Land Quality Management Ltd

For: Department for Environment, Food and Rural Affairs

Methane Emissions from Landfill Sites in the UK

Final Report

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EXECUTIVE SUMMARY

UK methane emissions from landfill have been estimated using national assessments since the early 1990s. The latest assessment model (Brown et al., 1999) is based on the International Panel on Climate Change (IPCC) Tier Two model, with UK specific modifications. This project evaluates the current methodology, assesses data quality, considers the impact of methane in the operational phase of landfilling, develops a revised methodology, and produces emission forecasts based on the effect of the Landfill Directive and the new Waste Strategies of the Devolved Administrations. In addition, the balance of methane flared or utilised has been ascertained from industry sources, and a methodology to update these sources has been developed.

The evaluation of the methodology produced the following modifications:

- New waste inventory data for 1999 was added to the model, and eight scenarios for municipal solid waste (MSW) and five scenarios for commercial and industrial waste (C&I) were developed by ERM for projecting emissions.
- The degradable organic carbon (DOC) and fraction dissimilated (DOC_F) were considered by Brown et al. (1999) to have wide error limits, and these parameters were tailored in the 1999 model to allow the model forecasts and site measurements made by Milton et al. (1997) to converge (calibration of the model). Following calibration LQM found that the gas yield from the model was too low, and a new set of DOC and DOC_F parameters, as well as methane generation rate constants, were built into the model using the approach developed for the Environment Agency's GasSim model.
- A new methane oxidation model has been developed here, again using an approach first employed in GasSim. This model estimates that for the period 1980 – 2025 nearly 6 times as much methane oxidation may have taken place within the landfill cap, as that predicted using the IPCC default value recommended for well managed sites (10% for residual methane oxidised). The mechanistic model developed by LQM, based on field and laboratory measurements of methane oxidising capacity by many authors, allows much higher residual oxidation to take place in the capping layers, while allowing no oxidation in fractures. This model reconciles UK emissions from landfills to a level approaching the estimate of Milton et al. (1997), based on measured data.

The onset of methanogenesis has not been specifically implemented in the model. New and ongoing research suggests a much shorter period for this process to develop in engineered landfills. So any improvement to the national emissions inventory from allowing the aerobic degradation in the early stages of landfilling is likely to be negligible.

A significant part of the project involved the identification, in co-operation with industry stakeholders, of amounts of methane utilised and flared, and how the determination of how many flares sold were actually used as standby units. This information shows that currently 63% of the landfill gas generated is flared or utilised, and this is forecast to rise to 72% by 2005. Even accounting for uncertainties in the forecasts, utilisation and flaring is the largest

factor in mitigating methane emissions, far outweighing landfill diversion or recycling scenarios from the Waste Strategies over the time periods considered here. This is because of the quantities of methane generating wastes already landfilled.

The emission projections are based on eight Municipal Solid Waste (MSW) and five Commercial and Industrial (C&I) scenarios. MSW scenarios included achieving the Waste Strategy 2000 and Landfill Directive targets with current growth rates plus current material recycling rates; emphasis on paper/compost recycling; emphasis on paper recycling only; emphasis on recovery (using energy from waste, combined heat and power or anaerobic digestion (EfW/CHP/AD)); or emphasis on glass metals and plastics recycling. The MSW scenarios also considered higher growth rates with current material recycling rates and excess recovery; or excess material recycling rates. Current trends in diversion rates were considered as the base case or business as usual (BAU) case. C&I Scenarios included the current position as the base case (BAU); 15% diversion based on food wastes, paper & card and other general biodegradables to AD, EfW) and recycling; 15% diversion based on general biodegradable wastes to combustion; 15% diversion based on general biodegradable wastes to recycling; or 15% diversion through construction and demolition (C&D) and mineral wastes recycling.

All the MSW strategies considered shared some benefit in methane emissions reduction compared with the base cases (BAU), but the effects were not as significant as the impact on emissions reduction due to flaring or gas utilisation. The impact of any of the C&I scenarios compared to the base case were negligible in terms of methane emissions abatement. The most significant reduction in a MSW scenario involves paper recycling, which in 2005 shows a reduction of 2% of residual landfill methane emissions (8 kt methane abated), growing to a reduction of 19% of residual landfill methane emissions by 2025 (31 kt methane abated). The least effective MSW scenario involves glass, metal and plastics recycling and gives a forecast residual methane emissions reduction of 11% by 2025 (19 kt methane abated). Both sets of figures are, however, small when compared with the amount of methane abated by flaring or utilisation, which was 1750 kt in 2000, rising to a forecast level of 2465 kt in 2005 and remaining constant in this model to 2025. The role of flaring and utilisation technologies in managing methane emissions, recognised in the Landfill Directive as a key emissions management tool, should not therefore be underestimated.

CONTENTS

1 INTRODUCTION

Policy and Technical Background to the Project

Under the requirements of the UN Framework Convention on Climate Change (UNFCCC), the UK produces annual national inventories of anthropogenic emissions of all greenhouse gases (GHGs) not controlled by the Montreal Protocol. These are disaggregated by sector and are compatible with the IPCC 1996 guidelines (IPCC, 1996) and the IPCC Good Practice Guidance (IPCC, 2000). These inventories are produced by the UK National Atmospheric Emissions Inventory (UK-NAEI) at NETCEN. The most recent publication was in April 2002 (Salway et al., 2002).

The GHG inventory includes estimates for methane emissions from UK landfills. The current estimates were produced by AEA Technology in collaboration with the National Physical Laboratory (NPL) using a first order exponential decay model compatible with IPCC guidelines. This model, reported in Brown et al. (1999), made projections up to 2010, taking into account waste management policies and measures known or proposed at the time of the report.

The principal driver tending to reduce UK landfill methane emissions is at present the EU Landfill Directive (Council of the European Union, 1999). The reductions will partly reflect the implementation of the waste strategies of the devolved administrations: (DETR, 2001; SEPA, 1999; National Assembly Wales, 1999; DoE(NI), 2001). These strategies will help reduce landfill emissions on new landfills but landfills currently operational will continue to emit gases to atmosphere in potentially more significant quantities than post-Directive landfills and these emissions can only be reduced by flaring and utilisation.

The UK's National Assessment Model has been updated and revised to produce new modelling estimates of national emissions and forecasts under a number of waste management scenarios. The approach has been designed to be consistent with IPCC Guidelines and IPCC Good Practice guidance (IPCC, 1996; 2000), taking account of the flexibility allowed in the IPCC guidance for site/country specific data/information and sound scientific principles to be accommodated into the assessment model.

The Project Specification and Objectives

Environmental Resources Management (ERM), with Land Quality Management Ltd (LQM) as a major subcontractor, have been commissioned by the Department for Environment, Food and Rural Affairs (DEFRA) to produce reports on two related topics:

- Impact of EU Landfill Directive and National Strategies on UK Greenhouse Gas Emissions – EPG 1/1/144 (performed by ERM); and
- Methane Emissions from UK Landfills – EPG 1/1/145 (performed by LQM, this report).

Both projects were let as a single contract, managed by ERM, since both projects shared a commonality in waste arisings data, which were collated and produced by ERM for use in the LQM project, which in turn has fed back methane and carbon dioxide inventories from various waste management scenarios to the ERM project.

The aim of the project on Methane Emissions from UK Landfills is to provide DEFRA with an estimate of annual emissions of methane from UK landfill sites for the period 1990 – 2000 and projected emissions from 2001 – 2025, based on the latest available waste data, generally from the period 1995 – 2000. In the short contract time available, LQM considered the best approach was to revise (where required) the existing spreadsheet model. This was done by using certain algorithms, data and functional relationships already developed and validated in the GasSim model (Environment Agency, 2002a) and its precursor HELGA framework (Gregory et al., 1999). GasSim (the Environment Agency's new risk assessment tool for landfill gas emissions) and GasSim Lite (the Agency's proposed tool for calculating individual landfill site Pollution Inventories) were developed by Golder Associates (UK) Ltd and LQM using the most recent scientific research available. These models were used to develop add-on calculation modules for the National Assessment Model and to revise key parameters (such as the amount of degradable carbon in waste) according to current best practice and scientific thinking.

There are four objectives to the Methane Emissions from UK Landfills project.

1. *To review the methodology currently used in the UK-NAEI to estimate annual emissions of methane from landfill sites.*

The methodology currently used in the UK National Atmospheric Emissions Inventory (UK-NAEI) to estimate annual emissions of methane from landfill sites is based on IPCC Guidelines and Good Practice Guidance. Any revisions would therefore arise from new scientific state-of-the-art knowledge within the context of the Good Practice Guidance and/or UK specific waste management practice such as the practical level of implementation of methane emission control measures on UK landfills.

2. *To develop the most appropriate and up-to-date methodology for estimating the annual emissions from the UK taking account of the type of data in waste arisings, landfill site characteristics, and landfill gas recovery currently available.*

While the research reviewed all the parameters in the IPPC Tier Two methodology, it was clear from the start that the key drivers for the revision of the methane emissions estimate were going to be:

- an improved understanding of the fraction of degradable carbon available in waste for generation of landfill gas;
- improving knowledge on the proportion of landfill gas recovered and flared/utilised; and
- an improved understanding of the proportion of residual methane not collected and flared or utilised which is oxidised in the capping layers of the landfill.

3. *To provide national emission estimates for 1970, 1980, and each year from 1990 to 2025 using the recommended methodology, together with an estimate of the uncertainties.*

Once the drivers for the revision of the methane emissions estimate had been updated and the new methodology coded into the spreadsheet model, the National Assessment Model was used to generate the national emissions estimates, with uncertainty bands at the agreed confidence intervals, for the periods required.

4. *To advise on annual updating of emissions estimates, including the most appropriate use of collected/planned waste statistics and data on landfill sites.*

This objective required a documented approach to updating the assumptions and data used to drive the National Assessment Model.

The updated methodology and model has taken account of:

- latest research results on measured methane emissions from landfills;
- latest statistics on waste arisings and compositions;
- likely effects of the Waste Strategies and EU Landfill Directive; and
- actual quantities of methane collected for energy recovery and flaring.

Structure of the Report

Section 1 of the report sets out the policy and technical background to the research. Section 2 sets out the basic IPCC Tier Two methodology used in the National Assessment Model, and the AEAT/NPL modifications to the IPCC methodology. Section 3 reviews the methodology adopted, and considers the research used to support changes in the current revision of the National Assessment Model. Section 4 provides the latest statistics on waste arisings and composition, and the likely effects of the Waste Strategies and the Landfill Directive. Section 5 of the report shows how data on actual quantities of methane collected for energy recovery and flaring were derived, and what approach may be used for regularly updating these data. Section 6 shows the results of running the National Assessment Model against previous forecasts and against some of the potential future waste management scenarios. Section 7 is a complete reference list for the report.

Appendix 1 gives the baseline waste composition data used for the various scenarios described in the report, and Appendix 2 the contact details for updating the flare and gas utilisation inventory data on a yearly basis.

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2 BASIS OF THE IPCC TIER TWO METHODOLOGY

Background to the model

The *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 1996) outlines two methods to estimate methane emissions from solid waste disposal sites. The Tier 1 method (the default method) assumes that all the methane is released from the waste in the year of disposal, while the Tier 2 model is a first order decay (FOD) model which produces a time dependent emissions profile that better reflects the true pattern of the degradation process over time. IPCC (2000) states that the default model will give a reasonable annual estimate where waste composition and quantity vary little with time. In the UK, however, where both waste composition and quantity are changing more rapidly, due to legislative drivers impacting on the landfill chemistry, the IPCC Tier 2 methodology is likely to give the more accurate trend, and is therefore the basis of the UK's National Assessment Model.

To be consistent with good practice, as defined by the IPCC (2000), inventories should neither over nor underestimate, so far as can be judged, and the uncertainties in these estimates should be reduced as far as practicable. Addressing these uncertainties is, in part, performed by review of the model approach and, in part, by review of model parameters and other data drivers. These evaluations are in Sections 3 – 5 of this report.

Defining equations

The Tier 2 methodology is described by the Equations 2.1 – 2.3 below (replicating Equations 5.1 (including supplementary explanation of L_0 term) and 5.2 from IPCC (2000)). The generation equation is defined as:

$$CH_4 \text{ generated in year t (Gg/yr)} = \sum_x [\, (A \cdot k \cdot MSW_T(x) \cdot MSW_F(x) \cdot L_0(x)) \cdot e^{-k(t-x)} \,]$$

for x = initial year to year t   *Equation 2.1 (5.1 in IPCC 2000)*

where

t	=	year of inventory
x	=	years for which input data should be added
A	=	$(1 - e^{-k})$; a normalisation factor which corrects for summation
k	=	methane generation rate constant (1/yr)
$MSW_T(x)$	=	total municipal solid waste (MSW) generated in year x (Gg/yr)
$MSW_F(x)$	=	fraction of MSW disposed to solid waste disposal sites (SWDS) in year x
$L_0(x)$	=	methane generating potential (defined in Equation 2.2 below)

The methane generating potential, $L_0(x)$, is defined as:

$$L_0(x) = [\, MCF(x) \cdot DOC(x) \cdot DOC_F \cdot F \cdot 16 / 12 \,] \text{ (Gg } CH_4\text{/Gg waste)}$$

Equation 2.2

where

MCF(x)	=	methane correction factor in year x (fraction)
DOC(x)	=	degradable organic carbon (DOC) in year x (fraction) (Gg C/Gg waste)
DOC_F	=	fraction of DOC dissimilated (constant)
F	=	fraction by volume of CH_4 in LFG
16 / 12	=	conversion from C to CH_4

The methane emitted in any year t is defined as:

CH_4 emitted in year t (Gg/yr) = [CH_4 generated in year t – R(t)] . (1 – OX)

Equation 2.3 (5.2 in IPCC 2000)

where

R(t)	=	recovered CH_4 in inventory year t (Gg/yr)
OX	=	oxidation factor (fraction)

These equations are essentially those which drive the National Assessment Model.

Brown et al. (1999) implemented the basic IPCC methodology as follows:

- Three methane generation rate constants, k, were adopted for different types of waste. This approach follows that first used by Manley et al. (1990a; 1990b) to represent the differential degradation rates for the different cellulose-rich components of the waste.
- Commercial and Industrial (C&I) waste streams were introduced alongside municipal solid waste (MSW). C&I wastes represent a much larger inventory in mass terms but much of the C&I waste is not methane generating.
- Different methane generating potential terms were used for MSW and C&I wastes.
- Four different landfill site types were simulated, each with different degrees of engineering and gas collection, to represent the evolution of landfill engineering and landfill gas management in the UK since 1945. These are:
  - Type 1. waste emplaced from 1980-99 inclusive, with no gas collection.
  - Type 2. waste emplaced from 1980-99 inclusive, with limited gas collection.
  - Type 3. waste emplaced from 1986-99 inclusive, with comprehensive gas collection.
  - Type 4. waste emplaced from 1945-79 inclusive, with no gas collection.
- Gas recovered in an inventory year (by flaring or gas utilisation) was represented by scaling factors: for example, for the base case, it was assumed that 85% of LFG generated in type 3 landfills, and 40% of LFG generated in type 2 landfills was collected and flared or utilised. No gas was collected or utilised in type 1 or type 4 landfills.
- A number of additional data handling routines enabled the data to be set up as different uploadable scenarios for comparative data assessment purposes.

Implemented in this manner, the IPCC defining equations in the National Assessment Model can be used to generate the emissions projections. The parameters and data used to drive the model are reviewed in Sections 3 – 5 below.

3 REVIEW OF METHODOLOGY

Introduction

A significant part of the contract brief was to review all the model parameters and to determine whether recent research could be used to refine the model and reduce uncertainty. The IPCC model remains the core of the National Assessment Model, but following Brown et al. (1999), LQM has improved the scientific basis of the model and reduced uncertainties in emission projections. The waste-independent parameters are reviewed and discussed in this section. The total municipal solid waste (MSW) generated in a year, and the fraction which is disposed to landfill (the waste composition derived terms $MSW_T(x)$ and $MSW_F(x)$ in Equation 2.1 above) are discussed in Section 4 below. The calculation of the quantity of recovered methane via flaring or utilisation (the term R(t) in Equation 2.3 above) is discussed in Section 5.

Model Parameters

Methane generation rate

This is the term k in Equation 2.1 above. IPCC (2000) proposed a single value of 0.05 per year corresponding to a half life of 15 years. Manley et al. (1990a; 1990b) were the first to use three rate constants for slowly degradable, moderately degradable, and rapidly degradable waste, and Brown et al. (1999) introduced three rate constants to the National Assessment Model. Short half-life values for readily degradable waste introduces an unrealistic and unobserved peaks in gas forecasting models, so for consistency with the Environment Agency's GasSim Model (Environment Agency, 2002a), the three rate constants have been replaced with GasSim defaults (see Table 3.1). These have been validated against UK landfills and are considered appropriate in most UK cases (Environment Agency, 2002a). The GasSim defaults are on professional experience of UK landfill sites with varying degrees of saturation. There has been very little research to quantify the rate of gas generation, although it is known that the initial hydrolysis step from the cellulose polymer to the glucose monomer is the rate determining step. GasSim users are encouraged to use site-specific rate constants. LQM considers these default rate constants are suitable for use in the National Assessment Model, since this model integrates degradation from many different landfills, and so will be less sensitive overall to potentially different waste degradation rates at different landfills due to site specific differences.

The rate constants used by Manley et al. (1990a; 1990b), Brown et al. (1999), GasSim and the current implementation of the National Assessment Model are given in Table 3.1 below. It is interesting to note that in all cases, the slowly degradable half life is consistent with the IPCC default value, and there has been a trend to increase the half-life period of readily and moderately degradable wastes over the last decade, to avoid immediate peaks corresponding to short half lives in simulations.

IPCC (2000) indicate that the default rate constant has an uncertainty of –40% +300%. Since the GasSim rate constants have been successfully calibrated against UK sites, it is considered that these values will reduce the uncertainty in this parameter significantly, and an uncertainty estimate of ±25% is considered more appropriate.

Table 3.1. Waste Degradation Rate Constants

	Rate constant, k (per year) also expressed as a half life, $t_{1/2}$ (years)					
	Manley et al. (1990a; 1990b)		Brown et al. (1999)		GasSim (Environment Agency 2002a), and the current data set for the National Assessment Model	
	k	**$t_{1/2}$**	**k**	**$t_{1/2}$**	**k**	**$t_{1/2}$**
Rapidly degradable waste	0.69	1	0.185	3.75	0.116	6
Moderately degradable waste	0.14	5	0.1	6.9	0.076	9
Slowly degradable waste	0.05	~15	0.05	~15	0.046	15

Methane Correction Factor

This is the term MCF(x) in Equation 2.2 above and accounts for the fact that unmanaged solid waste disposal sites (SWDS) produce less methane compared to managed SWDS, because a larger fraction of waste decomposes aerobically in the top layers of unmanaged SWDS. IPCC (2000, see Table 5.1 of this document) states that the MCF for a managed solid waste disposal site should be 1.0. Values less than 1.0 may be adopted for developing countries or countries with unmanaged sites. It is considered that in the UK, all sites are managed and therefore MCF(x) = 1.0. A default uncertainty range of –10%, + 0% is proposed by the IPCC for managed sites (Table 5.2 of IPCC, 2000).

Fraction of methane in LFG

This is the term F, the fraction by volume of methane in LFG, in Equation 2.2 above. This fraction can be affected by a number of processes, and it is how these processes are considered in the model which governs the value of F.

The decomposition of cellulose in landfilled waste gives rise to both methane and carbon dioxide, in approximately equal quantity by volume. The mechanics of this process are a number of different biochemically mediated reaction schemes (AFRC, 1988), and so the actual quantity of methane or carbon dioxide produced by decomposition will vary according to the dominant microbiological processes. For a single site, the ratio of methane to carbon dioxide may differ from the typical 50:50 ratio observed. However, in a situation where the entire UK LFG inventory is being simulated (as in the National Assessment Model), these differences will tend to even out. For the purposes of modelling this process, a value of F of 0.5 has been used.

Field observations of LFG composition will often indicate air intrusion into the landfill, either by the action of a gas collection scheme drawing air through the cap, or in older sites where the generation rate is lower, by natural diffusion into the landfill site, thus reducing the observed concentrations of both methane and carbon dioxide in both cases. The former process is external to the biochemical degradation process and does not therefore alter the gas generation ratio significantly, although as identified by the IPCC, estimates of gas recovery will usually not consider entrained air in the gas collected for utilisation or flaring. Since entrained air may be up to 5% oxygen (and hence 20% nitrogen), the quantity of LFG recovered may be an overestimate by up to 25%, with a consequential and proportional effect on the modelled F term. The latest flaring survey has probably underestimated the installed capacity by 10 - 20% (see Section 5), and so these factors are currently considered to cancel each other out. The underestimate was accounted for in the AEAT 1995 model by the efficiency term, no longer used in the LQM model.

In older uncapped sites, natural diffusion of air through the cover materials led to a greater degree of aerobic degradation, and thus the proportion of methane produced changed from 50:50 reflecting the increased carbon dioxide and reduced methane production. Consequently, it is considered that for Type 1, 2 and 3 landfills (the more modern designs) the model should be run with a methane content in LFG of 50%, and so F = 0.5. For Type 4 landfills (the old unengineered design), a methane content in LFG of 30% has been used, and so F = 0.3. These settings are identical to those used by Brown et al. (1999).

Uncertainty in F is estimated to be no more than ± 10% if the effect of entrained air is considered in the model. Other related uncertainties (such as the quantity of landfill gas flared or utilised) are likely to be much larger in magnitude.

Degradable Organic Carbon (DOC) and Fraction Dissimilated (DOC_F)

These are the terms DOC(x) and DOC_F in Equation 2.2 above. IPCC (2000) states (Equation 5.4) that the degradable organic carbon (DOC) accessible to biochemical decomposition can be calculated using the default carbon content values found in the IPCC Guidelines (Table 6-3, Reference Manual). Given the IPCC recommendation that national values should be used, Brown et al. (1999) adopted figures for the DOC of the three different waste fractions (SDO, MDO and RDO) using data derived from the NPL study (Bellingham et al., 1994). The DOC that Brown et al. (1999) used for slowly, moderately and rapidly degradable waste fractions were 3.5, 12 and 9.2%, respectively.

IPCC (2000) states that the fraction of the DOC that actually degrades to release methane and carbon dioxide should by default be 0.77 (if lignin is excluded from the DOC value) or between 0.5-0.6 if lignin is included. Brown et al. (1999) used a value of 0.6, though they do not state if lignin was included in this assumption.

Brown et al. (1999) explain that the degradability of the waste was thought to be poorly understood, and this factor was therefore scaled in the National Assessment Model to allow the modelled forecast to converge with NPL field observations (Milton et al. 1997). This is considered to be *calibration* of the model with field data, but cannot be considered to be *validation* of the model. The modelled gas generation forecast in the 1999 model is now known to be an underestimate, since the amount of known installed flare and gas utilisation capacity from our current survey (see Section 5 below) exceeds the quantity of generated landfill gas forecast in the 1999 model in the year 2000, even though emissions are much more comparable. These degradation factors, which are believed to be the main reason for the National Assessment Model's underestimate, have been thoroughly reviewed and the current approach is described below.

LQM have updated the degradable carbon input parameters with values based on well-documented US research for the USEPA's life-cycle programme, which has been adapted to UK conditions and incorporated into (1) the Environment Agency's WISARD life cycle assessment model (WS Atkins, 2000); (2) the HELGA framework model (Gregory et al., 1999) and (3) GasSim (Environment Agency, 2002a). International peer review of the GasSim model has shown that similar degradation factors are used in the Netherlands (Oonk, Pers. Comm. 2002).

Cellulose and hemi-cellulose are known to make up approximately 91% of the degradable fraction, whilst other potential degradable fractions which *may* have a small contribution (such as proteins and lipids) are ignored. The amount of degradable carbon that produces landfill gas was determined using the mass (expressed on a percentage dry weight basis) and degradability (expressed as a percentage decomposition) of cellulose and hemi-cellulose using data provided by Barlaz et al. (1997). The default input values for these parameters are provided in Table 3.2 and 3.3 below for each of the waste fractions for both municipal (MSW) and commercial and industrial (C&I) waste categories, respectively. Also included are the proportions of individual waste streams which are considered to be rapidly, moderately or slowly degradable.

This information was used within the model to determine the amount of degradable carbon that decays at the relevant decay rate. This process requires complete disaggregation of the waste streams into their component parts, followed by the allocation to each component a different degradability and rate of decomposition, and application of the IPCC model at this disaggregated level.

Table 3.2. Waste degradable carbon model parameters for MSW waste

Waste category	Fraction				Moisture content	Cellulose	Hemi-cellulose	Decomp-osition
	RD	MD	SD	Inert	(%)	(% DW)	(% DW)	(%)
Paper and card	0	25	75	0	30	61.2	9.1	61.8
Dense plastics	0	0	0	100	5	0.0	0.0	0.0
Film plastics (until 1995)	0	0	0	100	30	0.0	0.0	0.0
Textiles	0	0	100	0	25	20.0	20.0	50.0
Misc. combustible (plus non-inert fines from 1995)	0	100	0	0	20	25.0	25.0	50.0
Misc. non-combustible (plus inert fines from 1995)	0	0	0	100	5	0.0	0.0	0.0
Putrescible	100	0	0	0	65	25.7	13.0	62.0
Composted putrescibles	0	50	50	0	30	0.7	0.7	57.0
Glass	0	0	0	100	5	0.0	0.0	0.0
Ferrous metal	0	0	0	100	5	0.0	0.0	0.0
Non-ferrous metal and Al cans	0	0	0	100	10	0.0	0.0	0.0
Non-inert fines	100	0	0	0	40	25.0	25.0	50.0
Inert fines	0	0	0	100	5	0.0	0.0	0.0

Notes: RD – readily degradable . MD – moderately degradable. SD – slowly degradable

[Data sources: Barlaz et al. (1997), Bellingham et al. (1994), Environment Agency (2002a), Department of the Environment, 1994a,b]

Table 3.3. Waste degradable carbon model parameters for C&I waste

Waste category	Fraction				Moisture content	Cellulose	Hemi-cellulose	Decomp-osition
	RD	MD	SD	Inert	(%)	(% DW)	(% DW)	(%)
Commercial	15	57	15	13	37	76.0	8.0	85.0
Paper and card	0	25	75	0	30	87.4	8.4	98.0
General industrial waste	15	43	20	22	37	76.0	8.0	85.0
Food solids	79	10	0	11	65	55.4	7.2	76.0
Food effluent	50	5	0	45	65	55.4	7.2	76.0
Abattoir waste	78	10	0	12	65	55.4	7.2	76.0
Misc processes	0	5	5	90	20	10.0	10.0	50.0
Other waste	15	35	35	15	20	25.0	25.0	50.0
Power station ash	0	0	0	100	20	0.0	0.0	0.0
Blast furnace and steel slag	0	0	0	100	20	0.0	0.0	0.0
Construction/demolition	0	5	5	90	30	8.5	8.5	57.0
Sewage sludge	100	0	0	0	70	14.0	14.0	75.0

Notes: RD – readily degradable . MD – moderately degradable. SD – slowly degradable

[Data sources: Barlaz et al. (1997), Bellingham et al. (1994), Environment Agency (2002a), Department of the Environment, 1994a,b]

Using the parameters listed in Tables 3.2 and 3.3 the term $DOC(x).DOC_F$ from Equation 2.2 above, for each waste category and degradability fraction, is defined as:

$$(DOC(x).DOC_F)_{i,j} = M(x)_{i,j} \,.\, (\%C_i + \%HC_i) \,.\, \%DC_i \,.\, (1\text{-}\%MC_i) \,.\, 72/162 \quad \text{(Gg C/Gg waste)}$$

Equation 3.1

where

$M_{i,j}$	=	mass of waste category i in year x, degradability fraction j (Gg waste)
$\%C_i$	=	cellulose content of waste category i (fraction) (Gg cellulose/Gg waste)
$\%HC_i$	=	hemi-cellulose content of waste category i (fraction) (Gg hemi-cellulose/Gg waste)
$\%DC_i$	=	degradability of the cellulose and hemi-cellulose of waste category i (fraction)
$\%MC_i$	=	moisture content of waste category i (fraction)
72/162	=	conversion from cellulose/hemi-cellulose to carbon (Gg C/Gg cellulose and hemi-cellulose)

The total degradable organic carbon that is dissimilated, within each waste fraction (rapidly, moderately or slowly degradable), was summed across all waste categories using Equation 3.1 above. This estimate was then used to derive the specific methane generation potential for each waste fraction, using Equation 2.2 above. This provides the input to Equation 2.1 above, to obtain the value of the methane generated per year. The moisture content of the waste is required to covert from parameters provided by Barlaz et al. (1997) in dry weight to wet weight of waste, as used within the model. Such an approach assumes that the cellulose and hemi-cellulose contents, moisture contents and degradability fraction of individual waste categories does not vary with time. However, the term $DOC(x).DOC_F$ does vary with time as a function of the mass of each individual waste category, which is a realistic assumption for the National Assessment Model.

The approach outlined above is numerically and mathematically consistent with the Environment Agency's GasSim Model (Environment Agency, 2002a). The uncertainty in L_0, which incorporates MCF, DOC and DOC_F is estimated to be similar to that stated for the Netherlands, namely ±15% (Oonk and Boom, 1995).

Methane in the operational phase of landfilling

Until recently there has been no research on the onset of methanogenesis in operational phases of landfills, or on the effectiveness of gas collection in the operational phase. WS Atkins has been carrying out research since 2000 on a project funded through the Landfill Tax Credit Scheme entitled *Minimising methane emissions from municipal landfills*. This project has yet to complete and report findings. For practical purposes, the onset of methanogenesis is defined here as:

- concentrations of carbon dioxide and methane characteristic of established methanogenic conditions are seen (at least 40% methane v/v and 40% carbon dioxide); *and also*
- methane generation (i.e. flux) is measurable and exceeds the Environment Agency's draft methane emissions protocol threshold (i.e. $> 1 \times 10^{-3}$ $mg.m^{-2}.s^{-1}$) (Environment Agency, 2002c).

Prior to these conditions being achieved, the gas generated from within the fresh waste will be hydrogen and carbon dioxide rich (from aerobic, acidogenic, and acetogenic degradation processes), and therefore of little consequence to the methane budget. Once the process has entered the fully methanogenic phase of waste degradation, methane emission rates greater than the Agency's draft protocol (Environment Agency, 2002c) are taken to indicate that proper methanogenic gas generation is taking place.

Manley et al. (1990a,b) estimated that the onset of methanogenesis took place within 32–52 weeks (7–12 months). The WS Atkins study (in progress) looked at two sites (probably only one in sufficient detail) to ascertain the onset of methanogenesis within a cell unaffected by other waste beneath it. At site A, some methane was detected in 4 week old waste, although no flow was observed until 1.3 months. Some pressure was indicated in landfill gas which had reached a gas composition of up to 50% methane after 3.85 months at this site. At site B, again, methane was detected almost immediately, but no pressures until after 3 – 4 months after waste placement. These data seem to suggest that the onset of stable methanogenic conditions may be as little as four months (16 weeks) (Schwarze, pers. comm., 2002).

For modelling purposes, it is not considered that there is sufficient information to reduce the quantity of methane forecast by the model in year 1 to account for early degradation processes, since the time frame for achieving methanogenesis appears to be (a) site-specific; and (b) relatively short in modern engineered landfills, compared to the estimates from 1990.

Methane oxidation

This is the term OX in Equation 2.3 above. IPCC (2000) states that the oxidation factor for well-managed landfills at a national level should be 0.1, based on available information. This factor should only be applied to the residual methane - i.e. the amount generated less that recovered.

LQM have developed a new model for this contract which involves updating the oxidation factor with values based on well-documented research. Methane oxidation is generally accepted to follow a four stage bacteriological conversion of methane into carbon dioxide:

$CH_4 \rightarrow$	$CH_3OH \rightarrow$	$HCHO \rightarrow$	$HCOOH \rightarrow$	CO_2
methane	methanol	methanal	methanoic acid	carbon dioxide

Methanotrophic bacteria use these reactions to gain energy and carbon for their growth (Hanson and Hanson, 1996). Methane oxidation has been linked to the two main types of methanotrophic bacteria (Borjesson at al, 1998) but not in any easily interpreted mechanistic fashion. Field and laboratory based observations exhibit variation of the conversion of methane to carbon dioxide over many orders of magnitude, some of which may be explained by a seasonality relationship for the field data (Table 3.4). The laboratory scale observations of conversion of methane to carbon dioxide are likely to be at favourable conditions (i.e. close to the theoretical maximum for biological activity within the soil medium). Data on the estimates of the rate of methane oxidation in soil covers using ^{13}C analysis gives a measure of the fraction of methane which is actually converted. An empirical approach has been derived using the known range of methane oxidation rates (Table 3.4) in different cover materials and in-situ conversion efficiencies to develop a series of empirical equations for the removal of methane from landfill gas emitted through the surface. The data supplied in Table 3.4 has been standardised to units of m^3 $CH_4/m^2/h$ from the units provided in the publications listed (either as g or l $CH_4/m^2/h$).

The model is built on a number of simple underlying concepts: methane oxidation within the soil cap is only assumed to occur if the soil cover depth is greater than 0.3m if an engineered barrier is present (modern lined landfills), or for caps with a soil cover depth greater than 1.0m if an engineered barrier is not present (old unlined landfills). If either of these conditions are not met then no methane oxidation will take place, on the basis that the surface soil cover is insufficiently thick and/or the flow of methane (the methane flux) is too fast to permit a significant amount of methane oxidation to take place within the cap.

Table 3.4. Methane oxidation rates for cover materials (laboratory and field studies)

Study type	Cap type and scenario	Value	Standardised Oxidation rate (m^3 $CH_4/m^2/h$)	Reference
Field study	0-80 cm	Max Min	3.22×10^{-4} 2.86×10^{-3}	Hoecks (1983)
Laboratory columns	-	Max	1.02×10^{-2}	Mennerich (1986)
Laboratory columns	Topsoil	Max	6.30×10^{-2}	Whalen et al. (1990)
Laboratory columns	Sand cap	Max Min	5.60×10^{-3} 7.00×10^{-4}	Figueroa (1993)
Field study	0-32 cm	Max (July) Min	1.01×10^{-2} 1.88×10^{-8}	Jones and Nedwell (1993)
Laboratory columns	Coarse sand	Max	9.73×10^{-3}	Kightley et al. (1995)
Laboratory columns	Topsoil	Max Min	3.30×10^{-3} 1.18×10^{-3}	Boeckx and van Ceemput (1996)
Field study	Sand cap 0-80 cm Sandy loam Sewage sludge	Max Min Max Min Max Min	8.82×10^{-3} 2.66×10^{-3} 1.22×10^{-2} 1.96×10^{-4} 2.35×10^{-2} 2.24×10^{-3}	Borjesson and Svensson (1997)
Field study	0-30 cm 0-100 cm	Max Min Max Min	5.90×10^{-3} 3.00×10^{-4} 3.80×10^{-3} 1.00×10^{-3}	Scharff et al. (2001)

The methane oxidising capacity of the soil cover ($Soil_{oxd\ cap}$) represents the size of the 'sink' for methane conversion to carbon dioxide. This is defined as:

$$Soil_{oxd\ cap} = \Delta_{field\ eff}(SOC.24.365)A_{surface}\frac{M_m}{M_v}10^{-9}\ [\text{kt } CH_4/y]$$

Equation 3.2

where

$Soil_{oxd\ cap}$	=	maximum methane that can be oxidised in year x by the soil cover (kt CH_4/y)
SOC	=	soil oxidising capacity of landfill (m^3 CH_4/ m^2 landfill/ h)
$\Delta_{field\ eff}$	=	effectiveness of methane oxidation under field conditions (fraction)
$A_{surface}$	=	cumulative surface area of the landfill type under consideration (m^2) (see Equation 3.3)
M_v	=	molar volume (at STP) ($0.02241 m^3$ CH_4/ mole)
M_m	=	molecular mass of methane (16g CH_4/ mole)

The factor 10^{-9} converts from g CH_4 to kt CH_4.

The cumulative area of the landfill in year x is defined as:

$$A_{surface}(x) = \sum_{x=1}^{x=T} \frac{WasteInput\ (x)}{\rho(x) d_{site}(x)} 10^6$$

Equation 3.3

where

WasteInput(x) = total waste input to landfill for year x (Mt/y)
ρ_{waste} = average density of waste emplaced within landfill type for year x (t/m^3)
$d_{site}(x)$ = average depth of waste within landfill site type (1-4) for year x (m)
The factor 10^6 converts from millions of m^2 landfill surface area to m^2.

Within this module (for the purposes of national projections of methane oxidation) the values of site depth, waste input density, soil oxidising capacity of the landfill cap and effectiveness of methane oxidation under field conditions are assumed to remain constant over the entire landfilling period. The input values for the soil oxidising capacity of the landfill cap and effectiveness of methane oxidation under field conditions were determined as the median values obtained from the probability density functions (pdf) defined for these particular parameters (see Table 3.5 below).

The actual methane that is available for potential oxidation in the cap ($Avail_{oxd\ cap}$) to carbon dioxide is determined after the quantity that is utilised or flared (i.e. recovered) is subtracted from the generated methane. The available methane for oxidation (kt/y) is defined as:

$$Avail_{oxd\ cap}(x) = (1 - \Delta_{fissure})(CH_4 generated(x) - R(t)) \ [kt\ CH_4/y]$$

Equation 3.4

where
$Avail_{oxd\ cap}$ = methane available for oxidation in year x (kt/y)
$\Delta_{fissure}$ = fraction of methane lost directly through fissures (fraction)
CH_4 generated(x) = methane generated in year x (kt/y)
R(t) = methane recovered in year x (kt/y)

The actual fraction of generated methane that is oxidised (OX) after energy recovery is calculated after determining whether oxidation is limited by the sink capacity of the soil ($Soil_{oxd\ cap}$) or the source or quantity of methane available for potential oxidation ($Avail_{oxd\ cap}$). The two situations are defined as:

For $Soil_{oxd\ cap} > Avail_{oxd\ cap}$ (source limited oxidation), under these circumstances the oxidation factor is:

$$OX = (1 - \Delta_{fissure})\left(\frac{CH_4 \, generated\,(x) - R(t)}{CH_4 \, generated\,(x)}\right)$$

Equation 3.5

For $Avail_{oxd\ cap} > Soil_{oxd\ cap}$ (sink limited oxidation), under these circumstances the oxidation factor is:

$$OX = (1 - \Delta_{fissure})\left(\frac{Soil_{oxd\ cap}}{CH_4 \, generated\,(x)}\right)$$

Equation 3.6

where

$Soil_{oxd\ cap}$ = maximum methane that can be oxidised in year x by the soil cover (kt CH_4/y)

CH_4 generated (x) = methane generated in year x (kt/y)

R(t) = methane recovered in year x (kt/y)

$\Delta_{fissure}$ = fraction of methane lost directly through fissures (fraction)

The inputs for this methane oxidation module in the National Assessment Model are associated with a high degree of uncertainty and/or variability. Subsequently, a number of input parameters have been assigned probability density functions (pdfs) to account for this variation, based upon the literature review and expert judgement. The 'best-estimate' (median) default input parameters (derived from 1001 iterations using Decisioneering's Crystal-Ball software package, version 5.0) are presented in Table 3.5, along with their pdf (type and critical values), for each type of landfill considered in the National Assessment Model.

Table 3.5. Inputs required for methane oxidation module and associated pdf

Input	Landfill Type	Best-estimate	PDF	Source
Soil oxidising capacity (SOC) [$m^3 CH_4/m^2/h$]	1	0.00415	LN (0.00798, 0.01383)	See Table 3.4
	2	0.00425		
	3	0.00379		
	4	0.00389		
Field oxidation efficiency ($\Delta_{field\ eff}$) [fraction]	1	0.75	Single input value	Based on relative proportion of field ($\Delta_{field\ eff}$=1) and laboratory ($\Delta_{field\ eff}$=0.25) data
	2	0.75		
	3	0.75		
	4	0.75		
Fraction through fissures ($\Delta_{fissure}$) [fraction]	1	0.10	Single input value	Expert judgement
	2	0.10		
	3	0.10		
	4	0.10		
Soil cover depth (above cap) [m]	1	1.0	U (0.5, 1.5)	Expert judgement
	2	1.0	U (0.5, 1.5)	
	3	1.0	U (0.5, 1.5)	
	4	0.65	U (0.15, 1.5)	
Landfill site depth ($d_{site}(x)$) [m]	1	11.3	T(5.00, 7.00, 25.00)	Expert judgement
	2	25	T (10.0, 25.0, 40.0)	
	3	25	T (10.0, 25.0, 40.0)	
	4	10	T (5.00, 7.00, 20.00)	
Waste density ($\rho(x)$) [t/m^3]	1	1.00	Single input value	Expert judgement
	2	1.00		
	3	1.00		
	4	1.00		

Note: Log Normal distribution = LN (mean, standard deviation)

Triangular distribution = T (minimum, likeliest, maximum)

Uniform distribution = U (minimum, maximum)

Of the oxidation module parameter listed in Table 3.5, the model output is most sensitive to the values for field oxidation efficiency and the fraction through fissures. These sensitivities are explored in more detail in Section 6 of the report.

4 WASTE COMPOSITION DATA AND WASTE MANAGEMENT SCENARIOS

Introduction

Brown et al. (1999) compiled waste arisings data from 1945 to 1995, and produced forecasts to 2010. LQM have used these waste arisings as the baseline for the 2002 assessment (see Appendix 1), and have updated the waste arisings data and forecasts with the current 1999 estimates of municipal solid waste (MSW) and commercial and industrial (C&I) wastes from the companion study by ERM. Waste management scenarios also developed by ERM have been used to examine the effect of different scenarios on methane generation and emission, and these data have been passed back to ERM for use in their study.

Landfill types

As described in Section 2 above, Brown et al. (1999) introduced four types of landfills, which were considered differently in terms of their waste composition, engineering and gas collection in the National Assessment Model. Although not strictly part of the IPCC FOD model, this was considered at the time to allow some resemblance of the distribution of landfill site types as recorded in the WRc Landfill Database. It is considered that with current landfill engineering requirements, all new waste arising will be emplaced in landfill Type 3 (with comprehensive gas collection) and no waste has been partitioned to the other landfill types since 1999.

Municipal Solid Waste Arisings

The National Assessment Model uses the MSW arising data as provided by Brown et al. (1999) from 1945 to 1994 inclusive (Appendix 1 Table A1.1). The MSW arisings for 1995 to 2025 have been provided by ERM (2002), with values from 1995 to 1998 back-calculated from the 1999 figures.

ERM have retained, as far as possible, compatibility with the break down of MSW as defined by Brown et al. (1999) (Table 4.1) for the purposes of the updated National Assessment Model. The most significant change is in putrescibles, to include composted putrescibles after 1994. This accounts for the greater emphasis on the composting of organic materials and a redefinition of this waste stream after this time in accordance with current national waste management strategies. This change from putrescibles to composted organic material is associated with a corresponding decrease in the amount of degradable carbon for producing landfill gas (Table 3.2).

Table 4.1. Breakdown of Municipal Solid Waste Arisings (MSW)

Updated National Assessment Model	Brown et al. (1999)
Paper and card (weighted paper & card based on the GasSim default waste stream, 1980s-2010)	Paper and card
Dense plastics	Dense plastics
Film plastics (until 1994 only)	Film plastics
Textiles	Textiles
Misc. combustible (plus non-inert fines from 1995)	Misc. combustible
Misc. non-combustible (plus inert fines from 1995)	Misc. non-combustible
Putrescible (GasSim garden waste)	Putrescible
Composted putrescibles (GasSim composted organic)	Not included
Glass	Glass
Ferrous metal	Ferrous metal
Non-ferrous metal and Al cans	Non-ferrous metal
Non-inert fines (GasSim 10mm fines)	Non-inert fines
Inert fines	Inert fines

Commercial and Industrial waste arisings

The National Assessment Model uses the CIW arising data as provided by Brown et al. (1999) from 1945 to 1998 inclusive (Appendix 1 Table A1.10). The CIW arisings for 1998 to 2025 have been provided by ERM (2002) and are derived from the Strategic Waste Management Assessments (SWMAs) produced by the Environment Agency (2001).

ERM have retained, as far as possible, compatibility between the breakdown of CIW wastes reported in the SWMAs and that as defined by Brown et al. (1999) (Table 4.2), for the purposes of the updated National Assessment Model. The arisings figures for sewage sludge defined by Brown et al. (1999) have been retained in the updated National Assessment Model, in the absence of more up to date data.

Table 4.2. Breakdown of Commercial and Industrial Waste Arisings (CIW)

Updated National Assessment Model	**Brown et al. (1999)**
Commercial ERM general commercial from 1995 (treated as GasSim commercial mix: 10% newspapers; 50% other papers; 15% other putrescibles; 25% inert)	Commercial
Paper and card ERM Paper & Card and Paper Pulp wastes from 1995 (treated as GasSim Other Paper)	Not included
General industrial waste ERM general industrial & commercial from 1995 (treated as GasSim commercial mix: 10% newspapers; 50% other papers; 15% other putrescibles; 25% inert)	General Industrial waste
Food solids 10% of ERM food wastes from 1995 (treated as GasSim other putrescible)	Food solids
Food effluent 80% of ERM food wastes from 1995 (treated as GasSim other putrescible)	Food effluent
Abattoir waste 10% of ERM food wastes from 1995 (treated as GasSim other putrescible)	Abattoir waste
Misc. processes ERM chemical and other wastes from 1995 (expert judgement)	Misc. processes
Other waste ERM other general and biodegradable from 1995 (expert judgement)	Other waste
Power station ash ERM Pulverised Fuel Ash (PFA) and Furnace Bottom Ash (FBA) wastes from 1995 (treated as Inert)	Power station ash
Blast furnace and steel slag ERM blast furnace, basic oxygen and electric arc furnace slags from 1995 (treated as Inert)	Blast furnace and steel slag
Construction/demolition ERM Inert C&D, metals and scrap, contaminated general, mineral wastes and residues, construction and demolition from 1995 (treated as GasSim incinerator ash)	Construction/demolition
Sewage sludge AEAT default input values	Sewage sludge

Scenario Development

Eight MSW scenarios have been developed by ERM to investigate the various waste management options available, which are described below. Future waste arisings have been modelled using anticipated levels of growth as set out below to reflect the Government's commitment to waste minimisation, in accordance with waste minimisation programmes outlined in both the Waste Strategy 2000 and the Landfill Directive. ERM provided UK

MSW waste data to landfill from 1995/1996 until 2025/26. These data are given in Appendix 1, Tables A1.2 – A1.9.

MSW scenarios

1. Achieving the Waste Strategy 2000 and Landfill Directive targets with current material recycling rates
2. Achieving the Waste Strategy 2000 and Landfill Directive targets with emphasis on paper/compost recycling
3. Achieving the Waste Strategy 2000 and Landfill Directive targets with emphasis on paper recycling
4. Achieving Landfill Directive targets with emphasis on recovery (EfW/CHP/AD)
5. Achieving the Waste Strategy 2000 targets with emphasis on glass metals and plastics recycling
6. Higher growth rate, achieving the Waste Strategy 2000 and Landfill Directive targets with current material recycling rates and excess recovery
7. Higher growth rate, achieving the Waste Strategy 2000 and Landfill Directive targets with excess material recycling rates
8. Current trends in diversion continued (Base case)

The detailed assumptions for each of the above MSW scenarios and sources of data are provided by ERM (2002).

In addition, five C&I scenarios have been developed (by ERM) to investigate the various waste management options available, which are described below. ERM provided UK C&I waste arisings from the SWMAs and the breakdown of methods of disposal/treatment for 1999/2000, taken from the DEFRA Municipal Waste Management Survey 1999/2000.

C&I Scenarios

These are:

1. Baseline - current landfill
2. 15% diversion based on food wastes, paper & card and other general biodegradables to digestion, EfW and recycling (lose readily degradables from total C&I excluding C&D)
3. 15% diversion based on general biodegradable wastes to combustion (lose readily and moderately degradable organics)
4. 15% diversion based on general biodegradable wastes to recycling (lose readily and moderately degradable organics)
5. 15% diversion through C&D and mineral wastes recycling (lose inerts)

The detailed assumptions for each of the above C&I waste scenarios and sources of data are provided by ERM (2002) and are given in Appendix 1 Table A1.11.

5 FLARING AND ENERGY RECOVERY

Representation of Flaring and Energy Recovery in Previous Assessments

Flaring and energy recovery constitutes the method likely to reduce methane emissions from landfills by the largest amount, and is probably the most readily auditable management method for achieving actual (as opposed to modelled) methane emissions reductions. As set out below, it is estimated that in 2002 at least 63% of the total landfill gas generated in the UK was flared or utilised, and that this rises to approximately 72% by 2005 (beyond which it becomes impracticable to forecast future trends with any accuracy).

Aitchison et al. (1996) carried out the first National Assessment under the IPCC methodology (the ETSU 1996 study). This 1996 assessment included utilisation data from 1988 – 1994 and a survey of flare manufacturers to ascertain the quantities of landfill gas controlled in this fashion for the period 1984 – 1995. The quality of this historical data is considered to be very good, and the information has been retained and used in this 2002 update. It is not clear, however, from the Aitchison et al. (1996) report exactly how the utilisation and flaring data was used in the modelling forecast.

Brown et al. (1999) carried out the second National Assessment under the IPCC methodology (the AEAT 1999 study). This assessment does not appear to have updated the flare and utilisation data collected in the ETSU 1996 study, but rather has applied “recovery effectiveness” terms to the gas generated by the different landfill categories represented in the model. This modelling approach therefore appears not to use actual information on utilisation and flaring, but to assume that the flaring and utilisation term in the IPCC is proportional to the amount of gas forecast in any year. This approach is considered unsuitable for two reasons. Firstly, it is dependent upon the ability of the model to estimate gas generation accurately, and it has already been demonstrated in Section 3 of this report that the waste degradation factors used in the 1999 model are well below accepted levels of gas generation per tonne of waste. Secondly, the derivation of the proportionality constants is not clearly set out, and so while these may be accurate, it is difficult to independently validate these against actual figures for gas utilisation and flaring.

This survey (the LQM 2002 survey) has used the approach adopted by ETSU 1996, as this was considered to be both a robust and auditable approach. If additional information becomes available, then the data can be readily revised to account for new or missed data sources.

Gas Utilisation

Information sources

The utilisation data, below, is mainly based on comparison of information from the trade association (the Biogas Association (Gaynor Hartnell, Pers. Comm. 2002))[1] and current DTI

[1] The Biogas Association was formerly the Landfill Gas Association. The Biogas Association merged with other renewable trade associations in 2002 to become the Renewable Power Association.

figures[1]. In addition, we included data on utilisation prior to the first round of the Non Fossil Fuel Obligation (NFFO) contracts (Richards and Aitchison, 1990). The first four NFFO rounds (NFFO 1-4) and the Scottish Renewables Order (SRO) round are all assumed to be completed and operational schemes, since there are relatively few outstanding schemes still to be implemented. It is known that not all of the proposed early schemes were found to be economic, and no NI-NFFO schemes have progressed, so those known schemes have not been included in the total (Gaynor Hartnell, Pers. Comm. 2002).

This approach, comparing the trade association and Government data sources, provides a reasonable correlation, and so we are confident in the accuracy of our estimates of current installed capacity. The latest round of NFFO (NFFO 5) has been implemented in the forecasting model over the period 2000 – 2005, to give a reasonable lead in time for these new projects. Various industry sources have indicated in confidence that some of the proposed NFFO 5 projects are now also considered uneconomic under NFFO. Some of these have definitely been abandoned, while others are more likely to proceed under the new renewables order.

Data and assumptions

The data used in the model is shown in Table 5.1. The data for installed power generation capacity each year (expressed as m^3 LFG) is derived by multiplying the figure in the final column of Table 5.1 by 2, assuming that LFG is typically 50% methane. These figures are likely to have only a small uncertainty, as they are directly derived from power generation figures supplied by the industry and DTI.

[1] http://www.dti.gov.uk/energy/inform/energy_stats/renewables/index.shtml

Table 5.1. Derivation of Landfill Gas Utilisation Data used in the National Assessment Model 2002

Year	ETSU 1996 (kt CH_4 abated/yr)[1]	ETSU 1996 (equivalent GWhr)[2]	DTI (GWhr conv. from oil equivalent at 35%effic.)[3]	Non-NFFO generation (MW_e)[4]	NFFO 1-5 etc generation (MW_e)[5]	NFFO + non-NFFO generation (MW_e)[6]	NFFO (GWhr at 5% downtime)[7]	NFFO + non-NFFO (GWhr)[8]	NFFO + non-NFFO (1000s m^3CH_4/yr)[9]
1985									
1986				3		3		25	7114
1987				12		12		99.8	28454
1988	47	231		12		12		99.8	28454
1989	61	300	187.5	19		19		158.1	45053
1990	69	339	187.5	19	10	29	83.2	241.3	68765
1991	90	442	277.2	19	20	39	166.4	324.5	92477
1992	133	653	505.5	19	46.1	65.1	383.6	541.6	154365
1993	139	687	599.3	19	61.4	80.4	510.8	668.9	190644
1994	162	796	693.1	19	77.2	96.2	642.3	800.4	228109
1995			750.1	19	104.5	123.5	869.4	1027.5	292843
1996			945.8	19	131.9	150.9	1097.4	1255.5	357814
1997			1227.1	19	204.5	223.5	1701.4	1859.5	529963
1998			1585.9	19	249.7	268.7	2077.5	2235.6	637141
1999			2274.9	19	321.8	340.8	2677.4	2835.5	808105
2000			2923.1	19	348.8	367.8	2902	3060.1	872127
2001				19	403	422	3353	3511	1000646
2002				36	453	439	3769	3652.5	1040957
2003				36	505	541	4201.6	4501.1	1282819
2004				36	558	594	4642.6	4942.1	1408493
2005				36	610	646	5075.2	5374.7	1531795

Notes:

1. Data from Aitchison et al. (1996)
2. Data derived from Aitchison et al. (1996), assuming a typical $1MW_e$ gas engine consumes $570m^3$/hr of LFG at 50% CH_4
3. Data derived from DTI (2002) assuming 1 ktoe = 11.63 GWhr, and 35% thermal efficiency of power generator
4. Data from Richards and Aitchison (1990) and industry sources (Pers. comms., 2002)
5. Data from installed capacity for NFFO 1-4 plus SRO and NI-NFFO (Gaynor Hartnell, Biogas Association, Pers.comm. 2002) plus NFFO5 installed over period 2001-2005, but excluding sites which industry sources have advised are non-economic.
6. Sum of previous two columns data.
7. Derived from column 5 assuming 5% total down time for all operating gas engines
8. Derived from column 6 assuming 5% total down time for all operating gas engines
9. Derived from column 8, assuming a typical $1MW_e$ gas engine consumes $570m^3$/hr of LFG at 50% CH_4

Flaring

Information sources

Initially two approaches were adopted, with the aim of identifying which provided a better estimate of flaring capacity, and which would prove to be the better approach for updating the estimate of installed capacity. These were as follows:

- Identification of all operational landfills followed by consultation with the operators; and
- Identification of flare manufacturers followed by consultation with the manufacturers.

Each approach had associated advantages and disadvantages. The former approach involved making many more contacts, but potentially offered better understanding of the installed flare capacity and how it was used. The latter approach involved making fewer contacts, but required more information from each contact. Additionally, information on the use of the flare is second-hand and may not be reliable.

Initially, both approaches were trialled. It soon became apparent that the timing of the survey corresponded with a reporting requirement under NFFO and very few operators were particularly keen to provide information because of their other reporting commitments. We therefore followed the same general approach as Aitchison et al. (1996) and focused on the flare manufacturers.

Table 5.2 below lists all the companies identified from the previous survey (Aitchison et al., 1996) plus other known manufacturers and suppliers who have entered the market since 1996. Some of these have not yet sold flares in the UK landfill market but are included for subsequent updating exercises as they may become active in the future.

Several of the companies listed have changed ownership or ceased trading since the last published survey. These are generally companies which have failed to respond to the Environment Agency's requirement for high-temperature enclosed flaring of landfill gas first published in 1999 (Environment Agency, 2002b). It has therefore245 Tw nment E4r l i05 Tw nmn0 Tw (

Table 5.2. Flare Manufacturers and Suppliers surveyed 2002

Supplier	Trading status	Current marketing status
AFS[1]	Active	Manufactures and supplies flares
Apex Tubes and Valves (formerly Anglia Mechanical Environmental Ltd)	Active	Does not make or supply flares
Biffa Environmental Technology	Active	Sources externally
Biogas	Active	Manufactures and supplies flares
Clarke Energy[1]	Active	Supplies HAASE flares
Covertronic (formerly MB Geosphere)	No longer trading	No longer trading
Energy Developments[1]	Active	Manufactures and supplies flares
Enitial Projects[1]	Active	Manufactures and supplies flares
Flare Products Ltd	Active	No data made available to us
Fuel and Combustion Technology Ltd	No longer trading	No longer trading
GBA Ltd[1]	Active	Manufactures and supplies flares. Offshore flare sales only
HAASE[1]	Active	Manufactures and supplies flares. Some direct sales to UK (see also Clarke Energy)
Hi-Lo Ltd	Active	Manufactures and supplies flares
Hirt Combustion Engineers Ltd	Active	Manufactures and supplies flares
Marton Geotechnical Services Ltd[1]	Active	Manufactures CPL designed flares
Novera Energy (formerly CPL Energy)[1]	Active	Holds patents, but does not build own flares (see Marton Geotechnical Services)
Organics Ltd (formerly UKPS Ltd)	Active	Manufactures and supplies flares
Process Combustion[1]	Active	Manufactures and supplies flares
Pro2[1]	Active	Manufactures and supplies flares
PCC Sterling Ltd[1]	Active	Manufactures and supplies flares
Summerleaze Re-generation[1]	Active	Supplies Hofstetter flares
Thomas Graveson	Sold to Enviros then to Summerleaze (see above)	See Summerleaze Re-generation

We were able to contact all the companies listed above who are actively supplying flares within the UK. We were able to collect information from all but one of the companies we contacted.

[1] Not included in the ETSU 1996 survey (Aitchison et al., 1996).

Data and assumptions

Table 5.3 below lists the cumulative flare capacity sold or hired by the manufacturers and suppliers active in the UK market, for use within the UK (Table 5.2). Companies were asked to divide their data into flares supplied for routine flaring and flares supplied as back-up to generation sets. All the companies who were able to supply data were also able to split their sales and rentals into these two categories. The flares used for utilisation plant back-up have been shown separately. The information is also shown graphically as Figure 5.1.

Table 5.3. Flare Surveys 1996 and 2002

	ETSU (1996)	This market survey 2002		
Year	Flare capacity from cumulative sales (m^3/hr)	Flare capacity from cumulative sales (m^3/hr)	Flare capacity used for utilisation plant back-up (m^3/hr)	Modelled net flaring capacity (m^3/hr)
1980				
1981		500		500
1982		500		500
1983		1250		1250
1984	3500	2250		3500
1985	10000	5750		10000
1986	16500	6250		16500
1987	28000	12000		28000
1988	50000	22500		50000
1989	78350	37500		78350
1990	111700	51750		111700
1991	163300	80500	11500	151800
1992	208300	98250	17500	190800
1993	256700	119550	20500	236200
1994	301700	140300	27500	274200
1995	350000	176900	41500	308500
1996		207350	43500	336950
1997		246600	50500	369200
1998		294000	66000	401100
1999		347500	93150	427450
2000		405850	117350	461600
2001		518900	175150	516850
2002		578700	189700	562100

Use of data in the model

Uncertainties, Errors and Omissions

The ETSU survey data should have more accurate figures for the period 1984 – 1995 than the LQM survey, since some of the flare manufacturers of that period have ceased trading. The flare capacity modelled is therefore a combination of LQM flare sales (1980 – 1983 and post 1995) and ETSU flare sales (1984 – 1995) less the LQM data on flares sold solely for backup purposes (1991 – 2002).

These data show the total capacity, as opposed to the actual volumes of gas being flared in each year. There are difficulties in ascertaining the actual volumes of LFG burnt, as detailed records, if they exist at all, will be held by individual site operators. It is rare to find a flare stack with a flow measurement device installed, even though the capital cost of such a device is relatively small.

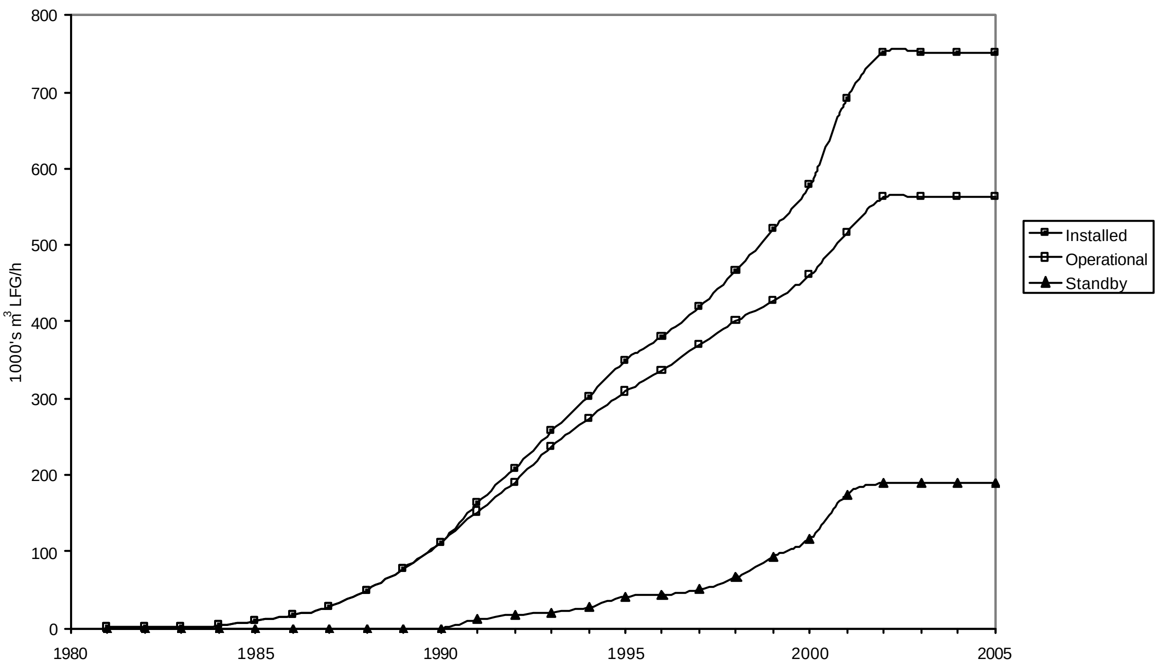

Figure 5.1. Installed flare capacity and the proportions of that capacity which are considered operational and standby

The data relating to total flaring capacity and usage have a potentially large margin of error. The installed capacity (in m^3 LFG/hr) is based on our own survey of manufacturers, coupled with existing data from the previous survey. The latter have been used, particularly for earlier years, as several manufacturers have gone out of business, or are no longer active in the UK market, and our survey is therefore an underestimate of those years. Our survey is also likely to slightly underestimate installed flare capacity due to being unable to elicit information from some companies.

On the other hand, many companies have significant overseas sales, and also sell many flares for sewage gas treatment. These figures have not been included in our totals, but we do not know if previous surveys have inadvertently included any of these (in which case the apparent installed capacity would have been higher than that actually achieved).

The data for flares sold solely for generation back-up purposes is believed to be fairly accurate. The operational capacity is derived by subtracting the back-up capacity from the total. In the model, there is a further correction factor used in arriving at the final volume of gas flared each year, to take account of maintenance downtime (15%) and the probability that some recent flares are direct replacements for earlier sales (7%, see section 5.4.2). Our total for generation back-up capacity remains at a fairly constant percentage of the installed generation capacity (around 60%), indicating that these figures are realistic.

We have no reason to doubt the methodology used to compile the earlier figures, with the caveat that they included some generation back-up sales in the total flaring capacity figures. Various assumptions were also made in the previous survey regarding the total installed capacity, particularly in respect of missing data. These included using an average flare capacity and multiplying by the number of units sold. This was one reason for the large uncertainties in the final estimate of the volume of flared LFG. The ETSU survey's 90% confidence interval for the total volume of landfill gas flared was between 320 and 880 kt CH_4 oxidised, using a total flare capacity of 350,000 m^3/hr. Our current estimate of the total installed net flare capacity, using LQM and ETSU survey figures minus LQM survey back-up capacity, is 308,500 m^3/hr for the same year (1995).

Trends

Installed backup flaring capacity is consistently less than the installed generation capacity, on the basis that landfill sites with multiple gas engines will never suffer complete failure of all utilisation plant at anyone time (Figure 5.2). This suggests that the net flaring capacity is likely to increase more slowly in the future as additional landfills acquire gas utilisation plant rather than additional flare capacity. The 2002 levels have been assumed valid after this date for the data shown in Figure 5.2, since it is not possible to predict future flare sales with any certainty. The increase in landfill gas utilisation is based on the projected take-up of NFFO and non-NFFO contracts.

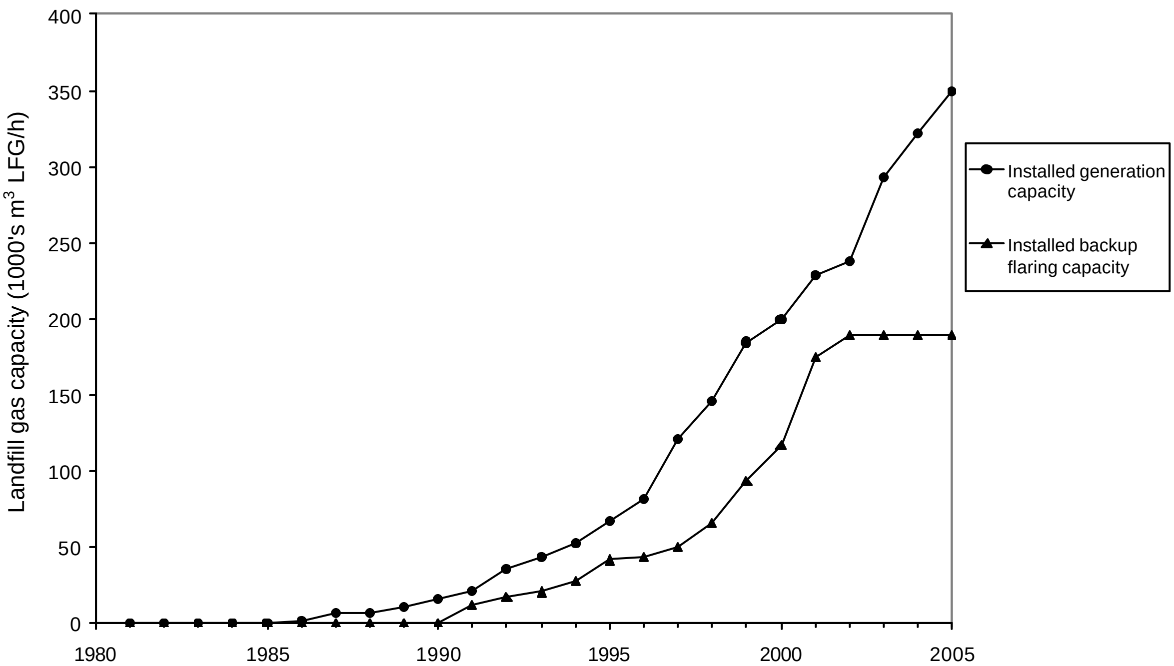

Figure 5.2. The relationship between installed generation capacity and corresponding backup flaring capacity.

The 1996 ETSU (Aitchison et al., 1996) survey made the assumption that most flares sold since 1980 remained in service, with older units being repaired rather than scrapped. We have no direct evidence whether this is still the case, although we suspect some sales are direct replacements for older open flares being taken out of service. It has not been possible to ascertain how much plant, if any, has been de-commissioned or scrapped. The previous survey assumed that no flares had been scrapped or mothballed at that point. From our current survey, it is apparent from anecdotal evidence from operators that a very small number of the total have recently been scrapped, or at least are not currently in use. We have catered for this in the model by assuming that since 1984 (i.e. three years after the first flare was commissioned, 7% of capacity in any given year is treated as replacement. This effectively gives the flare an expected 15 year operational lifetime.

In the early years of flare usage, most equipment sold was small capacity mobile units. The average capacity of each flare unit sold has increased steadily over the last few years, but there is an increasing hire market, which mainly provides for relatively short term use of smaller operational flares.

The installed capacity of standby flares at landfill sites with power generation has stayed within a fairly narrow range of 45-60% backup capacity. This is presumably based on the assumption that at sites with more than one gas engine, not all of them would be out of action at the same time therefore 100% backup capacity will not be required.

Methodology for annual revision of flare and gas engine data

There was unwillingness on the part of many of the landfill operating companies approached for the survey to spend the time necessary to compile full yearly statistics on LFG flares. It was considered by some of them to be a duplication of previous attempts to collect the same data (whether or not these data have been routinely requested remains to be determined).

However, most operating companies that were approached indicated that they would be happy to notify a centralised database (e.g. one run by the Agency, DEFRA or DTI) each time a new flare was commissioned.

On the other hand, manufacturing companies were more concerned about the commercial-in-confidence nature of such information, particularly from their customers' perspective. They did supply very complete data for this survey but, in general, they were happier with the idea that responsibility for reporting the commissioning of new flares should reside with their customers. As new companies are entering the UK market, and existing companies cease trading, the data are likely to be more accurate if the operators were under an obligation to inform a relevant agency of their installed capacity, possibly as part of the PPC licensing process.

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6 EMISSION ESTIMATES AND PROJECTIONS

Methane generation and emissions

This section of the report considers the three base cases of generation and emissions from the time of implementation of the IPCC Tier Two model (Aitchison et al., 1996; Brown et al. 1999; and this study). Figure 6.1 shows the ETSU (Aitchison et al., 1996) and LQM 2002 models have very similar gas generation curves, whereas the AEAT 1999 model is calibrated to converge with the Milton et al. (1997) field data report. The AEAT 1999 model does not represent realistic gas generation quantities from waste (low values for DOC and DOC_F). The Milton et al. (1997) UK surface emissions value is derived by extrapolation of emissions from a sample of landfills to match the entire UK inventory of landfills. This brings with it significant uncertainty, but it provides an estimate for comparison with the modelled approach which is based on gas generation from a known waste mass.

The methane generation forecasts by both the AEAT 1999 and LQM 2002 models show a sharp increase after 1979 (Figure 6.1). This arises because all of the waste to landfill is assumed to be distributed between landfill types 1, 2 and 3 (modern designs) after 1980, and prior to this waste was placed solely within landfill type 4. The latter landfill type is assumed to have a methane content in LFG of 30%, compared to 50% for the more modern designs, because it is a non-containment landfill and more methane is expected to oxidise prior to emission.

On the basis of the ETSU (Aitchison et al., 1996) and LQM models it is likely that the historical generation and emissions of methane are much higher than have been previously been reported (Brown et al., 1999). However, the emissions of methane from UK landfills are forecast to be similar to previous estimates since the early 1990s (Figure 6.1).

Milton et al. (1997) used the WRc Landfill Database as the guide for extrapolation from a few landfills to the UK total. This database was frozen in 1995, and the data collected within it dates from a few years previous to that, and so it is not likely to be an appropriate method for generating an updated assessment of emissions from the waste inventory or the newer landfills built since that database was completed. A number of factors were applied by Milton et al. (1997) to the waste data obtained from the landfill GIS in order to estimate UK totals for the four categories of landfill that were assumed to best represent landfill design at that time. A "limited data" factor (mean value = 1.19 and assumed standard deviation = 0.10) corrected methane emissions for those landfill sites excluded because of incomplete data. A "database factor" corrected for the population (and therefore the waste generated by that population) excluded by the landfill GIS coverage (mean = 1.45 and assumed standard deviation). These probability distributions were combined with distributions derived from observations of specific methane emission rates ($mg/m^3/s$) over 35 landfill sites and the total mass in place to derive best estimates of methane emissions for 1995. Milton et al. (1997) report the 1995 best-estimate methane emission to be 887 kt/year with a 90% confidence interval of between 652 and 1135 kt/year.

The data of Milton et al. (1997) for the year 1995 provides the best-available validation estimate for that period (Figure 6.3, 90% confidence interval for the 1995 estimate also shown), and has been taken to represent the most likely emission scenario for the UK.

The two key parameters in the LQM model to which methane oxidation is most sensitive are:

- The amount of fissures in the landfill cap; and
- The field efficiency of the methane oxidation capacity data.

If the fissuring in the cap is high, the proportion of methane oxidised is low, and vice versa. The model defaults at 10% of the methane lost through fissures, and this is remarkably close to the estimate of Milton et al. (1997) (Figure 6.2). The fissure fracture term may vary between 1% (a low estimate) and 30% (a high estimate) without significantly deviating from the estimate Milton et al. (1997).

Similarly, the model has a scaling factor to determine how much of the methane oxidising capacity (determined by laboratory and field measurements) is actually utilised in the field. The default value for the oxidation efficiency is 75%, and this too results in a forecast very close to the Milton et al. (1997) data. This default value (75%) was derived from a combination of the field data (field measurements include field efficiency and are therefore given a model efficiency value of 100%) and laboratory data (which would possibly overestimate oxidising capacity and has therefore been attributed a 25% field efficiency). Figure 6.3 shows that the sensitivity of this term is such that it may be varied between 50% and 100% overall and not significantly deviate from the estimate of Milton et al. (1997).

Flaring and Energy Recovery

Figure 6.4 shows the growth in installed landfill gas flaring and utilisation capacity compared with the amount of landfill gas generated. This information shows that approximately 63% of the landfill gas generated is currently flared and/or utilised, and this is forecast to rise to 72% by 2005. In kilotons of methane emissions abated per year, this is 1750 kt in 2000, rising to a forecast level of 2465 kt in 2005 (and remaining constant in this model to 2025 since flare sales and the growth of utilisation are difficult trends to predict).

Even accounting for uncertainties in the forecasts, utilisation and flaring is the largest sink for methane emissions and far outweighs the effects of the most stringent landfill diversion or recycling scenarios from the Waste Strategies considered in the assessment. This is because of the quantities of methane generating wastes already landfilled. The role of flaring and utilisation technologies in managing methane emissions, recognised in the Landfill Directive as a key emissions management tool, should not therefore be underestimated.

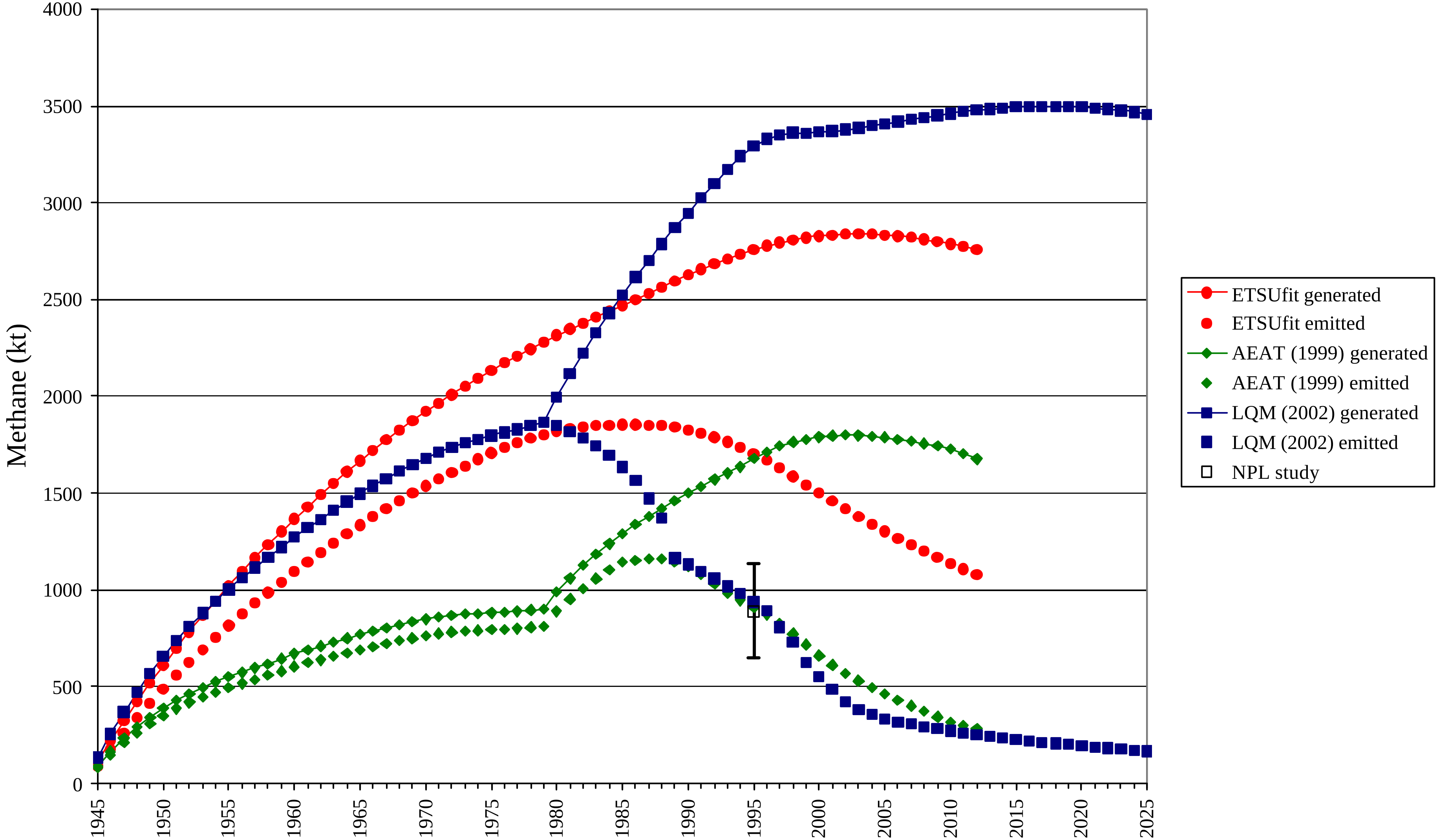


Figure 6.1. Base Case Landfill Gas Generation and Emission Forecasts for (1) the ETSU 1996 study (Aitchison et al., 1996); (2) the AEAT 1999 Study (Brown et al., 1999) with accompanying NPL emissions calibration data (Milton et al., 1997); and (3) the LQM 2002 model (this study)

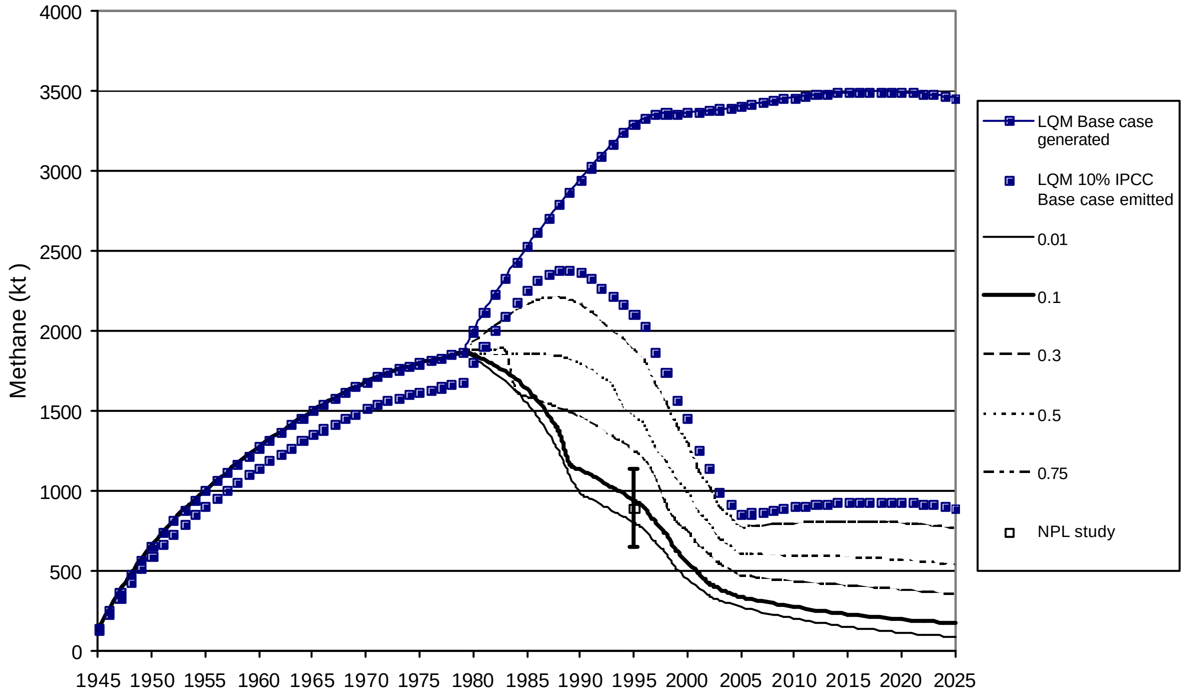


Figure 6.2. Effect of the fissure fracture term in the LQM Methane Oxidation Model upon the Base case methane emissions and comparison with a Base case for an IPCC 10% methane oxidation default

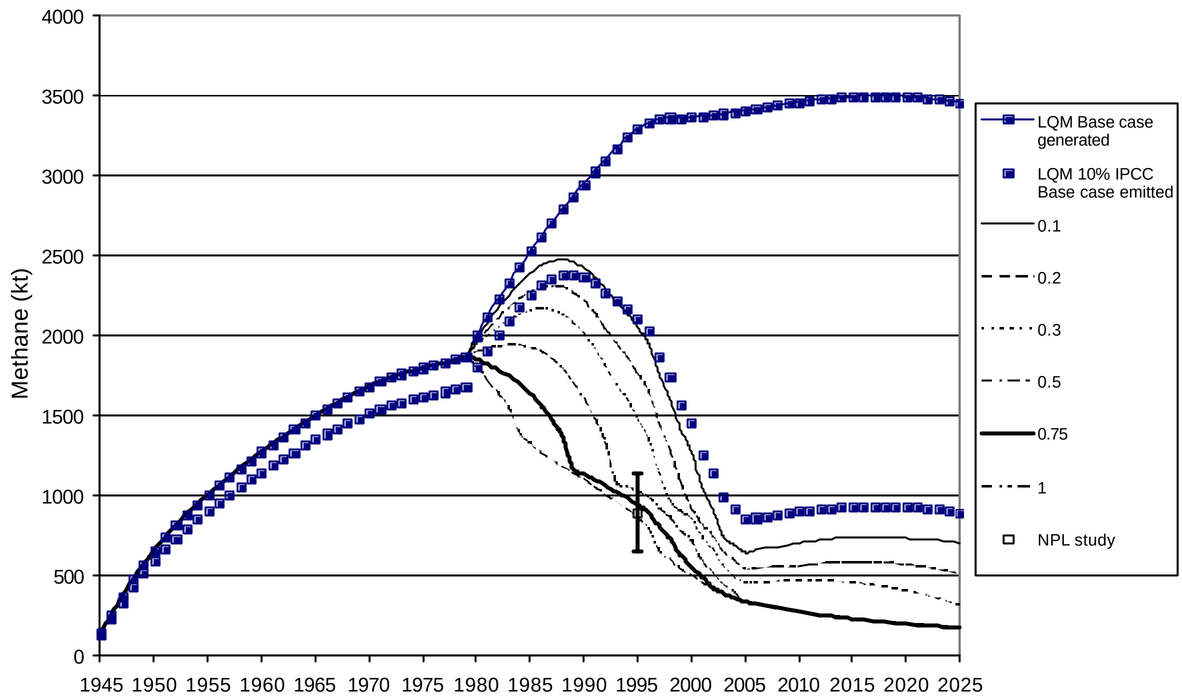


Figure 6.3. Effect of the field efficiency term in the LQM Methane Oxidation Model upon the Base case methane emissions and comparison with a Base case for an IPCC 10% methane oxidation default

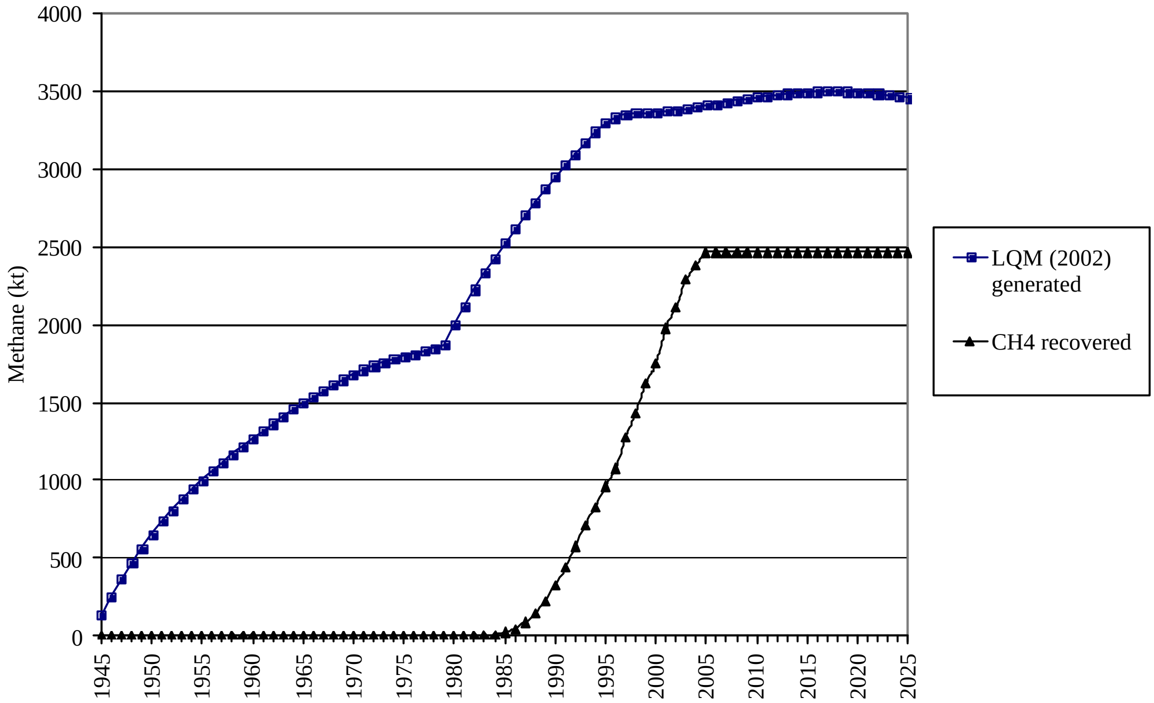


Figure 6.4. The growth in installed landfill gas flaring and utilisation capacity compared with the amount of forecasted landfill gas generated by the LQM model (Base case scenario)

Waste Management Scenarios

Figures 6.5 – 6.8 show the effects of the eight MSW scenarios and five C&I scenarios modelled (scenarios described in Section 4.5). The emission forecasts considered were based on eight MSW and five C&I scenarios: MSW scenarios included achieving the Waste Strategy 2000 and Landfill Directive targets with current and projected growth rates plus current material recycling rates; emphasis on paper/compost recycling; emphasis on paper recycling only; emphasis on recovery (EfW/CHP/AD); or emphasis on glass metals and plastics recycling.

In addition, MSW scenarios considered higher growth rates with current material recycling rates and excess recovery; or excess material recycling rates. Current trends in diversion rates were considered as the base case (Business as Usual or BAU). C&I Scenarios included the current position as the base case (BAU); 15% diversion based on food wastes, paper & card and other general biodegradables to digestion, EfW and recycling; 15% diversion based on general biodegradable wastes to combustion; 15% diversion based on general biodegradable wastes to recycling; or 15% diversion through C&D and mineral wastes recycling.

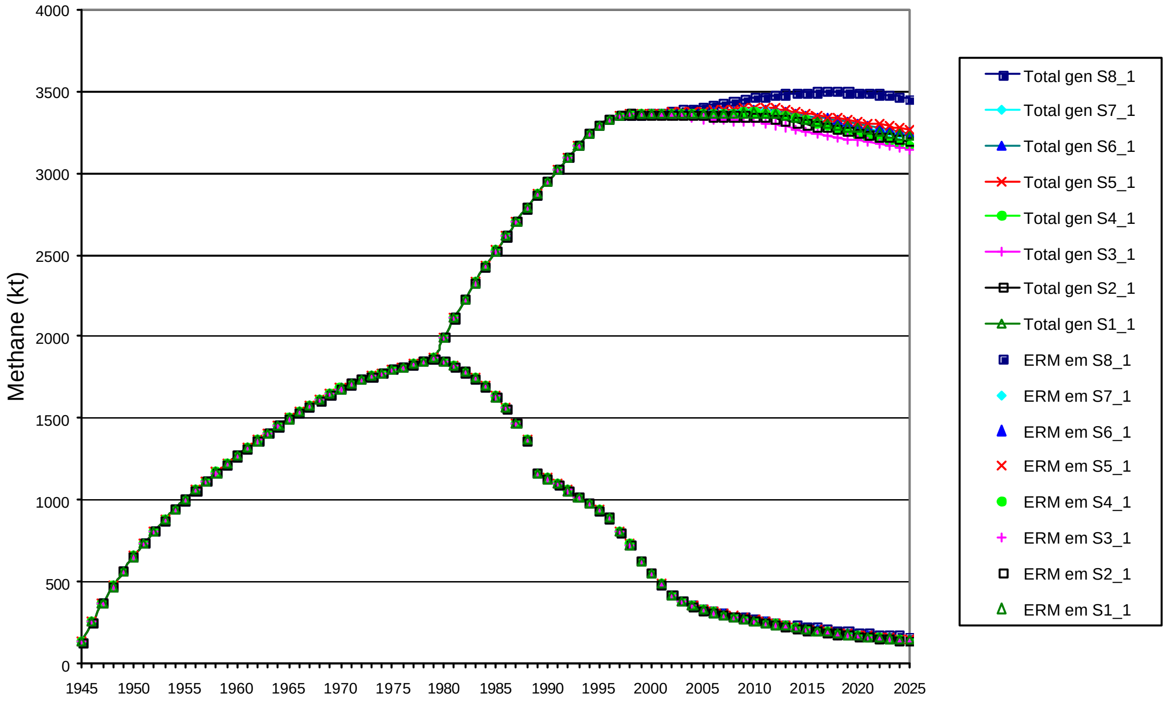


Figure 6.5. The effect on Methane Generation and Emissions of ERM's MSW Scenarios 1 – 8 (with C&I Scenario 1 fixed) period 1945 – 2025 (scenarios described in Section 4.5)

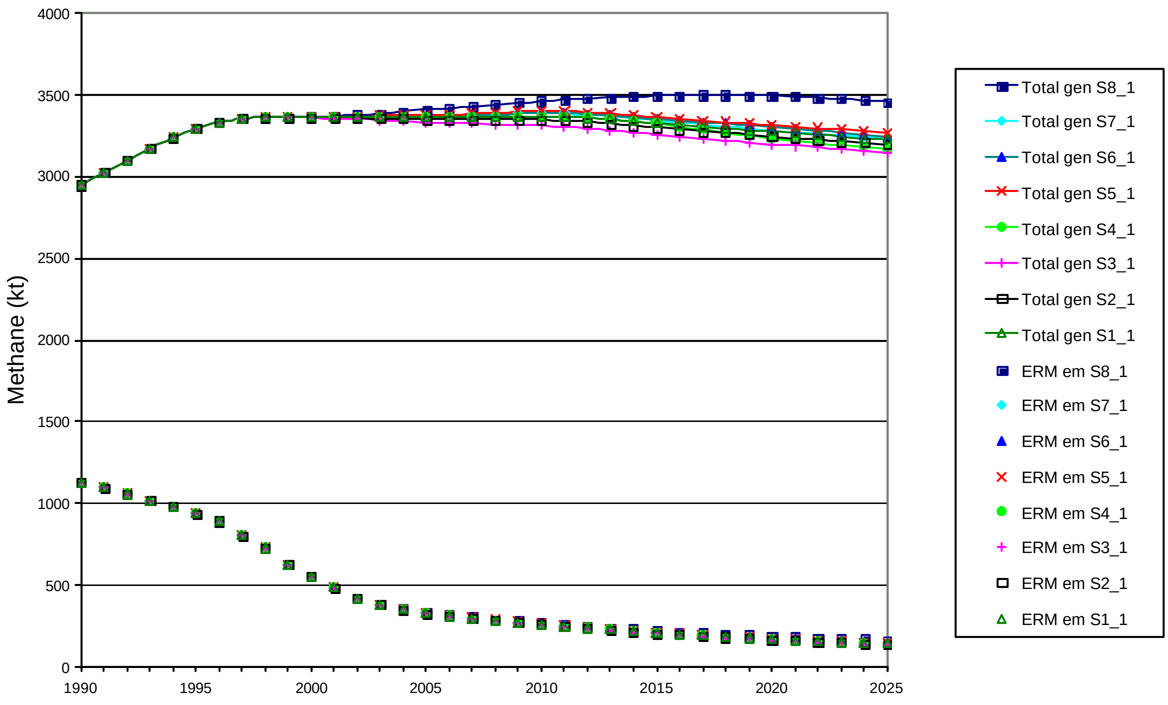
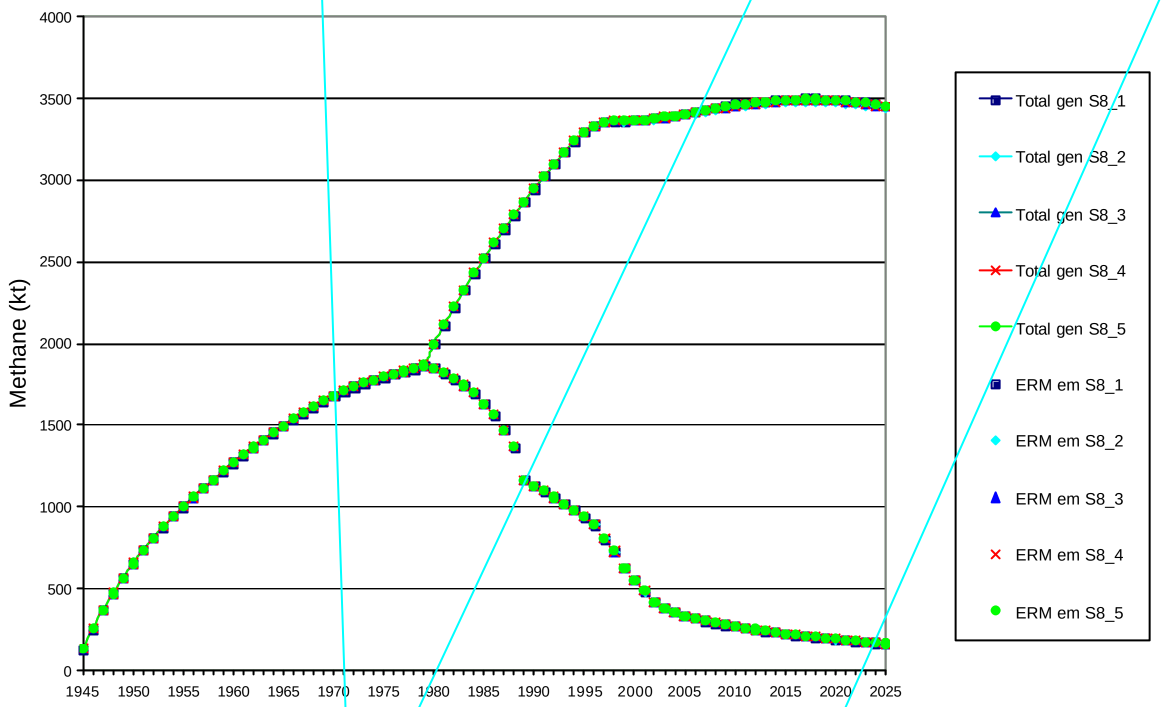
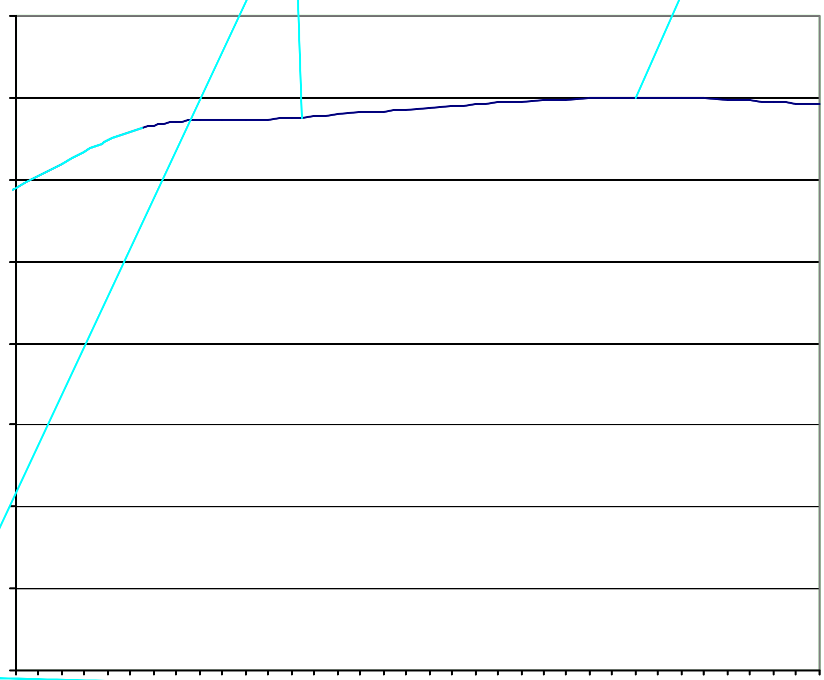


Figure 6.6. The effect on Methane Generation and Emissions of ERM's MSW Scenarios 1 – 8 (with C&I Scenario 1 fixed) period 1990 – 2025 (scenarios described in Section 4.5)


4000
3500
3000
2500
2000
1500
1000
500
0
Methane (kt)
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
2025
Total gen S8_1
Total gen S8_2
Total gen S8_3
Total gen S8_4
Total gen S8_5
ERM em S8_1
ERM em S8_2
ERM em S8_3
ERM em S8_4
ERM em S8_5



Summary

All the MSW strategies considered achieved some benefit in methane emissions reduction compared with the base cases (Business as Usual), but the effects were not as significant as the impact on emissions reduction due to flaring or gas utilisation. The impact of any of the C&I scenarios compared to the base case were negligible in terms of methane emissions abatement.

The base case (MSW scenario 8, C&I scenario 1) methane generation is at least 31kt greater than any other scenario in 2005, rising to 190 kt by 2025 (Figure 6.4). The most significant MSW scenario is scenario 3 (paper recycling) which in 2005 indicates a reduction of 2% of residual methane emissions (8 kt methane abated), growing to a reduction of 19% of residual methane emissions by 2025 (31 kt methane abated). The worst MSW scenario, scenario 5 (glass, metal and plastics recycling) gives a forecast residual methane emissions reduction of only 11% by 2025 (19 kt methane abated). These figures are, however, small when compared with the amount of methane abated by flaring or utilisation, which is 1750 kt in 2000, rising to a forecast level of 2465 kt in 2005 (and remaining constant in this model to 2025). Therefore, the role of flaring and utilisation technologies in managing methane emissions, recognised in the Landfill Directive as a key emissions management tool, should not be underestimated.

An estimate of the overall uncertainty in the emission projections for the model was determined using the estimated uncertainty ranges outlined within Chapter 3. A sensitivity analysis was carried out using the individual uncertainties to determine the individual effects of the various parameters upon emission projections and then combined to give the upper and lower limits for methane emission projections.

It was found that methane emissions were increased by:

1. assuming a default methane correction factor (MCF) of 1.0 (Section 3.2.2);
2. using the Brown et al. (1999) default degradation rate constants (Table 3.1);
3. increasing the fraction of methane to LFG by 10% (Section 3.2.3); and
4. increasing the degradable carbon by 15% (Section 3.2.4).

It was found that methane emissions were decreased by:

1. decreasing the MCF by 10% (Section 3.2.2);
2. decreasing the fraction of methane to LFG by 10% (Section 3.2.3); and
3. decreasing the degradable carbon by 15% (Section 3.2.4).

Using the above findings the range of methane emissions for 2000 are estimated at between 287 and 1078 kt methane (best estimate of 552 kt methane) and for 2025 at between 59 and 227 kt methane (best estimate of 166 kt methane). These ranges effectively represent the 100% (i.e. minimum and maximum) confidence limits of the model. In practice, a fully probabilistic model is required, which can incorporate all of the model parameter uncertainties in a less systematic way, in order to properly determine the 95% confidence interval.

Disaggregated emissions data

In order to disaggregate the emission forecasts for the Devolved Administrations (DA), for the period 1980 – 2025, it has been necessary to make a number of assumptions as outlined below for both the MSW and C&I. The relative proportion of waste arisings within each of the DAs is assumed to be proportional to the likely methane emissions at the DA level.

Municipal Solid Waste

Brown et al. (1999) provided data for MSW arisings for England and Wales (1995/96), Scotland (1994) and Northern Ireland (1992). The relative proportion of arisings to each DA have been assumed valid for the entire period 1980-1994 and used as input to the LQM model for the MSW estimates for that period. The ERM MSW split is based on data obtained from the England and Wales National Waste Production Survey (1998/99); for Scotland the Waste Data Digest (2001); and for NI the Waste Management Strategy Northern Ireland (DoE(NI), 2001, data referenced as 1998/99). Where data were not available, reasonable forecasts (or back calculations) have been applied to the period 1995 – 2025. The relative proportion of arisings to each DA is assumed to not vary between the different MSW Scenarios. Within the ERM MSW a distinction between arisings from England and Wales is not available.

Based on these assumptions, the actual variation in the relative MSW waste arisings between the different DAs is not very great over the period 1980 – 2025: 86-88% for England and Wales, 8-11% for Scotland and approximately 3% for Northern Ireland.

Commercial & Industrial

Brown et al. (1999) did not provide any split of the relative arisings of C&I wastes between England and Wales, Scotland or Northern Ireland. Therefore, the data provided by ERM are assumed to be valid over the entire period 1980-2025. The ERM C&I split is based on data obtained direct for England and Wales from the National Waste Production Survey (1998/99)[1]; for Scotland the Waste Data Digest (2001) (SEPA, 2001); and for NI the Waste Management Strategy Northern Ireland (DoE (NI) 2001, data referenced as 1998/99). Where data were not available, reasonable forecasts (or back calculations) have been applied to the period 1995 – 2025. The relative proportion of arisings to each DA is assumed to not vary between the different C&I Scenarios. Within the ERM C&I a distinction between arisings from England and Wales is provided, though it has been bulked to retain compatibility with the MSW data also supplied by ERM.

Based on these assumptions, the relative C&I waste arisings between the different DAs over the period 1980 – 2025 is assumed to be 94% for England and Wales, 5% for Scotland and 1% for Northern Ireland.

[1] Statistics available from: http://www.environment-agency.gov.uk/subjects/waste

England and Wales, Scotland and Northern Ireland

The disaggregated emission forecasts for the DAs are presented in Table 6.1 for the period 1980 – 2025, for the Base Case C&I Scenario (Scenario 1) and the 8 different MSW Scenarios (MSW 1 – 8). Prior to 1995 there are no differences across the different scenarios because the waste input data provided by Brown et al. (1999) drive the emission forecasts until this time. It is not until 2000 that any differences across the various Scenarios is noticeable, with the emphasis on paper recycling scenario (MSW 3) forecasted as the lowest emitter of methane. The emissions of methane are dominated by those arising from England and Wales which accounts for about 92% of total UK emissions in 2000 and 93% in 2025.

Generally, the variation at the present time between the various Scenarios is very small (2-3 kt difference), but does increase with time, as the waste already in place makes a smaller contribution to the overall methane emissions and the ERM waste Scenarios make a more significant contribution.

The ranking and value of the total UK methane emissions across all 40 of the ERM waste Scenarios is presented for the year 2025 in Table 6.2, with the highest ranking (value 1) attributed to the highest methane emission. It is clear that the difference between the highest and lowest ranked emitter is relatively small (14 kt), if the MSW Base case is excluded (i.e. MSW 8). The lowest emitters are those MSW Scenarios with emphasis on paper recycling (MSW 3), energy recovery (MSW 4) and paper/compost recycling (MSW 2), with forecast methane emissions of 140 kt or less for the year 2025.

Channel Islands and Gibraltar

No data on waste arisings are available and emission forecasts will have to be made based upon population data.

Table 6.1. Methane emission forecasts (kt) for the Devolved Administrations for ERM's MSW Scenarios 1 – 8 (with C&I Scenario 1 fixed) period 1980 - 2013

Year	E&W	S	NI	UK	E&W	S	NI	UK	E&W	S	NI	UK	E&W	S	NI	UK
MSW		8				7				6				5		
C&I		1				1				1				1		
1980	1728	99	22	1849	1728	99	22	1849	1728	99	22	1849	1728	99	22	1849
1985	1525	89	20	1634	1525	89	20	1634	1525	89	20	1634	1525	89	20	1634
1990	1054	63	14	1131	1054	63	14	1131	1054	63	14	1131	1054	63	14	1131
1995	871	55	13	939	871	55	13	939	871	55	13	939	871	55	13	939
2000	509	35	9	553	509	34	8	551	509	34	8	551	510	34	8	552
2001	449	31	8	488	449	30	7	486	449	30	7	486	451	30	7	488
2002	387	26	7	420	387	26	6	419	387	26	6	419	387	26	6	419
2003	354	24	6	384	353	23	6	382	353	23	6	382	354	23	6	383
2004	330	22	6	358	328	21	5	354	328	21	5	354	329	21	5	355
2005	307	21	5	333	304	20	5	329	304	20	5	329	306	20	5	331
2006	294	20	5	319	290	19	5	314	290	19	5	314	291	19	4	314
2007	281	19	5	305	277	18	4	299	277	18	4	299	279	18	4	301
2008	270	18	5	293	265	17	4	286	265	17	4	286	267	17	4	288
2009	259	17	4	280	254	17	4	275	254	17	4	275	256	16	4	276
2010	250	17	4	271	244	16	4	264	244	16	4	264	245	15	4	264
2011	241	16	4	261	234	15	3	252	234	15	3	252	236	15	3	254
2012	232	15	4	251	225	14	3	242	225	14	3	242	226	14	3	243
2013	224	15	4	243	215	13	3	231	216	13	3	232	217	13	3	233

Notes: E&W, England and Wales; S, Scotland; NI, Northern Ireland; UK, total for E&W, S & NI (Channel Islands and Gibraltar not included).

Table 6.1. Methane emission forecasts (kt) for the Devolved Administrations for ERM's MSW Scenarios 1 – 8 (with C&I Scenario 1 fixed) period 1980 – 2013 (continued)

Year	**E&W**	**S**	**NI**	**UK**	**E&W**	**S**	**NI**	**UK**	**E&W**	**S**	**NI**	**UK**	**E&W**	**S**	**NI**	**UK**
MSW	4				3				2				1			
C&I	1				1				1				1			
1980	1728	99	22	1849	1728	99	22	1849	1728	99	22	1849	1728	99	22	1849
1985	1525	89	20	1634	1525	89	20	1634	1525	89	20	1634	1525	89	20	1634
1990	1054	63	14	1131	1054	63	14	1131	1054	63	14	1131	1054	63	14	1131
1995	871	55	13	939	871	55	13	939	871	55	13	939	871	55	13	939
2000	509	34	8	551	507	34	8	549	508	34	8	550	509	34	8	551
2001	449	30	7	486	445	30	7	482	447	30	7	484	449	30	7	486
2002	387	25	6	418	385	25	6	416	386	25	6	417	387	25	6	418
2003	353	23	6	382	351	23	6	380	352	23	6	381	353	23	6	382
2004	328	21	5	354	326	21	5	352	327	21	5	353	328	21	5	354
2005	304	20	5	329	301	19	5	325	303	19	5	327	304	20	5	329
2006	290	19	4	313	287	18	4	309	289	19	4	312	290	19	4	313
2007	277	18	4	299	273	18	4	295	275	18	4	297	277	18	4	299
2008	264	17	4	285	260	17	4	281	263	17	4	284	264	17	4	285
2009	253	16	4	273	248	16	4	268	251	16	4	271	253	16	4	273
2010	243	15	4	262	237	15	4	256	241	15	4	260	243	15	4	262
2011	233	14	3	250	227	14	3	244	231	14	3	248	233	14	3	250
2012	223	14	3	240	217	13	3	233	221	13	3	237	223	14	3	240
2013	214	13	3	230	208	12	3	223	211	13	3	227	214	13	3	230

Notes: E&W, England and Wales; S, Scotland; NI, Northern Ireland; UK, total for E&W, S & NI (Channel Islands and Gibraltar not included).

Table 6.1. Methane emission forecasts (kt) for the Devolved Administrations for ERM's MSW Scenarios 1 – 8 (with C&I Scenario 1 fixed) period 2014 – 2025 (continued)

Year	E&W	S	NI	UK	E&W	S	NI	UK	E&W	S	NI	UK	E&W	S	NI	UK
MSW	8				7				6				5			
C&I	1				1				1				1			
2014	217	14	3	234	206	12	3	221	207	12	3	222	208	12	3	223
2015	210	14	3	227	198	11	2	211	198	12	3	213	200	12	3	215
2016	203	13	3	219	190	11	2	203	190	11	2	203	192	11	2	205
2017	197	13	3	213	182	10	2	194	183	11	2	196	184	11	2	197
2018	191	12	3	206	175	10	2	187	176	10	2	188	177	10	2	189
2019	185	12	3	200	168	10	2	180	169	10	2	181	171	10	2	183
2020	180	11	3	194	161	9	2	172	163	9	2	174	164	9	2	175
2021	174	11	3	188	155	9	2	166	157	9	2	168	159	9	2	170
2022	169	10	2	181	150	8	2	160	151	9	2	162	153	9	2	164
2023	164	10	2	176	144	8	2	154	146	8	2	156	148	8	2	158
2024	160	10	2	172	139	8	2	141	141	8	2	151	143	8	2	153
2025	155	9	2	166	135	7	2	144	136	8	2	146	138	8	2	148

Notes: E&W, England and Wales; S, Scotland; NI, Northern Ireland; UK, total for E&W, S & NI (Channel Islands and Gibraltar not included).

Table 6.1. Methane emission forecasts (kt) for the Devolved Administrations for ERM's MSW Scenarios 1 – 8 (with C&I Scenario 1 fixed) period 2014 – 2025 (continued)

Year	E&W	S	NI	UK	E&W	S	NI	UK	E&W	S	NI	UK	E&W	S	NI	UK
MSW	4				3				2				1			
C&I	1				1				1				1			
2014	205	12	3	220	199	12	3	214	203	12	3	218	205	12	3	220
2015	196	11	2	209	190	11	2	203	194	11	2	207	196	11	3	210
2016	188	10	2	200	182	10	2	194	186	11	2	199	188	11	2	201
2017	180	10	2	192	174	10	2	186	178	10	2	190	181	10	2	193
2018	172	9	2	183	167	10	2	179	171	10	2	183	173	10	2	185
2019	164	9	2	175	160	9	2	171	164	9	2	175	167	9	2	178
2020	157	8	2	167	153	9	2	164	158	9	2	169	161	9	2	172
2021	151	8	2	161	147	8	2	157	152	9	2	163	155	9	2	166
2022	145	8	2	155	142	8	2	152	146	8	2	156	149	8	2	159
2023	139	7	2	148	136	8	2	146	141	8	2	151	144	8	2	154
2024	134	7	1	142	131	7	2	140	136	8	2	146	139	8	2	149
2025	129	7	1	137	127	7	1	135	131	7	2	140	134	7	2	143

Notes: E&W, England and Wales; S, Scotland; NI, Northern Ireland; UK, total for E&W, S & NI (Channel Islands and Gibraltar not included).

Table 6.2. Ranking of total UK methane emissions for each of the ERM MSW – C&I waste Scenarios (2025)

MSW	C&I	kt CH_4	Rank	MSW	C&I	kt CH_4	Rank
8	1	166.4	1	7	4	142.3	20
8	5	165.8	2	1	3	141.8	22
8	3	165.1	3	1	4	141.8	22
8	4	165.1	3	7	2	141.4	24
8	2	164.2	5	1	2	140.9	25
5	1	147.4	6	2	1	140.1	26
5	5	146.8	7	2	5	139.5	27
5	3	146.1	8	2	3	138.9	28
5	4	146.1	8	2	4	138.9	28
5	2	145.2	10	2	2	137.9	30
6	1	145.1	11	4	1	137.3	31
6	5	144.5	12	4	5	136.7	32
6	3	143.9	13	4	3	136.1	33
6	4	143.9	13	4	4	136.1	33
7	1	143.6	15	3	1	135.2	35
1	1	143.1	16	4	2	135.1	36
7	5	143.0	17	3	5	134.6	37
6	2	142.9	18	3	3	133.9	38
1	5	142.5	19	3	4	133.9	38
7	3	142.3	20	3	2	133.0	40

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Appendix 1

Table A1.1. MSW waste to landfill 1945-1994 (Mt) used as input to the LQM 2002 model (Brown et al., 1999 default input)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1945	0.50	0.00	0.00	0.14	0.00	0.65	0.22	0.00	0.29	0.29	0.00	1.12	4.48	7.68
1946	0.50	0.00	0.00	0.14	0.00	0.65	0.22	0.00	0.29	0.29	0.00	1.12	4.48	7.69
1947	0.50	0.00	0.00	0.14	0.00	0.64	0.21	0.00	0.29	0.29	0.00	1.11	4.45	7.64
1948	0.50	0.00	0.00	0.14	0.00	0.64	0.21	0.00	0.28	0.28	0.00	1.11	4.43	7.59
1949	0.63	0.00	0.00	0.14	0.00	0.57	0.31	0.00	0.32	0.38	0.00	1.13	4.51	7.98
1950	0.77	0.00	0.00	0.14	0.00	0.49	0.42	0.00	0.35	0.49	0.00	1.14	4.58	8.38
1951	0.69	0.00	0.00	0.11	0.00	0.96	0.57	0.00	0.43	0.47	0.00	1.11	4.44	8.77
1952	0.59	0.00	0.00	0.07	0.00	1.48	0.74	0.00	0.52	0.44	0.00	1.07	4.26	9.17
1953	0.71	0.00	0.00	0.08	0.00	1.12	0.67	0.00	0.53	0.45	0.00	1.05	4.21	8.82
1954	0.83	0.00	0.00	0.08	0.00	0.78	0.60	0.00	0.54	0.46	0.00	1.04	4.15	8.46
1955	0.93	0.00	0.00	0.08	0.00	0.46	0.54	0.00	0.54	0.46	0.00	1.02	4.08	8.11
1956	1.31	0.00	0.00	0.12	0.00	0.66	0.53	0.00	0.61	0.50	0.00	1.02	4.07	8.80
1957	1.73	0.00	0.00	0.16	0.00	0.88	0.52	0.00	0.69	0.53	0.00	1.00	4.00	9.50
1958	2.21	0.00	0.00	0.21	0.00	1.12	0.49	0.00	0.77	0.56	0.00	0.97	3.87	10.20
1959	2.23	0.00	0.00	0.20	0.00	0.82	1.57	0.00	0.76	0.56	0.00	0.95	3.81	10.90
1960	2.23	0.00	0.00	0.19	0.00	0.46	2.78	0.00	0.74	0.56	0.00	0.93	3.71	11.60
1961	2.49	0.00	0.00	0.17	0.00	0.43	1.87	0.00	0.69	0.61	0.00	0.89	3.09	10.25
1962	2.62	0.00	0.00	0.16	0.00	0.40	1.11	0.00	0.64	0.64	0.00	0.82	2.52	8.90
1963	3.24	0.00	0.00	0.23	0.00	0.61	1.75	0.00	0.76	0.38	0.00	1.41	3.84	12.22
1964	3.04	0.00	0.00	0.24	0.00	1.04	1.76	0.00	0.72	0.56	0.00	1.14	2.78	11.28
1965	3.25	0.03	0.03	0.25	0.00	0.86	1.88	0.00	0.79	0.74	0.00	1.16	2.54	11.52
1966	3.47	0.06	0.06	0.26	0.00	0.66	2.00	0.00	0.85	0.92	0.00	1.17	2.30	11.76
1967	3.69	0.09	0.09	0.28	0.00	0.46	2.12	0.00	0.92	1.11	0.00	1.16	2.07	12.00
1968	4.60	0.09	0.09	0.28	0.00	0.28	2.16	0.00	1.13	1.13	0.00	1.04	1.68	12.49
1969	5.26	0.10	0.10	0.29	0.00	0.29	2.24	0.00	0.97	0.97	0.00	0.79	1.16	12.18
1970	5.71	0.09	0.09	0.37	0.00	0.28	2.34	0.00	0.94	0.94	0.00	0.76	1.02	12.54
1971	5.04	0.09	0.09	0.36	0.00	0.46	2.18	0.00	1.00	0.91	0.00	0.87	1.05	12.06
1972	4.42	0.09	0.09	0.35	0.00	0.62	2.03	0.00	1.06	0.88	0.00	0.97	1.07	11.58
1973	3.69	0.10	0.10	0.41	0.00	0.72	2.15	0.00	1.23	1.03	0.00	1.12	1.13	11.69
1974	3.45	0.14	0.14	0.45	0.00	0.82	1.82	0.00	0.91	1.27	0.00	0.94	0.87	10.81
1975	3.89	0.26	0.26	0.51	0.00	0.82	1.94	0.00	1.02	0.92	0.00	1.17	0.98	11.76
1976	2.74	0.26	0.26	0.32	0.00	1.05	2.53	0.00	1.05	0.84	0.00	1.01	0.78	10.86
1977	3.09	0.27	0.27	0.53	0.00	0.64	2.67	0.00	1.28	0.96	0.00	0.82	0.57	11.09
1978	3.38	0.34	0.34	0.45	0.00	0.79	3.60	0.00	1.13	0.90	0.00	0.83	0.52	12.26
1979	4.04	0.45	0.45	0.45	0.00	0.56	2.81	0.00	1.23	1.01	0.00	1.07	0.62	12.68
1980	4.68	0.47	0.47	0.35	0.00	0.47	2.81	0.00	1.17	1.17	0.00	1.08	0.56	13.21
1981	4.18	0.41	0.41	0.35	0.00	0.70	3.14	0.00	1.39	0.81	0.00	0.40	0.19	11.97
1982	3.63	0.45	0.45	0.45	0.00	0.45	3.29	0.00	1.25	1.02	0.00	1.20	0.51	12.70
1983	3.89	0.51	0.50	0.46	0.09	0.46	3.41	0.00	1.31	1.05	0.02	1.25	0.47	13.42
1984	4.15	0.56	0.55	0.47	0.19	0.46	3.53	0.00	1.38	1.08	0.04	1.30	0.44	14.13
1985	4.41	0.62	0.59	0.48	0.30	0.46	3.63	0.00	1.44	1.11	0.06	1.34	0.40	14.83
1986	4.68	0.67	0.64	0.48	0.42	0.46	3.73	0.00	1.50	1.13	0.08	1.38	0.36	15.53
1987	4.94	0.74	0.70	0.48	0.55	0.46	3.81	0.00	1.56	1.14	0.11	1.41	0.32	16.21
1988	5.21	0.80	0.75	0.48	0.68	0.45	3.89	0.00	1.61	1.16	0.14	1.43	0.27	16.88
1989	5.49	0.86	0.80	0.48	0.83	0.45	3.96	0.00	1.67	1.17	0.16	1.44	0.23	17.54
1990	5.76	0.93	0.86	0.47	0.98	0.43	4.02	0.00	1.72	1.18	0.19	1.45	0.19	18.19
1991	6.04	1.00	0.92	0.46	1.14	0.42	4.07	0.00	1.78	1.18	0.23	1.45	0.15	18.84
1992	6.31	1.07	0.98	0.46	1.31	0.41	4.12	0.00	1.83	1.19	0.26	1.43	0.11	19.47
1993	6.59	1.15	1.04	0.45	1.49	0.39	4.15	0.00	1.88	1.18	0.29	1.41	0.07	20.09
1994	6.87	1.22	1.10	0.43	1.68	0.37	4.18	0.00	1.93	1.18	0.33	1.38	0.03	20.71

Table A1.2. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 1)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	8.27	3.35	0.00	0.57	2.46	2.20	0.00	5.29	2.08	1.37	0.56	0.00	0.00	26.14
2001	7.83	3.33	0.00	0.55	2.44	2.04	0.00	4.97	1.90	1.24	0.54	0.00	0.00	24.84
2002	7.36	3.30	0.00	0.53	2.42	1.87	0.00	4.63	1.71	1.10	0.52	0.00	0.00	23.44
2003	6.86	3.24	0.00	0.51	2.38	1.70	0.00	4.27	1.51	0.96	0.50	0.00	0.00	21.94
2004	6.33	3.17	0.00	0.49	2.34	1.53	0.00	3.89	1.31	0.83	0.47	0.00	0.00	20.35
2005	6.36	3.24	0.00	0.50	2.39	1.52	0.00	3.89	1.29	0.81	0.48	0.00	0.00	20.48
2006	6.32	3.28	0.00	0.50	2.42	1.49	0.00	3.85	1.25	0.78	0.48	0.00	0.00	20.39
2007	6.28	3.33	0.00	0.50	2.46	1.47	0.00	3.81	1.21	0.75	0.48	0.00	0.00	20.29
2008	6.23	3.37	0.00	0.51	2.49	1.44	0.00	3.77	1.17	0.72	0.49	0.00	0.00	20.18
2009	6.10	3.36	0.00	0.50	2.49	1.39	0.00	3.67	1.12	0.68	0.48	0.00	0.00	19.79
2010	5.59	3.12	0.00	0.46	2.31	1.26	0.00	3.35	1.01	0.61	0.44	0.00	0.00	18.16
2011	5.01	2.83	0.00	0.42	2.09	1.12	0.00	2.99	0.88	0.54	0.40	0.00	0.00	16.28
2012	4.41	2.53	0.00	0.37	1.87	0.98	0.00	2.63	0.76	0.46	0.36	0.00	0.00	14.37
2013	3.81	2.21	0.00	0.32	1.63	0.84	0.00	2.26	0.65	0.39	0.31	0.00	0.00	12.41
2014	3.21	1.88	0.00	0.28	1.40	0.70	0.00	1.90	0.53	0.32	0.26	0.00	0.00	10.47
2015	3.11	1.85	0.00	0.27	1.37	0.67	0.00	1.84	0.51	0.30	0.26	0.00	0.00	10.18
2016	3.02	1.82	0.00	0.26	1.35	0.65	0.00	1.78	0.48	0.28	0.25	0.00	0.00	9.89
2017	2.93	1.79	0.00	0.26	1.33	0.62	0.00	1.71	0.45	0.26	0.24	0.00	0.00	9.60
2018	2.83	1.76	0.00	0.25	1.30	0.60	0.00	1.65	0.43	0.25	0.24	0.00	0.00	9.31
2019	2.74	1.72	0.00	0.25	1.28	0.57	0.00	1.59	0.40	0.23	0.23	0.00	0.00	9.01
2020	2.64	1.69	0.00	0.24	1.25	0.54	0.00	1.53	0.38	0.21	0.23	0.00	0.00	8.70
2021	2.53	1.64	0.00	0.23	1.22	0.52	0.00	1.46	0.35	0.20	0.22	0.00	0.00	8.36
2022	2.42	1.59	0.00	0.22	1.18	0.49	0.00	1.39	0.32	0.18	0.21	0.00	0.00	8.01
2023	2.31	1.54	0.00	0.22	1.15	0.46	0.00	1.32	0.30	0.16	0.20	0.00	0.00	7.66
2024	2.21	1.49	0.00	0.21	1.11	0.43	0.00	1.25	0.27	0.15	0.20	0.00	0.00	7.32
2025	2.10	1.44	0.00	0.20	1.07	0.41	0.00	1.19	0.25	0.13	0.19	0.00	0.00	6.97

Table A1.3. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 2)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	8.00	3.38	0.00	0.59	2.46	2.40	0.00	5.03	2.22	1.48	0.59	0.00	0.00	26.14
2001	7.49	3.36	0.00	0.58	2.44	2.29	0.00	4.65	2.06	1.38	0.58	0.00	0.00	24.84
2002	6.96	3.33	0.00	0.57	2.42	2.18	0.00	4.24	1.91	1.27	0.57	0.00	0.00	23.44
2003	6.39	3.28	0.00	0.56	2.38	2.05	0.00	3.82	1.74	1.16	0.56	0.00	0.00	21.94
2004	5.81	3.21	0.00	0.54	2.34	1.92	0.00	3.39	1.57	1.04	0.54	0.00	0.00	20.35
2005	5.80	3.29	0.00	0.55	2.39	1.94	0.00	3.36	1.56	1.04	0.55	0.00	0.00	20.48
2006	5.73	3.33	0.00	0.56	2.42	1.93	0.00	3.29	1.54	1.03	0.56	0.00	0.00	20.39
2007	5.66	3.38	0.00	0.56	2.46	1.93	0.00	3.22	1.51	1.01	0.56	0.00	0.00	20.29
2008	5.58	3.42	0.00	0.57	2.49	1.93	0.00	3.15	1.49	0.99	0.57	0.00	0.00	20.18
2009	5.43	3.42	0.00	0.57	2.49	1.89	0.00	3.03	1.44	0.96	0.57	0.00	0.00	19.79
2010	4.96	3.17	0.00	0.52	2.31	1.74	0.00	2.74	1.31	0.88	0.52	0.00	0.00	18.16
2011	4.42	2.88	0.00	0.47	2.09	1.56	0.00	2.43	1.17	0.78	0.47	0.00	0.00	16.28
2012	3.88	2.57	0.00	0.42	1.87	1.38	0.00	2.12	1.02	0.68	0.42	0.00	0.00	14.37
2013	3.33	2.25	0.00	0.37	1.63	1.20	0.00	1.81	0.88	0.58	0.37	0.00	0.00	12.41
2014	2.79	1.92	0.00	0.31	1.40	1.01	0.00	1.50	0.73	0.49	0.31	0.00	0.00	10.47
2015	2.70	1.89	0.00	0.31	1.37	0.99	0.00	1.44	0.71	0.47	0.31	0.00	0.00	10.18
2016	2.61	1.86	0.00	0.30	1.35	0.96	0.00	1.38	0.68	0.45	0.30	0.00	0.00	9.89
2017	2.51	1.83	0.00	0.30	1.33	0.93	0.00	1.32	0.65	0.44	0.30	0.00	0.00	9.60
2018	2.42	1.79	0.00	0.29	1.30	0.91	0.00	1.26	0.63	0.42	0.29	0.00	0.00	9.31
2019	2.33	1.76	0.00	0.28	1.28	0.88	0.00	1.20	0.60	0.40	0.28	0.00	0.00	9.01
2020	2.23	1.72	0.00	0.28	1.25	0.85	0.00	1.14	0.58	0.38	0.28	0.00	0.00	8.70
2021	2.13	1.67	0.00	0.27	1.22	0.82	0.00	1.07	0.55	0.36	0.27	0.00	0.00	8.36
2022	2.02	1.62	0.00	0.26	1.18	0.79	0.00	1.01	0.52	0.35	0.26	0.00	0.00	8.01
2023	1.92	1.58	0.00	0.25	1.15	0.76	0.00	0.94	0.49	0.33	0.25	0.00	0.00	7.66
2024	1.82	1.52	0.00	0.24	1.11	0.72	0.00	0.88	0.46	0.31	0.24	0.00	0.00	7.32
2025	1.72	1.47	0.00	0.24	1.07	0.69	0.00	0.82	0.43	0.29	0.24	0.00	0.00	6.97

Table A1.4. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 3)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	7.55	3.35	0.00	0.59	2.46	2.40	0.00	5.53	2.22	1.48	0.57	0.00	0.00	26.14
2001	6.92	3.33	0.00	0.58	2.44	2.29	0.00	5.27	2.06	1.38	0.55	0.00	0.00	24.84
2002	6.27	3.30	0.00	0.57	2.42	2.18	0.00	4.99	1.91	1.27	0.54	0.00	0.00	23.44
2003	5.60	3.24	0.00	0.56	2.38	2.05	0.00	4.69	1.74	1.16	0.52	0.00	0.00	21.94
2004	4.92	3.17	0.00	0.54	2.34	1.92	0.00	4.36	1.57	1.04	0.50	0.00	0.00	20.35
2005	4.86	3.24	0.00	0.55	2.39	1.94	0.00	4.39	1.56	1.04	0.50	0.00	0.00	20.48
2006	4.74	3.28	0.00	0.56	2.42	1.93	0.00	4.38	1.54	1.03	0.51	0.00	0.00	20.39
2007	4.62	3.33	0.00	0.56	2.46	1.93	0.00	4.37	1.51	1.01	0.51	0.00	0.00	20.29
2008	4.49	3.37	0.00	0.57	2.49	1.93	0.00	4.35	1.49	0.99	0.51	0.00	0.00	20.18
2009	4.30	3.36	0.00	0.57	2.49	1.89	0.00	4.27	1.44	0.96	0.51	0.00	0.00	19.79
2010	3.89	3.12	0.00	0.52	2.31	1.74	0.00	3.92	1.31	0.88	0.47	0.00	0.00	18.16
2011	3.43	2.83	0.00	0.47	2.09	1.56	0.00	3.52	1.17	0.78	0.42	0.00	0.00	16.28
2012	2.98	2.52	0.00	0.42	1.87	1.38	0.00	3.11	1.02	0.68	0.38	0.00	0.00	14.37
2013	2.53	2.21	0.00	0.37	1.63	1.20	0.00	2.69	0.88	0.58	0.33	0.00	0.00	12.41
2014	2.10	1.88	0.00	0.31	1.40	1.01	0.00	2.27	0.73	0.49	0.28	0.00	0.00	10.47
2015	2.00	1.85	0.00	0.31	1.37	0.99	0.00	2.21	0.71	0.47	0.27	0.00	0.00	10.18
2016	1.91	1.82	0.00	0.30	1.35	0.96	0.00	2.15	0.68	0.45	0.27	0.00	0.00	9.89
2017	1.81	1.79	0.00	0.30	1.33	0.93	0.00	2.09	0.65	0.44	0.26	0.00	0.00	9.60
2018	1.72	1.76	0.00	0.29	1.30	0.91	0.00	2.02	0.63	0.42	0.26	0.00	0.00	9.31
2019	1.63	1.72	0.00	0.28	1.28	0.88	0.00	1.96	0.60	0.40	0.25	0.00	0.00	9.01
2020	1.54	1.68	0.00	0.28	1.25	0.85	0.00	1.90	0.58	0.38	0.24	0.00	0.00	8.70
2021	1.44	1.64	0.00	0.27	1.22	0.82	0.00	1.82	0.55	0.36	0.24	0.00	0.00	8.36
2022	1.35	1.59	0.00	0.26	1.18	0.79	0.00	1.75	0.52	0.35	0.23	0.00	0.00	8.01
2023	1.25	1.54	0.00	0.25	1.15	0.76	0.00	1.68	0.49	0.33	0.22	0.00	0.00	7.66
2024	1.16	1.49	0.00	0.24	1.11	0.72	0.00	1.60	0.46	0.31	0.21	0.00	0.00	7.32
2025	1.07	1.44	0.00	0.24	1.07	0.69	0.00	1.53	0.43	0.29	0.20	0.00	0.00	6.97

Table A1.5. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 4)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	8.27	3.35	0.00	0.57	2.46	2.20	0.00	5.29	2.08	1.37	0.56	0.00	0.00	26.14
2001	7.83	3.33	0.00	0.55	2.44	2.04	0.00	4.97	1.90	1.24	0.54	0.00	0.00	24.84
2002	7.36	3.30	0.00	0.53	2.42	1.87	0.00	4.63	1.71	1.10	0.52	0.00	0.00	23.44
2003	6.86	3.24	0.00	0.51	2.38	1.70	0.00	4.27	1.51	0.96	0.50	0.00	0.00	21.94
2004	6.33	3.17	0.00	0.49	2.34	1.53	0.00	3.89	1.31	0.83	0.47	0.00	0.00	20.35
2005	6.36	3.24	0.00	0.50	2.39	1.52	0.00	3.89	1.29	0.81	0.48	0.00	0.00	20.48
2006	6.32	3.28	0.00	0.50	2.42	1.49	0.00	3.85	1.25	0.78	0.48	0.00	0.00	20.39
2007	6.28	3.33	0.00	0.50	2.46	1.47	0.00	3.81	1.21	0.75	0.48	0.00	0.00	20.29
2008	6.23	3.37	0.00	0.51	2.49	1.44	0.00	3.77	1.17	0.72	0.49	0.00	0.00	20.18
2009	6.10	3.36	0.00	0.50	2.49	1.39	0.00	3.67	1.12	0.68	0.48	0.00	0.00	19.79
2010	5.59	3.12	0.00	0.46	2.31	1.26	0.00	3.35	1.01	0.61	0.44	0.00	0.00	18.16
2011	5.01	2.83	0.00	0.42	2.09	1.12	0.00	2.99	0.88	0.54	0.40	0.00	0.00	16.28
2012	4.41	2.53	0.00	0.37	1.87	0.98	0.00	2.63	0.76	0.46	0.36	0.00	0.00	14.37
2013	3.81	2.21	0.00	0.32	1.63	0.84	0.00	2.26	0.65	0.39	0.31	0.00	0.00	12.41
2014	3.21	1.88	0.00	0.28	1.40	0.70	0.00	1.90	0.53	0.32	0.26	0.00	0.00	10.47
2015	2.69	1.58	0.00	0.23	1.17	0.59	0.00	1.59	0.45	0.27	0.22	0.00	0.00	8.78
2016	2.16	1.27	0.00	0.19	0.94	0.47	0.00	1.28	0.36	0.21	0.18	0.00	0.00	7.04
2017	1.60	0.94	0.00	0.14	0.70	0.35	0.00	0.95	0.27	0.16	0.13	0.00	0.00	5.23
2018	1.46	0.85	0.00	0.13	0.63	0.32	0.00	0.86	0.24	0.14	0.12	0.00	0.00	4.75
2019	1.46	0.86	0.00	0.13	0.64	0.32	0.00	0.87	0.24	0.14	0.12	0.00	0.00	4.78
2020	1.47	0.86	0.00	0.13	0.64	0.32	0.00	0.87	0.24	0.15	0.12	0.00	0.00	4.80
2021	1.47	0.86	0.00	0.13	0.64	0.32	0.00	0.87	0.24	0.15	0.12	0.00	0.00	4.80
2022	1.47	0.86	0.00	0.13	0.64	0.32	0.00	0.87	0.24	0.15	0.12	0.00	0.00	4.80
2023	1.47	0.86	0.00	0.13	0.64	0.32	0.00	0.87	0.24	0.15	0.12	0.00	0.00	4.80
2024	1.47	0.86	0.00	0.13	0.64	0.32	0.00	0.87	0.24	0.15	0.12	0.00	0.00	4.80
2025	1.47	0.86	0.00	0.13	0.64	0.32	0.00	0.87	0.24	0.15	0.12	0.00	0.00	4.80

Table A1.6. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 5)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	8.64	2.81	0.00	0.59	2.46	2.17	0.00	5.72	1.99	1.30	0.48	0.00	0.00	26.14
2001	8.29	2.65	0.00	0.58	2.44	2.01	0.00	5.50	1.78	1.15	0.44	0.00	0.00	24.84
2002	7.91	2.48	0.00	0.57	2.42	1.84	0.00	5.26	1.56	1.00	0.40	0.00	0.00	23.44
2003	7.49	2.30	0.00	0.56	2.38	1.66	0.00	5.00	1.34	0.84	0.36	0.00	0.00	21.94
2004	7.04	2.11	0.00	0.54	2.34	1.48	0.00	4.72	1.12	0.69	0.32	0.00	0.00	20.35
2005	7.12	2.11	0.00	0.55	2.39	1.47	0.00	4.77	1.09	0.66	0.32	0.00	0.00	20.48
2006	7.12	2.09	0.00	0.56	2.42	1.44	0.00	4.78	1.04	0.63	0.31	0.00	0.00	20.39
2007	7.12	2.08	0.00	0.56	2.46	1.41	0.00	4.78	0.99	0.59	0.30	0.00	0.00	20.29
2008	7.11	2.06	0.00	0.57	2.49	1.38	0.00	4.78	0.94	0.56	0.29	0.00	0.00	20.18
2009	7.01	2.01	0.00	0.57	2.49	1.33	0.00	4.72	0.88	0.51	0.28	0.00	0.00	19.79
2010	6.45	1.84	0.00	0.52	2.31	1.21	0.00	4.35	0.78	0.45	0.26	0.00	0.00	18.16
2011	5.80	1.64	0.00	0.47	2.09	1.07	0.00	3.91	0.67	0.38	0.23	0.00	0.00	16.28
2012	5.14	1.45	0.00	0.42	1.87	0.93	0.00	3.47	0.57	0.32	0.20	0.00	0.00	14.37
2013	4.45	1.25	0.00	0.37	1.63	0.80	0.00	3.01	0.48	0.26	0.17	0.00	0.00	12.41
2014	3.77	1.05	0.00	0.31	1.40	0.66	0.00	2.55	0.38	0.21	0.14	0.00	0.00	10.47
2015	3.68	1.02	0.00	0.31	1.37	0.64	0.00	2.49	0.36	0.19	0.13	0.00	0.00	10.18
2016	3.59	0.98	0.00	0.30	1.35	0.61	0.00	2.43	0.33	0.17	0.13	0.00	0.00	9.89
2017	3.49	0.95	0.00	0.30	1.33	0.58	0.00	2.37	0.30	0.16	0.12	0.00	0.00	9.60
2018	3.40	0.92	0.00	0.29	1.30	0.56	0.00	2.30	0.28	0.14	0.12	0.00	0.00	9.31
2019	3.30	0.89	0.00	0.28	1.28	0.53	0.00	2.24	0.25	0.12	0.11	0.00	0.00	9.01
2020	3.20	0.85	0.00	0.28	1.25	0.51	0.00	2.17	0.23	0.11	0.10	0.00	0.00	8.70
2021	3.09	0.82	0.00	0.27	1.22	0.48	0.00	2.10	0.20	0.09	0.10	0.00	0.00	8.36
2022	2.97	0.78	0.00	0.26	1.18	0.45	0.00	2.02	0.18	0.07	0.09	0.00	0.00	8.01
2023	2.85	0.74	0.00	0.25	1.15	0.42	0.00	1.94	0.16	0.06	0.09	0.00	0.00	7.66
2024	2.73	0.71	0.00	0.24	1.11	0.40	0.00	1.86	0.13	0.05	0.08	0.00	0.00	7.32
2025	2.62	0.67	0.00	0.24	1.07	0.37	0.00	1.78	0.11	0.03	0.08	0.00	0.00	6.97

Table A1.7. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 6)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	8.27	3.35	0.00	0.57	2.46	2.20	0.00	5.29	2.08	1.37	0.56	0.00	0.00	26.14
2001	7.91	3.36	0.00	0.56	2.47	2.06	0.00	5.02	1.92	1.25	0.55	0.00	0.00	25.08
2002	7.50	3.36	0.00	0.54	2.47	1.91	0.00	4.72	1.74	1.12	0.53	0.00	0.00	23.90
2003	7.06	3.34	0.00	0.53	2.46	1.75	0.00	4.39	1.56	0.99	0.51	0.00	0.00	22.58
2004	6.58	3.29	0.00	0.51	2.43	1.59	0.00	4.05	1.36	0.86	0.49	0.00	0.00	21.16
2005	6.67	3.40	0.00	0.52	2.51	1.59	0.00	4.09	1.35	0.85	0.50	0.00	0.00	21.49
2006	6.70	3.48	0.00	0.53	2.57	1.58	0.00	4.08	1.33	0.83	0.51	0.00	0.00	21.61
2007	6.72	3.56	0.00	0.54	2.63	1.57	0.00	4.08	1.30	0.81	0.52	0.00	0.00	21.72
2008	6.74	3.64	0.00	0.55	2.69	1.55	0.00	4.07	1.27	0.78	0.53	0.00	0.00	21.81
2009	6.66	3.67	0.00	0.55	2.71	1.52	0.00	4.00	1.22	0.75	0.53	0.00	0.00	21.60
2010	6.16	3.44	0.00	0.51	2.54	1.39	0.00	3.69	1.11	0.67	0.49	0.00	0.00	20.01
2011	5.47	3.09	0.00	0.46	2.29	1.23	0.00	3.27	0.97	0.59	0.44	0.00	0.00	17.81
2012	4.76	2.73	0.00	0.40	2.02	1.06	0.00	2.84	0.82	0.50	0.38	0.00	0.00	15.51
2013	4.02	2.33	0.00	0.34	1.73	0.89	0.00	2.39	0.68	0.41	0.33	0.00	0.00	13.11
2014	3.73	2.19	0.00	0.32	1.62	0.82	0.00	2.21	0.62	0.37	0.31	0.00	0.00	12.19
2015	3.60	2.14	0.00	0.31	1.59	0.78	0.00	2.12	0.58	0.35	0.30	0.00	0.00	11.77
2016	3.43	2.07	0.00	0.30	1.53	0.74	0.00	2.01	0.54	0.32	0.28	0.00	0.00	11.22
2017	3.25	1.99	0.00	0.29	1.47	0.69	0.00	1.90	0.50	0.29	0.27	0.00	0.00	10.66
2018	3.07	1.90	0.00	0.27	1.41	0.65	0.00	1.79	0.46	0.27	0.26	0.00	0.00	10.08
2019	2.89	1.82	0.00	0.26	1.35	0.60	0.00	1.68	0.42	0.24	0.25	0.00	0.00	9.50
2020	2.70	1.72	0.00	0.25	1.28	0.56	0.00	1.56	0.38	0.22	0.23	0.00	0.00	8.89
2021	2.58	1.67	0.00	0.24	1.24	0.53	0.00	1.49	0.36	0.20	0.22	0.00	0.00	8.53
2022	2.47	1.62	0.00	0.23	1.20	0.50	0.00	1.41	0.33	0.18	0.21	0.00	0.00	8.15
2023	2.35	1.56	0.00	0.22	1.16	0.47	0.00	1.34	0.30	0.16	0.21	0.00	0.00	7.77
2024	2.23	1.51	0.00	0.21	1.12	0.44	0.00	1.27	0.28	0.15	0.20	0.00	0.00	7.39
2025	2.11	1.45	0.00	0.20	1.08	0.41	0.00	1.19	0.25	0.13	0.19	0.00	0.00	7.01

Table A1.8. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 7)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	8.27	3.35	0.00	0.57	2.46	2.20	0.00	5.29	2.08	1.37	0.56	0.00	0.00	26.14
2001	7.91	3.36	0.00	0.56	2.47	2.06	0.00	5.02	1.92	1.25	0.55	0.00	0.00	25.08
2002	7.50	3.36	0.00	0.54	2.47	1.91	0.00	4.72	1.74	1.12	0.53	0.00	0.00	23.90
2003	7.06	3.34	0.00	0.53	2.46	1.75	0.00	4.39	1.56	0.99	0.51	0.00	0.00	22.58
2004	6.58	3.29	0.00	0.51	2.43	1.59	0.00	4.05	1.36	0.86	0.49	0.00	0.00	21.16
2005	6.67	3.40	0.00	0.52	2.51	1.59	0.00	4.09	1.35	0.85	0.50	0.00	0.00	21.49
2006	6.70	3.48	0.00	0.53	2.57	1.58	0.00	4.08	1.33	0.83	0.51	0.00	0.00	21.61
2007	6.72	3.56	0.00	0.54	2.63	1.57	0.00	4.08	1.30	0.81	0.52	0.00	0.00	21.72
2008	6.74	3.64	0.00	0.55	2.69	1.55	0.00	4.07	1.27	0.78	0.53	0.00	0.00	21.81
2009	6.66	3.67	0.00	0.55	2.71	1.52	0.00	4.00	1.22	0.75	0.53	0.00	0.00	21.60
2010	5.99	3.40	0.00	0.50	2.52	1.34	0.00	3.57	1.05	0.63	0.48	0.00	0.00	19.48
2011	5.22	3.06	0.00	0.45	2.27	1.14	0.00	3.09	0.87	0.52	0.43	0.00	0.00	17.03
2012	4.42	2.68	0.00	0.39	1.99	0.94	0.00	2.59	0.69	0.40	0.37	0.00	0.00	14.48
2013	3.60	2.26	0.00	0.32	1.68	0.75	0.00	2.09	0.53	0.30	0.31	0.00	0.00	11.83
2014	3.47	2.21	0.00	0.31	1.64	0.72	0.00	2.01	0.50	0.28	0.30	0.00	0.00	11.42
2015	2.90	1.87	0.00	0.27	1.39	0.59	0.00	1.67	0.40	0.23	0.25	0.00	0.00	9.57
2016	2.83	1.84	0.00	0.26	1.37	0.57	0.00	1.62	0.38	0.21	0.25	0.00	0.00	9.33
2017	2.75	1.81	0.00	0.26	1.35	0.55	0.00	1.57	0.36	0.20	0.24	0.00	0.00	9.09
2018	2.67	1.78	0.00	0.25	1.33	0.53	0.00	1.52	0.34	0.19	0.24	0.00	0.00	8.85
2019	2.59	1.75	0.00	0.25	1.30	0.51	0.00	1.47	0.32	0.17	0.23	0.00	0.00	8.60
2020	2.51	1.72	0.00	0.24	1.28	0.49	0.00	1.42	0.30	0.16	0.22	0.00	0.00	8.34
2021	2.42	1.68	0.00	0.23	1.25	0.46	0.00	1.36	0.28	0.14	0.22	0.00	0.00	8.04
2022	2.32	1.63	0.00	0.23	1.21	0.44	0.00	1.30	0.26	0.13	0.21	0.00	0.00	7.73
2023	2.22	1.58	0.00	0.22	1.18	0.41	0.00	1.24	0.24	0.12	0.20	0.00	0.00	7.42
2024	2.13	1.54	0.00	0.21	1.14	0.39	0.00	1.18	0.22	0.11	0.20	0.00	0.00	7.11
2025	2.03	1.48	0.00	0.20	1.11	0.37	0.00	1.12	0.20	0.09	0.19	0.00	0.00	6.79

Table A1.9. MSW waste to landfill 1995-2025 (Mt) used as input to the LQM 2002 model (ERM MSW Scenario 8)

Year	Paper and card	Dense plastics	Film plastics (until 1995)	Textiles	Misc. combustible (plus non-inert fines from 1995)	Misc. non-combustible (plus inert fines from 1995)	Putrescible	Composted putrescibles	Glass	Ferrous metal	Non-ferrous metal and Al cans	Non-inert fines	Inert fines	Total
1995	7.63	2.62	0.00	0.48	1.91	2.14	0.00	5.00	2.14	1.43	0.48	0.00	0.00	23.83
1996	7.92	2.72	0.00	0.50	1.98	2.23	0.00	5.20	2.23	1.49	0.50	0.00	0.00	24.76
1997	8.36	2.88	0.00	0.52	2.09	2.35	0.00	5.49	2.35	1.57	0.52	0.00	0.00	26.14
1998	8.30	2.85	0.00	0.52	2.08	2.33	0.00	5.45	2.33	1.56	0.52	0.00	0.00	25.94
1999	8.65	2.97	0.00	0.54	2.16	2.43	0.00	5.68	2.43	1.62	0.54	0.00	0.00	27.03
2000	8.73	3.44	0.00	0.59	2.51	2.34	0.00	5.62	2.25	1.48	0.58	0.00	0.00	27.54
2001	8.75	3.50	0.00	0.59	2.56	2.33	0.00	5.61	2.23	1.46	0.59	0.00	0.00	27.62
2002	8.76	3.56	0.00	0.60	2.61	2.32	0.00	5.60	2.20	1.44	0.59	0.00	0.00	27.69
2003	8.76	3.62	0.00	0.61	2.65	2.31	0.00	5.59	2.18	1.42	0.60	0.00	0.00	27.73
2004	8.76	3.68	0.00	0.61	2.70	2.29	0.00	5.57	2.15	1.40	0.60	0.00	0.00	27.76
2005	8.75	3.74	0.00	0.62	2.74	2.27	0.00	5.55	2.11	1.37	0.60	0.00	0.00	27.75
2006	8.64	3.76	0.00	0.62	2.76	2.23	0.00	5.46	2.06	1.33	0.60	0.00	0.00	27.46
2007	8.53	3.78	0.00	0.61	2.77	2.18	0.00	5.37	2.00	1.29	0.60	0.00	0.00	27.14
2008	8.41	3.79	0.00	0.61	2.79	2.13	0.00	5.28	1.94	1.25	0.60	0.00	0.00	26.80
2009	8.28	3.80	0.00	0.61	2.80	2.08	0.00	5.18	1.88	1.20	0.59	0.00	0.00	26.43
2010	8.15	3.81	0.00	0.61	2.81	2.03	0.00	5.08	1.81	1.16	0.59	0.00	0.00	26.04
2011	7.92	3.78	0.00	0.60	2.78	1.96	0.00	4.92	1.73	1.10	0.58	0.00	0.00	25.37
2012	7.70	3.75	0.00	0.59	2.76	1.88	0.00	4.76	1.64	1.04	0.57	0.00	0.00	24.69
2013	7.46	3.71	0.00	0.58	2.73	1.81	0.00	4.60	1.56	0.98	0.56	0.00	0.00	23.99
2014	7.23	3.66	0.00	0.57	2.70	1.73	0.00	4.43	1.48	0.93	0.54	0.00	0.00	23.27
2015	6.99	3.62	0.00	0.55	2.67	1.65	0.00	4.26	1.39	0.87	0.53	0.00	0.00	22.53
2016	6.71	3.55	0.00	0.54	2.62	1.57	0.00	4.07	1.30	0.81	0.52	0.00	0.00	21.67
2017	6.42	3.47	0.00	0.52	2.57	1.48	0.00	3.88	1.21	0.74	0.50	0.00	0.00	20.80
2018	6.14	3.40	0.00	0.51	2.51	1.40	0.00	3.69	1.12	0.68	0.49	0.00	0.00	19.93
2019	5.85	3.31	0.00	0.49	2.45	1.31	0.00	3.50	1.03	0.62	0.47	0.00	0.00	19.04
2020	5.56	3.22	0.00	0.47	2.39	1.23	0.00	3.30	0.94	0.57	0.45	0.00	0.00	18.14
2021	5.25	3.12	0.00	0.45	2.31	1.14	0.00	3.10	0.86	0.51	0.43	0.00	0.00	17.15
2022	4.93	3.00	0.00	0.43	2.22	1.05	0.00	2.89	0.77	0.45	0.41	0.00	0.00	16.16
2023	4.61	2.88	0.00	0.41	2.14	0.97	0.00	2.69	0.69	0.39	0.39	0.00	0.00	15.17
2024	4.30	2.76	0.00	0.39	2.05	0.88	0.00	2.48	0.60	0.34	0.37	0.00	0.00	14.18
2025	3.99	2.63	0.00	0.37	1.95	0.80	0.00	2.28	0.53	0.29	0.35	0.00	0.00	13.18

Table A1.10. C&I waste to landfill 1945-1998 (Mt) used as input to the LQM 2002 model (Brown et al., 1999 default input)

Year	Commercial	Paper and card	General industrial waste	Food solids	Food effluent	Abbatoir waste	Misc processes	Other waste	Power station ash	Blast furnace and steel slag	Construction/demolition	Sewage sludge	Total
1945	10.00	0.00	8.40	2.40	12.60	1.40	12.96	1.53	5.50	1.50	22.80	0.11	79.20
1946	10.00	0.00	8.45	2.41	12.64	1.40	13.01	1.53	5.52	1.51	22.92	0.11	79.50
1947	10.00	0.00	8.50	2.42	12.68	1.40	13.05	1.54	5.54	1.51	23.04	0.11	79.80
1948	10.01	0.00	8.55	2.43	12.72	1.40	13.10	1.54	5.56	1.52	23.16	0.11	80.10
1949	10.01	0.00	8.60	2.44	12.76	1.40	13.15	1.54	5.58	1.52	23.28	0.11	80.39
1950	10.01	0.00	8.65	2.45	12.80	1.40	13.19	1.55	5.60	1.53	23.40	0.11	80.69
1951	10.01	0.00	8.70	2.46	12.84	1.40	13.24	1.55	5.62	1.54	23.52	0.11	80.99
1952	10.01	0.00	8.75	2.47	12.88	1.40	13.29	1.55	5.64	1.54	23.64	0.11	81.29
1953	10.02	0.00	8.80	2.48	12.92	1.40	13.33	1.56	5.66	1.55	23.76	0.11	81.59
1954	10.02	0.00	8.85	2.49	12.96	1.40	13.38	1.56	5.68	1.55	23.88	0.11	81.89
1955	10.02	0.00	8.90	2.50	13.00	1.40	13.43	1.56	5.70	1.56	24.00	0.11	82.18
1956	10.21	0.00	8.94	2.51	13.08	1.40	13.47	1.57	5.72	1.57	24.60	0.11	83.18
1957	10.40	0.00	8.98	2.52	13.16	1.40	13.52	1.57	5.74	1.57	25.20	0.11	84.17
1958	10.58	0.00	9.02	2.53	13.24	1.40	13.57	1.57	5.76	1.58	25.80	0.11	85.17
1959	10.77	0.00	9.06	2.54	13.32	1.40	13.62	1.58	5.78	1.58	26.40	0.11	86.16
1960	10.96	0.00	9.10	2.55	13.40	1.40	13.66	1.58	5.80	1.59	27.00	0.11	87.16
1961	11.15	0.00	9.14	2.56	13.48	1.40	13.71	1.58	5.82	1.60	27.60	0.11	88.15
1962	11.34	0.00	9.18	2.57	13.56	1.40	13.76	1.59	5.84	1.60	28.20	0.11	89.14
1963	11.52	0.00	9.22	2.58	13.64	1.40	13.80	1.59	5.86	1.61	28.80	0.11	90.14
1964	11.71	0.00	9.26	2.59	13.72	1.40	13.85	1.59	5.88	1.61	29.40	0.11	91.13
1965	11.90	0.00	9.30	2.60	13.80	1.40	13.90	1.60	5.90	1.62	30.00	0.11	92.13
1966	11.97	0.00	9.22	2.57	13.76	1.40	13.94	1.60	5.92	1.63	29.28	0.11	91.39
1967	12.03	0.00	9.13	2.53	13.72	1.40	13.99	1.60	5.94	1.63	28.56	0.11	90.66
1968	12.10	0.00	9.05	2.50	13.68	1.40	14.04	1.61	5.96	1.64	27.84	0.11	89.92
1969	12.16	0.00	8.97	2.47	13.64	1.40	14.08	1.61	5.98	1.64	27.12	0.11	89.19
1970	12.22	0.00	8.88	2.43	13.60	1.40	14.13	1.62	6.00	1.65	26.40	0.11	88.45
1971	12.29	0.00	8.80	2.39	13.56	1.40	14.18	1.62	6.02	1.66	25.68	0.11	87.71
1972	12.35	0.00	8.71	2.36	13.52	1.40	14.22	1.62	6.04	1.66	24.96	0.11	86.96
1973	12.41	0.00	8.63	2.32	13.48	1.40	14.27	1.63	6.06	1.67	24.24	0.11	86.22
1974	12.48	0.00	8.54	2.28	13.44	1.40	14.32	1.63	6.08	1.67	23.52	0.11	85.48
1975	12.54	0.00	8.46	2.24	13.40	1.40	14.36	1.63	6.10	1.68	22.80	0.11	84.73
1976	12.64	0.00	8.49	2.25	13.41	1.40	14.41	1.64	6.12	1.69	22.32	0.11	84.47
1977	12.74	0.00	8.51	2.25	13.42	1.40	14.46	1.64	6.14	1.69	21.84	0.11	84.20
1978	12.83	0.00	8.54	2.26	13.43	1.40	14.50	1.64	6.16	1.70	21.36	0.11	83.94
1979	12.93	0.00	8.57	2.27	13.44	1.40	14.55	1.65	6.18	1.70	20.88	0.11	83.68
1980	13.03	0.00	8.60	2.27	13.45	1.40	14.60	1.65	6.20	1.71	20.40	0.11	83.41
1981	13.13	0.00	8.62	2.28	13.46	1.40	14.64	1.65	6.22	1.72	19.92	0.11	83.15
1982	13.23	0.00	8.65	2.28	13.47	1.40	14.69	1.66	6.24	1.72	19.44	0.11	82.89
1983	13.32	0.00	8.68	2.29	13.48	1.40	14.74	1.66	6.26	1.73	18.96	0.11	82.62
1984	13.42	0.00	8.70	2.30	13.49	1.40	14.79	1.66	6.28	1.73	18.48	0.11	82.36
1985	13.52	0.00	8.73	2.30	13.49	1.40	14.83	1.67	6.30	1.74	18.00	0.11	82.09
1986	13.64	0.00	8.76	2.31	13.57	1.40	14.88	1.67	6.32	1.75	17.64	0.11	82.04
1987	13.76	0.00	8.78	2.32	13.64	1.40	14.93	1.67	6.34	1.75	17.28	0.11	81.99
1988	13.87	0.00	8.81	2.33	13.72	1.40	14.97	1.68	6.36	1.76	16.92	0.11	81.93
1989	13.99	0.00	8.84	2.34	13.79	1.40	15.02	1.68	6.38	1.76	16.56	0.11	81.88
1990	14.11	0.00	8.87	2.35	13.87	1.40	15.07	1.68	6.40	1.77	16.20	0.11	81.83
1991	14.23	0.00	8.89	2.36	13.95	1.40	15.11	1.69	6.42	1.78	15.84	0.11	81.77
1992	14.34	0.00	8.92	2.37	14.02	1.40	15.16	1.69	6.44	1.78	15.48	0.11	81.72
1993	14.46	0.00	8.95	2.38	14.10	1.40	15.21	1.69	6.46	1.79	15.12	0.11	81.66
1994	14.58	0.00	8.97	2.39	14.17	1.40	15.25	1.70	6.48	1.79	14.76	0.11	81.61
1995	14.70	0.00	9.00	2.40	14.25	1.40	15.30	1.70	6.50	1.80	14.40	0.11	81.56
1996	14.62	0.02	9.09	1.53	9.12	0.92	10.75	3.06	5.52	1.82	21.98	0.11	78.53
1997	14.35	0.07	9.17	0.85	5.12	0.54	7.00	3.75	4.56	1.80	26.57	0.11	73.90
1998	13.91	0.16	9.25	0.36	2.26	0.25	4.05	3.75	3.61	1.77	28.16	0.11	67.65

Table A1.11. C&I waste to landfill 1999-2025 (Mt) used as input to the LQM 2002 model (ERM C&I Scenarios 1 to 5)

Waste Category	C&I Scenario				
	1	2	3	4	5
Commercial	13.28	13.28	13.28	13.28	13.28
Paper and card	0.29	0.25	0.29	0.29	0.29
General industrial waste	9.33	9.33	9.33	9.33	9.33
Food solids	0.07	0.06	0.07	0.07	0.07
Food effluent	0.53	0.45	0.53	0.53	0.53
Abbatoir waste	0.07	0.06	0.07	0.07	0.07
Misc processes	1.91	1.91	1.91	1.91	1.91
Other waste	3.39	3.09	3.09	3.09	3.39
Power station ash	2.67	2.67	2.67	2.67	2.67
Blast furnace and steel slag	1.70	1.70	1.70	1.70	1.70
Construction/demolition	26.75	26.75	26.75	26.75	23.15
Sewage sludge[1]	0.11	0.11	0.11	0.11	0.11
Total	60.09	59.65	59.80	59.80	56.48

[1] AEAT 1999 values used

Appendix 2

Table A2.1. Flare Manufacturers and Suppliers

Supplier	Contact Details
AFS[1]	2A Hockley Lane, Eastern Green, Coventry CV5 7FR Tel. 02476 474877
Apex Tubes and Valves (formerly Anglia Mechanical Environmental Ltd)	Empson Road, Eastern Industry, Peterborough Tel. 01733 244600
Biffa Environmental Technology	Withnell Service Centre, Bolton Road, Withnell, Chorley, Lancs. PR6 8BT Tel. 01254 831389
Biogas	6 Brookside Industrial Estate, Glatton Road, Sawtry, Huntingdon, Cambs. PE28 5SB Tel. 01487 831701
Clarke Energy[1]	898 Plymouth Road, Slough Trading Estate, Slough SL1 4LP Tel. 01753 567616
Covertronic (formerly MB Geosphere)	No longer trading
Energy Developments[1]	Watford Business Centre, Parade House, 135 The Parade, High Street, Watford, Herts. WD1 1NS Tel. 01923 491212
Enitial Projects[1]	Unit 12, Four Ashes Industrial Estate, Station Road, Four Ashes, Wolverhampton WV10 7DB Tel. 01902 798798
Flare Products Ltd	Unit 14, Broadmead Business Park, Stewartby, Bedford MK43 9NX Tel. 01234 768624
Fuel and Combustion Technology Ltd	RMC House, The Grange, Coldharbour Lane, Egham, Surrey TW20 8TD
GBA Ltd[1]	4 Kingfisher Court, Farnham Road, Slough, Berks. SL2 1JF Tel. 01753 575710

[1] Not included in the ETSU 1996 survey.

HAASE[1]	Via Clarke Energy (above) or Gadelander Str. 172, D-24531 Neumuenster, Germany Tel. +49 4321 8780
Hi-Lo Ltd	Vanguard Road, Gapton Hall Industrial Estate, Great Yarmouth, Norfolk NR31 0NT Tel. 01493 440111
Hirt Combustion Engineers Ltd	Woodford Green Works, Leslie Road, Woodford Park Industrial Estate, Winsford, Cheshire CW7 2RB 01606 861366
Marton Geotechnical Services Ltd[1]	Geotechnical Centre, Rougham Industrial Estate, Bury St Edmunds, Suffolk IP30 9ND Tel. 01359 271167
Novera Energy (formerly CPL Energy)[1]	2nd Floor, The Malt Building, Wilderspool Park, Greenalls Avenue, Warrington, Cheshire, WA4 6RH Tel. 01925 438300
Organics Ltd (formerly UKPS Ltd)	The Barclay Centre, University of Warwick Science Park, Coventry CV4 7EZ Tel. 02476 412170
Process Combustion[1]	Hornbeam Park, Hookstone Road, Harrogate, Yorks. HG2 8PB Tel. 01423 879944
Pro2 Anlagentechnik GmbH[1]	Hanns-Martin-schleyer-Str. 8, D-47877 Willich, Germany Tel. +49 2154 4880
PCC Sterling Ltd[1]	Brunel Road, Rabans Lane, Aylesbury, Bucks. HP19 8TD Tel. 01296 487171
Summerleaze Re-generation[1]	7 Summerleaze Road, Maidenhead, Berks. SL6 8SP Tel. 01628 762350
Thomas Graveson	See Summerleaze (above)

[1] Not included in the ETSU 1996 survey.