November 2014

DEPARTMENT OF THE ENVIRONMENT, FOOD AND RURAL AFFAIRS

Review of Landfill Methane Emissions Modelling

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Submitted to:
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REPORT

Report **Number** 13514290381.506/A.1

Distribution:

DEFRA - 2 copies (1 pdf and 1 Word format)
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Executive Summary

The Department for Environment, Food and Rural Affairs (Defra) considers that waste management accounts for 3% of the United Kingdom's (UK's) greenhouse gas emissions, with the majority being emitted from landfills. Current practice is to model these emissions rather than measure them directly. The estimates for methane emissions from landfills come from computer models. For national emissions MELMod is used and for site specific and Pollution Inventory (PI) reporting estimates the model is usually GasSim. Whilst there has been a substantial investment programme in methane capture technology over the last two decades, the precise rate of methane capture remains uncertain. Defra and the Environment Agency (EA) along with the Department of Energy and Climate Change (DECC) have been working together to address this uncertainty.

The aim of this project is to provide Defra with an up-to-date, robust figure for the methane capture rate from landfill that can be used to inform policy decisions. Also, the project aims at achieving accurate and defensible reporting of emission from the waste sector in the European greenhouse gas inventory.

Golder Associates (Golder) has approached this task by developing a methodology for assessing the methane capture rate for the UK portfolio of large modern landfills with comprehensive gas collection specified as category Type 3 landfill in MELMod. This category of landfills contains all the UK organic waste emplaced since 1979, when the MELMod Type 4 landfills were considered to have ceased filling. Golder quantified the various elements of methane generation and emission for the year of 2011, the latest year for which MELMod reported methane emission estimates. As part of the process, Golder consulted with UK and international landfill gas experts, reviewed research undertaken under the umbrella of the Defra/DECC/EA Methane Capture Project, data made available by the EA as well as peer-reviewed literature. A bibliography detailing relevant articles is appended to the report.

This assessment entailed a review of methane generation factors to be used in MELMod to establish the 2011 methane generation from Type 3 landfills including Degradable Decomposable Organic Carbon Content (DDOC) for different waste fractions, waste degradation rates and methane content in landfill gas. Subsequently, the different terms of the managed methane capture were quantified including methane utilised in landfill gas engines, methane flared and methane slippage from engines. Finally, the uncontrolled methane emissions were assessed and estimates were derived for the quantities of methane fugitive emissions from landfill and methane oxidised in the cover soils. The summary of our findings are given below:

- MELMod and GasSim should continue to use current values of the parameter describing available degradable organic content under anaerobic conditions (DDOC).
- The half-lives of waste degradation for a large portfolio of Type 3 UK landfill sites are most realistically represented currently by GasSim "wet" waste degradation rates. This should be kept under review as landfill management practices evolve in the future. Further consideration is also required as to the relative allocation of waste fractions and DDOC to rapid, medium and slowly degrading organic materials (RDO, MDO and SDO) with the various models to better understand their comparability.
- The ratio of methane to carbon dioxide measured in UK landfill gas is calculated to be 57:43% rather than the 50:50% landfill gas production ratio which is the International Panel for Climate Change (IPCC, 2006) default value. Further review of existing research is recommended to investigate these differences.
- Review of the current mix of engine types across the UK portfolio has resulted in an average gross engine efficiency estimate of 40%. It has been assumed that parasitic and other losses are encompassed in a 4% loss factor leading to a net electrical efficiency assumption of 36%. The MELMod model needs to recognise these improvements in electrical efficiency for the UK's modern landfill portfolio.

- The total methane combusted in 2011 in the UK has been calculated as 1,325,427 tonnes. This is comprised of the following components:
  - The quantum of methane utilised in landfill gas engines is calculated be 1,012,501 tonnes for 2011.
  - The quantum of methane that is flared from operational sites with landfill gas utilisation is estimated to be 1/11th of the methane utilised in gas engines. The total estimate for 2011 is 92,242 tonnes.
  - The quantum of methane that is flared from sites with only flaring as gas control is actually very difficult to quantify. In the absence of representative data for the UK, Golder has suggested a methodology to determine this value, which we estimate is 220,685 tonnes. Additional research is required to refine this value.
- The quantum of methane which passes through landfill gas engines unburnt is calculated to be 1.5% of the gas supplied to gas engines in any one year. For 2011, this is calculated to be 14,836 tonnes of methane.
- The fugitive emissions estimate for 2011 is 1,286,251 tonnes. This is based on a limited and potentially unrepresentative data set. It is recommended that the results of further measurements are made at UK landfill sites, such as during the GAUGE project (2014) which is yet to report, and that these are analysed as they become available to refine this estimate.
- Calculations made on differential absorption lidar (DIAL) emissions measurement datasets suggest an overall methane oxidation value similar to the IPCC default value of 10%. Again, until further field measurements are available for analysis it is recommended that the IPCC default value for methane oxidation of 10% is retained.

Golder used these findings to calculate the 2011 methane capture rate for the Type 3 landfill portfolio. This whole life collection efficiency is calculated to be 52% using a methodology based on MELMod methane generation predictions. A second, model independent methodology was employed to validate these findings. This slightly more conservative approach arrived at an estimated methane capture rate of 48%. Applying the latter methodology to a subset of 43 large, operational, modern UK landfills resulted in an estimated instantaneous capture rate of 68% which is close to the median of the range of UK expert's assumptions for current operational sites of 55-85%.

The report includes a detailed sensitivity analysis exploring the impacts of different assumptions for DDOC, waste degradation rates, landfill gas methane content, engine electrical efficiency and amount of flaring on sites that are only using flaring as gas control. The report concludes with recommendations on the calculation of separate collection efficiencies for different modern landfill types that will help to inform current regulatory policy, potential considerations for future updates to MELMod, as well as proposed future research to decrease uncertainty in those elements observed above that are currently quantified based on small data sets or unreliable estimates. Future research may include studies into: the allocation of DDOC to RDO, MDO and SDO between the various models; review of publications to explain the difference in methane content between the measured UK field data and the IPCC (2006) default production value; an historical check on electrical efficiencies; improved quantification of landfill gas flaring; analysis of flaring data with respect to flare types and methane slippage; and analysis of on-going methane emissions monitoring field programmes such as GAUGE to better inform fugitive emissions estimates.

Acknowledgements

Golder would like to thank: the independent peer reviewers for their time and considered comments made to Defra; the Landfill Gas Industry Group (LGIG) for sharing of data and their expertise; the consulted UK and international experts and industry representatives for their honest opinions and time; NPL for discussions regarding their DIAL field studies and assessments; and DEFRA, DECC and the EA for their joint interactions supporting the project.

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1.0 INTRODUCTION

1.1 Background

The Department for Environment, Food and Rural Affairs (Defra) are the policy lead for waste management in the United Kingdom (UK). As such they are responsible for the development of policies to manage solid waste to landfill, the use and promotion of alternatives and the measurement and management of any resulting environmental impacts, including greenhouse gas emissions. Some of these responsibilities are implemented on the ground by the Environment Agency (EA). The Department of Energy and Climate Change (DECC) are the 'single national entity' responsible for submitting the UK's inventory of greenhouse gas emissions to both the UN Framework Convention on Climate Change (UNFCCC) and the European Union (EU) Monitoring Mechanism. As such they are responsible for ensuring that the methods used to model and estimate greenhouse gas emissions from landfill are compliant with the reporting guidelines set down by the Intergovernmental Panel on Climate Change, and adopted for use by the UNFCCC. As a result, both Defra and DECC have a joint responsibility for ensuring the accuracy of reported greenhouse gas emissions from landfill.

Defra considers that waste management accounts for 3% of the UKs greenhouse gas emissions, with the majority being attributed to methane emissions from landfills. Current practice is to model these emissions rather than measure them directly. The estimates of methane emissions from landfills come from computer models. For national emissions MELMod is used and for site specific and Pollution Inventory (PI) reporting estimates the model is usually GasSim.

In MELMod, methane recovery (flaring and utilisation) was assumed to have just achieved 15% by 1990. Driven by the introduction of first Non Fossil Fuels Obligation (NFFO) and then the Renewables Obligation (RO) to incentivise the exploitation of the energy resource, as well as the arrival of the Integrated Pollution Prevention and Control (IPPC) Regulations (2000) and the Environment Agency's Landfill Gas Guidance (Environment Agency, 2004) helping to improve and regulate the engineered infrastructure and landfill gas recovery, the quantum of recovery was assumed to have stabilised at 75% by 2004 (or 72% when taking into account historic sites with no adequate landfill gas capture infrastructure in place). The modelling used to reach this figure has been based on the best evidence available at the time, taken from an evaluation of gas use data for power generation and installed flare capacity from 2002. As time has progressed, Defra considers such estimates are becoming more difficult to justify, particularly where new data are emerging.

The UK claims the highest methane capture rate, followed by Ireland, France and Greece (Oonk, 2012). It is fair to say that the UK has greatest experience and the largest number of landfill gas to energy (LFGTE) installations of any European country, justifying a high comparative capture rate, but there are concerns about the quantum of this value.

Whilst there has been a substantial investment programme in methane capture technology over the last two decades, the precise rate of methane capture remains uncertain. Defra and the EA along with DECC have been working together to address this uncertainty.

1.2 Project Aims

There are two key project aims:

- The first project aim is to provide Defra with an up-to-date, robust figure for methane capture rate from landfill that can be used to inform policy decisions on waste management infrastructure, investment and advice. As any analysis used to inform decisions on the most preferable waste management/disposal routes is sensitive to the methane capture figure, an accurate figure is important both for domestic policy and also in the context of the EU review of future waste policy; and

- The second project aim is to achieve accurate and defensible reporting of emissions from the waste sector into the European greenhouse gas inventory.

1.3 Project Technical Objectives

The three key technical and scientific aspects which drive the estimate of methane emissions which need to be investigated to fulfil the project aims are:

1) **Methane Generation.** This covers a series of primary (first order) effects such as the absolute quantity of waste landfilled; the filling rate, and the effect of the economic downturn; the diversion of biodegradable waste from landfill; the impact of recycling on waste composition; the quantum of degradable carbon in that waste; and its degradation rate. Golder considers these factors as the most significant ones in determining the quantum of any impact. Some of these factors are explicitly excluded from the scope of this study, but their impact is discussed in Section 2 to help put the factors Golder has examined into context;

2) **Rate of gas capture.** This is also known as the collection efficiency. The rate of gas capture is usually expressed as equal to the quantum of gas collected, that is the gas combusted in an engine or flared, divided by the rate of gas generation, which in itself is not measurable but is derived from knowledge of the parameters in (1) above. An improvement in the level of knowledge of the primary methane generation factors, and the subsequent relationship with the validation measurements of emissions made, for example, using differential absorption lidar (DIAL) techniques is considered to be the true goal of this objective; and

3) **Oxidation of methane in cover soils.** This is a parameter which is very hard to measure with any degree of accuracy. The default level of oxidation is 10% of the fugitive surface emission rate but it is not a robust value. Methane oxidising bacteria work up to a certain loading rate beyond that they cannot oxidise the gas, so depending on the quantum of residual flux, the oxidation rate may by a high or a low percentage.

1.4 Project Policy Objectives

Defra and the EA along with DECC need to carry out an urgent review of available data to present a reworked figure for methane capture that stands up to scientific scrutiny, for the following reasons:

- There is a small but nevertheless present risk that without robust evidence to support the current or any revised methane capture rate, the UK could be forced to use the default rate of 20%;
- An UNFCCC review of the current approach was due in September 2013 and it was anticipated that the issue of the capture rate would be raised. There are serious implications of accepting a default value for this parameter;
- Beyond the September 2013 review, DECC have another deadline at the end of the summer in 2014 when the revised capture rate would feed into the next round of Kyoto Protocol reporting; and
- A review of methane capture rates will also provide an opportunity to reassess the need for further field measurements that would help substantiate the findings of the review as well as contributing to the overall robustness of the figures.

1.5 Workplan

This project is to deliver ways of improving those modelled estimates outlined in the project objectives by compiling recent evidence from a variety of sources.

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This assessment entailed a review of methane generation factors to be used in MELMod to establish the 2011 methane generation from Type 3 landfills including Degradable Decomposable Organic Carbon Content (DDOC) for different waste fractions, waste degradation rates and methane content in landfill gas. Subsequently, the different terms of the managed methane capture were quantified including methane utilised in landfill gas engines, methane flared and methane slippage from engines. Finally, the uncontrolled methane emissions were assessed and estimates were derived for the quantities of methane fugitive emissions from landfill and methane oxidised in the cover soils.

Where possible, the sensitivity of the models to particular changes identified has been tested. The key factors identified by this sensitivity analysis are one aspect which can be used to inform recommendations for possible field trials or further data collection.

1.5.1 Soliciting of National and International Expert Advice

Golder started its research activities immediately after the start-up meeting with Defra. In this initial data collection phase, Golder screened the information available and began to determine which factors have new information of relevance to both models. The data review allowed Golder to identify the major implications of current research on methane emission modelling undertaken for Inventory purposes. These were presented at an Expert Seminar, hosted by Defra, and attended by industry, to gain feedback on the shape and content of the study. Golder produced an interim report on the review (Golder Associates, 2013), giving the outline of where Golder's research was going to be focussed, and setting out what was considered to be the most suitable sources of information. We further identified a group of international practitioners working in the area of methane generation and emissions measurement, and we interviewed all of these practitioners in order to obtain a balanced and objective view of the significance of the parameters we were investigating. The list of consulted organisations and individuals is appended at Appendix A, along with the summary of the meetings undertaken in Sardinia.

1.5.2 Methane Generation

The estimate of bulk landfill gas (and methane) generation rates is the primary output from first order decay models such as MELMod and GasSim, and this forms the basis for calculated methane emission estimates. This approach is consistent with the IPCC guidelines on modelling methane generation and any proposed changes remain within these guidelines. The recommendations for modelling changes have considered the following:

- The sensitivity of certain input values such as the amount of DDOC present in landfilled waste and the proportion that is converted to methane and carbon dioxide;
- The related hypothesis that GasSim gives estimates of gas generation which are too low (or too high);
- The effect of waste degradation half-lives in the models;
- Consideration of other operators' in-house models; and
- Calculation of the true ratio of the methane content in landfill gas.

1.5.3 Methane Combusted and Methane Capture Rate

In the 2012 greenhouse gas (GHG) inventory submission, a 75% lifetime capture rate for modern landfills was assumed in MELMod; however, DEFRA and the EA have the intention for MELMod to move away from fixed capture rates to ones that are calculated from a balance of predicted gas generation rates with capture, emissions and oxidation. The 75% lifetime capture rate in MELMod appears high, as Golder's experience with UK landfill gas portfolios is that they may typically achieve an average gas recovery rate of 55-65% over the managed gas abstraction period of the portfolio, which is less than the site's gassing lifetime. Golder has critically reviewed this MELMod assumption, exploring in particular evidence provided by the industry that might be used to substantiate this figure.

The data investigated and recommendations for modelling changes include the following:

- Landfills surveyed using the DIAL technique (Defra R&D projects WR1125 The measurement of methane emissions and surface methane oxidation at landfills, and WR1906 Supplementary DIAL Survey of Methane Emissions and Surface Methane Oxidation at Landfills, Innocenti, 2012 and 2013); and

- Electricity generation data and landfill gas flaring data.

1.5.4 Methane Oxidation

Methane oxidation is potentially an important factor in determining methane emissions. The literature shows that cover soils can deliver much higher rates of methane oxidation than the 10% default figure, but clearly where fractures are present, or where the flux through the landfill cap is high, not all methane emissions at a landfill pass slowly through cover soils and achieve high oxidation rates. A bibliography on current key literature on methane oxidation is compiled in Appendix F.

The hypothesis that the 10% is close to the reality for whole site oxidation at operational sites was tested through the following approaches:

- A focussed literature review including interview of international practitioners;

- Analysis of Defra research report WR1125, *The measurement of methane emissions and surface methane oxidation at landfills;* and

- Analysis of Defra research report WR1906 *Supplementary DIAL Survey of Methane Emissions and Surface Methane Oxidation at Landfills*.

1.6 Layout of this Report

Golder has constructed a conceptual model for the factors which have needed to be assessed. This model is shown in Figure 1 below. All methane generated in a given year is either managed by combustion technology (i.e. methane collected), or lost through fugitive emissions (i.e. methane not collected). A fraction of the managed combustion is actually emitted through methane slippage in the gas engines (and flares), and a fraction of the fugitive emissions is actually managed by methane oxidation in the soil above the cap. This report therefore seeks to quantify the various elements of the conceptual model.

It is acknowledged that by design the conceptual model is a simplification and does not include, for example, methane generated in topsoil, methane migration underground or methane dissolved in leachate. All these areas may possibly be quantified through additional future research, but in Golders opinion (and confirmed via the discussions of the Expert Seminar) these are small in comparison to the main elements identified in the schematic as the focus of this project.

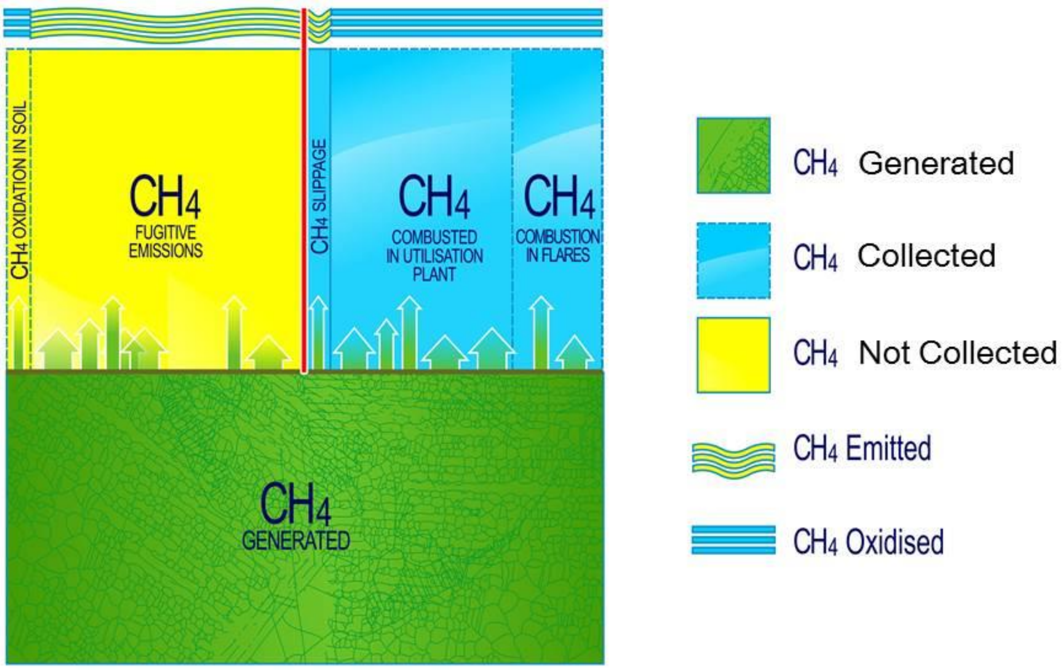

Figure 1: Conceptual Model of Methane Generation and Emission

The elements of the work plan have been organised by chapter and subchapter headings in the following fashion, to address in a stepwise fashion the factors which have been examined:

Chapter 2 – Methane Generation Factors, covering the amount of available degradable organic carbon (DOC) present in landfilled waste; and its degradation rate.

Chapter 3 – Managed Methane Capture, covering landfill gas utilisation; landfill gas flaring; and methane slippage from gas plant.

Chapter 4 – Uncontrolled Methane Emissions, covering landfill fugitive emissions, the methane capture rate, and landfill methane oxidation.

Chapter 5 – The 2011 Landfill Methane Collection Efficiency Estimate.

Chapter 6 – Sensitivity Analysis exploring the impact of parameter variations on the above 2011 Landfill Methane Collection Efficiency Estimate.

Chapter 7 – Recommendations.

Chapter 8 – References.

In each Chapter and/or sub-section where parameters are revised or recommendations made, Golder has indicated at the start of the sub-section (i) the key findings of the research; (ii) the size of the data set used to determine the findings; (iii) how representative that data set is of the UK as a whole; (iv) our judgement on the reliability of the dataset; and (v) the need for additional research to improve the accuracy of the estimate. The terms used and our intent regarding their absolute meaning is set out in Tables 1-3 below.

Table 1: The Descriptors used to define the number of the Data Examined

Descriptor of the number of data sets used	Number of Data Sets	Notes
Limited	1-5	It may be that what is limited in some respects (e.g. the number of studies) has yielded a substantive data set. This is made clear in the description.
Reasonable	5-50	
Significant	50-500	
Substantial	>500	

Table 2: The Descriptors used to define how Representative the Data are

Descriptor of how representative the data are	Notes
Unrepresentative	An insignificant sample set. An approximation, data which requires additional research, or adoption of the IPCC default value(s).
Reasonably representative	A representative subset of a parameter, or requiring additional research to make the data wholly representative.
Representative	A highly significant sample set. No additional research would be anticipated.

Table 3: The Descriptors used to define the reliability of values derived from the Data

Descriptor of the reliability of the datasets used	Notes
Unreliable	Additional research is required to firm up this parameter. IPCC defaults are recommended.
Reasonable	Additional research is required to firm up this parameter, but there is enough information to suggest that IPCC defaults need not be used.
Reliable	A predictable outcome would be obtained using the proposed values. Some additional research may be required.
Very Reliable	A predictable outcome would be obtained using the proposed values. No additional research would be anticipated.

As part of the independent peer review process feedback has also been received and this has been acknowledged at the end of each of the relevant sub sections.

2.0 METHANE GENERATION FACTORS

Methane generation factors which contribute to the total quantum of methane produced year on year include all of the following:

- The absolute quantity of waste landfilled in the past, present and future;
- The filling rate and the effect of the economic downturn;
- The diversion of biodegradable waste from landfill;
- The impact of recycling on waste composition;
- The amount of DOC present in landfilled waste; and
- The degradation rate of the available DOC present in landfilled waste.

The first four are defined by fact, and by future forecasting. They are not derived by scientific labour but looking forward by statistical understanding of anticipated human behaviour. Only the last two are the subject of detailed research in this project. The conceptual model within any model can also have an effect on the way methane generation is modelled.

2.1 Composition and Degradability

2.1.1 Available Degradable Organic Carbon Content

The degradability of materials, and their overall available DOC (i.e. DDOC), can be very site specific. The models examined were reasonably consistent, and the differences between model factors and the results of a recent Defra study can be explained.

The datasets used to derive the values in the models are reasonable in number, and are reasonably representative. A reasonable to reliable forecast can be obtained using the published factors.

As a result, continued use of the degradability factors in the MELMod and GasSim models is recommended.

No additional research is proposed to refine this value.

Landfill modelling is particularly sensitive to certain input values such as the amount of DOC present in landfilled waste, the fraction of degradable organic carbon that decomposes under anaerobic conditions (DOCf), and the proportion of DOC that as a result is available under anaerobic landfill conditions to be converted to methane and carbon dioxide, also referred to as DDOC. Recent Defra work into this parameter has provided new data through the sampling and laboratory analysis of wastes currently being sent to landfill (Project WR1003 *An assessment of the biodegradable content of mixed municipal and commercial and industrial waste*). Values in GasSim have been derived from early USEPA sponsored research (e.g. Barlaz et al 1989). Available DOC values in MELMod and GasSim are one of the few parameters which are derived, rather than determined from data “at the landfill gate”, which can have a significant effect on the gas generation forecasts, and so the accuracy of these values makes this a very important parameter.

The hypothesis that GasSim gives estimates of gas generation that are too low also requires review. The basis of the argument here is that capture rates are assumed to be high and the gas generation value therefore has to fit with the assumption that the collected gas (a known quantity) is a very high percentage of that generated. If the capture rates are lower than assumed then the collected gas is a smaller proportion of the generated gas therefore the generation rate should be higher. This is in fact a different take on the same question regarding the absolute values of available DOC used in modelling. If the gas yield per tonne of waste is underestimated, then the collection efficiency will appear a higher percentage than it really is.

Operators' models are calibrated with known collection figures and, as above, the assumption is made that collection closely matches generation rates and the generation rates are adjusted accordingly. Golder has experience of auditing such models during the many due diligence activities Golder has undertaken across approximately 85% of the ownership of the UK's portfolios of landfill sites. In line with Defra assumptions, we believe that many models could over-predict unless they are tuned against the actual collection which is undertaken. In other in-house models, we have found significant calculation errors. We feel that the empirical approach which some operators have historically used has some merit but needs to be carefully understood before adoption. Our experience is that currently, most landfill gas operators rely on GasSim in one form or another as the gas generation model of choice for their portfolios.

Golder calculated the available DOC on a dry basis for three current landfill gas models (GasSim v2.5 (Environment Agency, 2011); MELMod (MELMod, 2011) and the IPCC Model (IPCC, 2006). Our view is that while the regional composition of waste is variable, and needs to be determined at a local level, the degradability of specific components in the waste stream is readily comparable. These data are summarised in Table 4, along with selected results of the Defra Waste Analysis Study, project WR1003 (Agbasiere & Turrell 2013) and we have considered the significance of these data in our study.

The Defra Waste Analysis Study included the analytical testing of waste component fractions for a range of parameters and a subsequent determination of DOC, DOCf and DDOC as well as a sensitivity analysis on the estimates based on a variety of different calculation methods. The study included five methods of data analysis, to test the sensitivity of the approaches and their impacts. The first three methods (Methods A-C) were based on actual analytical test data and are discussed further below. The study also derived comparison data based on IPPC constants (Method D) and MELMod calculations (Method E) which have also been examined as part of this Golder review.

Method A of the Defra Waste Analysis Study uses calculations based on test data for moisture content, degradable carbon (as cellulose and hemicellulose) and percentage decomposition calculated from the difference between cellulose and hemicellulose pre- and post-anaerobic digestion testing (the BMc test, formerly the BM100 test, is an anaerobic biodegradation test used to determine the potential biogas production of the material under simulated landfill conditions for 100 days). Method B is similar to method A but assumes that degradable biochemical components include fats and soluble organic materials as well as cellulose and hemicellulose (i.e. non-lignin) from pre- and post-BMc fibre analysis. For Method C calculations, the degradable or organic carbon content of the waste fractions were estimated based on Volatile Solids (VS) or measured directly as total organic carbon (TOC). To examine the effects of changes in the proportion of the waste fraction that would be considered degradable, the same Methods described above were repeated with the degradable organic carbon calculation amended to include both lignin and non-lignin fractions. The resulting increase in DDOC led the authors to conclude that it is important to accurately measure the degradable organic carbon of the waste fractions using a suitable methodology.

Among the limitations of the study, the authors stress that the calculations and uncertainty assumptions are based on a single set of test data and should be interpreted and used with caution as the results may not be entirely representative of the characteristics of the different waste fractions over time and will be influence by factors such as representativeness of primary, composite or laboratory samples, or the reproducibility of analyses on the same or different sub-samples.

Further, obtaining reproducible data for the fibre tests on the test samples proved to be a significant challenge. Agbasiere & Turrell 2013 have observed that despite repeat testing of sample fractions, similar results were obtained that are not easily explained. For example, food waste was found to contain predominantly lignin with less than 15% fats, cellulose and hemicellulose pre and post digestion. Whilst the test results may be a true reflection of the composition of the sample provided, it would be considered highly unlikely to be representative of the general food waste stream. Alternatively the fibre method may not perform effectively with certain waste matrices. For several waste materials including garden waste, shoes and accessories, carpet and underlay as well as textiles, Method A produced a percentage decomposition value greater than 100% which suggest a possible anomaly in the fibre method for these waste types. These occasions have been marked as 'n/a' in Table 4. As Method B and C also include the reduction of fibre as part of their calculations, the values reported for these waste materials may also not be representative.

Comparing the findings of the different calculations method, Agbasiere & Turrell 2013 conclude that the results were broadly similar for Methods A, B and C by VS content. The authors further reported that the measurement and calculations based on TOC (Method C by TOC) resulted in significantly lower values. According to the authors this may indicate that the approach significantly underestimates the true values for degradable carbon matter and degradability in the landfill. Alternatively, the results may be closer to the true or actual values as the TOC method uses actual measured organic carbon content for the waste fractions.

DDOC values as derived from the study results are included in Table 4 below.

Table 4: DDOC Values from Three Models and from Defra Waste Analysis Study WR1003

Waste Category	Models			Defra Waste Analysis Study WR1003				
	GasSim v2.5	MELMod MSW and C&I wastes	IPCC Default	Method A	Method B	Method C by Volatile Solids	Method C by TOC	Method A with lignin included
Newspapers (%)	6.3							
Magazines (%)	7.4							
Other paper (%)	29.2	16.1	18.0	12.7	14.0	9.4	3.1	19.1
Liquid cartons (%)	13.4							
Card packaging (%)	13.4			23.1	23.6	29.6	5.7	20.1
Other card (%)	13.4	15.2		14.8	16.0	12.6	4.6	17.2
Wood (%)	8.5	12.5	18.3	10.1	10.8	16.6	5.0	19.7
Wood composites (%)				10.0	10.6	18.5	4.7	18.7
Textiles (%)	6.7	6.7	9.6	n/a	1.4	2.6	0.6	7.5
MSW - Furniture (%)		5.2						
MSW - Mattresses (%)		6.7						
Shoes and accessories (%)				n/a	2.3	2.7	1.5	1.3
Carpet and underlay (%)				n/a	0.4	0.2	0.1	6.4
Disposable Nappies and Absorbent Hygiene Products (AHP) (%)	8.9	4.3	4.8	3.9	4.7	0.4	2.3	3.0
Food waste (%)	7.4	9.5	3.0	0.5	0.9	0.3	0.1	0.3
Garden waste (%)	3.7	8.7	4.0	n/a	2.8	0.2	1.1	n/a
10mm fines (%)	6.7	6.3		12.2	10.7	2.2	0.6	10.9
Sewage sludge (%)	2.8	2.3	0.3					
Composted organic (%)	3.0	0.3						
Incinerator ash (%)	0.2							
Other misc. combustibles (%)	8.9	11.0						
C&I - Commercial (%)		13.9						
C&I - General industrial (%)		13.9						
C&I - Food and Abattoir (%)		8.5						
C&I - Food effluent /Biodegradable Industrial Sludges (%)		6.8						
C&I – C & D (%)		3.3						
C&I – Misc. (%)		4.4						
C&I – Other waste (%)		11.0						
C&I – Misc. Comb (%)		11.0						
C&I – Sanitary (%)		4.3						
Rubber (%)			16.4					

Paper and Card

DDOC assumptions for the models as well as calculated values are generally well aligned for both paper and card. In GasSim, 'other paper' is in fact based on white office paper and this is routinely recycled; however, the values for newspaper, which does not degrade so efficiently due to its complex lignin-cellulose structure, is suitably lower than for the other paper components. The calculated DDOCs are slightly lower than the model assumption if lignin is not taken into account. Method C by TOC shows exceptionally low DDOC values which may be the result of the possible underestimation of the true values for degradable carbon matter and degradability as suggested by Agbasiere & Turrell 2013. Calculated values for card packaging are high compared to the GasSim DDOC assumption, this may possibly reflect the character of the sample analysed.

Wood and Wood Composites

DDOC assumptions again align well between different models and calculated values. While Method C by TOC again produces the lowest DDOC assumptions, IPPC default values are highest among the models and similar to the calculated DDOCs if including lignin within the degradable carbon assumptions. GasSim DDOC assumptions are also relatively low. GasSim represents monolithic wood – whole timbers and the like – with a low surface area/mass ratio. The surface area of all timber products has a significant effect on the degradability, which reflects in the specific DDOC assumptions. In GasSim, the degradability of the wood can be changed if higher surface area material such as chipped wood is modelled.

Textiles

Across the models DDOC values for textiles are reasonably well aligned. For the Defra Waste Analysis Study, Method A produced a percentage decomposition value greater than 100% which suggest a possible anomaly in the fibre method for this waste type and as outlined above the results of the other methods may not be representative either.

Nappies and Absorbent Hygiene Products

DDOCs for nappies and absorbent hygiene products (AHP) are generally well aligned between models and calculated values, although GasSim appears high, and a very low result is produced using Method C by Volatile Solids, but this may reflect a sample or analysis issue rather than a true reflection of the DDOC. Further, variation seen in the data may reflect the variability observed between natural fibres and man-made fibres in nappies and AHP or underlying assumptions about these as man-made fibres do not contribute to landfill gas generation.

Food Waste, Garden Waste and Fines

For food waste the model DDOC assumptions are again reasonably aligned between both UK models, although the IPPC model seems low. For the calculated DDOCs in the Defra waste analysis study, food waste was found to contain predominantly lignin with less than 15% fats, cellulose and hemicellulose pre and post-digestion. Agbasiere & Turrell 2013 conclude that whilst the test results may be a true reflection of the composition of the sample provided, it would be considered highly unlikely to be representative of the general food waste stream. Alternatively they suggest that the fibre method may not perform effectively with certain waste matrices such as food waste. Thus the calculated DDOCs presented are unlikely to be representative of food waste in general.

Similarly, DDOC model assumptions align reasonably well for garden waste in GasSim and the IPPC model, but for the limitations outlined above calculated DDOC values in the Defra study cannot be regarded representative.

For fines, the model assumptions on DDOC are very well aligned, but the calculated DDOCs are higher if based on Method A or B or lower for Method C by Volatile Solids or TOC. The variability within the calculated DDOCs may reflect the character of the specific sample analysed.

Other Waste Categories

The degradability of other individual categories such as sewage sludge, composted organics, incinerator ash, and the C&I waste streams identified in the MELMod data demonstrate that very specific degradabilities can be determined for waste streams. On the other hand, there is seldom enough knowledge of the nature of waste materials going to landfill beyond an EWC code, and so the choice of one value over another invariably introduces an estimate and an uncertainty into the calculation. Indeed, IPCC has values for bulk MSW and industrial waste for just such a reason.

In addition to the consideration of degradable cellulose as a source of methane, Golder interviewed a number of international practitioners regarding the degradability and methane yield from proteins and lipids. These can yield methane in anaerobic digestion, but that process is a managed process and is hundreds of times faster than in a landfill. The overall view was that there is currently poor data on this topic, and indeed there are PhD students in Denmark currently researching the degradability and methane yield from proteins and lipids. The type of food source was considered important, with commercial food waste considered the greatest potential source of methane from proteins and lipids.

Golder concludes that the degradability of materials, and their overall available DOC, can be very site specific. At the current stage, continued use of the degradability factors in the MELMod and GasSim models is recommended. The alternative, a detailed analytical project examining the degradability of waste materials, will be a complex project, and while it will deliver UK specific data, the quality and uncertainty of other factors in the modelling, such as the total quantity of municipal and C&I waste tonnage going to landfill, and its detailed composition, may suggest that this level of detail is not warranted.

The potential impact on changes to DDOC has been assessed as part of the sensitivity analysis in Section 6.1 of this report. The sensitivity analysis looks at alternative DDOC assumptions for different waste fraction based on the Defra Waste Analysis Study WR1003 as well as IPCC assumptions, the impact on methane generation as predicted by MELMod and the implications on calculated collection efficiency assumptions for 2011.

2.1.2 Waste Degradation Rates

The half-live of waste degradation for a large portfolio such as the entire UK are most realistically represented currently by GasSim defined “wet” waste degradation rates (although this should be kept under review).

This is based on a significant and representative data set, and is considered to be a reliable assumption.

Further consideration is required as to the relative allocations of waste fractions and DDOC to rapid, medium and slowly degrading organic materials (RDO, MDO and SDO) within the various models to better understand their comparability.

It is well established that the initial hydrolysis reaction of cellulose and hemicellulose polymer to glucose monomer is the slowest and therefore the rate determining step in the entire process of waste degradation. It is this reaction step which is reflected in the various waste degradation rates per year published by the IPCC (2006) and others. Eunomia (2011) considered that cellulose and hemicellulose are the degradable components, and that they should be modelled separately, rather than the approach used in MELMod, GasSim and IPCC of splitting the waste into slowly, moderately and rapidly degrading waste streams, each containing cellulose and hemicellulose. None of the three modelling approaches mentioned above separate these two components, and that is due to lack of information on the rate of degradation of each component either in isolation or when combined with other materials such as lignin which moderates both the degradability and degradation rate. As a result, we consider both MELMod and GasSim should continue as before to represent rapidly degrading organic material (RDO), medium or moderately degrading organic material (MDO) and slowly degrading organic material (SDO) in the same fashion as the IPCC model.

The IPCC-recommended default methane generation rates (k values) for RDO, MDO and SDO fractions are given in Table 5. The equivalent k values in the GasSim model, with indications of infiltration rate and overall moisture content are given in Table 6. The paper/textiles fraction of the IPCC SDO is most appropriate for comparison with UK modelling approaches.

Table 5: IPCC Recommended Default Methane Generation Rate (k, year^{-1}) Values (IPCC, 2006)

Type of Waste		**Climate Zone**							
		Boreal and Temperate (MAT =< 20°C)				**Tropical (MAT > 20°C)**			
		Dry (MAP/PE < 1)		**Wet (MAP/PE > 1)**		**Dry (MAP < 1000 mm)**		**Moist/Wet (MAP >= 1000 mm)**	
		Default	**Range**	**Default**	**Range**	**Default**	**Range**	**Default**	**Range**
RDO	Food waste/ sewage sludge	0.06	0.05 – 0.08	0.185	0.1 – 0.2	0.085	0.07 – 0.1	0.4	0.17 – 0.7
MDO	Other (non-food) organic putrescible/ garden and park waste	0.05	0.04 – 0.06	0.1	0.06 – 0.1	0.065	0.05 – 0.08	0.17	0.15 – 0.2
SDO	Paper/textiles	0.04	0.03 – 0.05	0.06	0.05 – 0.07	0.045	0.04 – 0.06	0.07	0.06 – 0.085
	Wood/straw	0.02	0.01 – 0.03	0.03	0.02 – 0.04	0.025	0.02 – 0.04	0.035	0.03 – 0.05
Bulk Waste		0.05	0.04 – 0.06	0.09	0.08 – 0.1	0.065	0.05 – 0.08	0.17	0.15 – 0.2

Note: MAP – Mean Annual Precipitation, PE – Potential Evapotranspiration, MAT – Mean Annual Temperature

Table 6: Equivalent GasSim v2.5 Model Default Waste Degradation/Methane Generation Rate (k, year^{-1}) Values

Type of Waste	**Dry Waste (e.g. very low infiltration)**	**Average Waste (e.g. low infiltration)**	**Wet Waste (e.g. high infiltration)**	**Super-wet Waste (e.g. very high infiltration or Bioreactor)**	**Saturated Waste**
RDO	0.076	0.116	0.694	0.694	0.076
MDO	0.046	0.076	0.116	0.116 – 0.694	0.046
SDO	0.013	0.046	0.076	0.076 – 0.116	0.013

Note: SDO in UK waste streams is more representative of paper/textiles in IPCC methodology than wood/straw

In GasSim, MELMod, and the IPCC model, each waste stream consigned to landfill is assumed to contain proportions of waste in three separate categories of organic material, depending on their likely rate of degradation in a landfill. The labels used, of 'readily degradable', 'moderately degradable' and 'slowly degradable' (RDO, MDO and SDO) are useful labels to understand the relationship between the degradability of each waste stream, i.e. putrescible waste from the RDO fraction is more quickly degraded than paper and card from the MDO fraction, in a given landfill situation, and these labels should only be used in that context. Each of the three degradability fractions is assigned a degradation rate, k (units of y^{-1}) based on first order kinetics. The relationship between the degradation rate, k, and the corresponding half-life for waste degradation is simply:

$$\textit{Degradation rate, } k\ (y^{-1}) = \textit{Ln}\ (2)/\textit{half-life}\ (y)$$

The IPPC approach is to allocate different sets of waste degradation half-lives for sites which are found in different climatic regions. These are

- Boreal and Temperate Dry;
- Boreal and Temperate Wet;
- Tropical Dry; and
- Tropical Wet.

It is clear when comparing Tables 5 and 6 that the range of k values provided in GasSim (which, apart from dry values, are values specifically chosen for modelling UK sites for permitting purposes, where detailed knowledge of the sites exist) spans the range of all climatic regions represented in the IPCC dataset. We therefore want to highlight two important observations regarding the choice of waste degradation rates:

- Waste degradation rates form a continuum between dry and wet conditions (saturated landfills excluded) whether in temperate or tropical climates, and the simple labels used in GasSim are there solely to make it straightforward to understand where on the continuum the set of rates which apply to that label sit; and
- Experience tells us that climate alone is not the sole arbitrator of which particular set of waste degradation rates apply to either an individual landfill or an entire portfolio.

The moisture content of the waste is one of the main factors controlling the rate of waste degradation. Changing the moisture content within a model will not affect the total volume of gas produced (this is determined by the waste composition and the degradability of the waste) but it does affect the shape of the gas curve. 'Dry' conditions cause waste to degrade more slowly, and can reduce the peaked-ness of the gas generation curve. Choosing a 'wet' waste moisture content causes the waste to degrade more quickly, creating a much steeper increase and decrease in the gas production curve. An 'average' waste moisture content produces a curve somewhere between these dry and wet curves. These waste degradation/gas production curves are clearly on a continuum, and at the Site level, waste degradation rates are selected and can be fine-tuned to incorporate a number of secondary or site-specific effects which can modify the shape of the gas generation curve further.

Eunomia (2011) explain that measurement of the decay constant k in real landfill conditions is difficult. They also state that the attribution of fractions of the waste stream to the rates which are applied to RDO, MDO and SDO in MELMod is very hard to verify, but we disagree, and believe that this attribution procedure is entirely comparable to that used by the IPCC, and by GasSim:

- There is consistency in the approach used in all three models; and
- The numeric ranges of rates used are comparable between the models.

GasSim default waste degradation rates have become the default waste generation rates used in the UK industry since GasSim was first launched in 2002. GasSim was designed for permitting of landfills in the UK, and not as a portfolio tool, and so GasSim has to offer the user a range of rates for RDO, MDO and SDO. Eunomia (2011) incorrectly attribute only one set of rates for RDO, MDO and SDO to GasSim (the average set of rates). GasSim uses a series of fixed rates defined thus:

- Superwet (or bioreactor). From Golder experience, these k values are most suited to sites in Ireland and certain UK west coast sites. These rate constants would not be used in a portfolio context, but have been used for individual sites for permitting purposes.
- Wet. From experience, wet waste degradation rates are the UK default, though it is not clear whether this is due to waste moisture content or the effect of other factors as yet unknown.
- Average. Once the UK default, we find that this is typically no longer the case. Golder's view is that the practitioners have observed a migration from average to wet as a default, and this may be due to waste moisture content or the effect of other factors as yet unknown.
- Dry. The parameters for dry wastes represent truly desert conditions. These are not used in the UK. These rate constants would not be used in a portfolio context.
- Saturated. If a site's moisture content exceeds bioreactor conditions, the site becomes a flooded landfill, and the effect of saturation is to rapidly slow the degradation of waste. The k values used for saturated waste are the same as for dry waste. These rate constants would not be used in a portfolio context.
- MELMod currently uses the same waste degradation rates as specified in GasSim under the average category (Table 7).

Both the IPCC (2006) and EA (2004) states that climate and temperature are the prime factors for the selection of k factors. This is true for macro-scale approaches, but this is definitely not the case for the UK, where a maritime climate rather than a continental one applies. If the IPPC classification was adopted as a default, as proposed by Eunomia (2011), this would classify the UK as having a Boreal and Temperate Wet climate, but the degradation rates which these represent are between GasSim average and wet moisture content waste degradation rates. Currently, when considering landfill gas portfolios, it is our experience, based on ten years of modelling UK landfills, and working with 85% of the UK's landfill gas portfolios for resource management purposes, that GasSim wet waste degradation rates are closer to the portfolio norm than any other sets of waste degradation rates. GasSim wet degradation rate values are similar to IPPC Tropical wet degradation rates, and while the rate values differ in each, the net effect, in terms of gas generation, are similar.

Figure 2 illustrates Golder's experience of suitable default k factors based on the maritime influence, and the prevailing storm track from the southwest, but excluding the influence of site-specific factors.

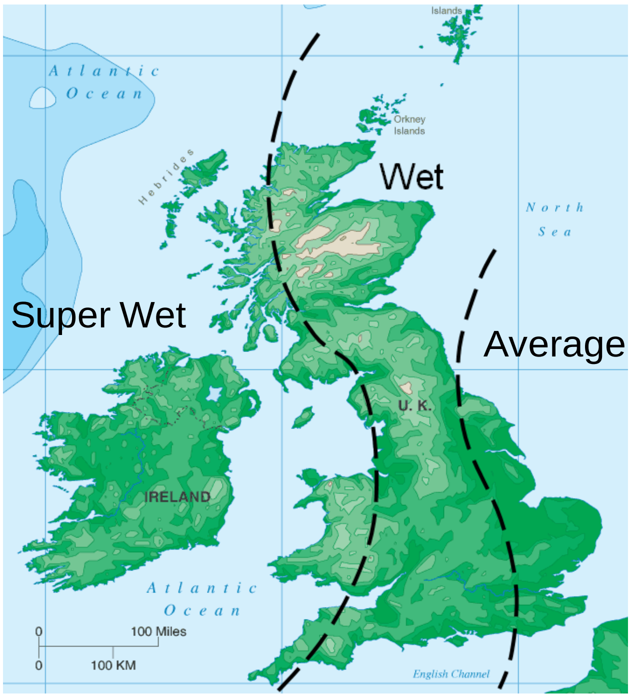

Figure 2: Approximation of the effect of a maritime climate with a south-westerly prevailing storm track on typical UK Waste Degradation Rates.

Eunomia (2011) discuss the origins of the half lives in MELMod, citing LQM (2003), which describes the first use of what have become GasSim wet half-lives by Manley et al (1990a; 1990b). In the 1990s, the waste degradation rates used in the UK were driven by early research by EMCON Associates (Pacey and Augenstein, 1990). A decade later, around the time of the LQM report, both the regulator and industry believed that the fast set of waste degradation rates which became GasSim wet rates were too fast for the UK, and GasSim average half-lives were appropriate for MELMod. These degradation rates would have reduced the peak gas generation rate, compared to effect of the Manley et al (1990a; 1990b) rates, and this choice of gas production rates was calibrated on the basis of what landfill gas recovery rates were being achieved by landfill operators at the time. At this time, GasSim had just been introduced to aid IPPC permitting, and there was a strong belief throughout the industry that gas collection efficiencies were high. Only a few landfills needed to use wet waste degradation rates to achieve modelled gas generation yields high enough for modelled gas recovery to match actual gas recovered.

Since the introduction of the IPPC regime, landfill operators have continued to strive for and achieve higher gas collection efficiencies. Consequently, if the industry had continued to use GasSim average half-lives, the modelled collection efficiencies would have exceeded 100%. In retrospect, the industry's efforts to capture more landfill gas over the last decade have demonstrated that the waste degradation half-lives which should apply in the UK are much faster than we believed were the case a decade ago.

This also means that we were not collecting as large a fraction of the gas generated than we believed we were collecting. Since Eunomia (2011) explained that the degradation rate cannot realistically be validated, the approach adopted for permitting purposes, when using gas generation models such as GasSim, has always been to ensure that there must always be more gas generated than collected. What we did not know was that a decade ago, when we set the use of average GasSim half-lives in MELMod, was that these rates were unrealistically low, and that gas recovery was not as efficient as we thought.

Table 7 below summarises the ranking of IPPC, GasSim and MELMod waste degradation rates, with ranges in brackets where applicable, ranked from the slowest to the fastest set of rates. Note that GasSim wet and IPPC tropical wet are very similar.

Table 7: Ranking by Waste Degradation Rate (year^{-1}) of GasSim, MELMod and IPPC

Type of Waste	GasSim Average Waste Conditions and MELMod	IPPC Boreal Temperate Wet Conditions	GasSim Wet Waste Conditions	IPPC Tropical Wet Conditions
Rank	Slowest rates	Faster than MELMod rates. Proposed by Eunomia (2011)	Comparably fast rates in overall gas production terms, the GasSim rates show elements of both Temperate and Tropical Wet defaults, which seem best suited to the Temperate Maritime climate of the UK	
RDO	0.116	0.185 (0.100-0.200)	0.694	0.400 (0.170-0.700)
MDO	0.076	0.100 (0.060-0.100)	0.116	0.170 (0.150-0.020)
SDO	0.046	0.060 (0.050-0.070)	0.076	0.070 (0.060-0.085)

Landfill operators commonly use wet, or slightly modified (hybrid) wet waste degradation rates. Hybrid rates (a combination of wet, wet, and average GasSim rates for RDO, MDO and SDO respectively) are used by two of the top three landfill gas operator's when valuing their portfolios, covering at least 50% of the installed capacity of the UK. These operators feel that the use of average waste degradation rates for the slowly degradable fraction helps the model represent the post closure lag in gas production often observed after sites stop accepting waste and are permanently capped. This effect has also been described as the dry tomb effect, where the waste environment is changed following capping and exclusion of infiltration. Such an effect is site specific, and would not be easily represented in a portfolio model, and so Golder does not recommend that this approach is used in MELMod.

Another site-specific observation reported by operators is a potential layering of landfills post closure, with a saturated base and a drier upper layer. Each layer may have a different waste degradation rate associated with it. It is believed that the drying out of the upper layers is a recent phenomenon due to the modern capping regime. However, this is not observed on all sites, and it is currently not included in the portfolio model.

Our understanding of landfill biochemistry has not changed significantly since it was first described by Farquhar and Rovers (1973). This is discussed in more detail in the section on methane:carbon dioxide ratio, but it is relevant to consider here whether landfill engineering and landfill operations have affected the degradation of cellulosic materials in landfills since landfilling was formalised. Gas production rates can be influenced by moisture content; temperature, aeration; pH, Eh, alkalinity, nutrition, and inhibition (Farquhar and Rovers, 1973).

- Moisture content is still considered to have the greatest effect on waste degradation rates overall, and the degree of infiltration and saturation is reflected in the naming of GasSim default waste degradation rates.

- Temperature is also significant, with waste degradation rates increasing up to 55 ^{o}C. Landfills are good at maintaining a steady temperature through insulation, and changes in engineering and cap design are unlikely to have influenced the overall operating temperature of a landfill sufficiently for this to cause waste degradation rates to change over the last 25 years.

- Aeration, the degree of air ingress into the landfill, has also been well managed over that timeframe, with guidance specifying first engineered clay caps, and then membrane caps over completed cells, while the operational areas remain uncapped, and so this factor also seems to be insensitive over the period considered, although aeration may well be relevant to the rate of decomposition in landfills constructed pre-1980 (Type 4 landfills), when average waste reduction rates might well apply.

- The waste composition has greatest effect on pH, Eh, alkalinity, nutrition and inhibition of microbes, and although waste composition has changed since 1990, when 'wet' waste degradation rates were first described in the UK (Manley et al, 1990a; 1990b), it has not been such a significant change to suggest that waste degradation rates would first slow and then speed up over the last 25 years.

In conclusion, we consider that the waste degradation rates which should apply in a portfolio model of the UK are defined by the GasSim wet waste degradation rates, which are most representative of the gas generation rate today.

While the waste degradation rates were reduced in 2003 from the rates used previously, which dated from Manley et al (1990a; 1990b), we have considered the possibility of improvements in landfill engineering and landfill management, or changes in waste composition, first slowing and then accelerating gas generation, but if anything has been observed, it is a slowing of waste degradation post-closure, and this is believed to be a recent phenomenon, caused by the exclusion of infiltration through early capping. It can therefore be inferred that as gas collection efficiency improved in the early 2000s following the impact of the IPPC regulatory regime, the selection of the average waste degradation rates in 2003 appears now to have been inappropriate.

We consider that the GasSim wet rates are currently used throughout the MELMod model for Type 3 landfills from 1980 to the present day assuming that the relative allocation of waste fractions and DDOC to RDO, MDO and SDO are comparable in both models. It may be appropriate to retain average waste degradation rates for Type 4 landfills due to the significantly different aeration regime which applied to those landfills (see also Section 7.1).

Whilst the application of GasSim wet degradation rates is recommended to MELMod, the allocation of single waste fractions to RDO, MDO and SDO which will impact on the overall predicted gas release rates has not been investigated in detail as part of this study. This was also noted in comments by the peer review process. As such, if the relative allocation of waste fractions and DDOC to RDO, MDO and SDO are significantly different across the varying waste component descriptors between GasSim and MELMod, then further review and sensitivity analysis into the impacts is recommended.

The impact of changes in degradation rate has been assessed as part of the sensitivity analysis in Section 6.2, where the use of average and wet GasSim degradation rates as well as IPPC boreal temperate wet degradation rates (Table 7) in MELMod, the implication for methane generation, and impact on the 2011 collection efficiency estimates for Type 3 landfills have been examined.

2.1.3 The Methane/Carbon Dioxide Ratio in UK Landfill Gas

The ratio of methane to carbon dioxide in UK landfill gas is calculated to be 57:43% rather than the generally assumed 50:50%.

This is based on a substantive and representative data set, and is considered to be a very reliable calculation.

A sensitivity analysis, increasing the methane content from 50% to 57% in MELMod, results in a predicted increase in generated methane, for the MELMod Type 3 landfill portfolio, from 2.22 Mt to 2.53 Mt in 2011 (a 14% uplift).

Given the robust calculation of this value, no additional research is proposed to refine this value. However, further research is recommended to investigate the differences between the UK field ratio and the IPCC (2006) 50:50% default.

The proportion of the DOC that is in the form of methane (rather than carbon dioxide) is important in the amount of methane generated and this assumption must be tested using data on methane content. MELMod currently includes default methane to carbon dioxide ratio assumption of 50% to 50%. The methane to carbon dioxide for the UK landfill portfolio was assessed as described below.

Landfill gas monitoring data from the gas utilisation plant were supplied by three operators for the three calendar years 2010, 2011 and 2012. The operators manage over 60% of the total UK utilised landfill gas portfolio. Two operators provided monitoring data sets for each of their landfill sites or for each of their assets (engines) whereas one operator provided monitoring data averaged for each landfill on an annual basis. Over 50,000 data points comprise this data set.

Data quality assurance was undertaken for each data set with combined methane and carbon dioxide concentrations for each measurement expected to be between 20 and 100% (including balance gas). Data outside above ranges were excluded from further analysis. As part of the data analyses the following parameters were calculated for each monitoring point:

- Balance gas concentration at the gas utilisation plant (balance including oxygen);
- Methane and carbon dioxide concentration in landfill gas excluding balance gas; and
- Methane to carbon dioxide ratios excluding balance gas.

Following the analyses of each single data set, all data were combined yielding a combined data set of 53,781 data points. For the combined data set, all methane and carbon dioxide concentrations were plotted as a scatter diagram to identify any potential outliers.

The parameters methane concentration (excluding balance gas), carbon dioxide (excluding balance gas) and balance gas (oxygen plus nitrogen) were described statistically and plotted as histograms to visually assess the shape of the distribution.

Table 8 summarises the findings for average balance gas concentrations as well as concentrations of methane and carbon dioxide (without balance gas).

Table 8: Statistical Summary of Landfill Gas Composition

	Concentration (%)	Standard Deviation	No. of Samples
Methane (Without Balance Gas)	57	3	53,781
Carbon Dioxide (Without Balance Gas)	43	3	
Balance Gas	22	10	

Figures 3-5 show the histograms for each parameter. While methane and carbon dioxide concentrations (without balance gas) are normally distributed, the balance gas distribution is slightly skewed, which is likely to be caused by chemical interaction between landfill gas and ingress air.

As can be determined from Table 8, abstracted landfill gas including balance gas based on the analysed data set has an approximate methane concentration of 44.5% and carbon dioxide concentration of 33.5%. However the amount of balance gas in the abstracted landfill gas can be highly variable depending on landfill-specific conditions and adopted gas management practice, and thus the actual concentrations of methane and carbon dioxide in landfill gas diluted by balance gas will be equally variable.

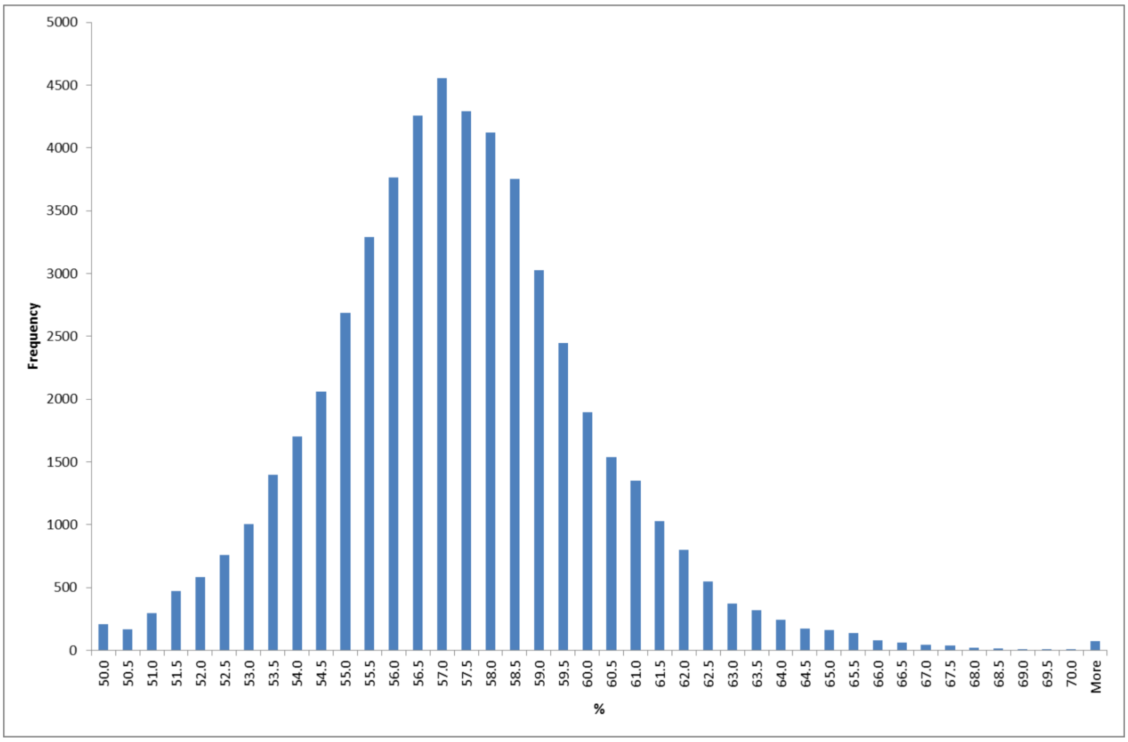

Figure 3: Methane Concentration Distribution

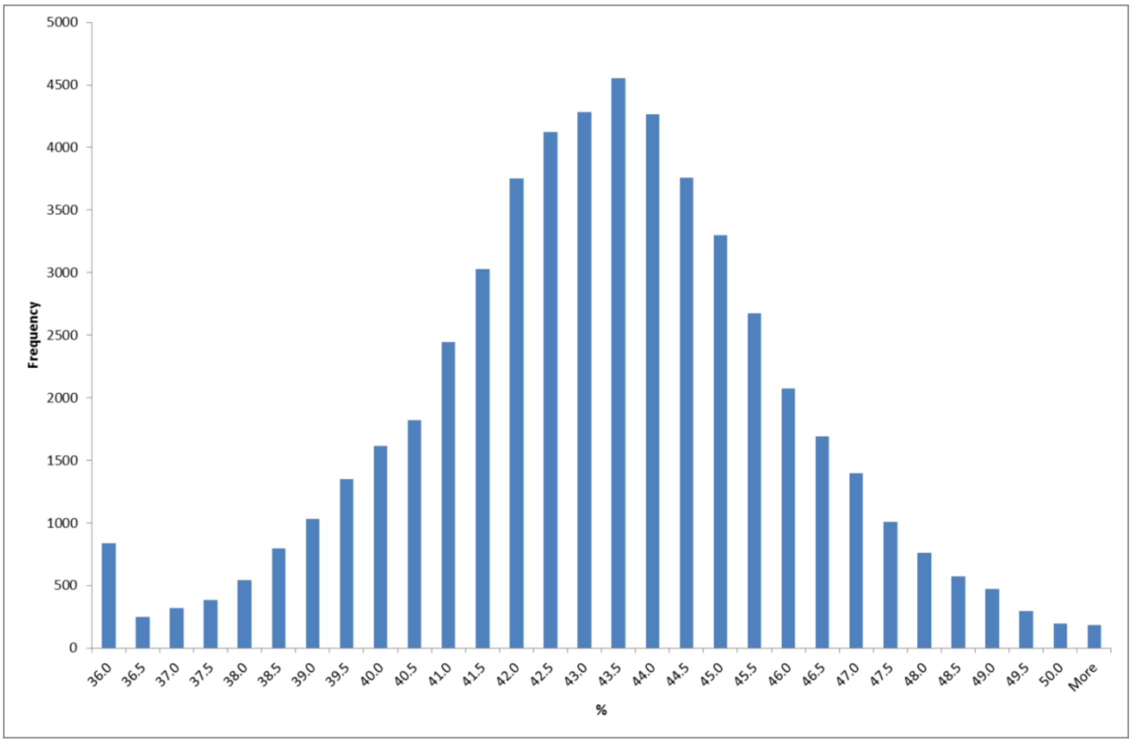

Figure 4: Carbon Dioxide Concentration Distribution

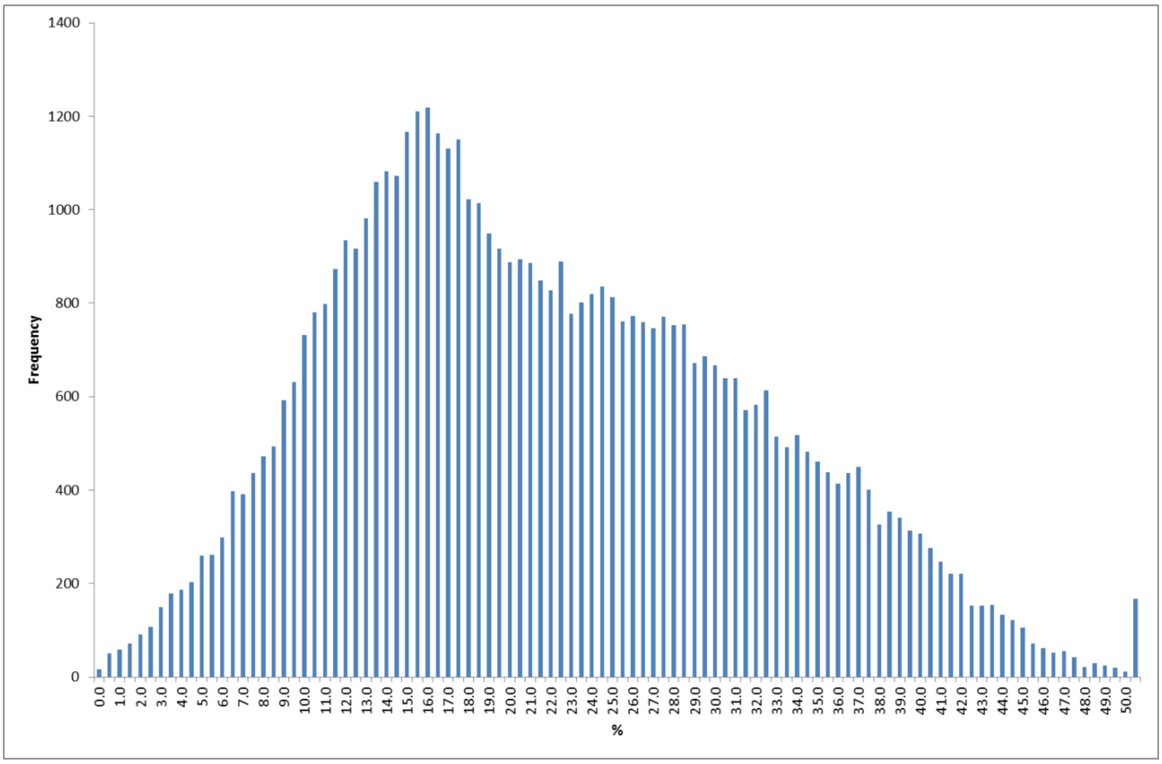

Figure 5: Balance Gas Concentration Distribution

Within MELMod, modern UK landfills are represented as Type 3 landfills. The spreadsheet "MELMod_2011_v1-2_(2011 Inventory)" was used to establish the impact on predicted methane generation from the Type 3 UK landfill portfolio in 2011 for an increased methane content of 57% as shown in Table 9 below.

Table 9: MELMod Predicted Methane Generation 2011

Methane Content in Landfill Gas	Value	Unit
50%	2,215,874	tonnes
57%	2,526,096	tonnes
Uplift	310,222	tonnes
	14	%

Within MELMod, the difference between an assumption of 50% methane and 57% methane is significant, and so it is important to determine whether the 57% concentration is pertinent to:

- Previous years of landfilling, when the landfill engineering might not have been so effective in keeping atmospheric air out; and
- At what stages in an individual landfill's gas generating history is 57% applicable, and would this percentage need to be devalued to account for fresh wastes and wastes past their peak gassing period.

In an attempt to answer the first point, we examined the guidance developed for the industry since the earliest years of landfill gas management. This guidance has typically been developed by regulators and policy makers, but recently, the Environment Agency has accepted the Industry Code of Practice (ICoP) on landfill gas produced in 2012 as an Environmental Services Association (ESA) document as a suitable guidance document for industry to help them meet their regulatory requirements.

We examined all relevant guidance documents with landfill gas compositions cited (Table 10), and found that most reflected the concentrations first cited in guidance in 1986, of 63.8% methane content as a most likely concentration. We know this value came from a single gas analysis, but it continued to be retained in guidance as a representative value, and it still remains in current guidance, in LFTGN03 (2004).

The landfill gas flaring guidance (version 2.0 of 1999 (draft) and 2.1 of 2002 (final) adopted slightly different data which included entrained air, but the methane content did not drop below 55-56% methane, and when this value is normalised, the concentration rises to more than 64% methane. The 2012 ICoP continues this theme of high methane content, quoting 60% methane, 40% carbon dioxide.

It is clear from this examination of most likely methane contents in landfill gas that for previous years, and for older wastes, consideration should be given to revising the methane content of landfill gas assumed in MELMod to the observed ratio of 57% methane, 43% carbon dioxide. Further research to investigate the difference between the measured UK field ratio and the IPCC (2006) 50:50% default is recommended.

Table 10: Typically Accepted Concentrations of Methane and Carbon Dioxide in Landfill Gas in UK Guidance (normalised composition in brackets)

Source Document	Methane Average (%)	Methane Observed Maximum (%)	Carbon Dioxide (%)	Carbon Dioxide Observed Maximum (%)	Balance Gas (%)
Landfilling Wastes. Department of Environment Waste Management Paper 26, HMSO London, 1986	63.8	77.1	33.6	89.3	-
Landfill Gas. Department of Environment Waste Management Paper 27, HMSO London, 1989,	63.8	88.0	33.6	89.3	-
Interim Internal Technical Guidance for Best Practice Flaring of Landfill Gas. Report LFG2 v2.0, 1999.	55.0 (64.7)	-	30.0 (35.2)	-	15.0 (0.0)
Guidance on Landfill Gas Flaring, v2.1. Environment Agency, 2002.	56.0 (64.3)	-	31.0 (35.6)	-	13.0 (0.0)
Guidance on the Management of Landfill Gas. LFTGN03, Environment Agency, 2004	63.8	88.0	33.6	89.3	
Landfill Gas Industry Code of Practice. ESA. 2012	60	-	40	-	-

Landfill gas composition also varies with time, and rates of landfill gas generation vary with time. The Farquhar and Rovers (1973) conceptual model is still considered today to be the defining model of landfill gas production. The model was developed further to include both gas generation and compositional changes, and was extended in time to include the final phase of landfilling where gas generation slows and the landfill finally becomes aerobic. This conceptual model of gas generation and gas compositional variation is shown in Figure 6, in its final form from LFTGN03 (Environment Agency, 2004).

In Stage 1 of landfill gas generation, waste degrades aerobically, like compost, consuming the air which surrounds it. Only when this air has been consumed does Stage 2 commence, which is the start of acidogenic waste degradation. This is characterised by carbon dioxide and hydrogen generation, and no methane is produced at this stage. Waste is hydrolysed and degrades to produce long chain organic acids. Stage 3 is known as the acetogenic phase, when carbon dioxide and hydrogen production peaks, methane is starting to be generated, and acetic acid is a degradation product. Landfill gas generation reaches its peak in Stage 4, the fully methanogenic phase.

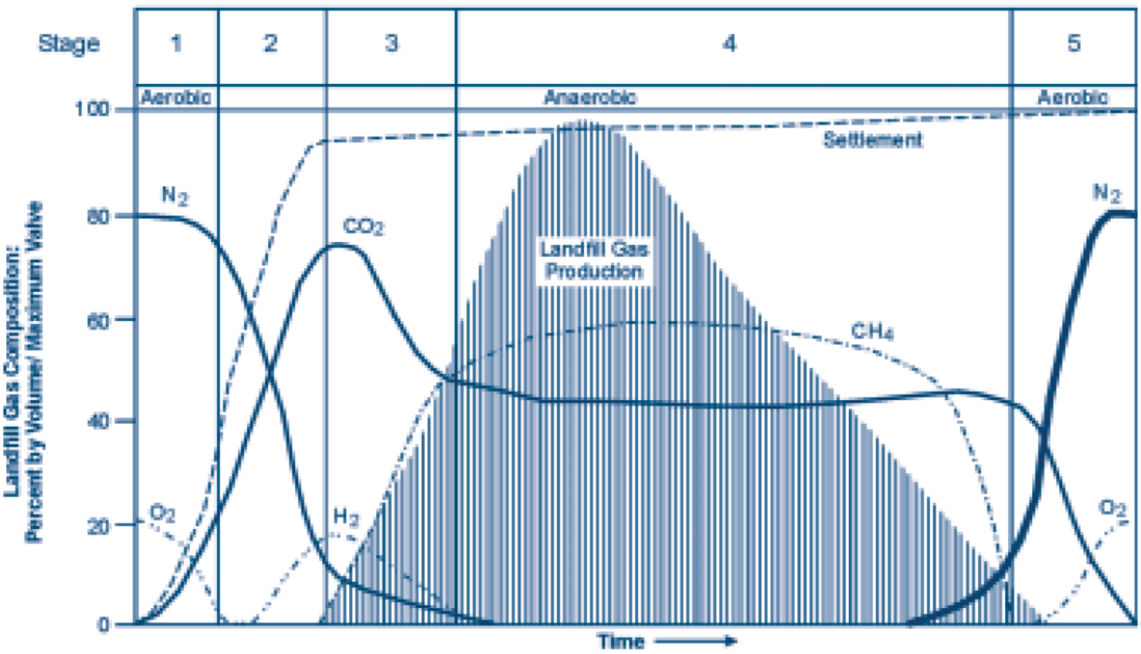

Figure 6: Landfill Gas Composition v Time (Environment Agency, 2004, after Farquhar and Rovers (1973))

Farquhar and Rovers did not achieve quantification of the timeline of this figure, but the start of Stage 4, which is fully anaerobic methane production, has since been demonstrated in the UK by Barry et al (2004), with methane production achieving viable recovery rates in the sixth month after placement in a new waste cell. This means that stages 1-3 occur in fresh waste over a typically six month timeline in a landfill's 100 year plus gas generation lifetime. This could be represented in a model as a six-monthly delay in gas generation from the time of emplacement. While this is relevant in a site specific model, representation of stages 1-3 in a portfolio or country-wide landfill gas model is not necessary.

Once established, the gas generation process produces landfill gas at a typical 57% methane to 43% carbon dioxide ratio due to the biochemistry of the many processes involved, which are quite stable in the landfill environment. When the gas is abstracted for utilisation purposes, suction applied to the gas wells draws air into the landfill site. This air has the same composition as atmospheric air to start with, i.e. 78% nitrogen, 20.95% oxygen, 1% argon, 0.035% carbon dioxide, and the balance made up of inert gases. The oxygen in air will react with waste in the landfill and compost it, producing carbon dioxide and water, rather than allow it to degrade to form landfill gas, but this reaction is limited by the rate of supply of oxygen to the landfill and never in practice goes to completion, so there is always oxygen present in a small quantity in abstracted landfill gas. The air drawn into a landfill site during the active operational stage of landfilling will affect the natural methane/carbon dioxide ratio due to the additional oxidation taking place in the system, and we believe this is why the ratio which has been observed across the UK operational portfolio averages out at

57% methane to 43% carbon dioxide rather than the oft quoted 60% methane to 40% carbon dioxide, which is closer to the methane concentrations achieved in biogas plants, where air ingress is actively, and effectively, minimised.

The final question which needs to be addressed is the question of what happens to air which ingresses in the final phase of landfilling. The landfill gas which is produced will of course continue to be produced at same ratio as has been observed in actively gassing landfills, and which is close to that achieved in a biogas plant. Gas production continues for a long while after gas utilisation stops, and so long as gas is being generated, this will tend to keep air ingress into the landfill at a low level. Once there is abstraction applied at these low gas generation rates, if abstraction is maintained without careful balancing of the gas field, the landfill gas tends to be exhausted quickly, and a cycle of methane exhaustion and recovery can develop in the landfill.

To date there is limited information in the public domain on the methane/carbon dioxide ratio and the air ingress levels in such Stage 5 (aerobic) landfills. Research studies provided by C&P Environmental (Tom Parker, personal communication, 2014) for two sites where biofilter technologies have been trialled for late stage gas management shows a similar pattern of the distribution of methane in landfill gas emerging as was seen in the large dataset for operational landfills. For the smaller dataset of 73 samples, the normalised methane content has a mean of 53.1%, median of 55.6% and most likely value of 58.4%. For the larger dataset of 2966 samples, the mean was 62.6%, the median was 65% and the most likely value 64.7%. For this larger dataset, carbon dioxide is quite suppressed, at an average of 37.4%, a median of 35% and a most likely value of 36.9%. The population of this dataset fitted a near normal distribution. While the sample is limited to two landfills, there are sufficient data points to indicate that until additional work is undertaken, the ratio observed from operational sites is sufficiently similar to be extended to sites in the final stages of gas generation, where there is significant air ingress. Retaining a lower methane content of 50% in MELMod for older sites where methane management is less effective is therefore not appropriate.

The peer review opinion was divided on the recommendation to amend the proportion of methane produced from IPCC default value of 50% (IPCC 2006) to 57% for modelling. The underlying question is whether the methane to carbon dioxide ratio observed during monitoring i.e. at point of release is reflective of the molar concentration rates assumed during landfill gas generation, and or whether there are any secondary processes that significantly change the ratio prior to landfill gas emissions monitoring.

One reviewer considers the recommendations based on the field data in this report robust, and in line with controlled laboratory experiments as well as theoretical on potential carbon dioxide dissolution using Henry's law. Two other reviewers disagree that the landfill gas monitoring data can be used for a surrogate for the ratios at the gas generation stage. One reviewer considers that the IPCC (2006) 50% assumption for landfill gas production should be maintained, the other suggests further research into the topic in line with the IPCC good practice recommendation to adjust for the carbon dioxide absorption from leachate if the fraction of methane in landfill gas is based on monitoring data (IPPC 2006).

Based on the divided peer review opinion, a further review to explain the difference between the landfill gas monitoring data and the IPCC (2006) default for the likely methane generation ratio may be appropriate. The work could entail a review of existing research or experimental work into the likely magnitude of the carbon dioxide dissolution processes acting as a sink of carbon dioxide in landfills as well as the stoichiometric ratio of both landfill gas components at the point of generation. The impact of changes to the landfill gas methane content has been examined as part of the sensitivity analysis in Section 6.3.

3.0 MANAGED METHANE CAPTURE

3.1 Landfill Gas Utilisation

The quantum of methane utilised in landfill gas engines is calculated be 1.0 Mt for 2011.

This is based on a significant and representative data set for electricity generated but does require assumptions to be made for conversion factors from GWh to m^3 of methane utilised. These calculations are reasonably reliable.

No additional research is proposed to refine this value.

The amount of methane combusted by landfill gas engines and flares was determined for 2011 based on UK industry data as detailed below.

To estimate the amount of methane combusted in 2011, information on GWh generated in the UK by landfill gas engines was retrieved from DECC as detailed in Table 11 below.

Table 11: Electricity Generated by Landfill Gas Engines in the UK 2011

Organisation	GWh	Source
DECC	5092	www.gov.uk/government/uploads/system/uploads/attachment_data/file/209148/et6_1.xls

To convert electricity generated to the amount of methane combusted, it was assumed that 1 m^3 of methane has an energy content of 36.0 MJ (net heating value) under standard conditions (STP). Assumptions on the landfill gas electrical efficiency were derived as detailed below.

The electrical efficiency of landfill gas engines has, like all combustion technology, improved as drivers to improve energy efficiency have been put in place. Our review of the current mix of engine types has resulted in an estimate that the average engine efficiency, as supplied and without considering parasitic loads, and other degrading factors, is 40% across the UK landfill engine portfolio. This value has been determined from a review of operator-supplied data on engine type distributions in the UK and a review of engine technical specifications summarised in Table 12.

Table 12: Electrical Efficiency Assumptions for the UK Landfill Gas Engine Portfolio

Engine Type	No. of Units	%	Electrical Efficiency %
Jenbacher	347	71	40.8
Caterpillar	102	21	36.8
Deutz and Others	41	8	36.8
Total	490	100	40

Notes:
1) Majority of Jenbacher gas engines are assumed to be J320 variant;
2) Majority of Caterpillar gas engines are assumed to be 3516 (A/A+) variant;
3) All other engine types are assumed to have a similar electrical efficiency as Caterpillar gas engines; and
4) Engines are assumed to be running on full load and therefore full efficiency.

While it is correct to use this value for the energy produced currently ‘at the alternator terminals’, there are various energy sinks on landfill sites that will degrade this value further, and other factors that will not affect the electrical efficiency calculation. The following factors have been considered in the degradation of the theoretical electrical efficiency.

- Most landfill gas utilisation plants have associated parasitic, auxiliary and site loads to manage.
  - Parasitic loads are those which are used by the engine in its operation (losses from operation of fans, oil pumps and cooling). Some engines use mechanical pump systems driven directly from the crankshaft motion, while others use electrical pumps, so a direct comparison of the overall efficiency of different engine types is not straightforward.
  - Auxiliary loads are ancillary electrical loads which reduce the electrical power delivered to the grid by a gas engine. Auxiliary loads are generally used to power other components of the landfill Site operations, and are associated with gas delivery and conditioning. This includes, for example, gas boosters.
  - Site loads are loads arising from on-site use not previously defined as parasitic or auxiliary loads, e.g. Leachate Treatment Plant.

Industry figures suggest that on average, these combined loads might be considered to be 40 kW for the first MW of installed capacity on a single landfill site and 20 kW thereafter. This equates to 4% electrical losses for the first MW installed, dropping to 3% for a 2 MW installation, 2.7% for a 3 MW installation, and so on.

- It is also true to say that some landfill sites take their energy from the grid rather than from the energy generated on site, so these particular load losses might not occur on all sites.
- In the early years of landfill gas utilisation, gas engines were not as efficient as calculated in Table 12 above. Nor was there the strong bias toward Jenbacher gas engines, so there were probably more Caterpillar engines employed in the early years, along with other engines from less well known manufacturers. Early Caterpillar gas engines used a relatively crude deltec engine management system (compared to current electronic designs), and these were common up to the late 1990s and early 2000s. These gas engines would have been rated at 34% electrical efficiency or less.
- With the implementation of the IPPC regulatory regime in 2002, the regulations pushed for improvements in engine emissions. The engine manufacturers responded to this regulation not just by designing the gas engines to meet the lower emission standards, but which also yielded energy efficiency improvements. Sophisticated engine management systems are now the norm.
- Finally, the deterioration of engine performance with age needs to be considered. This could introduce a loss in electrical efficiency of typically 2% or more over an engine lifetime.

There is no simple relationship which can represent all these independent factors at a portfolio level, and so an assumption is made that all parasitic losses and other age and performance related losses are encompassed in a 4% loss factor leading to a net electrical efficiency assumption of 36%.

The MELMod model needs to recognise these improvements in electrical efficiency. It is recommended as an initial step, that a linear adjustment between 1996 and 2012 would cover the transition between old engine designs and newer ones. This could be checked via a consideration of historical data on landfill gas production and electrical energy exported. Pre 1996 gas plant should be modelled with a 34% electrical efficiency, with a 4% parasitic and age related losses term, giving an electrical efficiency conversion factor of 30% for pre 1996 gas plant. This 30% factor is then modified by a linear increase in electrical efficiency of 0.375% per year, until at 2012 the raw electrical efficiency is modelled at 40%, as based on Table 12, with an overall 4% loss term based on the cumulative effect of considering parasitic, auxiliary, site and age related losses, reducing the overall electrical efficiency to 36% from 2012 onwards.

Based on the above assumptions on methane net heating content and net engine electrical efficiency, methane combusted in landfill gas engines in 2011 was calculated to be 1,012,501 tonnes as detailed in Table 13.

Table 13: Landfill Engine Methane Combustion 2011

	Number	Unit
Electricity Generated	5092	GWh
Net Engine Efficiency Assumption	36	%
Methane Engine Combustion	1,414,502,561	m^3
Methane Density STP	0.7158	kg/m^3
Methane Engine Combustion	1,012,501	tonnes

The impact of assuming different engine efficiencies has been assessed further as part of the sensitivity analysis in Section 6.4.

3.2 Landfill Gas Flaring from Gas Utilisation Sites

The quantum of methane that is flared from operational sites with landfill gas utilisation is estimated to be $1/11^{th}$ of the methane utilised in gas engines. The total estimate for 2011 is 92,242 tonnes.

This is based on a significant and reasonably representative data set for landfills with up-to-date permit conditions in England and Wales. However, no estimate is included for sites which only flare.

Given the data gap associated with this value, additional research is proposed to refine this value to include closed sites which are likely to have a greater proportion of flaring.

Methane is not only combusted in engines but also flared. The amount of methane flared in the UK in 2011 was estimated from a dataset assembled by the EA including operator data on the volumes of landfill gas combusted in flares and engines at sites in England and Wales with permit conditions requiring such reporting. This dataset provided the ratio of flares to gas engines, and that ratio was then applied to the UK engine portfolio to determine the amount of flaring at UK gas utilisation sites. In 2011, this subset of sites contributed approximately 70% of all methane combusted in engines in 2011 (based on a methane content of 45%, see section 2.1.3). After excluding sites that flare only from the above dataset, the quantum of methane that is flared and utilised at sites with landfill gas utilisation is detailed in Table 14.

Table 14: Flare to Engine Methane Combustion Ratios 2011 (England and Wales only)

	Methane Collected in Engines	Methane Collected in Flares	Units
Total	721,385	65,720	tonnes

The proportion of landfill gas which is flared compared to utilised is 1/11, i.e. for every 1 m^3 methane combusted in a flare, 11 m^3 of methane are combusted in engines. If this ratio is applied to the entire UK, methane combustion estimates for 2011 result in an estimated 92,242 tonnes of methane being flared at sites with landfill gas utilisation in the UK.

3.3 Landfill Gas Flaring from Sites without Gas Utilisation

The quantum of methane that is flared from sites with only flaring as gas control is difficult to quantify. In the absence of representative data for the UK, Golder has suggested a methodology to determine the potential quantum of methane combusted in these sites.

Based on this methodology, the estimate for flaring from sites without gas utilisation is 220,685 tonnes. This calculation is based on limited data and entails a number of estimates and interpolations which by our definitions in Tables 1-3 above is likely to be unrepresentative and unreliable for future forecasts, although it is considered to be a current best estimate based on the assumptions made.

Given the data gap associated with this value, additional research is proposed to refine this value to include closed sites which are likely to have a greater proportion of flaring.

There is a potentially significant missing element in the component of methane combusted in flares on landfill sites where sites are less well managed, or where gas utilisation has finished, but the flare continues to operate, as discussed during the expert seminar.

The smallest gas engines typically used on landfills today are around 300kW installed capacity. Below this size, the economics become marginal. It is also likely that not all landfills with the capacity for a 300kW gas engine have one fitted. In flaring terms, this power output might be the equivalent of approximately 200 m^3/h landfill gas at 57% methane, but there may also be landfills operating with flaring as the only gas control with more than 200 m^3/h being flared. 200 m^3/h is also the lower operational limit of a 1000 m^3/h flare with a 5:1 turndown ratio, meaning that such commonly installed flares might operate only on an occasional and infrequent basis. It is therefore hard to judge exactly what fraction of methane from these landfills is combusted, and what fraction is emitted.

For the purpose of estimating the missing element, Golder has considered a typical flaring value of 200 m^3/h which is based on the point above, which a 300kW gas engine might be considered. Many historic landfills with gas control may not be flaring continuously. It was therefore assumed that half of the flaring-only sites do so continuously at a rate of 200 m^3/h (including a 5% annual flare downtime) whereas the remaining sites split equally into sites flaring either 50% or 25% of the time on an annual basis.

In order to evaluate the total contribution of this component, the number of landfill sites in the UK that are flaring only needs to be estimated. Based on the Renewable Energy Foundation information (http://www.ref.org.uk/roc-generators/index.php), Golder estimates there are 356 landfills in the UK currently employing landfill gas utilisation plant for power generation (on both open and closed sites) in 2011. We also analysed data provided by Environment Agency Report SC030143/R5 (Environment Agency 2012b, unpublished) to identify all sites in England and Wales with gas control and found 119 which were operational and 596 which were closed landfills. In the absence of equivalent data for Scotland and Northern Ireland, the number of landfill sites with some form of gas control was scaled up to include the devolved administrations. These estimates were based on Defra's Waste Statistics Regulation Return to Eurostat for 2008 (http://www.defra.gov.uk/statistics/environment/waste/wrfg01-annsector/). This extrapolation results in a total of 822 landfills assumed to have some form of gas control in the UK. Taken into account the 356 sites with landfill gas utilisation, this means that the number of sites with only flaring as their means of gas control is estimated to be 466.

Based on this approach, the total amount of landfill gas flared at flaring-only sites was estimated to be 220,685 tonnes per annum. However, the precise contribution of this missing element is unknown, and there appears to be very limited data on this, especially for more historic sites and sites outside England and Wales. We recommend that research into how much landfill gas is flared, particularly at sites that only flare and are not governed by modern permitting requirements, is carried out to firm up this estimate.

During peer review the ad hoc character of the methodology used to estimate gas flaring from sites without gas utilisation as well as the lack of substantiation for the assumptions made, including the methane content at such sites, was criticised. As detailed in the report, the quantum of methane that is flared from sites with only flaring as gas control is difficult to quantify due to the absence of any representative data. Given the data gap, the report suggests additional research to refine this value. In the meantime it was considered most appropriate to adopt a simple, straight-forward approach to close the gap and quantify the unknown parameter.

An alternative methodology to estimate the amount of methane flared in the UK has been proposed by DECC (see Section 3.4 below). The impact of changes to the assumptions underlying the amount flaring undertaken in the UK at landfill sites has been explored as part of the sensitivity analysis (Section 6.5). As new data are made available it is strongly recommended that the quantification of landfill gas flaring from sites without gas utilisation is re-visited.

3.4 DECC Flaring Calculation Methodology

An alternative flaring calculation methodology has been proposed by DECC. Rather than distinguishing between sites with flaring and gas utilisation versus sites that flare only, this methodology attempts to quantify the amount of flaring for different landfill categories, i.e. modern permitted landfills, older permitted landfills, and local authority controlled sites.

The starting point of DECC's methodology is the same EA database on landfill gas engine combustion and flaring for sites with up-to-date permit conditions in England and Wales described in Section 3.2. DECC state there are 233 modern landfill sites in this category, which required the reporting of the quantity of landfill gas flared and combusted. DECC assumed an average methane content in the landfill gas from these sites of 44%. From this, the quantity of flared gas for England and Wales is deduced to be equivalent to 83 kt of methane from these landfills in 2011.

In addition, there are 214 landfills with older permits not requiring this information to be reported. Of these, 121 are equipped with engine and flares, and these were assumed to flare comparable fractions of landfill gas as modern permitted landfills with engines and flares. The remaining 93 sites with only flaring were assumed to flare comparable volumes of landfill gas as modern permitted landfills which were also only flaring. This last group was assumed to flare gas at a lower methane content of 35%. On this basis, the quantity of flared gas for England and Wales is deduced to be equivalent to 94 kt of methane from these 214 older permitted landfills in 2011.

In addition, 50% of the estimated 324 historic landfills controlled by local authorities in England and Wales were assumed be equipped with active gas control and flares (162 landfills). The annual quantity of landfill gas available for flaring at these sites was assumed to be equivalent to the average quantity of landfill gas flared at modern permitted landfill sites that are flaring only, however at a lower methane content of only 25%. At 33% of these sites, flares were assumed to run continuously, whereas at 67% of these sites flares were assumed to operate for only 25% uptime. The landfill gas flaring quantities for England and Wales are deduced to be equivalent to 31 kt of methane at these 162 local authority controlled closed landfills.

The resulting aggregated total of 208 kt in 2011 is scaled on the basis of population data to give a total flaring estimate of 234 kt for the UK in 2011. Like the Golder approach, the DECC methodology strongly relies on estimates and assumptions in the absence of more detailed available data. The 2011 result from DECC is comparable to the outcome of the Golder approach for estimating methane flaring at landfills in the UK. The result of DECC's methodology for estimating flaring form part of the sensitivity analysis carried out in Section 6.5.

3.5 Total Methane Combusted

Using the flare to engine combustion ratio of 11 as a scaling factor, the total amount of methane combusted in 2011 on UK landfill sites generating power was estimated as detailed in Table 15 below.

Table 15: Total Methane Combustion Estimates 2011

	Tonnes
Methane Combustion in Gas Engines	1,012,501
Methane Combustion in Flares on Sites with Gas Engines	92,242
Methane Combustion in Flares on Sites without other gas utilisation equipment	220,685
Total Methane Combustion in Gas Engines and Flares	1,325,427

3.6 Methane Slippage from Landfill Gas Engines

The quantum of methane which passes through landfill gas engines unburnt is calculated to be 1.5% of the quantum of gas fed to gas engines in any one year. For 2011, this is calculated to be 14,836 tonnes of methane.

This is based on a significant and representative data set, and is considered to be a reliable calculation.

Given the quantum of this value, no additional research is proposed to refine this value.

A similar analysis for methane slippage for gas flares is recommended by the peer reviewers.

Methane slippage occurring during the combustion process is a source of methane emissions at the gas utilisation plants of landfill sites. The phenomenon is not significant in landfill gas flaring. Methane slippage was derived theoretically based on collated engine emission monitoring data provided by the Environment Agency. The analysed data set comprised 58 engine monitoring measurements including for volatile organic compounds (VOCs) and non-methane volatile organic compounds (NMVOCs) provided under normalised conditions in mg/Nm^3 at 5% oxygen. For the analysis it was assumed that methane emissions are VOCs minus NMVOCs as calculated for each measurement. Where NMVOCs were below the detection limit, methane emissions were assumed to equal VOC emissions. Figure 7 shows the distribution of methane monitoring results (calculations are detailed in Appendix B).

Given the shape of the histogram, the median of the distribution of 862 mg/Nm^3 was considered to be most representative and was used further in the analysis.

The methane slippage was then derived based on a methane to carbon dioxide ratio of 57% to 43% (already determined as a highly accurate ratio in Section 2.1.3 above), and an air to fuel ratio of 12.42. This air to fuel ratio which is greater than the stoichiometric air to fuel ratio of 9.6 was chosen as it provides a 5% oxygen content in the fuel/air mix, which is the same as the normalised ratio of 5% oxygen in which engine emission data are reported. We then used the average mass of methane in VOC emissions per m^3 at the normalised oxygen content multiplied by the total exhaust volume passing through the stack as detailed in Appendix B, to calculate the total methane slippage at the normalised oxygen content.

Based on the above calculations and the engine VOC emission monitoring data, the methane slippage is 1.5% of the fuel entering the gas engine. This value is in good agreement with methane slippage estimates found by analysing the results of the three supplementary DIAL study sites, from Defra report WR1906 *Supplementary DIAL Survey of Methane Emissions and Surface Methane Oxidation at Landfills*. (Innocenti et al 2013) which are between 1-2% of engine methane emissions.

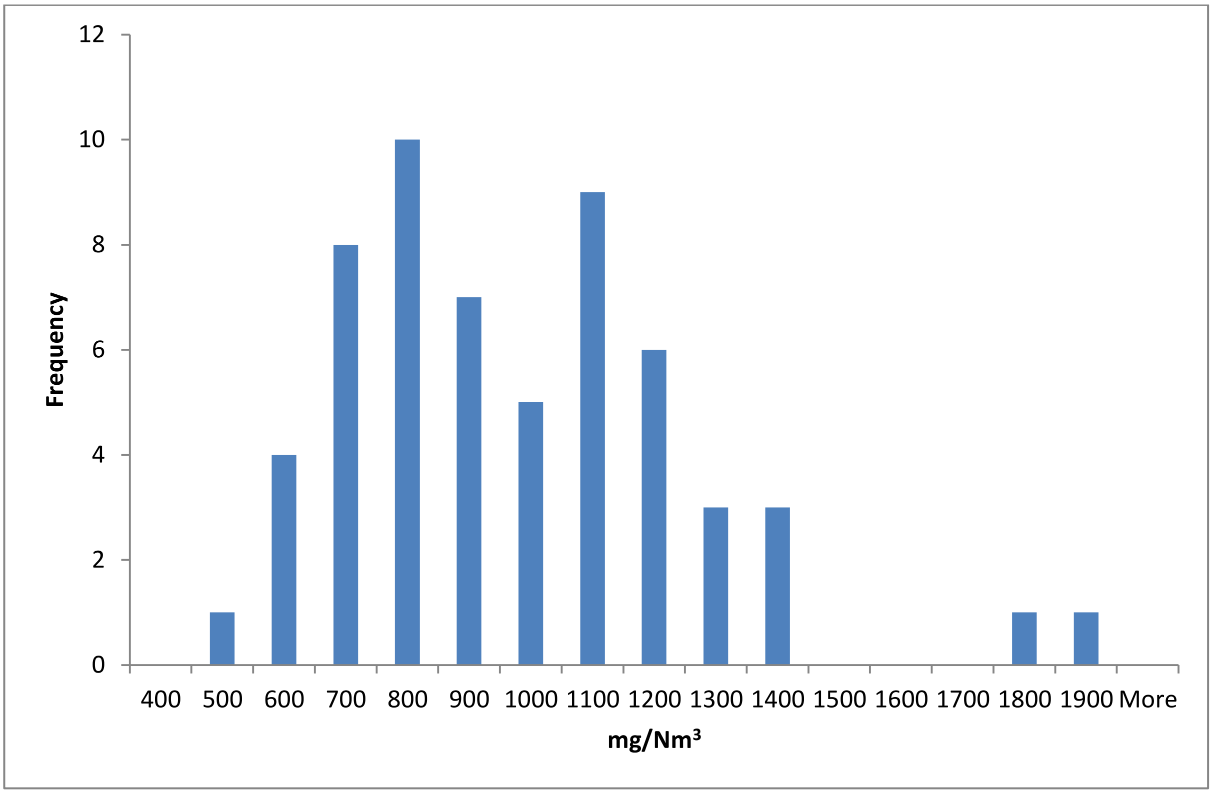

Figure 7: Engine Methane Emissions

Applying a methane slippage assumption of 1.5% to the entire quantum of methane combusted by gas engines in 2011, there is an estimated methane slippage of 14,836 tonnes as shown in Table 16. Given that the estimated methane slippage from engine is well below 1% of the total methane generated by Type 3 landfill sites in 2011 in MELMod, methane slippage is not deemed to have a significant impact on the calculation of methane collection efficiency.

Table 16: Methane Slippage Estimates

	Tonnes
Methane Engine Combustion	1,012,501
Methane Slippage	14,836

During the peer review two reviewers requested further justification for only including methane slippage from engines but not from flaring in the quantification of methane slippage. Both reviewers agree that modern flares are likely to have insignificant methane slippage and as pointed out by one reviewer this could be easily demonstrated based on emission test data submitted to the EA which is included as a recommendation. However reviewers would like to see further evidence for applying this assumption to flares of older designs or open type flares as used historically. This could be explored by further work and review. However given that even the estimated methane slippage from engines was not deemed to have a significant impact on the calculation of the methane collection efficiency, it appears very unlikely that the latter would be the case for any methane slippage from flaring. Further, access to historical monitoring data on methane slippage in open flares might be difficult to acquire.

4.0 UNCONTROLLED METHANE EMISSIONS

4.1 Landfill Fugitive Emissions

4.1.1 Introduction

Greenhouse gas emissions in the form of methane from landfill sites were estimated to account for approximately 3% of the UK's total GHG emission in 2009. Furthermore, this reported figure accounts for approximately 42% of methane emissions from the entire UK. IPCC guidelines indicate that methane emission characterisation and measurements are necessary to validate models and to provide confidence in model parameters for country specific waste emissions.

Defra employed the services of the National Physical Laboratory (NPL) to undertake DIAL measurements in order to monitor emission fluxes of methane from selected landfill sites across the UK (EA, 2012a). DIAL is a reliable and tested method of methane emission, which can resolve methane concentrations both vertically and horizontally (typical resolution 3.75 m – Innocenti et al, 2012) across a two dimensional plane and as such was deemed the most appropriate method to undertake the study. Additional measurements using carbon isotope ratios were made during the DIAL studies to characterise methane oxidation.

4.1.2 Focused Literature Review

A targeted literature review was used to identify likely emission rates of methane from active landfill areas. These data were required to allow a back calculation from the supplementary DIAL study estimates of surface emissions i.e. surface emission estimate/estimate of the active area, to give an approximate flux of methane per unit area.

Methane emission rates are summarized in Table 17 below. The data are from a mixture of location and estimated via a number of different methods. The benefits and limitations of the different methods were reviewed by Armstrong et al. (2007).

All studies highlight the large spatial (small scale on site hotspots, but also large scale climatic variations around the globe) and temporal (seasonal) variability in the measurements. Measurements results can vary by many orders of magnitude (Bogner et al 1997). Negative rates can be observed as the soil actual oxidises atmospheric concentrations of methane as well.

Table 17: Literature Review for Methane Surface Emissions Estimates

Paper	Year	Location	Method	Ranges $g/m^2/day$
Goldsmith et al	2012	USA but considers mix of climates	Radial plume mapping	Working face – 85-207 Temporary cover - 11 – 127 Final – 0.09 to 32
Spokas et al	2006	France	Mix	Negative to >10
Scheutz et al	2008	France	Flux Chamber	Negative to 29
Abichou et al	2006	USA	Flux chamber	Negative to 1755 depending upon cover or capping Mean 71.3
Bogner et al	2011	USA	Flux chamber	0.01 to 100 Maximum hot spots 353-794
Schuetz et al	2003	Demark		Negative to 0.008 for capped Temporary cover 50

4.1.3 Analysis of the DIAL Studies

The Environment Agency report SC0100009/R (2012a, Table 2.10) suggests that the emission rates back calculated from the initial 12 DIAL studies are 74 g/m^2/day for operational sites and approximately 7.5 g/m^2/day for closed sites. These estimates are at the lower end of the ranges detailed above for active emission areas and potentially higher than expected for fully capped areas.

Based on our calculations for the supplementary DIAL sites (Innocenti, 2013) it is clear that the majority of surface emissions are from the active area (between 63 and 91%, Figure 8); capped area emissions are between 9 and 27% (Figure 8). Estimates of the methane flux rates using an estimate of the active areas (see Appendix C) give a range between 83 and 211 g/m^2/day which are in the same order of magnitude with the above literature review ranges; and is in extremely close agreement with the findings of Goldsmith et al. (2013). For the capped areas, estimates of methane flux rates range from 3 to 22 g/m^2/day. This is higher than the current emission standards of 0.0864 g/m^2/day and 8.64 g/m^2/day for permanently and temporary capped landfill zones, respectively (EA, 2010). This discrepancy is likely caused by the limitations of the flux box approach with regard to establishing actual methane fluxes over large areas.

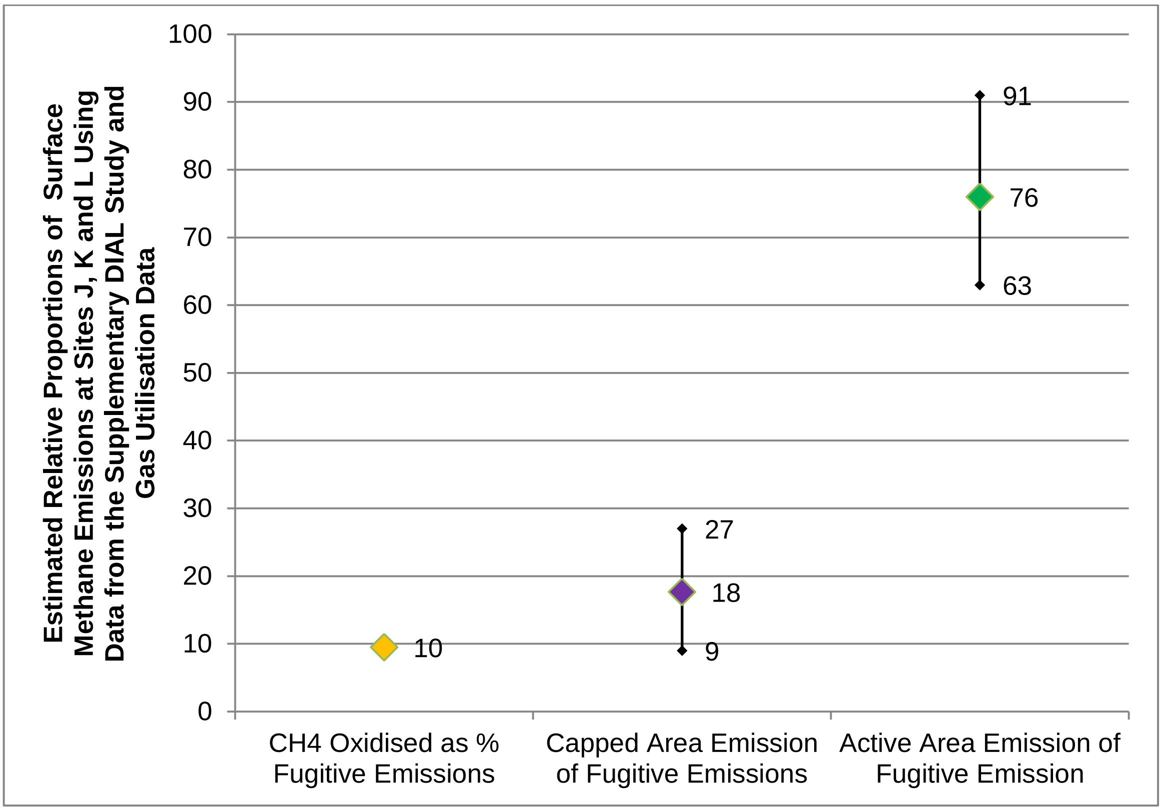

Figure 8: DIAL Supplementary (Sites J-L) Estimated Surface Emissions (Innocenti, 2013)

4.1.4 Fugitive Emission Estimates for 2011

The fugitive emissions estimate for 2011 is 1,286,251 tonnes.

This is based on a limited and potentially unrepresentative data set.

Given the quantum of this value, additional research is proposed to refine this value.

Given the potential unreliability of the derived figures, estimated fugitive emissions were used for confirmatory purposes only when establishing the 2011 UK collection efficiency for modern landfills.

To estimate fugitive emissions from landfills in 2011, an estimate of the areas covered by operational landfill areas (working face), temporary and permanently capped areas in the UK was derived. These approximations were based on total areas of operational and closed landfill sites in England and Wales as calculated based on information provided by Environment Agency Report SC030143/R5 – Methane emissions from different categories of landfills (Environment Agency 2012, unpublished). A detailed description on the approach can be found in Appendix D.

In the absence of access to equivalent area data for Scotland and Northern Ireland, landfill areas for operational and closed sites for the entire UK were scaled up based on landfilled waste in the devolved administrations. Estimates were based on the Defra's Waste Statistics Regulation Return to Eurostat for 2008 as detailed in Appendix D.

An average distribution of operational, temporary and permanently capped areas across operational UK landfill sites was derived based on observations made on a subset of 53 operational UK landfills in 2011. These average assumptions were then applied to the UK area estimates for operational landfills. All closed landfills were assumed to be permanently capped resulting in the area estimates shown in Table 18.

Table 18: Operational, Temporary and Permanently Capped Area Estimates for UK Landfills

	m^2	%
Operational Area	8,211,007	1
Temporary Capped Area	12,052,504	2
Permanently Capped Area	562,467,104	97
Total	582,730,616	100

Based on the targeted literature review as well as the DIAL study, typical emission rates from operational areas in the UK were assumed to be 108 g/m^2/day which is the weighted average for the supplementary DIAL studies. For temporary and capped areas (the latter including all closed site areas), a weighted emission rate of 5 g/m^2/day was assumed.

Applying these emission rate assumptions to the UK area estimates detailed in Table 18 results in an overall annual UK fugitive emission estimate of 1,286,251 tonnes as detailed in Table 19.

Table 19: UK Landfill Area Methane Emission Estimates

Landfill Area	Tonnes
Operational Area	322,821
Temporary Capped Area	20,211
Permanently Capped Area	943,219
Total	1,286,251

As detailed above, these estimates are based on a number of assumptions with regard to UK landfill areas and the distribution of operational and capped sites within the operational landfill portfolio (Appendix D). When establishing the 2011 UK collection efficiency, the estimated fugitive emissions were therefore used for confirmatory purposes only.

4.2 Landfill Methane Oxidation

For the UK climate, modelled methane oxidation rates for different soil cover types may range from 4.5% (daily cover) through 11.7% for intermediate cover and up to 90.8% for final cover. This does not take into account uncontrolled losses through infrastructure which would have the effect of decreasing the net observed value.

However, calculations made on DIAL measurements show that measurement data which integrate the uncontrolled losses with methane oxidation rates on intact caps suggest an overall methane oxidation value similar to the IPCC default value of 10%. These calculations are based on a limited but reasonably representative data set, and are considered to be a reliable set of calculations. Further DIAL measurements, ideally in conjunction with tracer studies, would be beneficial to further substantiate methane oxidation values for the UK.

It is recommended that until further measurements are made at UK landfill sites, the IPCC default value for methane oxidation of 10% is retained. Applied to the quantification of methane generated, flared and combusted as well as fugitively emitted as detailed above, this translates in an estimated 120,067 to 142,917 tonnes of methane oxidised in 2011 by cover soils in the UK.

Methane oxidation by methanotrophic bacteria in the soil reduces the emissions of methane from the surface of landfills. Many studies have been published investigating the percentage oxidation that is most likely; oxidation rates are reported to range between 0 and 100%. A consideration of published literature and the DIAL UK measurement data has been undertaken to determine, for the UK landfill portfolio, whether the 10% IPCC default methane oxidation value is reasonable, or should be reconsidered.

Published literature emphasises the variation in oxidation rates both spatially and temporally. There is a strong dependency of methane emissions with engineering parameters such as cover soil thickness and texture. International opinion (Table 2, Appendix A) is that the Chanton et al (2009) document, which reports methane oxidation rates between 22 -55% depending on soil type (clays to sandy soils), is definitive. Modelling by Spokas (2011) using the CalMIM model suggests that for the UK climate methane oxidation rates for different soil cover types may be: daily cover 4.5%; intermediate cover 11.7% and final cover up to 90.8%.

Climate is also important with temperature and moisture the key parameters (Spokas 2011). Seasonal variations in the Chanton et al (2009; 2011) studies were found to produce a range in methane oxidation between 11 - 89% (with the most oxidation occurring in warm moist conditions). The study concludes an average of 36% +/- 6% as typical oxidation, which is also supported by the range of 30-50% detailed in the study by Bogner (2011).

During the DIAL studies the methane oxidation rate was calculated based on ratios of methane isotopes (EA, 2012a). In the initial DIAL studies, an oxidation rate for the 5 closed sites was estimated as 18.4 +/- 4.6% and for the 3 operational sites as 9.8 +/- 4%. The supplementary DIAL sites had a methane oxidation rate of 10 +/- 5%, which is supported by our analysis (estimated as 8-10%, Figure 9). These measurement data do not suggest a methane oxidation value significantly different from the IPCC default value of 10%. As such it is recommended that until further measurements are made at UK landfill sites the 10% IPCC default value for methane oxidation is retained. Golder also considers that it would be beneficial to repeat the DIAL surveys, in conjunction with complementary tracer studies, to further substantiate methane oxidation rates for the UK.

Applying a 10% oxidation rate to the difference between MELMod derived total methane generated (2,526,096 tonnes) and the estimates for combusted methane by engines and flares (1,325,427 tonnes) in 2011 results in an estimated 120,067 tonnes of methane oxidised in landfill cover soil in 2011. Based on the estimated fugitive methane landfill emissions of 1,286,251 tonnes, a 10% oxidation rate results in 142,917 tonnes of methane oxidised.

5.0 THE 2011 LANDFILL METHANE COLLECTION EFFICIENCY ESTIMATE

5.1 Background

International research supports instantaneous collection efficiencies ranging from 29% to 99% depending on the landfill gas collection infrastructure and the type of landfill cover (Barlaz et al 2009; Barlaz 2012). A lot of theorisation around how many years at what collection efficiency for different stages of the landfill lifetime has been made, but there is no set answer for a landfill lifetime collection efficiency, as it depends on so many factors. As Oonk (2012) pointed out, estimated national average collection efficiencies vary from 45% to more than 70%.

International research findings are generally well aligned with the results of the DIAL studies undertaken in the UK (EA, 2012a). From both the initial and supplementary DIAL studies (Innocenti, 2012 and 2013), methane capture rates ranged between 23% and 91% (Figure 9 and Appendix C). Data from the more recent supplementary DIAL Studies (Sites J, K and L) reported Methane Capture Rates of between 71 and 91%); from the initial DIAL studies (Sites A to I) methane capture rates ranged between 23 and 85%. The categorisation of the Sites is explained below:

- Sites A-C are operational landfills;
- Sites D-I are closed landfills;
  - Site E, F and H are a subset which closed after 2001;
  - Sites D, G and I are a subset which closed before 2001; and
- Sites J-L are operational landfills investigated in the supplementary DIAL study programme with a more detailed meteorological measurement regime.

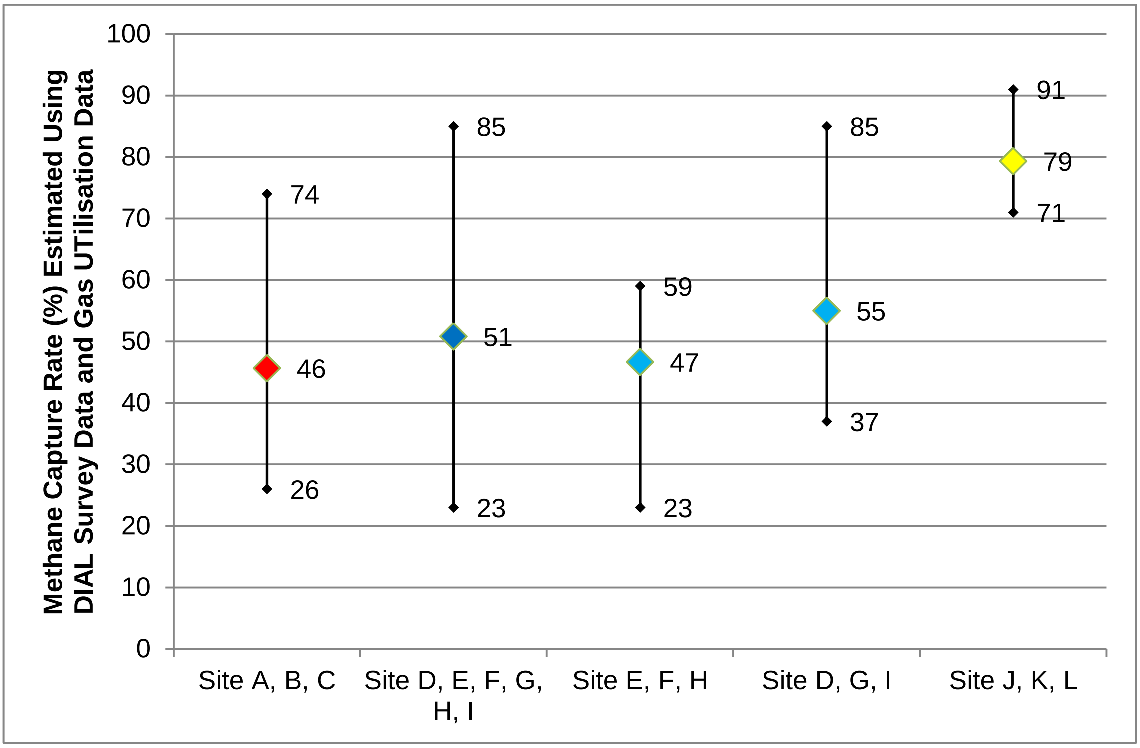

Figure 9: Methane Capture Rate Estimates from DIAL Studies, at Initial Sites (A-I) and Supplementary Sites (J-L)

These observations are generally in line with the UK landfill operators' views expressed during the expert seminar who estimated that once gas collection infrastructure had been installed, the collection efficiency of modern landfills was anticipated to range from 55 – 85% with a possible mean and median of 75% and 70%, respectively.

While the above values are instantaneous collection efficiencies, the aim of this report is to establish a defendable collection efficiency estimate for the Type 3 landfill portfolio within MELMod. This category of landfills contains all the UK organic (i.e. landfill gas producing) waste emplaced since 1979, when the MELMod Type 4 landfills were considered to have ceased filling.

Golder has not attempted to model a single landfill throughout its entire life cycle, and attribute collection efficiencies to each stage, although there is enough information available to do that for an individual site (e.g. Barlaz, 2012). Rather, Golder has taken the view that calibration against the 2011 gas generation estimates for all landfills in Type 3 will give a more realistic lifetime collection efficiency value, as there are many sites in this category and they will all be at different stages of their gassing lives. The collection efficiency Golder aims to establish is not therefore equivalent to the lifetime collection efficiency of a typical modern UK landfill.

Golder approached the aim of establishing the Type 3 portfolio collection efficiency by quantifying the various elements of methane generation and emission (see Figure 1) for the year of 2011, the latest year for which MELMod methane generation numbers are established. The quantification process for each element is described in Sections 2, 3 and 4 of this report. The results were used to establish the estimated collection efficiency as the quotient of methane combusted in engines and flares and the total methane generated by Type 3 landfill sites in 2011 as predicted by MELMod. This is indicated by the left pictogram in Figure 10.

In addition, Golder established the collection efficiency by replacing the MELMod predicted methane generation in 2011 with the sum of combusted methane, fugitive methane emissions and methane oxidised in the landfill cover soil. For the reasons detailed in Section 4.1, the deducted figure for UK fugitive landfill methane emissions is subject to significant uncertainty. This second approach which is not reliant on any methane generation modelling is therefore meant as a confirmatory tool only appraising the sensibility of the MELMod output based approach. This is indicated by the right pictogram in Figure 10.

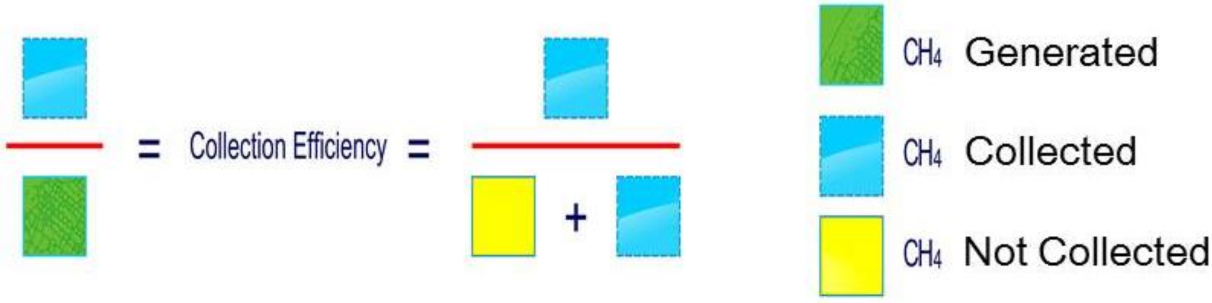

Figure 10: Golder Approach to Establishing 2011 Methane Collection Efficiency (see also Barlaz 2012)

5.2 Collection Efficiency based on MELMod Methane Generation

A theoretical collection efficiency was established as the quotient of the methane combusted in engine and flares in 2011 as derived in Section 3 and the MELMod predicted methane generation from Type 3 landfills in 2011.

This collection efficiency estimates establishes the base case for the sensitivity analysis undertaken in Section 6 is based on the following assumptions:

- MELMod default DDOC assumptions for different waste types;
- Wet degradation rate with k-values of 0.076, 0.116 and 0.694 for slow, moderately and fast degrading waste fractions;
- 57% methane content in landfill gas (if corrected for balance gas);
- A net landfill gas engine electrical efficiency of 36%;
- A flare to engine ratio at UK sites that both combust and flare methane, of 1:11; and
- An average flaring rate of 200 m^3/h at 466 estimated sites that only flare as means of gas control with 50% of the sites flaring continuously (apart from a 5% annual engine downtime), 25% of the sites flaring 50% of the time and 25% of the sites flaring 25% of the time only.

Based on the above assumption, the 2011 collection efficiency for Type 3 landfills in MELMod is 52% as detailed in Appendix E.

5.3 Collection Efficiency based on Area Emission Assumptions

The second approach is meant to provide an independent validation of the values derived above. It excludes any modelling assumptions, but uses the DIAL study findings. Collection efficiency is derived as the quotient of the methane combusted in engine and flares in 2011 (as derived in Section 3) and the sum of combusted methane and estimates for UK landfill area emissions and methane oxidation (as derived in Section 4). Due to the uncertainty surrounding these area estimates, this approach is used to confirm the modelling approach and is not proposed as an alternative methodology.

In line with the first approach the following assumptions are made:

- A net landfill gas engine efficiency of 36%;
- An flare to engine ratio at UK sites that both, combust and flare methane, of 1:11; and
- An average flaring rate of 200 m^3/h at 466 estimated sites that only flare as means of gas control with 50% of the sites flaring continuously (apart from a 5% annual engine downtime), 25% of the sites flaring 50% of the time and 25% of the sites flaring 25% of the time only.

In addition this approach assumes that:

- In the UK operational, temporary capped and permanently capped landfill areas cover 8,211,007 m^2, 12,052,504 m^2 and 562,467,104 m^2, respectively; and
- The emission rates from operational and capped landfill areas are 108 g/m^2/day and 5 g/m^2/day, respectively. These emissions estimates are based on the area weighted average of the Supplementary DIAL studies results for Sites J, K and L (Appendix C).

Based on the above assumption, the 2011 collection efficiency for Type 3 landfills in MELMod is 48% as detailed in Appendix E. Table 20 summarises the findings.

Table 20: Type 3 Landfill Portfolio Collection Efficiency Estimates 2011

Basis of Collection Efficiency Estimate	Collection Efficiency Estimate %
MELMod Methane Generation	52
UK Landfill Area Emission Assumptions	48

While the estimates based on MELMod methane generation predictions are slightly higher than estimates based on landfill area emission assumptions there is good convergence between both approaches. The slightly lower collection efficiency estimate based on landfill area emission assumptions may reflect an over-estimate of landfilled area as the shape files used to deduct them indicate the permitted area of landfills rather than the actual area of waste deposition (Appendix D).

5.4 Instantaneous Collection Efficiency of UK Large Modern Landfills based on Area Emissions Assumptions

The collection efficiency estimate of 52% for the Type 3 landfill portfolio in MELMod are at the lower end of collection efficiencies reported for modern landfills in international research; measured by DIAL in the supplementary survey; and estimated by the UK landfill experts during consultation. Golder therefore applied the methodology detailed above to a subset of 43 large modern UK landfills which generated approximately 30% of the entire electricity from landfill gas exported in 2011. Areas for these sites were estimated using the same methodology as detailed in Section 4 and Appendix D; however, as all sites are situated in England or Wales no scaling up was required. As the subset of sites assessed are highly managed and generating power, only the 1:11 flare to engine ratio was used to determine the flaring parameter associated with these sites.

The same limitations and uncertainties detailed above for Golder's independent validation approach using area emissions applies to this subset, and the findings should therefore be interpreted as a confirmation check against the UK landfill experts' estimates only. As the vast majority of sites in the analysed subset are operational, the estimated collection efficiency is indicative of the operational period of large modern UK landfills, which we propose in our recommendations should be classed as Type 5 landfills (see Section 7). Table 21 details the input parameters for this subset of the UK portfolio.

Table 21: Input Parameters for Sensitivity Test on Subset of UK Portfolio

Parameter	Value	Unit
Electricity generated 2011 from Portfolio Subset	1,605	GWh
Operational Area	2,678,391	m^2
Temporary Capped Area	3,931,468	m^2
Permanently Capped Area	22,076,816	m^2

Processing the above data in the same manner as the entire portfolio estimates based on landfill area emissions resulted in an estimated collection efficiency of 68%. As detailed above, this is a conservative estimate due to the limitations of the use of shape files to derive landfill areas.

Based on this assessment, the 2011 collection efficiency for a subset of modern, large landfill operations in the UK is 68%. This is within the range of the UK expert's assumptions for current operational landfills of 55-85% as detailed above and close to the expected median of 70%.

A collection efficiency of 68% indicates that this subset of 43 large, modern landfills, which producing a third of the electricity from landfill gas in the UK, only consumes approximately 20% of the methane generated in Type 3 landfills in MELMod. This underlines the role that modern, highly managed landfills in the UK play in reducing the overall methane emissions and increasing the UK's landfill portfolio collection efficiency. If a separate set of landfills, similar in design and performance to the subset examined here, were defined as Type 5 (see Section 7 below), according to the sites adopting the standards of IPPC regulations from 2002 onwards, then the collection efficiency of the remaining Type 3 landfills would be lower than the 52% calculated in this report.

While Oonk (2012) showed that estimated national average collection efficiencies vary from 45% to more than 70%, countries that measure their landfill gas collection including, Austria, Denmark, the Netherlands, Finland and Canada have generally much lower national averages in the range of 8 to 37%. Thus if comparing the presumed UK collection efficiency of 52% with these monitored figures, the UK still scores well.

6.0 SENSITIVITY ANALYSIS

Golder has undertaken a sensitivity analysis to explore the relative sensitivity and impact of different parameters that contribute to the Type 3 landfill collection efficiency for 2011. Changes are assessed against the collection efficiency of 52% resulting from the Golder base case as described in Section 5 and discussed for each parameter.

6.1 DDOC

Golder has undertaken a sensitivity analysis to assess the impact of different DDOC assumptions on the estimated collection efficiency in 2011.

Basis for the sensitivity analysis were the results of Defra Project WR1003 (Agbasiere & Turrell, 2013). The base case for the sensitivity analysis is the use of DDOC assumptions currently contained within MELMod.

These assumptions were altered to integrate calculated DDOC values for Method A, Method B, Method C by VS, Method C by TOC as well as Method A including lignin within the biodegradable carbon content assumption (Section 2.1.1). Details on the analytical programme and calculations methodologies are given in Agbasiere & Turrell, 2013. In addition IPPC default values for DDOC were used to create another DDOC scenario.

Table 22 summarises the allocation of different waste fractions to the waste fraction categories available in MELMod. Note that for the calculated DDOCs, no assumptions for food, textiles, garden waste, shoes and accessories or carpet and underlay were made because of the potential anomalies in the fibre method reported for these categories in Agbasiere & Turrell (2013). If a particular waste fraction in MELMod had no equivalent within the calculated DDOCs or IPPC defaults, the MELMod value was maintained.

The resulting DDOC assumptions that have been used in MELMod for the sensitivity analysis are detailed in Table 23. There are many additional waste fractions in MELMod compared to the other data sources, and these individual fractions have not been reallocated to more major waste streams, so the sensitivity analysis is only carried out in terms of the major waste fractions.

Table 22: Waste Category Allocations

MELMod	Defra WR1003 Method A	Defra WR1003 Method B	Defra WR1003 Method C based on VS	Defra WR1003 Method C based on TOC	Defra WR1003 Method A (with lignin)	IPPC Default
Paper	All Paper	All Paper	All Paper	All Paper	All Paper	Paper
Card	(All flat card + Corrugated cardboard)/2	(All flat card + Corrugated cardboard)/2	(All flat card + Corrugated cardboard)/2	(All flat card + Corrugated cardboard)/2	(All flat card + Corrugated cardboard)/2	n/a
Nappies	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	Disposable Nappies
Textiles (and footwear)	n/a	n/a	n/a	n/a	All Textiles	Textiles
Misc. combustible	n/a	n/a	n/a	n/a	n/a	n/a
Wood	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	Wood and Straw
Food - corrected	n/a	n/a	n/a	n/a	n/a	Food
Garden	n/a	n/a	n/a	n/a	n/a	Garden
Soil and other organic (as composted putrescibles)	n/a	n/a	n/a	n/a	n/a	n/a
Furniture	n/a	n/a	n/a	n/a	n/a	n/a
Mattresses	n/a	n/a	n/a	n/a	n/a	n/a
Material 1	n/a	n/a	n/a	n/a	n/a	n/a
Material 2	n/a	n/a	n/a	n/a	n/a	n/a
Non-inert Fines (as before)	Fines	Fines	Fines	Fines	Fines	n/a
Other (as 100% inert, as before)	n/a	n/a	n/a	n/a	n/a	n/a

MELMod	Defra WR1003 Method A	Defra WR1003 Method B	Defra WR1003 Method C based on VS	Defra WR1003 Method C based on TOC	Defra WR1003 Method A (with lignin)	IPPC Default
MELMod C&I Waste	n/a	n/a	n/a	n/a	n/a	n/a
Commercial	n/a	n/a	n/a	n/a	n/a	n/a
Paper and Card	(Paper + Card)/2	(Paper + Card)/2	(Paper + Card)/2	(Paper + Card)/2	(Paper + Card)/2	Paper
General industrial waste	n/a	n/a	n/a	n/a	n/a	n/a
Food and Abattoir	n/a	n/a	n/a	n/a	n/a	Food
Food effluent / Biodeg Ind Sludges (from 1997)	n/a	n/a	n/a	n/a	n/a	n/a
C&D	n/a	n/a	n/a	n/a	n/a	n/a
Misc processes	n/a	n/a	n/a	n/a	n/a	n/a
Other waste	n/a	n/a	n/a	n/a	n/a	n/a
Misc Comb	n/a	n/a	n/a	n/a	n/a	n/a
Furniture	n/a	n/a	n/a	n/a	n/a	n/a
Garden	n/a	n/a	n/a	n/a	n/a	Garden
Sewage sludge	n/a	n/a	n/a	n/a	n/a	Sewage Sludge
Textiles / Carpet and Underlay	n/a	n/a	n/a	n/a	(Textiles + Carpet & Underlay)/2	Textiles
Wood	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	(Wood + Wood Composites)/2	Wood and Straw
Sanitary	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	All Absorbent Hygiene Products (AHP)	Disposable Nappies
Other	n/a	n/a	n/a	n/a	n/a	n/a

Table 23: DDOC Assumptions for Sensitivity Analysis

Municipal Solid Waste	MELMod (Base Case)	Defra WR1003 Method A	Defra WR1003 Method B	Defra WR1003 Method C based on VS	Defra WR1003 Method C based on TOC	Defra WR1003 Method A (with lignin)	IPPC Default
Paper	16.114%	12.70%	13.97%	9.37%	3.13%	19.08%	18.00%
Card	15.166%	18.94%	19.83%	21.11%	5.15%	18.65%	15.166%
Nappies	4.304%	3.92%	19.26%	0.39%	2.26%	3.03%	4.80%
Textiles (and footwear) (NB since we are looking at biodeg only, this has cell and hemi doubled)	6.669%	6.669%	6.669%	6.669%	6.669%	7.48%	9.60%

Municipal Solid Waste	MELMod (Base Case)	Defra WR1003 Method A	Defra WR1003 Method B	Defra WR1003 Method C based on VS	Defra WR1003 Method C based on TOC	Defra WR1003 Method A (with lignin)	IPPC Default
Misc. combustible	10.998%	10.998%	10.998%	10.998%	10.998%	10.998%	10.998%
Wood	12.532%	10.02%	10.71%	17.54%	4.85%	19.22%	18.28%
Food - corrected	9.507%	9.507%	9.507%	9.507%	9.507%	9.507%	3.00%
Garden	8.724%	8.724%	8.724%	8.724%	8.724%	8.724%	4.00%
Soil and other organic (as composted putrescibles)	0.269%	0.269%	0.269%	0.269%	0.269%	0.269%	0.269%
Furniture	5.212%	5.212%	5.212%	5.212%	5.212%	5.212%	5.212%
Mattresses	6.669%	6.669%	6.669%	6.669%	6.669%	6.669%	6.669%
Material 1	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
Material 2	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
Non-inert Fines (as before)	6.345%	12.15%	10.67%	2.15%	0.58%	10.89%	6.345%
Other (as 100% inert, as before)	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
C&I waste							
Commercial	13.910%	13.910%	13.910%	13.910%	13.910%	13.910%	13.910%
Paper and Card	16.114%	15.82%	16.90%	15.24%	4.14%	18.86%	18.00%
General industrial waste	13.910%	13.910%	13.910%	13.910%	13.910%	13.910%	13.910%
Food and Abattoir	8.546%	8.546%	8.546%	8.546%	8.546%	8.546%	3.00%
Food effluent / Biodeg Ind Sludges (from 1997)	6.759%	6.759%	6.759%	6.759%	6.759%	6.759%	6.759%
C&D	3.272%	3.272%	3.272%	3.272%	3.272%	3.272%	3.272%
Misc processes	4.399%	4.399%	4.399%	4.399%	4.399%	4.399%	4.399%
Other waste	10.998%	10.998%	10.998%	10.998%	10.998%	10.998%	10.998%
Misc Comb	10.998%	10.998%	10.998%	10.998%	10.998%	10.998%	10.998%
Furniture	5.212%	5.212%	5.212%	5.212%	5.212%	5.212%	5.212%
Garden	8.724%	8.724%	8.724%	8.724%	8.724%	8.724%	4.00%
Sewage sludge	2.310%	2.310%	2.310%	2.310%	2.310%	2.310%	0.25%
Textiles / Carpet and Underlay	6.669%	6.669%	6.669%	6.669%	6.669%	4.39%	9.60%
Wood	12.532%	10.02%	10.71%	17.54%	4.85%	19.22%	18.28%
Sanitary	4.304%	3.92%	19.26%	0.39%	2.26%	3.03%	4.80%
Other	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%

Applying the above DDOC assumptions in MELMod produces different estimates for methane generation from Type 3 landfills for 2011 as shown in Table 24.

Table 24: Type 3 Landfill Methane Generation Potential 2011 including different DDOC Assumptions

	MELMod (Base Case)	Defra WR1003 Method A	Defra WR1003 Method B	Defra WR1003 Method C based on VS	Defra WR1003 Method C based on TOC	Defra WR1003 Method A (with lignin)	IPPC Default
Methane Generation (t)	2,526,096	2,411,487	2,574,655	2,458,461	1,475,072	2,871,838	2,336,866

This in turn translates into the collection efficiencies detailed in Table 25 when applying the Golder approach outlined in Section 5 to calculate the 2011 collection efficiency estimates. Following the approach, increased methane generation will result in decreased estimated collection efficiency and vice versa.

Table 25: DDOC Sensitivity Analysis Results

	MELMod (Base Case)	Defra WR1003 Method A	Defra WR1003 Method B	Defra WR1003 Method C based on VS	Defra WR1003 Method C based on TOC	Defra WR1003 Method A (with lignin)	IPPC Defaults
2011 Methane Collection Efficiency %	52	55	51	54	90	46	57

In summary, the different sets of DDOCs derived as described above do not generally result in significant changes to the collection efficiency. Comparison to MELMod default settings, substituting waste fractions for calculated DDOCs (Method A, B, and C based on VS) leads to a variation of 1-3%.

Using results for Method C based on TOC results in a significantly higher collection efficiency assumption of 90%. As Agbasiere & Turrell (2013) pointed out, the DDOC values derived by Method C based on TOC may significantly underestimate the true values for degradable carbon matter and degradability in the landfill. Alternatively, they may be closer to the true or actual values for DDOC assumptions of available organic carbon (Agbasiere & Turrell, 2013). The latter explanation however would mean that the current DDOC assumptions in different models including MELMod and IPPC as well as the results derived from other methods to derive DDOC in the same study all significantly over-predict, which appears the less likely explanation.

Including all lignin within the biodegradable carbon content predictably increases bulk gas generation and thus lowers collection efficiency. However degradation of the lignin to similar degrees as cellulose and hemi-cellulose under anaerobic conditions appears unlikely and. This case was only included to better reflect the full work undertaken for Defra Project WR1003 and for the benefit of exploring the sensitivity of the method to changes in assumptions.

Using IPPC default values to replace MELMod defaults where applicable results in slightly increased methane collection efficiency predictions (5%), and so this larger deviation using the IPPC data suggests that MELMod, based on UK statistics, is the more conservative approach.

Based on these findings it appears that a complex sampling and analytical study exploring the degradability of different waste fractions in depth may not result in a significant advance in understanding the UK's landfill portfolio's gassing potential. This is particularly the case given the current uncertainty with regard to the activity data in MELMod, especially in the industrial and commercial waste streams (Hogg, Ballinger and Oonk 2011).

Based on the experiences of Agbasiere & Turrell (2013) any further work undertaken to fine tune MELMod waste property assumptions would need to include a peer-review of the appropriate and most widely accepted methodology for deriving DOC, DOCf and DDOC. Also, the study results are based on a single sample only. The number of samples and analyses in each waste fraction category would need to be significantly increased to allow for statistical analysis and confidence in the results. As a result, Golder does not recommend an alteration of the current MELMod default assumptions to adopt the findings of Project WR1003, and does not recommend further waste studies due to the complexity of the work involved and the low impact this would have on the modelled results.

6.2 Waste Degradation Rates

Golder has undertaken a sensitivity analysis to assess the impact of different waste degradation rate assumptions on the estimated collection efficiency in 2011.

Golder's base case is based on GasSim wet degradation rates whereas previously GasSim average degradation rates were used in MELMod to derive methane generation. An alternative waste degradation scenario is the IPPC default for boreal/temperate wet climate zone which applies to the UK. Waste degradation rates as well as associated k-values for fast, moderately and slowly degrading waste fractions are detailed in Section 2.1.2.

Applying GasSim wet or average waste degradation rates as well as the IPPC waste degradation rates for boreal/temperate wet climate zones in MELMod produces different estimates for methane generation from Type 3 landfills for 2011 as shown in Table 26.

Table 26: Type 3 Landfill Methane Generation Potential 2011 including different Waste Degradation Rates

	GasSim Wet Waste Degradation Rates (Base Case)	GasSim Average Waste Degradation Rates	IPPC Boreal/Temperate Wet Waste Degradation Rates
Methane Generation (t)	2,526,096	2,670,657	2,662,000

This in turn translates into the collection efficiencies detailed in Table 27 when applying the Golder approach outlined in Section 5 to calculate the 2011 collection efficiency estimates. Following the approach, increased methane generation will result in decreased estimated collection efficiency and vice versa.

Table 27: Waste Degradation Rate Sensitivity Analysis Results

	GasSim Wet Waste Degradation Rates (Base Case)	GasSim Average Waste Degradation Rates	IPPC Boreal/Temperate Wet Waste Degradation Rates
2011 Methane Collection Efficiency %	52	50	50

In summary, applying different waste degradation rates in MELMod does not result in significant changes to the collection efficiency in 2011. The impacts may vary historically depending on the waste input tonnages and breakdown assumptions on an annual basis in MELMod.

Based on the results further work on a detailed assessment of UK waste degradation rate assumptions appears not warranted. Golder recommends the application of GasSim wet degradation rates for modern UK landfills within the UK portfolio.

6.3 Methane Content

Golder has undertaken a sensitivity analysis to assess the impact of different landfill gas methane content assumptions on the estimated collection efficiency in 2011.

Golder's base case assumes a methane content of 57% based on the landfill gas analysis detailed in Section 2.1.3. MELMod has previously been using the IPCC (2006) default methane content of 50%. To explore the impact of different methane content assumptions in MELMod on the 2011 methane collection efficiency, methane content assumptions of 50%, 57% and 60% were used.

Applying these methane content assumptions in MELMod produces different estimates for methane generation from Type 3 landfills for 2011 as shown in Table 28.

Table 28: Type 3 Landfill Methane Generation Potential 2011 including different Methane Content Assumptions

	50% CH_4 (IPCC Default)	57% CH_4 (Base Case)	60% CH_4
Methane Generation (t)	2,215,874	2,526,096	2,659,049

This in turn translates into the collection efficiencies detailed in Table 29 when applying the Golder approach outlined in Section 5 to calculate the 2011 collection efficiency estimates. Following the approach, increased methane generation will result in decreased estimated collection efficiency and vice versa.

Table 29: Methane Content Sensitivity Analysis Results

	50% CH_4 (IPCC Default)	57% CH_4 (Base Case)	60% CH_4
2011 Methane Collection Efficiency %	60	52	50

In summary, the application of different methane content assumptions does have an impact on the resulting 2011 collection efficiency assumptions with a variation of about 10%. However as detailed in Section 2.1.3 the methane content analysis is based on a substantive and representative data set and is in line with underlying theoretical assumptions on landfill chemistry. Golder would therefore recommend using a methane content of 57% within MELMod.

6.4 Engine Efficiency

Golder has undertaken a sensitivity analysis to assess the impact of different engine efficiency rate assumptions on the estimated collection efficiency in 2011. The Golder base case assumes a typical net engine efficiency of 36% which includes 4% to cater for parasitic losses. Historically engine efficiencies have been lower, typically in the range of 34% which – assuming 4% parasitic losses – results in a net engine efficiency of 30%.

To explore the impact of different engine efficiency rate assumptions on the 2011 methane collection efficiency estimates, engine efficiency rates of 30%, 34%, 36% and 40% were tested.

Table 30 details the outcome when using these different engine efficiency rates.

Table 30: Net Engine Efficiency Sensitivity Analysis Results

	30% Engine Efficiency	34% Engine Efficiency	36% Engine Efficiency (Base Case)	40% Engine Efficiency
2011 Methane Collection Efficiency %	61	55	52	48

In summary, decreasing the engine efficiency increases the estimated methane collection efficiency. For the test cases run, the resulting 2011 methane collection efficiency varies from 48 – 61%. While Golder is of the opinion that a 36% net engine efficiency is applicable to the UK's modern landfill portfolio, older landfill gas engines are likely to perform less efficient and a lower engine efficiency is more likely to be applicable to the portfolio pre-1996 as detailed in Section 3.1.

6.5 Flaring

Golder has undertaken a sensitivity analysis to assess the impact of different flaring scenarios on the estimated collection efficiency in 2011. From all parameters discussed the amount of flaring is carrying the largest amount of uncertainty due to the very limited data available for quantification in particular for sites flaring only as detailed in Section 3.

The Golder base case assumes:

- An flare to engine ratio at UK sites that both, combust and flare methane, of 1:11; and
- An average flaring rate of 200 m^3/h at 466 estimated sites that only flare as means of gas control with 50% of the sites flaring continuously (apart from a 5% annual engine downtime), 25% of the sites flaring 50% of the time and 25% of the sites flaring 25% of the time only.

While the flare to engine ratio is based on a significant and reasonably representative data set, the assumptions for sites flaring only are strongly relying on assumptions. For this reason the sensitivity analysis while assuming a flare to engine ratio of 1:11 focuses on different scenarios for flaring only sites including:

- Scenario 1: An average flaring rate of 200 m^3/h at 466 estimated sites that only flare as means of gas control with 100% of the sites flaring continuously (apart from a 5% annual flare downtime);
- Scenario 2: An average flaring rate of 200 m^3/h at 466 estimated sites flaring only with 25% of the sites flaring continuously (apart from a 5% annual flare downtime), 25% of the sites flaring 50% of the time, 25% of the sites flaring 25% of the time and 25% of sites albeit still equipped with flares do not effectively flare at all; and
- Scenario 3: No flaring occurring at all at UK landfills.

In addition, DECC's flaring methodology as discussed in Section 3.4 has been included in the sensitivity analysis. The resulting 2011 collection efficiency estimates are detailed in Table 31 below.

Table 31: Flaring Scenario Sensitivity Analysis Results

	Flaring Base Case	Flaring Scenario 1	Flaring Scenario 2	Flaring Scenario 3	DECC Flaring Methodology
2011 Methane Collection Efficiency %	52	56	49	40	49

In summary, there is good agreement between the 2011 collection efficiency estimates based on the Golder flaring base case and the DECC flaring methodology. Flaring Scenario 1 and 2 did not result in significant variations to the collection efficiency. The collection efficiency however drops significantly if no landfill gas flaring is included at all, stressing the importance of the flaring term. While these results provide some level of assurance in the quantification of the flaring term, the latter is still by far the most uncertain among the discussed parameters and relying on large amounts of assumptions. To reduce this uncertainty, Golder proposes further investigations into the amount of landfill gas flared in the UK, in particular at sites that are flaring only.

7.0 RECOMMENDATIONS

A bibliography featuring literature relevant to future work is compiled in Appendix F for further reading. Outlined below are recommendations for future experimental and modelling work.

7.1 Future Calculation of Separate Collection Efficiency for Modern Landfills to Inform Current Regulatory Policy

In addition to deriving a collection efficiency estimate for the Type 3 landfill portfolio filling 1980 to present as currently established in MELMod, Defra requires an indicative value for gas collection efficiency at current landfill sites in the near future to inform current regulatory policy.

Golder proposes the methodology outlined below to derive two different sets of collection efficiencies based on the introduction of a new landfill type (Type 5) in MELMod that properly reflects the properties of currently operating modern landfills. The allocation of waste input tonnage in Type 3 and Type 5 sites is important to allow the representation of improvements in collection efficiency reflected by industry achievements in the past decade. The combination of the effect of abated methane from each category will give an overall methane capture ratio or collection efficiency for the portfolio as a whole.

In discussion with Ricardo-AEAT, it was agreed that from 1980 to 2002, all waste inputs should be represented by Type 3 landfills in MELMod. From 2003 onwards, the transition should be linear, moving 10% of each year’s waste arisings into Type 5 until in 2012, all 100% of waste arising are in Type 5 landfills in the model. The reason for implementing this approach is to reflect the impact of the regulatory regimes of IPPC and EP. This transition has seen an increase in gas collection efficiency achieved by the landfill operators. We know from experience that all landfill sites have been transitional in nature in this timeframe. This modelling approach is based on one which reflects improving standards and regulation, so it has justification, and is appropriate for a portfolio approach.

When modelled, the aggregate gas collection efficiency observed will be the weighted difference between that seen on Type 3 landfills, and that seen on Type 5 landfills, which from our calculations achieved 68% collection efficiency in 2011. Type 3 landfills will accept less and less waste between 2003 and 2012, while Type 5 landfills are filled in a complementary fashion. There will always be waste in existing Type 3 and Type 4 landfills post 2012 to reduce the aggregate gas collection efficiency compared to that seen in Type 5 landfills, from the Type 5 observed collection efficiency of 68% down to 52% (excluding the effect of Type 4 landfills on this parameter).

The calculation of collection efficiency for Type 3 and Type 5 landfills could be estimated by attributing the operational landfills in 2012 all to Type 5, and the closed but generating landfills into Type 3 in 2012. Flaring would need to be assessed as described below, in the section on future research. For the period of interpolation, the modelling might consider the date of permitting of the landfills as the stage at which the landfill moved from Type 3 to Type 5 as an estimate of how the power generation may be partitioned between the two landfill Types. An alternative approach would be to simply make a smooth transition between 2002 and 2012, maintaining the overall weighted collection efficiency as that which has been historically determined by DECC over this timeframe.

7.2 Future Changes to MELMod

It is understood that the MELMod and GasSim models each have a different role, and as such there is no reason to force alignment in every part of each model's structure. We understand why these models have diverged, particularly since 2011, but we consider that certain aspects of the algorithms and data employed in both models should be aligned to enable the models to replicate basic results, and to allow the EA to use GasSim PI reporting to support the validation of MELMod forecasts.

MELMod was updated for the 2011 inventory reporting exercise. Ideally, a completely new model based on GasSim algorithms and the data parameter revisions identified in this report would be desirable. MELMod has had over a decade of adaptation. The MELMod model is written in Excel, and the revision history makes bug fixing and traceability difficult to undertake. However, we can understand that this might not be considered necessary, despite the ultimate benefits a complete rebuild would offer.

However, to align MELMod with current knowledge, the following changes are recommended for MELMod:

1) From detailed examination of waste degradation, we consider that GasSim wet rates are used throughout the MELMod model for Type 3 and Type 5 landfills from 1980 to the present day assuming that the relative allocation of waste fractions and DDOC to RDO, MDO and SDO are comparable in both models. It may be appropriate to retain average waste degradation rates for Type 4 landfills due to the significantly different aeration regime which applied to those landfills.

2) From detailed examination of landfill gas composition, it is proposed that for the current waste mix, and for previous years and older wastes, consideration should be given to revising the methane content of landfill gas assumed in MELMod to the observed ratio of 57% methane, 43% carbon dioxide. Further research to confirm that the measured UK field ratio is a better reflection of the produced gas ratio in the UK rather than the IPCC (2006) 50:50% default is recommended.

3) The MELMod model needs to recognise improvements in the electrical efficiency of landfill gas plant. It is recommended that a linear adjustment between 1996 and 2012 would cover the transition between old engine designs and newer ones. Pre-1996 gas plant should be modelled with a 34% electrical efficiency, with a 4% parasitic and age related losses term, giving an electrical efficiency conversion factor of 30% for pre-1996 gas plant. This 30% factor is then modified by a linear increase in electrical efficiency of 0.375% per year, until at 2012 the raw electrical efficiency is modelled at 40%, again with an overall 4% loss term based on the cumulative effect of considering parasitic, auxiliary, site and age related losses, giving an overall electrical efficiency of 36% from 2012.

4) If it is considered useful for the PI returns to give validation data for MELMod (particularly Type 5 landfills) It would be necessary to align waste categories, DDOC assumptions, and the split between RDO, MDO and SDO of these waste categories in the two models. The selection of the most appropriate waste compositions is beyond the scope of this study.

7.3 Future Research

7.3.1 Allocation of DDOC to RDO, MDO and SDO

Whilst the application of GasSim wet degradation rates is recommended to MELMod, the allocation of single waste fractions to RDO, MDO and SDO which will impact on the overall predicted gas release rates has not been investigated in detail as part of this study. This was also noted in comments by the peer review process. As such, if the relative allocation of waste fractions and DDOC to RDO, MDO and SDO are significantly different across the varying waste component descriptors between GasSim and MELMod, then further review and sensitivity analysis into the impacts is recommended.

7.3.2 Methane Content

The ratio of methane to carbon dioxide in UK landfill gas is calculated to be 57:43%. This is based on a substantive and representative data set, and is considered to be a very reliable calculation. However this ratio differs from the IPCC (2006) default 50:50% generation ratio. We recommend that further review of published studies should be undertaken to help to explain why the ratio based on measured UK data is different from the IPCC (2006) default values.

7.3.3 Electrical Efficiency

The MELMod model needs to recognise improvements in engine electrical efficiency and it is recommended as an initial step, that a linear adjustment between 1996 and 2012 to cover the transition between old engine designs and newer ones. A check and refinement of this update is advisable via a consideration of historical data on landfill gas production and electrical energy exported.

7.3.4 Flaring

The amount of flaring undertaken in the UK plays an important role in the quantification of the methane collection efficiency; however flaring data is sparse and limited to sites with modern up-to-date permits in England and Waste. Golder believes it important to better quantify the flaring term (including slippage estimates) in particular from sites that are flaring only in the UK, to add reliability to the reported methane capture rates in the future. As flare data are made available it is strongly recommended that the quantification of landfill gas flaring is re-visited.

7.3.5 DIAL Studies

It is considered beneficial to repeat the DIAL surveys using the refined method at different times of the year and also on a wider range of landfill sites in order to obtain robust estimates for lifetime capture rates. It is suggested that analysis on a cell by cell basis can reduce the amount of sites requiring surveying because cells of a similar waste input and containment engineering can be used as ‘surrogate’ cells for landfills of similar characteristics.

7.3.6 Complementary Emission Measurement Studies for Fugitive Emissions

The discussions around the table at Sardinia suggest that a comparative trial between the tracer methods used by the Technical University of Denmark (Charlotte Scheutz and Peter Kjeldsen) and the DIAL approach would be a sensible way to compare these two techniques. The Danish method, pioneered by FluxSense in Sweden in the early 2000s, and previously recommended by Golder as a suitable technology in our 2007 review of optical emissions measurement methods to Defra (Gregory and Armstrong, 2007), is seen to be a reliable and pragmatic method with similar or smaller error limits to the NPL approach, and which can be implemented at much lower cost.

The Natural Environment Research Council-funded Greenhouse Gas UK and Global Emissions (GAUGE) project is a collaboration between a number of the UK’s most prestigious atmospheric science institutions including Cambridge, Manchester, Edinburgh and Leicester. GAUGE intends to use a combination of land-based and remote sensing instruments (including aircraft) to derive 3D methane concentration maps together with associated thermodynamic parameters from which mass emissions rates may be calculated on an operational landfill in East Anglia in summer 2014. Results from this study (yet to be published) should be reviewed and considered with respect to better understanding landfill methane emissions. It would be useful if DIAL could also be present during the field-based campaign to allow inter-comparison of methane concentration data with other platforms and remove some of the residual uncertainty regarding the validity of associated meteorological measurements previously made during DIAL measurements.

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Report Signature Page

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APPENDIX A

National and International Experts Consulted

Table 1: Consulted UK Experts and Industry Representatives

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Andrew Leeding	Infinis	andrew.leeding@INFINIS.com
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Table 2: Consulted International Experts

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Morton Barlaz	North Carolina University, USA	barlaz@ncsu.edu
Peter Kjeldsen	Technical University of Denmark, Denmark	pekj@env.dtu.dk

BULK GAS GENERATION

- Source term estimates in MELMod and GasSim are believed to be reasonably accurate. There is no indication from the international experts consulted that the gas yields per tonne of waste are either under or over-predicting, or the gas generation rates are not appropriate, although there is an academic preference to focus on individual substance gas yields than specific waste stream gas yields, for greater accuracy in prediction.
- There is little international support for considering lignin and lipids as separate sources in a landfill context. If they do contribute at all, they will contribute as part of the total degradation source term value for that waste component and therefore will have been captured in the overall degradation attributed to cellulose, and there is no need to consider them separately.
- However, while this is considered a small component of bulk gas generation, there are PhD students in Denmark currently researching the degradability and methane yield from proteins and lipids. They consider the type of food source important, with commercial food waste considered the greatest potential source of methane from proteins and lipids.
- We asked if we should track cellulose or carbon. Cellulose seems to be the preferred parameter to track, as it can be verified directly.

WASTE DEGRADATION RATES (K VALUES)

- Golder's view of K values has not changed since we spoke to the international experts. The UK exhibits a range of K values which probably approximates to the "fast" K value rates for a portfolio or inventory. MELMod presently uses "average" K values which are slower waste degradation rates.

COMBUSTION EMISSIONS

- Engine emissions can be quantified reasonably accurately from kW generated returns. MELMod could use these data directly.
- Flare emissions can already be semi-quantified from LFG utilisation company data of run time x installed capacity as a straightforward zero order estimate for the entire UK based on the operational sites which report this to the EA. This results in a net reduction in overall flaring assumed by Ricardo-AEA based on MELMod estimates, and so is potentially a conservative assumption.
- There is a view internationally that flares installed on older sites only operate intermittently due to the lack of investment in their infrastructure, and as such these are not seen to be a significant methane emissions mitigation routes. That view probably applies in the UK too. The use of measured run hours and an assumption that this is at installed capacity will be an upper bound value for the managed sites, but this may offset the exclusion of any other flare contribution.

METHANE SLIPPAGE

- Methane slippage was considered to be a maximum of 2.5% of the fuel consumed or less by international experts – Golder has determined the actual value from EA stack emissions data submitted by operators to be 1.5%, in agreement with the experts.

FUGITIVE EMISSIONS AND COLLECTION EFFICIENCY

- Uncontrolled emissions to atmosphere remain the largest uncertainty and are internationally an area of active research. Flanks, operational areas, discrete penetration sources (leaking gas and leachate wells) and exhaust stack emissions (noting that these are also quantified separately and we should not double count) are seen as the primary sources of uncontrolled emissions.

METHANE OXIDATION

- Methane oxidation research has progressed significantly since the IPCC 10% default was established and the international community felt it was possible to justify an oxidation factor in the range of 20 – 45% and maybe higher.

FUTURE RESEARCH

- The discussions around the table at Sardinia suggest that a comparative trial between the tracer methods used by the Technical University of Denmark (Charlotte Scheutz and Peter Kjeldsen) and the DIAL approach would be a sensible way to compare these two techniques.

- The Danish method, pioneered by FluxSense in Sweden in the early 2000s, and previously recommended by Golder as a suitable technology (Armstrong and Gregory 2008), is seen to be a reliable and pragmatic method with similar or smaller error limits to the NPL approach, and which can be implemented at much lower cost.

APPENDIX B

Methane Slippage Calculations

Combustion Formula

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Reactions with Air Fuel Ratio at the Stoichiometric Ratio

	Air	**CH_4**
Air/CH_4 ratio	9.6	1

1m^3 of CH_4 combines with ~10m^3 of air. All oxygen is consumed.

Gas	**%v/v**	**Ratio x %**	**Ratio post combustion**	**Exhaust Composition normalised**
CH_4	57.00	1.00	0.00	0.00
CO_2	43.00	0.75	1.75	18.75
O_2	21.00	2.02	0.02	0.17
N_2	79.00	7.58	7.58	81.07
Total Volumes involved		11.35	9.35	100.00

Air Fuel Ratio with typical excess air

	Air	**CH_4**
Air/CH_4 ratio	12.42	1

The air fuel ratio is increased until the oxygen content achieves 5%, which is the percentage at which stack emissions are normalised.
The resulting methane slippage can then be estimated

Gas	**%v/v**	**Ratio x %**	**Ratio post combustion**	**Exhaust Composition normalised**
CH_4	57.00	1.00	0.00	0.00
CO_2	43.00	0.75	1.75	14.41
O_2	21.00	2.61	0.61	5.00
N_2	79.00	9.81	9.81	80.59
Total Volumes involved		14.17	12.17	100.00

Incoming Landfill Gas

Gas	**%v/v**	**kg/m^3 @ STP**
CH_4	57	0.716
	Golder Data Analysis	http://yeroc.us/calculators/gas-density.php

CH_4 in 1m^3 of the outgoing Exhaust Gas

Slippage calculated as a function of the amount of mass of methane in VOC emissions per m^3 x the total volume through the stack

Gas	kg of CH_4/Nm^3 of Exhaust	Nm^3 of CH_4/Nm^3 of Exhaust	
CH_4	0.00086	0.00120	m^3 CH_4 per unit of exhaust

For every 1m^3 CH4 burnt there is 0.015 m^3 of CH_4 slipped

APPENDIX C

DIAL Analysis

1.0 INTRODUCTION

The Department of Environment, Food and Rural Affairs (Defra), the Department of Energy and Climate Change (DECC) and the Environment Agency are running a joint programme on methane capture from landfill. As part of this programme, Defra has commissioned two surveys to date (an initial pilot survey, and a smaller more focussed supplementary study) to measure methane emissions from landfills. The National Physical Laboratory (NPL) measured methane emissions using the DIAL, differential absorption lidar, measurement technique. Methane oxidation was measured using the stable isotopes of carbon method with analysis performed by Royal Holloway University of London.

2.0 DIAL STUDIES

Initial studies were undertaken by the NPL at nine landfill sites in the UK[1]. A second DIAL study was undertaken at three UK landfill sites, each with active and restored areas, using a refined meteorological method, longer study duration, and the addition of emission flux determination for the gas engines. This report utilises the data from the second DIAL study[2].

During the DIAL studies methane oxidation was measured using isotopic analysis on samples collected using three different methods:

1) Ambient air sample collection (upwind and downwind);

2) Flux box sample collection; and

3) Soil spike sample collection.

2.1 Initial DIAL Study Conclusions

Methane emissions measured by DIAL were significantly higher for active sites than for closed sites, in part due to methane emitted directly to air from the uncapped active area. The study determined that there was no significant observable difference in methane emissions between sites that were closed both before and after 2001.

It was generally found that methane emissions were not uniform across the whole site, with several areas having much higher emissions compared with the rest of the site. It is suggested that the efficiency of operation of the landfill gas collection system was lower in some areas of the site.

Data from the DIAL studies was processed to calculate methane capture rates[3] and it was found that methane capture rates were highly variable. For the three operational landfills, these were determined to be between 26% - 74% and for the six closed landfills capture rates were determined to be 23% - 85%.

Of the oxidation measurements it was determined that upwind/downwind ambient air sampling was the most appropriate method as it gives a measure of the whole site oxidation. Ambient air sampling also includes fugitive emissions from operational areas and point sources e.g. gas extraction system leakage where the methane does not undergo soil oxidation. Another advantage of ambient air sampling over flux box and soil spike sampling was that the latter do not represent the heterogeneity of oxidation across the site, due to the spot sampling nature of these methods. To obtain high spatial resolution with flux box and soil spike sampling would be extremely labour intensive.

[1] F. Innocenti, R.A. Robinson, T.D. Gardiner, J. Tompkins, S. Smith, D. Lowry & R. Fisher (2012) Measurements of Methane Emissions and Surface Methane Oxidation at Landfills: WR1125. National Physical Laboratory.

[2] F. Innocenti, R.A. Robinson, T.D. Gardiner, A.J. Finlayson, A. Connor, D. Lowry, R. Fisher (2013) WR1125 – Measurement of Methane Emissions and Surface Methane Oxidation at Landfills : A Supplementary Survey DRAFT. National Physical Laboratory.

[3] M. Bourn and D. Browell (2013) Methane Capture Rates at UK Landfills. Proceedings Sardinia 2013, 14th International Waste Management and Landfill Symposium.

3.0 SUPPLEMENTARY DIAL STUDY ANALYSES

3.1 Data Processing Methodology

Capture rates were calculated using the same methodology as outlined by Bourn & Browell (2013)[2], highlighted below.

Methane Emission (DIAL Measurements)

Total methane not collected = Total site methane emission + Total site methane oxidation rate.

Landfill Gas (LFG) Collection Data

On site LFG collection data was sourced from the 3 main UK landfill operators and used to determine average total methane collected (kg/hr) and average total engine methane collected (kg/hr) from LFG flow rate, methane content and methane density at 30°C.

Methane Generation

Total methane generation = Total methane not collected + Total methane collected.

Capture Rate

Capture rate = Total methane collected/Total methane generation.

In addition to calculating the capture rate, the combustion rate and methane slippage at the gas utilisation plant (GUP) was also determined using the values calculated from the engine emission measurements.

Combustion Rate

Combustion rate = [Total methane collected – Total gas engine emissions] / Total methane generation.

Methane Slippage

Methane slippage = Total gas engine emissions / Total engine methane collected.

3.2 Results

Capture rates, combustion rates and methane slippage for the three sites studied in the supplementary DIAL survey are displayed in Table C1. Errors are combined from each input by summation in quadrature and the upper and lower values were used to calculate the maximum and minimum expected values for each parameter.

Table C1: Capture Rate, Combustion Rate and Methane Slippage

	Capture Rate	Combustion Rate	Methane Slippage
Site J	91 ± 1%	90 ± 1%	1.2 ± 0.1%
Site K	71 ± 1%	71 ± 1%	0.7 ± 0.3%
Site L	76 ± 2%	75 ± 2%	1.6 ± 0.3%

Note: Methane oxidation was not characterised during the study for Site K, therefore the capture rate and combustion rate will be lower than the quoted values.

3.3 Site Emission Characteristics

Further site emission characteristics were determined from the supplementary DIAL study data and on-site LFG collection data in order to categorise methane emissions from the sites as per Figure C1.

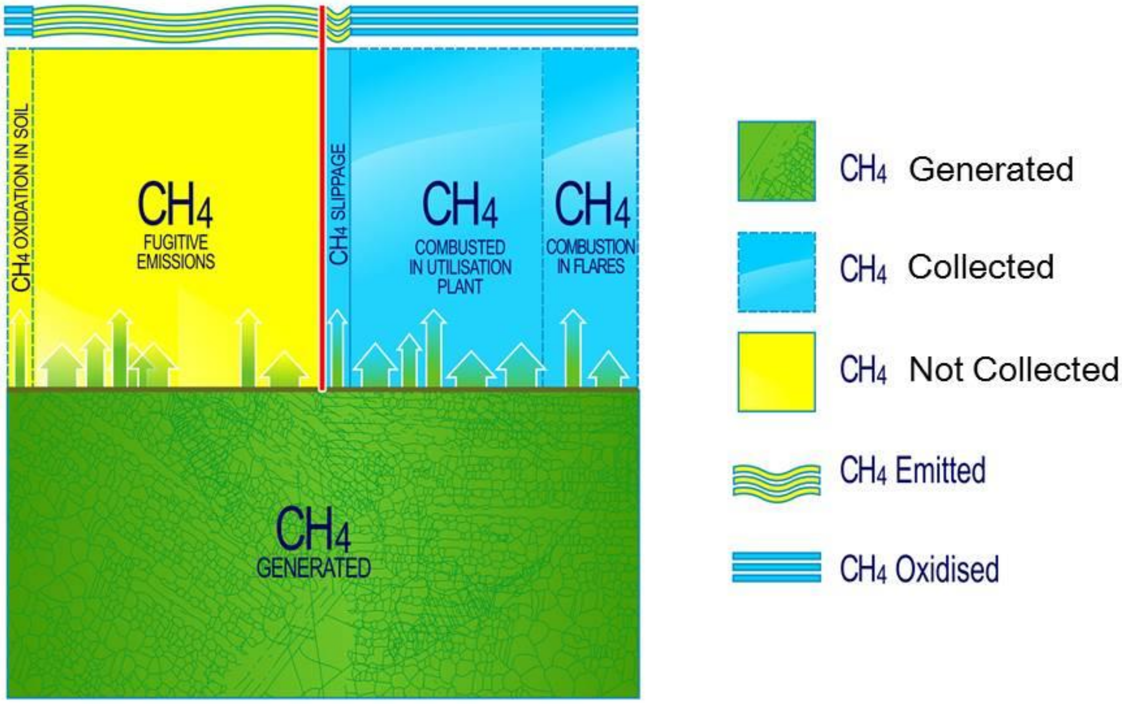


Figure C1: Conceptual Model of Methane Generation and Emission

3.3.1 Site J: 25 February – 4 March 2013

Site J is an active site, approximately 80% of which is finished and capped. It was confirmed with the site manager that on the days during which the DIAL survey took place, operations were as normal, the engines were all running as normal i.e. the site was under full extraction. Therefore site conditions were representative of ideal conditions for monitoring. Discrete emissions were not characterised, however it is assumed that for the most part these will have been included in the DIAL surface emission measurements. Utilising the surface area estimations an estimated daily emission rate was calculated for the closed areas (average of 6 $g/m^2/d$), active areas (83 $g/m^2/d$), and site average 12 $g/m^2/d$ (Tables C2 and C3).

Table C2: Site J Categorised Methane Emissions

CH_4 Oxidation	**Methane Oxidation**	**40.0**	**±**	**6.8**	**kg/hr**
CH_4 Emissions at Discrete Features	Discrete Emissions				
CH_4 Surface Emissions	KOP A (Old Cells - Capped) Emission	34.3	±	4.9	kg/hr
	KOP B (Capped) Emission	19.1	±	3.7	kg/hr
	KOP C (Capped) Emission	51.1	±	6.1	kg/hr
	Active Area	246.8	±	26.0	kg/hr
CH_4 Slippage	Methane Slippage	41.3	±	4.0	kg/hr
CH_4 Combusted	Engine	3569.2	±	12.6	kg/hr
CH_4 Flared	Flare	273.5	±	23.3	kg/hr

Table C3: Site J Methane Surface Emissions

	METHANE EMISSIONS				AREA		METHANE DAILY EMISSION RATE	
KOP A (Old Cells - Capped) Emission	34.3	±	4.9	kg/hr	90,000	m^2	9	$g/m^2/d$
KOP B (Capped) Emission	19.1	±	3.7	kg/hr	65,000	m^2	7	$g/m^2/d$
KOP C (Capped) Emission	51.1	±	6.1	kg/hr	450,000	m^2	3	$g/m^2/d$
Active Area	246.8	±	26.0	kg/hr	71,000	m^2	83	$g/m^2/d$
TOTAL	**351.3**	**±**	**27.4**	**kg/hr**	**676,000**	**m^2**	**12**	**$g/m^2/d$**

3.3.2 Site K

Site K consists of active and capped areas. Methane oxidation was not characterised for Site K. Discrete emissions were also not characterised; however, it is assumed that for the most part these will have been included in the DIAL surface emission measurements. Utilising the surface area estimations an estimated daily emission rate was calculated for the closed areas (22 $g/m^2/d$, unexpectedly large and perhaps influenced by discrete feature emissions), active areas (91 $g/m^2/d$), and site average 71 $g/m^2/d$ (Tables C4 and C5).

Table C4: Site K Categorised Methane Emissions

CH_4 Oxidation	**Methane Oxidation**				
CH_4 Emissions at Discrete Features	Discrete Emissions				
CH_4 Surface Emissions	Capped Area (Minimum)	67.6	±	6.7	kg/hr
	Active Area (Minimum)	653.8	±	30.6	kg/hr
CH_4 Slippage	Methane Slippage	10.0	±	3.4	kg/hr
CH_4 Combusted	Engine	1354.3	±	8.8	kg/hr
CH_4 Flared	Flare	451.4	±	2.9	kg/hr

Table C5: Site K Methane Surface Emissions

	METHANE EMISSIONS				AREA		METHANE DAILY EMISSION RATE	
Capped Area (Minimum)	67.6	±	6.7	kg/hr	72,200	m^2	22	$g/m^2/d$
Active Area (Minimum)	653.8	±	30.6	kg/hr	173,100	m^2	91	$g/m^2/d$
TOTAL	**721.4**	**±**	**31.3**	**kg/hr**	**245,300**	**m^2**	**71**	**$g/m^2/d$**

3.3.3 Site L

Site L is an active landfill. As a result of overtipping activities, the methane plumes measured using DIAL are a mixture of emissions from both the old and the new waste. Other than those wells which were disconnected due to overtipping, extraction was running as normal during the DIAL survey. There was some possible engine downtime, however the flare was operational and so extraction rates were not affected. Utilising the surface area estimations an estimated daily emission rate was calculated for the closed areas (3 $g/m^2/d$), active areas (211 $g/m^2/d$), and site average 16 $g/m^2/d$ (Tables C6 and C7).

Table C6: Site L Categorised Methane Emissions

CH_4 Oxidation	**Methane Oxidation**	**47.6**	**±**	**20.1**	**kg/hr**
CH_4 Emissions at Discrete Features	Discrete Emissions				
CH_4 Surface Emissions	Capped Area (Minimum)	91.1	±	11.1	kg/hr
	Active Areas (Approximate)	395.2	±	27.4	kg/hr
CH_4 Slippage	Methane Slippage	20.5	±	2.5	kg/hr
CH_4 Combusted	Engine	1264.9	±	42.1	kg/hr
CH_4 Flared	Flare	606.0	±	42.7	kg/hr

Table C7: Site L Methane Surface Emissions

	METHANE EMISSIONS				**AREA**		**METHANE DAILY EMISSION RATE**	
Capped Area (Minimum)	91.1	±	11.1	kg/hr	685,000	m^2	3	$g/m^2/d$
Active Areas (Approximate)	395.2	±	27.4	kg/hr	45,000	m^2	211	$g/m^2/d$
TOTAL	**486.3**	**±**	**29.6**	**kg/hr**	**730,000**	**m^2**	**16**	**$g/m^2/d$**

3.4 Supplementary DIAL Study Conclusions

For each site, the majority of the methane emissions were from the active area due to the escape of methane directly to air as a result of active areas being uncapped.

Table C8: Summary of Methane Surface Emissions by Area Type

Capped Areas	**METHANE EMISSIONS**				**AREA**		**METHANE DAILY EMISSION RATE**	
KOP A (Old Cells - Capped) Emission	34.3	±	4.9	kg/hr	90,000	m^2	9	$g\ m^{-2}\ day^{-1}$
KOP B (Capped) Emission	19.1	±	3.7	kg/hr	65,000	m^2	7	$g\ m^{-2}\ day^{-1}$
KOP C (Capped) Emission	51.1	±	6.1	kg/hr	450,000	m^2	3	$g\ m^{-2}\ day^{-1}$
Capped Area (Minimum)	67.6	±	6.7	kg/hr	72,200	m^2	22	$g\ m^{-2}\ day^{-1}$
Capped Area (Minimum)	91.1	±	11.1	kg/hr	685,000	m^2	3	$g\ m^{-2}\ day^{-1}$
Weighted Area Average							**5**	**$g\ m^{-2}\ day^{-1}$**
Active Areas	**METHANE EMISSIONS**				**AREA**		**METHANE DAILY EMISSION RATE**	
Active Area	246.8	±	26	kg/hr	71,000	m^2	83	$g\ m^{-2}\ day^{-1}$
Active Area (Minimum)	653.8	±	30.6	kg/hr	173,100	m^2	91	$g\ m^{-2}\ day^{-1}$
Active Areas (Approximate)	395.2	±	27.4	kg/hr	45,000	m^2	211	$g\ m^{-2}\ day^{-1}$
Weighted Area Average							**108**	**$g\ m^{-2}\ day^{-1}$**

In the supplementary study oxidation of methane was calculated using a far greater number of gas wells, downwind and on-site samples. The study used a mobile cavity ringdown spectrometer to measure real time methane concentrations which greatly assisted in locating the extent of plumes for sampling purposes.

The methane oxidation results suggested that the oxidation rates for older parts of the site was lower than those determined for the more recently covered areas. Variations in gas well isotopic compositions showed that calculations should be made on a cell by cell basis. The study suggests repeating the study during summer months, when oxidation rates are expected to be higher.

Capture rates determined from the study were in the range 71 – 91% which (although only a snapshot) are close to the previously assumed 75% lifetime capture rate, particularly considering the sites are all active and hence have areas which are uncapped. Combustion rates were similar, 71 – 90% and methane slippage from the engines was relatively low, 0.7 – 1.6%.

4.0 SUMMARY

DIAL has been shown to be a useful method for measuring landfill methane emissions and that ambient air sampling was the best form of sampling for methane isotope analysis. However, the DIAL method can be limited by meteorological uncertainty and the need for appropriate duration studies to better characterise the sites in question (and the background conditions which are subtracted from the measurements to give the site contribution).

Capture rates at the sites during the supplementary study were in the range 71 – 91%; however, further studies are required to look at different sites and seasonality in order to obtain robust lifetime capture estimates.

APPENDIX D

UK Landfill Area Estimates

ENGLAND AND WALES

The total area of operational and closed landfill sites in England and Wales was calculated based on information provided by Environment Agency Report SC030143/R5 – Methane emissions from different categories of landfills.

As part of the project a database of all landfill sites in England and Waste was produced from data held by the Environment Agency. The database aimed at including all identified landfills, including sites that no longer have an environmental permit or were operated prior to any form of pollution control authorisation. This includes sites formerly holding a Waste Management Licence (WML) – where, for example the licence was surrendered, pre-Control of Pollution Act 1974 (COPA) sites that are still with local authorities and old, historic landfills.

The report states that a key issue for the project has been the availability and quality of information that exists for landfill sites in England and Wales. The report appreciates that the formation of the EA in 1996 has helped to create a series of national data sets. However, the presence and quality of data from each source was found to be inconsistent and this issue was found to be increasingly significant with the age of a site. In general, data quality has found to improve as the legislation and regulation of the waste industry has developed. Key data sets used and assumptions made for data processing are detailed in the report.

The project further sought to develop a classification system based on the supplied information. All landfills in England and Wales were classified with respect to factors that may influence methane emissions. Table D1 below set out the classification system developed for the project.

Table D1: Definition of Subcategories

Symbols	Meaning
Emission class	
D1	Inorganic sites
D2	Last fill date before 13/07/1976
D3	Organic sites
Landfill area and gas control	
E1	Sites with area less than or equal to 1 hectare
E2	Sites with gas control and area >1 hectare
E3	Sites without gas control and area between 1 and 5 hectare
E4	Sites without gas control and area between 5 and 10 hectare
E5	Sites without gas control and area between 10 and 50 hectare
E6	Sites without gas control and area greater than 50 hectare
Regulatory positions	
R1	Regulatory position 1 (operational)
R2	Regulatory position 2 (closed under Landfill Directive, after 2001)
R3	Regulatory position 3 (closed before Landfill Directive but have waste management licence up to closure, i.e. between 1994 and 2001)
R4	Regulatory position 4 (closed without a permit, before 1994)
Waste compositions	
W1	R1 and R2 Biodegradable waste landfill - A04 and A01
W2	R1 and R2 Limited biodegradable waste landfill - A02 and A06 and A07 with gas control
W3	Regulatory position 3 composition
W4	Regulatory position 4 composition

Symbols	Meaning
Start date of sites	
S1	2001 onwards
S2	1994 – 2000
S3	July 1976 -1993
S4	1966 - July 1976
S5	Pre 1966

Based on the reviewed data, there were 22,997 recorded landfill sites in England and Wales in 2007. Of these sites, 5,873 landfills could not be fully classified either because there was no relevant data information or the data information was inconsistent with their regulatory position. The majority of sites that could not be fully classified were in classes D3_E1 and D3_E3. Where there was insufficient information to classify a site as either D1 or D2, the site is, by default, classified as D3. This means that some of the D3 sites which have not been fully classified may in reality be D1 or D2.

Inorganic sites or inert landfills are not expected to contribute to landfill methane emissions in the UK and have thus been excluded from the further analysis. Further excluded were sites that last filled before 13/07/1976 (D2). These were deemed to represent Type 4 rather than Type 3 landfills according to MELMod. For the purpose of estimating landfilled areas of operational and closed landfills, sites were attributed as follows (Table D2):

Table D2: Category Attribution to Operational and Closed Sites for Area Estimates

Operational	Closed
D3_Ex_R1	D3_Ex_R2, D3_Ex_R3, D3_Ex_R4

The project database, supplied to Golder in an Excel spreadsheet format, was used to derive area estimates based on the above category attribution. Part of the information provided for in the database was the area of each site in square metres as derived from GIS Shape File which have been used for the Golder area estimates.

Of the 22,997 recorded landfill sites, 12,252 sites are categorised as inorganic sites and 2,071 sites stopped filling before 13 July 1976 and were thus excluded. Of the remaining sites 187 are operational and 8,487 sites are closed. For 8 of the operational and 36 of the closed sites no shape area information was available. In these cases, the 'landfill area and gas control' subcategory E was used to estimate the size of landfills as detailed in Table D3.

Table D3: Area Estimates for Sites without Shape File

Subcategory	Description	Estimated Area (m^2)
E2	Area >1 hectare	50000
E3	Area between 1 and 5 hectares	50000
E4	Area between 5 and 10 hectares	100000
E5	Area between 10 and 50 hectares	500000
E6	Area greater than 50 hectares	1000000

Following the methodology above, it was estimated that in 2007 a total of 506,249,035 m^2 was covered by operational or closed landfill sites in England and Wales. Approximately 14% were covered by operational sites and 86% by closed sites as detailed in Table D4 below.

Table D4: England and Wales Area Estimates 2007

	n	m^2	%
Operational Sites	187	70,469,138.00	14
Closed Sites	8487	435,779,897.00	86
Total	8674	506,249,035.00	100

UNITED KINGDOM

In the absence of access to equivalent area data for Scotland and Northern Ireland, landfill areas for operational and closed sites for the entire UK were scaled up based on landfilled waste in the deployed administrations. Estimates were based on the Defra's Waste Statistics Regulation Return to Eurostat for 2008. Non-hazardous waste (excluding mineral waste) deposited onto or into land was found to distribute as shown in Table D5.

Table D5: Non-Hazardous Waste (excluding Mineral Waste) Deposited onto or into Land 2008

	%
England	82
Wales	5
Scotland	10
Northern Ireland	3

Based on the above figures landfill areas for England and Waste were scaled up by 13% to present an estimate for the entire UK as shown in Table D6.

Table D6: UK Area Estimates

	m^2
Operational Sites	81,115,264
Closed Sites	501,615,352
Total	582,730,616

OPERATIONAL, TEMPORARY AND PERMANENTLY CAPPED AREAS

An average distribution of operational, temporary and permanently capped areas across operational UK landfill sites was derived based on observations made on 53 operational UK landfills in 2011. The findings are shown in Table D7.

Table D7: Operational, Temporary and Permanently Capped Area Distribution

	%	STD
Total Operational Area	10	7
Total Temporary Capped Area	15	12
Total Permanently Capped Area	75	13

These average assumptions were applied to the UK area estimates for operational landfills. All closed landfills were assumed to be permanently capped resulting in the area estimates shown in Table D8.

Table D8: Operational, Temporary and Permanently Capped Areas on UK Landfills

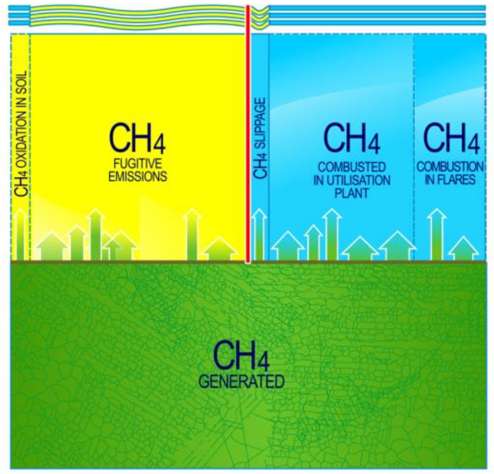
	m^2	%
Operational Area	8,211,007	1
Temporary Capped Area	12,052,504	2
Permanently Capped Area	562,467,104	97
Total	582,730,616	100

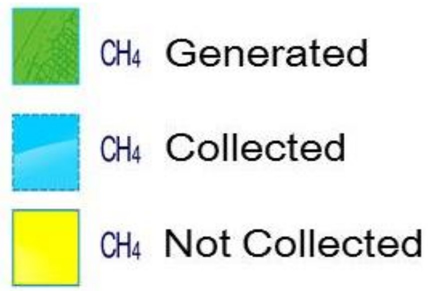
Based on the assumptions detailed above, this analysis indicates that approximately 1% of the total UK landfill portfolio is covered by operational areas with a size of approximately 800 hectares.

APPENDIX E

Calculation of Portfolio Collection Efficiency for 2011

Methane Collection Efficiency UK 2011 - Base Case Estimate





UK Methane Engine Combustion			Comment/Source
Electricity generated 2011 in the UK from LFG	5092	GWh	DECC
Average LFG Engine Electrical Efficiency	36	%	Golder Assumption
Methane combusted in Engines	1414502561	m^3	
Methane Density Under Standard Conditions	0.7158	kg/m^3	
Methane combusted in Engines	1,012,501	t	

UK Total Methane Combustion (Engine + Flare)		Comment/Source	
	Tonnes (t) CH4		
Engine Methane Combustion	1,012,501		
Flare Methane Combustion (Generating Portfolio)	92,242	11	Flare:Engine Ratio, Golder Assumption
Flare Methane Combustion (Flaring Only Portfolio)	220,685		
Total Methane Combustion	1,325,427		
Methane Slippage from Engines	14,836	1.5	% Methane Slippage, Golder Assumption

Total Methane Generated by Type 3 Landfills 2011		Comment/Source
	Tonnes (t) CH4	
Assuming 57% CH_4 in LFG	2,526,096	MELMod_2011_v1-2_(2011 Inventory)

Total Methane Oxidised 2011 (Assuming IPCC 10% Default)		
	Tonnes (t) CH4	
Assuming 57% CH_4 in LFG	120,067	Assuming IPCC 10% Default

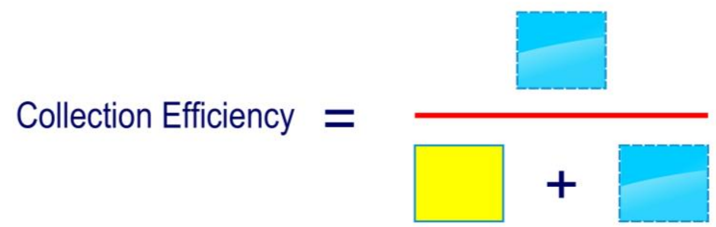
Theoretical Calculated Fugitive Emissions 2011		
	Tonnes (t) CH4	
Assuming 57% CH_4 in LFG	1,080,602	Assuming 57% CH_4 in LFG

Theoretical Collection Efficiency 2011	
	Collection Efficiency %
Assuming 57% CH_4 in LFG	52

Assumed UK Area Distributions by Capping		
	m^2	
Operational Area	8,211,007	Golder Assumption
Temporary Capped Area	12,052,504	
Permanently Capped Area	562,467,104	
Total	582,730,616	

Calculated UK Area Emissions		
	Tonnes (t) CH4	Assumed Emission Factor ($g/m^2/day$)
Operational Area	322,821	108
Temporary Capped Area	20,211	5
Permanently Capped Area	943,219	5
Total	1,286,251	

Total Methane Oxidised 2011 (Assuming IPCC 10% Default), based on UK Area Emissions		
	Tonnes (t) CH4	
	142,916.73	Assuming IPCC 10% Default



Area Emission Based Collection Efficiency 2011	
	Collection Efficiency %
Assuming 57% CH_4 in LFG	48

APPENDIX F

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