

**Golder Associates (UK) Limited**

Attenborough House  
Browns Lane Business Park  
Stanton-on-the-Wolds  
Nottinghamshire NG12 5BL  
England

Tel: [44] (0)115 9371111  
Fax: [44] (0)115 9371100  
E-mail: [nottingham@golder.com](mailto:nottingham@golder.com)  
<http://www.golder.com>



**REPORT ON**

**UK LANDFILL METHANE EMISSIONS:  
EVALUATION AND APPRAISAL OF WASTE POLICIES  
AND PROJECTIONS TO 2050**

Submitted to:

Stephen Cornelius  
Global Atmospheric Division  
DEFRA  
3/A1 Ashdown House  
123 Victoria Street  
London  
SW1E 6DE  
UK



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November 2005

05529424.500

## REPORT ISSUE FORM

<b>Version Code</b>	A.2	<b>Issue Date</b>	17 November 2005						
<b>Document Title</b>	<b>UK Landfill Methane Emissions Evaluation and Appraisal of Waste Policies and Projections to 2050</b>  05529424.500								
<b>Comments</b>	Formatted by ca								
<b>List of Authors</b>	Sam Arnold Zhiyuan Yang								
<b>Client</b>	DEFRA								
<b>Client Reference</b>									
<b>Project Manager Approval</b>	Sam Arnold <small>(name)</small>	 <small>(signature)</small>							
<b>Reviewer</b>	Bob Gregory Don Bradley	 <small>(signature)</small>							
<b>Report Distribution</b>	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 50%; text-align: left;">Name</th> <th style="width: 50%; text-align: left;">No. Copies</th> </tr> </thead> <tbody> <tr> <td>DEFRA</td> <td>1 PDF</td> </tr> <tr> <td>Golder Associates (UK) Ltd</td> <td>1 PDF</td> </tr> </tbody> </table>		Name	No. Copies	DEFRA	1 PDF	Golder Associates (UK) Ltd	1 PDF	
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  - C. Applied after the report has been reviewed but before it has been approved by the Project Manager.
  - B. Applied after the Project Manager has approved the report ready for issue to the client.
  - A. Applied to reports after external/client review.
- The version number starts at '0' and is raised by '1' at each re-type.

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## EXECUTIVE SUMMARY

Golder Associates (UK) Ltd has carried out an evaluation and appraisal of waste policies and projections to 2050 for UK Landfill Methane Emissions on behalf of DEFRA. An economic appraisal of the policies included within the Central Scenario was undertaken by Ecofys.

Three Scenarios (Central/Future1, Future3 and Future5) based on different Municipal Solid Waste (MSW) arisings generated from the Local Authority Waste Recycling Recovery and Disposal (LAWRRD) model, between 2001 and 2020, have been considered. The LAWRRD model uses fiscal drivers to determine the waste routes by which compliance with the Landfill Directive and Waste Strategy targets can be achieved.

A total of 18 Scenarios have been created by combining three elements of 'variation in waste growth', 'increase in lead time', and 'variation in build capacity'. The variation in the waste growth element includes two circumstances, namely central estimate waste growth and low waste growth. The increase in the lead time element contains three situations, namely central estimate lead time, low lead time (increase) and high lead time (increase). The variation in build capacity comprises three situations, namely central estimate build capacity, low build capacity (reduced) and high build capacity (increased).

The Central/Future1 Scenario is described as a central estimate waste growth with central estimate lead time and central estimate build capacity. The predicted Central Scenario is for the achievement of waste targets on time. Total MSW to landfill from 2001 to 2020 is an estimated 283 million tonnes (Mt). The Future3 Scenario is described as a central estimate waste growth with central estimate lead time and high build capacity. It has the fastest reduction in MSW going to landfill of all the 18 Scenarios generated by the LAWRRD model suites. Total MSW to landfill from 2001 to 2020 is an estimated 270 Mt. The Future5 Scenario is described as a central estimate waste growth with high lead time and low estimate build capacity. It has the slowest reduction in MSW going to landfill of all the 18 Scenarios generated by the LAWRRD model suites. Total MSW to landfill from 2001 to 2020 is an estimated 324 Mt.

Output from the LAWRRD model for the existing years (to 2005) has been compared against actual waste arisings published by DEFRA. For 2002 and 2003 the difference between the LAWRRD model predictions and the actual waste arisings data were 2% and 4% respectively. The differences between the actual waste arising data and the LAWRRD model data were considered insignificant. The LAWRRD model data were taken to be representative of the current situation. The MSW data from the LAWRRD model are for England only and so scaling factors for conversion between the different Devolved Administrations and the UK as a whole were employed. The scaling factors are based on waste arisings data from 2003/04, with England making up 83% of the UK total.

The tonnages of waste to landfill from waste reception and pre-treatment facilities have been calculated assuming that 10% of Civic Amenities (CA) waste is not recycled and goes ultimately to landfill; 100% Dirty Materials Recovery Facilities (MRFs) wastes go to landfill; 50% Biowaste, 50% Mechanical-biological pre treatment (MBT) compost and 100% unprocessed wastes go to landfill. The calculated data have been compared with actual landfill data. For example, the calculated data to landfill in the UK are 22.1 million tonnes in 2001, 22.3 million tonnes in 2002 and 21.6 million tonnes in 2003. Compared with the actual tonnage of MSW disposed in landfill in the UK the differences are 1.3% in 2001, 0.9% in 2002 and 3.2% in 2003. The calculated data to landfill based on the LAWRRD model have been applied in the National Methane Assessment Model.

Commercial and Industrial (C&I) data have been based on draft data from the Strategic Waste Management Assessments (SWMAs), which are produced by the Environment Agency, and which will be imminently formalised. These data include information on inert, construction and demolition, hazardous, municipal, waste transfer stations and civic amenity sites. The Central Scenario C&I data are based on Scenario S8\_1 (Baseline Current Landfill) in the report "Methane Emissions from Landfill Sites in the UK" (LQM, 2003).

All Scenarios have been projected to 2050 using the National Methane Assessment Model. The National Methane Assessment Model is based on the International Panel on Climate Change (IPCC) Tier 2 model with UK specific modifications. Additional modifications to the model for this current project have included: 2000-2005 projections updated with real data where appropriate; utilisation of landfill methane by engines or flares after 2005; reduced methane oxidation from 75% to more realistic values; new scenarios; and model projections to 2050.

The MSW projections in the modified National Methane Assessment Model are based on extrapolation of the trend in growth of waste arisings from the previous MSW waste projections between 2001 and 2020. For other waste streams a constant value based on the 2005 data was maintained until 2050, as was originally assumed in the National Methane Assessment Model. Output from the National Methane Assessment Model is in tonnes of methane (CH<sub>4</sub>) or carbon dioxide equivalent (CO<sub>2</sub>e) per year. The total methane generated from 1945 to 2050 for the Central Scenario is 266,162 kt, for the Future3 Scenario 265,783 kt and for the Future5 Scenario 270,008 kt.

A sensitivity analysis based on the fraction of methane emitted through fissures and field oxidation efficiency, within the methane oxidation module of the National Methane Assessment Model, was undertaken for all Scenarios. The maximum and minimum methane emitted were generated by the IPCC default values and the LQM default values within the methane oxidation module, respectively. A central estimate, named the Golder revised methane oxidation model case, lies between the two extremes of the IPCC and LQM default values. The LQM case has 10% methane loss through fissures, a field oxidation efficiency of 75%, and 90% overall oxidation. The Golder revised methane oxidation model case has 50%

methane loss through fissures, a field oxidation efficiency of 50%, and 25% overall oxidation. The IPCC case has 10% overall oxidation. Methane oxidation modelling has a much greater impact on the results than the scenario modelling.

The guidance of the Environment Agency with respect to landfill gas collection states that there must be at least 85% gas recovery from wastes during the gas utilisation phases of a landfill. The 85% gas collection efficiency is generally applied without consideration of the non-gas utilisation phases of a landfill and so, to maintain consistency with previous work, an 85% gas collection efficiency was applied in the modelling of both the LQM and IPCC oxidation sensitivity analyses. An expert review group, in consultation with DEFRA, agreed that a 75% gas collection efficiency is actually more representative over the whole life time of a landfill site to take into consideration both the gas utilisation and non-gas utilisation phases. A 75% gas collection efficiency was applied to the Golder revised methane oxidation model case to represent current best understanding.

In 2003 the CH<sub>4</sub> emitted varies between 384 and 996 kt per year for the Central/Future1 Scenario. The range reflects the variance observed between the LQM base case (default case and lowest emissions), the Golder revised methane oxidation model case, and the IPCC default (maximum forecast emissions). For the Future3 and Future5 Scenarios the CH<sub>4</sub> emitted varies between 386 and 1016 kt.. By 2050, the total CH<sub>4</sub> emitted per year has decreased for all three scenarios considered. For the Central/Future1 Scenario the CH<sub>4</sub> emitted varies between 66 and 450 kt per year. Again, the range reflects the variance observed between the LQM base case, the Golder revised methane oxidation model case, and the IPCC default. For the Future3 and Future5 Scenarios the CH<sub>4</sub> emitted varies between 65 and 463 kt.

The predicted methane emissions from 2020-2050 from the Golder revised methane oxidation model, with an assumed 75% gas collection efficiency, are closer to the predicted methane emissions from the IPCC default oxidation model, with an assumed 85% gas collection efficiency, than the results from the LQM oxidation model, with an assumed 85% gas collection efficiency. The greatest contribution of methane emissions in the future are from the managed landfills (Types 1-3). The emissions from historical waste from closed unmanaged landfills (Type 4) is relatively insignificant.

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**GLOSSARY**

AD	Anaerobic Digestion
ACT	Advanced Conversion Technologies
CA	Civic Amenity
C&I	Commercial and Industrial
CCP	UK Climate Change Programme
CHP	Combined Heat and Power
CH <sub>4</sub>	Methane
CO <sub>2</sub>	Carbon Dioxide
CO <sub>2e</sub>	Carbon Dioxide Equivalent (includes all greenhouse gases)
CHP	Combined Heat and Power
BAU	Business as Usual
DETR	Department of the Environment, Transport and the Regions
EA	Environment Agency
ERM	Environmental Resources Management
EU	European Union
FOD	First Order Decay
Foe	Field Oxidation Efficiency
GHG	Greenhouse Gas (emissions)
GQ CHP	Good Quality Combined Heat and Power
GWh	Gigawatt hour
kWh	kilowatt hour
IPPC	Integrated Pollution Prevention and Control Regulations
LA	Local Authorities
LATS	Local Authority Trading Scheme
LAWRRD	Local Authority Waste Recycling Recovery and Disposal
lfg	Landfill Gas
LQM	Land Quality Management
MAC curve	Marginal Abatement Cost curve
MBT	Mechanical-Biological pre Treatment
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
MW	Megawatts
MWh	Megawatt hour
mtoe	Million Tonnes Oil Equivalent
NFFO	Non-Fossil Fuel Obligation
NFPA	Non-Fossil Purchasing Agency
NPL	National Physical Laboratory
O&M	Operation and Maintenance
Of gem	Office of Gas and Electricity Markets
PPA	Power Purchase Agreement
PPC	Pollution Prevention and Control
RO	Renewables Obligation
ROC	Renewables Obligation Certificate (1 ROC = 1 kWh renewable electricity)
RPI	Retail Price Index
SEPA	Scottish Environment Protection Agency
SWMAs	Strategic Waste Management Assessments
Tote	Thousand Tonnes Oil Equivalent
WRAP	Waste and Reduction Action Programme



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## 1.0 INTRODUCTION

### 1.1 Policy Background

Golder Associates (UK) Ltd (Golder) has been commissioned by Defra to provide an evaluation and appraisal of waste policies and projections to 2050 for UK Landfill Methane Emissions (Project Reference CPEG 25). The economic implications of the current policies were assessed by Ecofys on behalf of Golder. The aim was:

*To evaluate the effectiveness of existing policies and measures in limiting emissions of methane from landfill sites for the UK and disaggregated by devolved administration; similarly, to review the scope for strengthening existing policies and/or introducing new policies to tackle emissions from this sector in the longer term; to appraise new policies that may be introduced; and to extend existing projections of methane arising from landfill sites to 2050.*

The UK is currently conducting a review of its Climate Change Programme (CCP) and a revised programme is expected to be produced by the end of 2005. The UK also had a reporting deadline of 15 June 2005 to the EC for its final greenhouse gas projections. 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 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 latest publications can be found at <http://www.naei.org.uk/reports.php>. and also see Solway et al. 2002.

The Green House Gas (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) and in the LQM study (2003), 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, 2000 (Waste Strategy 2000 is currently under review ahead of publication of a revised strategy next year); SEPA, 1999; National Assembly Wales, 1999; DoE (NI), 2001. These strategies will help decrease landfill emissions on new landfills by requiring them to reduce emissions by flaring and utilisation.

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The guidance of the Environment Agency with respect to landfill gas collection states that there must be at least 85% gas recovery from wastes during the gas utilisation phases of a landfill. The 85% gas collection efficiency is generally applied without consideration of the non-gas utilisation phases of a landfill. An expert review group, in consultation with DEFRA, however agreed that a 75% gas collection efficiency is actually more representative over the whole life time of a landfill site to take into consideration both the gas utilisation and non-gas utilisation phases.

This report will contribute to the review of the Climate Change Programme (CCP) by: updating the Methane Emissions model through the consideration of the most appropriate oxidation and gas collection efficiencies; extending the model projections to 2050; and incorporating the estimated impacts of new policies that may be introduced.

## **1.2 Report Structure**

The forecasting models used in the generation of the data used in this report are presented in Section 2. Section 3 summarises the model data manipulation, validation and output. The Scenarios modelled and the associated sensitivity analyses are detailed in Section 4. The economic assessment methodology, undertaken by Ecofys, is discussed in Section 5. All model outputs in tabular and graphical format are included in the appendices.

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## **2.0 FORECASTING MODELS**

### **2.1 LAWRRD**

The Local Authority Waste Recycling Recovery and Disposal (LAWRRD) model was developed for Defra by AEA Technology. The model uses fiscal drivers to determine the waste routes by which compliance with the Landfill Directive (99/31/EC) and Waste Strategy targets can be achieved. The LAWRRD model outputs estimate Municipal Solid Waste (MSW) arisings from 2001 to 2020, which is the end of the timeframe for consideration of all current policies, for different policy initiatives.

The LAWRRD model is a cost-driven, bottom-up model, which uses input data on waste arisings, numbers of facilities (actual and planned) from each Local Authority and sums the relevant outputs to give a representation of England. Three types of Local Authority are categorised: urban, suburban and rural. The assignment of typology is determined by socio-economic and demographic characteristics in area, and allows local variations to be incorporated.

Each year the cost of additions to different waste management facilities is compared with the cost of making no changes. The LAWRRD model considers both the costs and benefits of recycling and residual waste via Civic Amenities. The LAWRRD model considers 9 different technologies at 3 different scales (in addition to landfill). These include residual waste management facilities (e.g. MBT, BMT, EfW and gasification/pyrolysis). By basing decisions on economic cost the model aims to simulate the main driver for local authority decision making. Non-economic drivers of local authorities are represented in the model through pressure factors.

### **2.2 National Methane Emissions 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 than in many other countries, 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 Methane Assessment Model.

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

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International Panel on Climate Change (IPCC) Tier 2 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 National Methane Assessment Model was developed and later updated for Defra by Land Quality Management Ltd (LQM). Brown et al. (1999) compiled waste arisings data from 1945 to 1995, and produced forecasts to 2010. LQM has used these waste arisings as the baseline for the 2002 assessment, and updated the waste arisings data and forecasts with the 1999 estimates of municipal solid waste (MSW) and commercial and industrial (C&I) wastes from the companion study by Environmental Resources Management (ERM). Waste management scenarios also developed by ERM were used by LQM to examine the effect of different scenarios on methane generation and emission, and these data were passed back to ERM for use in their companion study.

For this current project the following modifications and changes to assumptions to the above version of the model have been made:

- 2000 - 2005 projections updated with real data where appropriate (last year of real data in model 1994);
- Potentially fugitive landfill methane managed by gas engines or flares after 2005;
- Methane oxidation reduced from 75% to intuitively more realistic values, while remaining close to the error bounds of the earlier validation studies;
- New Scenarios added; and
- Model projections extended from 2025 – 2050.

### 3.0 MODEL DATA MANIPULATION, VALIDATION AND OUTPUT

#### 3.1 MSW Arisings and Scalings

The MSW data were generated from the LAWRRD model (see Section 2.1). Output from the LAWRRD model for the existing years (to 2005) has been compared against actual waste arisings published by DEFRA. For 2002 and 2003 the difference between the LAWRRD model predictions and the actual waste arisings data were 2% and 4%, respectively. These differences were considered insignificant and the LAWRRD model data were taken to be representative of the current situation.

The tonnages of waste to landfill from waste reception and pre-treatment facilities have been calculated assuming that 10% of Civic Amenities (CA) waste is not recycled and goes ultimately to landfill; 100% Dirty Materials Recovery Facilities (MRFs) wastes go to landfill; 50% Biowaste, 50% Mechanical-biological pre treatment (MBT) compost and 100% unprocessed wastes go to landfill. The calculated data have been compared with actual landfill data. For example, the calculated data to landfill in the UK are 22.1 million tonnes in 2001, 22.3 million tonnes in 2002 and 21.6 million tonnes in 2003. Compared with the actual tonnage of MSW disposed in landfill in the UK the differences are 1.3% in 2001, 0.9% in 2002 and 3.2% in 2003. The calculated data to landfill based on the LAWRRD model have been applied in the National Methane Assessment Model.

The MSW data from the LAWRRD model are for England only. Scaling factors for conversion between the different Devolved Administrations and the UK as a whole were employed. The scaling factors were supplied by Defra (EPE & ESI) and are based on waste arisings data from 2003/04 (see Appendix 1).

**Table 1: MSW Scaling Factors**

Region	As a % of UK Total Waste Arisings from 2003/04
England	83
Scotland	9
Wales	5
Northern Ireland	3

#### 3.2 Commercial and Industrial

Commercial and Industrial (C&I) arisings are based on Environment Agency data. Draft information from the Strategic Waste Management Assessments (SWMAs), which will be imminently formalised, has been sourced (Environment Agency, Personal Communication, 2005). These data include information on inert, construction and demolition, hazardous, municipal, waste transfer station and civic amenity waste and the details of C&I waste in 2002 has been given in Table A4 in Appendix 2. The Central Estimate Scenario C&I approach is based on Scenario S8\_1 (Baseline Current Landfill) in the LQM (2003) report.

### **3.3 Projections**

All the Scenarios have been projected to 2050 using a modified National Methane Assessment Model. The MSW projections are based on extrapolation of the trend in growth of waste arisings from the previous MSW waste between 2001 and 2020. The Landfill Directive requires that BMW landfilled does not rise above target level in any subsequent year. Therefore, the fraction of BMW landfilled does not increase post 2019/20, but we cannot assume that it continues to fall as there are no additional drivers/targets. For other C&I waste streams a constant value based on the 2005 data were maintained until 2050, as was originally assumed in the LQM (2003) study.

### **3.4 Total Greenhouse Gas Emissions**

Output from the Methane National Assessment Model is in tonnes CH<sub>4</sub> and tonnes CO<sub>2</sub> equivalent per year. The annual total methane emission estimates for the Central Scenario (with sensitivities) between 2000-2050, was passed to Entec to incorporate in the non-CO<sub>2</sub> greenhouse gas emissions projections to 2050 and reported in the June 15 submission to the EC. Both of these results will be reported in the revised Climate Change Programme (CCP).

## 4.0 SCENARIOS AND SENSITIVITY ANALYSES

### 4.1 MSW Scenarios

A total of 18 future MSW arisings scenarios have been generated by the LAWRRD model between 2001 and 2020 (See Appendix 1, Figure A1 and Table A1). The scenarios are created from a  $2 \times 3 \times 3$  Matrix as shown below in Table 2.

**Table 2: How the 18 Future MSW Arisings Scenarios were Created**

Future Scenarios	Variation in Waste Growth		Increase in Lead Time			Variation in Build Capacity		
	Central Estimate Waste Growth	Low Waste Growth	Central Estimate Lead Time	Low Lead Time (increase)	High Lead Time (increase)	Central Estimate Build Capacity	Low Build Capacity (reduced)	High Build Capacity (increased)
<i>Future1</i>	x		x			x		
<i>Future2</i>	x		x				x	
<i>Future3</i>	x		x					x
<i>Future4</i>	x				x	x		
<i>Future5</i>	x				x		x	
<i>Future6</i>	x				x			x
<i>Future7</i>		x	x			x		
<i>Future8</i>		x	x				x	
<i>Future9</i>		x	x					x
<i>Future10</i>		x			x	x		
<i>Future11</i>		x			x		x	
<i>Future12</i>		x			x			x
<i>Future13</i>		x		x		x		
<i>Future14</i>		x		x			x	
<i>Future15</i>		x		x				x
<i>Future16</i>	x			x		x		
<i>Future17</i>	x			x			x	
<i>Future18</i>	x			x				x

*Note: Future1/Central, Future3 and Future5 scenarios were considered in the subsequent evaluation.*

Three Scenarios, based on different MSW arisings generated from the LAWRRD model between 2001 and 2020 have been considered, namely Central/Future1, Future3 and Future5 Scenarios. The predicted Central/Future1 Scenario is for the achievement of waste targets on time. Estimates of the economic costs associated with of the policies considered within the LAWRRD model have been made and are presented in Section 5.

Future3 and Future5 Scenarios were taken from the suite of 18 Future MSW arisings generated by the LAWRRD model. The Future3 Scenario is described as a central estimate waste growth with central estimate lead time and high build capacity. It has the fastest reduction in MSW going to landfill of all the 18 Scenarios generated by the LAWRRD model suites. The Future5 Scenario is described as a central estimate waste growth with high lead

time and low estimate build capacity. It has the slowest reduction in MSW going to landfill of all the 18 Scenarios generated by the LAWRRD model suites.

#### **4.2 Sensitivity Analyses (Methane Oxidation and Gas Collection)**

Methane emissions from UK landfills have been estimated and projected using the modified Methane National Assessment Model to 2050. A sensitivity analysis for all Scenarios has focussed on variations in the 'fraction methane through fissures' and 'field oxidation efficiency' (foe) values within the methane oxidation module of the National Methane Emissions Model. Three sensitivities have been investigated for each Scenario:

- LQM default base case (fissures 10%, foe 75%) - 90% overall oxidation of residual emissions;
- Central case (fissures 50%, foe 50%) - 25% overall oxidation of residual emissions; and
- IPCC defaults - 10% oxidation of all residual emissions.

The guidance of the Environment Agency with respect to landfill gas collection states that there must be at least 85% gas recovery from wastes during the gas utilisation phases of a landfill. The 85% gas collection efficiency is generally applied without consideration of the non-gas utilisation phases of a landfill. To maintain consistency with previous work, an 85% gas collection efficiency was applied in the modelling of both the LQM and IPCC oxidation sensitivity analyses. An expert review group, in consultation with DEFRA, agree that a 75% gas collection efficiency is actually more representative over the whole life time of a landfill site to take into consideration both the gas utilisation and non-gas utilisation phases. A 75% gas collection efficiency was therefore applied to the Golder revised methane oxidation model case to represent current best understanding.

#### **4.3 Results Summary**

In 2003 the CH<sub>4</sub> emitted varies between 384 and 996 kt per year for the Central Scenario. The range reflects the variance observed between the LQM base case (default case and lowest emissions), the Golder revised methane oxidation model case, and the IPCC default (maximum forecast emissions). For the Future3 and Future5 Scenarios the CH<sub>4</sub> emitted varies between 386 and 1016 kt.

By 2050, the total CH<sub>4</sub> emitted per year has decreased for all three scenarios considered. For the Central Scenario the CH<sub>4</sub> emitted varies between 66 and 450 kt per year. Again, the range reflects the variance observed between the LQM base case, the Golder revised methane oxidation model case, and the IPCC default. For the Future3 and Future5 Scenarios the CH<sub>4</sub> emitted varies between 65 and 463 kt. (see Tables A5-A7 in Appendix 3 and Figures A2-A4 in Appendix 4).



A breakdown of the contribution of methane emissions from the four different types of landfill modelled within the National Methane Assessment Model are provided in Appendix 5. Four landfill types are considered within the National Methane Assessment Model: Type 1 landfills have no gas collection; Type 2 landfills have limited gas collection; Type 3 landfills have comprehensive gas collection; and Type 4 landfills are old closed sites with no gas collection. The greatest contribution of methane emissions in the future forecasts are from the managed landfills (Types 1-3). The emissions from historical waste from closed unmanaged landfills (Type 4) is relatively insignificant.

The predicted methane emissions from 2020-2050 from the Golder revised methane oxidation model, with an assumed 75% gas collection efficiency, are closer to the predicted methane emissions from the IPCC default oxidation model, with an assumed 85% gas collection efficiency, than the results from the LQM oxidation model, with an assumed 85% gas collection efficiency. A reduction in gas collection efficiency, which could be a result from the diversion of biodegradable wastes from landfills, could result in a doubling of the emissions of methane to the atmosphere, all other factors being equal.

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## 5.0 ECONOMICS

### 5.1 Ideal Policy Evaluation Approach

The economic implications of the current waste policies were assessed by Ecofys on behalf of Golder. A qualitative discussion of the policy impacts on greenhouse gas emissions was undertaken. The main policies considered as measures in the Central Scenario included the following:

- Non-fossil Fuel Obligations (NFFOs);
- Renewables Obligation (RO);
- UK Landfill targets and EU Landfill Directive (99/31/EC); and
- Landfill Tax and Landfill Allowance Trading Scheme (LATS). LATS is England's mechanism for meeting the LFD, whereas the Landfill Tax underpins achievement of the Landfill Directive and drives diversion of non-municipal from landfill.

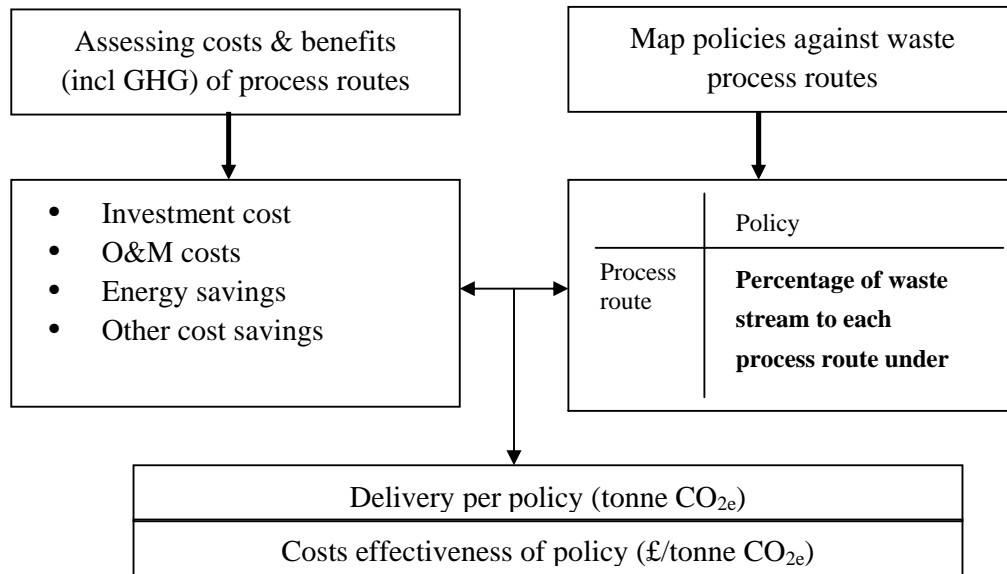
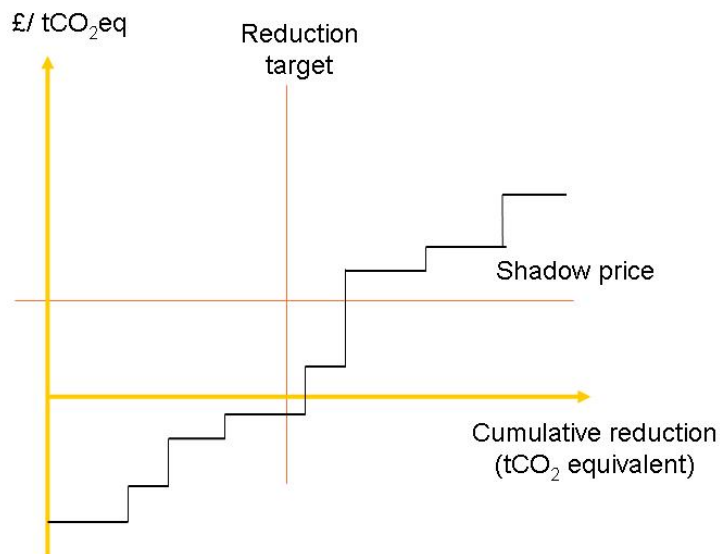
It should be noted that there are other policies and independent factors outside the scope of this report that affect the viability of renewables, ranging from the exemption to the Climate Change Levy to rising global oil prices.

Within this report the ideal methodology for policy evaluation is presented and the results based on the impacts of each of the main policies and measures from the Central Scenario. The aim of the bottom-up methodology is to gain an understanding of the relative effectiveness and impact of the existing landfill site policies with respect to methane emissions.

To do this, it is necessary to calculate the costs/benefits for the Central/Future1 Scenario which involves an understanding of:

- The investment costs per process route additional to business-as-usual in £/tonne waste;
- The cost savings (including O&M, energy generation, avoided other costs) in £/tonne waste;
- The greenhouse gas reduction in tonne CH<sub>4</sub> (or CO<sub>2</sub> equivalent, CO<sub>2</sub>e) per tonne waste;
- The policy costs for each relevant policy; and
- The relationship between process routes and individual policies.

Using this information, the cost-effectiveness of each policy in £/tonne CO<sub>2</sub>e can be calculated as demonstrated in the figure below.

**Figure 1: Bottom-Up Methodology to Calculate Policy Cost Effectiveness.****Figure 2: Marginal Abatement Cost Curve (MAC)**

To calculate policy delivery business as usual (BAU), which was assumed to be without policies and measures so that this could be compared to the four policies discussed (NFFO, RO, Landfill targets, Landfill tax), baseline emissions projections would need to be compared to 'policy additionality' projections also taking into account technology penetration levels. Another useful tool for bottom-up policy appraisals is the Marginal Abatement Cost (MAC) curve (as shown in Figure 2). This curve ranks internal emission reduction options and measures on the basis of their marginal abatement costs. The point where the MAC curve intersects the market shadow price marks the transition between cost-effective internal and external emissions reductions. The purpose of the shadow price is to provide a reference for long-term internal investments.

## **5.2 Relationship Between Process Routes and Individual Policies**

There are several methodological issues in this project which make the analysis for waste policies difficult. Firstly, it has not been possible within the scope of this analysis to map the waste disposal technologies directly onto waste policies as the UK waste policies are too generic. For example, targets to divert biological municipal waste away from landfill could be achieved using a number of different waste disposal/treatment technologies. Making a direct link between Government policies and the technologies used in practice would therefore require more in-depth and detailed analysis to enable the direct link between policies, costs and GHG emissions to be made.

Secondly, waste policies have multiple objectives, of which climate change is rarely a primary one. GHG emission reductions from waste policies are therefore a secondary benefit. Although the GHG abatement from waste policies could potentially be very large, this is not necessarily the case. Calculating the cost-effectiveness of waste policies in GHG terms alone can therefore be misleading and could result in very high costs per tonne of emissions reduction when compared to specific climate change policies. A fair analysis of the cost-effectiveness of waste policies would have to be able to take into account other benefits of the policy, for example impacts on local air quality emissions. However this is not straightforward as the different benefits are difficult to quantify in a way that enables direct comparison.

These issues complicate the use of the methodology described above. Therefore, instead the analysis will focus on a qualitative assessment of policies that impact on UK Landfill Methane Emissions.

## **5.3 Environmental Impact of Central Scenario with 3 Sensitivity Cases**

Table 3 below summarises the total methane emitted for the 3 sensitivity cases considered within the Central/Future1 Scenario. The total methane generated from 1945 to 2050 for the Central/Future1 Scenario considered is 266,162 kt. The maximum and minimum methane emitted are generated by the IPCC default case and the base case (LQM default), respectively.

The case with revised methane oxidation model parameters lies between these two extremes. The projections have been undertaken to 2050 to investigate the possibly options for long-term policy targets.

**Table 3: Methane Generations and Emissions Summary for Central Scenario**

Year	Total Methane Generated (kt)	Total Methane Emitted (kt)		
		Base Case (LQM Default)	Golder revised methane oxidation model	IPCC Default Case
2005	3432.3	332.7	602.5	845.7
2010	3418.2	249.5	487.3	706.0
2025	3210.2	126.3	333.9	533.9
2050	3153.9	66.3	258.6	449.0
1945-2050	266,162	78,153	99,807	113,071

#### 5.4 Economic Impact of Central Scenario with 3 Sensitivity Cases

The following section discusses the impact of the UK policies that affect landfill methane. The main policies considered as measures in the Central Scenarios included the Non-Fossil Fuel Obligations (NFFOs), the Renewables Obligations (RO), the UK Landfill targets and EU Landfill Directive (99/31/EC) and the Landfill tax and Landfill Allowance Trading Scheme (LATS). For each of these policies the discussion is split into the following six sections:

- The policy;
- How does the policy work;
- Theoretical impact on landfill methane;
- Theoretical impact on UK GHG emissions;
- Success so far; and
- Cost to UK plc.

It should be noted that in addition to these policies the IPPC regulations require landfill operators to either flare or utilise all the available landfill gas, with a target of 85% gas collection efficiency during the gas utilisation phase of a landfill. Flaring methane decreases GHG impact by a factor of approximately 21 by oxidising methane to carbon dioxide. Therefore when assessing the impacts of the above policies it could be argued that the baseline scenario should be that of flaring methane rather than venting it to the atmosphere.

##### 5.4.1 Non-fossil fuel obligation

###### 5.4.1.1 The Policy

The Non-Fossil Fuel Obligation (NFFO) was in place in the UK from 1990 to 1998 (preceding the Renewables Obligation) and enabled renewable electricity generators to receive a guaranteed premium price for the electricity they generated.

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#### 5.4.1.2 How did the Policy Work

A series of five NFFO rounds were held in 1990, 1991, 1995, 1997 and 1998. In each round the Non-Fossil Purchasing Agency (NFPA) would invite bids from renewable generators for proposed renewables projects. A bid would include the price in pence per kilowatt-hour (p/kWh) that the renewable generator would require to generate and their proposed generating capacity in megawatts (MW). NFFO contracts would then be awarded to the projects with the lowest bid price, up to the generating capacity ceiling set in each round.

Once a NFFO contract had been secured the project owner could complete all other arrangements such as securing planning permission and financing. Once the generating plant was built, electricity would be sold at the bid price (index-linked) for the duration of the NFFO contract, which could be up to 15 years. NFFO contracts from rounds 1 and 2 have expired, but some contracts from later NFFO rounds are still running.

The NFFO system allowed different price premiums to be paid for different technologies, according to their stage of commercialisation and also enabled specific levels of capacity to be contracted for each technology.

#### 5.4.1.3 Theoretical Impact on Landfill Methane

Combustion of methane produces carbon dioxide which is roughly 21 times less potent as a GHG. Therefore burning the methane will reduce the climate change impact of a specific landfill site. In terms of GHG emissions from a single landfill site, electricity generation from landfill gas (lfg) produces the same emissions impact as flaring methane, but utilization save the generation of energy, and hence emissions, elsewhere. The current regulatory requirement for full site gas management by flaring was not present at the time of the earlier NFFO rounds.

#### 5.4.1.4 Theoretical Impact on UK GHG Emissions

The impact of landfill gas electricity generation on overall UK GHG emissions depends on the electricity that is being displaced, as well as the landfill gas utilised which was not otherwise flared. In 1990 when the NFFO was introduced, natural gas generation only made up 0.5% of all electricity used in the UK, with 67% being from coal (DUKES, 2004). Electricity generation from landfill gas would therefore have had much lower carbon intensity than the grid. However natural gas generation has increased significantly throughout the 1990s and accounted for 38% of electricity generated in 2003, with coal only accounting for 35% (DUKES, 2004). Marginal electricity generation which landfill gas displaces is now largely natural gas so landfill gas generation does not generally decrease the carbon intensity of generation, although it does decrease overall emissions.

#### 5.4.1.5 Success so Far

NFFO did succeed in stimulating generation from landfills and in reducing the cost of electricity generated from landfill. In 1990 79.8 thousand tonnes oil equivalent (Ttoe) [928 GWh] energy was generated from landfill gas and by 2000 this figure had risen by almost a factor of ten to 731.1 Ttoe [8503 GWh] (DUKES, 2004). Although NFFO is no longer in place, NFFO contracts could run for up to 15 years so there are roughly 170 landfill electricity contracts still running, equating to over 350 MW installed (DUKES, 2004).

#### 5.4.1.6 Cost to UK plc

The bid price for landfill electricity fell from around 9 p/kWh in 1990 to around 3 p/kWh in 1998, although many of the NFFO-5 contracted sites have not progressed to commissioning due to perceived marginal economic viability at the lower bid price.

### 5.4.2 **Renewables obligation**

#### 5.4.2.1 The Policy

The Renewables Obligation (RO) superseded NFFO and is now the main UK policy to encourage renewable electricity generation. The RO has been in place in the UK since April 2002 as an obligation on electricity suppliers to source a target percentage of their electricity from renewable electricity generation.

#### 5.4.2.2 How does the Policy Work

UK electricity generators must supply a rising percentage of their electricity from renewable sources. This target was set at 3% in 2002/03 and will increase incrementally to 10.4% in 2010/11 and then 15.4% in 2015/16. The UK Government has guaranteed that the policy will remain in place at least until 2027, although no targets have yet been set post-2016.

At the end of March each year, electricity suppliers must hold 'Renewables Obligation Certificates' (ROCs) equivalent to the amount of renewable electricity they are obliged to have supplied. A company gains ROCs either in exchange for selling renewable electricity it has generated, by purchasing ROCs directly from other renewable electricity generators or by trading ROCs with other parties. If an electricity supplier does not hold enough ROCs at the end of the year to cover their obligation they must pay a 'buy-out' price. The 'buy-out' price was set at £30/MWh in 2002/03 and increases in line with RPI annually. It was £31.39/MWh for the period 2004/05.

The 'buy-out' fund is redistributed to electricity suppliers according to the number of ROCs each holds, hence providing an added incentive to hold ROCs and keeping the ROC price higher than the buy-out price. The market price of ROCs is currently around £45/MWh.

Electricity generated from landfill gas is eligible to earn ROCs. If biodegradable MSW is diverted from landfill, certain fractions could theoretically be used to generate biomass electricity. Currently electricity generated from biodegradable MSW using Advanced Conversion Technologies (ACT), such as Anaerobic Digestion (AD), gasification and pyrolysis, is eligible to earn ROCs as it is considered to be 'carbon neutral'. However other forms of generation from mixed waste (i.e. Energy from Waste via direct mixed waste combustion) are not eligible to benefit from the RO.

#### 5.4.2.3 Theoretical Impact on Landfill Methane

The biodegradable fraction of waste decomposes in landfills and releases landfill gas. Methane from landfills can be collected and burned to generate heat and power, or more simply flared. Both processes oxidise the methane in landfill gas to carbon dioxide, which is emitted to the atmosphere. Carbon dioxide is around 21 times less potent as a GHG than methane. Landfill gas from landfills issued with a new pollution prevention and control (PPC) permit under the PPC Regulations will now have to be flared, with or without the RO.

Generating electricity from landfill gas does not itself reduce emissions compared with flaring. PPC permits are being issued to the approximately 1000 currently operational landfill sites in seven tranches between 2003 and 2006. However, there are many older sites which are either unregulated or retain a Waste Management License, and these are unlikely to achieve this level of landfill gas management. The scenarios modelled address the different regimes under which landfilling have taken place.

Reducing the amount of biodegradable waste to landfill will ultimately reduce landfill methane emissions. It should also be noted that reducing biodegradable waste to landfill will also reduce the lfg generation potential and may mean that only landfill gas flaring (and not power generation) is feasible on certain sites, although the biodegradable waste could be diverted to generate biomass electricity using ACT.

Anaerobic Digestion (AD) is a similar biochemical process to that which occurs in landfills, except that in this case the organic component of waste is separated out and placed in a specific tank under controlled conditions to maximise "biogas" (typically around 60% methane and 40% carbon dioxide) collection. More advanced biomass technologies include gasification or pyrolysis of organic material.

#### 5.4.2.4 Theoretical Impact on UK GHG Emissions

Overall generating electricity from landfill methane does reduce GHG emissions as it reduces demand for other forms of electricity generation, and therefore removes from the equation the emissions that the other generators would have emitted. Marginal grid electricity is typically from natural gas in the UK so this displacement by landfill gas is unlikely to significantly lower the carbon intensity of electricity generation and the electricity generation sector will



therefore not emit fewer GHG emissions per MWh generated, but overall electricity generation plus landfill emissions will be lowered. CHP on landfill sites would however increase overall heat and power generation efficiency.

Generating electricity using ACT will have a roughly similar effect on overall GHG emissions to generating electricity from landfill gas, although there will be differences in gas collection/electricity conversion efficiencies depending on the development stage of the technology and the scale of the operation.

#### 5.4.2.5 Success so Far

Almost 42% of ROCs issued in the UK in the period 2003/04 were from landfill gas electricity, making landfill generation the largest producer of renewable electricity in the UK at the moment. (For comparison, on-shore wind was second with 16% of ROCs issued.)

The RO offers an attractive incentive for landfill gas and utilisation has contributed to a further increase in generation following the end of NFFO. Following the introduction of the RO, electricity generation from landfill gas increased by over 20% in one year from 892.1 Ttoe in 2002 to 1088.1 Ttoe in 2003 (DUKES, 2004).

Electricity from ACT however is currently not quite close enough to market and is still very expensive. The RO alone is not sufficient to make such technologies economically viable at present.

#### 5.4.2.6 Cost to UK plc

As operational landfill sites must already invest in the technology to collect and flare methane to comply with PPC regulations, theoretically the RO need only provide the financial incentive to make the incremental investment in electricity generation or CHP technology.

The current market price of ROCs is around 4.5p/kWh, which renewable generators receive on top of the wholesale price for electricity, which is typically around 3-4p/kWh, although this will vary according to the Power Purchase Agreement (PPA) negotiated.

The RO therefore offers a higher price per kWh than (later) NFFOs, therefore providing a greater incentive to generate more landfill gas power, but often the most attractive sites have already been signed up to NFFO contracts. Most landfills that are currently obtaining ROCs are those from the earliest NFFOs where contracts have already ended but generation continues.

One commonly stated criticism of RO is that it only incentivises those technologies which are closest to market and does not help less commercially developed technologies. Unlike NFFO, the RO does not have the ability to distinguish between technology types. The RO provides a

good incentive for landfill gas utilisation but is not currently a sufficiently good incentive for ACT.

There is an administration cost to Government of the RO, and specifically to Ofgem (Office of Gas and Electricity Markets) who administer the scheme and keep a register of all ROCs generated. Because the RO and the precursor NFFO arrangements incentivise methane emissions abatement, and there is a regulatory requirement to flare the gas if utilisation was not carried out, UK landfill emissions are considered neutral for carbon emissions trading purposes.

### **5.4.3 UK Landfill targets and EU landfill directive**

#### **5.4.3.1 The Policy**

The EU Landfill Directive, and its transposition into UK legislation in the form of National Landfill Targets for biodegradable waste, makes up a key part of UK waste policy.

#### **5.4.3.2 How Does the Policy Work**

The EU Landfill Directive states that by 2006, biodegradable waste going to landfill must be 75% of the amount generated in 1995; by 2009 this is reduced to 50% and by 2016 to 35%. However member states such as the UK that landfilled more than 80% of their solid municipal waste in 1995 are allowed to use up to a 4 year derogation on these targets.

The targets could be met by reducing the amount of organic waste generated, or by treating the waste other than through landfills. Different treatment routes include:

- Composting;
- Recycling
- Anaerobic digestion;
- Refuse-derived fuel;
- Energy from waste; and
- Advanced conversion technologies (biomass).

The Landfill Allowance Trading Scheme (LATS) was launched in April 2005 as mechanism to help LAs in England and Wales meet their landfill targets in a cost-effective way. Each faces a cap to the amount of biodegradable MSW they can landfill, with a penalty of £150/tonne waste for exceeding the cap. LAs can trade LATS allowances in order to comply, or reprofile its own allowances through banking and borrowing.

If all active landfills accept less and less bio-active waste (to meet targets) without trading LATS allowances, fewer sites will be able to support landfill gas generation. This would necessitate more policy intervention to keep landfill gas generation economically feasible, or would lead to more landfills reverting to a policy of simply collecting and flaring the

methane. LATS gives LAs the ability to trade the right to landfill its own waste. Presumably if it is currently economic to generate electricity from landfill gas, LAs will continue to so in the future by concentrating landfill activity at the scale required.

LAs do have the theoretical ability to trade biodegradable waste between landfill sites to produce sites with high bio-active waste concentrations specifically suitable for landfill gas generation, but LATS does not explicitly provide the incentive to do this and it is unclear whether this is a strategy the LAs will choose to use.

#### 5.4.3.3 Theoretical Impact on Landfill Methane

Methane is produced in landfills by anaerobic (i.e. without oxygen) degradation of waste. There is a regulatory guidance expectation that landfill sites operating under the PPC regime will need to achieve utilisation or flaring of at least 85% of the generated gases overall. Recycling or diversion of the methane generating fraction will only have an impact on the landfill methane generated from newly deposited waste. Waste deposited prior to any diversion policy will continue to produce methane according to the production rate of the particular landfill.

#### 5.4.3.4 Theoretical Impact on UK GHG Emissions

The Landfill Directive will only have a major effect on the reduction of GHG arising from current and future waste arisings, which are subject to the targets in the Directive.

#### 5.4.3.5 Success so Far

The 1999 Landfill Directive has been successfully transposed into UK legislation and the LATS started in April this year providing LAs with a mechanism to reach their targets. At present it is too early to reflect on the results of the policies.

#### 5.4.3.6 Cost to UK plc

The cost-effectiveness of this policy as a means to reduce methane emissions overall will clearly depend on which treatment routes are favoured for the biodegradable waste. All the before mentioned routes could provide a revenue stream, either simply from compost sales or from renewable heat and power generation. Any electricity generation from the above routes would be eligible to benefit from the RO.

The administrative cost of LATS is likely to be lower than for the EU Emissions Trading Scheme as there are fewer players in the market. Also allowances are issued to LAs not individual installations and waste volumes are already measured. Waste data flow is a new measurement mechanism that will require increased administrative input. Fewer players however may lead to a less liquid market.

Decreasing biodegradable waste to landfills to meet the national targets will reduce methane emissions from landfills. However, the remaining biodegradable waste in landfills will continue to produce methane, in lower quantities than before – this may reduce the economic viability of generating at landfill sites. From an economic point of view the ideal situation might be to concentrate biodegradable waste in large landfills which could support landfill gas generation, while separated fractions of waste with lower biodegradability are consigned to other landfills without generation. However, the Landfill Directive targets in combination with the historic structure of landfills/LAs make this unlikely.

#### **5.4.4 Landfill tax**

##### **5.4.4.1 The Policy**

The 2003 landfill tax escalator is a levy on waste sent to landfills. Specifically, the landfill tax escalator refers to the increase from £10 to £15 (not £15 to £35).

##### **5.4.4.2 How Does the Policy work**

Landfill tax currently stands at £18/tonne waste and is payable by the landfill operator/owner, although the cost will be passed down to waste producers via gate fees. The tax will increase by at least £3/tonne per year until it reaches a maximum of £35/tonne. However, there is revenue neutrality for increases above £15.

##### **5.4.4.3 Theoretical Impact on Landfill Methane**

In principle the tax system is designed to decrease total volumes of waste, potentially reducing the biodegradable fraction and thus methane emissions from landfill.

##### **5.4.4.4 Theoretical Impact on UK GHG Emissions**

Landfill tax is the one policy within this scope that could have a direct impact on overall waste produced and therefore reduce total GHG emissions. Indeed, any policy that increases the cost of waste management will provide an incentive to minimize. Programmes such as Envirowise and Brew provide support to increase minimisation.

##### **5.4.4.5 Success so Far**

The landfill tax has been successful in encouraging pre-treatment and segregation of waste that enables the application of other waste treatment solutions, and minimise volumes going to landfill.

#### 5.4.4.6 Cost to UK plc

Landfill operators are responsible for paying the tax and will pass these costs on to industry and LAs. Hence, costs for industry will increase through rising gate fees which could be an incentive to invest in measures to reduce waste. However, this may lead to benefits for industry as well through process improvement/optimisation.

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## 6.0 CONCLUSIONS

The UK emission projections were based on a Central/Future1 Scenario with sensitivity analyses. The MSW Central Scenario data assumed achievement of the Waste Strategy 2000 and Landfill Directive targets on time. C&I Central Scenario data were based on the LQM base case (S8\_1) (LQM, 2003). Sensitivity analysis concentrated on the variations in the 'fraction methane through fissures' and the 'field oxidation efficiency' in the methane oxidation module of the National Methane Emissions Model. Three cases were considered: the LQM default values used in the 2003 assessment (the base case); a revised methane oxidation model case and the IPCC default value case.

The guidance of the Environment Agency with respect to landfill gas collection states that there must be at least 85% gas recovery from wastes during the gas utilisation phases of a landfill. The 85% gas collection efficiency is generally applied without consideration of the non-gas utilisation phases of a landfill. To maintain consistency with previous work, an 85% gas collection efficiency was applied in the modelling of both the LQM and IPCC oxidation sensitivity analyses. An expert review group, in consultation with DEFRA, agreed that a 75% gas collection efficiency is actually more representative over the whole life time of a landfill site to take into consideration both the gas utilisation and non-gas utilisation phases. A 75% gas collection efficiency was therefore applied to the Golder revised methane oxidation model case to represent current best understanding.

The total methane generated for the Central Scenario considered is 266,162 kt. The maximum and minimum methane emitted are generated by the IPCC default case and the LQM default case, respectively. The revised methane oxidation model case lies between these two extremes. The predicted methane emissions from 2020-2050 from the Golder revised methane oxidation model, with an assumed 75% gas collection efficiency, are closer to the predicted methane emissions from the IPCC default oxidation model, with an assumed 85% gas collection efficiency, than the results from the LQM oxidation model, with an assumed 85% gas collection efficiency.

The greatest contribution of methane emissions in the future are from the managed landfills (Types 1-3). The emissions from historical waste from closed unmanaged landfills (Type 4) is relatively insignificant. A reduction in gas collection efficiency at managed landfills, which could be a result from the diversion of biodegradable wastes from landfills, could result in a doubling of the emissions of methane to atmosphere, all other factors being equal. Methane oxidation modelling therefore has a much greater impact on the results than the scenario modelling.

A qualitative economic appraisal of the policies included within the Central/Future1 Scenario was undertaken. In considering landfill gas emissions specifically there are two main routes for achieving abatement. First, reducing the organic waste landfilled will eventually reduce landfill methane emissions. However, if this waste is still being produced, it will have to be

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treated elsewhere. Secondly, landfill methane can be captured and flared, rather than vented, reducing its global warming impact by a factor of approximately 21. More beneficially for the atmosphere, the methane can be burned to generate electricity, displacing other non-renewable electricity sources. While this does not reduce the emissions from the landfill, compared with flaring, it does reduce overall emissions by displacing other generators.

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## 7.0 REFERENCES

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**RELEVANT WEBLINKS**

<http://www.naei.org.uk/reports.php>.

**Scotland:**

<http://www.scotland.gov.uk/stats/envonline/menu1.asp?cat=8&des=Waste+and+Recycling>

[http://www.sepa.org.uk/nws/data/data\\_digest.htm](http://www.sepa.org.uk/nws/data/data_digest.htm)

<http://www.sepa.org.uk/publications/wds/html/wdd04/index.html>

**Northern Ireland:**

[http://www.oakdenehollins.co.uk/pdf/RPA\\_ICEEfRW.pdf](http://www.oakdenehollins.co.uk/pdf/RPA_ICEEfRW.pdf)

<http://www.monaghan.ie/download/pdf/Environment/crossborderwastemanagementplan.pdf>

[http://www.repak.ie/db\\_factsheet.pdf](http://www.repak.ie/db_factsheet.pdf)

**Renewables and NFFO's:**

A database of all registered ROC holders <http://www.rocregister.ofgem.gov.uk>

A list of NFFO projects as of 31/12/1997

<http://www.dti.gov.uk/NewReview/nr36/html/nffo.html>

A list of NFFO projects as of 31/12/2000

<http://test.netgates.co.uk/nre/obligation.html>

A list of NFFO projects as of 31/12/2003

[http://www.restats.org.uk/renewables\\_obligations.html](http://www.restats.org.uk/renewables_obligations.html)

A graph of NFFO projects from 1992-2003

[http://www.restats.org.uk/renewable\\_obligations\\_-\\_over\\_10.html](http://www.restats.org.uk/renewable_obligations_-_over_10.html)

A list of NFFO projects as of 31/12/2004 (most recent)

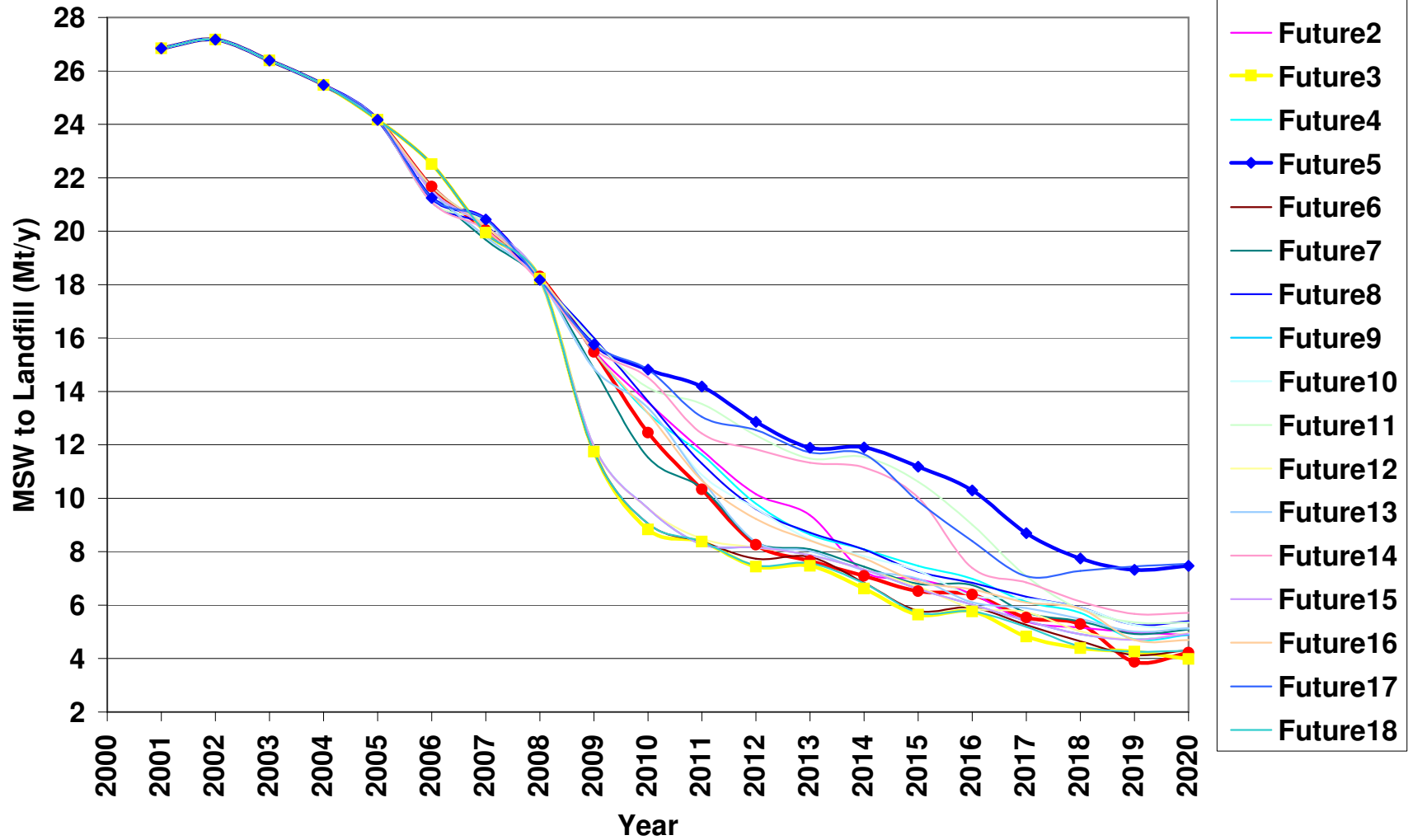
[http://www.dti.gov.uk/renewables/policy\\_pdfs/nffofsdec2004.pdf](http://www.dti.gov.uk/renewables/policy_pdfs/nffofsdec2004.pdf)

## **APPENDICES**

**APPENDIX 1**

**MSW WASTE ARISING (WITH DIVERSIONS)**

Figure A1 MSW to Landfill for all the 18 Scenarios from the LAWRRD Model



**Table A1 MSW to Landfill for all the 18 Scenarios generated by the LAWRRD model**

Suite of Scenarios from the LAWRRD Model with the Central (Future1), Future3 & 5 extremes, named.																				
MSW to Landfill, kt/y	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Central Scenario	27	27	26	25	24	22	20	18	15	12	10	8	8	7	7	6	6	5	4	4
Scen 2	27	27	26	25	24	21	20	18	16	14	12	10	9	7	7	6	5	5	5	5
Future3 Scenario	27	27	26	25	24	23	20	18	12	9	8	7	7	7	6	6	5	4	4	4
Scen 4	27	27	26	25	24	22	20	18	15	13	12	10	9	8	7	7	6	6	5	5
Future5 Scenario	27	27	26	25	24	21	20	18	16	15	14	13	12	12	11	10	9	8	7	7
Scen 6	27	27	26	25	24	23	20	18	12	9	8	8	8	7	6	6	5	5	4	4
Scen 7	27	27	26	25	24	22	20	18	15	12	10	8	8	7	7	7	6	5	5	5
Scen 8	27	27	26	25	24	21	20	18	16	14	11	10	9	8	7	7	6	6	5	5
Scen 9	27	27	26	25	24	22	20	18	12	10	8	8	8	7	7	6	5	5	5	5
Scen 10	27	27	26	25	24	22	20	18	15	13	11	10	8	8	7	6	6	6	5	5
Scen 11	27	27	26	25	24	21	20	18	16	14	14	12	11	12	11	9	7	6	5	5
Scen 12	27	27	26	25	24	22	20	18	12	10	8	8	8	7	7	6	6	5	5	5
Scen 13	27	27	26	25	24	22	20	18	15	13	11	8	8	7	7	6	6	5	5	5
Scen 14	27	27	26	25	24	21	20	18	16	15	12	12	11	11	10	7	7	6	6	6
Scen 15	27	27	26	25	24	22	20	18	12	10	8	8	8	7	7	6	5	5	5	5
Scen 16	27	27	26	25	24	22	20	18	15	13	11	9	8	8	7	7	6	6	5	5
Scen 17	27	27	26	25	24	21	20	18	16	15	13	13	12	12	10	8	7	7	7	8
Scen 18	27	27	26	25	24	23	20	18	12	9	8	7	8	7	6	6	5	4	4	4
Min	27	27	26	25	24	21	20	18	12	9	8	7	7	7	6	6	5	4	4	4
Max	27	27	26	25	24	23	20	18	16	15	14	13	12	12	11	10	9	8	7	8
Average	27	27	26	25	24	22	20	18	14	12	11	9	9	8	7	7	6	6	5	5

**Table A2: MSW Throughput for the Central Scenario (Using LAWRRD Version 7.0)**

Facility inputs of MSW, kt/y	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CA site recovery & recycling	1517	1709	1907	2113	2326	2547	2598	2650	2703	2757	2812	2855	2897	2941	2985	3030	3075	3121	3168	3216
Bring recycling	528	544	561	578	595	613	632	651	670	691	712	729	748	767	786	806	826	847	868	890
MRF	1047	1130	1330	2290	3212	3438	3444	3450	3576	3583	4570	5976	6453	7064	7747	8221	8947	9673	10458	10698
Dirty MRF	47	48	49	50	51	52	55	57	59	62	64	60	62	64	66	68	70	70	70	70
GW composting	957	1195	2141	2304	2410	2624	2800	2848	2890	2954	3071	3133	3179	3233	3281	3333	3415	3467	3510	3570
Biowaste composting/digestion	40	40	40	40	40	90	90	90	90	90	90	447	698	1080	1129	1408	1563	1784	1847	1959
BMT RDF	0	0	0	0	0	2000	3966	4331	5859	7226	8748	8998	9448	9540	9607	9677	9717	9797	10824	10954
MBT compost/RDF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBT compost and residue landfill	0	0	0	0	100	100	200	300	300	358	459	1634	1707	1714	1921	1925	1904	1880	2099	2145
EFW	2887	2894	2900	3107	3591	3862	3853	5693	7223	9170	9197	9218	9387	9726	10120	10356	11038	11185	11287	11433
ACT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unprocessed MSW direct to landfill	22065	22310	21647	20857	19708	17585	16177	14672	12323	9782	7955	5472	4804	4137	3527	3268	2480	2174	855	1063
Total (England only), kt/y	29089	29870	30575	31339	32035	32913	33815	34742	35694	36672	37678	38521	39384	40266	41168	42091	43034	43999	44987	45996
Total (UK), kt/y	35047	35988	36838	37757	38596	39654	40741	41857	43005	44184	45395	46411	47451	48513	49600	50712	51849	53011	54201	55417

**Table A3: Calculation of MSW to Landfill for the Central Scenario (Using LAWRRD Version 7.0)**

Facility inputs of MSW, kt/y	% to landfill	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CA site recovery & recycling	10	152	171	191	211	233	255	260	265	270	276	281	285	290	294	298	303	308	312	317	322
Bring recycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MRF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dirty MRF	100	47	48	49	50	51	52	55	57	59	62	64	60	62	64	66	68	70	70	70	70
GW composting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biowaste composting/digestion	50	20	20	20	20	20	45	45	45	45	45	45	223	349	540	564	704	781	892	924	979
BMT RDF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBT compost/RDF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBT compost and residue landfill	50	0	0	0	0	50	50	100	150	150	179	230	817	853	857	960	963	952	940	1049	1072
EFW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ACT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unprocessed MSW direct to landfill	100	22065	22310	21647	20857	19708	17585	16177	14672	12323	9782	7955	5472	4804	4137	3527	3268	2480	2174	855	1063
Total (England only), kt/y		22284	22549	21907	21138	20062	17987	16636	15189	12848	10344	8575	6858	6359	5892	5416	5306	4590	4389	3215	3506
Total (UK), kt/y	(= England/0.83)	26848	27167	26394	25468	24171	21671	20044	18300	15479	12462	10331	8262	7661	7099	6525	6392	5531	5288	3874	4225

## **APPENDIX 2**

### **C&I WASTE ARISING**



**Table A4: Details of Commercial and Industrial Waste in 2002**

<b>Region</b>	<b>Waste Returns Figures – Ton</b>					
	<b>1 Inert/C&amp;D</b>	<b>2 Special</b>	<b>3 Municipal</b>	<b>4 Ind/Comm</b>	<b>5 Mun- Ind-Comm</b>	<b>Total</b>
<b>East Midlands</b>	6,630,384	225,615	1,803,698	<b>3,808,016</b>	5,611,714	12,467,713
<b>East of England</b>	6,469,129	740,779	4,553,788	<b>6,792,307</b>	11,346,095	18,556,004
<b>London</b>	3,507,943	83,505	3,234,976	<b>3,627,386</b>	6,862,362	10,453,811
<b>North East</b>	2,214,328	176,766	1,876,614	<b>5,447,996</b>	7,324,610	9,715,705
<b>North West</b>	4,125,998	867,571	4,048,620	<b>11,163,937</b>	15,212,557	20,206,126
<b>South East</b>	12,131,933	669,329	7,522,093	<b>7,335,203</b>	14,857,297	27,658,558
<b>South West</b>	3,891,161	408,310	3,221,273	<b>5,602,729</b>	8,824,001	13,123,472
<b>West Midlands</b>	4,385,941	474,807	3,081,139	<b>6,634,254</b>	9,715,393	14,576,141
<b>Yorkshire &amp; Humberside</b>	4,418,033	670,355	4,904,409	<b>5,899,126</b>	10,803,536	15,891,924
<b>England Total</b>	47,774,850	4,317,037	34,246,611	<b>56,310,955</b>	90,557,565	142,649,452
<b>Wales</b>	2,016,089	261,872	2,252,960	<b>2,166,214</b>	4,419,174	6,697,136
<b>England &amp; Wales Total</b>	49,790,939	4,578,909	36,499,571	<b>58,477,168</b>	94,976,740	149,346,588

**APPENDIX 3**

**METHANE GENERATION AND EMISSION RESULT TABLES**

**Table A5 Total CH4 Generated and Emitted - Central (Future1) Scenario**

Year	Total CH4 Generated (kt)	Total CH4 emitted (kt)		
		Base Case - LQM Default (with 85% collection eff.)	Golder Revised Methane Oxidation Model (with 75% collection eff.)	IPCC Default Case (with 85% collection eff.)
1945	134	134	134	120
1950	655	655	655	589
1955	1003	1003	1003	902
1960	1272	1272	1272	1144
1965	1498	1498	1498	1348
1970	1682	1682	1682	1513
1975	1797	1797	1797	1618
1980	1998	1849	1943	1798
1985	2524	1633	2179	2250
1990	2947	1131	1814	2363
1995	3294	961	1612	2099
2000	3384	562	1066	1461
2005	3432	333	648	846
2010	3418	250	593	706
2015	3341	195	539	639
2020	3267	155	498	580
2025	3210	126	467	534
2030	3139	105	441	498
2035	3122	90	427	476
2040	3129	80	419	463
2045	3139	72	413	455
2050	3154	66	410	449
<b>Total</b>	<b>266162</b>	<b>78153</b>	<b>105771</b>	<b>113072</b>

**Table A6 Total CH4 Generated and Emitted - Future3 Scenario**

Year	Total CH4 Generated (kt)	Total CH4 emitted (kt)		
		Base Case - LQM Default (with 85% collection eff.)	Golder Revised Methane Oxidation Model (with 75% collection eff.)	IPCC Default Case (with 85% collection eff.)
1945	134	134	134	120
1950	655	655	655	589
1955	1003	1003	1003	902
1960	1272	1272	1272	1144
1965	1498	1498	1498	1348
1970	1682	1682	1682	1513
1975	1797	1797	1797	1618
1980	1998	1849	1943	1798
1985	2524	1633	2179	2250
1990	2947	1131	1814	2363
1995	3294	961	1612	2099
2000	3384	565	1066	1472
2005	3432	332	661	837
2010	3405	238	592	605
2015	3324	186	536	554
2020	3251	148	495	516
2025	3198	121	465	489
2030	3131	102	440	465
2035	3117	88	426	453
2040	3125	78	418	446
2045	3136	71	413	442
2050	3151	65	410	439
<b>Total</b>	<b>265783</b>	<b>77936</b>	<b>105739</b>	<b>111047</b>

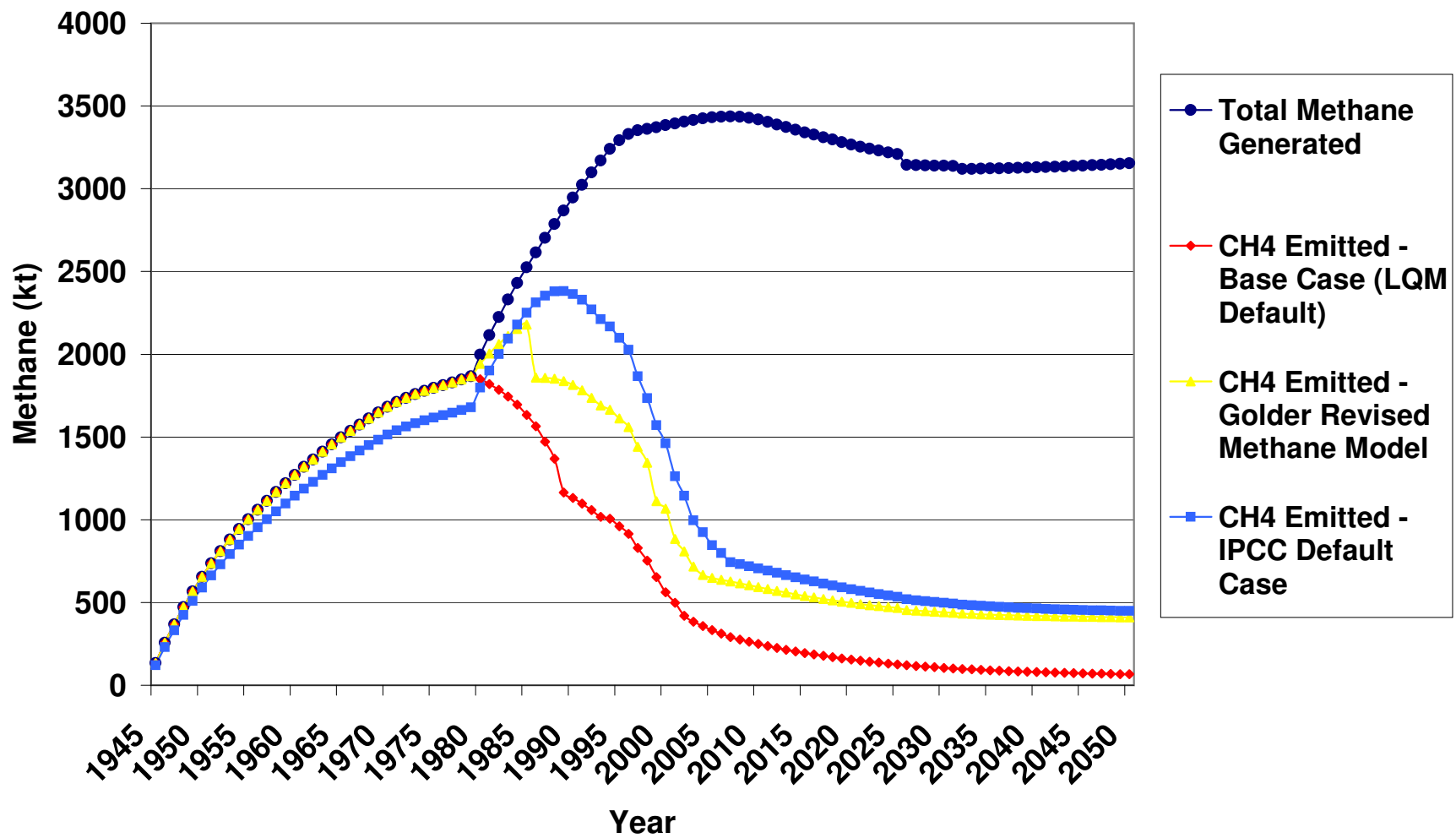
**Table A7 Total Methane Generated and Emitted - Future5 Scenario**

Year	Total CH4 Generated (kt)	Total CH4 emitted (kt)		
		Base Case - LQM Default (with 85% collection eff.)	Golder Revised Methane Oxidation Model (with 75% collection eff.)	IPCC Default Case (with 85% collection eff.)
1945	134	134	134	120
1950	655	655	655	589
1955	1003	1003	1003	902
1960	1272	1272	1272	1144
1965	1498	1498	1498	1348
1970	1682	1682	1682	1513
1975	1797	1797	1797	1618
1980	1998	1849	1943	1798
1985	2524	1633	2179	2250
1990	2947	1131	1814	2363
1995	3294	961	1612	2099
2000	3384	565	1066	1472
2005	3432	332	661	837
2010	3423	239	594	608
2015	3383	186	543	562
2020	3326	149	504	526
2025	3286	123	476	501
2030	3232	103	453	479
2035	3234	89	441	468
2040	3259	80	435	464
2045	3290	73	432	462
2050	3325	68	432	463
<b>Total</b>	<b>270008</b>	<b>78000</b>	<b>106267</b>	<b>111617</b>

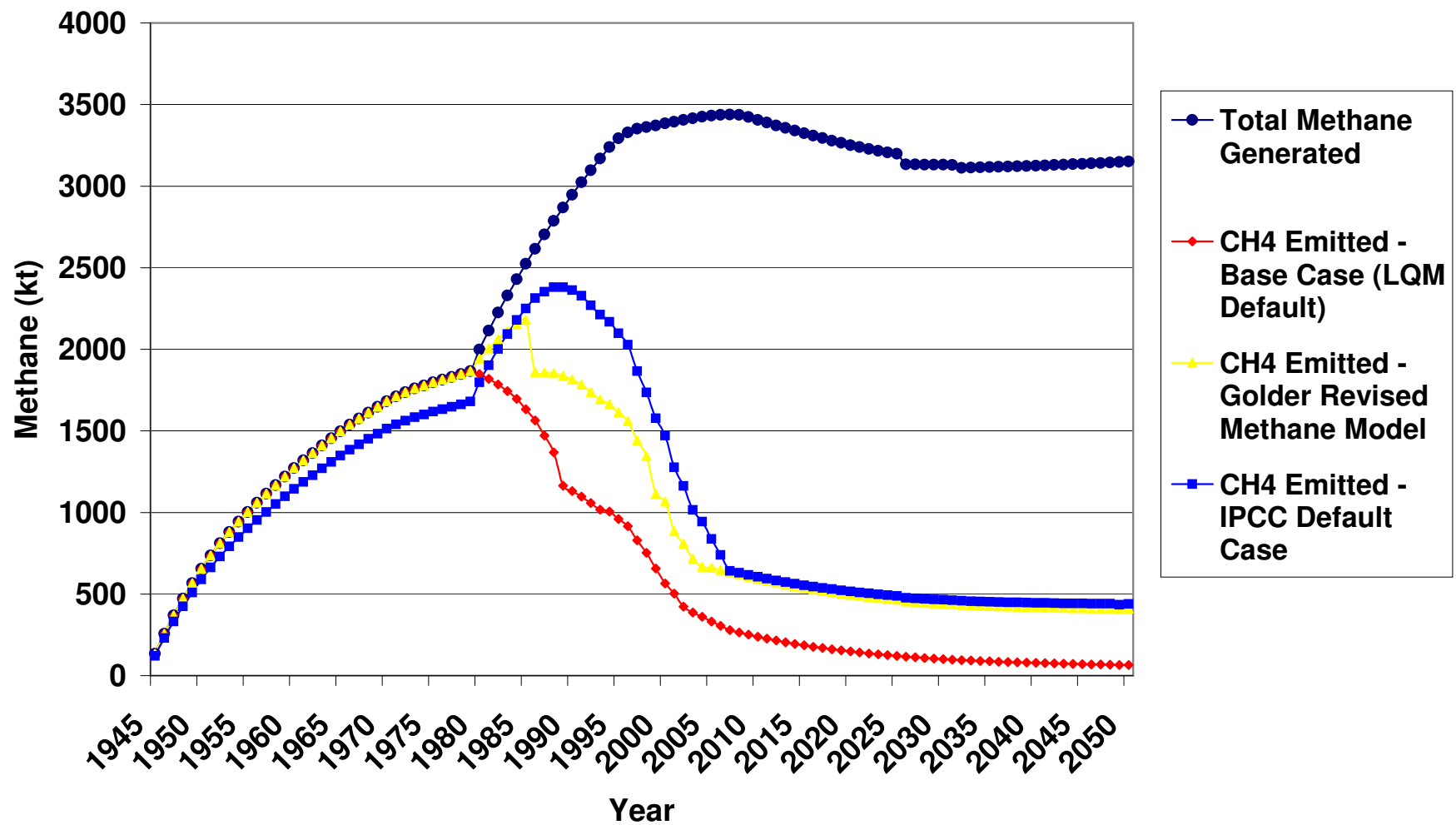
## **APPENDIX 4**

### **METHANE GENERATION AND EMISSION RESULT PLOTS**

**Figure A2 Total Methane Generated and Emitted - Central (Future1) Scenario**

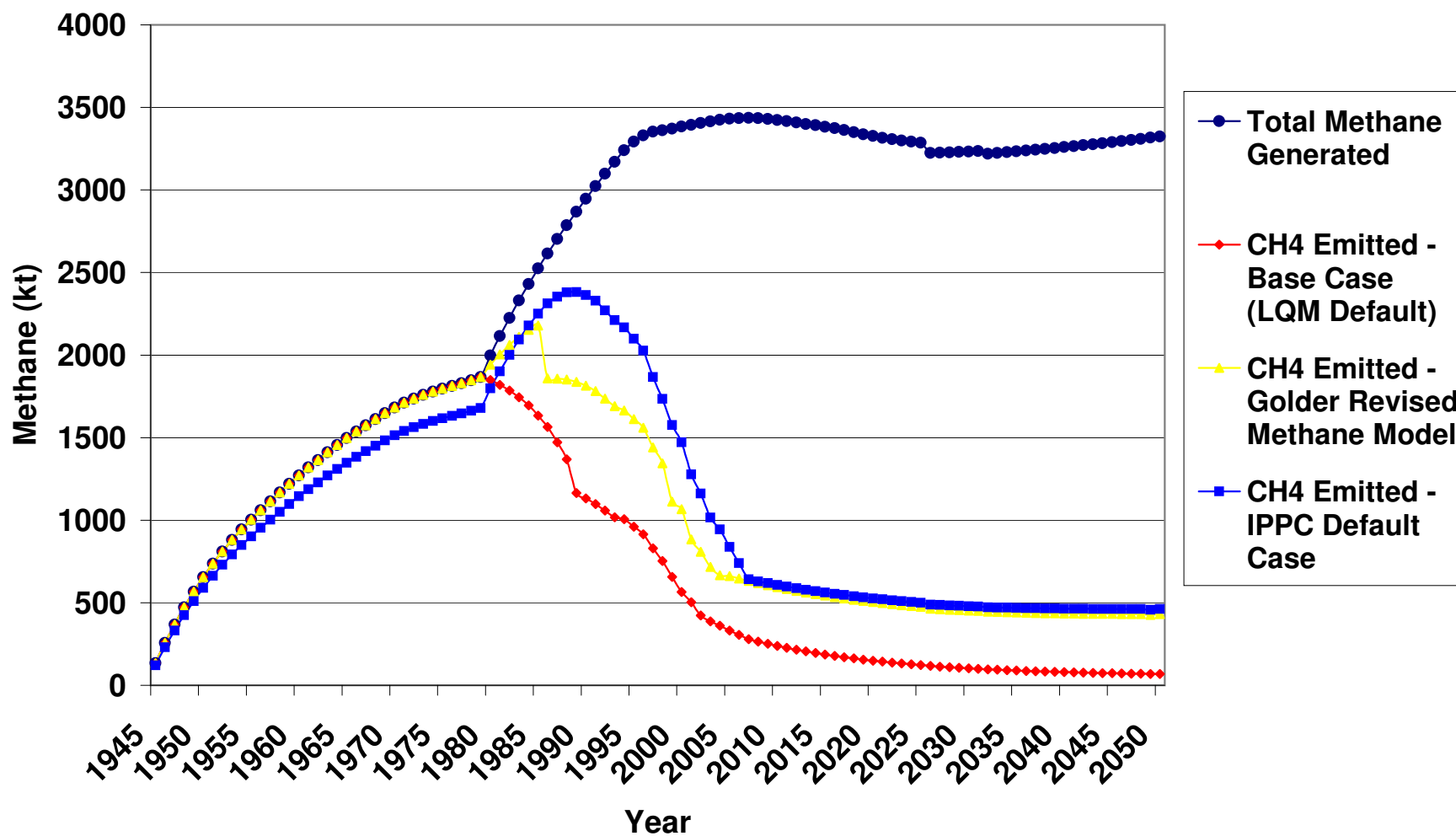


**Figure A3 Total Methane Generated and Emitted - Future3 Scenario**





**Figure A4 Total Methane Generated and Emitted - Future5 Scenario**



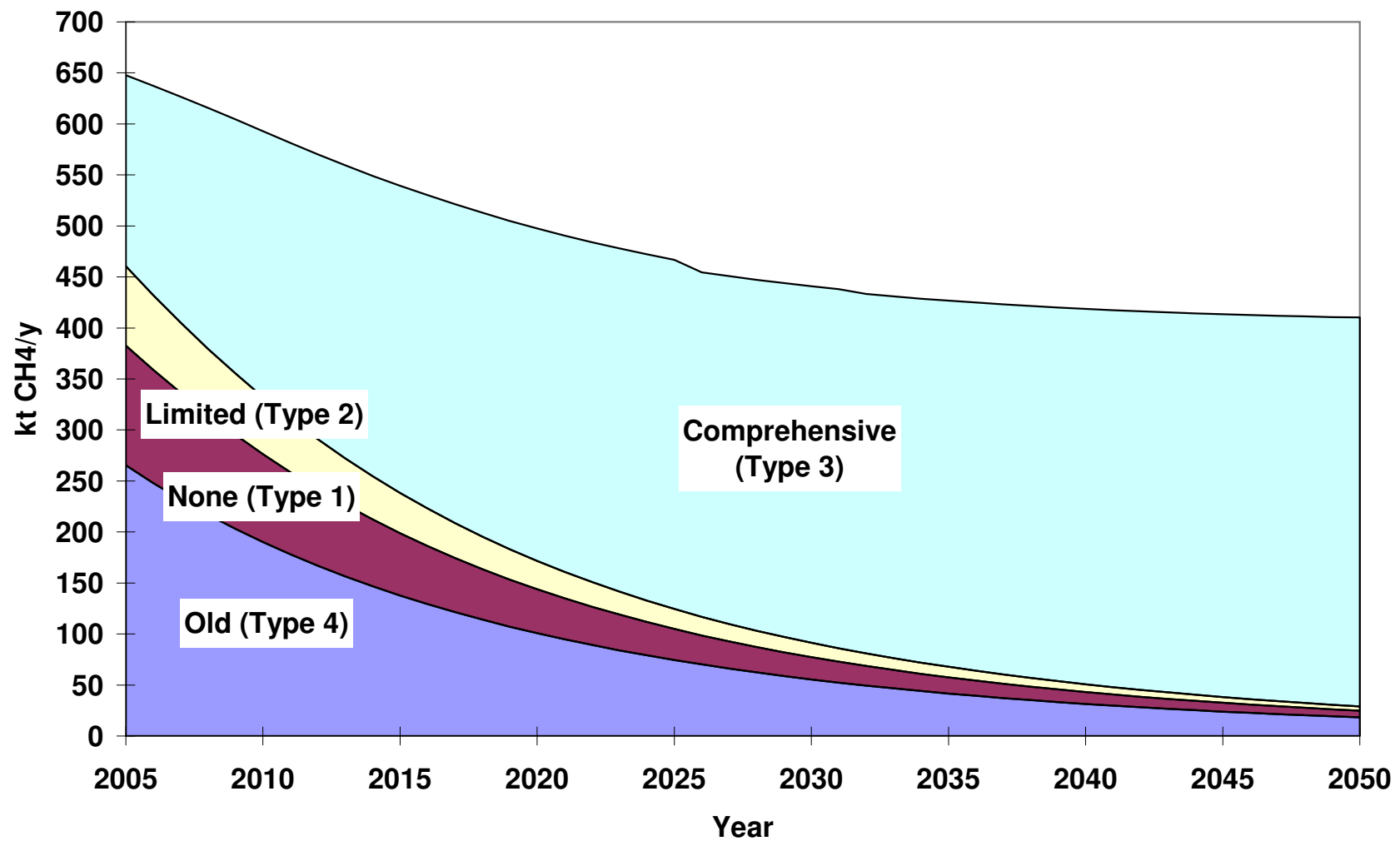
## **APPENDIX 5**

### **METHANE EMISSIONS BY LANDFILL TYPE**

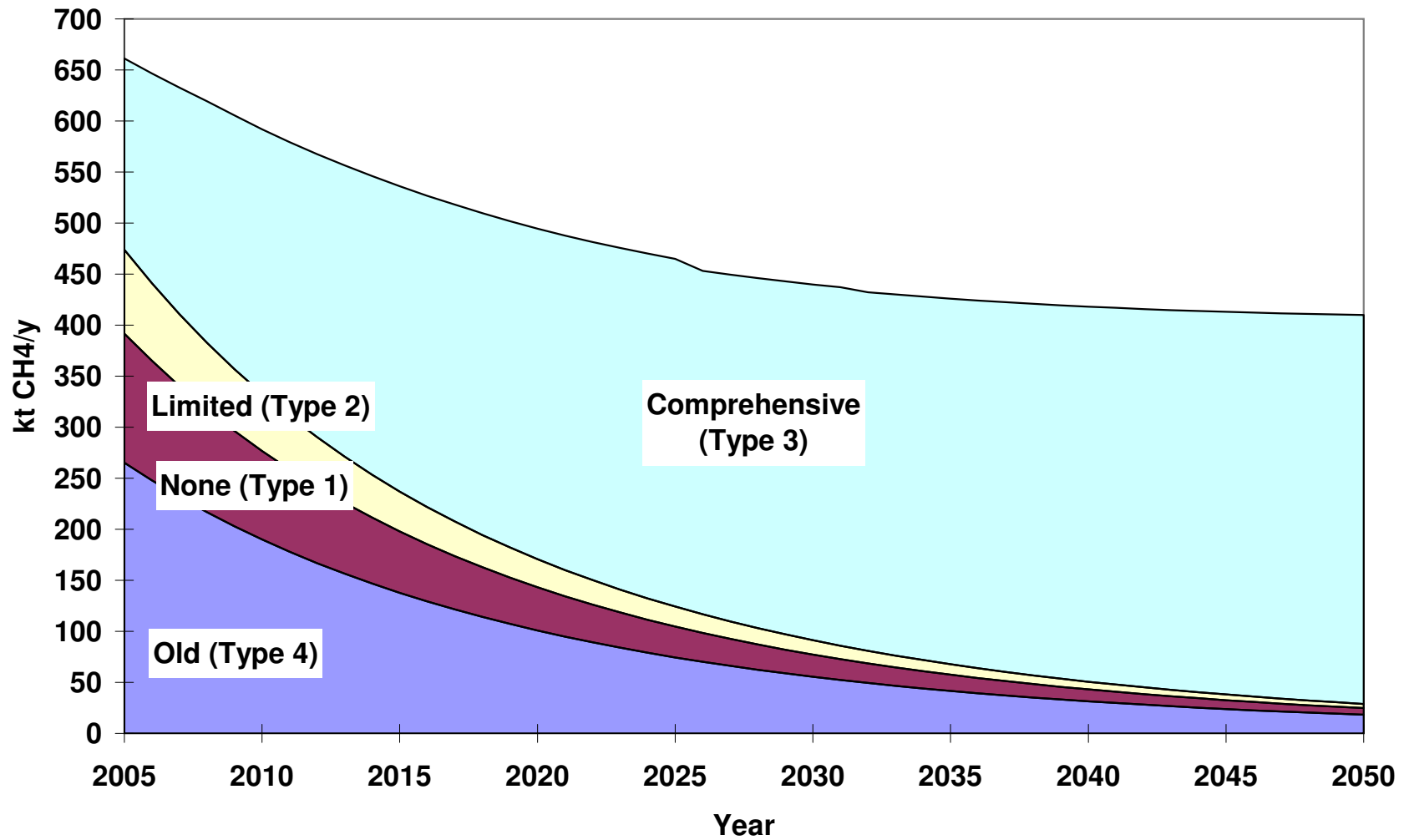
**Table A8 CH4 Emitted from Different Landfill Site Types, for the Central (Future1), Future 3 & 5 Scenarios.**

Year	Central (Future1) Scenario					Future3 Scenario					Future5 Scenario				
	Type 1	Type 2	Type 3	Type 4	Total	Type 1	Type 2	Type 3	Type 4	Total	Type 1	Type 2	Type 3	Type 4	Total
<b>2005</b>	117	78	187	265	648	126	82	187	265	661	126	82	187	265	661
<b>2010</b>	86	56	261	190	593	87	56	259	190	592	87	56	261	190	594
<b>2015</b>	61	39	301	138	539	60	39	299	138	536	60	39	306	138	543
<b>2020</b>	43	28	326	101	498	42	27	324	101	495	42	27	333	101	504
<b>2025</b>	31	20	342	74	467	30	20	341	74	465	30	20	352	74	476
<b>2030</b>	22	14	350	55	441	22	14	349	55	440	22	14	361	55	453
<b>2035</b>	16	10	359	42	427	16	10	358	42	426	16	10	373	42	441
<b>2040</b>	12	8	368	31	419	12	8	368	31	418	12	8	384	31	435
<b>2045</b>	9	6	375	24	413	9	6	375	24	413	9	6	394	24	432
<b>2050</b>	6	4	381	18	410	6	4	381	18	410	6	4	403	18	432

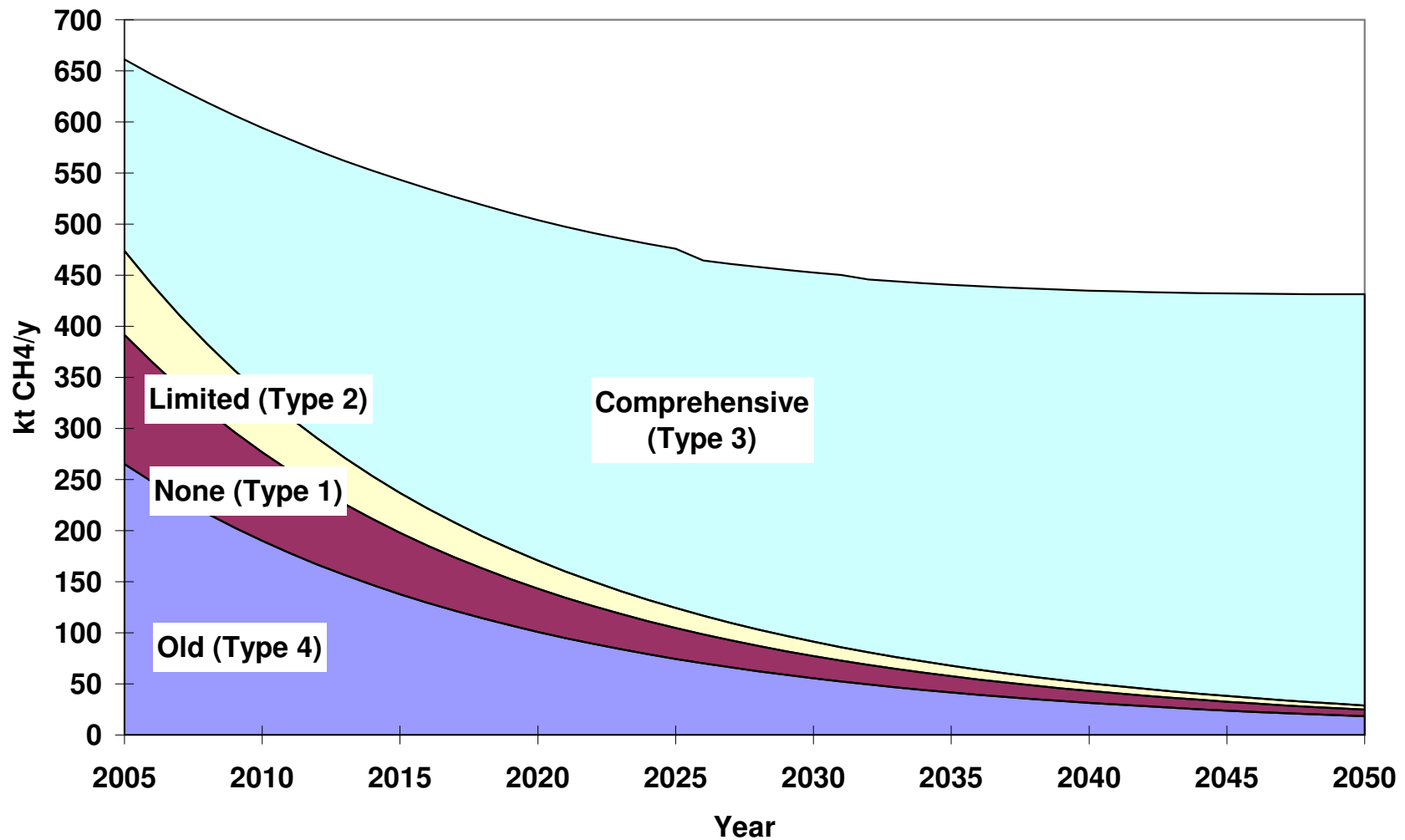
**Figure A5 Methane Emitted by Landfill Site Type - Central (Future1) Scenario**



**Figure A6 Methane Emitted by Landfill Site Type - Future3 Scenario**



**Figure A7 Methane Emitted by Landfill Site Type - Future5 Scenario**



## **APPENDIX 6**

### **DESCRIPTION OF MODEL**

## 1.0 BACKGROUND TO THE MODEL

### 1.1 Introduction

This Appendix has taken the text and defining equations from the LQM (2003) study and has upgraded the description of the model to include all the changes which have been carried out since that report and in the production of this report.

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 carried out below.

### 1.2 Defining Equations

The Tier 2 methodology is described by the Equations 1 – 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:

$$\text{CH}_4 \text{ generated in year } t \text{ (Gg/yr)} = \sum_x [ ( A \cdot k \cdot \text{MSW}_T(x) \cdot \text{MSW}_F(x) \cdot L_0(x) ) \cdot e^{-k(t-x)} ]$$

for  $x$  = initial year to year  $t$

*Equation 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)
$\text{MSW}_T(x)$	=	total municipal solid waste (MSW) generated in year $x$ (Gg/yr)
$\text{MSW}_F(x)$	=	fraction of MSW disposed to solid waste disposal sites (SWDS) in year $x$
$L_0(x)$	=	methane generating potential (defined in Equation 1.2 below)



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

$$L_0(x) = [ \text{MCF}(x) \cdot \text{DOC}(x) \cdot \text{DOC}_F \cdot F \cdot 16 / 12 ] \text{ (Gg CH}_4\text{/Gg waste)}$$

*Equation 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 <sub>F</sub>	=	fraction of DOC dissimilated (constant)
F	=	fraction by volume of CH <sub>4</sub> in LFG
16 / 12	=	conversion from C to CH <sub>4</sub>

The methane emitted in any year t is defined as:

$$\text{CH}_4 \text{ emitted in year t (Gg/yr)} = [ \text{CH}_4 \text{ generated in year t} - \text{R}(t) ] \cdot (1 - \text{OX})$$

*Equation 3 (5.2 in IPCC 2000)*

where

R(t)	=	recovered CH <sub>4</sub> 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 into the National Assessment Model 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, originally with no gas collection.
  - Type 2. waste emplaced from 1980-99 inclusive, originally 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.
- As gas collection has increased through time, more sites in categories Type 1 and Type 2 have received comprehensive gas collection systems, although such sites no longer accept waste.
- Gas recovered in an inventory year (by flaring or gas utilisation) was originally represented by scaling factors: for example, for the LQM 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.

- A number of additional data handling routines enabled the data to be set up as different uploadable scenarios for comparative data assessment purposes in the LQM model.

Implemented in this manner, the IPCC defining equations in the National Assessment Model can be used to generate the emissions projections.

### **1.3 LQM Review of Methodology**

LQM reviewed all the model parameters and determined 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 improved the scientific basis of the model and reduced uncertainties in emission projections. The validation of the quantity of recovered methane via flaring or utilisation (the term  $R(t)$  in Equation 3 above) is also discussed.

### **1.4 Model Parameters**

#### **1.4.1 Methane generation rate**

This is the term  $k$  in Equation 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 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 A6.1). These have been validated against UK landfills and are considered appropriate in most UK cases (Environment Agency, 2002a). The GasSim defaults are based 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. 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 A6.1 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  $\pm 25\%$  is considered more appropriate.

**Table A6.1: 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	$t_{1/2}$
<b>Rapidly degradable waste</b>	0.69	1	0.185	3.75	0.116	6
<b>Moderately degradable waste</b>	0.14	5	0.1	6.9	0.076	9
<b>Slowly degradable waste</b>	0.05	~15	0.05	~15	0.046	15

#### 1.4.2 Methane correction factor

This is the term MCF(x) in Equation 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) 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 4.2 of IPCC, 2000).

#### 1.4.3 Fraction of methane in LFG

This is the term F, the fraction by volume of methane in LFG, in Equation 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 2), and so these factors are currently considered to cancel each other out. The underestimate was accounted for in the original AEAT 1995 National Assessment model by an efficiency term.

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  $\pm 10\%$  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.

#### **1.4.4 Degradable Organic Carbon (DOC) and Fraction Dissimilated ( $DOC_F$ )**

These are the terms  $DOC(x)$  and  $DOC_F$  in Equation 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). 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 LQM's survey 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 previous underestimate, have been thoroughly reviewed and the current approach is described below.

LQM 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 Tables A6.2 and A6.3 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 A6.2: Waste Degradable Carbon Model Parameters for MSW Waste**

Waste category	Fraction				Moisture content	Cellulose	Hemi-cellulose	DOC	DOC	Decomposition (DOC <sub>F</sub> )
	Readily degradable	Moderately degradable	Slow degradable	Inert	(%)	(% Dry waste)	(% Dry waste)	(% Dry waste)	(% Wet waste)	(%)
Paper and card	0	25	75	0	30	61.2	9.1	70.3	54.08	61.8
Dense plastics	0	0	0	100	5	0.0	0.0	0	0.00	0.0
Film plastics (until 1995)	0	0	0	100	30	0.0	0.0	0	0.00	0.0
Textiles	0	0	100	0	25	20.0	20.0	40	32.00	50.0
Misc. combustible (plus non-inert fines from 1995)	0	100	0	0	20	25.0	25.0	50	41.67	50.0
Misc. non-combustible (plus inert fines from 1995)	0	0	0	100	5	0.0	0.0	0	0.00	0.0
Putrescible	100	0	0	0	65	25.7	13.0	38.7	23.45	62.0
Composted putrescibles	0	50	50	0	30	0.7	0.7	1.4	1.08	57.0
Glass	0	0	0	100	5	0.0	0.0	0	0.00	0.0
Ferrous metal	0	0	0	100	5	0.0	0.0	0	0.00	0.0
Non-ferrous metal and Al cans	0	0	0	100	10	0.0	0.0	0	0.00	0.0
Non-inert fines	100	0	0	0	40	25.0	25.0	50	35.71	50.0
Inert fines	0	0	0	100	5	0.0	0.0	0	0.00	0.0

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

**Table A6.3: Waste Degradable Carbon Model Parameters for C&I Waste**

Waste category	Fraction				Moisture content	Cellulose	Hemi-cellulose	DOC	DOC	Decomposition (DOC <sub>F</sub> )
	Readily degradable	Moderately degradable	Slow degradable	Inert	(%)	(% Dry waste)	(% Dry waste)	(% Dry waste)	(% Wet waste)	(%)
Commercial	15	57	15	13	37	76.0	8.0	84	61.31	85.0
Paper and card	0	25	75	0	30	87.4	8.4	95.8	73.69	98.0
General industrial waste	15	43	20	22	37	76.0	8.0	84	61.31	85.0
Food solids	79	10	0	11	65	55.4	7.2	62.6	37.94	76.0
Food effluent	50	5	0	45	65	55.4	7.2	62.6	37.94	76.0
Abattoir waste	78	10	0	12	65	55.4	7.2	62.6	37.94	76.0
Misc processes	0	5	5	90	20	10.0	10.0	20	16.67	50.0
Other waste	15	35	35	15	20	25.0	25.0	50	41.67	50.0
Power station ash	0	0	0	100	20	0.0	0.0	0	0.00	0.0
Blast furnace and steel slag	0	0	0	100	20	0.0	0.0	0	0.00	0.0
Construction/demolition	0	5	5	90	30	8.5	8.5	17	13.08	57.0
Sewage sludge	100	0	0	0	70	14.0	14.0	28	16.47	75.0

[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 A6.2 and A6.3 the term  $\text{DOC}(x).\text{DOC}_F$  from Equation 2 above, for each waste category and degradability fraction, is defined as:

$$(\text{DOC}(x).\text{DOC}_F)_{i,j} = M(x)_{i,j} \cdot (\%C_i + \%HC_i) \cdot \%DC_i \cdot (1 - \%MC_i) \cdot 72/162$$

(Gg C/Gg waste)

*Equation 4*

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 4 above. This estimate was then used to derive the specific methane generation potential for each waste fraction, using Equation 2 above. This provides the input to Equation 4 above, to obtain the value of the methane generated per year. The moisture content of the waste is required to convert 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  $\text{DOC}(x).\text{DOC}_F$  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  $\text{DOC}_F$  is estimated to be similar to that stated for the Netherlands, namely  $\pm 15\%$  (Oonk and Boom, 1995).

Golder has carried out calculations of the percentages of degradable organic carbon (DOC) in MSW waste streams, C&I waste streams and overall waste streams. The details are presented in Table A6.4 below at a five-year interval from 1945 to 1990, a one-year interval from 1991 and 2005, and a five-year interval from 2005 to 2050. These data are presented alongside information on mass of waste landfilled for individual waste components, methane generated, methane capture, residual methane oxidised for Types 1 - 4 landfills and methane emitted. It can be seen that the DOC values vary with time. Since these country-specific DOC values are available, the IPCC default values have not been used in the model.

Golder has calculated the percentages of the total degradable organic carbon that is dissimilated ( $\text{DOC}_F$ ) for individual waste components (see Table A6.4). The calculated  $\text{DOC}_F$  values vary with time. Since these country-specific  $\text{DOC}_F$  values are available, the IPCC default values have not been used in the model.



**Table A6.4: The Percentages of DOC and DOC<sub>F</sub> in MSW Waste Streams and C&I Waste Streams**

Year	Mass of waste landfilled (Mt)			DOC (%)			DOC <sub>F</sub> (%)			Methane generated (kt)	Methane captured (kt)	Methane captured (%)	Residual methane oxidised, type 1-3 landfills (%)	Residual methane oxidised, type 4 landfills (%)	Methane emitted (kt)
	MSW	C&I	Combined waste streams	MSW	C&I	Combined waste streams	MSW	C&I	Combined waste streams						
1945	7.68	79.20	86.89	8.53	23.66	22.32	4.69	17.56	16.42	134	0	0	0	0	134
1950	8.38	80.69	89.07	9.79	23.60	22.30	5.51	17.51	16.38	655	0	0	0	0	655
1955	8.11	82.18	90.29	10.58	23.55	22.39	6.06	17.46	16.43	1003	0	0	0	0	1003
1960	11.60	87.16	98.76	15.58	23.47	22.55	9.29	17.39	16.44	1272	0	0	0	0	1272
1965	11.52	92.13	103.65	19.78	23.40	23.00	11.79	17.34	16.72	1498	0	0	0	0	1498
1970	12.54	88.45	100.99	27.64	23.80	24.27	16.77	17.69	17.58	1682	0	0	0	0	1682
1975	11.76	84.73	96.49	22.78	24.22	24.04	13.58	18.07	17.52	1797	0	0	0	0	1797
1980	13.21	83.41	96.63	23.54	24.73	24.57	14.17	18.54	17.94	1998	0	0	21	0	1943
1985	14.83	82.09	96.93	22.43	25.25	24.82	13.34	19.03	18.16	2524	24	0.97	50	0	2179
1990	18.19	81.83	100.02	23.90	25.71	25.38	14.15	19.45	18.49	2947	322	10.91	50	0	1814
1991	18.84	81.77	100.61	24.17	25.80	25.50	14.30	19.54	18.56	3024	436	14.43	50	0	1782
1992	19.47	81.72	101.19	24.43	25.90	25.61	14.44	19.62	18.63	3098	576	18.58	50	0	1737
1993	20.09	81.66	101.76	24.69	25.99	25.73	14.59	19.71	18.70	3170	712	22.47	50	0	1691
1994	20.71	81.61	102.32	24.94	26.08	25.85	14.72	19.79	18.77	3240	832	25.67	50	0	1664
1995	23.83	81.56	105.39	19.75	26.17	24.72	11.75	19.88	18.04	3294	962	29.20	50	0	1612
1996	24.76	78.17	102.93	19.75	26.38	24.79	11.75	19.89	17.93	3330	1077	32.36	50	0	1560
1997	26.14	72.86	99.00	19.75	26.92	25.03	11.75	20.28	18.02	3352	1279	38.15	50	0	1441

**Table A6.4: (cont'd): The Percentages of DOC and DOC<sub>F</sub> in MSW Waste Streams and C&I Waste Streams**

Year	Mass of waste landfilled (Mt)			DOC (%)			DOC <sub>F</sub> (%)			Methane generated (kt)	Methane captured (kt)	Methane captured (%)	Residual methane oxidised, type 1-3 landfills (%)	Residual methane oxidised, type 4 landfills (%)	Methane emitted (kt)
	MSW	C&I	Combined waste streams	MSW	C&I	Combined waste streams	MSW	C&I	Combined waste streams						
<b>1998</b>	25.94	65.63	91.57	19.75	27.91	25.60	11.75	21.15	18.49	3361	1433	42.65	50	0	1344
<b>1999</b>	27.03	63.84	90.87	19.75	28.30	25.76	11.75	21.53	18.62	3371	1620	48.04	50	0	1113
<b>2000</b>	27.54	62.05	89.59	20.09	28.72	26.07	11.90	21.93	18.85	3384	1749	51.68	50	0	1066
<b>2001</b>	26.85	60.27	87.11	20.09	29.16	26.36	11.90	22.36	19.13	3394	1975	58.19	50	0	884
<b>2002</b>	27.17	58.48	85.64	20.09	29.62	26.60	11.90	22.81	19.35	3405	2114	62.09	50	0	808
<b>2003</b>	26.39	58.48	84.87	20.09	29.62	26.66	11.90	22.80	19.41	3415	2287	66.96	50	0	716
<b>2004</b>	25.47	58.48	83.94	20.09	29.62	26.73	11.90	22.81	19.50	3425	2377	69.40	50	0	666
<b>2005</b>	24.17	58.47	82.65	20.09	29.62	26.84	11.90	22.81	19.62	3432	2402	69.99	50	0	648
<b>2010</b>	12.46	58.48	70.94	20.09	29.62	27.95	11.90	22.81	20.89	3418	2422	70.87	50	0	593
<b>2015</b>	6.52	58.48	65.00	20.09	29.62	28.67	11.90	22.81	21.71	3341	2400	71.83	50	0	539
<b>2020</b>	4.22	58.48	62.70	20.09	29.62	28.98	11.90	22.81	22.07	3267	2373	72.63	50	0	498
<b>2025</b>	4.61	58.48	63.09	20.09	29.62	28.93	11.90	22.81	22.01	3210	2351	73.23	50	0	467
<b>2030</b>	5.00	58.48	63.48	20.09	29.62	28.87	11.90	22.81	21.95	3139	2312	73.67	50	0	441
<b>2035</b>	5.39	58.48	63.87	20.09	29.62	28.82	11.90	22.81	21.89	3122	2310	74.00	50	0	427
<b>2040</b>	5.78	58.48	64.25	20.09	29.62	28.77	11.90	22.81	21.82	3129	2323	74.24	50	0	419
<b>2045</b>	6.17	58.48	64.64	20.09	29.62	28.71	11.90	22.81	21.77	3139	2337	74.43	50	0	413
<b>2050</b>	6.55	58.48	65.03	20.09	29.62	28.66	11.90	22.81	21.71	3154	2352	74.56	50	0	410

#### 1.4.5 Methane oxidation

Until recently there has been little research on the onset of methanogenesis in operational phases of landfills, or on the effectiveness of gas collection in the operational phase. Atkins has been carrying out research since 2000 on a project funded through the Landfill Tax Credit Scheme entitled *Minimising methane emissions from MSW landfills* (Barry et al. 2004). 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 methane emissions protocol threshold (i.e.  $> 1 \times 10^{-3} \text{ mg.m}^{-2}.\text{s}^{-1}$ ) (Environment Agency, 2004).

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 emissions protocol threshold (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 Atkins study looked at two sites 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).

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.

#### 1.4.6 Methane oxidation

This is the term OX in Equation 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 developed a new model 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:

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$\text{CH}_4 \rightarrow$	$\text{CH}_3\text{OH} \rightarrow$	$\text{HCHO} \rightarrow$	$\text{HCOOH} \rightarrow$	$\text{CO}_2$
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 et 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 A6.5). 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  $^{13}\text{C}$  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 A6.5) 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 A6.5 have been standardised to units of  $\text{m}^3 \text{CH}_4/\text{m}^2/\text{h}$  from the units provided in the publications listed (either as g or  $\text{l CH}_4/\text{m}^2/\text{h}$ ).

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 0.3 m if an engineered barrier is present (modern lined landfills), or for caps with a soil cover depth greater than 1.0 m 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 A6.5: Methane Oxidation Rates for Cover Materials (Laboratory and Field Studies)**

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

The methane oxidising capacity of the soil cover (Soil<sub>oxd cap</sub>) represents the size of the 'sink' for methane conversion to carbon dioxide. This is defined as:

$$\text{Soil}_{\text{oxd cap}} = \Delta_{\text{field eff}} (\text{SOC} \cdot 24.365) A_{\text{surface}} \frac{M_m}{M_v} 10^{-9} \text{ [kt CH}_4\text{/y]} \quad \text{Equation 5}$$

where

- Soil<sub>oxd cap</sub> = maximum methane that can be oxidised in year x by the soil cover (kt CH<sub>4</sub>/y)
- SOC = soil oxidising capacity of landfill (m<sup>3</sup> CH<sub>4</sub>/ m<sup>2</sup> landfill/ h)
- Δ<sub>field eff</sub> = effectiveness of methane oxidation under field conditions (fraction)
- A<sub>surface</sub> = cumulative surface area of the landfill type under consideration (m<sup>2</sup>) (see Equation 6)
- M<sub>v</sub> = molar volume (at STP) (0.02241m<sup>3</sup> CH<sub>4</sub>/ mole)
- M<sub>m</sub> = molecular mass of methane (16g CH<sub>4</sub>/ mole)
- The factor 10<sup>-9</sup> converts from g CH<sub>4</sub> to kt CH<sub>4</sub>.

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

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

where

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

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 A6.6 below).

The actual methane that is available for potential oxidation in the cap ( $\text{Avail}_{\text{oxd cap}}$ ) 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 ( $\text{kt/y}$ ) is defined as:

$$\text{Avail}_{\text{oxd cap}}(x) = (1 - \Delta_{\text{fissure}})(\text{CH}_4\text{generated}(x) - R(t)) [\text{kt CH}_4/\text{y}] \quad \text{Equation 7}$$

where

$\text{Avail}_{\text{oxd cap}}$  = methane available for oxidation in year x ( $\text{kt/y}$ )  
 $\Delta_{\text{fissure}}$  = fraction of methane lost directly through fissures (fraction)  
 $\text{CH}_4\text{generated}(x)$  = methane generated in year x ( $\text{kt/y}$ )  
 $R(t)$  = methane recovered in year x ( $\text{kt/y}$ )

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 ( $\text{Soil}_{\text{oxd cap}}$ ) or the source or quantity of methane available for potential oxidation ( $\text{Avail}_{\text{oxd cap}}$ ). The two situations are defined as:

For  $\text{Soil}_{\text{oxd cap}} > \text{Avail}_{\text{oxd cap}}$  (source limited oxidation), under these circumstances the oxidation factor is:

$$\text{OX} = (1 - \Delta_{\text{fissure}}) \left( \frac{\text{CH}_4\text{generated}(x) - R(t)}{\text{CH}_4\text{generated}(x)} \right) \quad \text{Equation 8}$$

For  $\text{Avail}_{\text{oxd cap}} > \text{Soil}_{\text{oxd cap}}$  (sink limited oxidation), under these circumstances the oxidation factor is:

$$\text{OX} = (1 - \Delta_{\text{fissure}}) \left( \frac{\text{Soil}_{\text{oxd cap}}}{\text{CH}_4\text{generated}(x)} \right) \quad \text{Equation 9}$$

where

$$\begin{aligned}\text{Soil}_{\text{oxd cap}} &= \text{maximum methane that can be oxidised in year } x \text{ by the soil cover} \\ &\quad (\text{kt CH}_4/\text{y}) \\ \text{CH}_4 \text{ generated } (x) &= \text{methane generated in year } x \text{ (kt/y)} \\ R(t) &= \text{methane recovered in year } x \text{ (kt/y)} \\ \Delta_{\text{fissure}} &= \text{fraction of methane lost directly through fissures (fraction)}\end{aligned}$$

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 A6.6, along with their pdf (type and critical values), for each type of landfill considered in the National Assessment Model.

Of the oxidation module parameter listed in Table A6.6, the model output is most sensitive to the values for field oxidation efficiency and the fraction through fissures. In 2005, series of technical meetings have been held with the with the UK waste sectoral experts, the Environment Agency and Defra to review the methane oxidation factor currently used in the model which produces estimates of methane from waste decomposition in landfills. The model now uses 50% values for both field oxidation efficiency and the fraction through fissures. The values of overall residual methane oxidation from 1945 to 2050 have been calculated and presented in Table A6.4.

**Table A6.6: Inputs Required for Methane Oxidation Module and Associated PDF**

Input	Landfill Type	Best-estimate	PDF	Source
Soil oxidising capacity (SOC) [m <sup>3</sup> CH <sub>4</sub> /m <sup>2</sup> /h]	1 2 3 4	0.00415 0.00425 0.00379 0.00389	LN (0.00798, 0.01383)	See Table A6.5
Field oxidation efficiency ( $\Delta_{\text{field eff}}$ ) [fraction]	1 2 3 4	0.50 0.50 0.50 0.50	Single input value	A value of 0.75 had been used in LQM report in 2003; a value of 0.50 has been adopted for the latest estimates based on expert judgment of Environment Agency, AEAT and Golder personnel.
Fraction through fissures ( $\Delta_{\text{fissure}}$ ) [fraction]	1 2 3 4	0.50 0.50 0.50 0.50	Single input value	A value of 0.10 had been used in LQM report in 2003; a value of 0.50 has been adopted for the latest estimates based on expert judgment of Environment Agency, AEAT and Golder personnel.
Soil cover depth (above cap) [m]	1 2 3 4	1.0 1.0 1.0 0.65	U (0.5, 1.5) U (0.5, 1.5) U (0.5, 1.5) U (0.15, 1.5)	Expert judgement
Landfill site depth ( $d_{\text{site}}(x)$ ) [m]	1 2 3 4	11.3 25 25 10	T(5.00, 7.00, 25.00) T (10.0, 25.0, 40.0) T (10.0, 25.0, 40.0) T (5.00, 7.00, 20.00)	Expert judgement
Waste density ( $\rho(x)$ ) [t/m <sup>3</sup> ]	1 2 3 4	1.00 1.00 1.00 1.00	Single input value	Expert judgement

Note: Log Normal distribution = LN (mean, standard deviation)  
 Triangular distribution = T (minimum, likeliest, maximum)  
 Uniform distribution = U (minimum, maximum)



## **2.0 VALIDATION OF MODEL USING FLARING AND ENERGY RECOVERY DATA**

### **2.1 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. This survey was carried out in 2002. 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.

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 did not update the flare and utilisation data collected in the ETSU 1996 study, but applied “recovery effectiveness” terms to the gas generated by the different landfill categories represented in the model. This modelling approach therefore assumes 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 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 validation 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.

### **2.2 Gas Utilisation**

#### **2.2.1 Information sources**

The utilisation data, below, is mainly based on comparison of information from the trade association (the Renewables Energy Association, formerly Biogas Association (Gaynor Hartnell, Pers. Comm.

2002))<sup>1</sup> and current DTI figures<sup>2</sup>. In addition, LQM 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 LQM is confident in the accuracy of its 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, some have been surrendered and re-started under the new renewables order, and others are likely to follow this route.

### **2.2.2 Data and assumptions**

The data used in the model is shown in Table A6.7. The data for installed power generation capacity each year (expressed as m<sup>3</sup> LFG) is derived by multiplying the figure in the final column of Table A6.7 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.

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<sup>1</sup> 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, and in 2005 became the Renewables Energy Association.

<sup>2</sup> [http://www.dti.gov.uk/energy/inform/energy\\_stats/renewables/index.shtml](http://www.dti.gov.uk/energy/inform/energy_stats/renewables/index.shtml)

**Table A6.7: Derivation of Landfill Gas Utilisation Data used in the National Assessment Model 2002**

Year	ETSU 1996 (kt CH <sub>4</sub> abated/yr) <sup>1</sup>	ETSU 1996 (equivalent GWhr) <sup>2</sup>	DTI (GWhr conv. from oil equivalent at 35%effic.) <sup>3</sup>	Non-NFFO generation (MW <sub>e</sub> ) <sup>4</sup>	NFFO 1-5 etc generation (MW <sub>e</sub> ) <sup>5</sup>	NFFO + non-NFFO generation (MW <sub>e</sub> ) <sup>6</sup>	NFFO (GWhr at 5% downtime) <sup>7</sup>	NFFO + non- NFFO (GWhr) <sup>8</sup>	NFFO + non- NFFO (1000s m <sup>3</sup> CH <sub>4</sub> /yr) <sup>9</sup>
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<sub>e</sub> gas engine consumes 570m<sup>3</sup>/hr of LFG at 50% CH<sub>4</sub>.
3. Data derived from DTI (2002) assuming 1 ktce = 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<sub>e</sub> gas engine consumes 570m<sup>3</sup>/hr of LFG at 50% CH<sub>4</sub>.

## **2.3 Flaring**

### **2.3.1 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. LQM therefore followed the same general approach as Aitchison et al. (1996) and focused on the flare manufacturers.

Table A6.8 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 therefore not always been possible to determine sales from these companies between the period of the last survey and the company ceasing trading.

**Table A6.8: Flare Manufacturers and Suppliers Surveyed 2002**

Supplier	Trading status	Current marketing status
AFS <sup>1</sup>	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 <sup>1</sup>	Active	Supplies HAASE flares
Covertronic (formerly MB Geosphere)	No longer trading	No longer trading
Energy Developments <sup>1</sup>	Active	Manufactures and supplies flares
Enitial Projects <sup>1</sup>	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 <sup>1</sup>	Active	Manufactures and supplies flares. Offshore flare sales only
HAASE <sup>1</sup>	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 <sup>1</sup>	Active	Manufactures CPL designed flares
Novera Energy (formerly CPL Energy) <sup>1</sup>	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 <sup>1</sup>	Active	Manufactures and supplies flares
Pro2 <sup>1</sup>	Active	Manufactures and supplies flares
PCC Sterling Ltd <sup>1</sup>	Active	Manufactures and supplies flares
Summerlease Re-generation <sup>1</sup>	Active	Supplies Hofstetter flares
Thomas Graveson	Sold to Enviros then to Summerlease (see above)	See Summerlease Re-generation

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

### 2.3.2 Data and assumptions

Table A6.9 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 A6.8). 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 A6.1.

<sup>1</sup> Not included in the ETSU 1996 survey (Aitchison et al., 1996).

**Table A6.9. Flare Surveys 1996 and 2002**

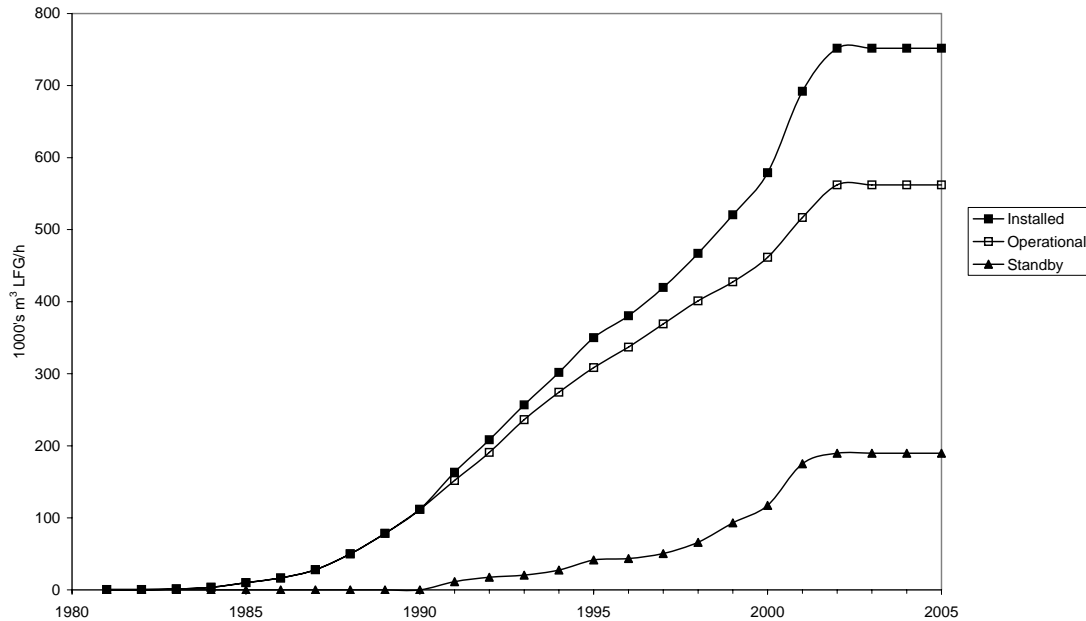
	ETSU (1996)	This market survey 2002		
Year	Flare capacity from cumulative sales (m <sup>3</sup> /hr)	Flare capacity from cumulative sales (m <sup>3</sup> /hr)	Flare capacity used for utilisation plant back-up (m <sup>3</sup> /hr)	Modelled net flaring capacity (m <sup>3</sup> /hr)
1980				
1981		500		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

## 2.4 Use of Data in the Model

### 2.4.1 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 A6.1: 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<sup>3</sup> LFG/hr) is based on LQM's 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 LQM's survey is therefore an underestimate of those years. LQM's 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 LQM's totals, but LQM did 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).

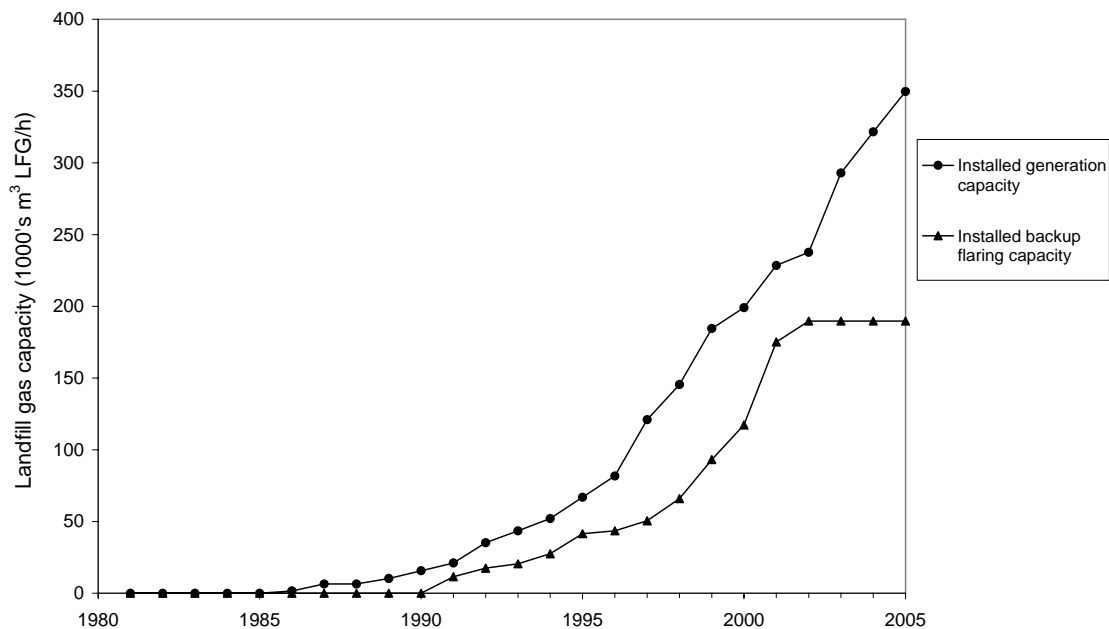
The data for flares sold solely for generation back-up purposes is believed to be fairly accurate. The operational capacity is derived by subtracting the back-up capacity from the total. In the model, there is a further correction factor used in arriving at the final volume of gas flared each year, to take account of maintenance downtime (15%) and the probability that some recent flares are direct replacements for earlier sales of 7%. LQM's 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.

There is 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<sub>4</sub> oxidised, using a total flare capacity of 350,000 m<sup>3</sup>/hr. LQM's estimate of the total installed net flare capacity, using LQM and ETSU survey figures minus LQM survey back-up capacity, is 308,500 m<sup>3</sup>/hr for the same year (1995).

## 2.4.2 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 A6.2). 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 A6.2, 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 A6.2: 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. LQM has no direct evidence whether this is still the case, although LQM suspects 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 LQM's 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. LQM has 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.

## **2.5 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.

## **2.6 Gas Collection Efficiency for Golder Report in 2005**

The guidance of the Environment Agency with respect to landfill gas collection states that there must be at least 85% gas recovery from wastes during the gas utilisation phases of a landfill. The 85% gas collection efficiency is generally applied without consideration of the non-gas utilisation phases of a landfill.

The last input of gas utilisation data on previous LQM model is year 2005 and the last input of flare data (AEAT & LQM) is year 2002. They are the last year for which actual data or best estimation have made for the model. Table A6.10 below presents the gas collection efficiency data for landfill sites in categories Types 1 – 3, and for overall landfill sites from 1990 to 2005.

**Table A6.10: Gas Collection Efficiency for Landfill Sites from 1990 to 2005 in Previous LQM Model**

<b>Year</b>	<b>Gas collection efficiency for landfill sites in categories Type 1 – 3 (%)</b>	<b>Gas collection efficiency for overall landfill sites (%)</b>
<b>1990</b>	14.8	10.9
<b>1991</b>	19.0	14.4
<b>1992</b>	23.7	18.6
<b>1993</b>	28.0	22.5
<b>1994</b>	31.2	25.7
<b>1995</b>	34.9	29.2
<b>1996</b>	38.1	32.4
<b>1997</b>	44.3	38.1
<b>1998</b>	48.9	42.6
<b>1999</b>	54.5	48.0
<b>2000</b>	58.1	51.7
<b>2001</b>	64.9	58.2
<b>2002</b>	68.7	62.1
<b>2003</b>	73.5	67.0
<b>2004</b>	75.7	69.4
<b>2005</b>	75.8	70.0

From Table A6.10 the gas collection efficiency has been increased steadily from 14.8% to 75.8% from 1990 to 2005 for landfill sites in categories Types 1 – 3. A technical meeting was held with UK waste sector experts from Golder, AEAT, the Environment Agency, and UK Defra, to review gas collection efficiencies currently used in the Golder model which produces estimates of methane from waste decomposition in landfills. It has been agreed that the 85% gas collection efficiency which is the Regulatory requirement for operational landfills does not account for emissions from closed landfills, and so 75% would be a more representative value for whole life period of a landfill sites. This value is directly comparable with the gas collection efficiency determined in the 2002 validation survey and reported in Table A6.10 above. A value of 75% gas collection efficiency has been used for landfill sites in categories Types 1 – 3 from 2005 to 2050 in the 2005 Methane National Assessment Model.

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