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METHANE FROM ANAEROBIC DIGESTION (MEAD) STUDY

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ABSTRACT

Results and discussion of methane emission measurements from seven UK anaerobic digestion facilities using a variety of monitoring techniques.

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Approved on behalf of NPL by
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CONTENTS

GLOSSARY/ABBREVIATIONS

AD	Anaerobic digestion
ADBA	Anaerobic Digestion and Bioresources Association [https://adbioresources.org/]
BAT	Best available technique
BHFS	Bacharach Hi Flow Sampler®
BtG	Biomethane-to-grid (includes gas injection, but not gas upgrade)
CHP	Combined heat and power
CH_4	Methane
CO_2	Carbon dioxide
CRDS	Cavity ring-down spectroscopy
CRF	Controlled release facility
DIAL	Differential absorption lidar
EA	Environmental Agency
EC	Eddy covariance
EF	Emission factor
EN	European Norm
EP	Environmental permit
EU	European Union
FEDS	Fugitive emissions detection system
FE	Functional element
FID	Flame ionisation detection
FTIR	Fourier-transform infrared [spectroscopy]
GC	Gas chromatography
GC-MS	Gas chromatography–mass spectrometry
GGSS	Green Gas Support Scheme [UK Government]
GHG	Greenhouse gas
GMI	Gas Measurement Instruments [Teledyne]
GPS	Global positioning satellite
GtG	Gas-to-grid (includes gas upgrade and grid injection)
ICOS	Integrated cavity output spectroscopy
IDMM	Inverse dispersion modelling method
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
LDAR	Leak detection and repair
LEL	Lower explosive limit
LGR	Los Gatos Research [company]
Lidar	Light detection and ranging
MEAD	Methane Emissions at Anaerobic Digestion sites [project]
MetHarmo	Methane Harmonisation [European project]
MS	Mass spectrometry
MWe	Megawatt equivalent
N_2O	Nitrous oxide

NDIR	Nondispersive infrared [spectroscopy]
OGI	Optical gas imaging [camera]
OP-TDLAS	Open-path tunable diode laser absorption spectroscopy
ppm	Parts per million (1,000,000)
ppb	Parts per billion (1,000,000,000)
PRV	Pressure release valve
TC	Tracer Correlation
TDLAS	Tunable diode laser absorption spectroscopy
UNFCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compound

EXECUTIVE SUMMARY

The primary aim of the Methane Emission at Anaerobic Digestion (MEAD) project was to increase the level of understanding regarding the potential sources of methane emissions from the various functional elements (FEs) of an anaerobic digestion (AD) site and to highlight which stages, processes and FEs should be prioritised for emission reduction. During the MEAD study methane emissions were measured at seven different AD facilities, all of which had gas-to-grid (GtG) capabilities.

Different techniques for methane detection and quantification were used throughout the project, this included both short-term and long-term approaches. Differential absorption lidar (DIAL) and walkover surveys were performed at all seven sites as short-term, campaigned based techniques. Another short-term technique, tracer correlation (TC), was deployed only at Site G as a novel measurement approach for National Physical Laboratory (NPL). Similarly, the fugitive emissions detection system (FEDS), NPL's long-term monitoring solution, was only deployed at Site G for several months.

Summary of the methane monitoring techniques used.

Technique	Measurement Timeframe	Site						
		A	B	C	D	E	F	G
DIAL	Short-term	✓	✓	✓	✓	✓	✓	✓
Walkover survey	Short-term	✓	✓	✓	✓	✓	✓	✓
TC	Short-term	-	-	-	-	-	-	✓
FEDS	Long-term	-	-	-	-	-	-	✓

The primary technique used for the quantification of site emissions was NPL's DIAL. The DIAL data showed the total site emissions ranged from 14.5 kg/h to 95.9 kg/h. Using activity data provided by the sites, it was possible to estimate the methane emission factor (EF), this ranged from approximately 4% to 22% of the total site methane production (biomethane injected, combined heat and power (CHP) throughput, flare throughput and fugitive emissions) as shown in the table below. Site G, where a methane EF of 22% was measured, had a known issue that was rectified after the DIAL campaign. Following the maintenance at Site G, FEDS measurements estimated the EF was reduced to approximately 5%. The issues on Site G are not uncommon, hence the loss measured by DIAL can be considered indicative of the potential emissions at facilities with large digester leaks or during periods of ongoing maintenance. The benefit of a thorough repair and maintenance program on AD facilities are shown by the loss reduction measured by FEDS after the issue was addressed.

A 2022 review of the AD industry by Bakkaloglu et al. employed Monte Carlo simulations utilising literature data to estimate total site methane EFs. In this work EFs of approximately 2% (at the 5th percentile) to approximately 13% (at the 95th percentile) were determined, with a median methane EF of approximately 5%[1]. The observed EFs varied between approximately 4% and 15% for Sites A to F. Although not dissimilar to those determined in Bakkaloglu et al. (2022), the smallest methane EFs observed from the DIAL surveys was approximately double (~4%) those estimated from the 5th percentile of the Bakkaloglu study (~2%) and the emissions from Site D were above Bakkaloglu's the 95th percentile methane loss rate.

Summary of the derived methane EF (%) from sites A to G using DIAL.

Site Total	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site A	22.2	1.5	7.8%	2.6%
Site B*	14.5	1.5	4.5%	0.4%
Site C	19.1	1.5	4.1%	0.6%
Site D	38.8	3.7	14.2%	1.2%
Site E	17.4	1.4	7.8%	0.9%
Site F	53.7	1.9	10.4%	2.4%
Site G	95.9	2.9	22.0%	2.0%

*Emissions from Stage 3 could not be measured from Site B and so the emission rate and methane EF reported should be treated as minimum values.

Using the DIAL, it was possible on some of the sites to separate the emissions from five main FEs: feedstock storage, digesters, CHP, upgrade units and digestate (the solid/liquid by-product of AD) separation/storage. While CHP, upgrade and feedstock storage losses varies from approximately zero to 5%, the digester shows a higher variability (from zero to about 13%) and the digestate storage has a minimum loss of about 3% up to about 8%. This makes digestate storage, both solid and liquid, an ideal candidate for methane emission abatement particularly for all storage areas that are left uncovered. Significantly large emissions of about 21 kg/h were observed from the feedstock storage area of Site F, while other sites had emission of less than 1 kg/h. Site F was the only site which utilised solely commercial/municipal waste, therefore it is not possible to know if this was an isolated issue at Site F or a common problem from site utilising similar feedstocks.

The main source of emissions from the upgrade unit was the upgrade vent, which vents the carbon dioxide (CO_2) removed during upgrading, presumably caused by inefficient separation during the gas upgrade process. The measured slippage from the CHP exhausts was relatively small; however, in a couple of instances larger emissions were observed from the CHP unit at lower elevations.

A walkover survey is comparable to the leak detection and repair (LDAR) programme which is routinely carried out at oil and gas facilities. This allows to identify leaks at a component level enabling the operator to carry out an efficient maintenance programme. Within the survey it is also possible to quantify the emission from some of the components. Therefore, upon first inspection it may seem difficult to reconcile the differences seen between the DIAL and walkover survey datasets presented in Section 6. However, differences should be expected considering that walkover surveys are not suitable for quantifying elevated or diffuse emissions, which were typically the dominant sources found during the DIAL emission surveys. Walkover surveys are in fact not designed to quantify whole site emissions, but rather to detect and quantify accessible leaking components. As such, walkover surveys are of real value at AD facilities for leak detection/quantification and repair.

During the DIAL measurement survey at Site G, significant methane losses were observed. However, prior to NPL's arrival it was known there was an issue with the digester, although the full extent of the problem was not understood. The site had planned maintenance of the digester roof in the weeks

following the DIAL measurement survey, making it an interesting candidate for long-term monitoring. It was decided that NPL would employ the FEDS long-term monitoring technique at Site G to try to capture the maintenance period and to demonstrate the impact on the emissions following the repair of the digester roof. The results of the FEDS monitoring presented in Section 7 indicate that the whole-site emissions decreased by approximately 75% in the weeks following maintenance to the digester roof.

One of the aims of the project was to test TC as a cost effect short-term monitoring technique, which was done at Site G, where both FEDS and DIAL were also deployed. The methane emission rates measured were not directly comparable with what had been measured by the DIAL and FEDS techniques. While DIAL and FEDS data compare well and show similar level of emission, the TC measurements (carried out in the period between the DIAL and FEDS measurements) showed on average lower emission rates. This may have been due to systematic uncertainties in the TC measurements. For this project NPL started the development of a novel quality assurance approach allowing the exclusion of poor-quality data. Further developing and testing of these quality assurance criteria and the implementation of the procedures identified in EN 17628 are both critical to ensure the overall quality of TC measurements and establish TC as suitable candidate for whole-site emission quantification.

1 INTRODUCTION

Biomethane, sometimes referred to as green gas, is expected to play a critical role in the UK's strategy to decarbonise the energy sector and reach Net Zero[2]. As part of this strategy the UK government has introduced the Green Gas Support Scheme (GGSS)[3,4], a government scheme open to applicants in England, Scotland and Wales that offers financial incentives to new anaerobic digestion facilities, with the goal of increasing the proportion of biomethane in the gas grid.

Anaerobic digestion (AD) produces biogas, which can be converted to biomethane through the purification process known as 'upgrading'. The upgraded biomethane is then checked for quality and subsequently injected into the gas grid, provided it meets the quality threshold. The magnitude of methane emissions to atmosphere from AD facilities is a key factor in understanding the environmental impact of the industry's life cycle. This is important because methane is a potent greenhouse gas and methane losses from leakages can cancel out the benefits of reduced natural gas consumption. Previously it has been reported that emissions of 1% to 13% of the total CH_4 produced on site are to be expected[1]. However, a recent study of Danish AD facilities suggests that emissions could be as high as 40%[5]. However, these estimations of the methane emissions are significantly higher than previously understood by UK government, where the emissions were assumed to be between 0.05% and 2.5%[6]. To better understand the industry, more measurements of AD facilities are still required to characterise the range of possible emissions. Moreover, the methane emissions during the different stages of the AD process also require further investigation.

The aim of the MEAD project is to assess the methane emissions from the AD and biomethane production processes, using a range of suitable measurement techniques. MEAD will add further evidence to the GGSS and reinforce the intent to reduce national net methane emissions by 2030[3]. Part of the purpose of the MEAD project is to understand the potential sources of methane emissions from the various functional elements (FEs) of an AD site to highlight which stages, processes and FEs should be prioritised for emission reduction. A secondary objective for the project was to trial a method of monitoring for methane emissions that NPL had not used before.

This report details the key findings from the MEAD project. Section 2 gives a brief overview of the AD industry, highlighting the different stages of the AD process and potential methane sources, as well as suitable techniques for measuring these sources. Section 3 details a comprehensive summary of all the different measurement methods which were used to measure methane emissions within the MEAD project. Section 4 outlines the strategy used for site selection. Sections 5 to 8 give an overview of the results from the different measurement techniques used within this study. Lastly, Section 9 highlights the main conclusions from the study and identifies some targeted strategies to reduce methane emissions from the AD industry.

2 OVERVIEW OF ANAEROBIC DIGESTION FACILITIES

AD is a process by which organic materials are broken down by microorganisms (e.g. bacteria) in the absence of oxygen[7]. This biochemical process produces biogas, a gaseous mixture comprised primarily of methane (CH_4) and carbon dioxide (CO_2) in roughly equal proportions. AD occurs in nature, when organic matter decays in a low oxygen environment, this process leads to the release of greenhouse gases (GHGs) into the atmosphere. Methane produced by AD is a major source of GHG emissions from the waste sector. One solution to reducing GHG emissions from the waste industry is to create controlled (enclosed) environments for AD to take place, capture the biogas produced and then utilise this as a source of energy. This is the concept behind AD and landfill facilities.

It should be noted that AD facilities are generally categorised as waste management facilities and as such are required to operate under an environmental permit (EP). However, sites can apply for a waste exemption meaning they do not require an EP, provided they compile limits and conditions of the exemption[8–10]. Moreover, if their feedstock (e.g. maize, wheat, beet, etc.) is specifically grown to be used for AD and no other waste products are handled or used as feedstock, then AD facilities do not require an EP to operate[11].

Controlled anaerobic digestion of organic materials takes place at AD facilities. Figure 2.1 highlights the AD processes and the different areas, or FEs, which make up a typical AD facility. The FEs listed in Table 2.1 have been grouped into four stages. Note that not every FE may be present at each facility, and some may be combined.

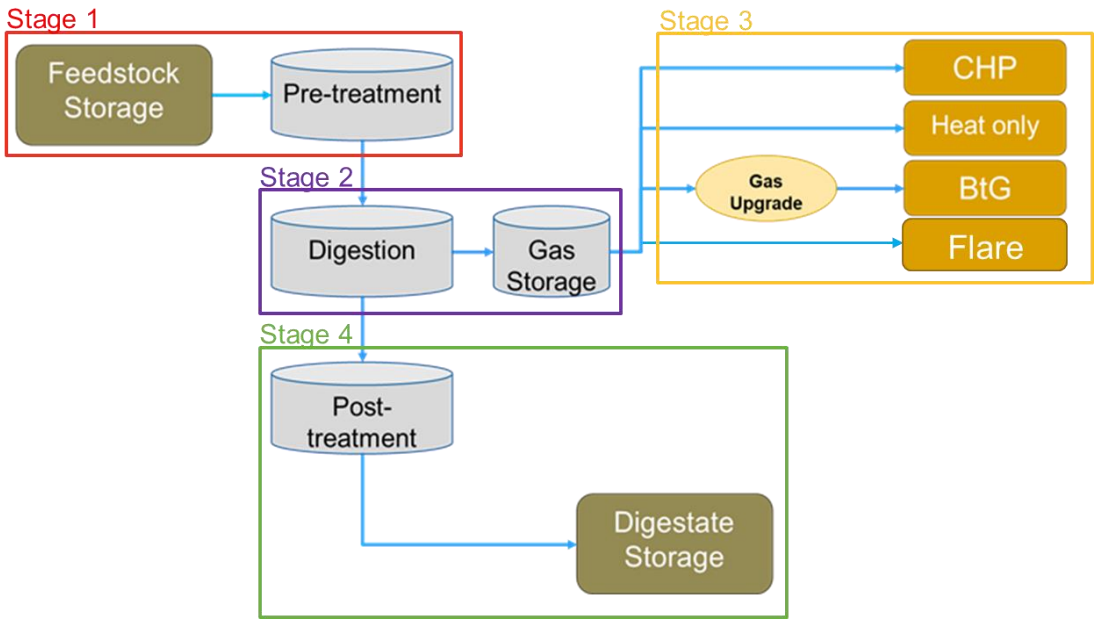

Figure 2.1 Illustration of the different stages of the AD process and their associated functional elements.

Table 2.1. Description of functional elements.

Stage	Functional Element	Description
1	Feedstock storage	Storage area for site feedstock.
	Pre-treatment	Mixing of different feedstocks.
2	Digestion	Digestion tanks and associated plant equipment.
	Gas storage	Tanks.
3	Gas upgrade	Purification and CO_2 removal.
	Biomethane-to-Grid (BtG)	Compression to grid pressures.
	Combined heat and power (CHP)	Heat and electricity generation.
	Heat only	Boilers.
	Flare	Use in emergency or maintenance. May have pilot light.
4	Post-treatment	Liquid and solid separation.
	Digestate storage	Storage of the liquid and solid by-product from the AD process (i.e. digestate).

Much of the information presented below was first presented in the NPL report entitled 'An assessment of potential methodologies for assessing methane emissions from anaerobic digestion plants'[12].

2.1 STAGE 1

Stage 1 of the AD process includes the following FEs: feedstock storage and pre-treatment area.

Methane emissions from the feedstock storage are expected to be low, this has been observed previously in the literature[1]. If the feedstock storage in open to atmosphere any emissions are likely to be diffuse, if enclosed ventilation outlets may produce point sources[6]. Methods to estimate the total emission on-site may include flux boxes: containers, open at the base, with a sampling line connected to gas monitoring equipment, which can be to extrapolate total emissions with a high level of uncertainty[13,14]. Remote sensing techniques could provide total emissions but if the emissions are at low rates and diffuse, they may be close to the detection limit of remote sensing techniques[12].

The pre-treatment includes mixing of materials and different feedstock prior to digestion and is typically carried out in enclosures with specific vents. Emissions from the vents could be monitored by direct measurement of the vent depending on the accessibility. Remote methods should be able to capture and measure these emissions. Certain other methods have only a limited capability for monitoring elevated sources such as open-path, fence-line monitoring, or inverse dispersion modelling methods (IDMMs). These techniques may not be ideal for monitoring elevated plumes[12].

2.2 STAGE 2

Stage 2 includes the following FEs: digesters and gas storage.

The digester and associated gas production plant can have emissions from agitators, seals, pressure release valves (PRVs), agitator supports and access ports[6]. PRV emission monitoring requirements are the same as for vents in pre-treatment. Other emission sources will be fugitive and should be detected and measured using on-site techniques. Quantification may be difficult depending on the accessibility of the leak(s). Quantification of the emissions from this FE would be best carried out using remote sensing techniques[12].

Gas is stored on-site in tanks. Emissions can be from fugitive sources, such as leaks from valves, safety valves, flanges, and seals. Where access is possible, on-site measurement techniques could be used for FE quantification, although remote sensing techniques may be more appropriate.

2.3 STAGE 3

Stage 3 refers to all the potential end uses of the biogas and primarily includes the following FEs: GtG, CHPs, flares and heaters.

Gas supplied to the national grid must be upgraded first to meet a quality specification and so impurities must be removed. The main requirement is a reduction in the amount of CO_2, yielding a minimum biomethane purity of 95%[15]. Methane may still be present in the vented CO_2 and fugitive emissions could result from leaks in valves, pumps and other plant components[6]. Compressors may be used to increase the gas pressure to that of the grid input, and these can produce emissions. Compressors are also regularly vented for maintenance or when taken offline. Vents are often elevated so quantification can be difficult. Remote sensing methods would be most suitable[12].

Produced biogas is often used in engines and turbines to produce electricity and boilers to generate heat. Sites often use the biogas to generate the power on site, even if most of the gas is upgraded and injected to the grid. Methane present in the engine exhaust is known as slippage. Exhausts are often elevated above ground so direct quantification can be difficult. Emission factors are often used to estimate emissions from these sources, but they may be measured by remote sensing techniques.

Flares are often present and are used to burn gas when it cannot be used or sold to the grid, for instance during maintenance or during emergencies. Emissions are often calculated using flow rate and flare destruction efficiency. Emissions are likely to be elevated above ground and remote sensing systems should be able to measure these emissions.

2.4 STAGE 4

Stage 4 of the AD process includes the following FEs: post-treatment (pasteurisation) and digestate storage.

After gas production is finished, the processed digestate may be separated into liquid and solid phases. Post treatment may include disinfection for pathogen reduction, and removal of potential toxic compounds such as heavy metals. If vents are at a low level (close to ground) then open-path and fence-line monitoring could also be used[12]. Remote sensing monitoring system would be most appropriate to measure emissions.

Liquid digestate may be stored in lagoons consisting of large bags with vents. Access to the vents may be difficult making direct measurement problematic. Remote sensing monitoring would be most appropriate. If vents are at low level (close to ground) then open-path and fence-line monitoring could also be used[12]. Alternatively, open liquid digestate storage will have diffuse emissions, the appropriate monitoring techniques would be similar to those suggested for feedstock storage.

The solid digestate storage can either be open or enclosed. Although emissions are expected to be at low level, the appropriate monitoring techniques would be similar to those suggested for liquid digestate.

3 MEASUREMENT TECHNIQUES

Within the MEAD project a selection of both short-term and long-term techniques of methane monitoring were utilised. Section 3.1 gives an overview of the different monitoring techniques considered as part of this work. The information presented in Section 3.1 was first presented in the NPL report entitled 'An assessment of potential methodologies for assessing methane emissions from anaerobic digestion plants'[12]. An overview of the techniques eventually utilised within the MEAD project are given in Sections 3.2 to 3.5.

3.1 OVERVIEW OF MEASUREMENT TECHNIQUES

Table 3.1 outlines a range of short-term techniques used for methane monitoring; these techniques are typically labour intensive. Table 3.1 aims to highlight the advantages and disadvantages of the various technique described.

Table 3.1. Short-term campaign methane measurement techniques/methods.

Measurement technique	Additional data and processing requirements	Advantages	Disadvantages
Differential absorption Lidar (DIAL)[16,17]	Wind speed & direction. Position and pointing.	Comprehensive measurement of emissions. Standardised method. Elevated sources can be measured.	Relatively high cost and limited operators.
Tracer Correlation (TC)[18]	Tracer release rate. Vehicle position. Similar dispersion for both emission and tracer plumes	Doesn't require wind measurements. Standardised method.	Does not handle multiple or unknown sources well. Quantification of emissions from specific FEs is a challenge
Solar Occultation Flux[19]	Wind speed & direction. Vehicle position and pointing (solar tracking). Plume elevation.	Passive technique for campaign measurements.	Not generally used for methane measurements. Relies on good weather (sunshine).
Walkover surveys, detection only[20]	Measures methane concentration in the vicinity of a leak using Sniffing or Optical Gas Imaging (OGI). Leak location	Quick for sites with limited and accessible components. Standardised method for leak detection.	Difficult for large sites. Not all emissions will be accessible.
Walkover surveys, quantification[21]	Methane concentration and flowrates using Bacharach Hi Flow Sampler® (BHFS).	Gives a quantified estimate of the mass emission rates for observed leaks.	Difficult for large sites. Not all emissions will be accessible.
Mobile (land) measurement (non-tracer)[22]	Wind speed & direction. Vehicle position. Modelling for quantification.	Good at mapping concentrations and may be	May not measure elevated emissions.

		able to identify leak locations.	
Open-path / fence-line[23–25]	Wind speed, wind direction, turbulence characteristics. Plume and reverse modelling.	Low operating costs.	Elevated sources difficult to measure.
Mobile (drone) measurement[26,27]	Wind speed & direction. Positioning. Mitigation or interpretation of the impact of drone turbulence on plumes.	Many systems in development and can deploy different measurement technologies.	Yet to be a validated technique.
Mobile (aircraft) Lidar[28]	Wind speed & direction. Position and pointing.	Has proved quick and accurate.	High cost and limited availability.
Satellite[27]*	Ground wind speed and direction, meteorological data and albedo. Satellite positioning, topographic data and pixel analysis.	Can cover large areas.	Limited by weather and, currently, sensitivity.

* Development in these areas is increasing and it is recommended that the latest developments are investigated, particularly the use of unmanned aerial vehicles (UAVs). UAVs have been recently used to successfully quantify methane emissions from different sources, but their use is not yet fully validated. See Shaw et al. (2021) for a comprehensive review of UAV use for methane flux quantification.

As part of the MEAD project 3 short-term methods were used:

- DIAL
- Walkover surveys
- TC

Table 3.2 outlines the techniques that can be deployed for long-term continuous deployment, without regular intervention.

Table 3.2. Continuous methane measurement techniques/methods.

Measurement technique	Data and processing requirements	Advantages	Disadvantages
Open-path / fence-line[23,24]	Wind speed, wind direction, turbulence characteristics. Plume and reverse modelling.	Can cover large lengths of fence line. Good for large sites. Low operating costs.	Elevated sources difficult to measure. Expensive installation costs.

Fixed OGI	Wind speed & direction or image processing. Pointing for plume tracking.	Low operating costs. Good identification of source locations.	Expensive installation costs, especially for large sites. Currently no scientific paper/reports available.
Imaging Lidar[30]	Wind speed & direction.	Can be autonomous to identify leaks.	Quantification is in early stages of validation.
Point concentration / distributed sampling[20]**	Wind speed & direction. Plume and reverse modelling.	Low operating costs.	Elevated sources can be difficult to measure if the source height is unknown and inlets positioned poorly. Still undergoing validation.
Flux towers[31]	Eddy covariance.	Can cover large areas.	Can only measure when emission is upwind.

** NPL's Fugitive Emissions Detection system (FEDS) is an example of this measurement technique.

During the MEAD campaign NPL's FEDS facility was utilised at one of the AD sites measured.

3.2 OVERVIEW OF DIAL TECHNIQUE

Differential absorption lidar (DIAL) is a remote sensing laser-based technique which records spatially resolved concentration measurements of a target species along the path of an eye-safe laser beam transmitted into the atmosphere[16]. Range-resolved remote DIAL measurements enable total site emissions and area-specific (i.e., FEs) emissions to be measured, without disrupting operational activities. NPL's DIAL facility (Figure 3.1) is a world leading self-contained mobile platform for monitoring of emissions remotely. Over the past 35 years NPL have developed a mobile DIAL capability measuring in the infrared part of the electromagnetic spectrum, as well as the ultraviolet. The ability to utilise the infrared part of the spectrum allows for the measurement of hydrocarbon species (e.g., CH_4, ethane, and volatile organic compounds (VOCs)). During this period NPL have used this technology to monitor emissions from a wide variety of industries including oil and gas, LNG terminals, and chemical and waste management[17,32,33]. Confidence in this technology is underpinned by the fact that the system has undergone field validation and measurements are traceable to primary gas standards[34]. The European Union, as part of its Industrial Emissions Directive 2010/75/EU, has published a Best Available Techniques (BAT) reference document (BREF) for the refining of mineral oil and gas that includes DIAL[35]. In response to this, the European Committee for Standardisation (CEN) produced a standard (EN 17628) for the use of techniques listed in the BREF, including DIAL[35,36]. DIAL is considered a 'gold standard' for quantifying mass emissions rates and is capable of measuring emissions at a FE-level of granularity. Multiple FE-specific emissions can be combined to give whole site emissions with low uncertainty. In previous NPL validation studies, DIAL measurements of total emission rate have shown agreement with known emission sources of between 5% and 20%[37,38].

Figure 3.1. Photograph of NPL's DIAL facility.

3.3 OVERVIEW OF NPL WALKOVER SURVEYS

NPL walkover surveys are carried out in two stages. The first stage involves an initial screening of all assessable components using a sniffer, GMI Gasurveyor 700 (henceforth referred to as GMI) in this case, to identify any leaking components. This is carried out based on BS EN 15446-2008 and US EPA Method 21 and any leaking component with a measurement >10,000 ppm is then tagged for subsequent quantification.

The second stage uses a Bacharach Hi Flow Sampler® (BHFS; Bacharach, Inc., New Kensington, PA) to determine the mass emission from each labelled component. The BHFS was developed specifically for natural gas leak rate measurement. Using the BHFS, leaking components are loosely enclosed using dedicated adaptors, such that a measured flow of ambient air is drawn past the leak and the resulting concentration of methane is measured. To confirm the leak is captured entirely, two measurements are made: one at a high flow rate and another at a lower flow rate. Using the measured concentration and flow rate, a mass emission in kilograms per year (kg/y) is then estimated. Using the lowest reliable flow rate of the BHFS of 150 L/min, and a detection limit of 0.05% methane gas, a limit of detection of ~24 kg/y is obtained for the BHFS emission rate measurements.

Once the leaks are quantified, the tags are left to aid site maintenance of these leaks. Walkover surveys are limited in that they capture only those leaks measured on the day of the survey and thus the annual

emission estimate reported assumes that these measured emission rates are constant throughout the year. Furthermore, it will not include emissions from inaccessible components.

3.4 OVERVIEW OF FEDS TECHNIQUE

The FEDS is a mobile monitoring system developed by NPL which is capable of both locating and quantifying fugitive methane emission sources over long-term periods. The FEDS has been successfully deployed at sites around the UK to detect and measure methane leaks from the natural gas supply chain. Prototype versions have also been deployed at a UK landfill site.

The FEDS uses a high-precision gas analyser, Los Gatos Research, Inc. Ultraportable Methane-Ethane Analyzer (LGR), housed in an air-conditioned mobile trailer. The analyser provides fast and continuous measurements of the ambient atmospheric methane concentration. Methane measurements are calibrated using traceable gas standards. The gas analyser is coupled to a multiple inlet unit which allows for sampling from various inlets strategically distributed around the target site. Each inlet is sampled in sequence providing a concentration measurement with parts-per-billion precision. Using this approach, discrete concentration data can be acquired from multiple sampling points across a wide area every hour. A telescopic meteorological mast is incorporated into the mobile trailer to provide data on wind speed, wind direction and temperature from two heights.

Methane and meteorological data acquisition can be controlled and monitored remotely. Once processed, hourly-averaged data is used to drive a reverse dispersion model to calculate emission estimates. Currently, a Gaussian reverse dispersion model, Airviro (version 4), is used for this. Airviro can be used to locate the source(s) of fugitive emissions and, once potential sources are identified, can calculate the emission rates required to generate the concentrations measured at each inlet. This provides reliable long-term monitoring of site emissions even if the distribution of sources changes over the duration of the measurement period. Statistical analyses can be used alongside emission rate quantification to identify potential trends and seasonal variations.

3.5 OVERVIEW OF TRACER CORRELATION TECHNIQUE

The TC technique works by combining a controlled release of a tracer gas at the same location as the target gas emission, with measurements of concentrations of both gases downwind of the site[18]. The general principle of TC assumes that a tracer gas released at the same location as the source of the target gas will be subjected to the same atmospheric dispersion characteristics as the target gas. If these assumptions are satisfied and the fluxes of the gases remain constant (tracer release rate and target emission rate), the target gas emission rate can be calculated from the integrated cross-plume enhancement concentrations of both gases and the release rate of the tracer gas using E3.1[39]:

$$E_{target} = Q_{tracer} \times \frac{\int_{Plume\ end\ 2}^{Plume\ end\ 1} C_{target}\, dx}{\int_{Plume\ end\ 2}^{Plume\ end\ 1} C_{tracer}\, dx} \times \frac{MW_{target}}{MW_{tracer}} \qquad \text{(E3.1)}$$

Where Q_{tracer} is the release rate of the tracer (kg/h), C_{target} and C_{tracer} are the cross-plume concentrations above background of the target and tracer gases (ppmv), MW are the molecular weights of the gases, and plume ends are the beginning and end of the plumes. The start of the emission plumes can be identified when the target gas concentration starts to increase from the averaged background level. The plume closure can be determined when the target gas concentration goes back to background level.

For the measurement of the gases downwind of the site, the LGR analyser from the FEDS was used, and set up in the back compartment of a suitable vehicle. The LGR, along with a monitor for real-time manual inspection of measurements and a separate laptop for running a GPS system, were operated using a lead-acid battery and a power inverter. The setup is illustrated in Fig. 3.2:

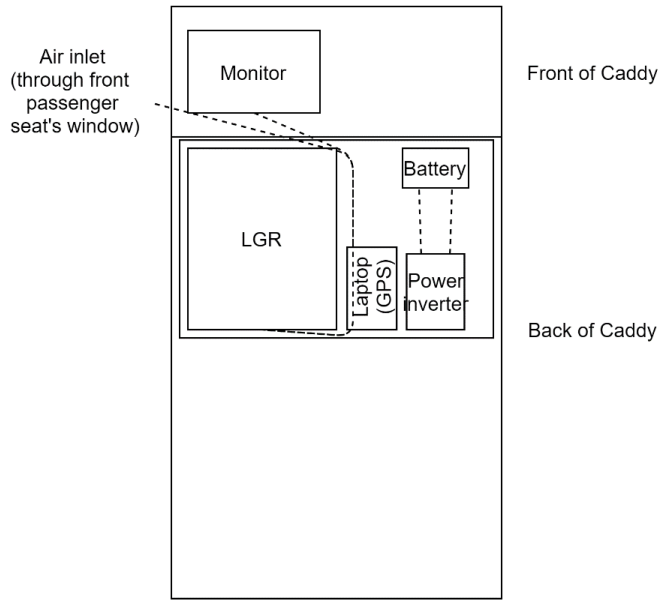

Figure 3.2. Setup of the measurement system inside a VW Caddy van.

To precisely control the flow rate of the tracer gas being released, a controlled release facility (CRF) was deployed. The CRF is typically calibrated for the specific tracer gas before each campaign, in this case ethane. The calibration process was done by measuring the ethane flow at each of the mass flow controllers contained in the CRF, using a traceable gas standard and a flow calibration device at NPL. From this, the calibration curve and the set points correlating to the actual ethane flows were obtained. After the measurement campaign was done, all the data from the CRF (flow rates and set points) during the campaign were processed based on the calibration curve to acquire the calibrated flow rates and mass emission rates of the tracer gas, as well as the standard uncertainties used in the calculation of the final uncertainties. A mass balance to weigh the tracer gas cylinders before and after each release was also used, this data was used to calculate mass release rates of the tracer gas as a comparison with the values obtained with the CRF. No discrepancies were observed between the two methods.

At the beginning of the measurement days, after calibrating the analyser and setting up the tracer release, a drive around the site is made to investigate the baseline conditions of both gases in the vicinity. After that, based on the wind direction, a drive along available paths downwind of the facility

is made several times at as low speed as possible to account for the response time of the analyser. A speed of between 5 to 10 mph is generally used. Measurement paths are always completed (emission plumes properly closed) as per criteria described above before new ones are started, so that baseline conditions are clearly defined[40]. At facilities where multiple sources are present, the assumption that a single tracer gas release point is subjected to the same atmospheric dispersion characteristics as all the sources of the target gas is generally invalid. Transects (paths/roads along which the tracer vehicle travels during a measurement) made close to the facility boundaries will therefore have a large systematic uncertainty. In these cases, transects as far away as possible from the facility should be made, albeit the overall uncertainty will increase due to the decrease of both the tracer and target gas concentrations measured at longer distances from the sources.

4 SITE SELECTION

As part of the measurement phase of the MEAD project, it was planned that six to nine different sites would be measured over six (non-consecutive) weeks. Following discussions with the Department for Energy Security & Net Zero (DESNZ) and other stakeholders, NPL decided to focus on measuring at sites with gas upgrading and BtG, together known as GtG capabilities. There were several reasons for this decision: firstly, the GGSS is focussed on biomethane production[3] and it is thought the majority of new AD facilities will have GtG capabilities. GtG sites also have additional FEs to be measured (biogas gas upgrading units and BtG) which non-GtG site do not have. Moreover, most GtG sites also have CHPs which represent the other primary mode of biogas utilisation commonly used at non-GtG sites. Therefore, GtG sites provided a greater range of FEs to assess the emissions from with DIAL. There are approximately 700 AD sites in the UK including wastewater, therefore trying to get a fully representative sample using less than 10 sites was not feasible. However, the GtG subset has approximately 100 sites, making the selection of the sites for this project more representative.

Within the AD industry, sites can be categorised by feedstock type: agricultural, industrial, commercial/municipal or mixed as shown in Figure 4.1. To try understanding the impact (if any) the different feedstock had on site operations, a range of feedstocks were targeted for measurement. It was also noted that the majority of facilities had a medium or small capacity as shown in Figure 4.2[41]. Therefore, it was decided that most of the AD plants selected should have a combined output of less than 5 MWe as representative of the population. As well as trying to understand the emissions from a range of different sites (feedstock type, size, etc.), it was decided to have a sub-group of sites with similar properties, so that direct comparison of the emissions could be made between these different sites.

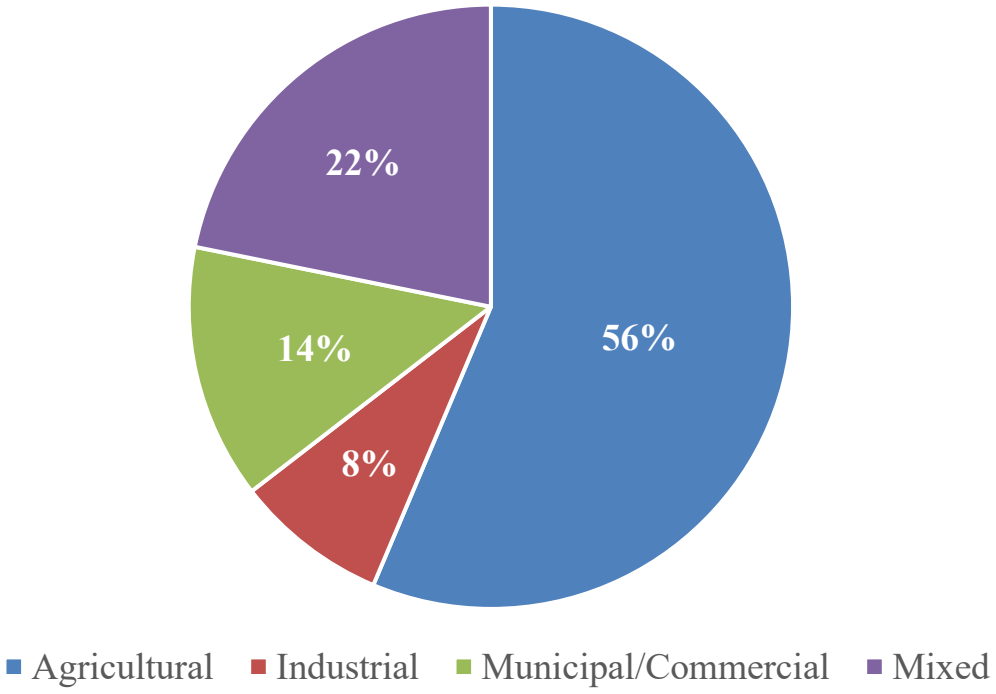

Figure 4.1. A pie chart showing the proportion of GtG sites which utilise the different feedstock types. Derived using data from the ADBA database[41].

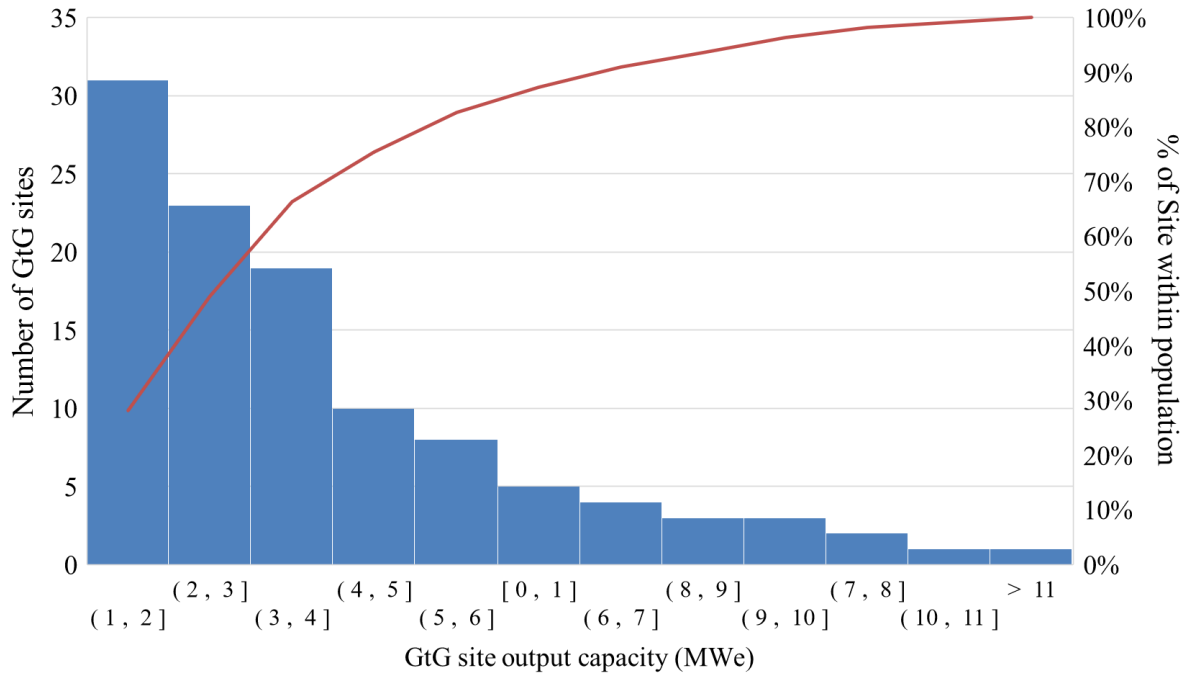

Figure 4.2. A plot highlighting the output capacities of operational GtG AD sites (excl. wastewater sites). The red line highlights the cumulative percentage of sites which are included within population which have at or below the capacity shown on the x-axis. Derived using data from the ADBA database[41].

With this in mind, a set of selection criteria was developed to rank the sites. Some of the criteria were seen as critical and were thus given double the weighting in the ranking. For example, the DIAL facility was identified as the primary method for methane emission quantification; it was therefore critical that the facilities had sufficient accessibility (and space) to accommodate the 14 m long DIAL trailer. The selection criteria used are listed below:

- Accessible for the DIAL trailer.
- Suitable parking locations for DIAL with potential line-of-sight (LOS).
- GtG capabilities.
- CHP utilisation.
- Site location relative to NPL (reduced travel days would maximise measurement days).
- Were other potential sites available within the region (again minimising travel).
- Site size (could the site be measured by DIAL within 3 days).
- Feedstock type.

Following this ranking, a short-list of approximately 30 sites was compiled and the operators/managers were invited to participate in the project; this activity was assisted by Anaerobic Digestion and Bioresources Association (ADBA). Approximately 10 of the operators replied to the invitation; some operators declined to participate or upon further discussion were found to be not suitable. However, additional sites were identified by industry contacts and site operators. In total, 7 (suitable) sites were identified and subsequently agreed to participate in the project. The sites agreed to

participate in MEAD with the condition that the results would be anonymised. Table 4.1 gives some background information about these sites. As mentioned in Section 2, AD facilities are required to obtain an EP, however, those exempt or designated as 'non-waste' facilities are exempt from requiring an EP[8,15,42]. NPL wanted to measure at a mix of permitted and unpermitted sites to understand if the resultant emissions observed were significantly different.

As can be seen from Table 4.1, all sites measured had GtG capabilities but utilise a range of different feedstock types. All the sites are accredited with the government's renewable heat incentive (RHI) scheme and a mix of permitted and unpermitted sites were selected as shown in Table 4.1. It should be noted that, due to the sample size, the fact that all sites are accredited by the RHI cannot be used to draw conclusions on the RHI scheme itself.

Table 4.1. Overview of the selected GtG sites accredited with the government's RHI scheme [41].

Site	Year	Feedstock Type	Feedstock	EP	Feedstock (t/y)	Site capacity (MWe)	GtG Technology	CHP
A	2022	Agricultural	manure	Y	40,000	4	Membrane	Y
B	2015	Agricultural	maize, rye and grass	Y	30,000	2	Membrane	N
C	2014	Agricultural	maize, rye, grass and sugar beet	N	30,000	3	Membrane	Y
D	2016	Agricultural	maize, rye and manure	Y	30,000	2	Membrane	Y
E	2016	Agricultural	maize, rye	N	22,000	2	Membrane	Y
F	2017	Commercial	food waste	Y	48,500	2	Water-wash	Y
G	2016	Mixed	food waste, crops and manure	Y	40,000	2	Membrane	Y

Due to the limited number of sites included in the project scope, selecting a set of sites representative of the UK's AD industry as a whole was not feasible. However, the decision to concentrate on sites with GtG capabilities was a pragmatic solution which made sure that the greatest range of FEs were assessed at all the participating sites. Furthermore, within the set of selected sites, a suitable subset of sites (B to E) was identified. These sites all utilised similar feedstock, capacities and GtG technology, the sites are therefore suitable for intercomparison.

Although generally the site selection process was successful, there are ways in which the process could have been improved. For example, it would have been preferable to have measured at multiple municipal/commercial and mixed feedstock sites or have had a greater range of site capacities. However, due to the low response rate of the sites shortlisted, options were very limited as fewer than 10 sites agreed to participate. If this exercise was repeated in the future, more sites would have been shortlisted (50 to 100 sites), with the hope of getting a greater pool of sites to select from.

5 DIAL RESULTS

5.1 OVERVIEW OF DIAL RESULTS

Within the MEAD project, NPL's DIAL facility was used to quantify the methane emissions at 7 AD facilities. The measurements and analysis were carried out in accordance with the standard method EN 17628:2022[36]. A summary of these sites and the results of their DIAL surveys are reported in sections 5.1.1 to 5.1.7. In the following sections the values reported are the average methane emission rate and associated standard uncertainty. Where possible the methane emissions have been attributed to the relevant FEs. Within Section 5.1, the percentage capacities reported are given in reference to the site BtG capacities given in the ADBA database[41].

5.1.1 Site A

Site A utilises manure (predominantly sourced from a local farm) as a feedstock, the site has the capacity to use approximately 55,000 t/y. Site A has a 6000 m^3 digester with a separate combi-bag for gas storage, a 500 kW CHP and GtG capabilities. It can produce up to 600 m^3/h of upgraded biomethane to be injected into the national grid. The biogas is upgraded using membrane technology which removes the CO_2; the separated CO_2 is subsequently vented. At the time of the DIAL campaign, Site A was only operating at approximately 45% of the BtG capacity[41]. The site has a 500 kW CHP that can be used to generate electricity and heat for on-site consumption for less than 500 hours per year.

It should also be noted that on the first and second day of the campaign the site was undergoing emergency maintenance work to clear waste liquid digestate from the biogas pipeline. The emergency maintenance was completed by 10:00 on the second day.

During the remainder of the campaign the site was measured under 4 different operational modes.

1. GtG on (operational) and CHP off (not in operation).
2. GtG intermittent (changed operational state during measurements) and CHP off.
3. GtG and CHP on.
4. GtG on and CHP intermittent.

The wind conditions were stable during the measurement campaign resulting in only a couple of different measurement locations being available for the DIAL. The campaign was considered successful, and it was possible to measure the whole site emissions. There has been attempts to attribute some of these emissions to the different FEs. However, due to a combination of the predominant wind direction and the site layout, it was impossible to separate the emissions from the pre-treatment area, digester, CHP and GtG. Hence, these FEs are reported as a combined measurement termed 'Area A'.

A summary of DIAL measurements is shown in Table 5.1. Whole site emissions of 22.2 ± 1.5 kg/h were measured whilst the site was in operational mode 2. Most of the emissions from the site can be

attributed to Area A. In addition, a methane emission rate of 6.2 ± 2.1 kg/h was attributed to gas storage. A 3D visualisation of the methane emissions observed downwind from Area A is shown in Figure 5.1.

Table 5.1. Summary of DIAL emissions survey from Site A.

Measured Area	Emission Rate	Standard Uncertainty
	kg/h	kg/h
Whole site. Operational mode 2.	22.2	1.5
Area A. Operational mode 1.	13.5	0.8
Area A. Operational mode 3.	15.3	0.7
Gas Storage/Lagoon (covered)	6.2	2.1
Flare on.	0.9	0.3
Flare off.	0.0	0.0

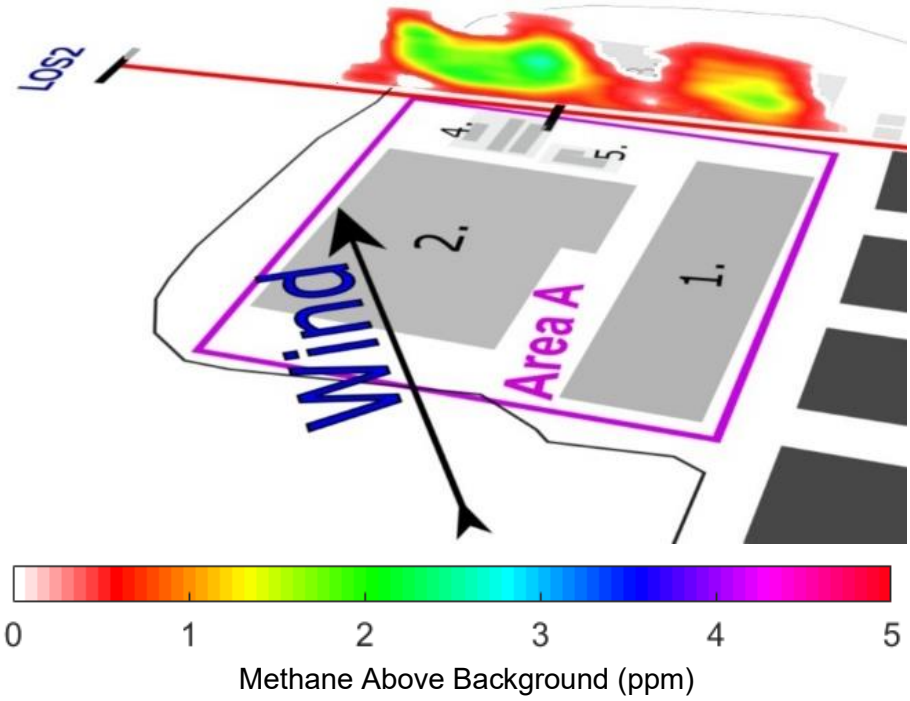

Figure 5.1. 3D visualisation of methane emissions from Site A, Area A. The numbers shown on the base map are associated to specific FEs of the plant but for anonymity these are not detailed.

5.1.2 Site B

Site B is relatively flat with a waste recycling and transfer facility to the north and composting to the northeast. The site uses 33,000 t/y of maize, rye and grass supplied by local farmers as feedstock. It has a 3000 m^3 mesophilic working volume digester, a 4000 m^3 post-digester and a 5000 m^3 storage tank. As part of the upgrade process CO_2 is captured and liquified before being sold to a gas company

and can be used in the food industry. The site operators confirmed that Site B can produce approximately 500 m^3/h of methane and produces 20,000 t/y of digestate which is used as a fertilizer. A CHP unit was in place but had not been commissioned and was not operational at the time of the measurements. During the measurement campaign that biomethane was being injected to the grid at nearly 100% of the BtG capacity.

The wind speed and wind direction were generally constant during each set of measurements. Due to the limited variability in wind directions and the site layout it was not possible to measure the emissions from the upgrade (incl. CO_2 plant) and BtG FEs.

The results are summarised in Table 5.2. The largest emissions observed were from the Southern storage area where digestate had recently been deposited and the Digester and storage tank area which included the separator and solid digestate output. Note that the emission rate from the Digester is not included in the total as it is already included in the Digester, Digestate Output & Separator measurement.

Table 5.2. Summary of DIAL emissions survey from Site B.

Measured Area	Emission Rate	Standard Uncertainty
	kg/h	kg/h
Liquid digestate storage tank	0.2	0.4
Flare	0.0	0.2
Southern storage area	8.5	1.2
Digester	2.7	2.0
Digester, Digestate Output & Separator	6.0	0.8
Total	14.5	1.5

5.1.3 Site C

Site C is located in a rural area and is surrounded by farmland. The site uses approximately 45,000 t/y whole crop maize and rye supplied by local farmers as feedstock and the gas produced is upgraded before being injecting into the National Grid. As the feedstock used is grown specifically for the AD usage, the site does not require an environmental permit to operate. As part of the upgrade process CO_2 is separated and vented to atmosphere. The site can produce up to 600 m^3/h of upgraded biomethane to be injected into the national grid. The solid digestate produced is utilised as an agricultural fertilizer. A 500 kW CHP unit provides power for on-site use and surplus is exported to the electricity grid. At the time of the DIAL campaign, Site C was operating at approximately 80% of the BtG capacity[41]. At some point overnight between the penultimate and final day of the campaign there was a large leak of liquid digestate from the post digester storage tank which impacted operations, however the DIAL data did not show any clear difference when compared to measurements carried out during the rest of the campaign.

The wind speed and wind direction were generally constant during each set of measurements. The limited variability in wind directions did not allow to specifically separate the emissions from all the FEs.

The upgrade CO_2 vent was the largest emission source identified on Site C with a measured emission rate of 11.4 ± 0.6 kg/h as shown in Table 5.3. A cumulative site total emission rate of 19.1 ± 1.5 kg/h was calculated for Site C. It should be noted that the cumulative site total does not include the whole site (excl. feedstock storage) single measurement, but rather is derived from the summation of all the measured areas. Notably, the cumulative site total derived is not significantly different (i.e. it is within the expanded uncertainties using a coverage factor of k=2) from the single measurement of the whole site (excl. feedstock storage) emissions, where an emission rate of 13.1 ± 1.9 k/h was measured.

Table 5.3. Summary of DIAL emissions survey from Site C.

Measured Area	Emission Rate	Standard Uncertainty
	kg/h	kg/h
Feedstock Storage areas	1.0	0.7
CHP Exhaust	1.2	0.3
Upgrade unit vent	11.4	0.6
Digester	2.3	0.2
Post-digester, Gas Storage and Digestate Output	3.0	0.4
Flare	0.3	1.1
Whole site (excl. feedstock storage)	13.1	1.9
Site Total	19.1	1.5

5.1.4 Site D

Site D is surrounded by farmland to the north and east with woodland to the south and west. Site D has a feedstock capacity of approximately 30,000 t/y, at the time of the measurements the site was using animal manure and potatoes supplied by local farmers as a feedstock. As part of the upgrade process CO_2 is separated and vented to atmosphere. The site utilises two parallel digestion tanks capable of processing up to 150 tonnes of feedstock per day. The biogas generated is stored in gas bags in the head of the digester. During the DIAL campaign it is understood that Site D was operating between 50% and 60% of this BtG capacity, generating approximately 200 m^3/h of upgraded biomethane to be injected into the national grid, the upgrade units utilise membrane technology. In addition, the biogas gas produced was also used to power a 250 kW CHP and the digestate produced is used as an agricultural fertiliser.

The wind conditions during the measurement campaign were generally good with stable conditions from a suitable variety of directions and at a constant wind speed allowing most of the site to be measured successfully with an ideal wind direction.

The results are summarised in Table 5.4. The largest emission was from the lagoon at approximately 50% of the site total. A cumulative site total emission rate of 38.7 ± 3.7 kg/h was measured for Site D. This was calculated by summing the combined GtG units, Digesters & Flare measurement with the Lagoon and Clamps 1 & 2 measurements.

Table 5.4. Summary of DIAL emissions survey from Site D.

Measured Area	Emission Rate	Standard Uncertainty
	kg/h	kg/h
GtG units, Digesters & Flare	19.0	1.5
GtG units	9.7	0.7
Lagoon (liquid digestate storage)	19.7	3.4
Clamps 1&2	0.0	0.4
Flare (offline)	0.2	0.6
Digesters	9.2	1.7
Clamps 4&5 + partial rest of site	6.7	0.7
Site Total	38.8	3.7

5.1.5 Site E

Site E is located in a rural area and is largely surrounded by farmland. It has a feedstock capacity of approximately 22,000 t/y and utilises waste potatoes from local farmers and crops such as maize and rye as feedstock. As the feedstock used is grown for specifically for the AD usage, the site does not require an environmental permit to operate. During the DIAL measurement campaign, the site was producing approximately 250 m^3/h of biomethane which was subsequently injected into the grid, approximately 50% of the BtG capacity. The site uses a membrane upgrade unit, in which CO_2 is separated and then vented to atmosphere. The site also utilises a 500 kW CHP which helps to power the site.

The wind direction and speed were stable allowing DIAL measurements to successfully measure all the areas on site. However, due to the layout of the site it was not possible to separate all the FEs. Some of these areas are reported as part of a combined measurement termed ‘Area E’. Area E includes the feed input, hydrolysis tank, digester, gas storage, the CHP and separator bay (digestate output).

The largest methane emissions were observed from Area E. A partial measurement of the lagoon also showed a significant emission rate of 7.2 ± 1.1 kg/h.

Table 5.5 lists the methane emissions measured for specific areas and FEs. The site total methane emission of 10.2 ± 0.9 kg/h, excluding the lagoon, has been calculated by adding the emissions from the West Clamps to the measurement of the whole site excluding West Clamps. With the partial lagoon emission included a cumulative site total emission rate of 17.4 ± 1.4 kg/h was calculated for Site E.

Table 5.5. Summary of DIAL emissions survey from Site E.

Measured Area	Emission Rate	Standard Uncertainty
	kg/h	kg/h
Area E	8.5	0.4
East Clamps & Separator Bay	1.7	0.4
Upgrade Unit	1.1	0.1
Upgrade Unit Stacks	0.3	0.0
CHP Stack	1.9	0.2
West Clamps (partial)	0.1	0.2
Whole Site Excluding West Clamps	10.1	0.9
Partial Lagoon (liquid digestate storage)	7.2	1.1
Site Total excluding Lagoon	10.2	0.9
Site Total including Lagoon	17.4	1.4

5.1.6 Site F

Site F is on a slope running from the northwest to southeast and is to the west of a disused water treatment plant. The site processes household and commercial food waste and handles up to 50,000 t/y of solid and liquid waste. There is a reception building where the food waste is unloaded and sorted. The ventilation extraction from this building goes through a bio-filter consisting of wet wood chips to reduce odorous emissions. Maize or similar solid material is added to balance the digestion process. There are 4 digester tanks and a single post digester tank. Waste digestate is used as a fertilizer on local farmland. Operational data from the site was not forthcoming, however, the ADBA database indicates that the site can produce up to 600 m^3/h of upgraded biomethane to be injected into the national grid. It uses a water wash system to recover the CO_2 which is vented to atmosphere before the biomethane is fed to the grid. There is also a CHP plant for heat and power.

The conditions during the measurement campaign were good for DIAL measurements with some variation in wind directions to enable each area to be measured successfully. However, there were limited available locations for the DIAL trailer which made the separation of the emissions from different FEs challenging. The wind speed was generally constant during each set of measurements.

Large emissions were seen from the area where the CHP, reception building and bio-filter are located as shown in Table 5.6. The CHP was the major emission source, but only a minor proportion of its emission was from the CHP exhaust. Methane emissions were measured from the upgrade unit vent of 7.4 ± 0.3 kg/h. A summary of the continuous emissions is shown in the table below with a site total of 53.7 ± 1.9 kg/h. It should also be noted that a large emission event was seen coming from the digester tank area at one point during the campaign, but it has not been included in the site total emissions since it was non-continuous emission. This may have been the result of maintenance being carried out at the time. A 3D visualisation of the methane emissions observed downwind from the CHP is shown in Figure 5.2.

Table 5.6. Summary of DIAL emissions survey from Site F.

Measured Area	Emission Rate	Standard Uncertainty
	kg/h	kg/h
CO_2 Stripper Columns (upgrade unit)	0.5	0.2
Upgrade unit vent	7.4	0.3
Tanks	0.0	0.2
Reception Building	5.9	0.2
Twin Stacks	1.2	0.5
CHP	24.5	2.2
Bio-Filter	14.3	2.8
Site Total	53.7	1.9

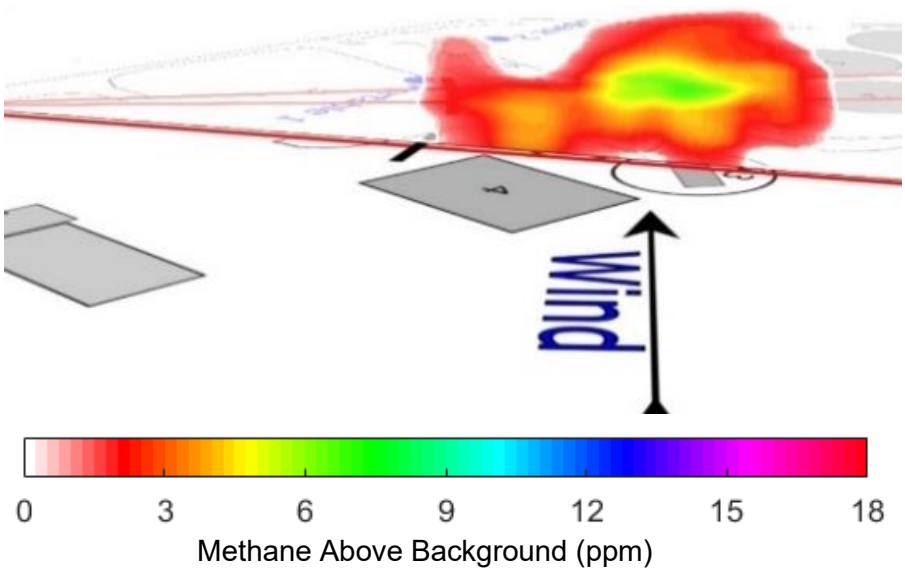

Figure 5.2. 3D visualisation of methane emissions downwind of the reception building and CHP at Site F.

5.1.7 Site G

Site G is relatively flat but does slope gradually upwards in the northern part of the site. The area surrounding the site is flat farmland. The site utilises approximately 40,000 t/y of mixed feedstock comprised of animal slurry, food waste and energy crops. The waste materials make up 70% of the feedstock used. The site has 3 digesters and 2 CHPs (250 kW per CHP). However, most of the gas produced is upgraded, using membrane technology, before being injecting into the National Grid. As part of the upgrade process CO_2 is separated and vented to atmosphere. Typically, Site G produces up to 500 m^3/h of upgraded biomethane. During the DIAL campaign, the site was operating at a reduced capacity of about 70%. It was known that Site G had on-going problems with the digester roof and had recently undertaken an independent FE survey. This survey had highlighted a problem but did no quantification of the emissions observed. New PRVs were fitted to the digester during the DIAL measurement period and approximately a month after the campaign the digester roof was replaced.

The wind direction and speed were stable allowing the successful measurement of all the methane emissions on site, albeit the limited variability in wind directions did not allow to separate the emissions from certain FEs on site.

A summary of DIAL measurements is shown in Table 5.7. The whole site methane emission rate of 95.9 ± 2.9 kg/h were measured on the final day of the campaign, excluding the east area of the lagoon due to the combination of wind conditions and site layout. The largest source of emissions was from the digesters/feeders area where a methane emission rate of 50.4 ± 2.4 kg/h was observed. Most of this emission can be attributed to the digester roof, which had a known significant leak. The northern lagoon and GtG units were not measured separately but are included in the whole site measurement, although this was only a partial measurement of the northern lagoon liquid digestate storage. A 3D visualisation of the methane emissions observed downwind from Area G is shown in Figure 5.3.

Table 5.7. Summary of DIAL emissions survey from Site G.

Measured Area	Emission Rate	Standard Uncertainty
	kg/h	kg/h
Upwind Site	0.0	0.8
Liquid/Solid Digestate & Pasteurisation building	20.7	0.9
Digesters/feeders	50.4	2.4
CHP	6.0	0.5
Upgrade Vents	2.0	0.2
Pasteurisation Vent	0.4	0.2
Whole Site (Partial northern lagoon)	95.9	2.9

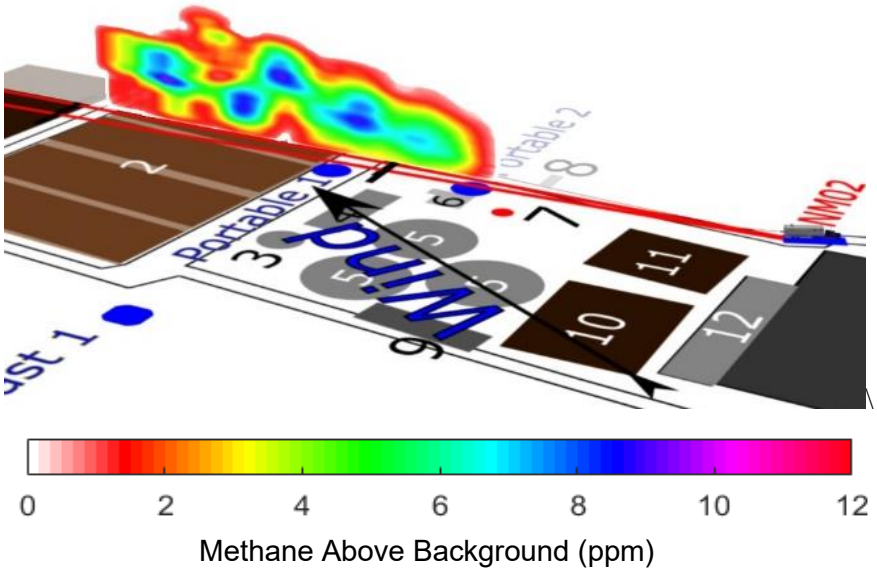

Figure 5.3. 3D visualisation of methane emissions downwind of the Area G at Site G.

5.2 DISCUSSION OF RESULTS

5.2.1 Comparison to Tier 1 Inventory Estimates

The 2006 IPCC guidelines for the National Greenhouse Gas Inventories, Vol. 5: Waste[43] states that Tier 1 methane emission estimations can be calculated from AD facilities on the basis of the feedstock tonnage. The Tier 1 method assumes that, on a dry weight basis, 2 kg of CH_4 will be emitted per tonne of waste treated[43]. The Tier 1 dry weight assumption was applied to estimate emissions for all the sites. An initial analysis of the data was performed to see if there was a correlation between the feedstock tonnage and the site methane emissions, this was compared to the estimated emissions calculated using the Tier 1 method as shown in Figure 5.4. Note that not all feedstocks reported in Table 4.1 were on a dry weight basis, however, the wet weight basis emissions are even lower (0.8 kg per tonne) and so using the dry weight basis should yield an overestimation of the Tier 1 emissions reported in Figure 5.4[43].

The DIAL data shows only a weak positive correlation, this suggests that simple methods such as the Tier 1 method, are not suitable approach for the accurate evaluation of emissions from the AD industry. These results imply that factors such as operating procedures and maintenance (or lack thereof) may heavily influence the magnitude site emissions. Despite a sample size of 7 plants for this study, it is important to notice that all the DIAL results are larger than the Tier 1 method data, suggesting this Tier 1 method may systematically underestimate AD methane emissions.

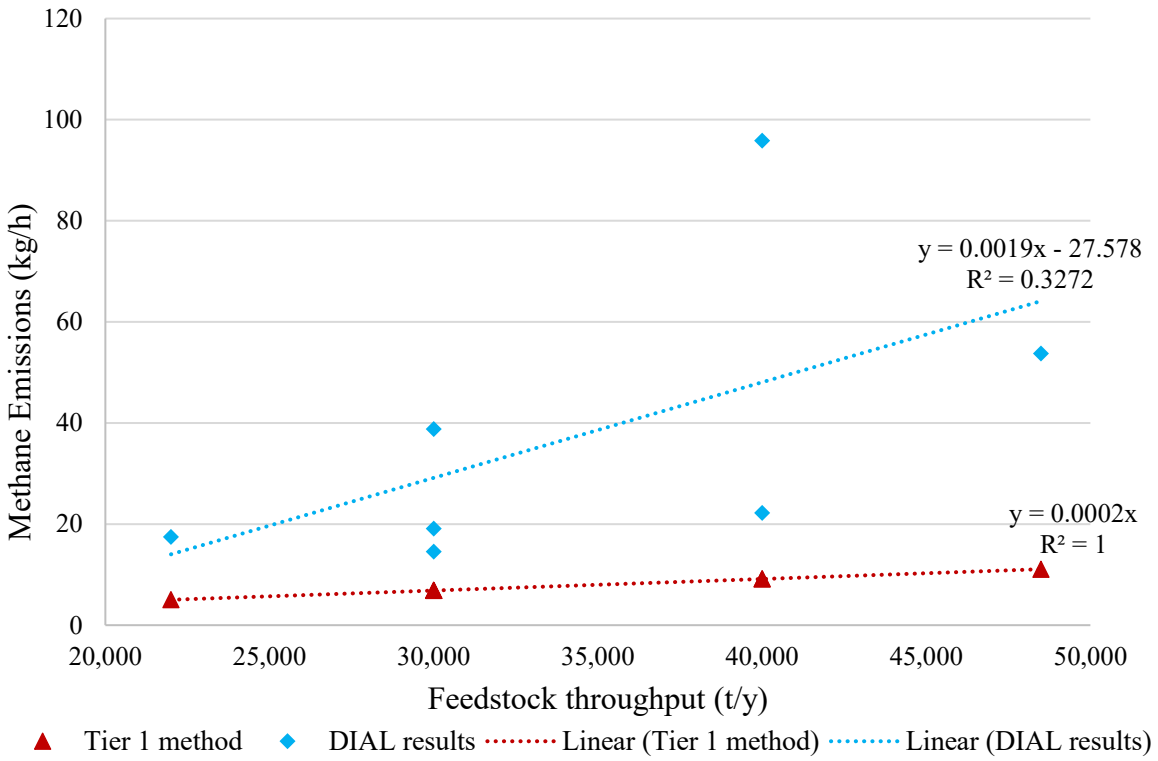

Figure 5.4. Scatter plot showing the correlation between the site feedstock throughput and the methane emissions. The data plotted in grey represents the emissions data collected from the DIAL campaigns within MEAD. The data plotted in blue is derived using the Tier 1 method for estimating emissions.

5.2.2 Total Site Methane Emission Factors

A good metric for the intercomparison of the emissions from Sites A to G is as a percentage methane loss, henceforth referred to as emission factor (EF), of the total site methane production, however, there are several different methods in which this can be done. For example, in a recent study by Fredenslund et al. (2023) the percentage emissions are calculated by using E5.1[5]:

$$methane\ EF\ (\%)\ =\ \frac{E_T}{P_S\ +\ E_T} \times 100\% \qquad \text{(E5.1)}$$

Where E_T is the total methane emissions measured (kg/h) from the four stages (Figure 2.1) and P_S is the site methane production rate (kg/h) during the measurements metered in Stage 2 between the digestors and the gas storage. Although E5.1 is an appropriate approximation, any emissions measured after the point at which the biogas production rate is metered (Stages 3 and 4) should not be added in the denominator as these emissions would be double counted. For this reason, E5.1 was not used for this study. The correct formula would be E5.2:

$$methane\ EF\ (\%)\ =\ \frac{E_T}{P_S\ +\ E_{AD}} \times 100\% \qquad \text{(E5.2)}$$

Where E_{AD} is the combined methane emission rates (kg/h) from all the FEs prior to the biogas metering (typically Stage 1 and digestors). The main issue with this equation is that most of the techniques currently used for remote monitoring are not able to separate emissions from all the FEs. Even with DIAL it was not always possible to separate the emissions from before the digester metering. With regards to the MEAD project there was also the issue that not all the sites were forthcoming with biogas production rates from the measurement period. For these reasons E5.2 was not used in this project.

An alternative mathematically correct method of calculating the methane EF would be to look at the end usage of the biogas/biomethane (E5.3):

$$methane\ EF\ (\%)\ =\ \frac{E_T}{U_T\ +\ E_U} \times 100\% \qquad \text{(E5.3)}$$

Where U_T is the total methane throughput of all the potential uses for the biogas metered at Stage 3 (BtG, CHP, Heat and Flare) and E_U is the combined emission rates (kg/h) from all the FEs prior to each FE metering point where U_T is measured. Using this equation would avoid double counting any emissions. It should be noted that the DIAL data collected does not differentiate whether emissions were observed before or after the metering for a specific FE. However, it is likely these emissions would be small when compared to the whole emission of each of these FEs and it can be assumed that E_U is approximately equivalent to E_T. Hence, E5.4 should minimise the double counting of the overall site methane production:

$$methane\ EF\ (\%) = \frac{E_T}{U_T\ +\ E_T} \times 100\% \qquad \text{(E5.4)}$$

Since E5.4 offers a better approximation than E5.1, it should be used, when possible, for reporting EFs. This equation is also best suited to use for the MEAD dataset as it translates to the data available

from the site operational data. Therefore, E5.4 was selected to calculate the methane EF from the DIAL data, the results from this analysis are shown in Table 5.8. The assumptions made when deriving U_T (kg/h) from the site data (typically in m^3/h) are shown below:

- In most cases, an average U_T was calculated for the measurement period. However, in certain cases where the total site emissions were calculated in one measurement (e.g. Site A), U_T was calculated for the specific period (or day) of the measurement.
- Unless specified otherwise by the site, it was assumed that the composition of biomethane injected to the grid was 95% methane. Biogas was assumed to be 55% methane by composition unless otherwise stated.
- It is observed that sites reported the methane production using a variety of temperature (T) and pressure (P) conditions. One site reported standard temperature and pressure (STP, T = 273.15 K and P = 101,325 Pa), another site reported NTP (T = 293.15 K and P = 101,235 Pa). However, the other sites did not specify the temperature and pressure conditions. This could have been STP, NTP or ambient with the latter being close to NTP given the measurements were made in summer. NTP was therefore used to calculate the methane throughput (kg/h) as this was considered to cover two of the three possible scenarios. At NTP methane has a density of 0.667 kg/m^3, the difference with STP is approximately 7% which is less than the reported uncertainty of each EF.
- The standard uncertainties from the site data were derived from the variability reported by the site during the campaign. Where insufficient data was supplied standard uncertainties of 15% were assumed and propagated.
- Site F did not supply NPL with operational data. In this case, information from the ADBA database was used to derive the total methane throughput and CHP throughput based on Site C (500 kW at approximately full load). For the GtG and CHP throughput data a standard uncertainty of 30% of the GtG and CHP throughputs were assumed and propagated.

It is not known if the emission rate varies linearly with the site biomethane production or if it is independent. Different FEs may behave differently as a function of the biomethane production, with some FEs that may have a constant emission while other a variable emission. Consequently, it is not possible to predict the effect of the biomethane production on the EF value. In the future, it could be valuable to measure the emissions from sites when operating at both full and reduced capacity to observe the effect on the EFs. Measuring individual FEs under different operational statuses could also give critical information on the overall emissions from AD facilities.

A 2022 review of the AD industry by Bakkaloglu et al. employed Monte Carlo simulations utilising literature data to estimate total site methane EFs[1]. In this work EFs of approximately 2% (at the 5th percentile) to approximately 13% (at the 95th percentile) were determined, with a median methane EF of approximately 5%[1]. From Table 5.8 and Figure 5.5 show that the measured methane EFs varied between approximately 4% and 15% for Sites A to F showing a reasonable comparison with those determined in Bakkaloglu et al. (2022). The smallest methane EFs observed from the DIAL surveys was approximately double (~4%) those estimated from the 5th percentile of the Bakkaloglu study (~2%)[1]. Lastly, it should be noted that no obvious difference was observed in the characteristics or magnitude of emissions from the two unpermitted Sites C and E.

Table 5.8. Summary of the total site emissions measured at sites A to G. The methane EF (%) have also been derived using equation E5.4.

Site Total	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site A	22.2	1.5	7.8%	2.6%
Site B*	14.5	1.5	4.5%	0.4%
Site C	19.1	1.5	4.1%	0.6%
Site D	38.8	3.7	14.2%	1.2%
Site E	17.4	1.4	7.8%	0.9%
Site F	53.7	1.9	10.4%	2.4%
Site G	95.9	2.9	22.0%	2.0%

*Emissions from Stage 3 could not be measured from Site B and so the methane emission rate and EF reported should be treated as minimum values.

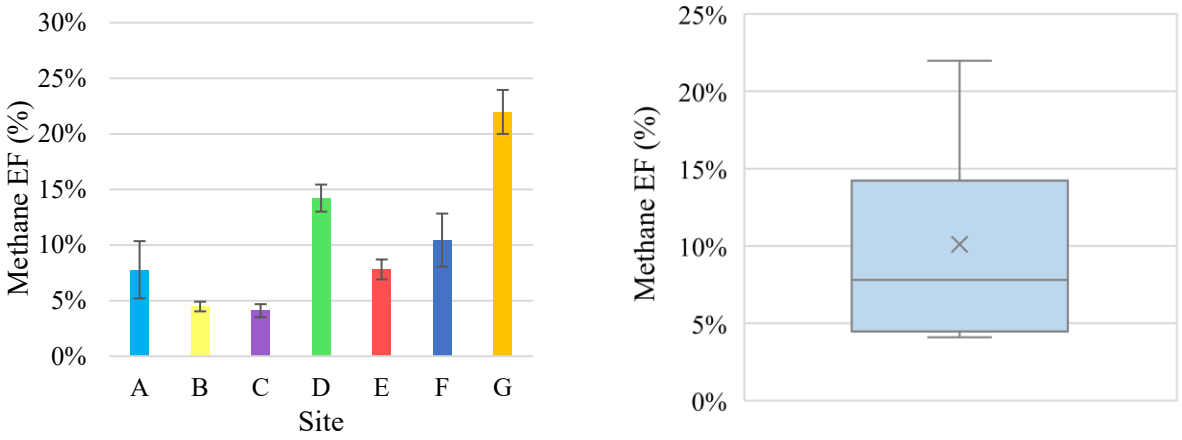

Figure 5.5. (Left) Summary plot highlighting the variation in the methane EF (%) observed from the DIAL measurement surveys as part of the MEAD project. The error bars on the plot are the expanded uncertainties where k = 2. (Right) Box-whisker plot of methane EF (%) from Sites A to G. The '×' denotes the mean value from the sample.

Figure 5.5 shows that the total site methane emission rate from Site G was significantly larger than any of the other sites; this corresponded to a methane EF of 22.0% ± 4.0% (k=2). Prior to the campaign it was known that Site G had recently undertaken an independent leak detection survey and the site understood there were several issues with the PRVs and digester roof. This is potentially due to the fact the site produces higher quantities of upgraded biomethane than the capacity given in the ADBA database. Moreover, the emissions from this site were measured during a period of ongoing maintenance. Despite these issues, it should be noted that Site G was still producing biogas during this time. Site G results could therefore be thought as anomalous as the methane EF was significantly higher than the other sites. However, issues with PRVs and leaking roofs are not uncommon. Moreover, in a recent study of Danish AD facilities by Fredenslund et al. (2023) a similar large emission of 81 ± 12.3 kg/h was measured[5]. Using E5.1, Fredenslund et al. (2023) observed methane EFs between 0.3% and 40.6% across 69 different AD facilities in Denmark[5]. This suggests that while

the emissions from Site G are high, they may not be anomalous, but rather indicative of the potential emissions at facilities with large digester leaks or during periods of ongoing maintenance.

Although it is encouraging that Site G was proactive about resolving these issues, the magnitude of these emissions was cause for concern. It also highlights the value of periodic leak detection surveys, as these may help to flag any large emissions or point sources.

5.2.3 Emissions from Selected FEs

An advantage of the DIAL technique is that it can be used to measure the emissions from specific FEs, as well as whole site emissions. Due to time pressures, compact site footprints and unfavourable wind conditions it was not possible to separate all the FEs at all the sites. However, on multiple occasions it was possible to separate the emissions from selected FEs and the results are reported below. The methane EF for each FE is calculated using the total site throughput as in E5.4 and replacing E_T with the FE emission rate.

Feedstock Storage

The methane emissions from the feedstock storage areas are reported in Table 5.9. From the agricultural sites (C, D and E) the emissions from the feedstock storage area were relatively low, close to the DIAL detection limit, equivalent to methane EFs of 0.0% to 0.2%. Significantly larger emissions of 21.4 ± 2.8 kg/h were observed from feedstock storage area of Site F, the reception building, equivalent to a methane EF of 4.4%. Notably, Site F was the only site which utilised solely commercial/municipal waste. With the MEAD dataset it is not possible to know if this was an isolated issue at Site F or a common problem from site utilising similar feedstocks. It would therefore be important in future studies to assess the emission from the feedstock storage of other facilities that utilise commercial/municipal waste.

Table 5.9. Summary of the feedstock storage emissions from the MEAD project.

Feedstock Storage	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site C	1.0	0.7	0.2%	0.2%
Site D	0.0	0.4	0.0%	0.2%
Site E	0.1	0.2	0.1%	0.1%
Site F	21.4	2.8	4.4%	0.7%

Digester

Table 5.10 summarises the methane emissions from the digesters measured within MEAD. These emissions vary from zero to 50.4 kg/h, which is equivalent to a methane EF from zero to 12.9%. This is the highest site-to-site variability observed compared to the other FEs. Typical emissions from the digesters include leaks from the roof membranes and PRVs, these emissions are typically elevated. Notably, a large methane EF of 12.9% ± 1.4% were measured from the digester area at Site G that had ongoing maintenance problems during the measurement campaign.

Table 5.10. Summary of the digester emissions.

Digester	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site B	2.7	2.0	0.9%	0.6%
Site C	2.3	0.2	0.5%	0.1%
Site D	9.2	1.7	3.8%	0.7%
Site F	0.0	0.2	0.0%	0.0%
Site G*	50.4	2.4	12.9%	1.4%

*Emissions reported from Site G include emissions from the feeders, however, these are expected to be minor.

Upgrade Units

The methane emissions from the gas upgrade units are reported in Table 5.11. The emissions ranges from 1.4 kg/h to 11.4 kg/h and the EFs varied from approximately 0.6% to 4.0%. The main source of these emissions was from the upgrade vent, which vents the CO_2 removed during upgrading. The methane emissions observed are presumably caused by inefficient separation during the gas upgrade process. Other than Site F, all the sites utilised membrane technology for gas upgrading; Site F utilised water washing technology. The results suggest that both technologies can lead to significant emissions from the upgrade process.

Table 5.11. Summary of the upgrade unit emissions.

Upgrade units	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site C	11.4	0.6	2.5%	0.3%
Site D	9.7	0.7	4.0%	0.3%
Site E	1.4	0.1	0.7%	0.1%
Site F	7.9	0.4	1.7%	0.4%
Site G	2.0	0.2	0.6%	0.1%

CHP

In Table 5.12 the methane emissions from the CHP units are reported. These emissions ranges from 1.2 kg/h to 24.5 kg/h which is equivalent to methane EFs from approximately 0.3% to 5.0%. The CHPs from sites C, E and G all had a total power rating of 500 kW, no information regarding the CHP power ratings from Site F were available. Site C and E are measurements of the exhausts only, with the lower parts of the CHP measured with the total site measurements. Whereas for Sites F and G, it was noted that methane was observed primarily from lower elevations and not the exhausts. From this data it can be concluded that the measured slippage from the exhausts was relatively small (Sites C, E). When larger emissions were observed, a significant portion was coming from the main unit rather than the exhausts (Sites F, G).

Table 5.12: Summary of the CHP emissions.

CHP	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site C	1.2	0.3	0.3%	0.1%
Site E	1.9	0.2	0.9%	0.1%
Site F	24.5	2.2	5.0%	1.3%
Site G	6.0	0.5	1.7%	0.2%

Digestate Storage

Table 5.13 summarises the methane emissions from the digestate storage areas. These emissions varied from 8.6 kg/h to 20.7 kg/h whilst the methane EFs range from approximately 2.7% to 7.8%. Typically, the emissions observed from these regions were diffuse. At Site G a GMI sniffer was used to measure the digestate storage and methane concentrations of between 100 ppm and 1000 ppm were recorded.

Table 5.13. Summary of the digestate storage emissions.

Digestate Storage	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site B	8.6	1.3	2.7%	0.4%
Site D	19.7	3.4	7.8%	1.2%
Site E	8.9	1.1	4.1%	0.6%
Site G*	20.7	0.9	5.7%	0.6%

*Emissions reported from Site G include emissions from the pasteurisation building.

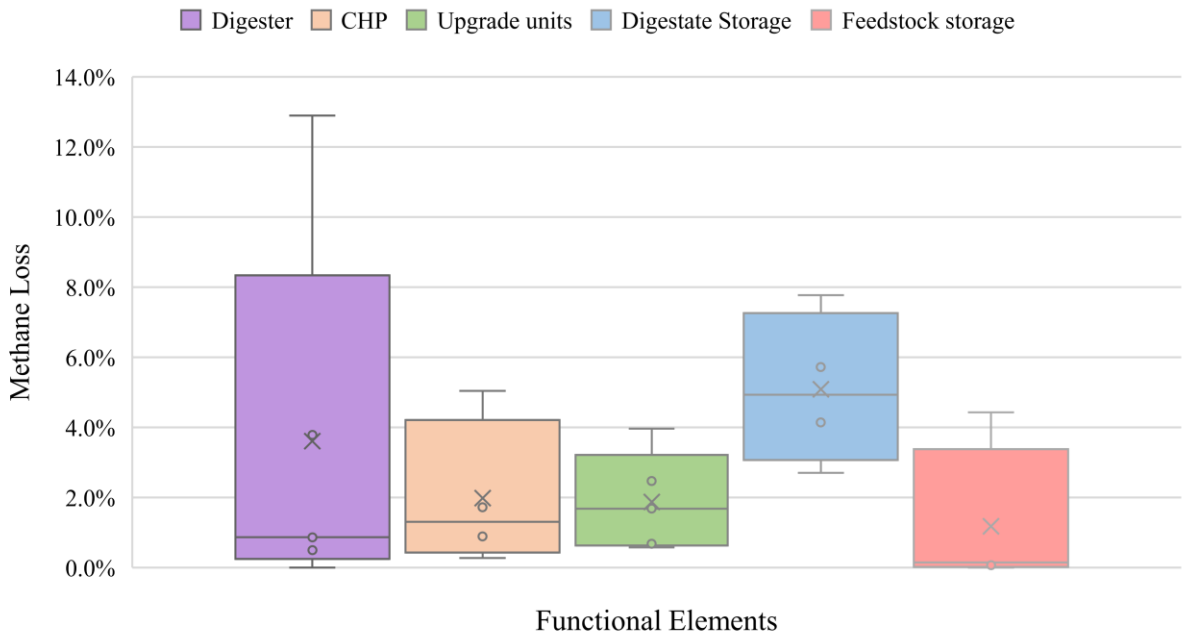

Figure 5.6. Summary box-whisker plots highlighting the range in methane EFs (%) from various FEs.

Figure 5.6 summaries the EFs observed during this project from the five main FEs. While CHP, upgrade and feedstock storage losses varies from approximately zero to 5%, the digester shows a higher variability and the digestate storage has a minimum EF of about 3%. This makes digestate storage, both solid and liquid, an ideal candidate for methane emission abatement particularly for all storage areas that are left uncovered.

Sites A to E could all be described as small to medium GtG sites utilising agricultural feedstock. These sites were therefore grouped together as a subset of data with which direct comparison could be made. Within this subset the emissions observed from the feedstock storage are reduced (Figure 5.7), implying emissions from the feedstock storage is typically low for site utilising agricultural feedstocks. Significant emissions were observed from both solid and liquid digestate storage, which was exacerbated when storage areas were left open and uncovered. CHP emissions were also reduced, although it should be noted that these measurements were only of the exhaust stacks. Site F was the only facility to utilise purely commercial waste and it was observed that a significant fraction of the methane emissions was attributed to feedstock storage. Notably, the storage and pre-treatment process were much more involved (for example the sorting in the reception building, the utilisation of a biofilter), therefore there is greater potential for emissions to occur.

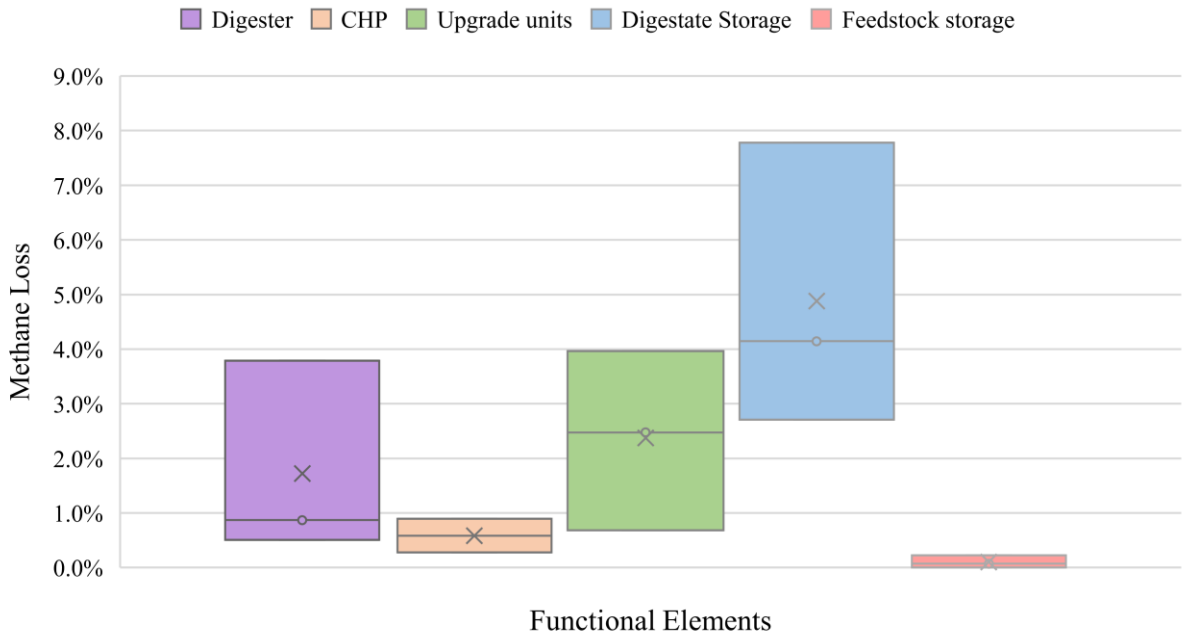

Figure 5.7. Summary box-whisker plots highlighting the range in methane EFs (%) from various FEs for the Sites A to E which utilised agricultural feedstocks.

6 WALKOVER SURVEYS RESULTS

As previously mentioned, methane emissions from different stages of the AD process are not well understood. Summarised in Table 3.1 are the different possible options currently available for characterising these emissions. Walkover surveys were identified as being potentially suitable for measuring emissions from the digestion, gas storage and gas upgrade processes and, in general, for the overall site. This is comparable to the leak detection and repair (LDAR) programme routinely carried out at oil and gas facilities. Walkover surveys combine methane concentration measurements to detect a leak using sniffing with BHFS measurements to quantify the leak and OGI observations for unreachable sources. Walkover surveys were carried out at 7 AD sites.

AD facilities can be classified into 4 main stages as described in Section 2: feedstock storage and feeding area, biogas production and storage area, biogas utilisation, digestate separation and storage area. All accessible components of each AD site were screened for possible methane leaks with the GMI. In total 5790 components were screened of which 82 were above the selected 10,000 ppm threshold for the BHFS quantification. All the other identified leaks below the threshold were not reported as part of the walkover survey. Of the 82 leaks tagged for quantification, 49 were above the limit of detection of the BHFS. The results of the measurements showed that the biogas production and storage area accounted for most emissions quantifiable by walkover surveys.

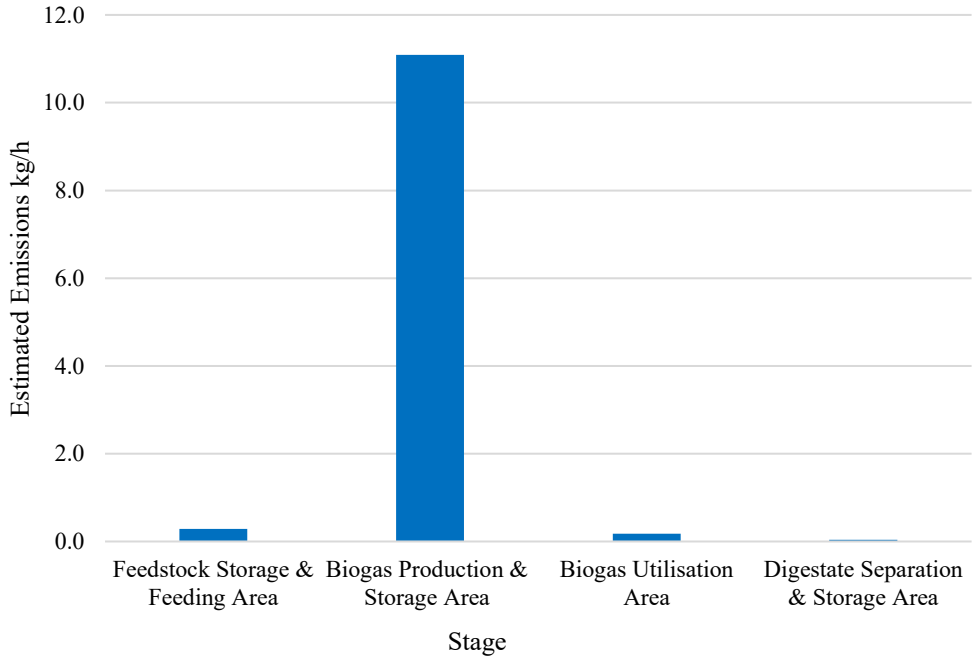

Figure 6.1. Distribution of the estimated methane emissions across the four main stages as measured during the walkover surveys.

Figure 6.1 shows the distribution of emissions measured across the 4 stages; this is also summarised in Table 6.1. A total of 49 leaks were quantified during the walkover surveys across the 7 AD sites, most of which (47) were detected from Stages 2 and 3. This is to be expected since Stages 1 and 4 typically have diffuse emissions from the feedstock and digestate storage areas and only one leak from each

area was detected. Table 6.2 shows the number of leaks observed by the OGI but not detected by the GMI as these leaks were outside of measurement scope i.e. not reachable. A significant number of leaks (32) were detected by OGI and the trend is similar to the walkover results with most of leaks observed by OGI located in Stages 2 and 3. While OGI, and GMI/BHFS have not identify and quantified any large emissions from Stages 1 and 4, DIAL observed significant emissions from digestate Stage 4 which is dominated by diffuse emissions.

Table 6.1. Summary of the leaks measured across the four main stages as measured during the walkover surveys.

Stage	Stage Description	Estimated Emissions (kg/h)	Quantity of leaks
1	Feedstock Storage & Feeding Area	0.29	1
2	Biogas Production & Gas Storage Area	11.09	36
3	Biogas Utilisation Area	0.17	11
4	Digestate Separation & Storage Area	0.04	1
Total		11.59	49

Table 6.2. Summary of number of OGI leaks observed outside of the walkover survey scope of work.

Stage	Stage Description	Quantity of OGI Leaks
1	Feedstock storage & feeding area	1
2	Biogas production & gas storage	2
3	Biogas utilisation	22
4	Digestate separation & storage	0
Total		32

Total methane emissions estimated for all sites was 11.6 kg/h ranging from <0.1 kg/h at Site F to 7.9 kg/h at Site G. The range of emissions measured at all sites is shown in Figure 6.2 and summarised in Table 6.3. Two leaks measured from pressure relief valves found on digester tanks at Site G accounted for approximately 60% of the overall estimated emissions measured across all sites. Stage 3 had 11 leaks while Stage 2 had 36 out of the total 49 leaks measured with BHFS, however most of the quantified emissions was from Stage 2. Specifically, 29 leaks were found from the digesters that accounted for 10.0 kg/h, which is 86% of the total emissions reported.

The emission distribution between the sites shown in Figure 6.2 is not so dissimilar to the distribution observed by DIAL as shown in Figure 5.7, with the most notable differences coming from Sites D and F. However, the distribution observed from the walkover surveys is mainly from Stage 2 and the DIAL emissions measured from Stage 2 at Site D were only about 20% of the total while no emission was detected at Site F.

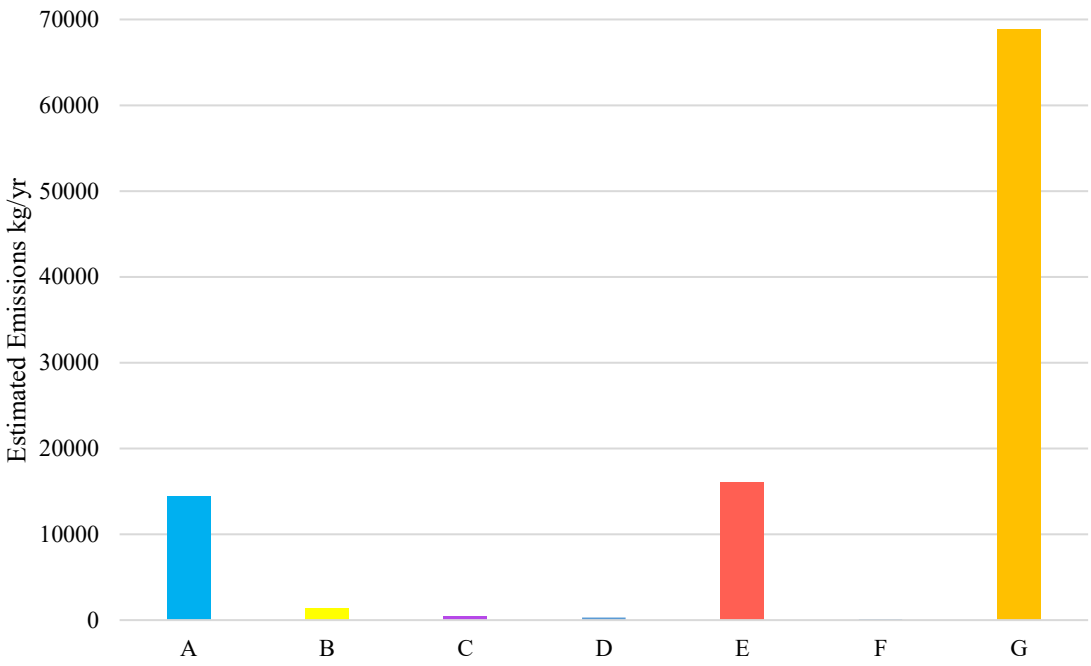

Figure 6.2. Range of emissions measured across the 7 AD sites.

Table 6.3. Summary of the walkover survey measurements across the 7 AD sites.

Site	No. of components screened	No. of quantified leaks	Leaking component (%)	Estimated Emissions (kg/h)
A	730	17	2.3	1.65
B	337	7	2.1	0.16
C	712	2	0.28	0.05
D	1247	1	0.1	0.03
E	1041	9	0.86	1.83
F	552	1	0.18	0.01
G	1171	12	1	7.86

Significant emissions were also observed from Stage 3 during the DIAL campaigns. However, these emissions were dominated by the emissions from the upgrade unit vents, which are elevated and hence outside of the walkover survey scope and is confirmed by the OGI data. Notably, approximately 70% of the OGI leaks not detected by the GMI/BHFS instruments were from Stage 3 of the AD process as shown in Table 6.2. The observation of large emissions outside of the walkover survey scope (either from elevated sources at Stage 3 or diffuse sources at Stages 1 and 4) makes it difficult to reconcile the walkover survey data shown in Table 6.3 with the DIAL data shown in Table 5.8. In most cases there is more than two orders of magnitude difference between the datasets. This changes when only the results from Stage 2 are compared for Sites B, D and G where both DIAL and BHFS measured emissions above the detection limits. The ratio between DIAL and BHFS emissions varies between approximately 6, 19 and 275 for Sites B, D and G respectively, with Side D being the main outlier.

It should be noted that the purpose of the walkover surveys is to measure point source emissions at component level using handheld equipment. This limits walkover surveys when it comes to accurately capturing whole site emissions. As discussed, it is not possible to quantify diffuse emissions nor elevated emissions like those from the upgrade vents or CHP. This explains why most emissions reported were found in Stage 2 and the discrepancy between the magnitude of the emissions reported from the DIAL and walkover surveys.

7 FEDS (LONG-TERM MONITORING) RESULTS

Fourteen sampling inlets were placed around AD Site G at approximately regular intervals (Figure 7.1). The sample locations were chosen to both maximise the probability of measuring emissions from known methane sources (from DIAL work) and to provide representative measurements of the local methane background (upwind) and any methane enhancements (downwind) across a range of wind directions. Sampling took place over 15 weeks between September 2022 and January 2023. A multiple inlet unit automatically controlled the switching of inlets every four minutes. The first 90 seconds of data recorded after switching inlets were removed due to the possibility of contamination of the sampling lines and spectroscopic cell (within the analyser) with gas sampled from the previous inlet. Unfortunately, no flow rate was detected at either of inlet numbers 13 or 14 at the end of the campaign period (possibly due to obstructions within the sample tubing) and hence data from these inlets were removed for emission analysis.

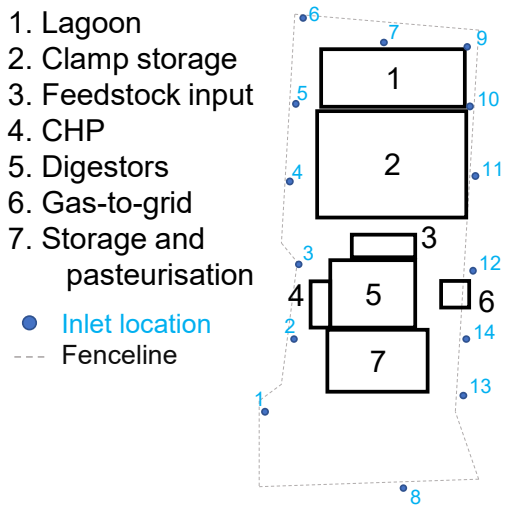

Figure 7.1 FEs and inlet locations at AD Site G.

Methane mole fractions were initially measured at 1 Hz. However, a software-related problem on the gas analyser led to a steady but slow reduction in sampling rate over time, so that measurements were made at roughly 0.25 Hz after approximately two weeks, and at roughly 0.15 Hz after approximately five weeks. Periodic cycles of instrument power (in weeks 4 and 11 of measurements) temporarily resolved the software issue and allowed the analyser to resume measuring at 1 Hz. The reduced sampling rate is not expected to impact the accuracy of quantified emissions but may lead to an increase in the associated uncertainties.

One-minute average meteorological parameters were measured on the telescopic mast located at the FEDS mobile trailer. Except for a small period of meteorological data loss in week 3 (equivalent to 4% of total campaign data), there were no other issues with the meteorological data.

Hourly-averaged methane data (for each individual inlet) and meteorological data were used for emission quantification. Airviro, a Gaussian reverse dispersion model, was used to quantify emissions

over weekly time-periods for the duration of the whole campaign, and over daily time-periods for the month of October.

Figure 7.2 shows time series of hourly-averaged methane concentrations measured at four of the sampling inlets. Whilst absolute concentration measurements are not wholly representative of emissions in isolation (meteorological measurements are needed for more robust conclusions regarding emission source location and strength), the time series provide a crude indication of proximity to methane emission sources. For example, it is immediately obvious that the distribution of measured methane concentrations at inlet 8 was much lower than those for other inlets. This could indicate that inlet 8 was not located nearby methane emission sources, or that inlet 8 was infrequently downwind of any such sources. For this reason, data from inlet 8 is more representative of the local methane background (~2 ppm). Conversely, inlets 7, 9, and 10 all showed regular strong but transient enhancements in methane above the local background. The magnitude and frequency of these spikes in concentration suggest that those inlets were in close proximity to, or commonly downwind of, a methane emission source.

The maximum hourly-averaged methane concentration was 128 ppm, observed at inlet 7 in week 3 at around midday. This concentration was almost two orders of magnitude greater than the global methane background in November 2022, which was reported to be 1.92 ppm[44]. A local methane background concentration (of 2.11 ppm) was defined using the 5th percentile value of all measured methane data. This is consistent with other works which have typically used percentile values at or below the 10th percentile to define a local background threshold.

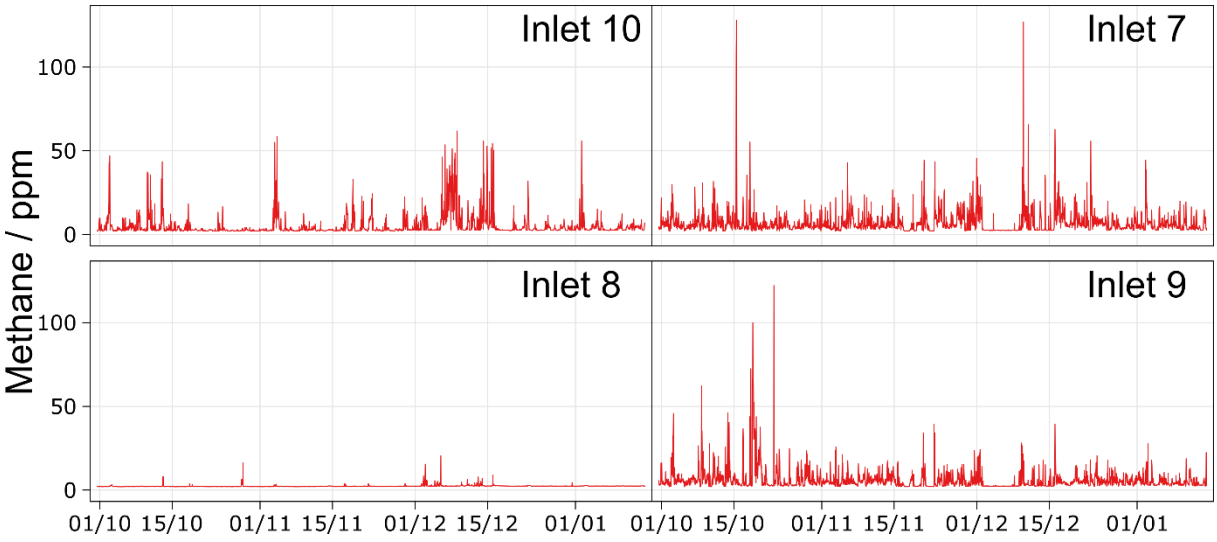

Figure 7.2. Time series of hourly-averaged methane concentrations measured at four sampling inlets.

Figure 7.3 shows the relationship between measured methane concentration and wind direction at each sampling inlet. The wind data for each inlet is identical as it is from the single measurement tower located at the FEDS mobile trailer. In these plots, the radii of the wedges indicate the frequency of data in that wind direction; southerly winds were the most frequent (62% of wind direction data was between 135° and 225°) and northerly winds the least frequent (8%, 315° – 45°). Methane concentration data within each wind direction wedge (15° intervals) is shown via the coloured bins. It

is immediately clear that the higher methane concentrations at inlet 7 occurred during southerly winds, due to the high frequency of concentrations greater than 5 ppm (light green and yellow bins) measured in that wind direction. For inlet 10, the higher methane concentrations occurred when wind directions were from the north-west, and for inlet 6, the higher concentrations occurred under south-easterly winds.

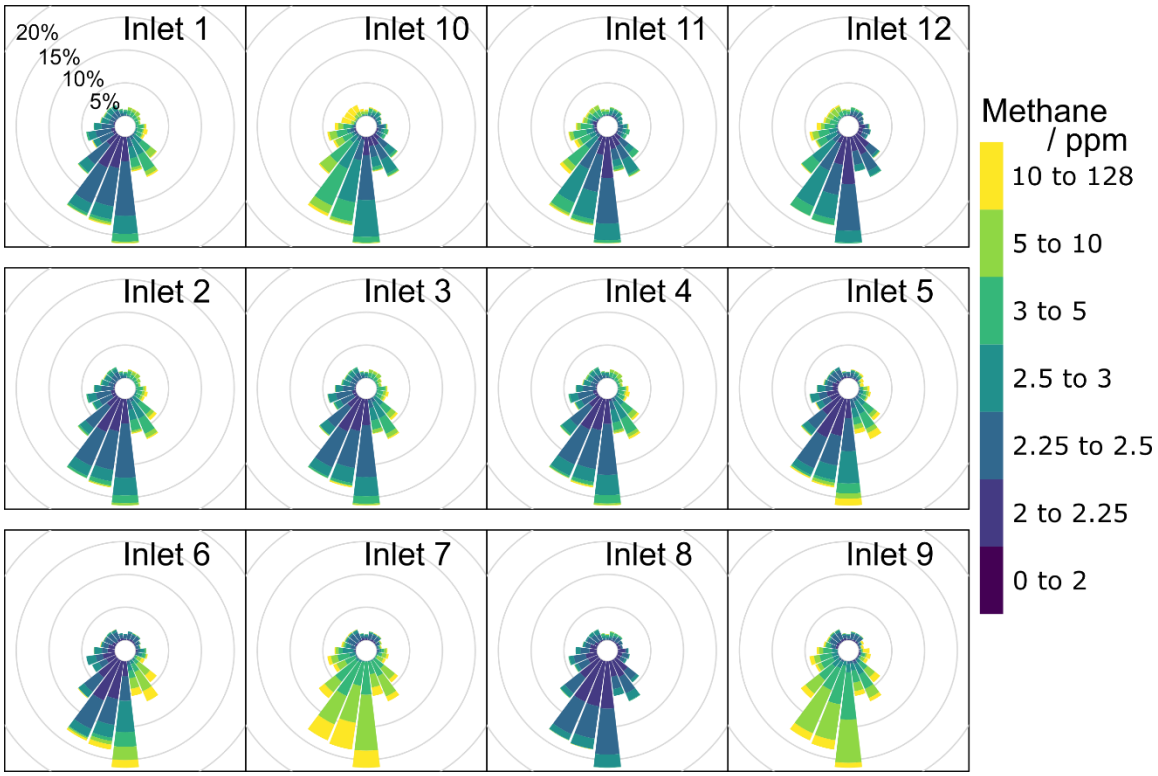

Figure 7.3. Hourly-averaged methane concentration as a function of wind direction for each inlet. Methane concentrations are divided into bins (see coloured scale bar) with the percentage frequency of occurrences within each bin plotted for each 15° wind direction wedge.

Maintenance at Site G to replace a digester roof took place in week 3. Figure 7.4 shows Airviro dispersion modelling of source location probability for the periods prior to maintenance ('pre-maintenance') and following maintenance ('post-maintenance'). The 'pre-maintenance' plot shows a high probability that the major sources of methane emission were located at the digesters and the lagoon. It should be noted that some of the emissions from the lagoon appear to be coming from off site. One possible explanation for this is local wind effects in the northeast of the site caused by trees lining the east side of the site. The 'post-maintenance' plot shows that the highest source location probabilities are observed from the northern lagoon and source probability from the digester area is reduced. It should be noted that the overall reduced source location probabilities observed from the post-maintenance plot are assumed to be a consequence of the longer period over which the model is run. Typically, lower source location probabilities are observed over longer time frames. This is because any random spurious data or emissions that are temporary/intermittent in nature will be smoothed and, hence, their source probability will tend to decrease. However, if a source is essentially continuous, such as the northern lagoon in Figure 7.4, then these effects will be less evident.

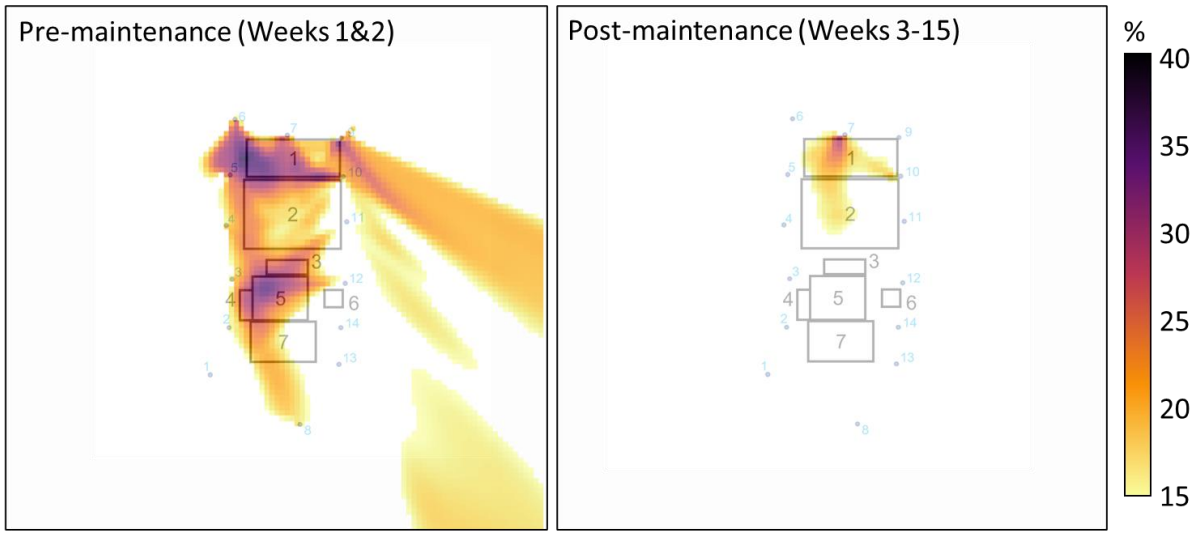

Figure 7.4. Source location dispersion results for the pre- and post-maintenance periods (maintenance occurred in week 3). The colour bar indicates the source probability output from Airviro.

Figure 7.5 shows weekly methane emission rates from seven areas containing FEs at AD site G, as modelled by Airviro. The seven FE areas were chosen based on the proximity of on-site FEs and included: CHP, clamp storage, three digesters, feedstock input (both solid and liquid), the GtG system, the lagoon, and a combined area containing pasteurisation and both solid and liquid digestate storage. Each of these areas were assigned a single emission source height representative of a rough average of each of the FEs within that box area. The assigned emission source heights are reported in the key in Figure 7.5, these were based upon NPL knowledge of the emission sources from the DIAL campaign and helped to optimise the model output.

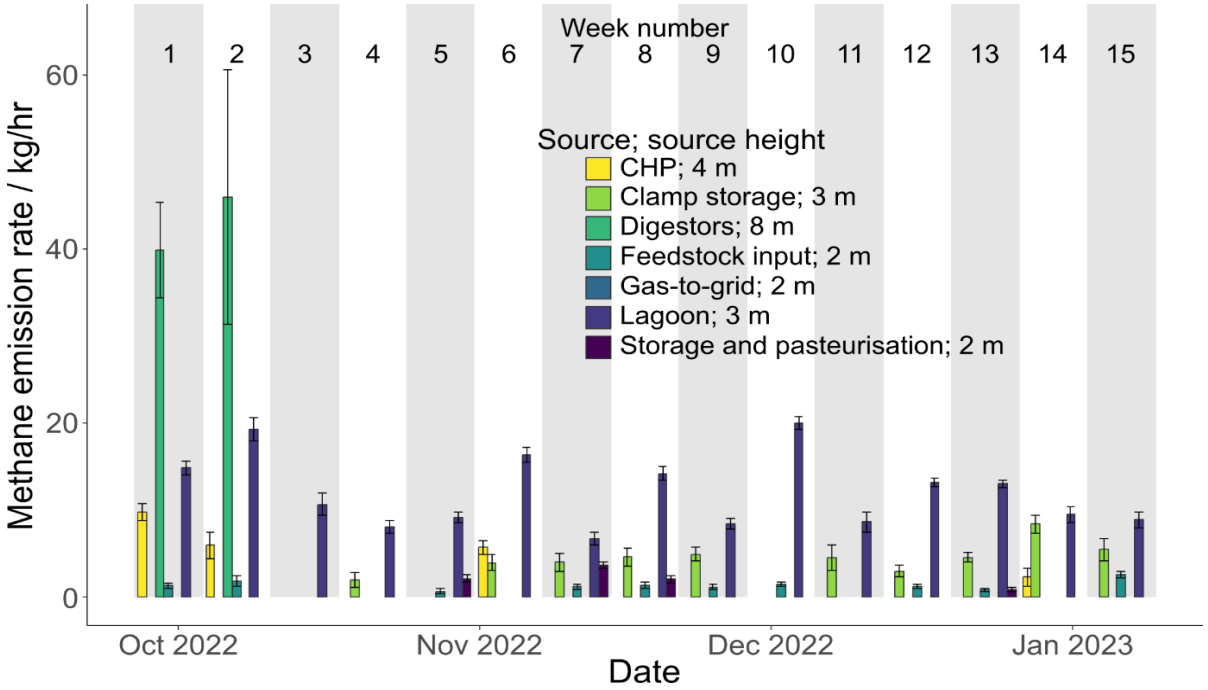

Figure 7.5. Modelled weekly methane emission rates (kg/h) from seven key FEs. Modelled uncertainties in emission rates are represented by the error bars but should be treated as minimum uncertainties in all cases.

Modelled uncertainties in emission rates are represented on Figure 7.5 by error bars. These uncertainties are representative of the uncertainty in dispersion and footprint modelling within the Gaussian reverse dispersion model, and therefore do not incorporate uncertainties in measured parameters (such as the measured methane concentration, source height, wind speed, and wind direction). As such, the uncertainties should be treated as minimum representations of uncertainty, where the true uncertainties are likely larger.

The greatest methane emission rates were modelled from the area containing the three digesters. Methane emission rates from this area at the start of the campaign exceeded 40 kg/h. However, the model was unable to estimate emissions for the weeks following maintenance work on a digester roof carried out during week 3. This suggests that the maintenance work was successful and that emissions were significantly reduced by fixing the leaks on the digester roof.

The lagoon was the second greatest source of methane emissions with a mean methane emission rate of 12 ± 4.2 kg/hr. The lagoon was the only source for which significant emissions were modelled every week. This is likely due to the proximity of several sampling inlets (7, 9, 10) to this source which allowed for the measurement of methane emissions even in non-ideal wind conditions (such as low wind speeds).

Significant methane emissions from other sources were modelled less frequently. The area containing the clamp storage showed modelled emissions for 67% of weeks (n = 10), the feedstock input (both solid and liquid) for 67% of weeks (n = 10), CHP for 27% of weeks (n = 4), and the area containing pasteurisation and digestate storage for 27% of weeks (n = 4). Significant emissions were not modelled for any weeks from the area containing the GtG system. Of these sources, the area containing the CHP had the greatest modelled methane emission rate, with a mean of 5.9 (± 3.0) kg/hr. The source area containing the clamp storage had a mean methane emission rate of 4.6 (± 1.7) kg/hr, whilst the other source areas (feedstock input, and pasteurisation and digestate storage) had mean methane emission rates below 3 kg/hr.

It should be noted that the absence of significant modelled emissions from a particular source for a particular week is not necessarily evidence that there were no emissions that week. There are a few reasons that might explain the absence of modelled emissions. Firstly, and most obviously, the emissions may have been below the limit of detection for the model. This limit of detection will differ depending on the proximity of inlets to each source as well as the strength and direction of local winds. Secondly, the emissions may not have been observed that week due to an unusual or inconsistent wind field; a strong vertical wind vector may loft emissions above the height of the sampling inlets, for example. Finally, dispersion models are highly sensitive to many of the input parameters, including the size of the prescribed source area, the estimated heights of both the emission sources and the sampling inlets, and the presence of any obstructions (walls, buildings, trees etc.) which may impact atmospheric transport. In this case, prior knowledge of Site G, as well as results from the DIAL emission survey, have been used to optimise the input source areas, source emission heights and inlet heights. However, small discrepancies in these values may still lead to inaccuracies in emission estimates. Such sensitivities to input parameters, and the difficulty of modelling

obstructions and interference to the local wind field, are known limitations of reverse dispersion modelling.

Figure 7.6 shows modelled whole-site emissions, calculated by summing the FE specific emissions in Figure 7.5. Whole-site emissions decreased by approximately 75% in the weeks following maintenance to the digester roof. The large difference in emission rates between the pre- and post-maintenance periods, as well as the lack of overlapping uncertainties, provides further confidence in this result. It is important to note that the emission rates observed by FEDS during the first two weeks compare very well with the total site emission measured by DIAL few weeks earlier. Moreover, between weeks 3 and 15, assuming the same site throughput as during the DIAL, an average methane EF of approximately 5% can be estimated. This is significant reduction from 22% measured during the DIAL campaign.

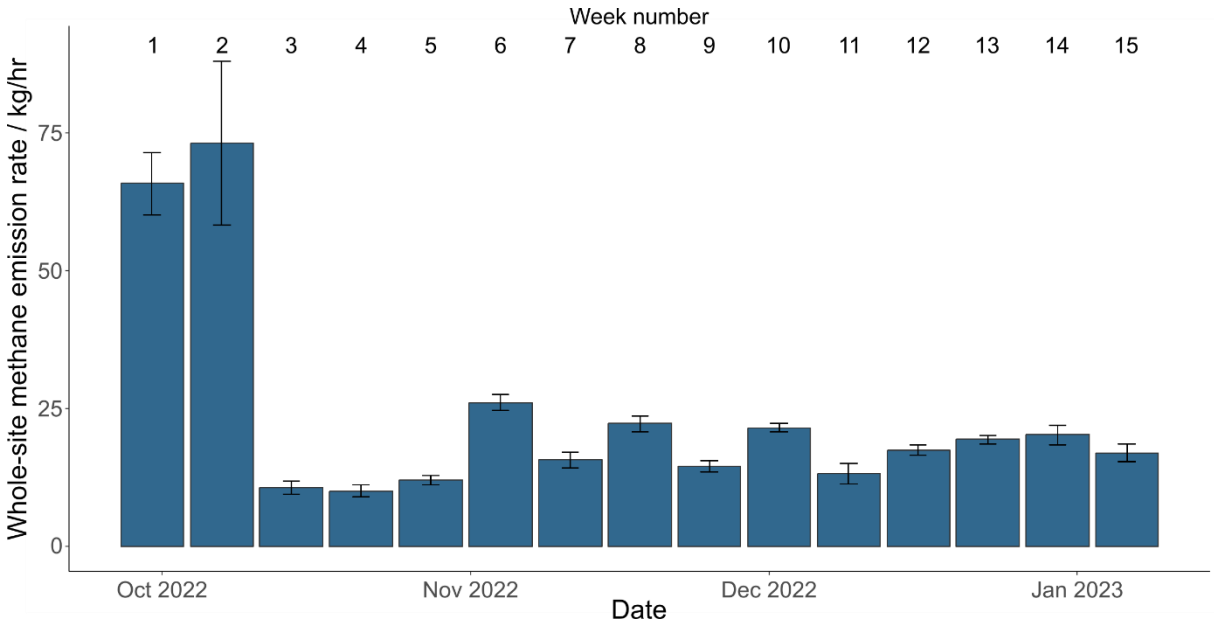

Figure 7.6. Modelled weekly whole-site methane emissions (calculated as the sum of source specific emissions in Figure 7.5**). Modelled uncertainties in emission rates are represented by the error bars but should be treated as minimum uncertainties in all cases.**

The emissions measured using FEDS are only representative of emissions from operations occurring on-site at the time of monitoring. Scaling up emissions estimates made during the 15-week period is therefore limited, as emissions will likely vary considerably with changes to operational activity on-site. If on-site activity is expected to vary over longer periods (e.g., in response to seasons) then longer-term monitoring would be required to provide a more accurate annual estimate of emissions.

8 TRACER CORRELATION RESULTS

Methane emissions from Site G were also measured using TC with ethane as the tracer gas, in a 3-day campaign carried out after the DIAL work and just before the FEDS measurements started. At the beginning of each day during the campaign, after warming up, the LGR analyser was calibrated using a cylinder containing 50 ppm of methane and 5 ppm of ethane. Each cylinder that was going to be used for tracer release was weighed three time using the mass balance. After that, two teams of two people each conducted different tasks: one team drove around the site to test the performance of the analyser whilst measuring the daily background concentration (baseline) of methane and ethane in the vicinity; and the other team stayed at the main site to set up the tracer release. For each release, an ethane cylinder was connected to the inlet of the CRF through ½″ tubing. The CRF was set to a certain flow rate to ensure a stable flow, see Table 8.1. The outlet of the CRF was connected to a 30 m-long length of tubing, the end of which was attached to a nearby structure. The release location was changed half-way through the campaign after release 3, about 5 m towards the downwind direction to improve the detection of ethane further away.

After setting up the release station, calibrating the analyser, and investigating the baseline conditions, the tracer release experiment was performed. During the campaign, 5 different release periods were conducted, with different ethane release rates and fairly constant north westerly wind direction:

Table 8.1. Summary of release periods

Release	Start time	End time	Ethane flow rate (L/min)	Release rate (kg/h)	Wind speed (m/s)	Wind direction (deg)
1	Day 1, 16:12:00	Day 1, 17:36:00	24.7	1.98	N/A	N/A
2	Day 2, 10:29:00	Day 2, 11:40:00	24.1	1.93	N/A	N/A
3	Day 2, 14:37:00	Day 2, 15:47:00	29.7	2.39	5.0	314.6
4	Day 2, 16:29:00	Day 2, 17:14:00	29.4	2.36	4.4	323.0
5	Day 3, 09:44:00	Day 3, 10:51:00	29.2	2.34	8.1	332.2

The wind data was collected from the meteorological equipment housed in the FEDS, which was not available during the first two releases since it was only possible to connect the FEDS trailer to the site power supply only in the afternoon of second day. During these two first releases the CRF was set to release at a flow rate of about 24 L/min. The flow was then increased to 29.7 L/min in the third release and around 29 L/min in the last two releases in an attempt to improve the data quality of the ethane measurements.

Three roads surrounding the site were surveyed during the campaign, one just south of the site along the East-West axis (path A); one to the east of the site along the North-South axis (path B); and another along the East-West axis further south (path C) as shown in Figure 8.2. Each measurement path was designed to capture the main emission plume and beyond each side of the plume to calculate the background levels (kept driving after the plume was detected until the methane measurements went back down to background levels). Path C was used to test whether methane or ethane was

detectable at about 1 km from the site. During measurements, the vehicle was driven at a speed of around 5 to 10 mph to minimise the effect of the inlet/LGR response time on the relative location of the plumes.

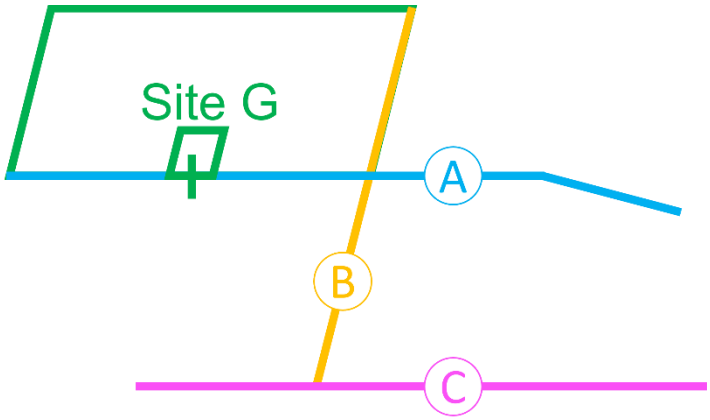

Figure 8.2. Measurement paths A (blue), B (orange) and C (pink) around site G during the campaign.

At the analysis stage the LGR time data was adjusted to account for the delays in measurements due to the length of the inlet tubing and overall LGR response time. During the first two releases 60 seconds were subtracted to the LGR time data, then the tubing was shortened and only 40 seconds were subtracted to the LGR time data.

To obtain the enhancement level of methane and ethane in each transect, the background levels were first identified. This was done by averaging as many stable datapoints as possible (mostly between 50 and 300 points depending on data availability) when the methane concentrations were at the lowest level beyond both ends of the plume. The ethane background levels were determined by averaging the same datapoints that coincided with the selected lowest concentrations of methane. The baseline values for both gases in each transect were then subtracted from each gas transect measurement to calculate the enhancement concentrations of both gases above background. These values were then used to calculate the methane emission rate using E3.1.

Across the 3-day campaign a total of 47 individual transects that were measured: 21 along path A, 20 along path B and 6 along path C. Figure 8.3 to 8.5 show examples of transects from path C, B and A. Two transects are shown for path A, the first while driving toward west, the second while driving toward east.

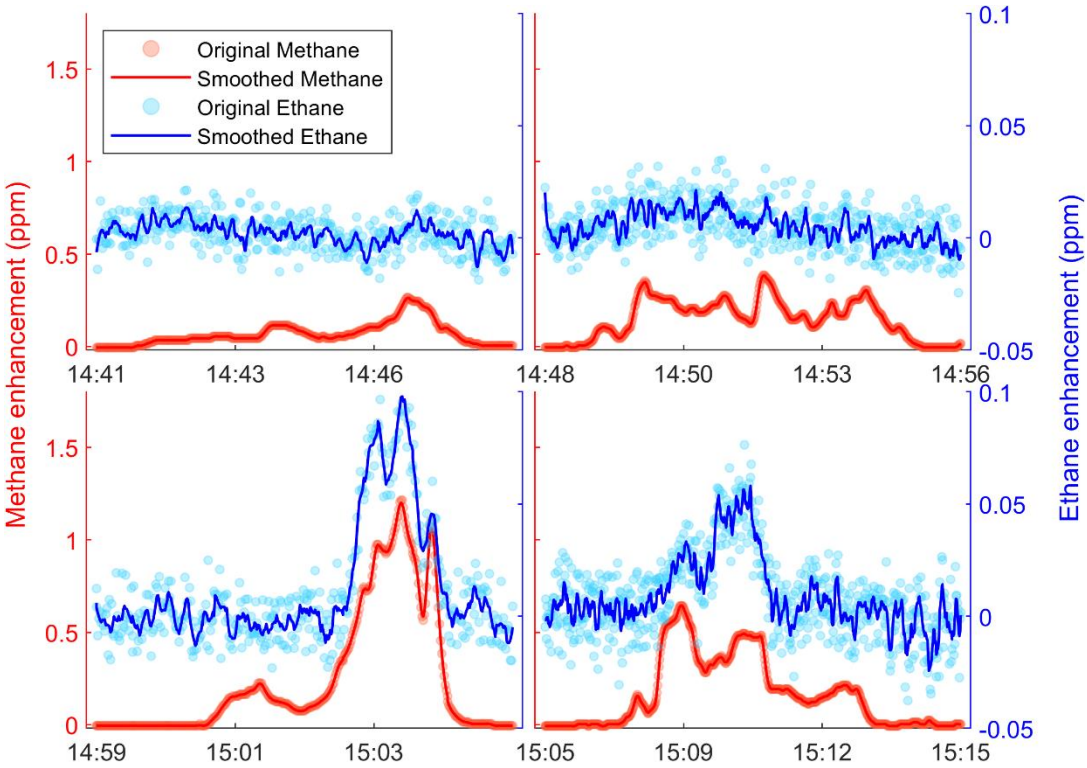

Figure 8.3. An example of measurements done on a campaign day, going from path C (top left) to path B (top right) to path A driving toward west (bottom left) and path A driving toward east (bottom right). Plotted in red are methane enhancement (ppm), with dots representing individual data points and lines representing Savitzky-Golay filtered data. Plotted in blue are the same for ethane enhancement (ppm).

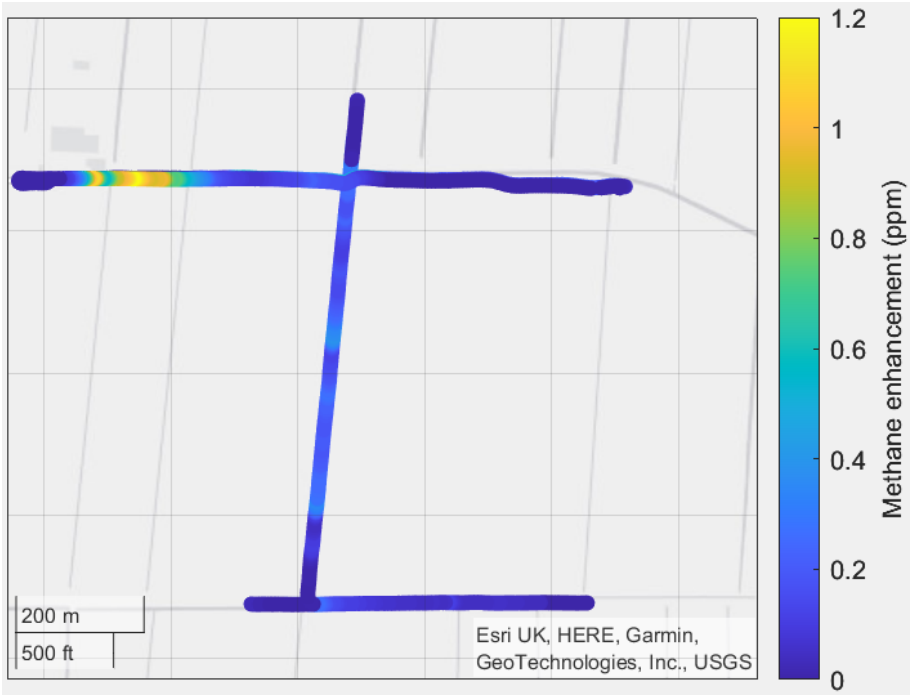

Figure 8.4. Same period of measurements as 8.3 but plotted with GPS coordinates instead of date-time data. Data points are for methane enhancement (ppm), colour-coded based on the enhancement concentration.

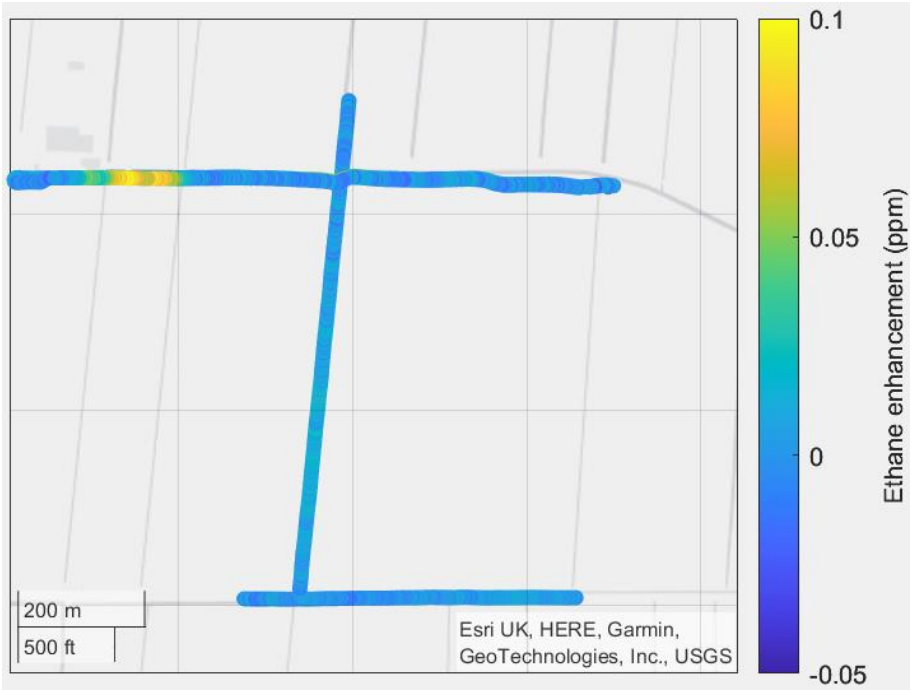

Figure 8.5. Same as 8.4 but for ethane enhancement (ppm).

As illustrated in Figure 8.3, there was a clear correlation between methane and ethane peaks along path A, albeit methane peaks were generally spread over a wider area indicating a non-perfect coverage of the methane source by the single tracer release point. This is a source of unknown systematic uncertainties that would generally either lead to overestimation (when sources are mostly downwind of the tracer release location) or underestimation (when sources are mostly upwind of the tracer release location) of the methane emissions. This is expected since path A was close to the site that has several known emission sources as shown by DIAL measurements. Path B was farther downwind of the site; therefore, it should be a better measurement location as it allows the two gases to mix more in the atmosphere improving the assumption of the site as single point emission source (i.e., the single tracer cylinder would cover better all the methane sources). However, the correlation between methane and ethane peaks was less prominent further away from the site along path B because the detection of ethane was lower and closer to the background level. For the same reason ethane enhancement was almost non-detectable along the farthest path C.

An uncertainty budget for each transects, based on the analyser and CRF performances, was developed for this project by propagating in quadrature all the five uncertainty sources in E3.1. These are the tracer release rate, the two cross-plume concentrations above background (also referred to as the peak area) of the target and tracer gases and the two offsets (backgrounds) of the target and tracer gases. The standard uncertainty of the tracer release rate was assessed using the CRF calibration data as described in Section 3.5. The standard uncertainty of each peak area was calculated by propagating in quadrature the analyser's uncertainty of each concentration point (as stated by the manufacturer) by the number of data points in the peak area. The standard uncertainty of each background value (calculated averaging *n* data points) was estimated by calculating the standard deviation of the mean of these *n* datapoints used in the calculation. The impact of the background uncertainties of both gases on

the total uncertainty budget was negligible (less than 0.001%). It was therefore decided to use a simplified uncertainty budget calculation using only the other three main uncertainty sources.

The standard uncertainty of each peak area calculated for the uncertainty budget also enabled us to develop quality assurance criteria for each transect based on the signal to noise ratio (SNR) of both tracer and target gases. The SNR is calculated by dividing the peak area of the tracer/target gas in a transect by its standard uncertainty. A low SNR value would indicate that there was not enough gas detected to evaluate the emission rate accurately, which should be reflected by a high overall uncertainty value. An SNR threshold value can be set in order to deem invalid any transect with a smaller SNR value for either the tracer gas or target gas. For this campaign, two thresholds were tested: SNR ≤ 1 (criteria 1 – excluding all transects with SNR ≤ 1) and SNR ≤ 2 (criteria 2 – excluding all transects with SNR ≤ 2). Table 8.2 summarises the methane emission rate for each transect during the five release periods. Transects with negative enhancement in either gas (leading to negative emission rates) are reported in Table 8.2 and coloured in red.

Table 8.2. TC summary of methane emission rate (ER, in kg/hr) and the budget standard uncertainty budget (BSU, in kg/hr) measured at site G. Coloured in red are the transects with negative values, in orange are the transects with SNR ≤ 1 and in blue are the transects with SNR ≤ 2.

Path	Release 1	Release 2	Release 3	Release 4	Release 5
A	60.1 ± 43.6	-369.7 ± 946.0	24.0 ± 2.4	42.8 ± 4.2	35.9 ± 4.4
	28.4 ± 5.8	-72.1 ± 94.6	22.4 ± 2.2		32.6 ± 6.0
	62.7 ± 22.1	31.5 ± 3.7	50.2 ± 24.0		70.8 ± 69.6
	35.8 ± 6.4	42.0 ± 4.8	131.8 ± 95.7		40.6 ± 7.5
	56.5 ± 25.7	44.4 ± 9.9			
	37.3 ± 7.6	19.1 ± 1.6			
B	-1.8 ± 0.3	55.0 ± 38.2	34.8 ± 7.4	67.6 ± 70.8	21.2 ± 3.7
	55.4 ± 36.9	-108.0 ± 437.9	45.7 ± 24.2	-2739.4 ± 135007.0	48.5 ± 25.3
	185.6 ± 354.2		57.2 ± 165.5	65.7 ± 31.7	86.5 ± 135.4
	55.9 ± 20.4			52.9 ± 11.6	34.1 ± 13.6
	85.1 ± 65.0			70.8 ± 59.9	-168.6 ± 568.6
C	-16.5 ± 89.7	40.4 ± 71.2	44.4 ± 30.4		-22.1 ± 8.8
	30.3 ± 111.7	10.6 ± 6.8			

Table 8.2 shows that transects along path A have generally a lower associated budget standard uncertainty (BSU) than transects along paths B and C. This is as expected since path A is closer to the site with generally higher SNR values. However, transects along path A are expected to have higher unknown systematic uncertainties than transects along path B and C. These systematic uncertainty sources, such the uncertainty from the basic TC assumption that the tracer and target gases are coaligned point sources, are not included in the BSU derived from the instrumentation performances. While paths B and C should be in theory better measurement locations providing a lower systematic uncertainty, their associated BSU values are high due to smaller SNR values of the methane/ethane peaks measured farther away from the site.

The European Standard EN 17628, developed for VOCs measurements, states that a TC measurement should be the average of at least 12 transects along a path over 3 different release periods (4 transects for each period). This is to randomise as much as possible systematic uncertainties intrinsic to the technique between different releases if the systematic uncertainties were different when the releases are performed under different meteorological conditions and/or using different tracer locations. If exclusion criteria were not used, there are enough transects in both paths A and B to calculate a measurement as defined in EN 17628. However, if the exclusion criteria 2 is used, none of the transects recorded along paths A, B, C could be averaged to give a valid measurement as defined in EN 17628. Nonetheless, Table 8.3 presents a comparison of the averaged methane emission rate in each measurement path based on all the transects available and on the three exclusion criteria described above. The reported BSU values are calculated propagating in quadrature the BSU value of each transect used in the average. Alongside the BSU values, the statistical standard uncertainties (SSU) are also reported. This is the standard deviation of the mean, which is the standard deviation of the emission rates used in the average divided by the square root of the number of transects used for the calculation.

Table 8.3. TC summary of averaged methane emission rate (ER, in kg/hr) across all 5 releases, the budget standard uncertainty (BSU, in kg/hr) and the statistical standard uncertainty (SSU, in kg/hr) measured at site G. Coloured in red are the values calculated excluding transects with negative values, in orange are the values calculated with the exclusion criteria 1 and in blue are the values calculated with the exclusion criteria 2.

Path	Exclusion	Mean ER	BSU	SSU
A	No exclusion	20.3	45.7	20.9
	No negative	44.9	7.1	6.0
	Criteria 1	44.9	7.1	6.0
	Criteria 2	37.9	2.9	3.0
B	No exclusion	-99.8	6750.5	139.8
	No negative	63.9	27.2	9.2
	Criteria 1	52.1	9.7	5.0
	Criteria 2	44.1	7.1	6.8
C	No exclusion	14.5	27.2	11.7
	No negative	31.4	34.0	7.6
	Criteria 1	27.5	15.6	16.9
	Criteria 2	N/A	N/A	N/A

Table 8.3 shows that for path B (and C) it is critical to setup correct threshold values to exclude transects with low accuracy. It is important to note that most of the TC data reported in the literature are likely to be average values using only the non-negative exclusion criteria and with associated uncertainty calculated based on the transects statistical data (SSU). In the case of path B this would be 63.9 ± 9.2 kg/h while the BSU values is significatively higher, 27.2 kg/h. It should also be considered the fact the SSU value should include any statistical variability due to the instrumentation, which is in fact the BSU, any variability from the site emission over the measurement period (3 days in this case) and the variability due to any systematic uncertainty source that may have (partially) varied over the

measurement period. It is therefore reasonable to expect SSU values to be similar or larger than BSU values and the exclusion criteria should be chosen accordingly. Excluding transects based on criteria 1 decreases significatively the BSU value for path B to 9.7 kg/h, however the associated SSU value was still lower than the BSU value. Excluding transects based on criteria 2 leads to similar BSU and SSU values for path B. This seems to suggest that criteria 2 has a more appropriate SNR threshold level.

For path C none of the 4 transects satisfies criteria 2 and the difference between the BSU and SSU values significantly decreases when criteria 1 is applied. The SNR values for path A were generally good and none of the transects had values below criteria 1 threshold, therefore the average values without exclusions and criteria 1 are identical. Only three transects had a SNR value below criteria 2 threshold, however the values calculated with criteria 2 were notably different. The SSU value was halved (3 kg/h from 6 kg/h), indicating the three transects excluded were outliers, and it also compares well with the BSU value (2.9 kg/h).

The BSU values for path B are higher than for path A. This is expected due to the difficulties with measuring ethane on paths further away from the source. On the other hand, the measurement along path A may have higher systematic uncertainty due to ethane not being subjected to the same amount of atmospheric mixing as methane and some methane emission sources potentially not be properly captured. Therefore, the methane emission rates measured with TC during the campaign may not be representative and not directly comparable with what had been measured by the DIAL and FEDS techniques. While DIAL and FEDS data compare well and show similar level of emission, the TC measurements (carried out between the DIAL and FEDS measurements) showed on average lower emission rates.

Even if more development is needed, the potential of TC for whole-site emission quantification was demonstrated. More importantly, exclusions criteria and an instrumentation uncertainties budget have been developed for this project which are both critical ensuring the overall quality of TC measurements. The use of different tracer gases and analysers with better detection limit and noise performances should be investigated. The amount of tracer released may also be reconsidered further with the aid of atmospheric dispersion models.

9 CONCLUSIONS

9.1 DATA SUMMARY

The primary aim of the MEAD project was to increase the level of understanding regarding the potential sources of methane emissions from the various FEs of an AD site and to highlight which stages, processes and FEs should be prioritised for emission reduction. During the MEAD study methane emissions were measured at seven different AD facilities, all of which had GtG capabilities.

Different techniques for methane detection and quantification were used throughout the project, this included both short-term and long-term approaches. DIAL and walkover surveys were performed at all seven sites as short-term, campaigned based techniques. Another short-term technique, TC, was deployed only at Site G as a novel measurement approach for NPL. Similarly, the FEDS, NPL's long-term monitoring solution, was only deployed at Site G for several months.

Summary of the methane monitoring techniques used.

Technique	Measurement Timeframe	Site						
		A	B	C	D	E	F	G
DIAL	Short-term	✓	✓	✓	✓	✓	✓	✓
Walkover survey	Short-term	✓	✓	✓	✓	✓	✓	✓
TC	Short-term	-	-	-	-	-	-	✓
FEDS	Long-term	-	-	-	-	-	-	✓

The primary technique used for the quantification of site emissions was NPL's DIAL. The DIAL data showed the total site emissions ranged from 14.5 kg/h to 95.9 kg/h. Using activity data provided by the sites, it was possible to estimate the methane EF, this ranged from approximately 4% to 22% of the total site methane production (biomethane injected, CHP throughput, flare throughput and fugitive emissions) as shown in the table below. Site G, where a methane EF of 22% was measured, had a known issue that was rectified after the DIAL campaign. Following the maintenance at Site G, FEDS measurements estimated the EF was reduced to approximately 5%. The issues on Site G are not uncommon, hence the loss measured by DIAL can be considered indicative of the potential emissions at facilities with large digester leaks or during periods of ongoing maintenance. The benefit of a thorough repair and maintenance program on AD facilities are shown by the loss reduction measured by FEDS after the issue was addressed.

A 2022 review of the AD industry by Bakkaloglu et al. employed Monte Carlo simulations utilising literature data to estimate total site methane EFs. In this work EFs of approximately 2% (at the 5th percentile) to approximately 13% (at the 95th percentile) were determined, with a median methane EF of approximately 5%[1]. The observed EFs varied between approximately 4% and 15% for Sites A to F. Although not dissimilar to those determined in Bakkaloglu et al. (2022), the smallest methane EFs observed from the DIAL surveys was approximately double (~4%) those estimated from the 5th percentile of the Bakkaloglu study (~2%) and the emissions from Site D were above Bakkaloglu's the 95th percentile methane loss rate.

Summary of the derived methane EF (%) from sites A to G using DIAL.

Site Total	Emission Rate	Standard Uncertainty	Methane EF	Standard Uncertainty
	kg/h	kg/h	%	%
Site A	22.2	1.5	7.8%	2.6%
Site B*	14.5	1.5	4.5%	0.4%
Site C	19.1	1.5	4.1%	0.6%
Site D	38.8	3.7	14.2%	1.2%
Site E	17.4	1.4	7.8%	0.9%
Site F	53.7	1.9	10.4%	2.4%
Site G	95.9	2.9	22.0%	2.0%

*Emissions from Stage 3 could not be measured from Site B and so the emission rate and methane EF reported should be treated as minimum values.

Using the DIAL, it was possible on some of the sites to separate the emissions from five main FEs: feedstock storage, digesters, CHP, upgrade units and digestate (the solid/liquid by-product of AD) separation/storage. While CHP, upgrade and feedstock storage losses varies from approximately zero to 5%, the digester shows a higher variability (from zero to about 13%) and the digestate storage has a minimum loss of about 3% up to about 8%. This makes digestate storage, both solid and liquid, an ideal candidate for methane emission abatement particularly for all storage areas that are left uncovered. Significantly large emissions of about 21 kg/h were observed from the feedstock storage area of Site F, while other sites had emission of less than 1 kg/h. Site F was the only site which utilised solely commercial/municipal waste, therefore it is not possible to know if this was an isolated issue at Site F or a common problem from site utilising similar feedstocks.

The main source of emissions from the upgrade unit was the upgrade vent, which vents the CO_2 removed during upgrading, presumably caused by inefficient separation during the gas upgrade process. The measured slippage from the CHP exhausts was relatively small; however, in a couple of instances larger emissions were observed from the CHP unit at lower elevations.

A walkover survey is comparable to the LDAR programme which is routinely carried out at oil and gas facilities. This allows to identify leaks at a component level enabling the operator to carry out an efficient maintenance programme. Within the survey it is also possible to quantify the emission from some of the components. Therefore, upon first inspection it may seem difficult to reconcile the differences seen between the DIAL and walkover survey datasets presented in Section 6. However, differences should be expected considering that walkover surveys are not suitable for quantifying elevated or diffuse emissions, which were typically the dominant sources found during the DIAL emission surveys. Walkover surveys are in fact not designed to quantify whole site emissions, but rather to detect and quantify accessible leaking components. As such, walkover surveys are of real value at AD facilities for leak detection/quantification and repair.

During the DIAL measurement survey at Site G, significant methane losses were observed. However, prior to NPL's arrival it was known there was an issue with the digester, although the full extent of the

problem was not understood. The site had planned maintenance of the digester roof in the weeks following the DIAL measurement survey, making it an interesting candidate for long-term monitoring. It was decided that NPL would employ the FEDS long-term monitoring technique at Site G to try to capture the maintenance period and to demonstrate the impact on the emissions following the repair of the digester roof. The results of the FEDS monitoring presented in Section 7 indicate that the whole-site emissions decreased by approximately 75% in the weeks following maintenance to the digester roof.

One of the aims of the project was to test TC as a cost effect short-term monitoring technique, which was done at Site G, where both FEDS and DIAL were also deployed. The methane emission rates measured were not directly comparable with what had been measured by the DIAL and FEDS techniques. While DIAL and FEDS data compare well and show similar level of emission, the TC measurements (carried out in the period between the DIAL and FEDS measurements) showed on average lower emission rates. This may have been due to systematic uncertainties in the TC measurements. For this project NPL started the development of a novel quality assurance approach allowing the exclusion of poor-quality data. Further developing and testing of these quality assurance criteria and the implementation of the procedures identified in EN 17628 are both critical to ensure the overall quality of TC measurements and establish TC as suitable candidate for whole-site emission quantification.

9.2 DISCUSSION

9.2.1 Recommendations for Improved Practices

From the data collected within MEAD there are several features observed with the types of emissions measured. Therefore, there is the potential to significantly reduce site emissions if there were certain changes implemented to the equipment and/or operating procedures.

It was common practice at sites measured (6 out of 7) that the CO_2 stripped during the upgrade process was vented straight into the atmosphere. On multiple occasions significant methane emissions were observed from this venting process. The majority (6 out of 7) of the sites monitored within MEAD utilised membrane technology for upgrading biogas to biomethane. The remaining site, Site F, used water washing technology. Notably, methane emissions were observed from CO_2 venting for both technologies. None of the sites measured utilised amine absorption upgrade technology. In a recent review by Odeh et al. (2017), it is commented that different technologies have different methane recovery efficiencies (>96-99.9% for amine absorption, 95-98% for water wash, 80-95% for membranes)[6]. Due to the higher methane capture rate, utilising amine absorption technology could potentially reduce the methane slip during the biogas upgrade process and lead to a reduction in methane emissions. Further research focussed on investigating this could establish whether this is a viable option for emissions reduction.

Significant emissions were observed from uncovered liquid and solid digestate at multiple sites. A potential method of reducing the site emissions significantly would be to cover the digestate storage and capture its methane emission. Common solutions to the problem are the use of a post-digestion

storage tank or a membrane gas holder to cover the digestate. Therefore, the methane trapped within the digestate is slowly released from the digestate, the gas can then be collected and recycled rather than vented.

During MEAD it was also observed that some of the sites were not operating within the specification of the equipment. For example, some PRVs were venting continually rather than in case of emergency. This has not only a negative impact for the environment, but it is also not cost-effective for the site. Further research could establish whether this is a common practice and if so, could be a focus for emissions reduction.

Another interesting observation from the project was the frequency of maintenance noted during the measurement campaigns. Four out of the seven sites had ongoing maintenance or emergencies during the measurement campaigns. This included two incidences where there was an overflow of digestate, and two sites where the PRVs were continuously open for prolonged periods and leaking digester roof. The data show some evidence that periods of maintenance can be associated with elevated emissions. Therefore, understanding the frequency of maintenance activities and the impact is critical. Flaring the gas rather than venting it could be a more efficient method, however it was observed that flaring was not commonly used during these maintenance periods.

Lastly, as demonstrated by Site B, capturing the CO_2 emissions from the gas upgrading process is also possible. If carbon capture was implemented at GtG sites this could lead to a significant reduction in the CO_2 emissions, and therefore the total GHG emissions from the AD industry. For example, a facility which produces 500 m^3/h of biomethane will typically vent approximately 500 m^3/h of CO_2, which is equivalent to CO_2 emissions of approximately 915 kg/h (assuming 293.15 K, 101.325 kPa). Therefore, capturing the vented CO_2 could significantly reduce the carbon footprint of such AD facility.

9.2.2 Recommendations for Site Monitoring

To fully gauge the benefit of any methane emission reduction strategy employed it is crucial to have a good understanding of the baseline emissions as well as a suitable strategy for monitoring emissions throughout the emission mitigation process. The techniques deployed during the MEAD study (DIAL, TC and FEDS) could be utilised in establishing baseline emissions from the AD industry, as well as being part of any industrywide future methane monitoring strategy.

The benefits of FEDS as continuous monitoring strategy for measuring methane reduction before and after planned maintenance has been highlighted in this project. FEDS would therefore be a suitable technique to observe any long-term trends or variations in site emissions. However, FEDS is not yet an established technique and more work is still required to fully validate FEDS. Furthermore, the standard operating procedure (SOP) is still under development. Alternatively, periodic short-term measurement campaigns could be used to assess the impact of any methane mitigation strategy. In this scenario TC could be deployed for a total site emission assessment or DIAL could be utilised giving accurate and detailed FE-level measurements. Either technique should follow a SOP and implement

suitable quality controls and assurance. As a minimum, those outlined in the recent European Standard EN 17628 for VOC fugitive emission monitoring should be followed[23].

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