almost inert waste has not been properly quantified.

It should also be noted that some parameters (transport and products from composting, anaerobic digestion and MBT) were not included to simplify the analysis. More precise data could have been generated using a more complex model. Furthermore, only carbon footprints were evaluated. Comparison with a more integrated approach including a full life cycle analysis taking into account the economics of MSW management would be beneficial.

6. Conclusions

This research has found that the carbon emissions resulting from MSW management in the UK are estimated to be about five times greater than those for Germany. The tightened waste acceptance criteria for landfills, an increased use of EfW, and recycling policy enabled by a proven source separation system in Germany were identified as the major reasons for this difference. Furthermore, the waste acceptance criteria for landfill have reduced GWP to only 16% of the conventional figure. The difference in CO_2 equ emissions resulting from the waste management systems in the two countries is estimated to be equivalent to the CO_2 equ emissions from 1.2 million cars.

Acknowledgements

The authors would like to acknowledge the ERASMUS Programme for supporting SM, the Environment Agency Wales, the Northern Ireland Environment Agency, and the Scottish Environment Protection Agency for data provision, and the Department for Environment Food and Rural Affairs for support. We also acknowledge Matt Webster from Viridor for providing information on energy generation from landfill gas and Professor David Wilson (Imperial College London) for valuable discussions.

Appendix A.

A.1. Approximation of the GWP of landfill in Germany

Chemical formula for landfill gas generation (Themelis and Ulloa, 2006):

$C_6H_{10}O_4 + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2$

Maximum allowed TOC content 1% (BMU, 2002) gives 10 kg/t biogenic C:

⇨ 833.33 mol/t C, 6C needed for 1 $C_6H_{10}O_4$
⇨ 139 mol/t $C_6H_{10}O_4$

Assumption: all biogenic carbon reacts to methane and carbon dioxide:

⇨ 139 mol/t × 3.25 = 451.39 mol/t CH_4
⇨ 7.22 kg/t CH_4

Efficiency factor of landfill gas engine: $CH_{4\ engine}/CH_{4\ fugitive} = 3\%$ (Defra, 2004):

⇨ 7.22 kg/t × 0.03 = 0.22 kg/t

Assuming 78% landfill gas is used for electricity generation and 22% is released (Defra, 2004):

⇨ GWP (landfill GER) = 18.5 × 0.22 kg/t × 0.78 + 18.5 × 0.22 × 7.22 = 32.56 kg/t

A.2. Calculation of the avoided burden by energy generation

Proportions electricity generation:
Germany (2008):
Nuclear 23%, brown coal 23%, black coal 20%, natural gas 13%, renewable energy 15% (considered as wind), others (considered as mineral oil) 6% (Unendlich-viel-energie, 2009):
Specific GWP for energy generation method (Dones et al., 2004):

⇨ GWP (energy generation GER) = 640 g/kWh

UK (2007):
Gas 43%, coal 34%, nuclear 15%, hydroelectric 1%, imports 1.5% (considered as oil), oil 1%, others 4.5% (considered as wind energy) (DTI, 2002).
Multiplied by specific GWP for each energy generation method (Dones et al., 2004):

⇨ GWP (energy generation UK) = 668 g/kWh

Assumption: GWP (heat generation) = 314 g/kWh for both countries (Beckmann et al., 2005).
Assumption: 70% of energy obtained used for heat generation, 30% for electricity from EfW facilities (Beckmann et al., 2005).
Energy generation per tonne of MSW EfW UK: 500 kWh/t (Porteous, 2001):

⇨ avoided GWP (EfW UK) = 0.3 × 0.668 × 500 + 0.7 × 0.314 × 500 = 210.1 kg/t

Energy generation per tonne of MSW EfW GER: 263 kWh/t (Beckmann et al., 2005):

Avoided GWP (EfW GER) = 0.3 × 263 × 0.64 + 0.7 × 263 × 0.314 = 108.3 kg/t.
Energy generation per tonne MSW anaerobic digestion: 125 kWh/t (Braber, 1995):

⇨ avoided GWP (anaerobic digestion GER) = 125 × 0.64 = 80.0 kg/t
⇨ avoided GWP (anaerobic digestion UK) = 125 × 0.67 = 83.5 kg/t

Energy generation per tonne MSW landfill UK: 181.1 kWh/t (Webster, 2009):
Avoided GWP (landfill UK) = 120.97 × 0.668 = 120.97 kg/t.

A.3. Approximation avoided burden landfill Germany

Chemical formula for landfill gas generation (Themelis and Ulloa, 2006):

$C_6H_{10}O_4 + 1.5H_2O \rightarrow 3.25CH_4 + 2.75CO_2$

⇨ 28.21 kg/t CH_4
⇨ 39.18 m^3 CH_4

Assumption: average CH_4 content in landfill gas 60%:

⇨ 65.3 m^3 landfill gas/t

Assumption: 1.61 kWh/m^3, energy demand for pumps and blowers is 25% (Webster, 2009):

⇨ 78.85 kWh/t net energy generation
⇨ avoided GWP (landfill GER) = 78.85 kWh/t × 0.64 kg/kWh = 50.5 kg/t

Assumption: 1.61 kWh/m^3, 150 m^3 landfill gas is captured per tonne of waste and the energy demand for pumps and blowers is 25% (Webster, 2009):

181.1 kWh/t net energy generation
Avoided GWP (landfill UK) = 181.1 kWh/t × 0.67 g/kWh = 120.97 kg/t

References

Beckmann M, Bilitewski B, Hery M, Kortmann R, Labuschewski J, Müller H, Opphard K, Rumphorst M, Scholz R, Tschersich C, Weyers M. Ökologische Effekte der Müllverbrennung durch Energienutzung. EdDE-Dokumentation 10. Köln: Entsorgungsgemeinschaft der Deutschen Entsorgungswirtschaft e.V; 2005.

Braber K. Anaerobic digestion of municipal solid waste: a new waste technology on the verge of breakthrough. Biomass and Bioenergy 1995;9(1–5):365–76.

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Technische Anleitung zur Verwertung, Behandlung und sonstigen Entsorgung von Siedlungsabfällen (Dritte allgemeine Verwaltungsvorschrift zum Abfallgesetz) BAnz. Nr. 99a. Berlin; 1993.

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Beseitigung von Abfällen (Kreislaufwirtschafts- und Abfallgesetz-KrW-/AbfG) BGBl IS. 2986. Berlin: BMU; 1994.

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Verordnung über die Vermeidung und Verwertung von Verpackungsabfällen (Verpackungsverordnung—VerpackV) BGBl. IS. 2379. Berlin; 1998.

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Verordnung über Deponien und Langzeitlager (Deponieverordnung—DeponieV) BGBl. IS. 2807. Berlin; 2002.

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), Siedlungsabfallentsorgung in Deutschland. http://www.bmu.de/files/pdfs/allgemein/application/pdf/bericht_siedlungsabfallentsorgung_2006.pdf (February 2009); 2006.

Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU), Fakten zur nachhaltigen Abfallwirtschaft. http://www.bmu.de/files/pdfs/allgemein/application/pdf/abfallw_fakten.pdf (February 2009); 2009.

Department for Environment Food & Rural Affairs (Defra). Review of environmental and health effects of waste management: municipal solid waste and similar wastes. Defra. Product Code PB 9052A; 2004.

Department for Environment Food & Rural Affairs (Defra). Waste strategy for England 2007; 2007, http://www.defra.gov.uk/environment/waste/strategy/strategy07/documents/waste07-strategy.pdf (October 2009).

Dehoust G, Wiegmann K, Fritsche U, Stahl H, Jenseit W, Herold A, Cames M, Gebhardt P. Statusbericht zum Beitrag der Abfallwirtschaft zum Klimaschutz und mögliche Potenziale. BMU. Forschungsbericht 2005;205(33):314.

Dones R, Hirschberg S, Heck T. Greenhouse gas emissions from energy systems, comparison and overview. Encyclopedia of Energy 2004;3:77–95.

Department of Trade and Industry (DTI). Energy consumption in the United Kingdom; 2002, http://www.berr.gov.uk/files/file11250.pdf.

European Union. Commission of the European Union. Brussels: Council directive on the landfill of waste 1999/31/EC; 1999.

Eurostat. Municipal waste generated—kg per capita; 2009a, http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdpc210 (February 2009).

Eurostat. Municipal waste by type of treatment—kg per person per year; 2009b, http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsien130 (February 2009).

Fisher K, Collins M, Aumônier S, Gregory B. Carbon balances and energy impacts of the management of UK wastes. DEFRA. DEFRA R&D Project WRD 237 2006.

Gesellschaft fur Verpackungsmarktforschung mbH (GVM). http://www.gvm-wiesbaden.de/pdf/infocus/2008_04MoevE2006_de.pdf (February 2009); 2008.

Houghton JP. Climate change 1995: the science of climate change. Cambridge University Press; 1996.

IFEU Beitrag der Abfallwirtschaft zur nachhaltigen Entwicklung in Deutschland Teilbericht Siedlungsabfälle. BMU. Förderkennzeichen 2005;203(92):309.

Porteous A. Energy from waste: a wholly acceptable waste-management solution. Applied Energy 1997;58(4):177–208.

Porteous A. Energy from waste incineration—a state of the art emissions review with an emphasis on public acceptability. Applied Energy 2001;70(2):157–67.

Themelis NJ, Ulloa PA. Methane generation in landfills. Renewable Energy 2006;32(7):1243–57.

Unendlich-viel-energie. Agentur für erneuerbare energie; 2009, http://www.unendlich-viel-energie.de/uploads/media/Strommix-2008.jpg (April 2009).

Verbüchelen M, Hansen W, Neubauer A, Kraemer RA, Leipprand A. Strategie für die Zukunft der Abfallentsorgung (Ziel 2020). BMU FuE—Vorhaben 201 2005;32:324.

Webster M. Landfill site manager (personal communication); May 2009.