Methodology to Assess Methane Leakage from AD Plants

Part 2: Monitoring methodology

Report for BEIS

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Executive summary

Ricardo Energy & Environment was commissioned by the Department for Business, Energy and Industrial Strategy (BEIS) to develop a methodology for monitoring methane leakage from AD plants. The wider objective is to implement this methodology to estimate methane emissions from different categories of AD plants across the UK as part of a large scale field trial. This report describes the approach undertaken in developing the methodology (Section 2), outlines the methodology developed in detail (Section 3) and gives a summary of the results from testing the methodology on a pilot plant (Appendix A). The data collected as part of the pilot study was used to provide real estimates of GHG savings resulting from the plant.

The development of the methodology is supported by comprehensive review of technologies used to monitor methane leakage and a study considering the categorisation of AD plants on the basis of potential for biomethane leakage. These are reported separately in a report titled "Methodology to Assess Methane Leakage from AD Plants, Part I: Report on proposed categorisation of AD plants, porposed counterfactuals *and* literature review of methane monitoring technologies" that will be referred to in this report as the 'literature review' or the 'literature review and categorisation report'[1].

The methodology developed for the large scale field trial is described in Section 3 of this report. It has been developed to be both practical and cost-effective so that it can be applied to as many sites as possible. The methodology is based on a whole site approach i.e. undertaking measurements of methane concentrations at the site boundary. This approach relies heavily on the assumption that there will be sufficient distance between the source and the point of measurement to ensure that all of the sources present contribute to the concentration at the measurement point. The specification of the measurement position is critical to ensure that activities not associated with the AD process are excluded.

Two measurement systems are proposed for use at the fence-line: open-path and multiple-point measurement, utilising sensors located around the site. To assess the site's methane emissions and to eliminate contributions from other sources upwind and downwind measurements should be undertaken. This approach means that the measurement technologies that can be deployed are restricted to those that are capable of distinguishing between the background concentration of methane (1.5 to 2 ppm or higher) and the combined concentration of the background and contribution from the process.

This approach also requires the measurement of the meteorological conditions to determine the emission rate from the site. Dispersion modelling is proposed to assess the mass emission rates in conjunction with the concentration, wind speed and direction data collected during the monitoring period. Reverse dispersion modelling is proposed to calculate leakage rates.

In addition to fence-line monitoring, it is also proposed to monitor methane emissions at vents and point sources on site. This data will allow the exclusion of emissions outside the boundary and can also allow the confirmation of the total methane emissions measured at the fence-line. Furthermore, as emissions associated with digestate storage are not required for reporting to Ofgem under the sustainability criteria reporting requirements, our methodology allows these to be subtracted from the calculation of total methane emissions, if required.

Our approach includes both point sources and fugitive emissions, including emissions generated from digester roofs, seals and leaks that occur due to failures which are difficult to detect due to random occurrences. We undertook a pilot study, applying both open-path and multiple-point measurement techniques to investigate the application of the proposed approach.

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[1] The report was the first part of the work to develop this methodology. It is available as Methodology to assess biomethane leakage from AD plants: Part 1: Review of the literature on classification of AD plants, sources of biomethane leakage and monitoring technologies

The primary purpose of the pilot study was to test the methodology. The study was of short duration (only 4 days) and therefore the results must not be considered to be representative of the plant over the whole year. However, for the site examined and for the short period of measurement, we estimated a whole site methane loss of 4.1%, with methane losses coming predominantly from the lagoons (3.4%), and much lower losses from the CHP unit (0.4% of methane produced or 3.1% of CHP plant methane throughput) and the upgrade unit (0.3% of methane produced or 0.3% of upgrade plant throughput). The emission rates indicate GHG saving of 77% under the current Ofgem reporting criteria and 59% under the counterfactual methodology proposed for this study.

These results refer to one site only, for a short period of time and must not be interpreted as representative of other UK sites.

The pilot study indicates that monitoring upwind and downwind concentrations can be used to establish methane emission rates. It has also provided data that has been used to modify the proposed approach.

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1 Introduction

The use of anaerobic digestion (AD) in the UK has been increasing significantly since 2011. Recent studies across Europe (see accompanying report on literature review and classification of AD plants) have shown that methane leakage from these plants can be significant and could significantly reduce GHG savings from the plant. If biogas production and biomethane injection is to fulfil its potential it will be important to understand biomethane leakage from these systems to be certain of GHG savings.

A biomethane measurement programme for estimating methane emissions and the corresponding GHG savings from different types and categories of AD plants in the UK is required. In order to allow such a programme to be implemented at a later stage, a methodology for monitoring methane leakage from AD plants should first be developed. The Department for Business, Energy and Industrial Strategy (BEIS) has commissioned a project to develop this monitoring methodology in preparation for a large-scale field trial. The objectives of this project are to:

(i) develop a methodology for the categorisation of AD plants (plants tested under large scale field trial will be selected from these categories) and define the boundaries for each of these categories,
(ii) define counterfactuals and develop a methodology for estimating GHG savings from AD plants, taking biomethane measurements into account,
(iii) undertake a literature review of the sources of methane leakage and fugitive emissions in an AD plant and of monitoring technologies and their suitability for methane measurements, and in parallel
(iv) develop a biomethane monitoring methodology and test it on a pilot plant.

This report is one of two deliverables for the project. A report on 'literature review and classification of AD plants', addressing (i) - (iii) above, is accompanying this one. This second report details the biomethane monitoring methodology (iv). The two reports are meant to be stand-alone but are cross-referenced where necessary.

The **main objectives of this report** are (a) to present the factors and parameters which we have taken into account in developing the methodology (**Section 2**), (b) to describe the comprehensive methodology developed (**Section 3**) and to (c) outline the results from a field trial where this methodology was tested (**Appendix A**).

The biomethane monitoring methodology described in this report has been developed for the purpose of estimating methane leakage (e.g. kg CH_4/h) from an AD plant, including from any biogas upgrading (i.e. biomethane to grid injection plants) and/or local consumption (e.g. combined heat and power (CHP) plant).

The method described provides a measurement of methane concentration which is relatively straightforward. The determination of a leakage rate (kg CH_4 / h) is, however, more challenging because of the difficulty in determining the discharge rates from leaks and open discharges. The estimated methane leakage rate resulting from this methodology will then be expressed as a fraction of the total methane produced by the plant.

The methodology developed is intended to be cost-effective, simple and practical and takes into consideration the different varieties and configurations of AD plant as described in the literature review and classification report mentioned above.

The main elements considered in developing the methodology described in Section 3 are:

(i) A site survey to undertake a short-term methane or surrogate[2] measurement campaign around key parts of the AD plant to screen potential emission sources and quantify methane emission rates where possible

(ii) Long-term measurements around the AD plant, coupled with wind speed/direction monitoring to assess the uplift in downwind ambient methane concentrations (compared to methane concentrations measured upwind) due to AD plant activities

(iii) Reverse dispersion modelling to characterise the total AD plant emission

(iv) Evaluation of data to exclude measurements which may include methane from AD plant components deemed to be outside the plant boundary

(v) Use of plant operation data to allow the amount of methane used for heat and electricity generation, grid injection or other purposes to be determined

(vi) Calculation of total methane production by adding the amount of methane leakage to the amount produced for heat and electricity generation/grid injection and calculating the proportion of methane leaked

(vii) Analysis of digestate to assess residual methane potential that could be released from digestate lagoons.

We undertook a pilot study to assess the suitability of the methodology developed. This pilot study included a partial upwind/downwind survey designed to match the prevailing wind direction (i.e. not around all sides of the AD plant). The pilot study was undertaken on a short-term basis (1 week) and details of the measurements undertaken are provided at Appendix A. For input to policy evidence, we suggest that a longer term measurement approach would be more appropriate. The following sections provide details on the approach to be adopted.

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[2] A surrogate being another measurement parameter that provides an indication of methane concentrations (for example flammable gas 'LEL' measurement).

2 Methodology considerations

2.1 Overview

As outlined above, the ultimate objective of the large-scale field trial is to provide better understanding of methane emissions from AD plants in the UK. It will also provide data for the quantification of these methane emissions. The aim of this study is to improve understanding of methane emissions from AD operations in the UK and to provide data to quantify methane emissions. The proposed methodology and the subsequent production of a site-specific protocol has been developed to reflect these aims. A number of considerations arise from the literature review task:

- Leak detection approaches (see literature review and classification report– Section 3)– these are useful to assess individual parts of the AD plant operation but generally do not allow determination of emission rates. The proposed methodology allows for some use of leak detection approaches for screening purposes, for example to identify possible high leak areas for siting monitoring equipment and information gathering.
- Quantification of methane emissions from individual AD plant components – where possible (for example through assessment of vented discharges) these may help minimise uncertainty in overall leakage rate.
- Collection of operational data from the AD plant during the monitoring campaign - it may be necessary to undertake additional monitoring of AD plant operations.
- Long-term or campaign approach – for policy evidence purposes it has been assumed that a long-term monitoring campaign, covering a range of diurnal, seasonal and operational variations would provide the most accurate estimate of annual methane leakage rates. However, this has implications for equipment costs (see Appendix B) and other factors. Most published studies have developed data from short-term measurement campaigns, but this may reflect the aims and technologies applied (for example the use of high cost supervised equipment).

2.2 Factors influencing development of a site specific methodology

There are a number of technologies that can be applied to measure methane concentrations from processes and the ambient environment. However, for AD plants there are various factors that affect the applicability of these technologies and how they are deployed. These are described in Table 1.

Table 1: Factors influencing a site-specific methodology

Factor influencing applicability of monitoring technology and Methodology	Details
Plant location	Activities surrounding the plant may • contribute to background levels of methane • influence wind speed and direction around the location • contribute compounds that may interfere with a particular detection principle Local topography • will influence wind speed and direction around the plant e.g. if the site is located in a valley Surrounding land ownership • may restrict access and prevent installation of monitoring equipment at a suitable distance to ensure mixing from the sources on the site.

Factor influencing applicability of monitoring technology and Methodology	Details
Plant layout	For example, some AD plant may be embedded within larger installations, e.g. on a large wastewater treatment plant. Also, lagoons holding spent digestate may be located offsite, perhaps at some distance from the rest of the AD plant. This will necessitate careful consideration of the boundary and the choice and placement of monitoring equipment. To some extent this may be resolved by the categorisation of the AD plant types, but plants will still differ. The height of discharge will influence the concentration at the fence-line (see literature review report – Section 3). If the methane measurement system is not carefully positioned this could result in an emission from a source being missed and not incorporated into the total. The challenge is to ensure that downwind sampling is close enough to the emission point that the uplift in methane concentration can be determined, but far enough downwind that emissions from different sources have mixed. The distance between source and fence-line is an important factor enabling complete mixing of the emissions from the sources present on site. The location of emission points will determine the position of downwind sample points along the fence-line as this will influence the average concentration measured. Individual sample points should be positioned to ensure that a representative average is obtained. Where possible/practicable the downwind measurements will be made at a distance of 5 to 10 times the height of the sources on site. The influences of obstructions between the source and measurement point can have a significant impact. The peer review of this methodology, undertaken by NPL[3], suggests that distances of 100 to 200m are required to eliminate these impacts. A concentration measurement should be made at this distance if possible and compared to the fence-line measurement to assess impacts of obstructions.
Variation in plant operational activities	As part of the AD process operation, there are occasional activities that could result in an emission of methane. These include; • Filling of silos – as the silo fills, gases present in the silo will be vented to atmosphere and, depending on the material stored, these gases could include methane; • Moving feed materials – these materials may be stored in covered storage clamps. When moving these materials, covers and surface materials will be moved resulting in exposure of surface materials and possible release of any gases produced within the store; • Mixing of materials in vessels prior to passing to digesters may result in a release from entrained gas and the start of decomposition reactions; • Filling of digesters occurs occasionally, but will result in gases being displaced by the additional material.
Seasonal variations	Some plants, for example municipal and commercial waste AD plant, will experience changes in materials used in the process throughout the year. This may influence the amount of methane generated. Seasonal factors that influence emissions are discussed in the Literature review and Classification report (Sections 1.2 and 2.6). Changes in ambient temperature may also influence the quantities of methane generated.

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[3] NPL peer review of draft methodology

Factor influencing applicability of monitoring technology and Methodology	Details
Variation in wind speed	High and low wind speeds will affect the data collected: • For low wind speeds, there may not be a measureable flow at the boundary; and • For high wind speeds, there could be limited mixing of emissions from different points before the fence-line. Using individual measurement/sensor points along the boundary could miss an emission under certain conditions.
Methane concentration	Concentrations – measurements during contained release (vent or stack) or at a leak will show a significantly higher concentration of methane than in the ambient environment. Background levels of methane will be 1.5-2 ppm or higher if there are other local sources. This requires a measurement system with a Limit of Detection well below background levels and with sufficient resolution to detect the small uplift due to the AD activity.
Services	Monitoring equipment requires services to enable its operation. These include; • Supply of power – due to the remote nature of AD plant and the area covered by the process, some monitoring locations will be a significant distance from a power supply. This will influence the selection of monitoring equipment e.g. battery or solar power or require the use of generators. • Mobile phone network (or local network) – to provide remote supervision and recovery of data.

2.3 Measurement technology

Table 2 provides a summary of the equipment to implement the monitoring methodology developed for this project. This is the equipment which was also deployed for the pilot study. Equipment costs are provided in Appendix B.

Our investigation of the technologies available showed that some of technologies do not have performance characteristics capable of providing data of sufficient quality (as discussed below). On the basis the literature review[4], a limit of detection (LoD) of 0.1ppm and resolution of at least 0.1ppm is required to enable measurement of the methane at the fence-line i.e. to distinguish between background levels and additional methane contributed by activities undertaken on an AD site. There is a possibility that moving to a downwind position of 100 to 200m will require the ability to resolve to better than 0.1ppm. This precludes the use of devices designed to monitor lower explosive limit (LEL). The lower explosive limit for methane is 5%. An LEL device for methane has a sensor range of 5% methane as 100% LEL. The quoted resolution for these devices is 1% of range, so the unit is capable of measuring to 500ppm methane. Such instruments would not be capable of measuring ambient levels i.e.1 to 2 ppm.

There are several technologies available that have been designed to measure ambient levels of methane. These include systems with the capability to measure at individual points and open path measurement systems. In addition there are systems that are designed to measure greenhouse gases, which combine the measurement of methane and carbon dioxide (CO_2) in the same system. During the digestion process CO_2 is produced in addition to methane. CO_2 is also the main combustion product of methane and CO_2 will be released from biomethane-to-grid plants. CO_2 may therefore provide a surrogate means to estimate methane leakage.

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[4] See the Literature review and classification report.

Table 2: Summary of Measurements - (lines in italics depend on site requirements and budget)

Measurement / activity	Type	Detection	No.	Main or pilot study	Use	LoD	Performance requirement	Comment
Methane concentration	Fixed sensor	Laser (IR) or FTIR	Multiple (4 in pilot study)	Main or pilot study	Methane Concentration in air	0.1ppm	0-10 ppm, concentration >10 LoD	To provide upwind and downwind concentrations. A single analyser sampling from multiple locations. In pilot study two instruments were deployed – one downwind and a second sampling upwind.
Methane concentration also CO_2	Portable	FTIR	1	Main or pilot study	Methane Concentration in air and vented release	0.1ppm	0-1000 ppm, concentration >10 LoD	To provide screening survey of process units and vented releases. To map downwind plume to aid positioning of fixed sensors. To provide validation of upwind/downwind sensors.
Flammable gas	Portable		1	Main or pilot study	%LEL	10 ppm	0-100% LEL	To provide screening survey of process units
Methane concentration	*Open path, multiple lines*	*Laser (IR)*	1	Main and pilot study	*Methane concentration*	0.1ppm	*0.1 ppm*	*To provide integrated upwind and downwind concentrations (used alongside fixed sensors in pilot study)*
Wind speed, wind direction, temperature, humidity	Met station		1	Main or pilot study	Wind speed and direction allows generation estimation of the emission flux			Filtering on wind direction (and speed if very low) allows selective exclusion or inclusion of valid methane data. Ideally, 3 Dimensional wind and directional measurement of wind speed
Temperature	*Thermocouple*		Multiple	Main or pilot study	*Allows validation of flare use or other process units*			*Possible addition to process monitoring. Not deployed in pilot study for flare (data available from plant monitoring system) but used on some process vents.*
Power meter	*Clamp meter*		Multiple	Main or pilot study	*Allows record of generation or power use (for example on agitators).*			*Possible addition to process monitoring. Not deployed in pilot study (data available from plant monitoring system).*
Data monitoring	Remote	Wireless and mobile router	1	Main or pilot study	To securely log measured information.		To provide remote access to data and check operation without need to visit site	Remote locations may prove a challenge but essential for any longer-term operation. Not deployed in pilot study.

* For definition of the acronyms, refer to Section 3 of the Literature review report.

2.4 Emission monitoring

There are two types of emissions encountered at an AD plant; emissions from a point source and fugitive emissions. The approaches adopted for each are discussed in the following sections.

2.4.1 Point sources

Measurements should be taken from emission point sources where possible. These include; stacks, ducts, vents and exhausts. These are constrained points where it is possible to measure both concentration and flow rate, thereby enabling emission rates to be calculated. It is possible to employ recognised standard methodologies such as EN standards at these positions, providing traceability of measurement. The concentrations at these points are significantly higher than those found at the fence-line and as such enable the use of more robust equipment such as lower explosive limit (LEL), landfill and biogas monitoring systems. Versions of such equipment are certified as intrinsically-safe, making it possible to undertake measurements within zoned areas on AD plant.

The higher emission concentrations found at vents can allow the application of EN or other standard measurement methods, which can reduce the uncertainty associated with these measurements. In addition, measurements of methane concentration and flow rate from specific emission points such as stacks, ducts and vents can be combined with meteorological data to model the methane concentrations from these sources at the fence-line. This allows cross comparison with the fence-line measurements.

2.4.2 Fugitive emissions

Fugitive emissions from sources such as double membrane roofs, concrete roofs, walls, lagoons and random leaks from seals can be assessed using an IR camera approach or a survey using portable instruments. Further details are given in Section 3 of the literature review report.

If a leak is discovered during a site survey, it may be assessed using a “bagging” approach[5] to measure the leak rate and the concentration of methane emitted. More typically, Leak Detection and Reporting can assess whether leak is significant so that the operator can undertake repairs.

2.5 Fence-line monitoring

Fence-line monitoring can be undertaken using open path and point measuring systems. This approach is suitable for measurements taken along lines upwind and downwind of the AD plant and associated equipment on site.

In both cases, care is needed to establish the appropriate locations and heights for measurements to provide representative samples. This should be planned based on site plans and prevailing wind direction and then verified by surveying the proposed measurement locations with portable methane concentration measurement systems to determine (in particular) an appropriate height for the sampling locations.

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[5] This approach can be used for leaks on valves and other small pieces of equipment. The equipment is bagged or enclosed to provide a means of capturing the leak and measuring leak rate directly or, more typically for a flammable gas, providing a known ventilation or purge flow through the enclosed space and monitoring the concentration in the gas flow leaving the enclosure.

2.5.1 Open path measurement

Open path systems (refer to Section 3 of literature review report) can be positioned to undertake measurements along a line of sight. These can be positioned to measure along the most appropriate line so that any contribution from activities other than from the AD plant can be measured upwind and the total methane emissions measured downwind. The difference in these two measurements is the contribution from the AD plant. The most appropriate line of measurement will be selected on a site-by-site basis. Factors that affect the selection of a suitable sample line include: site configuration; height of emission points; availability of location; wind speed and direction; and methane concentrations. These systems provide an average measurement along the measurement path.

There are a number of different system configurations that can be used. These include:

- Using one analyser/detector arrangement in combination with reflectors to measure along a number of different paths. This arrangement can provide measurements around the complete activity.
- Using two sources and detector systems arranged in one unit using two reflectors can provide measurements along four paths (two paths each).

The use of open path measurement systems provides an average concentration along the path measured. However the location of a plume is not defined without using multiple lines of measurement.

2.5.2 Point measurement

A single analyser that measures the concentration at a fixed point can be deployed to undertake measurements at the fence-line. When the analyser is used in conjunction with a multiplexer (a sample manifold to allow automatic switching between sampling points) a number of different points can be sampled using the same analyser. There are multiplexers available that enable the measurement of up to 32 individual points; the usual configuration of a multiplexer is 8 or 16 points. These systems can be used to set-up a grid of horizontal and vertical sample points which constitute an area over which a methane concentration can be determined.

2.6 Meteorological Measurements

A critical part of the proposed approach is the measurement of wind speed and direction. These measurements are combined with the measured methane concentrations to allow the calculation of a mass emission rate along the line of measurement.

Measurement of wind direction is required to preclude data when wind direction veers significantly from a prescribed range. Similarly, data will be excluded when the wind speed is too low, as the characteristics of the plume dispersion will be different and mixing of emissions from sources may not be completed before the point of measurement. This is particularly important when using point measurements to determine an average methane concentration[6]. Open path systems determine an average concentration along the path of measurement, so the impact of poor mixing is reduced.

Meteorological measurements should be undertaken using a dedicated portable meteorological (MET) station, ideally comprising a 3-dimensional anemometer to measure wind speed and vane to

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[6] In the worst case, a point measurement may be completely outside the plume.

monitor wind direction as well ambient temperature, pressure and relative humidity. The measurement of wind direction should ideally include both horizontal and vertical components.

2.7 Determining the emission rate

When the measured concentration is combined with the wind speed, the emission rate can be derived via a simple model or dispersion modelling of the data.

2.8 Plant Data

Plant data are required to enable quantification and correlation of the methane produced and/or used during the measurement period or periods. These are dependent on the type of plant and the usage of the methane produced:

- Gas produced for injection to the grid – the volume of the gas produced and injected into the grid.
- Gas produced for use to generate power – measured volume or calculated on the basis of performance of the engine used for generation.

It is important to assess the quality of this data by reviewing calibration, service records and published performance data.

2.9 Pilot Study

A pilot field trial was used to assess the methodology. It involved a trial at an agricultural AD plant. Details of the pilot study are provided at Appendix A. All the components of the methodology were tested during this study:

- Site selection – this involved a review of the site plan and site information to assess the suitability of the site for the pilot study
- Qualitative Site Survey – a visit to the site to:
    - Collect information on operational practices, routines and leak detection regimes;
    - Collect information relating to the AD plant and control systems on site; i.e. types of equipment used, data collected and monitoring equipment;
    - Review the type and location of emission points around the site associated with the AD process;
    - Review possible contributions from methane sources outside the site boundary;
    - Review contributions from sources on site such as storage clamps.
- Leakage device survey: a site measurement survey was undertaken with a methane leakage type device to locate sources around the site. This included assessment of:
    - Digester and gas holder areas – joints, seals, pumps and valves
    - Fugitive emissions – double membrane roofs, concrete roofs and solid walls
- Assessment of the availability of services and access for monitoring (this affects the type of monitoring technology that can be deployed or the requirement for alternative power supplies such as generators to be provided).
- Health and safety – to ensure that the work was undertaken in accordance with the Ricardo Energy & Environment and the site operator's health & safety requirements including issues such as:
    - Safe systems of work;
    - Zoned areas; and
    - Requirements for site inductions.

- Selection of measurement locations – this was assessed during a survey of concentrations at the fence-line using portable methane monitoring equipment.
- Installation of monitoring equipment – the position and height of sensors was investigated, using parameters such as:
    - distance/height from emission sources;
    - prevailing wind speed and direction; and
    - a survey of methane concentration at and near the measurement locations.
- Communication with the monitoring system – the location of the site influences the technology used to collect data remotely from the site. This can be achieved via:
    - a mobile phone network, in which case identification of the provider with the strongest signal in the area is needed; or
    - an internet connection if available.

The pilot study involved a short period of monitoring (one week). A limited number of sensors were deployed. These were located in a manner designed to match the prevailing wind direction at the time of the study. To assist in setting up the systems and deciding on the most appropriate wind direction, long term (5 to 8 day) forecasts were reviewed, as well as historic meteorological data for the area. Any data collected when the wind is not in the direction of measurement should be excluded from the determination of the methane leakage and any change in wind direction means that monitoring site locations have to be moved.

During the course of the pilot field trial the wind direction did change from southerly to westerly which enforced a change in sampling locations. This limited boundary approach was used to provide information/validation of the whole site methodology proposed. A single background (upwind) measurement point was adopted and methane concentrations assessed at several locations nearby to assure that this was at a representative measurement location.

Measurement of vent emissions and a leak survey were undertaken to provide further information to cross-check against measurements from the methodology which effectively measures a total methane emission.

The results from the pilot are provided in Appendix A.

3 Methodology

3.1 Overview

The approaches reviewed in the literature review (see Section 3 of report on literature review and plant classification) have most often focussed on the use of open path methods to assess aggregated methane concentrations, upwind and downwind of an AD plant. However, the use of fixed sensors provides the basis of a US Environmental Protection Agency (USEPA) 'other' test method[7] and this, coupled with a site survey to screen and quantify some onsite sources, forms the basis of the 'whole site' leakage assessment methodology provided here. This methodology has been selected as it provides a cost-effective, robust and practical way of metering methane leakage from a wide range of AD plants. The overall approach to the measurements for the different AD processes has been divided into the following sectors: (i) agriculture, (ii) municipal/commercial waste; and (iii) sewage sludge/industrial waste.

The key stages are:

(i) Identification of candidate sites – collection of information, survey of operators, questionnaire, review of site plan
(ii) Preliminary (reconnaissance) visit – understand plant, operation and process boundaries, prevailing wind direction, availability of monitoring points, power supplies, internet/mobile network access, access to plant data, security of site
(iii) Identification of monitoring needs – site monitoring plan, link to the categories of AD plant identified in previous tasks (see Appendix C)
(iv) Pre-installation equipment checks – calibration checks, verification of functionality including remote access of data
(v) Site survey – the objective the survey is to:
  a. screen potential emission sources;
  b. identify emission release points (vents, stacks);
  c. Identify suitable locations for fixed monitoring of methane emissions, meteorological measurement and location of data hub and communication systems.
(vi) Installation of fixed methane monitoring equipment, meteorological equipment, supporting data capture and remote monitoring equipment, sign-off of installation
(vii) Monitoring period supervision – review processes for data to assure data received is realistic, ongoing analysis, oversight of operation, arrangements for repair/replacement of faulty equipment, recovery and review of operating data.
(viii) Develop methane emission and leakage rates
(ix) Final survey – to repeat the initial survey to assess any changes (this could include repeat visits if required
(x) Site closure and equipment recovery
(xi) Summary reporting.

These key stages are shown in the flow chart below.

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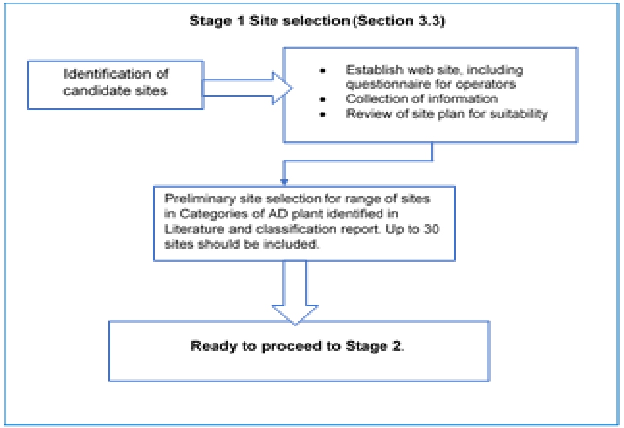
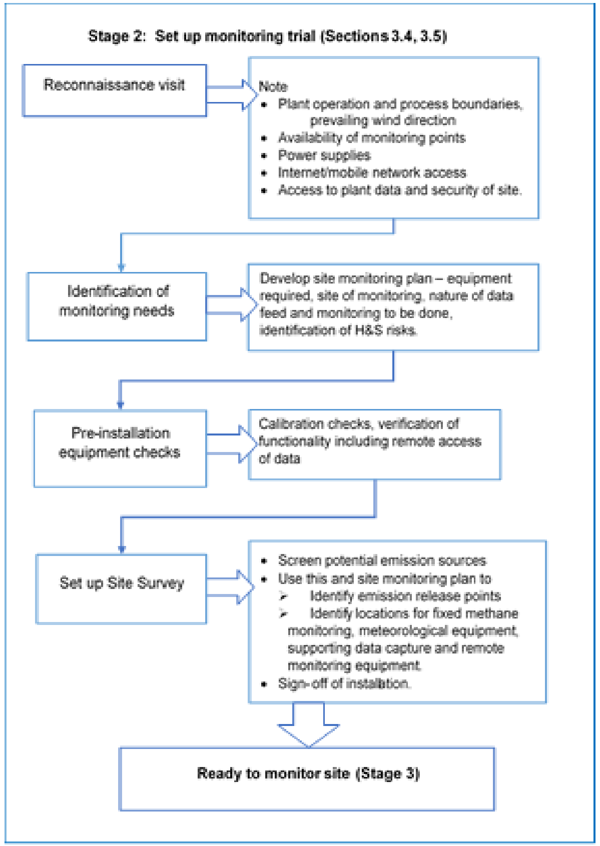
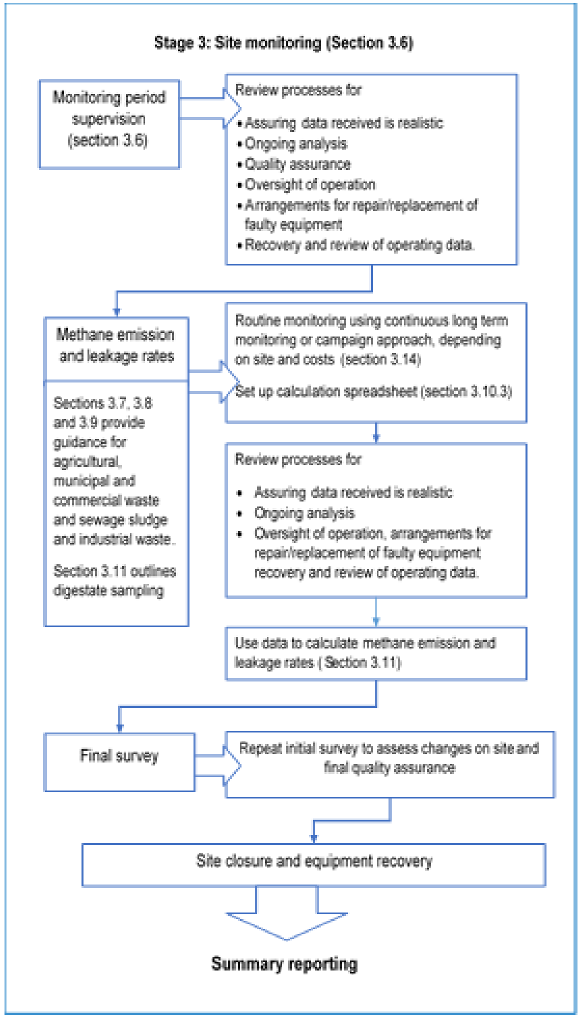
[7] For more information on this see the literature review and classification report that was produced as part of this project.


Stage 1 Site selection (Section 3.3)
Identification of candidate sites
Establish web site, including questionnaire for operators
Collection of information
Review of site plan for suitability
Preliminary site selection for range of sites in Categories of AD plant identified in Literature and classification report. Up to 30 sites should be included.
Ready to proceed to Stage 2.


Stage 2: Set up monitoring trial (Sections 3.4, 3.5)
Reconnaissance visit
Note
Plant operation and process boundaries, prevailing wind direction
Availability of monitoring points
Power supplies
Internet/mobile network access
Access to plant data and security of site.
Identification of monitoring needs
Develop site monitoring plan – equipment required, site of monitoring, nature of data feed and monitoring to be done, identification of H&S risks.
Pre-installation equipment checks
Calibration checks, verification of functionality including remote access of data
Set up Site Survey
Screen potential emission sources
Use this and site monitoring plan to
Identify emission release points
Identify locations for fixed methane monitoring, meteorological equipment, supporting data capture and remote monitoring equipment.
Sign-off of installation.
Ready to monitor site (Stage 3)


Stage 3: Site monitoring (Section 3.6)
Monitoring period supervision (section 3.6)
Review processes for
Assuring data received is realistic
Ongoing analysis
Quality assurance
Oversight of operation
Arrangements for repair/replacement of faulty equipment
Recovery and review of operating data.
Methane emission and leakage rates
Sections 3.7, 3.8 and 3.9 provide guidance for agricultural, municipal and commercial waste and sewage sludge and industrial waste.
Section 3.11 outlines digestate sampling
Routine monitoring using continuous long term monitoring or campaign approach, depending on site and costs (section 3.14)
Set up calculation spreadsheet (section 3.10.3)
Review processes for
Assuring data received is realistic
Ongoing analysis
Oversight of operation, arrangements for repair/replacement of faulty equipment recovery and review of operating data.
Use data to calculate methane emission and leakage rates (Section 3.11)
Final survey
Repeat initial survey to assess changes on site and final quality assurance
Site closure and equipment recovery
Summary reporting

3.2 Determination of methane leakage rate – whole site approach

The selected/proposed methodology is a "whole site" measurement approach using the site boundary to provide upwind and downwind measurement locations. This approach captures emissions from all the activities undertaken on site including methane released from vents and releases from, for example, material storage and other activities undertaken on the site that do not have a defined emission release point.

The method involves monitoring methane concentrations at up and downwind locations from the AD plant. Methane concentration data is combined with measurement of wind speed and direction to provide estimates of methane emission rates. The emission rate is determined using a simplified 'box' approach[8]. The data collected can be further assessed using reverse modelling based on concentrations measured at the line of measurement along with wind speed and direction.

Methane is a common background component in ambient air, present at approximately 1-2 ppm and would be present in the upwind measurement. In addition, upwind measurements include any contribution of methane from sources other than the AD plant. The downwind concentration comprises the upwind concentration and the contribution from the AD plant, so the difference in the up and downwind measurements is the contribution from the AD plant.

The contribution due to the AD plant is likely to be relatively small (at distances far enough from the plant to ensure adequate mixing). This means that to measure the likely concentration sensors will have to have a limit of detection of 0.1 ppm and a resolution of at least 0.1 ppm. It will not be possible to use this approach in low or at zero wind speeds as this condition will not provide a flow to the boundary. Also, high wind speeds may result in limited mixing of individual emission points.

Ideally, the location of downwind methane monitoring stations will be close enough to assure a measurable uplift in concentration but far enough that discrete sources merge into a common plume. In practice this may present a challenge in that the ideal methane monitoring locations may be outside the AD plant boundary. In most instances, the most practical methane monitoring location will be on the fence-line inside the AD plant boundary. Sites with tall discharges close to the plant boundary are preferably excluded.

Boundary considerations are discussed in Section 2.7 of the 'Literature review and classification report'. In general, sources of methane leakage located onsite are part of the boundary. However, complexities arise where:

- the AD plant is embedded within a wider facility;
- where AD related activities, such as storage of feedstock or digestate, are undertaken elsewhere (including at other AD plant sites) rather than at the site of the AD plant they serve.
- where unrelated activities may affect the results.

The survey should be used to assess whether the site is suitable for monitoring, and if so, how measurement points and lines can be located to eliminate the effects of other site activities unrelated to the AD plant.

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[8] This is a standard approach to calculating air emission rates. It assumes that the components being monitored are uniformly mixed throughout a fixed volume or box of air. The box is usually taken to extend vertically from the ground/terrain and horizontally to cover the region of distributed sources. There are a number of box models of various complexities described in the literature.

3.3 Site Selection

Candidate sites based on site categorisation (as developed literature review and classification report) and on the plant's operation should be identified for the large scale field trial. A prospective site should contain all the activities associated with the AD production of methane within its boundary. Plants with activities such as fuel and waste storage that are located a significant distance from the site are considered as unsuitable for the purposes of the large scale field trial. This screening assessment should be undertaken using the site plan and be desk-based.

Where possible the site plan should be a scaled drawing of the site and show the locations of the activities with distances between each location and the fence-line.

Following agreement between the site owner / operator and the measurement team who will install the equipment and conduct the measurements, a preliminary visit should be completed to understand the site activities, operations, physical layout and to undertake a site survey and to confirm categorisation (and associated process boundaries).

3.4 Site Survey

3.4.1 Background

The site survey should collect the following information;

- A description of the process, associated activities and location of emission points;
- A map and description of surrounding activities that could be sources of methane i.e. sites contributing to the background levels of methane other than the AD plant and its associated activities. This information should be combined with wind direction data collected during the survey and used to account for the impact of these sources on the results; impact;
- Prevailing wind direction – to be used as the basis for the initial positioning of the lines and points of measurement;
- Measurement requirements – power supplies, access, security, locations, communication signals, plant data capture systems;
- Health & Safety – site safety procedures, zoned areas, induction requirements, risk assessments.

A qualitative or semi-quantitative methane measurement survey is required to identify possible sources of methane emissions, the likely concentrations and suitable locations for monitoring equipment. This survey should include a review of concentrations from activities such as storage clamps and should be used to identify which onsite activities are sources of methane leakage.

The survey should be undertaken using a portable Fourier transform Infrared (FTIR) analyser configured to measure methane concentrations in two ranges (0-10 and 0-100 ppm), as well as CO_2 concentrations. Also a portable landfill or biogas analyser (for monitoring higher methane concentrations) should be used to assess potential leaks.

3.4.2 Source mapping, screening and sample point/plane location

The aim of the site survey is to provide an indication of the relationship of methane concentration with height relative to the source. Its objective is to define the survey points. This should be done by screening the AD plant activities in order to identify the major sources of methane leakage. Emission points include roofs, seals and walls, as discussed in the 'Literature review and classification report' (see Box 1).

Box 1: Sources of biomethane emissions in an AD plant

The following areas were identified in the Literature review and Classification report as being potential sources of biomethane emissions:

- Feedstock storage and feeding area
- Biogas production area
    - The digester
    - Gas storage
    - Pasteurisation
    - Gas equipment and pipework
- Digestate separation and storage area
    - Liquid digestate storage
    - Solid digestate storage
- Biogas utilisation area
    - Biogas combustion (CHP units and boilers)
    - Upgrading units
    - Utilisation of biomethane
    - Off-gas
    - Flares

To do this the location of each methane emitting source and its relationship to the fence-line should be mapped. The survey/sampling points can then be appropriately located for open path fence-line monitoring. They should be situated as far away from the methane sources as possible, to enable monitoring of the combined plumes from each source.

The measurement locations for these survey points should be determined from review of the site plan prior to the site survey being undertaken.

3.4.3 Selection of equipment for measurement

The selection of the monitoring technology should be undertaken on the basis of the concentrations measured in the site survey. These concentrations determine the limit of detection and the resolution required to achieve reliable data (and hence determine which monitoring equipment is most suitable).

3.5 Health & Safety

3.5.1 Risks

The site survey and monitoring measurements present a number of specific safety issues such as:

- Working at height
- Manual handling
- High temperatures at or near sampling points (e.g. engine exhausts)
- Presence of materials that can impact on health (asphyxiant gas, biohazard material)
- Flammable gas (zoned areas) and fire hazards
- Safe access to sample points: adequate space for equipment to be set-up and operated, avoiding hazards to monitoring contractors, plant operators or other potential visitors to the facility

- Weather, which may affect access and personnel safety.

Staff undertaking measurements should be required to undertake site safety inductions, operate to local safe systems of work and should be trained in the safe use of the equipment associated with the monitoring. A risk assessment should be carried out on the site prior to commencing work and reviewed at the beginning of each day to account for any changes.

3.5.2 Provision of Safe Systems of Work

Safe systems of work should be in place at the selected sites where the monitoring work is to be carried out. This will include working with:

- Platforms, safe means of access and egress to and from work areas, and a means by which monitoring equipment can be safely installed at each monitoring location.
- Power supplies – the measurement equipment requires power for its operation

The approach to safety must identify risks, eliminate them where possible, and reduce remaining risks as much as possible by training and the use of appropriate protective systems such as personal protective equipment (PPE).

All employees and contractors have a clear responsibility to co-operate and do their utmost to achieve a high level of safety awareness to prevent injury to themselves and others and to comply with all statutory obligations, as well as the safety requirements of their organisations.

All personnel undertaking measurements should have the right to refuse to enter any place where they believe significant risks exist, or where they consider there is not sufficient evidence to demonstrate that risks are adequately controlled. Staff should be supported in their assessment of the situation and solutions to eliminate and/or reduce the risk should be discussed and implemented.

3.6 Site Monitoring Plan

A site-specific monitoring plan should be developed to show what will be monitored, how it will be monitored and data recovery options at site survey. Each site should be divided into the following three process areas:

1. Storage & pre-processing
2. Gas production – AD/gasification
3. Usage - heat & power and upgrading of methane for injection into the grid.

Prior to the site survey, a site plan showing the activities and their respective locations can be used to provide a preliminary monitoring plan. Once the site survey is completed and the points and lines of measurement established, the monitoring plan can be refined to include these points and any data obtained from the site survey.

The plan will also include the collection of operating data available from the process so that methane production can be quantified during the period of measurement.

3.7 Agricultural AD Plant

These sites are associated with farms and can be located in the rural environments. They utilise manures, slurries and grains as feed materials.

3.7.1 Storage and pre & post-processing approaches

The potential activites that should be monitored for onsite methane emissions at agricultural AD plants are listed below. Measurement of the methane concentration, wind speed and direction up and downwind of the source should be recorded to determine each of their contribution to the site emissions.

Storage and pre & post-processing activities include sources such as;

- Feed material storage: slurry tanks, storage clamps and waste material storage such as lagoons.
- Transfer of grain materials that involve opening the store and allowing possible emissions of methane from the stored material
- Loading and unloading of slurries and grains.

Measurements from stores should be undertaken using a portable unit such as the FTIR or another device with a suitable limit of detection and resolution (LOD 0.1 ppm and resolution of at least 0.1 ppm) as these emissions are likely to be low compared to other emissions on site.

Mixing of materials prior to the digester is likely to be a source of methane. The vessels used are typically enclosed, with specific emission vents. These should be monitored for methane concentration and flow rate over a 24 hour period, to allow the calculation of the emission rate from each source.

Methane concentrations from mixing vessels are likely to be significantly higher than those emitted by the storage areas and other pre-processing activities. A number of existing devices are certified for use in explosion risk zones, which makes them suitable for use in explosion/fire-zoned areas including mixing vessels and digesters. When mixing systems are housed in containers or buildings, the vents from the buildings can be monitored to assess leaks by measuring concentration and flow rate.

Digestate lagoons contain material that has been processed, but may still have the potential to further produce methane. The type of containment in the lagoon will determine the monitoring approach to assess the methane contribution. For example, the material may be contained in bags with vents in the top surface to allow evolved gases to escape to prevent pressurisation of the bag. Safe access to these vents is likely to be difficult and therefore the methane emission rate should be measured by undertaking measurements up and downwind of the lagoons.

Solid material stores – end of process solid materials may be stored in a variety of ways e.g. in skips or silos. These are likely to be relatively low sources of methane. To confirm whether this is the case, leak detection measurements should be undertaken.

3.7.2 Gas production monitoring approaches

Digester emissions occur at vents, agitators, seals, valves, agitator supports and access ports. Monitoring of the digester vents should be undertaken using analysers located at the emission point where possible. Emissions from these vents should be determined by measuring concentrations and flow rates at the emission point. If flow rates cannot be determined (due to access or other constraints) then the digester vents should be assessed for leaks using a leak detection type approach.

It may also be difficult to quantify emission rates for digester seals, access hatches and other potential leak areas, and as a result of activities such as maintenance and cleaning, since the emissions are not usually from a defined area. In the site survey these components should be assessed for leaks using a leak detection type approach.

The boundary measurement line should be designed to capture the contribution from these sources.

3.7.3 Gas Usage

3.7.3.1 Heat and power

The biogas produced may be used in engines or turbines to generate electricity. These can be a source of methane emissions via unburnt fuel and from leakages within the supply system. These systems are usually housed in containers or similar enclosures.

- Methane leaks from the biogas supply system can be assessed by monitoring methane concentration and flow rate from the vents in the enclosure housing.
- Methane from unburnt fuel can be measured by monitoring concentration and flowrates from the exhaust stack(s).

The boundary measurement lines should be positioned to include the generation system, associated supply network and flare emissions.

3.7.3.2 Supply of gas to the grids

Any biomethane produced for injection into the grid must meet specific requirements, such as calorific value (CV). To achieve this, the biogas is upgraded to remove carbon dioxide and other contaminants and the methane content is enriched. The quality/composition of the biomethane produced is continually monitored to ensure that it meets the gas grid specification. Depending on the technology used, this clean-up process can result in emissions of biomethane. The vent from the CO_2 removal system should be monitored for methane concentration and flow rate. Care should be taken when making these measurements as CO_2 is an asphyxiant at concentrations greater than 7 to 10%.

To assess leaks from the upgrade system, measurements should be made at the enclosure vents.

3.7.3.3 Flares

In addition to the engines and injection to grid, there is usually a flare associated with the system. Flares are used to safely dispose of gas that cannot be used (for example during maintenance or breakdown periods).

Methane emissions from flares are generally a result of the flare’s ignition/start-up process and under conditions of poor operation, i.e. when the combustion conditions are not controlled correctly. The contribution from the flare should be calculated on the basis of the onsite gas composition as measured by the site’s gas analysis system, the flowrate to the flare and period required for ignition. This data should be available from the site control systems.

The boundary measurement lines should be positioned to include the potential flare emissions.

3.7.4 Plant Operating Data

Sites should be selected for monitoring only if adequate plant operating data are available to determine the quantity of methane produced during the period of monitoring. The calculation approach adopted should be defined on the basis of the data available and outlined in the monitoring plan for each site.

3.8 Municipal and Commercial Waste AD Plant

These plants deal with domestic and commercial waste materials including household wastes, commercial bakery, brewery and food processing wastes.

The potential activites that should be monitored for onsite methane emissions at municipal and commercial waste AD plants are listed below. Measurement of the methane concentration, wind speed and direction up and downwind of the source should be recorded to determine each of their contribution to the site emissions.

3.8.1 Storage and pre & post-processing approaches

Storage and pre & post-processing activities including feed material storage and waste material storage such as lagoons.

These emissions are likely to be low in comparison to other sources on a site and measurements should be undertaken using a portable methane measurement unit such as the FTIR or another device that has a suitable limit of detection and resolution (LOD 0.1 ppm and resolution of at least 0.1 ppm).

Waste materials tend to be stored and pre-processed inside enclosures due to potential odour issues. Measurement of the methane concentration and flowrate through building extraction/ventilation systems may be possible to provide an emission rate for the individual source and contribution to the overall site emission.

Mixing of materials prior to the digester is also likely to be a source of methane. The vessels used are typically enclosed and these enclosures have specific emission vents. This allows measurement of concentration of emissions and gas flow rate over a 24 hour period, enabling the calculation of the emission rate from each source. Concentrations from these sources are likely to be significantly higher than that produced within the storage areas and other pre-processing activities. This means that measurement technologies suitable for higher methane concentrations such as landfill, bio-gas, lower explosive limits and leak detection devices can be used. A number of these devices are certified for use in explosion risk zones which makes them useful as there are areas on an AD plant that are flame/explosion-zoned, typically around mixing vessels and digesters. When mixing systems are housed in containers or buildings the vents from the buildings should be monitored to assess methane leaks by measuring concentration and flow rate.

Digestate material stored in vessels or lagoons. Digestate has been processed, but may still have the potential to further produce methane. The type of containment will determine the monitoring approach. For example, vessels may have vents. In a lagoon, the material may be contained in vessels or bags with vents in the top surface to allow evolved gases to escape to prevent pressurisation of the bag. Safe access to these vents is likely to be difficult and therefore the methane emission rate should be measured by undertaking measurements up and downwind of the lagoons. This should be done to allow the contribution of the lagoon to be separated from background emissions. Methane emissions from digestate lagoons may vary seasonally, so long term monitoring is important. Seasonal factors that influence emissions are discussed in the Literature review and Classification report (Sections 1.2 and 2.6).

Solid material stores – the end of process solid materials can be stored in a variety of ways including skips and silos. These are likely to be relatively low sources of methane. Leak detection measurements will confirm if this is the case.

3.8.2 Gas production monitoring approaches

Digester emissions result from vents, agitators, seals, valves, agitator supports and access ports. Monitoring of the digester vents should be undertaken using analysers located at the emission point where possible. Emissions from these vents should be determined by measuring concentrations and flow rates at the emission point. If flow rates cannot be determined (due to access or other constraints) then the digester vents should be assessed for leaks using a leak detection type approach.

It may also be difficult to quantify emission rates for digester seals, access hatches and other potential leak areas (also during activities such as maintenance and cleaning) as the emissions are not usually from a defined area. In the site survey these components should be assessed for leaks using a leak detection type approach.

The boundary measurement line should be designed to capture the contribution from these sources.

3.8.3 Gas Usage

3.8.3.1 Heat and power

The gas produced can be used to fuel engines or, turbines to generate electricity. These can be a source of methane via unburnt fuel being emitted and from leakages within the supply system. These systems are usually housed in containers or other enclosures with vents to the atmosphere. Measurement of concentration and flowrates from these units will be undertaken by undertaking measurements in the exhaust stacks. Methane leaks from the biogas supply system can be assessed by monitoring methane concentration and flow rate from the vents in this enclosure housing.

The boundary measurement lines should be positioned to include the generation system and associated supply network.

3.8.3.2 Supply of gas to the grid

Any biomethane produced for injection into the grid must meet specific requirements e.g. calorific value (CV). To achieve this the biogas is upgraded to remove carbon dioxide and other contaminants and the methane content is enriched. The quality/composition of the biomethane produced is continually monitored to ensure that it meets the gas grid specification. Depending on the technology used, this clean-up process can result in emissions of biomethane. The vent from the CO_2 removal system should be monitored for methane concentration and flow rate. Care should be taken when making these measurements as CO_2 is an asphyxiant at concentrations greater than 7 to 10%.

To assess leaks from the system measurements will be made at the enclosure vents.

3.8.3.3 Flares

In addition to the engines and injection to grid, there is usually a flare associated with the system. Flares are used to safely dispose of gas that cannot be used (for example during maintenance or breakdown periods).

Methane emissions from flares are generally a result of the ignition/start-up process and under conditions of poor operation, i.e. when the combustion conditions are not controlled correctly. The contribution from the flare should be calculated on the basis of the onsite gas composition as measured by the site's gas analysis system, the flowrate to the flare and period required for ignition. This data should be available from the site control systems.

The boundary measurement lines should be positioned to include the potential flare emissions.

3.8.4 Plant Operating Data

Sites should be selected for monitoring only if adequate plant operating data are available to determine the quantity of methane produced during the period of monitoring. The calculation approach adopted should be defined on the basis of the data available and outlined in the monitoring plan for each site.

3.9 Sewage sludge and industrial waste AD plant methodology

Sewage and industrial waste AD plant are usually embedded within a site that also has a number of other activities in close proximity. These activities are also likely sources of methane that should be excluded from the methane measurements.

This can be achieved by careful placement of the measurement systems, combined with use of meteorological data to exclude periods where the wind direction indicates that other methane sources may influence the measured methane concentrations.

3.9.1 Storage and pre & post-processing approaches

Storage and pre & post-processing activities include feed material storage and waste material storage such as lagoons. The objective is to include emissions from these and associated activities such as transfer of waste materials.

Measurements from stores should be undertaken using a portable unit such as the FTIR or another device with a suitable limit of detection and resolution (LOD 0.1 ppm and resolution of at least 0.1ppm) as these emissions are likely to be low compared to other emissions on site.

Mixing of materials prior to the digester is also likely to be a source of methane. The vessels used are typically enclosed and these enclosures have specific emission vents. This allows measurement of emission concentration and flow rate of emissions over a 24 hour period, enabling the calculation of the emission rate from each source. Concentrations from these sources are likely to be significantly higher than that produced within the storage areas and other pre-processing activities. This means that technologies such as landfill, bio-gas, lower explosive limits and leak detection devices can be used. A number of these devices are certified for use in explosion risk zones which makes them suitable for use in explosion/fire-zoned areas, typically around mixing vessels and digesters. When mixing systems are housed in containers or buildings the vents from the buildings should be monitored to assess leaks by measuring concentration and flow rate.

Digestate material may be stored in vessels or lagoons. The material has been processed, but can still have the potential to further produce methane. The type of containment will determine the monitoring approach. For example, vessels may have vents. In a lagoon, the material may be contained in vessels or bags with vents in the top surface to allow evolved gases to escape to prevent pressurisation of the bag. Safe access to these vents is likely to be difficult and therefore the methane emission rate should be measured by undertaking measurements up and downwind of the lagoons. This should be done to allow the contribution of the lagoon to be separated from the background emissions. This approach would also enable the contribution to the methane leakage from a variety of different lagoon arrangements to be determined. Methane emissions from digestate lagoons may vary seasonally, so long term monitoring is important.

Solid material stores – the end of process solid materials can be stored in a variety of ways including skips and silos. These are likely to be relatively low sources of methane. Leak detection type measurements will confirm if this is the case.

3.9.2 Gas production monitoring approaches

Digester emissions result from vents, agitators, seals, valves, agitator supports and access ports. Monitoring of the digester vents should be undertaken using analysers located at the emission point where possible. Emissions from these vents should be determined by measuring concentrations and flow rates at the emission point. If flow rates cannot be determined (due to access or other constraints) then the digester vents should be assessed for leaks using a leak detection type approach.

It may also be difficult to quantify emission rates for digester seals, access hatches and other potential leak areas (also during activities such as maintenance and cleaning) as the emissions are not usually from a defined area. In the site survey these components should be assessed for leaks using a leak detection type approach.

The boundary measurement line should be designed to capture the contribution from these sources.

3.9.3 Gas Usage

3.9.3.1 Heat and power

The biogas produced may be used in engines or turbines to generate electricity. These can be a source of methane via unburnt fuel and from leakages within the supply system. These systems are usually housed in containers or other enclosures with vents to the atmosphere. Measurement of concentration and flowrates from these units will be undertaken by undertaking measurements in the exhaust stacks. Methane leaks from the biogas supply system can be assessed by monitoring methane concentration and flow rate from the vents in this enclosure housing.

The boundary measurement lines should be positioned to include the power generator and associated supply network.

3.9.3.2 Supply of gas to the grid

Any biomethane produced for injection into the grid must meet specific requirements e.g. calorific value (CV). To achieve this the biogas is upgraded to remove carbon dioxide and other contaminants and the methane content is enriched. The quality/composition of the biomethane produced is continually monitored to ensure that it meets the gas grid specification. Depending on the technology used, this clean-up process can result in emissions of methane. The vent from the CO_2 removal system should be monitored for methane concentration and flow rate. Care should be taken when making these measurements as CO_2 is an asphyxiant at concentrations greater than 7 to 10%.

To assess leaks from the system measurements should be made at the enclosure vents.

3.9.3.3 Flares

In addition to the engines and injection to grid, there is usually a flare associated with the system. Flares are used to safely dispose of gas that cannot be used (for example during maintenance or breakdown periods).

Methane emissions from flares are generally a result of the ignition/start-up process and under conditions of poor operation, i.e. when the combustion conditions are not controlled correctly. The contribution from the flare should be calculated on the basis of the onsite gas composition as measured by the site's gas analysis system, the flowrate to the flare and period required for ignition. This data should be available from the site control systems.

The boundary measurement lines should be positioned to include the potential flare emissions.

3.9.4 Plant Operating Data

Plant operating data is required to determine the quantity of methane produced during the period of monitoring. The available data should be assessed during the site selection process and if data is not available to determine the quantity of gas produced, the site should not be selected. The approach and calculation to be adopted will be defined on the basis of the data available and outlined in the monitoring plan for each site.

3.10 Measurement Quality Assurance

The following 'best practice' steps should be followed to provide quality assurance of the data generated during the site measurements.

3.10.1 Gaseous measurement

The operation of gaseous analysers should be checked before deployment to site, including checking and calibration against certified calibration gases. The following performance parameters must be checked, as they are recognised contributors to measurement uncertainty:

- The linearity of the analysers must be checked using calibration gases and a gas dilution system for five concentrations representative of the range of the analyser, this can be done before deployment to site;
- Before analysers are deployed they must be checked for known concentrations of methane and potential interferents (carbon dioxide);
- Onsite response checks must include, where possible, the use of certified calibration gases before and after each measurement.
- Records of these checks should be maintained.

3.10.2 Meteorological data

The methodology relies on the measurement of wind speed and direction to determine the emission rate from the site. As a consequence, anenemometers and wind vanes with current calibration certificates must be used. Once equipment is installed onsite, it should be checked against a second calibrated device.

3.10.3 Calculation Spreadsheet

For the purposes of assessing methane emissions from the AD plant, a spreadsheet or database to handle data and derive results will be needed. The template used should be developed according to quality assurance procedures that set out:

- Structure and design
- Development of references
- Reviewing and error checking

- Auditing – to enable auditing against Department for Business, Energy & Industrial Strategy's (BEIS) 30-criteria.

3.11 Calculations

3.11.1 Estimate of Uncertainty

Uncertainty has been estimated using quoted performance data from monitoring equipment in accordance with the methodology defined in internationally recognised standards[9]. Where applicable, the following factors are recognised and defined in BS EN 15267-3 as contributing to the uncertainty of measurement:

- 'Span' test gas[10] concentration (mg m^{-3})
- 'Zero' test gas[11] concentration (mg m^{-3})
- Lack of fit (%)
- Zero drift in the maintenance interval (%)
- Span drift in the maintenance interval (%)
- Influence of ambient temperature at zero (%)
- Influence of ambient temperature at span (%)
- Influence of sample gas pressure (%)
- Influence of sample gas flow (%)
- Influence of supply voltage (%)
- Cross sensitivity (interference) (%)
- Repeatability standard deviation at Zero (%)
- Repeatability standard deviation at Span (%)
- Standard deviation from paired measurement under field conditions (%)
- Uncertainty of the reference materials (%) Span
- Uncertainty of the reference materials (%) zero
- Excursion of measurement beam for open path systems.

The linearity (lack of fit) of the analysers should be checked using calibration gases and a gas dilution system to give a range of five concentrations within the range of the analyser. Published performance data should be used, where available, to determine the uncertainty of measurement associated with a particular technology.

In the absence of some of these data, a sensitivity analysis of the factors influencing the measurements can allow identification of the factors which contribute most to uncertainty of the results.

3.11.2 Emission Rates

Reverse dispersion modelling may be applied to estimate the emission rate from an assumed single discharge point(s) or region(s) within the AD plant. Proprietary modelling software tools such as the Cambridge Environmental Research Consultants ADMS[12] and the US Environmental Protection Agency AERMOD[13] packages enable such modelling. ADMS allows application of a simple screening

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[9] (CEN standards and the Joint Committee for Guides in Metrology "Evaluation of measurement data — Guide to the expression of uncertainty in measurement" (GUM)

[10] A reference gas of known concentration (of methane) used to assess the response of a measurement system.

[11] A reference gas with no or very low quantity of methane used to assess the response of the measurement system.

[12] Details here http://www.cerc.co.uk/environmental-software/ADMS-model.html

[13] Details here : https://www3.epa.gov/scram001/dispersion_prefrec.htm

package which enables input of measured windspeed and concentration data and the application of user-defined parameters (weather conditions, plant dimensions) to develop emission rates (see Appendix A).

Emission rates have been determined using a simplified approach that assumes that the line of measurement is a representative section of the face of a box, the area of which has been defined by the site dimensions and a height informed by a dispersion modelling assumptions, the emission rate from the site is given by:

$$E = (C_d - C_u) \times A \times V \times 0.001$$

Where:

E = emission rate, gs^{-1}
C_d = Downwind concentration, mgm^{-3}
C_u = Upwind concentration, mgm^{-3}
V = wind speed, ms^{-1}
A = area of box, m^2

3.12 Digestate Sampling

As explained in Section 2.8 of the 'Literature review and AD plant classification' report, Ofgem does not require operators to report methane emissions from digestate as part of its sustainability criteria reporting[14]. The methodology outlined in this paper, however, includes these emissions. In order to compare with the Ofgem criteria, we need a method for excluding digestate emissions from the total methane emissions. Methods for measuring fugitive methane emission from digestate storage that are available in the literature are usually complex and costly.

We have proposed instead that siting and selective use of measurement points for specific wind directions can allow the separate quantification of downwind methane concentrations for the lagoons and the rest of the plant. To do this sensors upwind and downwind from the site should be installed.

If the storage lagoons are located separately offsite then additional monitoring will be required.

Sampling of digestate is a common practice on AD sites for quality/end-of-waste purposes and as it helps site operators understand the stability of the digestate[15]. The key measurements are volatile fatty acids (concentration by species) and residual biogas potential (RBP) which is an estimate of the remaining methane content in the digestate. We propose that the monitoring methodology should allow for collecting and analysing samples of digestate at different points in time which will then allow an estimation of the methane leakage rate. Note that sample volumes of 1 litre are required for the analysis.

Using data on the RBP, the approach proposed can provide an estimate of the methane emission rate (kg CH_4 / hr). The procedure for translating data from the sample analysis report into methane leakage rates would have to be developed. The impact of different conditions and time may have a significant impact on the release rate. Estimates of the uncertainty of such an approach would need to be developed.

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[14] https://www.ofgem.gov.uk/system/files/docs/2017/01/sustainability_self-reporting_guidance_jan_2017.pdf

[15] See WRAP good practise guidance on digestate and compost use in agriculture available here : http://www.wrap.org.uk/sites/files/wrap/Digestate_compost_good_practice_guide_reference_version.pdf and PAS 110 http://www.wrap.org.uk/content/bsi-pas-110-producing-quality-anaerobic-digestate

3.13 Questionnaire for large scale field trial

In the large scale field trial, we recommend that a questionnaire is sent to site operators to help select the most appropriate sites for monitoring. Criteria for selecting the sites will include the operator's willingness to participate in the monitoring programme and ensuring that all the different AD plant categories are covered. We recommend that the contractor develops a dedicated website for the selection of sites or for the monitoring programme as a whole. The preliminary questionnaire should first ask site operators who are willing to participate in the programme to register. A second questionnaire should be sent to sites covering all AD plant categories and should explore questions related to:

- Site location and address (to allow investigating the site surroundings),
- Layout and access around the site,
- Availability and level of monitoring of the AD plant,
- Size of plant (feedstock throughput, CHP output),
- Type of technologies (digestion technology: dry vs. wet; mesophilic, thermophilic or both; upgrade technology: membrane, amine absorption, waterwash),
- Feedstocks and questions specific to processing of feedstocks and digestate and location of the digestate storage lagoons,
- Use of leak detection monitoring on the site .

3.14 Deployment of the Methodology

Long term emissions from sites can be determined using one of two alternative strategies: continuous long term monitoring or campaigns of measurements.

Continuous long term measurements require the installation of monitoring systems around the boundary and at emission points of selected sites. Monitoring systems would be left at each site for the period of monitoring. A period of one year of monitoring would provide data covering influences of:

- the environment (e.g. changes in temperature and humidity);
- differing feedstock materials used on site, which is important on sites where there may be seasonal differences;
- abnormal occurrences such as equipment failures;
- infrequent operational practices – such as cleaning and maintenance.

Wireless sensors should be deployed to collect data from each of the analysers and measurement devices. These sensors should be networked to a data storage and gateway unit designed to send data at regular intervals (twice a day) via an internet based system to a central database. This will allow calculation of emission rates and system checks for faults or other issues. For data security, logging and storage capacity should be situated on site as part of the monitoring system. Long term monitoring also requires site visits to service the systems and resolve any problems that may arise.

A campaign approach involves the monitoring of selected sites for repeated short periods (such as once a quarter) throughout the year. This approach reduces the capital investment in monitoring equipment as monitoring periods can be planned to allow the same equipment to be used at more than one site. As with continuous monitoring, the recommended project period is a year, enabling measurements to be undertaken under differing environmental (seasonal) conditions. A year will also be long enough to collect data during all activities associated with the plant. Careful planning by the contractor should also allow maintenance and cleaning of systems to be incorporated into a monitoring period. The monitoring systems should be installed and left throughout the monitoring period selected. Data should be collected remotely and reviewed on daily basis as above to allow calculation of emission rates and system checks.

Campaign monitoring requires measurements around the complete boundary to ensure that sufficient data was collected to allow calculation of leakage rate. This is because if only one up and downwind boundary pair were monitored, a change in wind direction could significantly reduce the quantity of data available, as data would have to be eliminated when the wind was not in the required direction. This could potentially mean that no useful data is collected during one or more monitoring periods, or that the campaign would need to be extended.

For AD plants that operate very consistently and where there are rigorous leak detection regimes, monitoring periods shorter than a week may also be acceptable. However, we believe this approach is likely to provide a restricted 'snapshot' view of operation. If this approach were adopted we believe it would be important to monitor many more AD plants to provide confidence that the range of operating conditions are adequately covered by the monitoring.

4 Conclusions and Recommendations

The development of the methodology in this report is supported by a comprehensive review of technologies and methodologies used to monitor methane leakage (See section 3 of the 'Literature review and AD plant classification' report[16]).

The methodology has been developed to be both practical and cost-effective, so that it can be applied to as many sites as possible. The methodology is based on a whole site approach i.e. undertaking measurements of methane concentrations at the site boundary. This approach relies heavily on the assumption that there will be sufficient distance between the source and the point of measurement to ensure that all of the sources present contribute to the concentration at the measurement point. The specification of the measurement position is critical so that it can be ensured that activities not associated with the AD process are excluded.

Two measurement systems are proposed for use at the fence-line: open-path and/or multiple-point measurement, utilising sensors located around the site. To assess the site's methane emissions and to eliminate contributions from other sources, upwind and downwind measurements should be undertaken. This approach means that the measurement technologies that can be deployed are restricted to those that are capable of distinguishing between the background concentration of methane and the small uplift in concentration due to the contribution from the process.

This approach also requires the measurement of the meteorological conditions to determine the emission rate from the site. Reverse dispersion modelling is proposed to assess the mass emission rates in conjunction with the concentration, wind speed and direction data collected during the monitoring period.

In addition to fence-line monitoring, it is also proposed to monitor methane emissions at vents and point sources where possible. This data allows the confirmation of the total methane emissions measured at the fence-line. Furthermore, as emissions associated with digestate storage are not required for reporting to Ofgem under the sustainability criteria reporting requirements, our methodology provides a method for estimating emissions from digestate storage so that it can be subtracted from the calculation of total methane emissions, if required.

Our approach includes both point sources and fugitive emissions, including emissions generated from digester roofs, seals and leaks that occur due to failures which are difficult to detect due to random occurrences. We undertook a pilot study on an agricultural AD plant consisting of both a CHP unit and a gas to grid injection unit. We applied both open-path and multiple-point measurement techniques to investigate the application of the proposed approach. The pilot study indicates that monitoring upwind and downwind concentrations can be used to establish methane emission rates.

There is scope to isolate AD plant operations using this approach, but this will depend on individual site layout, wind direction and other factors.

The primary purpose of the pilot study was to test the methodology. The study was of short duration (only 4 days) and therefore the results must not be considered to be representative of the plant over the whole year. However, for the site examined and for the short period of measurement, we estimated a whole site methane loss of 4.1%, with methane losses coming predominantly from the lagoons (3.4%), and much lower losses from the CHP unit (0.4% of methane produced or 3.1% of

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[16] The report was the first part of the work to develop this methology. It is available as Methodology to assess biomethane leakage from AD plants: Part 1: Report on proposed categorisation of AD plants *and* literature review of methane monitoring technologies

CHP plant methane throughput) and the upgrade unit (0.3% of methane produced or 0.3% of upgrade plant throughput).

The emission rates indicate a greenhouse gas saving of 77% under the current Ofgem reporting criteria and 59% under the counterfactual methodology proposed under this study.

These results refer to one site only, for a short period of time and must not be interpreted as representative of other UK sites.

Measurement of downwind methane concentrations can be undertaken using either:

- a measurement system sampling at discrete upwind and downwind measurement points. Use of a multiplexer enables a number of sample points to be measured using one analyser.
- an open path measurement system.

Additional measurement studies are recommended to assess suitability of the methodology for sites with adjacent activities with potential for methane emissions and for different site configurations, for example:

- different feedstock materials
- different ages of plant.

The selection of the downwind sample locations should be defined with reference to the position and height of emission points. Downwind sampling locations need to be sufficiently far downwind from emission sources to adopt the reverse dispersion modelling approach.

Long-term monitoring is recommended as a means of assessing variability of emissions through seasonal or operational factors however this would have a cost implication.

Campaign monitoring may be a more cost-effective approach for similar monitoring in future but the pilot study indicates that the amount of data can be seriously impacted by weather and plant operations during short-term campaigns.

5 Disclaimer

Note that mention of manufacturers and products does not represent endorsement of the products used in the study.

Appendices

Appendix A: Pilot study report

Appendix B: Equipment & Technology Costs

Appendix C: Category Methodology

Appendix A – Pilot study

A Pilot Study

A.1 Introduction

A pilot study employing the draft proposed methodology was undertaken during the week commencing 15 May 2017 at an AD plant that uses agricultural waste products i.e. grains, animal feeds and slurries to produce methane for injection into the gas grid.

Note that mention of product names in the following text and their use during these measurements does not represent an endorsement for these items.

A.2 Monitoring Systems deployed on site

A number of technologies were deployed to undertake the measurements in accordance with the proposed methodology described in Section 3.

A.2.1 Meteorological data station

Two devices were deployed

- A Wind Sonic Solid state wind speed and direction sensor; and
- A Windmaster 3D ultrasonic anemometer

The Windsonic unit provides wind speed and direction data into one serial stream to a Squirrel SQ2010 data logger. Data from which was downloaded to *.csv files using Squirrel view software. The WindMaster 3D ultrasonic anemometer is capable of monitoring wind speeds of 0-45m/s providing digital outputs. These parameters were recorded by the open path methane measurement system.

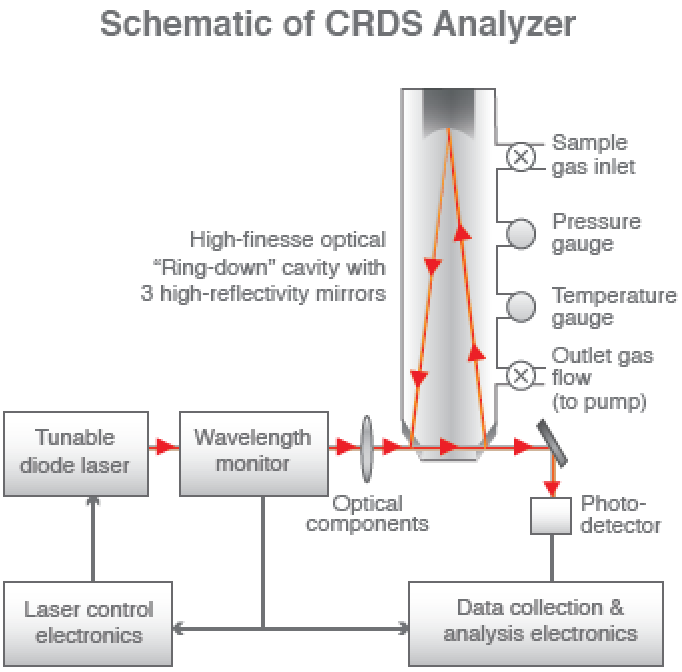
A.2.2 Los Gatos Research Green House Gas Portable analyser

The Los Gatos Research (LGR) system utilises off-axis integrated cavity Output Spectroscopy (OA-ICOS) to undertake the measurement of concentrations of gaseous species.

The analyser utilises a cavity enhanced absorption technique, which employs a high-finesse optical cavity as the measurement cell. The LGR technology is an advance over conventional first-generation cavity ring down spectroscopy (CRDS) techniques. LGR's technology can record absorption spectra over a far wider range of optical depths (absorbance values) and over a much wider range of mole fractions (concentrations). The entire absorption spectra can be displayed to the user in real time allowing for immediate system diagnostics and performance validation.

Cavity ring-down spectroscopy is a laser absorption system taking advantage of improved analytical sensitivities made possible by using long path lengths achieved by reflecting the measurement beam many times within the instrument. The system consists of a pulsed tuneable diode laser, tuned specifically to the absorption frequency of methane, two highly reflective mirrors that reflect the pulsed beam through the sample containing the target absorbing species (it can be in the order of 10,000 times). The light transmitted is through the exit mirror to the detector on each pass and measured against time. The signal measured will decay with respect to time. This decay time is dependent on the mirrors reflectivity, the distance between the two mirrors, the speed of light and the absorption coefficient of the absorbing species in the cavity. Figure A1 shows the arrangement of a typical CRDS system.

Figure A1 Schematic of a CRDS Analyser[17]



A.2.3 Gasmet Fourier Transform Infrared (FTIR) analyser

FTIR gas analysers identify and measure gaseous compounds by their absorbance of infrared radiation. This is possible because every molecular structure has a unique combination of atoms, and therefore produces a unique spectrum when exposed to infrared light. Instrumental analysis of the spectrum (2 to 12 micrometer wavelength) enables the qualitative identification and quantitative analysis of the gaseous compounds in the sample gas. Importantly, FTIR analysers are able to simultaneously measure multiple analytes in complex gas matrices, detecting virtually all gas-phase species (both organic and inorganic), except diatomic elements such as N_2, O_2 and noble gases He, Ne. For example, the Gasmet FTIR gas analyser collects a complete infrared spectrum (a measurement of the infrared light absorbed by molecules inside the sample gas cell) 10 times per second. The actual concentrations of gases are calculated from the resulting sample spectrum using a patented analysis algorithm.

A.2.4 Mirico LDS 100 Open Path System

The LDS 100 Open Path analyser is designed to undertake gas analysis over long distances. It has the capability to undertake measurements in a range of challenging conditions such as fog, rain and in the presence of high aerosol concentrations whilst maintaining performance.

The system utilises a tuneable diode laser (TDL) using molecular dispersion. The configuration of the Mirico LDS 100 is shown **Figure A2**2.

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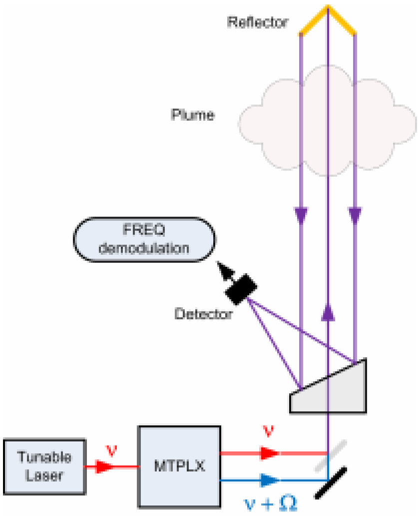
[17] This diagram is reproduced from Los Gatos product literature

Figure A2 Schematic of Mirico LDS 100 Spectrometer[18]



The output from the tuneable laser is directed to a frequency shifter, which splits the beam into a fundamental and the frequency-shifted wave. These are then combined into a single dual-frequency laser beam. This is focused onto a fast photo detector that extracts the beat-note between both frequency components. The area between the transmitter and reflector acts as the measurement path. The dual-frequency beam interacts with a molecular transition and both wavelengths experience slightly different refractive indices. As the laser is frequency-chirped, the difference in propagation velocities impacts the instantaneous frequency difference between the two optical waves, and this effect (that is proportional to the chirp rate) can be directly measured as an instantaneous frequency of the heterodyne beat-note signal. This signal enhancement due to the frequency chirp rate is central to the concept of LDS signal generation.

A.2.5 EcoTec TDL-500 portable laser methane analyser

The EcoTec TDL 500 Laser Methane Analyser is a portable, methane specific gas detector incorporating Tunable Diode Laser detection. It is ATEX- certified for potential use in flammable atmospheres and is designed for safe leak surveying in difficult environments including natural gas networks and landfill sites.

A.2.6 QRAE MultiRAE Lite

These units were deployed to measure the emission concentrations at emission points around the site. The units are configured to measure methane but indicated as a percentage of the lower explosive limit (% LEL). The LEL for methane is 5%. These analysers have an effective measurement range of 0-100% LEL (0-5% methane). The units utilise non-destructive infrared (NDIR) measurement cells to determine the concentration of methane present in a sample. The units deployed had internal pumps which drew a sample through sample lines to the measurement cell.

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[18] This diagram is from Mirico Ltd product literature

A.3 Procedure

A.3.1 Site Plan

Figure A3 shows the plan of the AD site selected for the pilot study.

A.3.2 Site Description

The AD plant utilises farm materials to generate methane; these include grains, silage and slurries. The site has three storage clamps where silage and other feedstock materials are stored. There is a covered grain store, which is pneumatically connected to the two mixing vessels. The slurries are tankered onto site and stored in a holding tank. The silage is placed in the mixing vessels using a bucket loader. The grains, silage and slurries are mixed with a proportion of digestate in the mixing vessels prior to being pumped into the digesters. There are two digesters on site producing biogas. The biogas is passed to a CHP plant (a gas engine providing power and heat to the site) or to a gas preparation unit that uses membrane technology to separate selectively remove CO_2 from the biogas. The CO_2 is vented to atmosphere and methane-rich biogas is passed to the natural gas grid with propane added as needed to moderate the gas quality.

The digestate is passed to a filter – solid digestate accumulates below the filter and small quantities can be held on site. Liquid digestate is passed to two lagoons. The lagoons are lined with bags that hold the liquid digestate. Each bag has a number of vents and agitators to ensure that there is no gas build-up and that the material is mixed. The solid and liquid digestate are removed from site by tanker for soil treatment.

A.3.3 Selection of Locations and Sampling Points

The direction and velocity of the wind determined the selection of the sampling positions around the site throughout the test periods. The boundary fence of the site formed the limit for the measurements with the exception of the upwind open path measurements. It was not possible to locate the upwind open path system on the site because of the site boundary and neighbouring buildings interfering with the line of sight across the southeastern corner of the site. Consequently the open path system was located outside the site boundary where an unobstructed upwind sampling location was available.

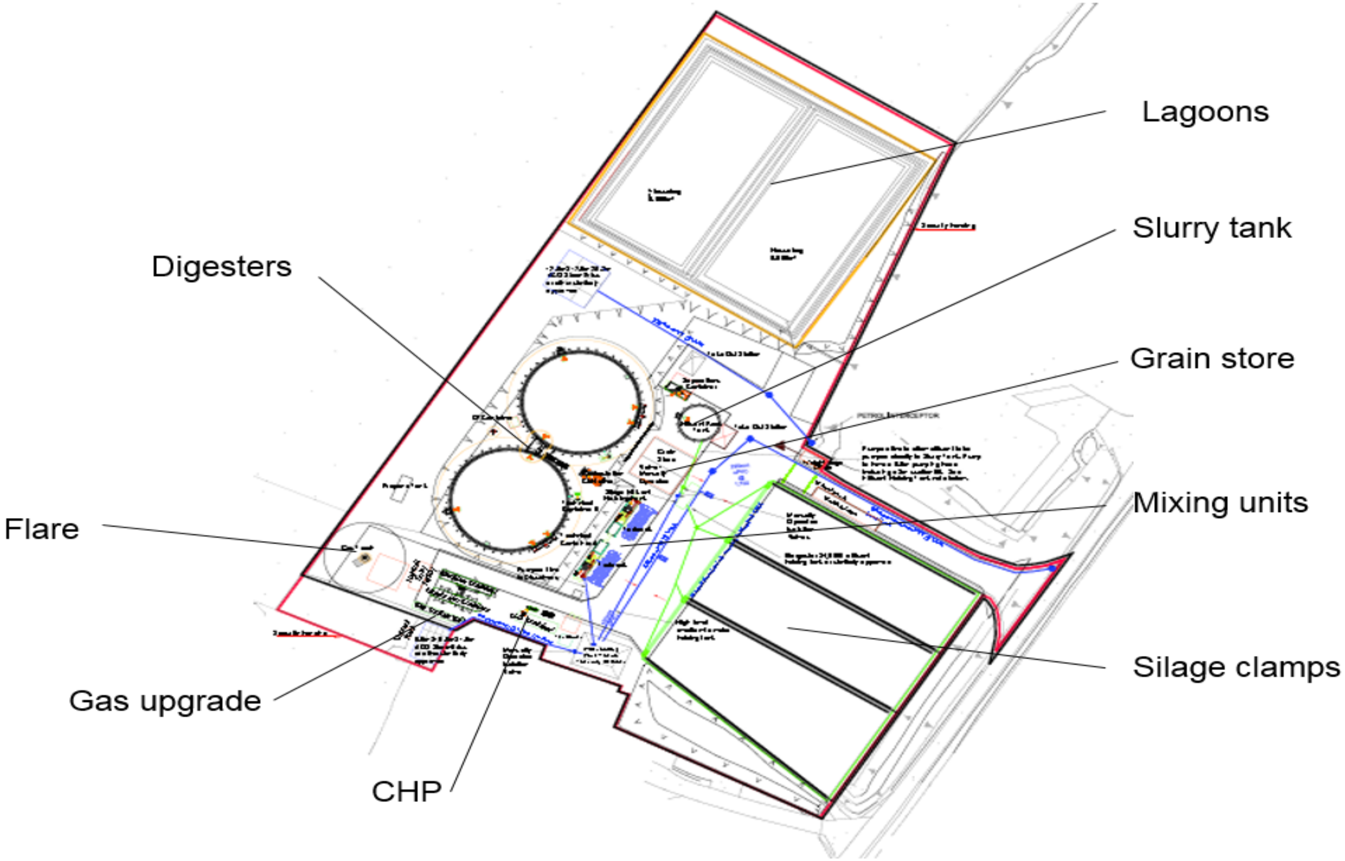
A.3.3.1 Upwind and downwind Sampling Points

The upwind sampling point was selected on the basis of wind direction and activities located in the prevailing wind direction. The MET station was the first instrument deployed on site and recorded data from the same position throughout each of the test days. The measurements used determined which region of the boundary fence was used for the up and downwind measurement locations. The upwind measurement point was located on the upwind (south or west) boundary fence broadly in line with the digesters.

The downwind sampling line was divided into three sampling points. The analyser used for these measurements was located centrally along the sample plane. An identical length of PTFE sample line was run to each of the three sample points used. The sample points were set at a height of about 1m above the ground level at the position. Note that the downwind positions were at the lagoon and edge of the storage clamps and elevated above much of the plant).

For future measurements it is suggested that the height and location of the sample points be adjusted according to the height of the emission points, especially if the boundary fence restricts the distance downwind of the AD plant.

Figure A3 Pilot Study Site Plan



A.4 Measurements

A.4.1 May 16

A.4.1.1 Methane measurement equipment

Methane measurements were made using the following instruments;

- Mirico open path TDL – to assess the background concentration
- Gasmet FTIR – to assess background methane concentration
    - To undertake upwind measurements at a selected point
- Las Gatos CRDS – to assess background methane concentration and provide comparative data with other systems deployed
    - To undertake downwind measurements at selected locations.

For measurements undertaken during this period up and downwind sample points were selected as shown in Figure A4.

A.4.1.2 Meteorology

The measurement of the wind direction and wind speed conditions plays an important role in the procedure i.e. selecting sampling locations and has a significant impact of the data collected and its relationship to the determined leakage rate.

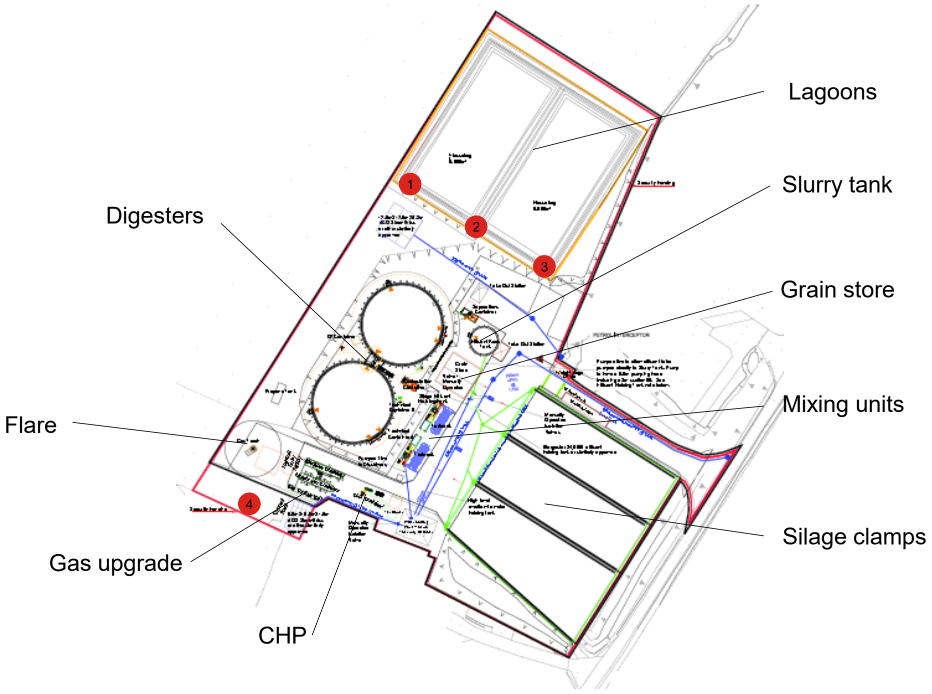
Initial assessment of wind speed and direction was made using weather forecasting sites such as darksky.net. This enabled prospective monitoring locations to be considered that would provide reasonable data.

The MET station was located in an area to the south side of the plant free from obstructions that could have interfered with the airflow to ensure that representative measurements of wind speed and directions were recorded.

The logging system was configured to provide one minute average data so that this could be correlated with the measurements made by the other measurement systems.

During the campaign, there were scattered showers with bright intervals.

Figure A4 May 16 2017 Sampling Positions



Where;
1, 2 and 3 are the downwind sample positions where the Los Gatos CRDS was deployed
4 the upwind sample location where the Gasmet FTIR was deployed.

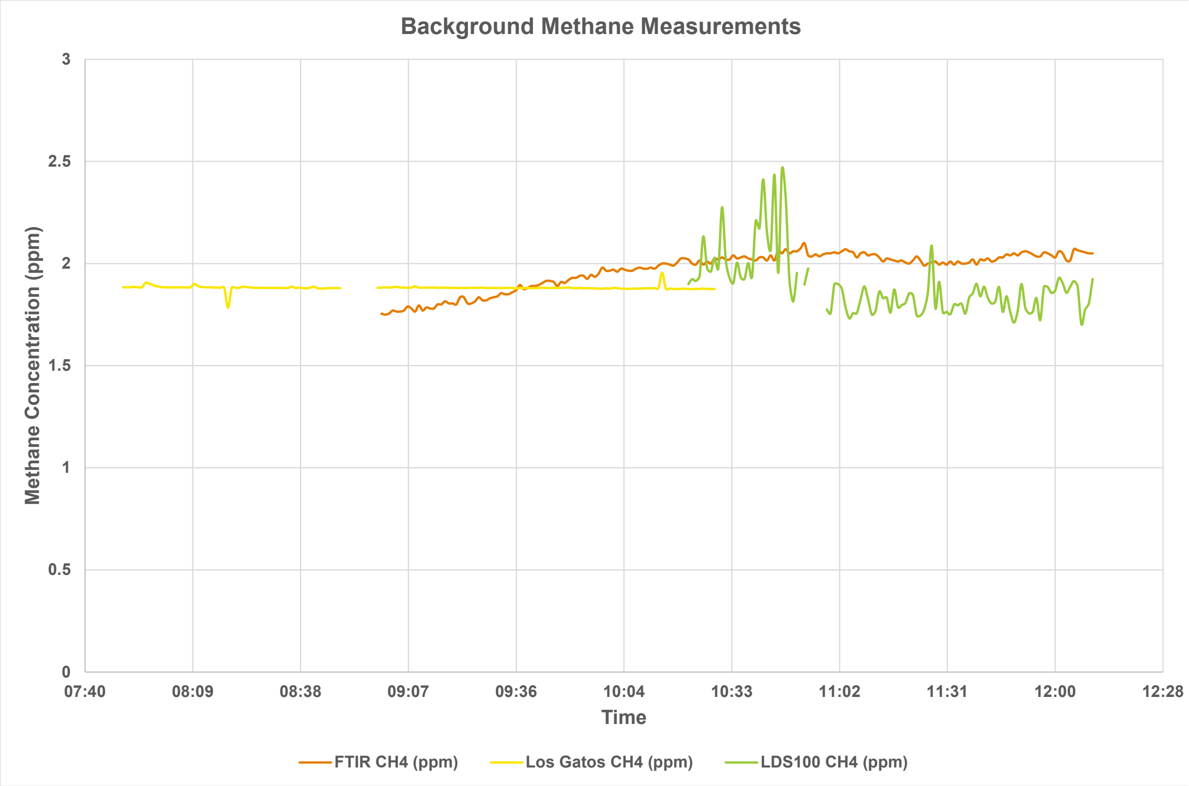
A.4.1.3 Comparative measurements of background methane concentrations

The measurement of background concentrations was used to assess the analysers and analyser systems. The Los Gatos CRDS and Gasmet FTIR were positioned at point 4 as shown in Figure A4 and sampled from a single point.

The Mirico LDS 100 TDL was positioned 100m upwind of this position and measured along a path length of about 125m. This location was selected because it was not possible to setup an unobstructed path along the southern edge of the process boundary due to neighbouring buildings.

Figure A5 compares the background methane measurements recorded by the Gasmet FTIR, Los Gatos CRDS and the Mirico LDS 100 TDL.

Figure A5 Background Methane Measurement



The CRDS showed a stable reading throughout the test period, whereas the FTIR showed a gradual increase in concentration until a stable reading is obtained after an hour of operation. The TDL system showed some significant variations throughout the period. This was traced to movements of the enclosure housing the analyser.

A.4.1.4 Methane Measurements

The wind direction was primarily from the south, which enabled the systems to be positioned as shown in Figure A4.

The downwind measurements were made at a position that eliminated the lagoons as a potential source being situated downwind of the plant but upwind of the lagoons.

A.4.1.5 Measured methane concentrations

Tables A1 and A2 summarise the measured methane and associated concentrations.

Table A1 Measured Methane Concentrations 16 May 2017

		FTIR (Upwind)			CRDS (Downwind)		
Sample pt	Period	Methane Conc. (ppm)	Carbon Dioxide Conc. (ppm)	Water Vapour (%)	Methane Conc. (ppm)	Carbon Dioxide Conc. (ppm)	Water Vapour (%)
1	11:00–11:30	2.02	382.37	1.52	2.81	420.40	1.48
2	11:30-12:00	2.03	381.46	1.52	3.94	428.71	1.50
3	12:00-12:30	2.03	380.53	1.54	2.76	434.49	1.49
1	12:30-13:00	2.08	379.69	1.56	2.57	431.18	1.45
2	13:00-1330	2.08	379.19	1.57	2.26	422.45	1.44
3	13:30-14:00	2.03	378.41	1.57	2.02	411.45	1.44
1	14:00-14:30	2.04	379.10	1.57	2.06	425.93	1.45
2	14:30-15:00	1.99	380.82	1.52	2.24	411.88	1.44
3	15:00-15:30	1.96	380.24	1.50	2.05	421.44	1.46
1	15:30-16:00	1.92	381.42	1.50	2.05	427.44	1.47

The Mirico TDL upwind open path data is shown Table A2. Several measurements did not meet the measurement system’s acceptance criteria. This was found to result from small movement of the enclosure in which the system was housed when vehicles passed on a nearby minor road. The data shown has been filtered to remove data which were outside the acceptance criteria. This data should be compared with the FTIR upwind data.

Table A2 Mirico TDL open path measured background Methane concentrations

Sample pt	Period	Methane (ppm)
OP	11:00-11:30	1.82
OP	11:30-12:00	1.81
OP	12:00-12:30	1.86

Table A3 shows the increase in the methane concentration resulting from the plant generated from the differences between the up and downwind methane concentrations.

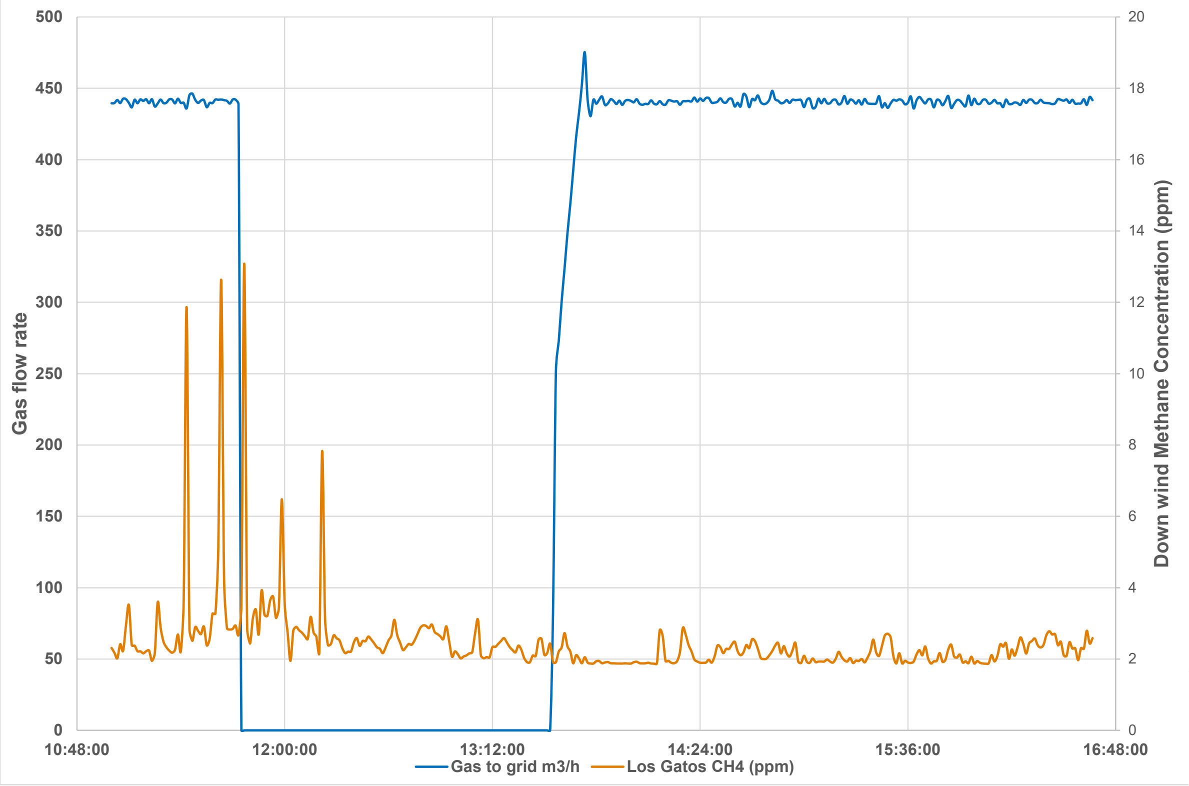
Table A3 Increase in methane concentration downwind of the plant

Sample Point	Period	Methane concentration increase (ppm)
1	1100-1130	0.79
2	1130-1200	1.91
3	1200-1230	0.73
1	1230-1300	0.49
2	1300-1330	0.18
3	1330-1400	-0.01
1	1400-1430	0.02
2	1430-1500	0.25
3	1500-1530	0.09
1	1530-1600	0.13

A.4.1.6 Plant Operation

The plant suffered a power cut at about 11:45 that interrupted gas processing until about 14:00. Figure A6 compares the gas sent to the grid and the measured downwind ambient methane concentrations. There are a number of concentration peaks immediately before and after the power outage, indicating potential short-term releases. However, after restoration of power, no further short-term increases were noted.

Figure A6 Downwind methane concentrations compared with gas flow to grid data 16 May 2017



A.4.1.7 Site Survey

A site survey was undertaken and comprised of a number of activities:

- A walk around measuring at a number of locations including an upwind survey at the Mirico sample path
- A survey of downwind concentrations at various heights around the lagoons
- A survey of downwind sample points excluding the Lagoons
- A survey of downwind sample point including the lagoons
- A leak survey
- A survey of concentrations at emission points.

Walk around site survey locations - the measurements were undertaken at 79 locations across the site. Table A44 shows the concentrations measured at these locations. These measurements were undertaken using the TDL 500 analyser. The walk-around survey indicated that (ground level) concentrations around the AD plant were generally low (1.0 to 10ppm methane) with almost 95% of methane concentrations <5ppm.

Upwind Survey

A set of measurments were made along the upwind measurement path used by the Mirico open system (125m long), in addition to those made during the walk-around survey. This measurement path was split equally into six sampling points. This was undertaken to provide a comparision for the Mirico system at the start of their measurements. The methane concentration at these sample points was measured using the TDL 500. Table A5 shows the data recorded at these measurement locations.

Table A4 Site Survey Measured Methane Concentrations

Sample Point	Location	Methane Conc. (ppm)	Sample Point	Location	Methane Conc. (ppm)	Sample Point	Location	Methane Conc. (ppm)
1	Fence-line south (upwind)	2.2	31	Clamp area (end wall)	1.8	61	Lagoons	5.0
2	Upwind of CHP	1.7	32	Clamp area	2.0	62	Lagoons	2.1
3	Eastern Fence-line, East of CHP	2.7	33	Clamp area	1.7	63	Lagoons	2.1
4	Eastern Fencline, East of CHP	2.3	34	Grain Store	1.5	64	Lagoons	2.9
5	Between CHP and Mixers	2.3	35	Weigh Bridge	1.9	65	Lagoons	2.3
6	As above	1.7	36	Site gate	1.7	66	Lagoons	1.8
7	As above	1.7	37	Mirico Upwind	1.7	67	Lagoons	1.9
8	As above	2.0	38	Mirico Upwind	1.7	68	Lagoons	1.8
9	Gas Clean-up	4.9	39	Upwind fence-line	1.9	69	Lagoons	1.8
10	Water holding pond	2.0	40	Upwind fence-line	1.2	70	Lagoons	2.2
11	In south clamp	2.0	41	Upwind fence-line	1.6	71	Lagoons	2.2
12	In south clamp	2.6	42	Upwind fence-line	2.0	72	Between Lagoons and digesters	2.9
13	In south clamp	2.5	43	Upwind fence-line	1.0	73	East fence-line	2.7
14	hardstanding	2.6	44	Slurry Reception	1.5	74	East fence-line	2.0
15	Silage hopper	2.6	45	Solid digestate	3.2	75	East fence-line	2.5
16	Between Mixers	2.5	46	hardstanding	2.0	76	East fence-line	2.3
17	Digester A	3.4	47	Hardstanding	2.0	77	East fence-line	2.1
18	Digester A	2.3	48	Hardstanding	2.3	78	East fence-line	2.0
19	Digester A	6.0	49	Septic Tank	1.2	79	East fence-line	2.2
20	Digester A	1.0	50	Between septic tank and lagoons	2.3			
21	Between Digesters	2.0	51	Lagoons	2.4			
22	Shaft between digesters	1.1	52	Lagoons	2.8			
23	Digester B	1.6	53	Lagoons	2.7			
24	Digester B	1.5	54	Lagoons (ctre)	3.8			
25	Digester B	1.3	55	Lagoons (ctre)	3.1			
26	Digester B	3.0	56	Lagoons	3.0			
27	Towards grain store	2.5	57	Lagoons	4.0			
28	Grain store	2.8	58	Lagoons	10.0			
29	Hard standing	3.0	59	Lagoons	7.0			
30	Middle Clamp	2.2	60	Lagoons	4.0			

Table A5 Upwind Open Path Spot Methane comparison measurements

Sample Point	Methane Concentration (ppm)
1	1.2
2	2.3
3	2.5
4	2.3
5	2.0
6	2.0

Downwind survey of methane concentration at different heights - A series of methane measurements at various heights around the west and south edges of the digestate lagoons was undertaken during 16 May. During this period the wind direction was from a southerly direction relative to the site. The initial part of the survey was during the period before normal processing had been restored after the power cut and some operation of the flare was noted. The site survey was undertaken around the lagoons at the sample locations shown in Figure A7. Measurements were undertaken using the TDL 500 analyser.

The selection of the sample positions was made on the basis of the wind direction at the time of measurement. The wind direction was generally in the range south westerly to south easterly.

Figure A7 Sample points used to investigate height variation of methane concentrations

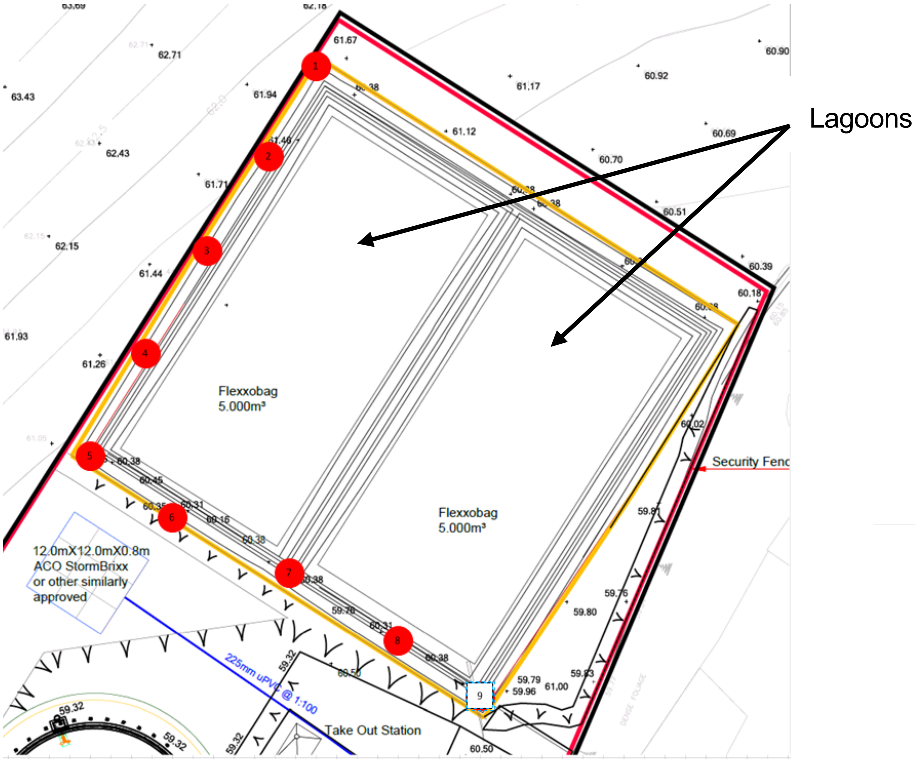


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Table A6 Methane Concentrations measured at various heights

Sample Point	Height (m)					
	4.5	4.0	3.5	3.0	2.5	2.0
	Methane Concentration (ppm)					
West side						
1	2.4	6.0	5.0	4.2	2.0[1]	2.0
2	1.9	7.0	5.0	3.0	5.0	3.5
3	2.0	5.0	6.0	4.2	4.0	4.0
4	2.3	2.3	10.0[1]	7.5	1.8	1.7
South side						
5	3.0	2.2	1.8	2.5	1.7	1.6
6	3.0[1]	3.6	2.5	2.5	1.9	2.3
7	3.0[1]	2.1	2.3	3.2	2.5	2.5
8	2.3[1]	2.1	1.9	2.1	2.8	2.9
9	1.8	2.1	0.8	1.0[1]	2.4	1.7[1]

1 – During these periods the flare was in operation due to a power failure on site.

Elevated concentrations were noted along the west side of the lagoons and at elevations of 3-4 metres but concentrations along the south side of the lagoons (sampling positions 5-9) were broadly similar at all heights. The elevated concentrations found along the west side may indicate potential for some plume grounding beyond the main measurement location, but may also have been associated with an intermittent operation on the site. The high reading recorded at sample point 4 at a height of 3.5m occurred during a period when the flare was in operation, however the wind direction at the time suggests that the flare may not have been the source of this high reading.

Downwind sample path excluding the Lagoons

Methane measurements were also made at the downwind sample points labelled 5, 6, 7, 8 and 9 in Figure A7. The survey of the downwind sampling points was undertaken to identify possible measurement points These were undertaken at about 1m i.e. the same height as the fixed downwind sample points measured by the FTIR system. These measurements were made at about 14:50 on the 16 May and are shown in Table A7. These measurements would not include any contribution from the lagoons.

Table A7 Downwind TDL Methane measurmentts

Location	Methane Concentration (ppm)
5	3.0
6	1.9
7	2.0
8	3.2
9	4.5

Downwind sample path including the Lagoons

Sample points were monitored at the field edge 130m downwind of the lagoons. The measurements were taken at intervals along the northern edge of the field. The measured methane concentrations ranged between 0.8 and 1.9 ppm (Table A8) which suggests that releases from the plant were well-dispersed at the measurement locations. The increase in methane concentrations at this distance was limited.

Table A8 Downwind measurements including lagoons

Sample	Methane Conc. ppm	Sample	Methane Conc. ppm	Sample	Methane Conc. ppm	Sample	Methane Conc. ppm
1	1.0	12	1.2	23	1.1	34	1.2
2	1.1	13	1.4	24	1.1	35	1.4
3	0.8	14	1.7	25	1.1	36	1.7
4	1.0	15	1.7	26	1.1	37	1.7
5	1.1	16	1.8	27	1.0	38	1.8
6	1.1	17	1.5	28	0.8	39	1.5
7	1.1	18	1.5	29	1.1	40	1.5
8	1.1	19	1.6	30	1.0	41	1.6
9	1.1	20	1.8	31	1.1	42	1.8
10	1.2	21	1.9	32	1.2	43	1.9
11	1.3	22	1.1	33	1.3	44	1.1

A.4.2 May 17

A.4.2.1 Methane measurement equipment

Methane measurements were undertaken using the following instruments;

- Mirico open path TDL – to measure the downwind methane concentration
- Gasmet FTIR – to measure the upwind methane concentration at the selected point.
- Los Gatos CRDS – to measure the downwind methane concentration.

A.4.2.2 Meteorological Station

Located at the same location as 16 May. The weather conditions were cloudy with significant rainfall throughout the period of these measurements. During the morning, the wind direction remained in the same direction as seen on the 16 May but a low wind speed. After 14:00 the wind direction changed to come from the west so the methane measurement systems were moved.

A.4.2.3 Plant Activity

The plant operated steadily throughout the sampling periods. Lagoon number one was being filled from 14:00 and was 50% full by 16:22.

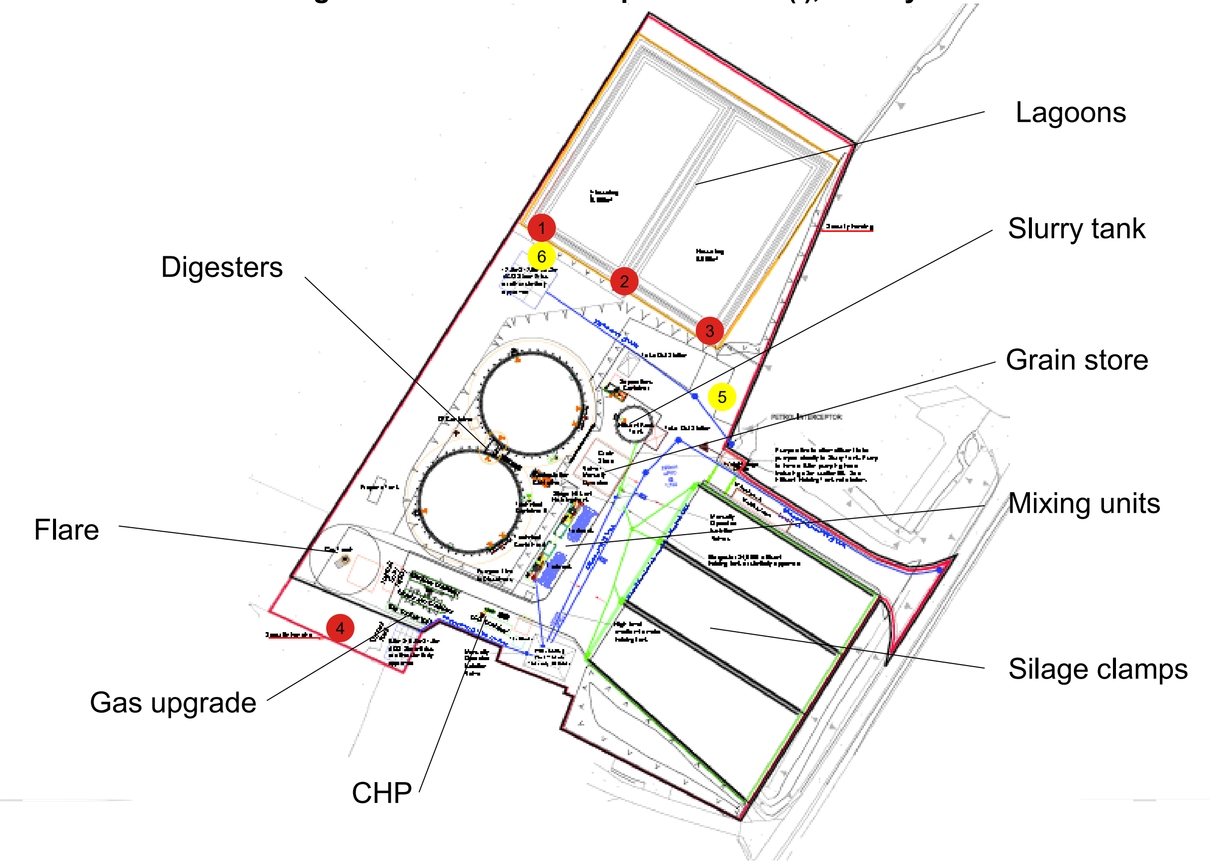
A.4.2.4 Methane Measurements

Figure A8 shows the positions of the points sampled on 17 May. The open path measurement system was placed in front of the measurements made by the CRDS system enabling comparison of open path and the single point measurement approach.
This orientation was adopted as at the time the wind direction remained in the same direction as seen on the 16 May. However, after 14:00 the wind direction changed so the systems and sample locations were moved to the configuration shown in Figure A9.

This configuration enables

- Measurement of the contribution of the lagoons from the Los Gatos data
- Measurement of the contribution from the process from the open path measurement
- Measurement of the whole site contribution by combining the open path and Los Gatos data.

Figure A8 Position A Sample locations (i), 17 May



Where;
1-3 Downwind sample points – Los Gatos CRDS
4. Is the upwind sample point - FTIR
5. Is the location of the Mirico LS100 TDL
6. Is the location of the Mirico LS100 reflector.
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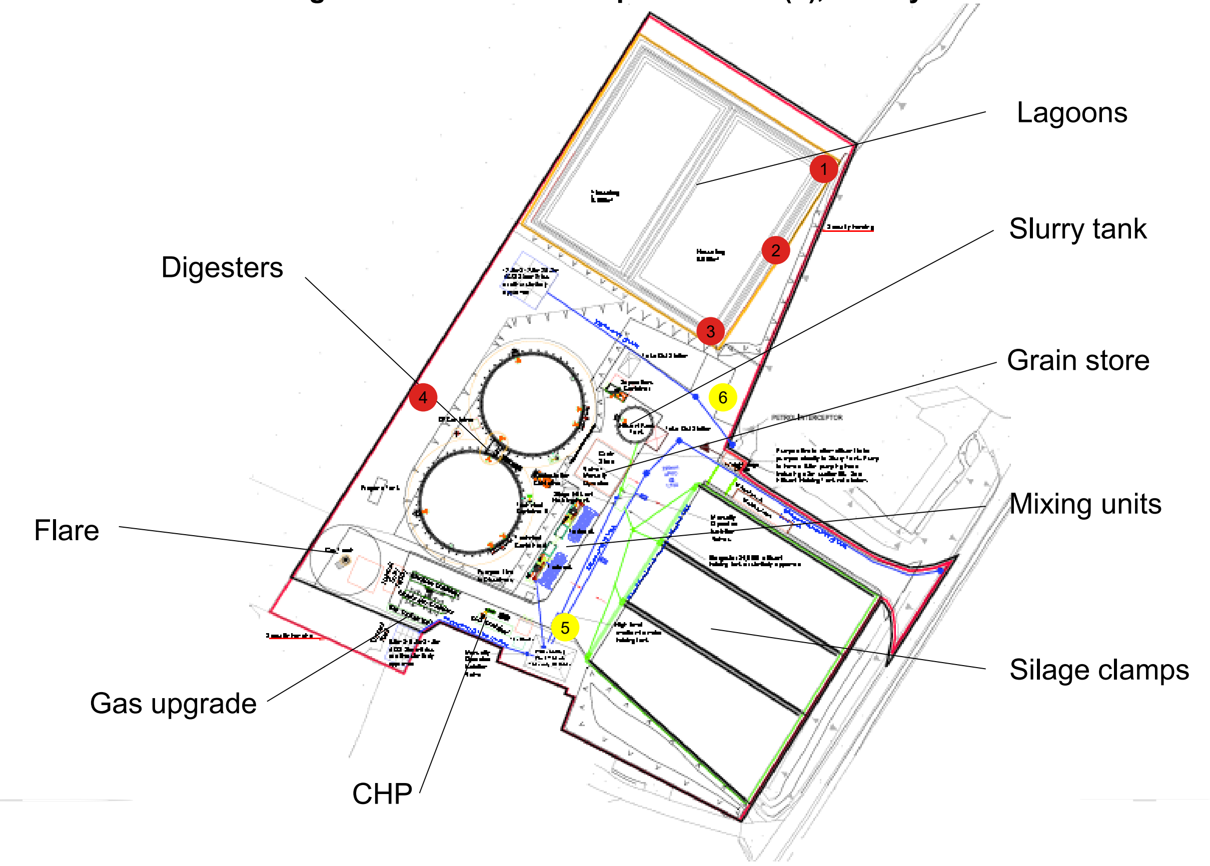
Figure A9 Position B Sample locations (ii), 17 May



Where;
1-3 Downwind sample points – Los Gatos CRDS
4. Is the upwind sample point - FTIR
5. Is the location of the Mirico LS100 TDL
6. Is the location of the Mirico LS100 reflector.
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A.4.2.5 Measured methane concentrations

Table A9 shows the measured methane concentrations.

Table A9 Measured concentrations of methane, CO_2 and water vapour, 17 May 2017

	FTIR (Upwind)			Los Gatos (Downwind)		
Period	Methane Conc. (ppm)	Carbon Dioxide Conc. (ppm)	Water Vapour (%)	Methane Conc. (ppm)	Carbon Dioxide Conc. (ppm)	Water Vapour (%)
1030-1100	1.23	323.81	1.25	2.23	439.23	1.60
1100-1130	1.25	320.90	1.25	1.96	433.36	1.60
1130-1200	1.25	315.05	1.25	2.26	455.76	1.60
1200-1230	1.24	309.78	1.25	2.19	423.49	1.61
1230-1300	1.27	307.59	1.24	1.96	419.00	1.60
1300-1330	1.35	309.42	1.22	1.89	409.43	1.59
1330-1400*	1.30	309.93	1.22	2.73	429.24	1.60
Change sample orientation						
1400-1430*	1.31	311.23	1.21	2.56	422.49	1.58
1430-1500	1.24	313.90	1.16	2.11	417.58	1.53
1500-1530	1.19	315.56	1.16	2.16	424.45	1.53
1530-1600	1.18	317.99	1.15	2.36	420.35	1.50

* Part period

A.4.3 May 18

A.4.3.1 Methane measurement equipment

Methane measurements were undertaken using the following instruments;

- Gasmet FTIR – to measure the upwind methane concentration at the selected point.
- Los Gatos CRDS – to measure the downwind methane concentration.

There was significant rainfall during these measurements but with some bright intervals in the afternoon.

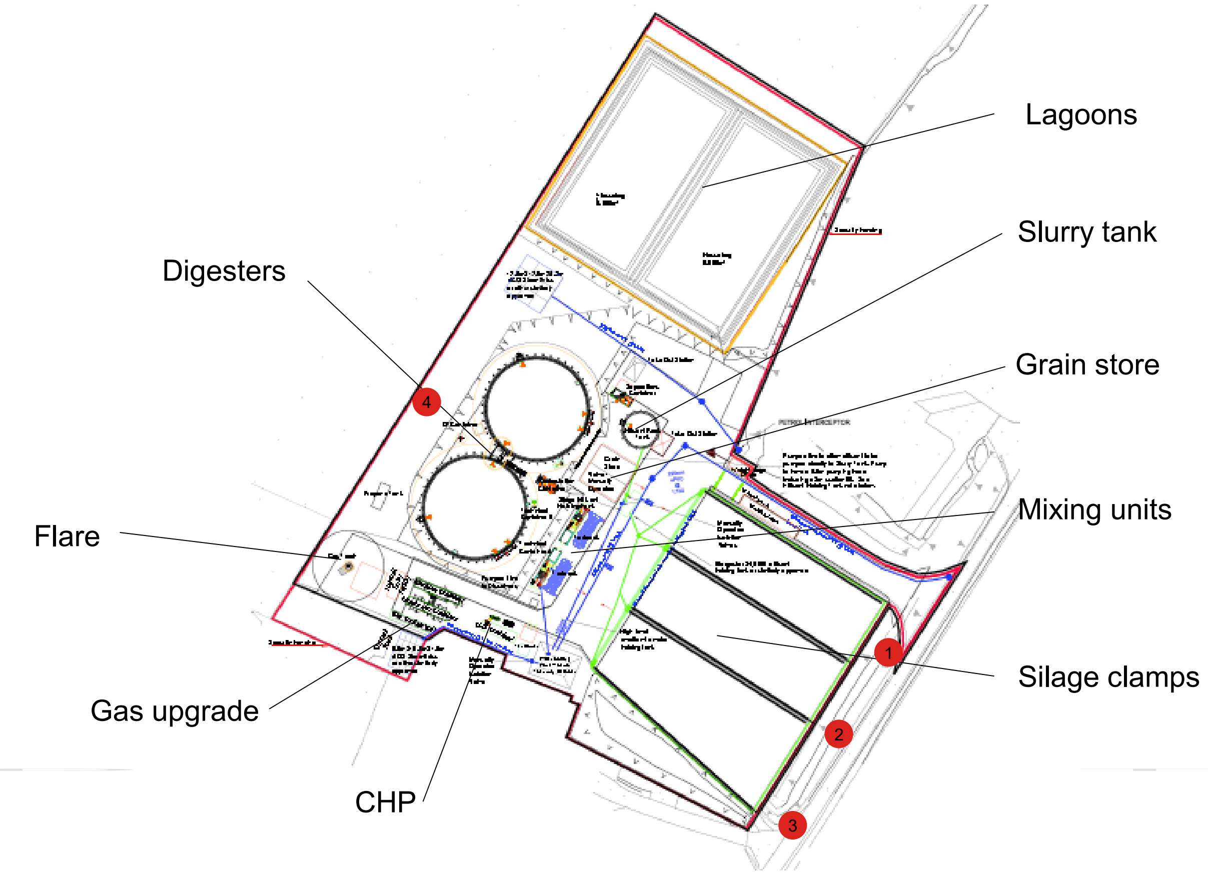
A.4.3.2 Meteorological Station

The weather monitoring station was located in the same location as previously used on 16 and 17 May. The wind speed was negligible during the morning however, after 14:00 the wind speed increased and from the west.

A.4.3.3 Methane Measurements

Figure A10 shows the positions of the points sampled.

Figure A10 Measurement locations, 18 May



Where :
1. Is a downwind sample point – Los Gatos CRDS
2. Is a downwind sample point – Los Gatos CRDS
3. Is a downwind sample point – Los Gatos CRDS
4. Is the upwind sample point - Gasmet, FTIR

A.4.3.4 Measured methane concentrations

Table A10 shows the measured methane concentrations.

Table A10 Measured methane concentrations, May 18

	FTIR (Upwind)			Los Gatos (Downwind)		
Period	Methane Conc. (ppm)	Carbon Dioxide Conc. (ppm)	Water Vapour (%)	Methane Conc. (ppm)	Carbon Dioxide Conc. (ppm)	Water Vapour (%)
1230-1300	1.51	260.71	0.66	2.73	418.22	0.97
1300-1330	1.55	261.42	0.65	2.03	414.29	0.97
1330-1400	1.48	264.78	0.60	2.44	417.74	0.91
1400-1430	1.49	268.57	0.61	2.40	410.56	0.93
1430-1500	1.93	267.07	0.72	2.19	412.48	0.86
1500-1530	1.96	294.54	0.56	1.95	409.84	0.90
1530-1600	1.78	317.01	0.67	1.95	418.19	1.03

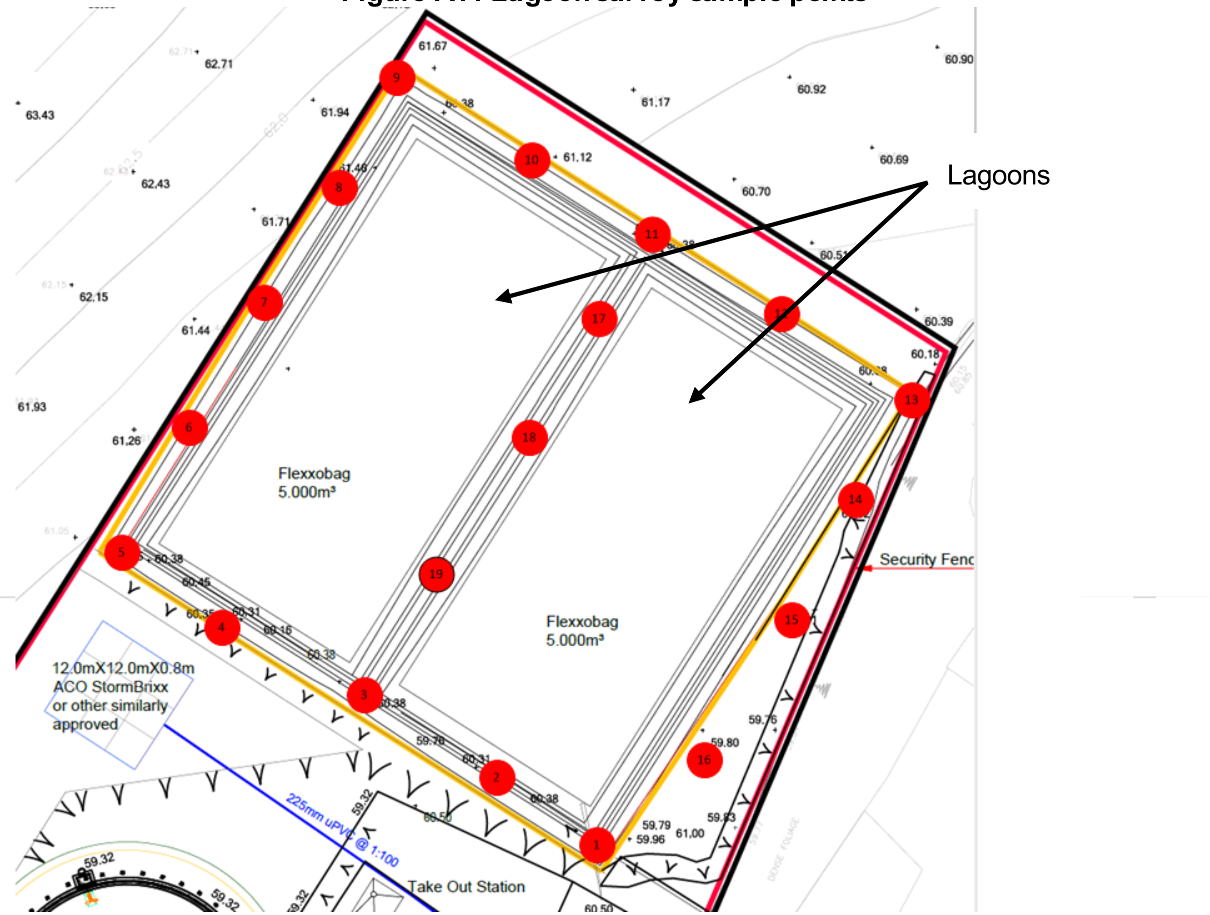
A.4.3.5 Plant Operation

The plant operated steadily throughout the sampling periods.

A.4.3.6 Lagoon methane concentration survey

A survey of methane concentrations around the lagoons was undertaken at the sample points shown in Figure A11.

Figure A11 Lagoon survey sample points



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The results of this survey is shown in Table A11

Table A11 Lagoon Survey

Sample point	CH_4 (ppm)	Sample Point	CH_4 (ppm)	Sample Point	CH_4 (ppm)	Sample Point	CH_4 (ppm)
1	2.1	6	2.4	11	3.2	16	2.0
2	2.1	7	2.2	12	1.6	17	28.0
3	3.0	8	2.0	13	1.6	18	3.0
4	1.8	9	2.8	14	1.5	19	3.0
5	1.6	10	6.5	15	2.0		

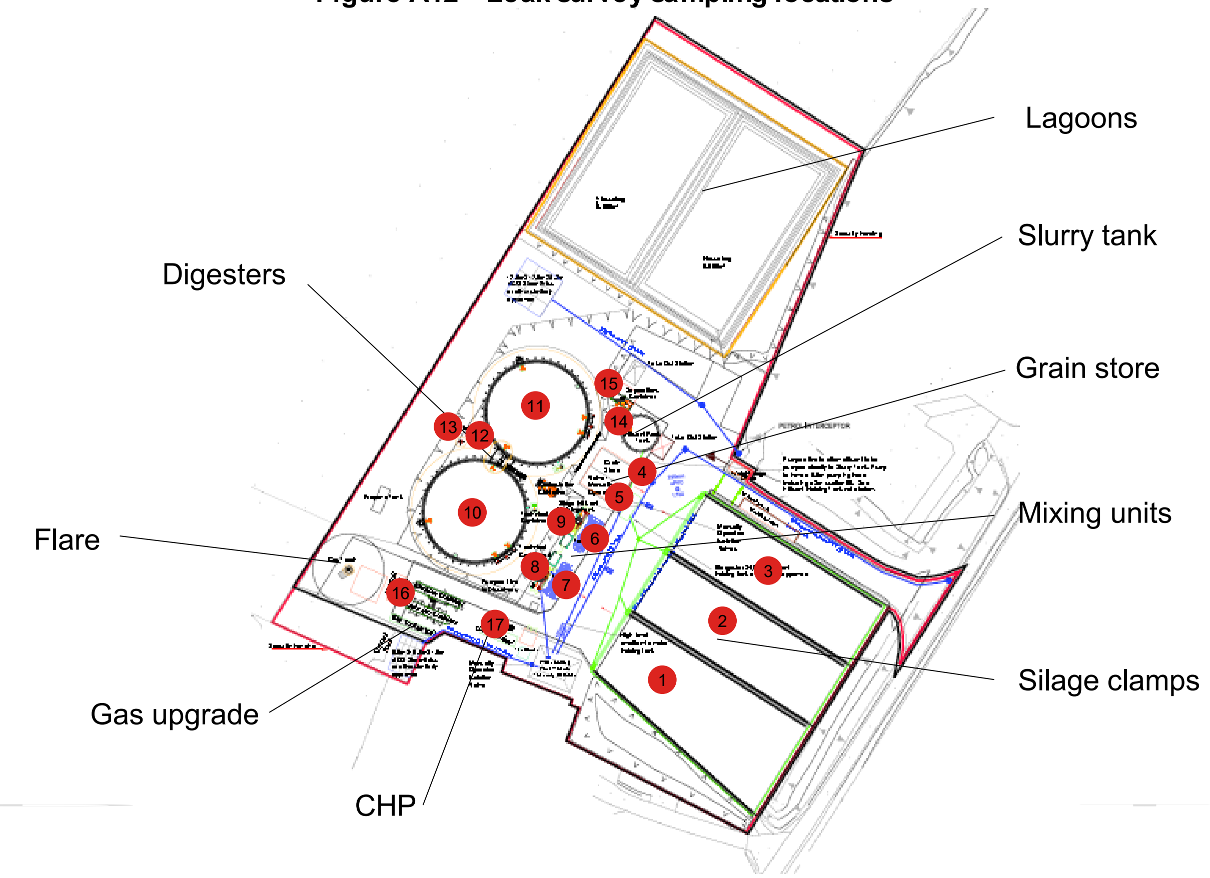
During the survey the wind speed increased in magnitude. The vents in the bags are open to the atmosphere. Consequently, when the wind speed across the lagoons increases, gas is drawn from the bags as result of the decrease in pressure above the bags. The peak concentration measured of 28 ppm occurred during one of these episodes of increased wind speeds.

A.4.3.7 Leak Survey

A walk around the process units on the site was undertaken with the objective of identifying leaks from sources around the site. The measurements were undertaken using the TDL 500 unit. Investigation was aimed at open stores, pumps, pipe work, vents, valves and seals to assess the possible contribution that leakage from these items may have made to the overall site leakage rate. The locations surveyed are shown in Figure A12.

This plant is relatively new (less than two years old) and little evidence of leakage was found, which suggests effective maintenance on the installation. It is not known if this is typical of all AD Plant in the UK.

Figure A12 – Leak survey sampling locations



Note : Points 10 and 11 are the digesters, points sampled around the digesters are detailed in figure A12
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Storage Clamps (Measurement Points 1, 2 and 3) - The storage clamps are divided up into three sections, Each storing materials used in the digestion process. Measurements were made at three equally spaced points across the front face of any material present in the clamp. The results of these measurements are shown in Table A12.

Table A12 Storage clamp methane concentrations

	Storage Clamp 1			Storage Clamp 2			Storage Clamp 3		
	Pt 1	Pt 2	Pt 3	Pt 1	Pt 2	Pt 3	Pt 1	Pt 2	Pt 3
CH_4 (ppm)	2.3	3.2	3.2	2.8	2.7	3.0	2.8	1.7	2.2

These values are higher than the levels recorded between the rest of the plant and the clamp areas (1.5 – 1.9ppm). With the exceptions of points 2 and 3 in storage clamp 1, point 3 in storage clamp 2, these areas were wet from the previous day's rain.

Grain Store (Measurement Points 4 and 5) - The grain store area involves a structure covers an open mound of grain and a pneumatic conveying system to move the grain into the mixing vessels.

Table A13 Grain store methane concentrations

	Grain store			Entry to pneumatic system		
	Pt 1	Pt 2	Pt 3	Pt 1	Pt 2	Pt 3
CH_4 (ppm)	2.0	1.4	1.7	5.0	4.7	3.6

The sample points at the entry to the pneumatic system were open to the pipework below and showed higher readings than the grain itself. This pipework leads to the mixing vessels which include material from the digesters.

Mixer 1 (Measurement Point 6) - Four measurement points were used around the mixer :

- Vent on the mixer feed receptor – recorded 2-3 ppm close to ground level,
- Vent on the side of the container housing the mixing vessels – recorded 1.0 ppm,
- The pipe work (point 9) behind the mixing container - recorded 2 – 5.1 ppm
- The gatevalve in the system - recorded 1.5 ppm

Mixer 2 (measurement Point 7) - Four measurement points were assessed around the mixer

- Vent on the mixer feed receptor – recorded 2.9-3.1 ppm,
- Vent on the side of the container housing the mixing vessels – recorded 2.9-3.1 ppm,
- The pipe work (point 8) behind the mixing container - recorded 1.4-5.2 ppm
- The gatevalve in the system - recorded 4.9-14.1 ppm

The gatevalve at Mixer 2 shows evidence of minor methane leakage.

Digesters

Figure A13 shows the measurement locations around the digesters

Figure A13 Digester Sample points

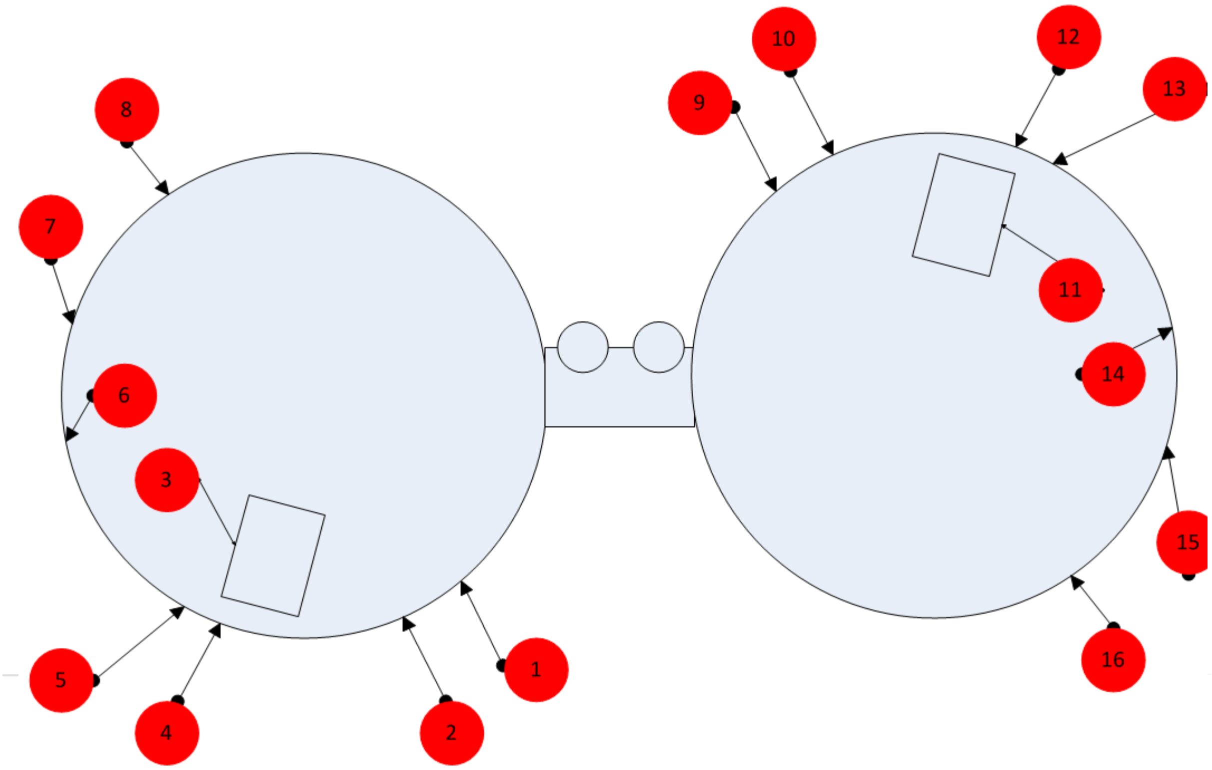


Table A13 – Methane measurements around digester

	Description	Methane Concentration (ppm)		Description	Methane Concentration (ppm)
1	Digester South	2.2	9	Digester North	2.0
2	Digester South	2.2	10	Digester North	3.0
3	Digester South Access cover	37	11	Digester North Access cover	150
4	Digester South agitator slide	>400	12	Digester North agitator slide	>400
5	Digester South agitator	>400	13	Digester North agitator	>400
6	Digester South	56	14	Digester North	0
7	Digester South agitator slide	>400	15	Digester North agitator slide	10
8	Digester South agitator	>400	16	Digester North agitator	>400

Elevated methane concentrations (indicating leakage) were noted at the access covers and, the suspension/movement guides for the agitators. To assess the contribution of the methane measured at these points to the overall emission rate would require systems to capture the leakage and measure the flow rate. However the measurement locations represent a mixture of features of different size and shape which would likely require different measurement approaches.

Condensate access shaft (Measurement point 13) - The condensate shaft is situated to the west of the digestors, measurements were taken at the centre of each of the eight sides and one at the centre of the cover (Table A14).

Table A14 Condensate access shaft cover methane concentrations

Point	TDL Methane (ppm)
Centre Point	>400
1	4.1
2	2.0
3	2.5
4	5.0
5	>400
6	70
7	80
8	20

The measurements indicate leakage at the cover.

Circulation Container (measurement point 11) - The circulation container is positioned between the mixer containers and the digesters. The container has two vents, one in each side

- Vent 1 measures 0.6 * 0.65m with 8 slats and a discharge velocity of 2.65 ms^{-1} Methane concentration recorded= 2.1ppm
- Vent 2 measures 0.6 * 0.65m with 8 slats and a measured velocity of 8.4 ms^{-1} Methane concentration recorded = 3.6 ppm

Container (measurement point 12) - There is a container to the west of the digesters that appears to contain pumps this has two vents

- Vent 1 measures 0.45 * 0.45m and a velocity of 5.6 ms^{-1} Methane concentration recorded = 2.3ppm
- Vent 2 measures 0.58 * 0.50m with 8 slated and a measured velocity of 3.2 ms^{-1} Methane concentration recorded =2.3 ppm

Filtration Effluent Vent (measurement point 14) - Measurements were made from the vent in the top of the effluent tank (Table A15). The effluent tank vent is 130mm diameter and the measured velocity was 0.6 ms^{-1}.

Table A15 Filtration effluent vent methane concentrations

Time	TDL Methane (%)
12:20:00	11.0
12:20:30	10.4
12:21:00	8.6
12:21:30	10.0
12:22:00	7.3
12:22:30	7.5
12:23:00	4.4
12:23:30	6.6
12:24:00	4.6

These concentrations levels are high and coincided with material being added to the tank with associated displacement of biogas in the headspace of the tank.

Filtration Unit Container (measurement point 15) - The container has a single 0.5*0.5m vent which had a velocity of 4.86 ms $^{-1}$ and a recorded methane concentration of 23.4 ppm .

A.4.4 May 19

A.4.4.1 Methane measurement equipment

Methane measurements were undertaken using the following instruments;

- Gasmet FTIR – to measure the downwind methane concentration at the selected point.

A.4.4.2 Meteorological Station

Located at the same location as 16 May. There were sunny intervals during the period of these measurements.

A.4.4.3 Comparative QRAE and TDL 500 methane measurements

Following a review of the data produced by the QRAE units a series of comparison measurments were undertaken using the TDL 500 monitor,

Gas upgrade plant vent Table A16 shows the methane concentration data recorded by the TDL 500 at the gas clean up exhaust. The duct is 0.55m in diameter and there is exit velocity of 12.96 ms^{-1}.

Table A16 TDL methane measurements of the Gas upgrade plant vent

Time	TDL Methane (ppm)	Time	TDL Methane (ppm)
10:37:00	2396	10:42:30	2584
10:37:30	2412	10:43:00	2561
10:38:00	2418	10:43:30	2598
10:38:30	2426	10:44:00	2645
10:39:00	2439	10:44:30	2646
10:39:30	2459	10:45:00	2646
10:40:00	2432	10:45:30	2647
10:40:30	2494	10:46:00	2743
10:41:00	2517	10:46:30	2720
10:41:30	2546	10:47:00	2749
10:42;00	2569	**Average**	**2554**

The QRAE unit showed an average of 6% Lower explosive limit (LEL) during this period. The LEL for methane is 5% so the QRAE was reporting 0.3% CH_4 (3000 ppm). Comparison with data in Table A16 gives assurance that the QRAE was providing consistent data as there is reasonable agreement between the two systems considering the resolution of the QRAE units of 0.1% LEL.

Mixer vessel vent - Mixing involves taking digestate material from the digester and mixing it with raw materials to initiate the digestion process before transfer to the digester. The data corresponds to a period of mixing resulting in the percentage concentrations obsereved.

Table A17 TDL methane measurements of the mixer vessel vent

Time	TDL Methane (ppm)	Time	TDL Methane (ppm)
10:50:00	846	10:55:30	9.0
10:50:30	642	10:56:00	28.3
10:51:00	206	10:56:30	40.9
10:51:30	98.6	10:57:00	19896
10:52:00	16	10:57:30	20000
10:52:30	7.4	10:58:00	24000
10:53:00	7.0	10:58:30	21000
10:53:30	7.0	10:59:00	29000
10:54:00	6.5	10:59:30	43000
10:54:30	6.2	11:00:00	55000
10:55:00	6.8		

The mixer outlets are 5.0 cm in diameter with a flow of 0.5 ms^{-1}. The QRAE results showed periods of readings of 100% of LEL which is 50,000ppm. Values of 55,000ppm were recorded, which is over range for the QRAE units. The QRAE measurements therefore underestimate the emission concentration during these periods. However, as the vent diameter and the flow from the vent are small. The highest concentrations were recorded during the mixing of the digestor material and new material, which is an intermittent activity. Between mixing periods, the methane levels recorded were less than 10 ppm.

Digester pressure relief valve

Table A18 TDL methane measurements of the digester pressure relief vent

Time	TDL Methane (ppm)	Time	TDL Methane (ppm)
11:20:00	6.0	11:25:30	3.0
11:20:30	5.2	11:26:00	2.8
11:21:00	5.2	11:26:30	2.2
11:21:30	5.1	11:27:00	2.2
11:22:00	5.0	11:27:30	2.4
11:22:30	4.0	11:28:00	2.4
11:23:00	3.7	11:28:30	2.2
11:23:30	3.1	11:29:00	2.2
11:24:00	2.7	11:29:30	2.6
11:24:30	2.8	11:00:00	2.2
11:25:00	3.0		

During these measurments the QRAEs recorded 0% LEL as these levels are below their resolution i.e. 0.1% of LEL which equals 50ppm.

A.4.4.4 Methane Measurements

Figure A11 shows the positions of the points sampled where locations 1, 2 and 3 were used to provide downwind methane concentrations. Upwind measurements could not be undertaken because the measurement equipment was not available.

A.4.4.5 Results

Table A19 shows the measured downwind methane concentrations.

Table A19 - Measured methane concentrations, 19 May

		FTIR (Downwind)		
Sample pt	Period	Methane Conc. (ppm)	Carbon Dioxide Conc. (ppm)	Water Vapour (%)
1	0845-0915	1.76	444.83	1.10
2	0915-0945	1.59	424.69	1.06
3	0945-1015	2.08	427.40	1.07
2	1015-1045	2.68	452.75	1.12
1	1045-1115	2.52	430.60	1.14
2	1115-1145	2.32	413.09	1.09

A.4.4.6 Plant Operation

During this measurement period the CHP unit was shutdown for service (from 10:15 until 14:30). The biogas usually used to fire the CHP was diverted to the gas upgrade unit for injection to the grid.

A.4.5 Methane emission rates

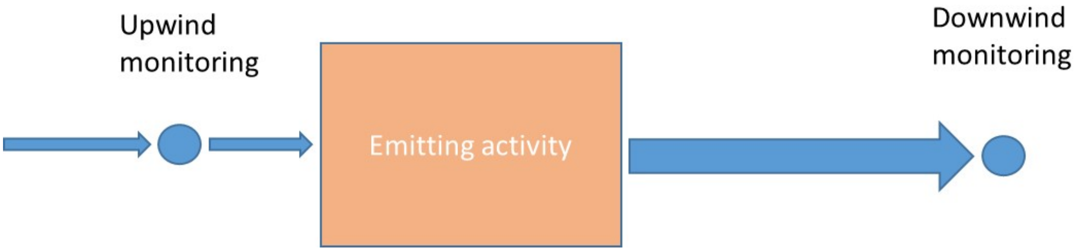
A.4.5.1 Preamble

The methane monitoring aspect of this study has determined:

- a series of upwind methane concentrations around the target AD plant – this essentially represents the natural background methane concentration; and
- a series of downwind methane concentrations around the target AD plant.

Figure A14 provides a schematic representation linking the two monitoring locations.

Figure A14 Schematic diagram showing the relative positions of monitoring equipment and the source of methane emission



The analysis shown in Figure A14 links the difference in concentrations between the upwind and downwind monitoring locations to the pollution contribution from any emitting activity which lies between the monitoring locations. However to be in a position to estimate the total pollutant emission from the process we need to extrapolate from the concentration measurements (expressed for example in mg/m^3) to determine a pollutant emission rate (expressed in for example mg/s).

A.4.5.2 Dispersion modelling estimation methodology

This note sets out a screening methodology to determine the emission rate from the emitting activity using a simple dispersion modelling technique.

In this study we have employed the air dispersion model ADMS v5.2. We anticipate that other air dispersion models (e.g. AERMOD) could also have been used.

In brief the methodology used is as follows:

a) The emitting activity on site has been described as a single volume with defined dimensions (length, width, height). The total volume of the source term is therefore known.
b) The dispersion model was set up with a series of 'receptor' points downwind of the source. Care was taken to ensure that the 'receptor' points stretched as far as the downwind as the downwind monitoring location.
c) The dispersion model was run using a simple meteorological data set containing a range of conditions which are commonly found in the UK. The data set was adjusted to take into account the actual wind speed found during the monitoring period. Figure A15 shows the simple meteorological conditions used to predict the likely pollution dispersion away from the emitting source. Categories A to G represent the range of atmospheric stability found, where

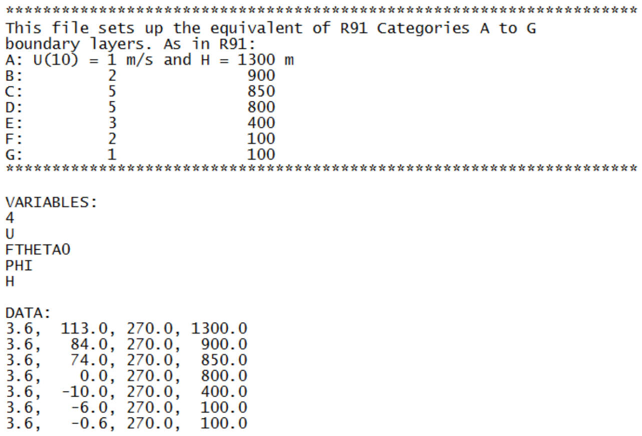
A-C represents various degrees of unstable conditions which typically occur during the day;

D represents a neutral condition which is the most common stability class; and

E-G represents various degrees of stable conditions which typically occur during the night;

d) The dispersion model was run using a volume emission rate of 1g/m^3/s to determine the predicted impact concentration (typically g/m^3) at the monitoring location.
e) Based on the ratio of the predicted impact concentration and measured concentration we could determine the emission rate from the volume source (in g/m^3/s) and knowing the total volume of the volume source used the total emission rate can be determined (in g/s).

Figure A15 Modified R91 metrological data set used in the estimation procedure



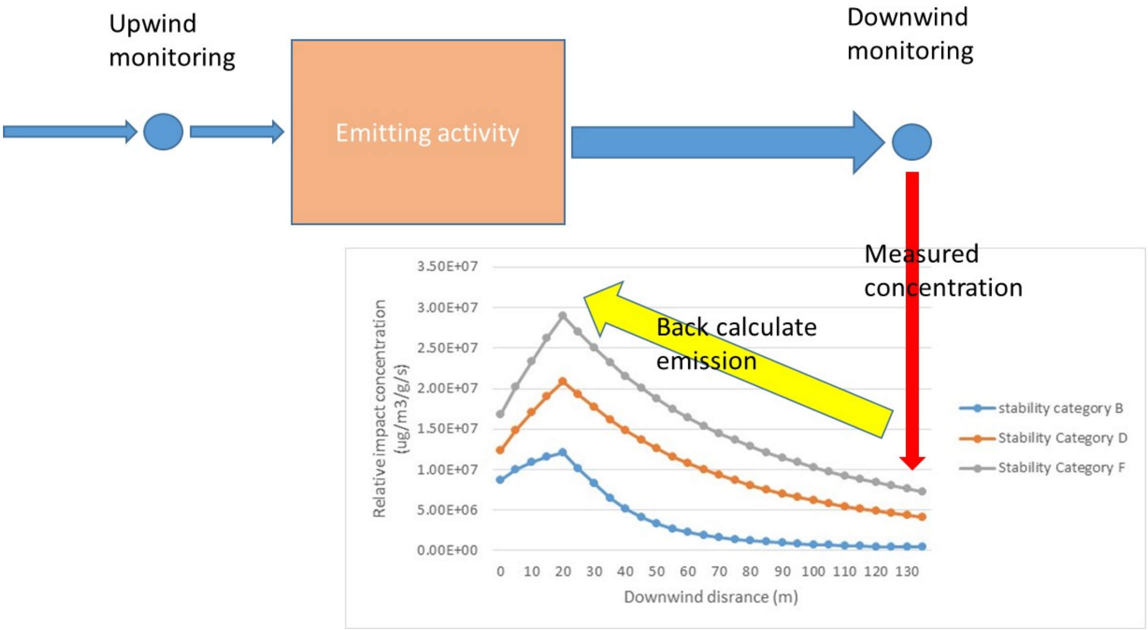
```
************************************************************************
This file sets up the equivalent of R91 Categories A to G
boundary layers. As in R91:
A: U(10) = 1 m/s and H = 1300 m
B:         2              900
C:         5              850
D:         5              800
E:         3              400
F:         2              100
G:         1              100
************************************************************************

VARIABLES:
4
U
FTHETA0
PHI
H

DATA:
3.6,  113.0, 270.0, 1300.0
3.6,   84.0, 270.0,  900.0
3.6,   74.0, 270.0,  850.0
3.6,    0.0, 270.0,  800.0
3.6,  -10.0, 270.0,  400.0
3.6,   -6.0, 270.0,  100.0
3.6,   -0.6, 270.0,  100.0
```

The overall methodology is captured schematically in Figure A16.

Figure A16 Schematic representation of emission estimation procedure



A.4.5.3 Results of dispersion modelling

Period 1 – 16th May

The monitoring covered the digesters, CHP, gas upgrade but not the lagoons.

Table A20 Methane emission estimate for 16th May, based on a volume source with dimensions of 40m x 80m x 6.5m and an average wind speed of 3.6m/s

Time period	Measured concentration difference (ppm CH_4)	Emission estimate based on different atmospheric stability categories prevailing (kg/h)		
		Stability Category B	Stability Category D	Stability Category F
1100-1130	0.57	3.35	2.48	2.29
1130-1200	1.37	8.10	5.99	5.53
1200-1230	0.52	3.09	2.29	2.11
1230-1300	0.35	2.08	1.54	1.42
1300-1330	0.13	0.76	0.56	0.52
1330-1400		No difference recorded		
1400-1430	0.01	0.08	0.06	0.06
1430-1500	0.18	1.06	0.78	0.72
1500-1530	0.06	0.38	0.28	0.26
1530-1600	0.09	0.55	0.41	0.38
	Average:	2.16	1.60	1.48

Period 2 17th May

The emitting source sitting between the upwind and downwind monitoring locations altered during this period. At the start of the monitoring period the emitting source was the AD plant (see Table A21 and Fig A8), while later in the day, the wind direction changed and the monitoring locations were moved the emitting source was the digestate lagoons (see Table A22 and Fig A9).

Table A21 Methane emission estimate the AD tanks for 17th May based on a volume source with dimensions of 40m x 80m x 6.5m and an average wind speed of 1.4m/s

Time period	Measured concentration difference (ppm CH_4)	Emission estimate based on different atmospheric stability categories prevailing (kg/h)		
		Stability Category B	Stability Category D	Stability Category F
			Focused on AD plant	
0930-1000	2.34	10.48	2.98	2.04
1000-1030	2.02	9.05	2.57	1.76
1030-1100	1.06	4.76	1.35	0.92
1100-1130	0.74	3.30	0.94	0.64
1130-1200	1.01	4.52	1.28	0.88
1200-1230	0.94	4.22	1.20	0.82
1230-1300	0.71	3.20	0.91	0.62
1300-1325	0.62	2.78	0.79	0.54
	Average	5.29	1.50	1.03

Table A22 Methane emission estimate the uncontained digestate lagoon for 17th May based on a volume source with dimensions of 10m x 10m x 1m centred on the digestate lagoon and an average wind speed of 1.4m/s

Time period	Measured concentration difference (ppm CH_4)	Emission estimate based on different atmospheric stability categories prevailing (kg/h)		
		Stability Category B	Stability Category D	Stability Category F
		Focused on storage lagoons		
1410-1430	1.42	95.9	14.0	8.4
1430-1500	1.32	88.8	13.0	7.8
1500-1530	0.91	61.5	9.0	5.4
1530-1600	0.98	65.8	9.6	5.8
1600-1630	1.08	72.7	10.6	6.4
1630-1700	2.06	138.9	20.3	12.2
	Average:	87.2	12.7	7.7

Period 3 18th May

The monitoring covered the digesters, CHP, gas upgrade and silage clamps but not the digestate lagoons. Two modelling runs have been undertaken with different source volumes to assess if the impact on determined emission rates.

Table A23(a) Methane emission estimate for 18th May estimate based on a volume source with dimensions of 40m x 80m x 2m and an average wind speed of 1.3m/s

Time period	Measured concentration difference (ppm CH_4)	Emission estimate based on different atmospheric stability categories prevailing (kg/h)		
		Stability Category B	Stability Category D	Stability Category F
1230-1300	1.22	51.07	4.89	2.76
1300-1330	0.48	20.29	1.94	1.10
1330-1400	0.96	40.26	3.86	2.18
1400-1430	0.91	38.20	3.66	2.07
1430-1500	0.26	11.00	1.05	0.59
1500-1530	No difference detected			
1530-1600	0.17	7.28	0.70	0.39
	Average:	28.02	2.68	1.52

Table A23(b) Methane emission estimate for 18th May based on a volume source with dimensions of 40m x 80m x 6.5m and an average wind speed of 1.3m/s

Time period	Measured concentration difference (ppm CH_4)	Emission estimate based on different atmospheric stability categories prevailing (kg/h)		
		Stability Category B	Stability Category D	Stability Category F
1230-1300	1.22	47.04	5.44	3.16
1300-1330	0.48	18.69	2.16	1.26
1330-1400	0.96	37.08	4.29	2.49
1400-1430	0.91	35.19	4.07	2.36
1430-1500	0.26	10.13	1.17	0.68
1500-1530	No difference detected			
1530-1600	0.17	6.71	0.78	0.45
	Average:	25.81	2.98	1.73

Period 4 19th May

The monitoring covered the digesters, CHP, gas upgrade and silage clamps but not the lagoons. Estimated emission rates are provided in Table A24.

Table A24: Methane emission estimate for 19th May estimate based on a volume source with dimensions of 40m x 80m x 6.5m and an average wind speed of 2.0m/s

Time period	Measured concentration difference # (ppm CH_4)	Emission estimate based on different atmospheric stability categories prevailing (kg/h)		
		Stability Category B	Stability Category D	Stability Category F
0845-0858	0.27	7.2	1.7	1.1
0859-0928	0.10	2.6	0.6	0.4
0929-0958	0.59	15.9	3.7	2.5
	Average	8.57	2.00	1.33
CHP off				
1029-1058	1.01	27.0	6.3	4.2
1059-1133	0.90	24.1	5.6	3.7
1133-1200	1.18	31.4	7.3	4.9
1230-1330	0.95	25.3	5.8	3.9
	Average:	26.95	6.25	4.18

no upwind measurement was carried out on this day. To enable an emission estimate to be made we have use the 'daily average' upwind concentration from 18th May monitoring.

A.4.5.4 Simple box modelling

In addition to the reverse dispersion modelling approach, it is possible to estimate the emission rate from wind speed data. However, this has not been undertaken for this investigation. This approach requires an estimate of the plume area at the downwind measurement location – and this may change as weather conditions (wind speed and direction) change. The reverse modelling approach requires an assumption regarding the source volume but this is guided by the plant footprint and discharge heights and will generally not change (except where weather conditions mean that leakage across different parts of the plant are being measured – for example separate treatment of lagoon emissions described above).

A.4.6 Process vents

A.4.6.1 Overview

Measurement data were obtained on 17, 18 and 19th May using the QRAELite instruments which use NDIR technology to monitor methane expressed as a percentage of the LEL (5% for methane). The data have been converted to volume concentrations. Although sensors were installed to monitor gas flow continuously at several ducts, the flows were too low for reliable data. Portable flow monitors were used on some ducts but for the CHP and Gas upgrade plant, the flow was estimated from combustion calculations or mass balance. Table A25 summarises the measured concentrations.

Table A25 Summary of process vent methane concentrations.

Date and period	Methane concentrations, %					
	CHP stack	Gas Upgrade plant	Digester		Mixer	
			South	North	South	North
17/5/17						
1204-1229	0.397	0.481	1.153	0.003	3.463	1.133
1230-1259	0.248	0.500	5.000	0.000	4.821	5.000
1300-1329	0.255	0.498	0.000	0.000	0.000	5.000
1330-1359	0.162	0.465	0.000	0.000	0.000	5.000
1400-1429	0.165	0.463	0.000	0.000	0.000	5.000
1430-1459	0.150	0.450	0.000	0.000	2.398	5.000
1500-1529	0.150	0.442	0.000	0.000	5.000	5.000
1530-1559	0.103	0.415	0.000	0.000	5.000	5.000
1600-1629	0.100	0.400	0.000	0.000	5.000	5.000
1630-1656	0.100	0.323	0.000	0.000	5.000	5.000
18/5/17						
0957-1029	0.298	0.341	0.000	0.000	-	0.000
1030-1059	0.200	0.350	0.000	0.000	-	0.000
1100-1129	0.200	0.350	0.000	0.000	-	0.000
1130-1159	0.200	0.350	0.000	0.000	-	0.000
1200-1229	0.200	0.350	0.000	0.000	-	0.000
1230-1259	0.200	0.350	0.000	0.000	-	0.000
1300-1329	0.200	0.350	0.000	0.000	-	0.000
1330-1359	0.168	0.350	0.000	0.000	4.550	0.000
1400-1429	0.150	0.350	0.000	0.000	5.000	0.000
1430-1459	0.150	0.362	0.000	0.000	5.000	0.000
1500-1529	0.138	0.350	0.000	0.000	5.000	0.000
1530-1559	0.100	0.350	0.000	0.000	5.000	0.000
1600-1629	0.100	0.377	0.000	0.000	5.000	0.000
1630-1639	0.011	0.130	0.000	0.000	1.250	0.000
19/5/17						
0904-0929	-	0.400	-	-	-	-
0930-0959	-	0.400	-	-	-	-
1000-1029	-	0.375	0.000	0.000	0.455	-
1030-1059	-	0.243	0.000	0.000	1.093	-
1100-1129	-	0.300	0.000	0.000	1.485	-
1130-1159	-	0.300	0.000	0.000	1.202	-
1200-1229	-	0.300	0.000	-	1.332	-
1230-1259	-	0.300	0.000	-	1.095	-
1300-1329	-	0.300	0.000	-	0.860	-
1330-1359	-	0.300	0.000	-	0.785	-
1400-1419	-	0.296	0.000	-	0.643	-
Averages	CHP (Avg)	Gas Upgrade (Avg)	Dig. Sth (Avg)	Dig. Nth (Avg)	Mix Sth (Avg)	Mix Nth (Avg)
17/05/2017	**0.166**	**0.403**	**0.615**	**0.005**	**3.068**	**4.613**
18/05/2017	**0.165**	**0.336**	**0.000**	**0.000**	**4.400**	**0.000**
19/05/2017	**-**	**0.319**	**0.000**	**0.000**	**0.994**	**-**

Note : Upper limit of detection was 5% , a '-' denotes no data.

A.4.6.2 CHP exhaust stack

The concentrations determined at the CHP stack were similar on 17 and 18th May. It was not possible to access the stack to determine velocity and an estimate of stack gas flowrate was made from the volume of gas passed to the CHP plant, the proportion of methane and other gases in the biogas (plant data), a flue gas volume factor for natural gas (US Environmental Protection Agency Method[19] 19) and an assumed oxygen content in the combustion exhaust gases. Future monitoring of combustion activities should include monitoring of oxygen to enable calculation of flue gas flowrate.

The estimated average methane emission rate from the CHP plant exhaust stack was 1.6 kg/hr (based on methane concentration data from 17 and 18 May).

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[19] Available in Table 19-2 here https://www3.epa.gov/ttnemc01/promgate/m-19.pdf

A.4.6.3 Gas upgrade plant discharge

The concentration of methane in the vent discharging carbon dioxide was generally less than 0.5%. The vent had a dilution system (although this was not operating during the measurements) and it was not possible to access the vent upstream of the dilution duct. An estimate of vent flowrate was made from the volume of biogas passed to the upgrade plant and to the gas grid (a mass balance on the carbon dioxide input to the upgrade plant and residual carbon dioxide in the gas injected to the grid). The estimated average methane emission rate from the upgrade plant exhaust stack was 1.0 kg/hr (based on methane concentration data from 17, 18 and 19th May).

A.4.6.4 Mixer vents

Concentrations of 5% were observed on several occasions indicating release of biogas. This is the upper limit of detection for the QRAE instrumentation however, a short comparison with another measurement technique (see Section **Error! Reference source not found.**) indicated that methane concentrations may not have been much higher than 5%.

A.4.6.5 Digester pressure relief valves

The concentrations were generally below the limit of detection but some methane was detected on 17th May.

A.4.7 Determination of leakage rate

A.4.7.1 Leakage metric

Leakage is expressed as a percentage of total methane production. Ofgem sustainability guidance expresses leakage as follows:

1. For AD plants: as a percentage of total production
2. For upgrading plant: as a percentage of the throughput through that unit
3. For boilers/engines: as a percentage of the throughput through these units

A.4.7.2 Summary of modelled methane emission rates

The average emission rates determined on each day are summarised in Table A26.

Table A26 Modelled emission rates from reverse dispersion modelling

		Average methane emission rate, kg CH_4/h (range)		
	Atmospheric stability class	*B*	*D*	*F*
16/5/17	Excluding lagoons, *may exclude silage clamps*	**2.16** **(0-8.1)**	1.60 (0-6.0)	1.48 (0-5.5)
17/5/17	Excluding lagoons, *may exclude silage clamps*	5.29 (2.8-10.5)	**1.50** **(0.8-2.6)**	1.03 (0.5-2.0)
17/5/17	Lagoons	87.2 (62-139)	**12.7** **(9.0-20)**	7.7 (5.4-12)
18/5/17	Excluding. lagoons, including Silage clamps	25.8 (0-47)	**2.98** **(0-5.4)**	1.73 (0-3.2)
19/5/17	Excluding. lagoons, including Silage clamps	8.6 (2.6-16)	**2.0** **(0.6-3.7)**	1.3 (0.4-2.5)
19/5/17	Excluding. lagoons, including Silage clamps, CHP off	27 (24-31)	**6.3** **(5.6-7.3)**	4.2 (3.7-4.9)

Note : The figures in parentheses representative the range in half-hour average emission rates
The figures in **bold** represent the most appropriate stability class for each set of measurements

For the purpose of determining an emission rate, we have applied the highest average emission rate for each group (Table A27). Note that these data are derived from different monitoring periods and the lagoons were only monitored during one period on 17 May. Table A27 includes average emission rates for calculated for the CHP and gas upgrade plant based on measured emission concentrations and flowrates derived from plant throughput data.

The sum of the CHP and gas upgrade methane emission rates (2.6 kg/hr or 3.6 m^3/hr) exceeds the average modelled emission rate for the site (excluding the lagoons but including the CHP and gas upgrade emissions). This provides an indication of the uncertainty associated with the modelling and measurement data but note that the CHP and gas upgrade emission rates are within the range of modelled emission rates.

The data suggest that, for this plant, methane ‘leakage’ from process units is less important than CHP and gas upgrade methane emissions. Excluding the digestate lagoons, the CHP and gas upgrade methane emissions are likely to be the most significant contribution to site emissions. The data suggest that emissions from the digestate lagoons are higher than process emissions and process leaks.

Table A27 Summary of derived emission rates

Plant included	Emission rate range (kg/hr)	Highest average emission (kg/hr)	Highest average emission (m^3/hr at 0°C, 1 atmosphere)
Site excldding Lagoons	0-8.1	2.5	3.5
Lagoons	9-20	12.7	17.8
CHP	-	1.6	2.2
Gas Upgrade	-	1.0	1.4

A.4.7.3 Methane production

Plant data has been used to estimate the biogas and methane production and these are summarised in Table A28.

Table A28 Summary of biogas and methane production

Date	Average biogas, m^3/hr (0°C, 1 atmosphere)				Average CH_4, m^3/hr (0°C, 1 atmosphere)			
	Production	To CHP	To Upgrader	To Flare	Production	To CHP	To Upgrader	To Flare
16/5/2017	*786*	*133*	*622*	*1387*	*425*	*72*	*336*	*749*
17/5/2017	913	127	771	1400	493	68	417	756
18/5/2017	963	132	830	0	520	72	448	0
19/5/2017	947	131	839	0	511	71	453	0

Note : From plant biogas volume and methane concentration daily data, all volumes are at STP (0°C and 1 atmosphere). Power cut on 16th May and instrumentation not available for part of day. On 19th May the CHP engine was not operating for several hours. Average production of biogas and biogas flow to upgrader is based on 24 hours operation but gas flowrate to flare and CHP is based on reported CHP and flare runtime.

A.4.7.4 Methane leakage

The methane leakage rates are summarised in Table A29 below and based on plant operating data for 18th May (Table A28) and the emission rates summarised in table A27.

Table A29 – Methane leakage rates

	CH_4 emission rate	CH_4 produced (through unit)	Methane Leakage	Comment
	m^3/hr (0°C, 1 atmos)	m^3/hr (0°C, 1 atmos)	%	
Whole site	21.3	520 [537.8]	4.1 [4.0]	Figures in square parentheses are for total biogas produced - including release from lagoons. Assumes no/negligible leakage before biogas volume measurement
Whole site excluding lagoons	3.5	520	0.7	Assumes no/negligible leakage before biogas volume measurement
CHP	2.2	520 (72)	0.4 (3.1)	Figures in parentheses are expressed for CHP throughput. Assumes no/negligible leakage after biogas volume measurement
Biomethane Upgrade plant	1.4	520 (448)	0.3 (0.3)	Figures in parentheses are expressed for upgrade plant throughput. Assumes no/negligible leakage after biogas volume measurement

A.4.8 Counterfactuals

The lifecycle greenhouse gas counterfactual emissions have been calculated as shown below. Assumptions regarding the biogas life cycle and the counterfactual are as outlined in Section 2.8 of the 'Literature review and AD plant classification' report. A simple spreadsheet (Figure A16) was developed to estimate actual life cycle emissions and counterfactual emissions, based on both current Ofgem sustainability criteria and on the new proposed counterfactual as outlined in the Literature review and AD plant classification' report.

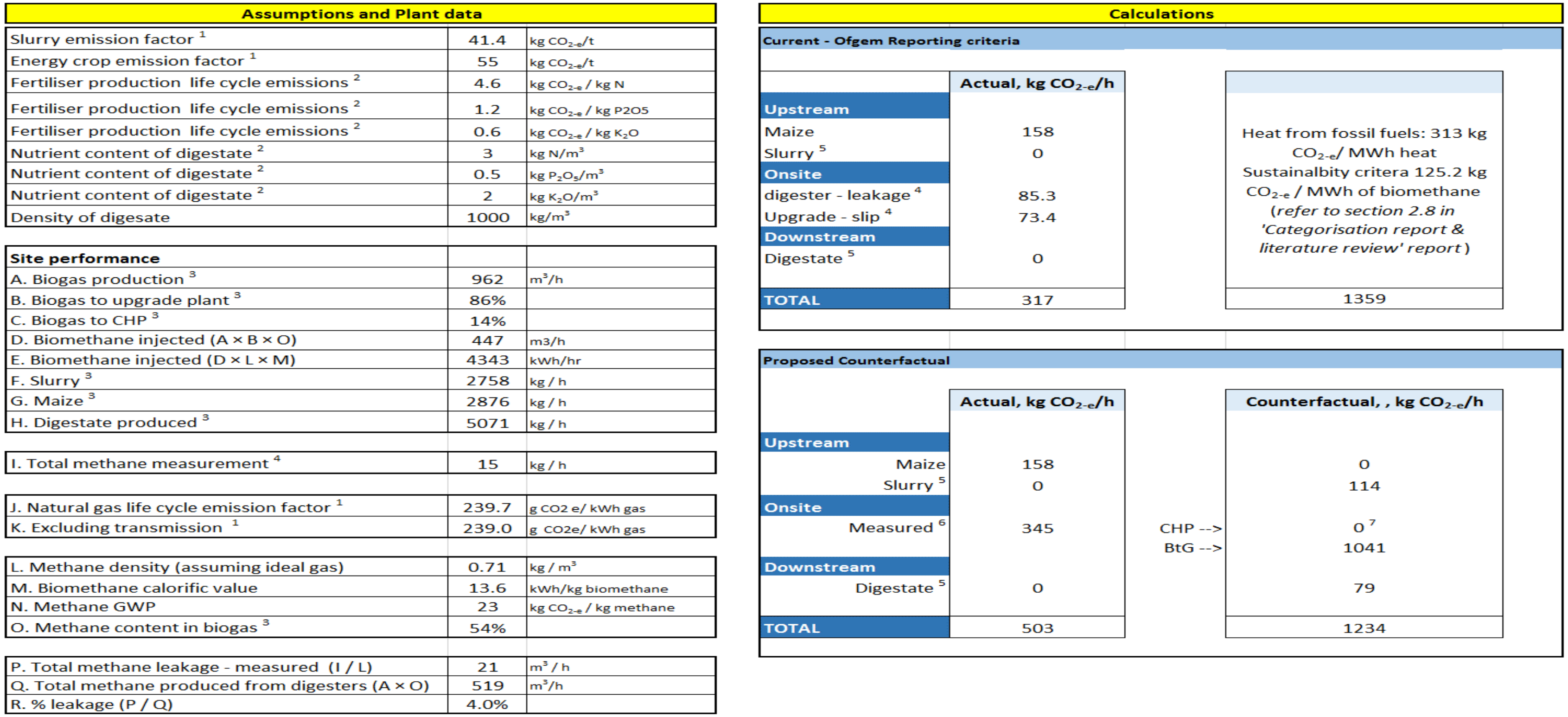
The assumptions regarding the calculation in Figure A16 are shown on the left hand side of this spreadsheet. The emission factors for slurry, energy crops and fertiliser are as described in the notes below the table.

The assessment in the table below is based on data for May 18 (962 m^3 of biogas /hr with 54% methane content, 86% of biogas is directed to upgrade plant with 14% used in CHP, 2.8 tonne slurry / hr, 2.8 tonne maize / hr, 5.1 tonne digestate production / hr).

The top right hand section of Figure A16 shows actual life cycle emissions as would be expected from in inputting data in the GHG calculator (excluding direct CO_2 emissions onsite due to energy consumption, which are expected to be minimal). In comparison to the current fossil fuel counterfactual (313 g $CO_{2\text{-}e}$ / kWh), estimated actual life cycle emissions, based on current reporting requirements (i.e. no reporting on waste or digestate), the site achieves 77% GHG savings.

In the lower right-hand corner, onsite methane emissions are re-calculated based on actual methane measurements (15 kg methane / h = 345 $CO_{2\text{-}e}$ / h). This compares to 159 kg $CO_{2\text{-}e}$ / h (4% leakage rate I comparison to the methane produced) based on the current default values of 1% for the digesters and 1% for the upgrade plant as discussed under the table. This gives total life cycle emissions of 503 kg $CO_{2\text{-}e}$ / h (excluding direct CO_2 emissions onsite due to energy consumption) which gives GHG savings of 63% in comparison to the current fossil fuel counterfactual (313 g $CO_{2\text{-}e}$/kWh) and 59% in comparison to the proposed counterfactual methodology (as described in Section 2.8 of the ‘Categorisation and literature review’ report). The proposed counterfactual methodology gives emission credit as a result of using the slurry in the AD plant and additional credit due to the fact that the digestate is replacing fertiliser. However, the proposed counterfactual shows lower emissions than the existing counterfactual because it is based on a gas counterfactual while the existing is based on EU fuel mix.

Figure A16 Counterfactual calculations



Assumptions and Plant data

Slurry emission factor [1]	41.4	kg CO_{2-e}/t
Energy crop emission factor [1]	55	kg CO_{2-e}/t
Fertiliser production life cycle emissions [2]	4.6	kg CO_{2-e} / kg N
Fertiliser production life cycle emissions [2]	1.2	kg CO_{2-e} / kg P2O5
Fertiliser production life cycle emissions [2]	0.6	kg CO_{2-e} / kg K_2O
Nutrient content of digestate [2]	3	kg N/m^3
Nutrient content of digestate [2]	0.5	kg P_2O_5/m^3
Nutrient content of digestate [2]	2	kg K_2O/m^3
Density of digesate	1000	kg/m^3

Site performance		
A. Biogas production [3]	962	m^3/h
B. Biogas to upgrade plant [3]	86%	
C. Biogas to CHP [3]	14%	
D. Biomethane injected (A × B × O)	447	m3/h
E. Biomethane injected (D × L × M)	4343	kWh/hr
F. Slurry [3]	2758	kg / h
G. Maize [3]	2876	kg / h
H. Digestate produced [3]	5071	kg / h

I. Total methane measurement [4]	15	kg / h

J. Natural gas life cycle emission factor [1]	239.7	g CO2 e/ kWh gas
K. Excluding transmission [1]	239.0	g CO2e/ kWh gas

L. Methane density (assuming ideal gas)	0.71	kg / m^3
M. Biomethane calorific value	13.6	kWh/kg biomethane
N. Methane GWP	23	kg CO_{2-e} / kg methane
O. Methane content in biogas [3]	54%	

P. Total methane leakage - measured (I / L)	21	m^3 / h
Q. Total methane produced from digesters (A × O)	519	m^3/h
R. % leakage (P / Q)	4.0%	

Calculations

Current - Ofgem Reporting criteria

	Actual, kg CO_{2-e}/h	
Upstream		Heat from fossil fuels: 313 kg CO_{2-e}/ MWh heat Sustainalbity critera 125.2 kg CO_{2-e} / MWh of biomethane *(refer to section 2.8 in 'Categorisation report & literature review' report)*
Maize	158	
Slurry [5]	0	
Onsite		
digester - leakage [4]	85.3	
Upgrade - slip [4]	73.4	
Downstream		
Digestate [5]	0	
TOTAL	317	1359

Proposed Counterfactual

	Actual, kg CO_{2-e}/h		Counterfactual, , kg CO_{2-e}/h
Upstream			
Maize	158		0
Slurry [5]	0		114
Onsite			
Measured [6]	345	CHP -->	0 [7]
		BtG -->	1041
Downstream			
Digestate [5]	0		79
TOTAL	503		1234

<u>1</u> Refer to Section 2.8 of 'Categorisation and literature review' report, Table 10. <u>2</u> Refer to Section 2.8 of 'Categorisation and literature review' report, Section 2.8.4.2. <u>3</u> Data based on plant performance parameters for May 18. <u>4</u> Based on current default values in Ofgem's GHG calculator 1% methane leakage from digesters and 1% methane slip from upgrade plant (refer to 'Categorisation and literature review' report for details). <u>5</u> Reporting on waste streams and digestate is not required as part of current Ofgem sustainability requirements. <u>6</u> This is the measured total methane leakage from the site (15 kg /h) developed based on the methodology described <u>7</u> Assumes all electricity is used on site and no export .

Results: Under the current Ofgem reporting criteria the GHG savings of the AD plant are 77%. Under the proposed counterfactual the GHG savings are 59%.

A.5 Recommendations

The pilot study indicates that monitoring upwind and downwind concentrations can be used to establish methane emission rates, subject to availability of suitable sampling locations. There is scope to isolate AD plant operations using this approach, but this will depend on individual site layout, wind direction and other factors.

Measurement of downwind methane concentrations can be undertaken using either :

- a measurement system sampling at discrete upwind and downwind measurement points . Use of a multiplexer enables a number of sample points to be measured using one analyser.
- an open path measurement system.

Additional measurement studies are recommended to assess suitability of the methodology for sites with adjacent activities with potential for methane emissions and for different site configurations; for example different feedstock, different age of plant, different upgrade technology, etc.

The selection of the downwind sample locations should be defined with reference to the position and height of emission points. Downwind sampling locations need to be sufficiently far downwind from emission sources to adopt the reverse dispersion modelling approach.

Long-term monitoring is recommended as a means of assessing variability of emissions through seasonal or operational factors however this would have a cost implication.

Campaign monitoring may be a more cost-effective approach for similar monitoring in future but the pilot study indicates that the amount of data can be seriously impacted by weather and plant operations during short-term campaigns.

Appendix B – Equipment & Technology Costs

Technology	Description	Measurement Range	Limit of Detection (LOD)	Resolution	Cost (£)
Flame Ionisation Detector (FID)	Used to measure methane emissions from stationary source in accordance with BS EN 12619	1-10000ppm	1.0	0.1	9000 -20000
Non-dispersive infrared detection (NDIR)	Specific methane measurement	0-5%	1.0	0.1	6000 -10000
Fourier Transform Infra-Red (FTIR)	Multicomponent capability	0-10%	0.1ppm	0.05ppm	30000-40000
Cavity enhanced adsorption spectroscopy (CEAS)	Tuneable diode based system	ppb to ppm	1 ppb	0.6 ppb	Approx. 35000
Open path TDLAS	Open path tuneable diode laser based system	ppm	1.0 ppm	0.1ppm	50000
Lower explosive Limit detector (LEL)	NIDIR or Electrochemical cells	% LEL (methane 5%)	0.1%		1500
Electrochemical cell	Designed for Bio or landfill gas measurement	0-100%	0.1%		1500-3000

Appendix C – Category Methodology

Category		Description	Section where Methodology is covered
1	a	Agricultural waste AD plants for electricity and / or heat production – Small - feedstock throughput < 25k tonnes / year)	5.7
	b	Agricultural waste AD plants for electricity and / or heat production – Medium - feedstock throughput: 25k – 49k tonnes / year)	5.7
	c	Agricultural waste AD plants for electricity and / or heat production – Large - feedstock throughput > 50k tonnes / year)	5.7
2		Municipal or Commercial waste for electricity and / or heat production	5.8
3	a	Agricultural waste AD plants with BtG injection – Membrane process for CO_2 removal	5.7
	b	Agricultural waste AD plants with BtG injection – Water wash for CO_2 removal	5.7
	c	Agricultural waste AD plants with BtG injection – Amine process for CO_2 removal	5.7
4		Municipal or Commercial waste with BtG injection	5.8
5	a	Sewage AD with electricity and / or heat production and / or BtG injection – Separate digester and gas holder	5.9
	b	Sewage AD with electricity and / or heat production and / or BtG injection – Joint digester & gas holder – Floating roof	5.9
	c	Sewage AD with electricity and / or heat production and / or BtG injection – Joint digester & gas holder – Expanding roof	5.9
6		All Industrial waste AD (electricity and / or heat production, and / or BtG)	5.8