UK Government

Methane Emissions from Anaerobic Digestion 2.0

Good Practice Guide for Point Source Emissions

Department for Energy Security and Net Zero (2026)

Acknowledgements

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1. Introduction

The UK Government has set an ambitious target to achieve net zero greenhouse gas emissions by 2050. To meet this goal, the UK must harness a wide range of renewable energy sources, balancing energy, heat and fuel generation with a reduction in national emissions. Biomethane, produced by anaerobic digestion (AD), is expected to play a significant part in the UK's energy mix, offering a renewable, drop-in alternative to conventional fossil natural gas.

Biomethane grid injection capacity in the UK was 7 TWh per annum at the time of writing (2025). With existing support from the UK Government, this was expected to increase to around 8 TWh by 2030 based on GGSS forecasts; and the UK Biomass Strategy[1] identified that 30-40TWh of biomethane would be needed to meet net zero cost-effectively by 2050. This anticipated growth reflects increasing support for biomethane as a fuel, that when produced efficiently can be carbon neutral, and even carbon negative, provided that emissions from the AD process are effectively monitored, captured and prevented from being released to the atmosphere.

While the efficient production of biomethane is one of the core objectives of any AD facility, fugitive methane emissions can be a consequence of the biomethane production process. The true extent of fugitive emissions can vary from site to site, but the loss of any methane is harmful to the environment and can exacerbate global warming impacts. Furthermore, methane emissions from AD can be detrimental to the commercial viability of AD facilities, as methane loss directly equates to lost production and profitability for owners and operators.

To address these concerns and raise awareness of fugitive methane emissions from AD, in 2024 the Department for Energy Security and Net Zero (DESNZ) commissioned a follow-on to the Methane Emissions from Anaerobic Digestion (MEAD) study which was published in January 2025[2], now referred to as MEAD 1.0. The aim of this follow-on study, referred to as MEAD 2.0, was to identify where, why, and how methane emissions occur in the AD process. In addition, MEAD 2.0 aimed to define good practices in asset selection, installation, operation and maintenance that can minimise point-source emissions, for operators active across the industry. This Good Practice Guide was produced based on these findings and should be read in conjunction with the main MEAD 2.0 project report. This document does not override permit or regulatory obligations for AD site operators, or requirements under the Green Gas Support Scheme or Non-Domestic Renewable Heat Incentive, and does not aim to provide a step-by-step process of addressing methane emissions. Relevant health and safety regulations, such as the Dangerous Substances and Explosive Atmospheres Regulations, should be considered when undertaking the activities mentioned here.

For the purpose of this guide, methane slip refers to the continuous and often inevitable release of methane from an asset, such as through off-gas, whilst leaks and other losses refer to unintended and avoidable release from assets and other plant elements, such as pipes, valves and flanges. Point-source emissions are defined as in the main MEAD 2.0 report: "***Point source emissions*** *originate from a single, identifiable location, such as a vent or pipe.*"

[1] Department for Energy Security & Net Zero. *Biomass Strategy*. 2023. Biomass strategy 2023 (accessible webpage) - GOV.UK

[2] Department for Energy Security & Net Zero. *Methane Emissions from Anaerobic Digestion*. 2025. Methane Emissions from Anaerobic Digestion (MEAD) - GOV.UK

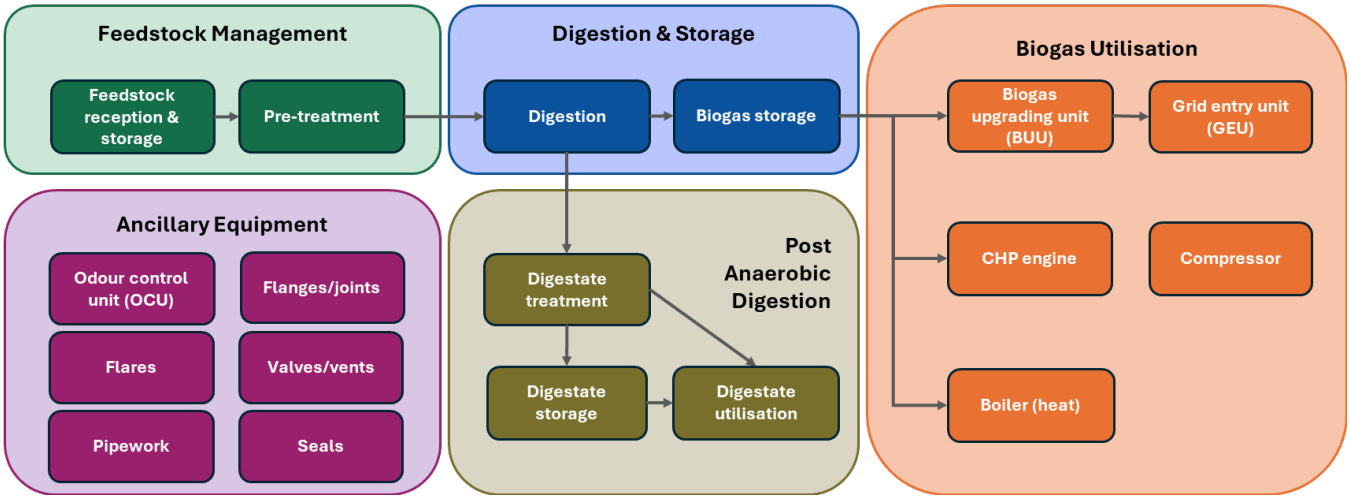
2. Methane Emissions From AD

Methane emissions from anaerobic digestion can arise at various stages of the biogas production process, including during:

- Feedstock reception, storage and pre-treatment
- Feedstock digestion and biogas storage
- Biogas utilisation (whether upgraded to biomethane and injected into the gas grid, combusted in a CHP, or flared to the atmosphere)
- Post-digestion as part of digestate treatment, storage and utilisation.

Figure 1 illustrates these key stages, and outlines noteworthy ancillary equipment used across an entire AD plant, as these can be possible sources of methane emissions irrespective of the stage of the process.

Figure 1: Overview of the AD process, broken down by discrete stages and assets involved.



Methane emissions may occur during the AD process, depending on the mode of operation at the biogas plant. When an AD facility is operating within **'normal operating conditions' (NOC)**, the extent of any methane emissions generated is typically determined by plant design and asset choices. When operating under **'other than normal operating conditions' (OTNOC)**, methane emissions may occur from infrastructure/equipment failures or operating issues due to the site not operating as expected (e.g., leaks from faulty equipment or as a result of poor site management). An additional category of emissions results from **temporary 'other than normal operating conditions' (TOTNOC)** i.e., where a period of maintenance at an AD facility may disrupt NOC, and result in methane emissions through the need to purge equipment or flare biogas/biomethane.

The following sections of this Guide discuss key areas where methane emissions may occur on an AD site, based on specific stages of the process and key assets involved. Guidance is aligned with asset selection, installation, and operation and maintenance, as key considerations and stakeholders involved at these stages will vary.

3. Leak Detection and Repair (LDAR)

Leak detection and repair (LDAR) refers to an environmental management practice used to identify and fix gas leaks, such as methane, from industrial equipment and infrastructure.[3] The core objective of fugitive emissions detection using LDAR technology is to identify the main areas where fugitive emissions are prevalent and to repair within the specified time frame.

Key stages of an LDAR survey include:

- **Identification of leak sources** – map potential leak points using the site's piping and instrumentation diagram (P&ID). Possible emission points can include assets such as tanks or upgrading units, or other elements such as valves, pumps or pipes, for example.
- **Detection** – use appropriate techniques to locate leaks e.g., visual and audio inspections, optical gas imaging (OGI) cameras, sniffer devices (i.e., flame ionisation detectors), and for hard-to-reach areas, drones with gas sensors.
- **Monitor** – conduct routine inspections, after maintenance or operational changes, and during plant commissioning and decommissioning.
- **Quantification (optional)** – estimate the leak volume and gas type using calibrated instruments. Record concentrations and flow rates (optional) together with any measurement uncertainties.
- **Repair and Maintenance** – repair leaks promptly, within a defined timeframe, replace faulty components if needed, re-test to confirm leak resolution.
- **Documentation and reporting** – maintain LDAR records, including leak source, detection method and date, repair actions, emission estimates (optional) and mitigation steps.

This document draws on data from Leak Detection and Repair (LDAR) surveys conducted across a sample of AD facilities that were selected to represent a fair and reasonable cross section of the UK's biomethane sector.[4]

A number of leak detection techniques exist and are available to the market today; specific methods are described in standards EN 17628 and 15446. Common methane detection techniques include OGI cameras, which use infrared light to visualise leaks; remote sensing such as the differential absorption light direction and ranging (DIAL) technique which uses laser sensors[5]; and, handheld gas sniffers or sensors like Flame Ionization Detectors (FIDs) that provide concentration readings. Other methods involve ultrasonic or acoustic cameras, which detect the sound of gas escaping. Increasingly, using a combination of sophisticated software and anemometer technology to determine wind speed and direction, methods such as Tunable Diode Laser Absorption Spectroscopy (TDLAS) can provide both detection and quantification of emissions both at site and source level down to grams per hour granularity. These are available

[3] Specific details of the LDAR survey protocols used during the point source emissions sampling are included in the MEAD 2.0 Final Report.
[4] Approximately 10% of the UK's biomethane sector was sampled, taking into account plant sizes, ages, site types (e.g., agricultural, waste or water treatment facilities), and feedstocks used for example.
[5] Tunable Diode Laser Absorption Spectroscopy (TDLAS) emits a narrow-band light beam whose wavelength can be precisely adjusted (or "tuned") across the absorption line of methane.

in handheld, vehicle-mounted, fixed perimeter or aerial (drone) devices, providing a holistic overview of plant emissions.

The LDAR surveys conducted throughout this study used a range of different detection and quantification devices, depending on the area of the plant sampled.[6]

All samples were direct measurements taken at site level using the vehicle mounted advanced mobile leak detection (AMLD) driven through and around the sites,[7] and at source level on assets with handheld methane specific detection and measurement devices. These provided granular results in terms of the varying breadth and depth of methane detection. Sampling was supplemented with a questionnaire to understand the scale, nature and operating conditions of the assets, as well as existing maintenance and repair programmes undertaken by the plant.

LDAR was used to investigate emissions across each of the gas containment assets involved in biogas production, storage, upgrading and utilisation.[8] This includes:

- Pre-treatment
- Digesters
- Gas storage units
- Biogas upgrading units (BUU)
- Combined heat and power (CHP) engines
- Grid entry units (GEU)
- Pipework
- Pressure relief valves (PRV)
- Safety relief valves (SRV)
- Odour control units (OCU)

Where methane emissions were identified as a result of design considerations due to safety or technology limitations then gas sampling techniques and engineering experience were used to determine, if possible, how much additional methane was being emitted above design parameters. This was the case for emissions such as slip from BUUs and OCUs. The results of the LDAR sampling carried out during MEAD 2.0 demonstrated that all sites exhibited fugitive methane such as leaks or additional methane losses to some extent, from one or more of the assets investigated.[9]

The total leaks per site and per asset are summarised in Figure 2 and Figure 3, with a more detailed overview provided in Appendix A.

[6] Full details of the LDAR methodology can be found in the MEAD 2.0 Final Report.
[7] The Discover Tunable Diode Laser Absorption spectroscopy (TDLAS) technology detects methane at the parts per billion (ppb) level. It is vehicle mounted and detects and visually locates emissions on a GPS mapping position with an accuracy of up to 10 metres. More information is provided on this technology and other technologies used during this project in the “MEAD 2.0 Project Report” (Appendix V).
[8] Feedstock reception and storage, and digestate storage fell outside the scope of the LDAR surveys.
[9] The number of different emissions sources identified across the sample of sites ranged from 1 to 17 per site, across various assets.

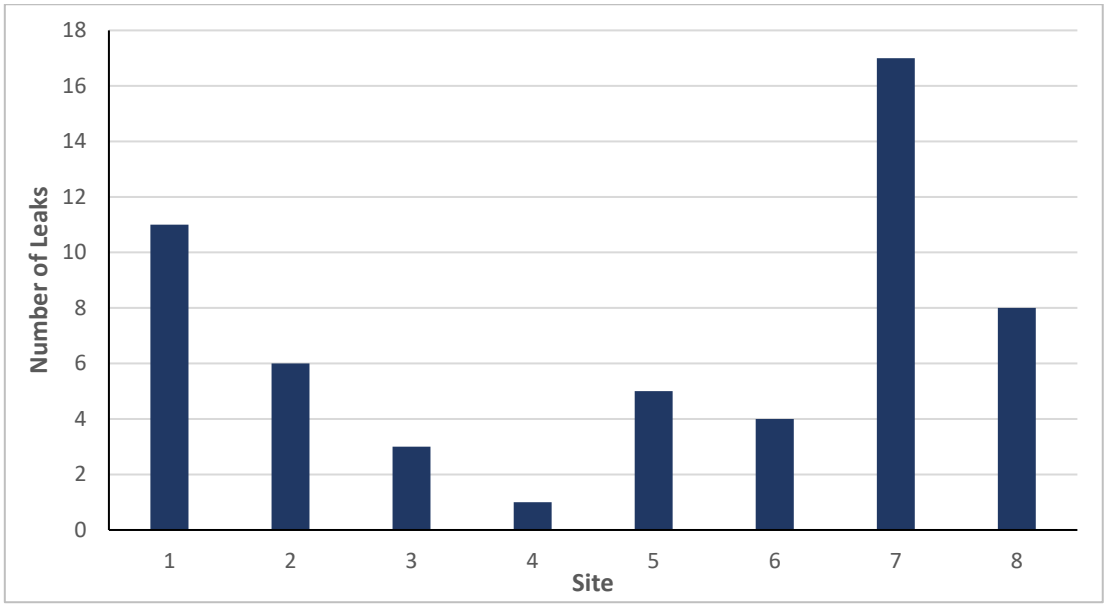


Figure 2: Total number of leaks identified per site

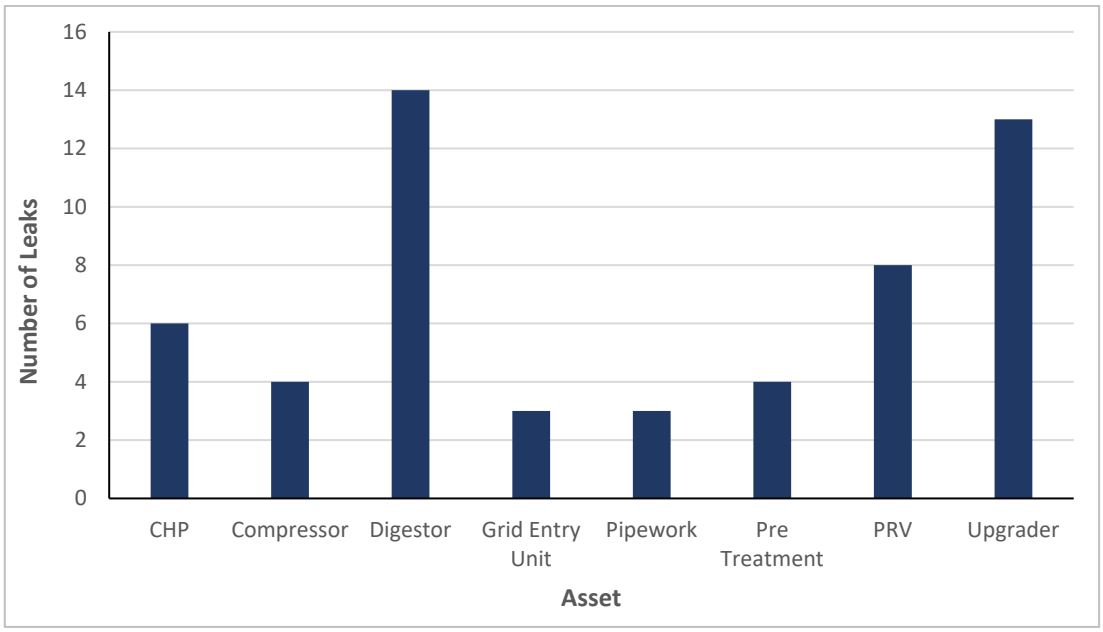


Figure 3: Total number of leaks identified per asset

This highlights the need for good practice guidance, to inform current and potential AD owners and site operators of potential emission sources, and to minimise impacts on the environment and on the commercial viability of AD sites nationwide.

Using the metadata from the study, the following sections highlight where leaks and losses were identified as a result of either asset selection, installation, or operation and maintenance (O&M). Key components are discussed, with recommendations for effective management and mitigation strategies to reduce point source emissions.

4. Good Practice Guidance

4.1. Feedstock Management

Methane emissions from AD can arise at various stages of the biogas production process, including upstream of digestion, during feedstock management. Feedstock reception is a critical first step in the operation of an AD facility, where organic materials are received, inspected, and prepared for digestion. Typical components of a feedstock reception area include the weighbridge (for recording delivery weights), unloading area, hopper or bunker (for temporary storage before feedstock processing), pretreatment equipment (e.g., shredders, de-packaging equipment, trommel screens, slurry tanks), and odour control units (OCUs) incorporated at appropriate stages.

Feedstocks that are easier to store and handle with reduced risk of uncontrolled emissions are generally less biologically active and do not rapidly degrade under ambient conditions. Key examples include crops (maize silage, grass silage, and whole crop wheat) and crop residues (e.g., straw and corn stover). However, it should be noted that emissions from the handling of these feedstocks can occur as poor feedstock management, long storage periods, or storage in warm, damp conditions can promote microbial activity and thus, result in methane formation.

Despite the low risk of methane emissions occurring at the feedstock reception and pretreatment stages of the AD process, proper feedstock management and sound operational practices are essential. Good practice recommendations for the handling, storage and treatment of feedstocks are provided below.

Good Practice Recommendations – Feedstock Management

- Consider the types of feedstocks that will be processed by the site; higher risk types (e.g. sewage sludge) may need more stringent controls in place for the management of emissions.
- Ensure that sites are designed for the processing of selected feedstocks from the outset; methane emissions at this stage are more likely to occur outside of normal operating conditions.
- Ensure fast and efficient feedstock throughputs, minimising the time that feedstock spends in reception. The use of just-in-time deliveries and automated conveyors or hoppers are beneficial, to move material quickly to preprocessing or storage.
- Consider enclosed reception halls with negative air pressures and gas capture if not already required by Best Available Technique (BAT) requirements
- Avoid warm, humid conditions that promote anaerobic decomposition.
- Store high-risk feedstocks separately in sealed tanks or silos with gas-tight lids.

- Clean reception areas frequently to remove residues and prevent the buildup of organic material that could decompose anaerobically. Consider installing sealed, sloped floors with drainage to collect leachate if not already required by BAT.
- Install methane sensors in reception halls and ensure that feedstock reception areas are always included as part of methane emissions site monitoring plans, to determine whether methane loss is occurring in this area.
- Follow best available techniques (BAT) as set out in site permits and train operators to recognise the signs of decomposition (e.g., odours, heat, bubbling).

4.2. Asset Selection

Key assets covered in this section include digesters (AD tanks), gas storage units, biogas upgrading units (BUUs), combined heat and power (CHP) engines, grid entry units (GEUs), pipework, pressure relief valves (PRV), safety relief valves (SRV), and odour control units (OCU).

With regards to equipment selection, high-quality, gas tight materials should be prioritised to minimise methane losses. BS EN ISO 24252 covers biogas production systems including anaerobic digestion, biogas conditioning, biogas upgrading and biogas utilisation, providing guidance on specifications for many key components. Additional elements where methane leaks are common may include:

- **Valves:** ISO-rated valves designed for gas service should be used, to ensure they are fit for purpose and effective during use.
- **Fittings:** fully welded joints should be favoured over flanged or threaded ones, and leak-proof seals and gaskets that are resistant to methane should be selected.
- **Corrosion-resistant materials:** stainless steel or HDPE materials should be considered for pipework, to reduce long-term leak potential due to corrosion or cracking.

4.2.1. Anaerobic Digesters

AD tanks, or digesters, are at the core of any AD process, as this is where the digestion of organic feedstocks takes place to produce biogas.

Digester roofs play a critical role in the containment of biogas during anaerobic digestion, preventing oxygen ingress (i.e., stopping oxygen from inhibiting the anaerobic process), and often for the storage of biogas itself. Key roof types are outlined below:

Fixed/Rigid Covers

Fixed/rigid covers are solid roofs that are permanently attached to the digester tank. They are typically made from materials like concrete, steel (e.g., fusion-bonded epoxy coated stainless steel), and glass-reinforced plastic (GRP). Rigid cover designs can be made from one solid cover or can be installed as separate sections which are then fixed to create a rigid cover. As they are fixed and rigid, these roofs do not move with changes in tank pressure. Therefore, fixed/rigid

covers typically require separate biogas holders (often a flexible membrane inside the tank or separate gas bags) to store the biogas; these are important to ensure that optimal pressures are maintained during biogas production. Fixed/rigid roofs are common in older municipal wastewater treatment plants, but less common across the AD fleet.

- **Advantages:** Durable, robust, and good for structural integrity. They can be sealed effectively to prevent gas leaks and odours from escaping.
- **Disadvantages:** Do not offer integrated biogas storage and can be more expensive to construct than some flexible options.

Flexible Membrane Covers (Single and Double)

Based on stakeholder discussions, flexible membrane covers are considered the most common roof types used by the AD fleet, typically made from strong, durable, flexible materials like HDPE, PVC, and polyethylene. They are often dome-shaped, consisting of either single or double membranes.

Single flexible membranes cover the digester with one membrane with no inflatable section and therefore holds the pressure of the gas in the digester using the design strength of the membrane only. They contain the biogas but typically offer less storage capacity than double membrane due to the risk of over pressure.

Double membranes are the most common flexible roof types in the modern fleet. Double membrane roofs provide integrated biogas storage, as the inner membranes can expand and contract to accommodate variations in gas production and demand. They are often tank mounted, consisting of an inner membrane that contains the biogas, and an outer membrane pressurised with air by a blower. This pressurisation has several important functions including keeping the outer membrane of the roof inflated, protecting the inner membrane from weather and UV light, and regulating the gas pressure within the tank. This ensures that biogas throughput can be more evenly controlled, preventing over pressurisation and limiting loss from the pressure relief valves (PRVs). In addition, should there be any failure of the primary membrane the resulting emission is contained within the secondary membrane.

- **Advantages:** Cost-effective, offer integrated biogas storage on double membranes, flexible to accommodate gas volume changes, provide insulation, and are relatively easy to install.
- **Disadvantages:** Can be susceptible to damage from wind, snow, or punctures if not properly designed and maintained. Single membrane designs offer no secondary protection against atmospheric emissions on failure.

Solid Floating Covers

Solid floating covers float directly on the surface of the digester contents. They are typically made of metal (e.g., steel) and have a skirt that extends into the liquid to maintain a seal. Floating covers allow digester volumes to change depending on loading rates and resultant biogas production or consumption. They provide some gas storage capacity and prevent air from entering the digester.

- **Advantages:** Provide self-regulating gas pressure, prevent air ingress, and can adapt to changing digester liquid levels.
- **Disadvantages:** Can be more complex to design and maintain and require guide mechanisms to ensure proper movement. Design is more prone to leakage.

A total of 36 digesters were sampled across 8 sites as part of MEAD 2.0. Figure 4 shows that anaerobic digesters, and in particular the roofing, are consistently found to be a key source of leaks. Plants have limited options for design changes once the plant is commissioned and therefore consistent monitoring via a regular LDAR program will ensure the continued integrity of this asset, with repairs recommended and actioned promptly. For new plants, it is important to consider the roof options in the early design phase.

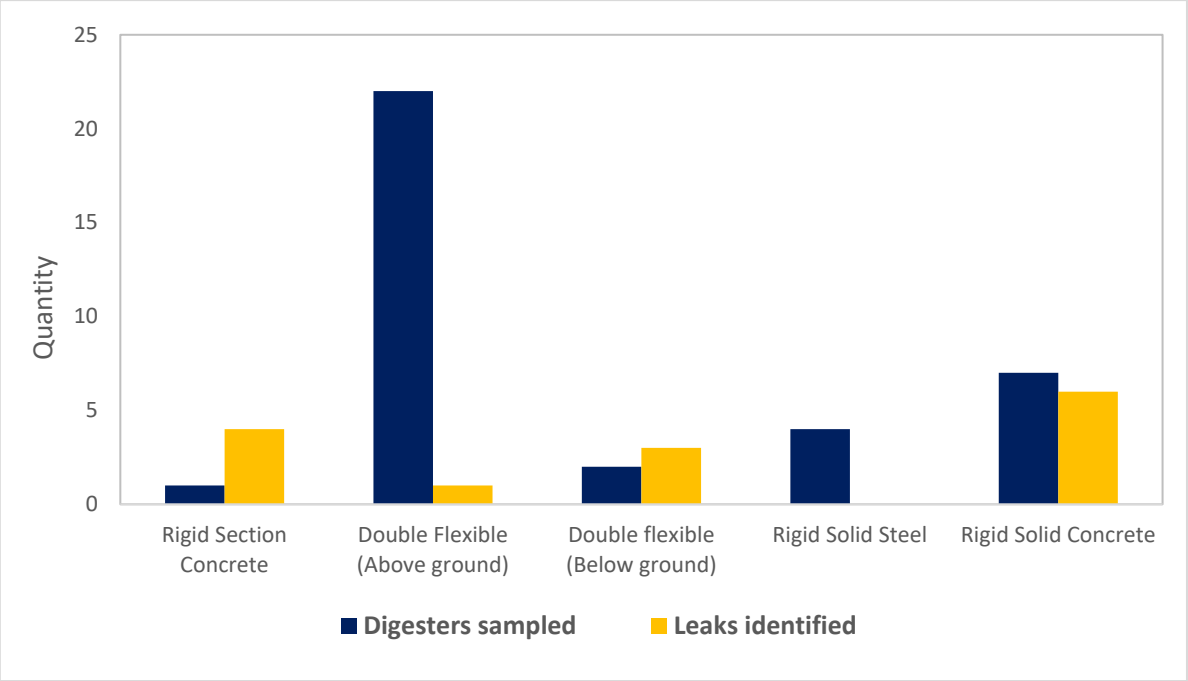


Figure 4: Number of digester leaks identified during MEAD 2.0 sampling, by digester type

The choice of digester roof can depend on a number of factors such as digester size, budget, desired biogas storage capacity, climatic conditions, and specific operational requirements. Table A1 outlines the roof types surveyed as part of the MEAD 2.0 study and sets out the corresponding emissions associated with each type. Figure 4 highlights the digester roof types that were sampled in blue and the number of leaks that were identified on each type in yellow. The double membrane roof type was the most prevalent design on the plants surveyed with relatively low leakage rates compared to the volume surveyed.

An overview of good practice considerations for the digestion and gas storage stage of the AD process is summarised below.

Good Practice Recommendations – Digestion and gas storage

- Methane emissions at this stage of the AD process are typically a result of OTNOC, i.e., equipment damage, operational failures, or scheduled maintenance activities.
- Since emissions should not be expected here, LDAR programmes should be put in place to test all possible areas of leaks, including walls, roofs, bases, valves, flares and any areas where joints, seals, gaskets etc are located.
- An LDAR surveyor should have access to digester roofs meaning that surveys and general maintenance can be conducted more thoroughly. During site design, ensure full access to roofs is a key consideration for new sites.
- Gas tight digesters should be specified, using reinforced concrete or steel digesters with certified gas-tight membranes. As found during the site surveys, steel tanks showed a lower frequency of leaks, so material choice and digester type is important.
- Leaks are most common in areas with joints and seals therefore site design and asset selection should minimise joints and seals where possible, considering integrated equipment with solid or impermeable joints would be advantageous. Sectional roofing should be avoided where possible and the number of inlets and outlets to and from the digester limited. Where unavoidable, regular monitoring and maintenance should be carried out.
- Methane leaks are common around viewing windows in digesters due to the presence of seals. Installation of inspection cameras instead of viewing windows to minimise seals should be considered where possible, and where unavoidable seek to maintain seals on viewing windows during planned maintenance schedules.
- Double flexible membrane roofs generally have fewer leaks than other digester roof types. Where site design and budget allow it, consider the use of these roof types.
- Test valves and flares for operational effectiveness. Where methane is released, either through asset design or through wear/faults ensure that equipment is repaired or replaced promptly.

4.2.2. Biogas Upgrading Units (BUU)

Biogas, when produced via AD, is a mixture of methane (CH_4) and carbon dioxide (CO_2), along with trace amounts of impurities like hydrogen sulphide (H_2S), water vapor, nitrogen (N_2), oxygen (O_2) and siloxanes. Biogas upgrading, therefore, refers to the process of removing CO_2 and other impurities to increase the methane content of the gas. The goal is to create biomethane, which is of pipeline-quality and can be used as a fuel or injected into the natural gas grid.

Biogas upgrading units (BUUs) are the assets involved in biogas upgrading. There are various different types of BUUs with various modes of operation. Key biogas upgrading units/technologies are outlined below:

Water Scrubbing (Pressurised Water Scrubbing - PWS)

Water scrubbing is a physical absorption method whereby raw biogas flows counter-current to pressurised water in a column. CO_2 and other water-soluble impurities (like H_2S) dissolve in the water, while methane remains largely undissolved. Water is then depressurised which releases dissolved gases. Water is regenerated and can be reused.

CO_2 quality: There is generally a low CO_2 concentration in the off-gas. Air is used in the stripping process to regenerate the water. This leads to a high nitrogen and oxygen content. Methane concentration can be up to 2% and there will be a relatively high moisture content too. H_2S and non-methane VOC concentrations will be dependent upon the source of the biogas and other mitigation measures that are in place. Capture of the CO_2 is difficult from these systems.

- **Advantages:** Relatively simple and mature technology; can achieve high biomethane purity.
- **Disadvantages:** Requires significant water consumption. Methane losses can result when scrubbing or depressurising the water.

Pressure Swing Adsorption (PSA):

Pressure swing adsorption is a dry physical separation process that uses adsorbent materials (like activated carbon or zeolites) to selectively capture CO_2, N_2, O_2, and water vapor under high pressure. When the pressure is reduced, the adsorbed gases are released, and the adsorbent material is regenerated. PSA systems typically have multiple vessels operating in cycles (i.e., adsorption, depressurisation, and regeneration).

- **Advantages:** Can effectively remove N_2 and O_2 (which are common in landfill gas). It is a dry process and so does not require significant water consumption.
- **Disadvantages:** More complex than water scrubbing. Methane loss may occur during regeneration.

CO_2 quality: Although the methane slip can be relatively high in PSA systems compared to others, the off-gas is still CO_2 rich. The off-gas will contain CH_4, N_2 and O_2. There may be a small amount of H_2S and non-methane VOCs depending on the adsorbent used and upstream processing. PSA is a dry process so a relatively small amount of moisture will be present. CO_2 from PSA is suitable for carbon capture with some downstream processing.

Membrane Separation

Membrane separation uses semi-permeable membranes that allow certain gas molecules to pass through more easily than others. Typically, smaller molecules like CO_2, H_2S, and water vapor permeate the membrane, while larger methane molecules are retained. Multiple stages of membranes are often used to achieve high purity methane.

CO_2 quality: The off gas will have a high concentration of CO_2 but will also contain small quantities of other contaminants such as CH_4, H_2S and non-methane VOCs which can be reduced with efficient filtering ahead of the upgrader. Membrane separation is a dry process so the gas stream will have low levels of moisture as it is removed before the upgrading step. CO_2 capture is possible from membrane upgraders.

- **Advantages:** Modular, compact, low energy consumption (relative to other BUUs), and no chemicals required.
- **Disadvantages:** Membranes can be sensitive to impurities (like H_2S and siloxanes) which may require extensive pre-treatment, with the potential for methane slip.

Chemical Scrubbing (Amine Scrubbing/Absorption)

Chemical scrubbing is a wet chemical absorption process where biogas is brought into contact with a chemical solvent (typically an amine solution) that chemically reacts with and absorbs CO_2 and H_2S. The solvent is then heated to release the absorbed gases, regenerating the solvent for reuse.

Amine solvents and their degradation products can have carcinogenic effects, so release to atmosphere needs to be kept to a minimum. The upgrader works as a closed loop system with the loss of amine coming via the CO_2 rich off-gas stream under normal operating conditions. Losses are relatively small e.g. 150 ug/ Nm^3 CO_2 (Wärtsilä) or 0.04 ml/Nm^3 biogas (Ammongas) and will be diluted in the atmosphere. The major area of concern will be in the handling of the amine solution and should be done with the appropriate protective clothing.

CO_2 quality: The CO_2 will be at a high concentration, but will contain traces of other contaminants such as methane, H_2S, non-methane VOCs and amine. In addition, there will be moisture in the off-gas. CO_2 capture is possible from amine upgraders with some downstream processing.

- **Advantages:** Can achieve very high purity biomethane. Effective for H_2S removal.
- **Disadvantages:** Requires heating for solvent regeneration (considered energy intensive). Use of harmful chemicals, and potential for solvent degradation and release.

Cryogenic Separation

Cryogenic separation works by cooling the biogas to very low temperatures. This causes the CO_2 present in biogas to solidify (de-sublimation) or liquefy, thus separating it from the methane. Methane remains in its gaseous form or can also be liquefied.

CO_2 quality: Cryogenic separation has the potential to produce high quality liquid CO_2, up to food grade with other contaminants removed in the process.

- **Advantages:** Can achieve high purity biomethane and potentially produce liquid CO_2 as a co-product.
- **Disadvantages:** High energy consumption due to refrigeration. Relatively complex and expensive.

The choice of upgrading technology usually depends on several factors, including the composition of the raw biogas (e.g., the presence of N_2, O_2, siloxanes), the desired purity of the biomethane, the required gas flow rate, energy availability and costs, operational costs, and environmental regulations.

Table A3 (found in the Appendix) outlines the BUU types surveyed as part of the MEAD 2.0 study and the corresponding emissions associated with each type.

For the BUUs sampled, two sets of results were obtained. Methane levels in the off gas were identified as a percentage of incoming biogas and as an average methane emission quantification. Some BUU designs, by the nature of the technology and materials used, will emit a certain amount of methane slip into the off-gas. The levels of methane measured in the off-gas are highlighted in Table A3 and range from 0.32 to 40.91 NM^3/hr. In line sampling found that all sites exhibited slip above design specifications during the sampling period.[10,11] This demonstrates that BUU operational efficiency is an area of increasing interest in reducing site emissions and asset selection and maintenance can make a significant difference to this.

Leaks were also identified from the LDAR survey and highlighted BUUs to be a consistent source of fugitive emissions from leaks. A total of 13 emission points were found from all the sites because of mechanical maintenance failures. These failure points were common across all the BUU technologies with examples such as flange, compression and threaded connections left untightened or unsealed (gaskets, O rings or PTFE tape missing) and leaking valves left unrepaired or unreplaced.

It is evident that some sites have installed methane and H_2S monitoring linked to automated shut down. Quick detection and action prevent the build-up of a hazardous atmosphere and alerts operators to the presence of a leak. These measures are generally more effective in containerised systems such as membrane upgraders. However larger companies are viewing methane loss and GHG emissions as an increasingly important aspect of the operation and are looking into sensor networks across the site to reduce emission events and the environmental impact of the site as a whole.

[10] The results of LDAR slip analysis are shown in Figure A1. Methane content ranged from 0.00% to 12.04% in the off-gas sample, by volume. The average methane content in the off-gas was 2%, by volume.

[11] The greatest methane loss was found on a membrane-based technology where the slip was sent to a liquid CO_2 (LCO_2) module for cryogenic separation. The reason for this seemed to be related to the fact that the 2nd stage of membranes was isolated as part of an upgrade to send the BUU off gas to the LCO_2 process. Ideally, the 2nd stage membranes would have been used as a pretreatment for the LCO_2 process to maximise the capture of methane as lowering the amount of slip at this point would significantly reduce the amount of slip in the LCO_2 process.

Good practice considerations for BUU asset selection and operation are presented below.

Good Practice Recommendations – Biogas Upgrading Units

- Off gas treatment or management is important to minimise methane emissions. The use of analysers for continuous or periodic monitoring of methane and CO_2 levels will ensure losses can be kept to design levels.
- Optimise the process by working closely with the upgrader manufacturer to ensure that the operation is the most efficient it can be, ensuring equipment is scaled and operated according to its capacity limits.
- Ensure raw biogas filtering is optimised to reduce H_2S and VOCs going to the upgrader. This will prevent unnecessary wear and tear on the upgrader unit and subsequent loss of efficiencies.
- In the event of feedstock changes, consult with the technology provider to ensure the upgrader will work efficiently and that there is nothing in the new feedstock which can damage or reduce upgrader efficiency if not adequately treated.
- Consider implementing rapid detection and shutdown measures to capture and prevent leaks as efficiently as possible; fully automated systems are available for this.
- CO_2 capture can reduce methane slip associated with the upgrading process and as markets develop, this option can be increasingly considered for new and existing sites. The use of this technology needs to be balanced with the extra energy usage for the site.
- The use of off gas combustion (e.g., RTO) can prevent any residual methane being lost to the atmosphere, but its use is not widespread at present due to high costs and energy use.
- Losses during maintenance require consideration. Carefully planned and executed maintenance activities and coordination between maintenance schedules for key assets and components can reduce losses by more effectively managing, diverting or using gas at such times. Provision of temporary gas storage capacity should be considered. Temporary gas storage capacity would also help reduce wastage during periods when biomethane cannot be injected into the grid. If the intention is for a new site to expand in the future, then designing the specification of the upgrader to account for this could reduce the need for additional compressors and pumps, reducing costs and optimising efficiency associated with add on equipment.
- Stakeholder engagement has demonstrated that the more the operators and site staff know about the equipment and its operation, the more engaged they are with the process, so ongoing education and training of operators is important. Expertise at this level means that potential problems can be diagnosed early and remedied efficiently, thus preventing more significant or longer-term impacts.

4.2.3. Pressure Relief Valves (PRVs) including Pressure/Vacuum Relief Valves (PVRVs)

AD sites have many pressure relief valves (PRVs) throughout their systems, designed to avoid over-pressurisation. As a result, emissions are intentionally vented into the atmosphere to protect the gas containment asset for both operational and safety reasons. PRVs should only vent during certain operational conditions. The MEAD 2.0 leak detection survey identified PRVs that emitted outside these conditions.

PRVs have varied design mechanisms to relieve during over pressurisation and reseat under normal pressure conditions. Here are the types normally used at AD plants:

Mechanical

The valve contains a loaded spring which is set to hold a seat closed against the valve orifice until the pressure overcomes the set pressure and relieves the biogas past the open seat. When pressure falls below the setpoint, the valve spring closes the seat to retain the biogas in the digester.

- **Advantages:** Relatively simple and affordable construction. Easy to set and maintain.
- **Disadvantages:** Moving parts are prone to wear or corrosion.

Liquid Level

There is a liquid (often water) column to maintain a seal under normal pressure. The pressure builds up above the set point, the gas pushes through the liquid seal by displacement, resulting in venting of the liquid vapour.

- **Advantages:** Fewer methane emissions as liquid will be displaced instead during overpressure.
- **Disadvantages:** Liquid level must be topped up and is often manually done; potential for failure if PRVs are not routinely checked and topped up (especially during months where there is potential for evaporation due to warmer ambient temperatures). Trace heating, and/or glycol addition, is required on the PRVs if located outdoors to prevent freezing over the winter months.

PRVs can be a consistent source of leakage with the original MEAD study reporting up to 53% of plants exhibited some form of PRV emission. This finding has been reflected in the LDAR surveys undertaken during MEAD 2.0, where over 50% of sites surveyed had leaking PRVs. In addition, the leaking PRVs were all found to be located on digesters.

Typically, the PRVs found to be emitting methane were those consisting of a mechanical function such as springs and weights. This is due to the possibility of wearing of springs, linkages and sealing faces within the mechanical valve mechanism. Biogas can have corrosive properties that can damage these components leading to the unwanted release of biogas and therefore methane. It was noted that the liquid level type (non-mechanical) were less prone to emissions as they do not rely on mechanical components. However, liquid level PRVs are typically for low pressure applications and therefore both types have their place on an AD plant.

A comparison table of the different PRVs which were surveyed can be found in Appendix A in Table A2. Good practice considerations relevant to PRV selection and operation are presented below.

Good Practice Recommendations – Pressure Relief Valves

- PRVs must be designed and installed to the operational pressure of the process, and calibrated and inspected by competent engineers.
- Mechanical seals are typically more prone to failure than liquid level valves due to moving parts which wear or fatigue over time. When using mechanical PRVs it is therefore recommended to follow the manufacturer's maintenance and servicing instructions such as changing springs and seats at recommended intervals to maintain the performance of the valve.
- PRVs with flanged connections into solid digester roofs can be a common emitter source. Monitor all PRV flanges as part of a regular LDAR plan and change gaskets or tighten flange bolts where required.
- BS EN ISO 24252 covers biogas production systems including anaerobic digestion, biogas conditioning, biogas upgrading and biogas utilisation, so includes PRVs, and requires monthly inspection and annual (documented) function testing. However, it may be helpful for a minimum quality standard to be set, given that higher quality PRVs showed less activity and fewer leaks.

4.2.4. Odour control units (OCUs)

Some sites have odour control units, such as activated carbon filters and biofiltration systems, to mitigate against odours. These units are commonly found within or adjacent to the reception hall to minimise odour release from the pre-digestion stages of the process, in addition to other buildings or parts of the AD site such as exhausts, dewatering plant, etc.

Biofilters are commonly used to treat ventilation air streams contaminated with relatively high concentrations of hydrogen sulphide, ammonia and other odorous compounds. They may also reduce low level methane concentrations through biological methane oxidation although this is generally incidental to their primary odour control function. Biofilters should therefore not be relied upon to prevent or minimise methane emissions.

As part of this research, only a small number of units were sampled due to the lack of adequate sampling points at the inlet and the outlet to make a confident assessment of the methane slip arising via the process. There were only 3 sites where a sample could be taken within the OCU stream. The data, containing the %vol of CH_4 & CO_2 along with the ambient temperature was recorded over a 30-minute timeframe for each site and the results showed zero CH_4 at the outlet for 2 of the sites and a peak of 0.02% CH_4 on the remaining site. However, these results are of marginal value given inlet monitoring could not be achieved on the same sites, which prevents statements in relation to OCUs' role in methane emissions. Therefore, the good practice consideration in regard to this element is primarily around awareness, understanding that OCUs

can be a means of reducing emissions but should not be relied upon as their purpose is to strip odour rather than methane emissions.

Surveys monitoring the inlet and outlet of OCUs would be beneficial, to understand the extent of emissions at both points, and to consider appropriate mitigating actions to minimise methane emissions at the inlet or outlet point, as appropriate.

4.3. Site Installation

With regards to the installation of assets across an AD site, a number of key measures should be considered from the early design and planning stages through to installation and commissioning, to ensure that fugitive methane emissions are minimised upon operation. Each of these aspects is discussed in more detail below.

4.3.1. Design & Planning

During the early design and planning stages, siting of equipment should be carefully considered to allow for easy access, maintenance and leak detection monitoring upon operation. Access routes and clearances should be designed around all key assets, to allow for effective inspection, repair and emergency response measures. The use of compact system designs can help to minimise the length of piping, potentially leading to fewer joints and thus fewer leak points.

Site layout is highly bespoke, driven by site needs, space, location, access etc but all designs should consider effective operation and maintenance. The significance of site layout from a methane emissions perspective is about the complexity of pipework, length of runs and connectivity. Asset proximity and ease of connection should be considered at the outset, to minimise the need for additional boosting pumps, joints and valves where possible. These additions are often necessary where sites are expanded or additional equipment is integrated at a later stage, so early consideration of future ambitions and possibilities is advantageous.

During the site surveys, access to some key plant items was challenging, in particular digester roofs. This highlighted how difficult digester roofs that did not have good access gantries and steps/ladders would be to maintain. Without being able to properly access these areas, it would be difficult to identify leaks (without the use of remote leak detection techniques) and even more difficult to repair them. One site had underground digesters with a roof at ground level that made the LDAR inspection a safer and a simpler process providing access to the most common leak points such as roof perimeter, connecting valves and pipework entry and exit points. A number of options exist for making roof access easier, including gantries and ladders, or smart design approaches such as reduced elevation. Appropriate options should be considered at the design stage, to ensure accessibility is good once operational.

4.3.2. Installation

Upon installation, it is important that trained professionals are employed to install the relevant assets. All joints and fittings must be properly welded or sealed. Welded joints should be tested with non-destructive testing (NDT) methods like X-ray or ultrasonic inspection. Only seals and gaskets specifically designed for methane-containing gases should be used. Furthermore, threaded connections should be avoided where possible as these are more prone to methane

leakage as identified during the survey, and the use of temporary or makeshift joints should be avoided during installation or commissioning as these are commonly identified methane sources.

All installation and maintenance teams should be trained in gas safety and leak prevention, and commissioning checklists should be kept, with records of leak testing and any emissions minimisation steps taken. Project developers should also ensure that the site complies with environmental permitting requirements, with particular care taken to ensure compliance with emissions limits during commissioning and regular operation. Environmental inspections can be proactively prepared for through the proper maintenance of detailed installation logs and test records. Fire and explosion risk assessments (e.g., DSEAR/ATEX compliance) must also be fully complied with during installation.

During site installation, gas monitoring should also be implemented, with methane detection systems (such as infrared sensors or in-line analytical equipment) located close to critical assets such as the roofs of digesters, gas storage roofs, pipeline junctions, near CHP engines or biogas upgrading units. These should be used to detect leaks and losses that would not be expected during routine operation (e.g. not regular methane slip from upgrading).

Infrared (IR) sensors offer high sensitivity to methane and are suitable for continuous monitoring with data logging and alarms. The use of flow meters and pressure sensors should be considered to monitor abnormal losses, pressure drops or flow anomalies. This can allow for the early detection of methane leaks, without relying solely on gas sensors. Finally, automated monitoring systems can allow for real-time alerting and remote shut down of key assets or gas transfer routes if emissions are detected. This can help to significantly minimise the impact of methane emissions as soon as they are detected.

During the site surveys, it was found that several CHP units had gas leaks from the fuel delivery system and the engine’s cylinder head. In some cases, it was evident that the leak was likely present from the initial installation and commissioning of the unit, so this could have been detected and avoided sooner if gas monitoring had occurred at this stage.

Flares are also essential to ensure that biogas is burnt off when purposely released to the environment. This may occur for a number of reasons:

- During commissioning, a flare may be used to burn off any biogas produced during start-up, before downstream utilisation (e.g., CHP or grid injection) is online.
- For safe pressure release during equipment shutdowns, overproduction, or downstream use failure, backup flares must be employed to ensure that released gas is burnt off. If this is regular, this may indicate a lack of sufficient gas use capacity (in CHP engines, boilers or upgrading units).

Although not a mechanical asset and often not considered a key leak source, flares should be routinely inspected to ensure safe and effective operation. Flares that are not fully burning off gas or are running under sub-optimal conditions may lead to significant losses to the environment. Flares should be designed appropriate to the scale and operational needs of the site, then operated and maintained according to the installer’s guidance. Furthermore, BS EN

ISO 22580 covers the design, manufacture, installation and operation of flares for the combustion of biogas, so the contents of this should be considered at all stages.

Good Practice Recommendations – Design and Installation

- Ensure installation teams can provide competency and safety credentials for pipework installation.
- Use welded, flanged and compression fittings where possible.
- The planning stage should include reduction of potential emission points and ease of maintenance as well as potential for expansion as core design objectives.
- Consider fenceline and off-gas continuous methane emission monitoring as part of the design phase to support hard to access assets within a future LDAR program.

4.3.3. Commissioning

Prior to commissioning, it is common practice for all digesters, gas lines and storage systems to be pressure tested to detect any leaks that may result from improper installation or equipment defects. Digesters and gas lines should be tested with inert gas (e.g. nitrogen) or water under pressure to check for leaks before introducing biogas.

Following site commissioning, a full leak audit should be carried out using LDAR. A number of tests can be used here, including:

- Handheld detectors: Flame ionisation detectors (FIDs) or tunable diode laser absorption spectroscopy (TDLAS), providing high-sensitivity and real-time monitoring.
- Optical gas imaging (OGI): Infrared cameras to visualise invisible methane leaks across the entire asset, often from a distance.
- Methane “sniffers”: Detect and measure concentrations around suspect areas.
- Post-thermal cycling test: After the system has experienced several temperature cycles, leak checks should be repeated, as seals and gaskets may expand/contract and develop new leak paths.

Any leaks found should be logged and dealt with as soon as possible.

Good practice considerations relevant to site installation are presented below.

Good Practice Recommendations – Site Installation

- Ensure compact system designs to minimise the length of piping, resulting in fewer joints and fewer potential leak points. Asset proximity and pipework connections should be considered at the outset (i.e., consider possible future expansions and pipework/connection requirements).

- The siting of equipment should also be carefully considered during site design to ensure ease of access for maintenance, leak detection monitoring, and repairs to take place. Good access to assets ensures a better chance of finding and repairing leaks.
- Trained professionals should be employed to install relevant assets. Joints and fittings must be properly welded or sealed.
- Installation and maintenance teams should be trained in gas safety and leak prevention. Commissioning checklists should be kept, with records of leak testing and the emissions minimisation steps taken.
- Fire and explosion risk assessments (e.g., DSEAR/ATEX compliance) must be fully complied with during installation and kept updated.
- Gas monitoring should be implemented during site installation, with methane detection systems located close to critical assets (e.g., digester roofs, gas storage roofs, pipeline junctions, CHP engines, BUUs etc.).
- Flares are essential to ensure that biogas is burnt off when purposely released to the environment. They must be routinely inspected to ensure safe and effective operation, and designed to suit the scale and operational needs of the site, in alignment with standards (BS EN ISO 22580). Pressure relief safety systems should be designed such that the flare acts as the primary overpressure relief system with PRVs being 'last resort' safety devices.
- Digesters and gas lines should be tested with inert gas (e.g., nitrogen) or water under pressure to check for leaks before introducing biogas.
- A full leak audit should be carried out using LDAR. Any leaks found should be logged and dealt with as soon as possible.

4.4. Operation & Maintenance

Methane emissions generated at AD facilities can be grouped into three distinct but related categories, as introduced above.

- Emissions generated when the AD facility is operating within **'normal operating conditions' (NOC)**.
- Emissions resulting from infrastructure, equipment or operational issues during **'other than normal operating conditions' (OTNOC)**.
- Emissions resulting from **temporary 'other than normal operating conditions' (TOTNOC)**.

Throughout this research it is evident that significant differences are seen in methane emissions between AD facilities operating under normal operating conditions (NOC) and those deviating from normal operating conditions. The impact of other than normal operations (OTNOC) on methane emissions is also evident from the original MEAD study where four of the sites in the study were undertaking maintenance or had emergencies during measurement campaigns.

Following the site surveys undertaken for MEAD 2.0, it was apparent that maintenance of the biomethane sites and individual components within has a direct relation to the amount of the methane emissions discovered.

Typical maintenance types are summarised in

Table 1 and further discussion on some key components are provided below.

Table 1: Maintenance types, by purpose and frequency, with examples.

Maintenance Type	Purpose	Frequency	Examples
Preventive Maintenance	To avoid breakdowns and ensure smooth operation	Daily, Weekly, Monthly	Checking for gas leaks; Cleaning filters; Lubricating moving parts; Monitoring temperature and pressure
Corrective Maintenance	To fix issues after a fault or failure	As needed	Repairing broken components; Replacing faulty sensors; Fixing leaks in gas pipelines
Predictive Maintenance	To anticipate failures using data and analytics	Periodic (based on monitoring)	Vibration analysis on motors; Thermal imaging of electrical panels; Biogas composition monitoring: Continuous methane emission monitoring of major assets
Routine Maintenance	Regular tasks to keep the system running efficiently	Daily to Weekly	Checking pH and tank levels; Monitoring gas quality and composition; Checking moving parts and mechanical components
Shutdown Maintenance	Major overhauls during planned downtime	As needed	Cleaning digester tanks; Replacing worn-out components; Inspecting structural integrity
Emergency Maintenance	Unplanned repairs due to sudden failures	Immediate	Fixing burst pipes; Emergency gas flaring; Electrical short circuit repairs

Digesters – a combination of routine, preventative and corrective maintenance can prevent losses from tanks, roofs and associated equipment, identifying potential leaks and detecting issues early.

BUUs – a combination of routine, preventative and predictive maintenance can help to reduce losses and preventable leaks from the upgrading stage, with the type, nature and frequency of maintenance depending on the upgrader technology being used. With membrane upgrading systems for example, membranes can become saturated if not monitored and replaced in a timely manner; using predictive maintenance and monitoring usage can prevent this. Additional factors which would impact process efficiency and influence losses at this stage would also include failure to eradicate contaminants such as volatile organic compounds which stick to the surface of the membrane material or failure to operate within the design parameters of the BUU or incorrect configuration settings. Such failures would often cause an increase in methane slip where methane is passed through the free venting side of the membrane and passed into the atmosphere with the waste CO_2. Periodic maintenance of scrubbing devices within the BUU system such as activated carbon vessels could prevent the build-up of contaminants and therefore improve the efficiency of the membranes and drive down methane slip.

PRVs – a combination of routine, corrective and emergency maintenance is required to effectively manage PRVs and reduce losses and leaks due to functional issues or failures. PRVs must be regularly checked, calibrated and maintained to ensure they function to the design pressure and prevent incidents from overpressure or under pressure. This is a requirement

under the Pressure Systems Safety Regulations (PSSR)[12], applicable to larger scale biomethane facilities where higher pressures are experienced. It is also important to understand that a PRV opening too early can emit large amounts of methane to the atmosphere unnecessarily. This would occur if the device were set to open below the operational pressure of a system, so biogas would be continuously passing through the valve. Periodic maintenance could identify incorrect set points and correct them to prevent potential detrimental effects to safety and the environment. Maintenance of the valve internals routinely can also prevent other failures related to their mechanical operation.

CHPs – a combination of routine, preventative, corrective and shutdown maintenance can reduce leaks and losses from CHP engines. Most existing and many new sites will include a CHP to provide heat and power to the site. Methane slip typically occurs from incomplete combustion, so mitigation techniques focus mainly on improving combustion performance. Monitoring performance is essential to minimising slip, and as CHPs require major overhaul or replacement periodically (every 5-10 years) shutdown maintenance is unavoidable; however, careful measurement, monitoring and prediction of replacement can be effectively coordinated with other shutdown activities to minimise losses and downtime. Routine maintenance of the CHP unit is also essential to effectively detect issues and allow timely repairs to minimise impacts.

Pipework and fittings – A combination of routine, preventative and corrective maintenance is required for effective leak reduction in pipework, seals, valves and flanges, for example. Missing gasket seals, open pipework, inadequate fastening and incorrect sealing methods are all examples of what was identified as a root cause of some of the emissions found during the surveying. It was apparent in some cases that inadequate maintenance was carried out, causing methane leaks. Routine checks should pay attention to such static components, as maintenance programmes are less stringent for such elements than they would be for key mechanical assets.

During the site surveys, it was identified that maintenance of plant items and in some cases the entire plant is often dealt with by a third-party contracting company. In these cases, maintenance according to the installation or operational guidance is adhered to but any static components that fall outside of such third-party contracts can be missed, and the whole site performance is not viewed in the same way as it would be by the site owner or operator. Furthermore, responses to maintenance and repairs was often observed to be immediate for plant owners and up to 2 weeks for the third-party service providers. It was often the case that a key plant item was maintained only by the manufacturer and the lack of availability of their maintenance team meant that methane leaks to atmosphere would continue until the manufacturer had availability to intervene. It is therefore important to consider an appropriate mechanism to encourage timely maintenance and repair, to optimise performance and to minimise impact.

To reduce maintenance time and build operational teams' awareness of typical failure points, poor maintenance practice and develop a deeper understanding of relevant LDAR standards, AD sites would benefit from continuous professional development of their operational teams in asset maintenance and LDAR planning. Training can be delivered by a combination of equipment manufacturers as well as LDAR service providers who can increase knowledge of

[12] The Pressure Systems Safety Regulations 2000

LDAR standards, relevant detection and quantification techniques and share multiple site insights to deliver quick wins and long term LDAR planning best practice.

5. Conclusion

Methane, while a valuable energy source, poses significant environmental and economic risks when released unintentionally or managed inefficiently. This research highlights the critical importance of identifying, quantifying, and mitigating methane emissions across anaerobic digestion (AD) facilities. The findings demonstrate that fugitive emissions and methane slip are prevalent across a range of AD sites, regardless of feedstock type, ownership model, or technology used.

Building on existing industry knowledge, guidance and regulations, this Good Practice Guide for point source emissions provides a practical framework for AD operators to reduce methane losses through improved asset selection, installation practices, and operation and maintenance regimes. Key recommendations include the adoption of double membrane digester roofs, non-mechanical digester pressure relief valves, and continuous monitoring of off-gas streams from biogas upgrading units which allows early detection of issues and timely action. The correlation between maintenance quality and emission levels was particularly evident, highlighting the importance of ownership, accountability, and timely intervention.

To ensure sector-wide impact, these practices can be adopted not only at the operational level but also embedded into industry standards and regulatory expectations. Furthermore, additional awareness raising should be encouraged via events, articles and sector wider communications to set out the environmental risks and economic implications associated with methane leaks and losses.

By implementing the recommendations outlined in this guide, AD operators can enhance environmental performance, improve plant efficiency, and contribute meaningfully to the UK’s net zero ambitions. Methane mitigation is not just a regulatory requirement; it is a commercial and environmental imperative.

Appendix A – Data

Table A1: Methane Emissions at Digesters surveyed

Site	Digester Type and Count	Methane Emissions
1	Above ground – Rigid sectional concrete roof x1 Above ground – Double flexible membrane dome roof x2	The sectional concrete roof was found to be emitting methane emissions from the joints of the concrete segments. The maximum concentration of methane here was 324 ppm. The perimeter of the concrete sectional segments also showed an emitted emission of 246 ppm.
2	Above ground – Double flexible membrane dome roof x6	None from digesters directly
3	Above ground – Rigid steel roof x4 Above ground – Double flexible membrane dome roof x1 Above ground – Double membrane gas bag x1	None from digesters directly
4	Above ground – Double flexible membrane dome roof x2	None from digesters directly
5	Above ground – Double flexible membrane pointed roof x5	Desulphurisation pump vent, integral to a digester was emitting methane with a maximum measured methane concentration of 10,984 ppm
6	Above ground – Double flexible membrane dome roof x2	None from digesters directly
7	Above ground – Rigid solid concrete roof x7 Above ground – Double membrane gas bag x1	Multiple overspill wells that are integral to this type of digester were found to be emitting methane emissions with the peak methane concentration reading of 20,811 ppm
8	Above ground – Double flexible membrane dome roof x2 Below ground – Double flexible membrane dome roof x2	Multiple inspection pits were found to be emitting methane on a below ground digester. This was found to be leaking through the concrete sidewall around the viewing windows. Maximum measured methane concentration of 50,000 ppm

* MEAD 2.0 was focussed on identifying emissions sources rather than quantifying leaks, so ppm values stated in this table are for context only and have not influenced the recommendations. The frequency of leaks identified at certain points, by technology type was a more useful indicator of significance.

Table A2: Methane Emissions at PRVs

Site	PRV Location	Type of PRV	Methane Emissions
1	Digester roof	Liquid	None directly from the PRV outlet. Emissions found at the flanged joint on 2 separate PRVs as they connected to the digester. Maximum methane concentrations of 629 ppm and 828 ppm respectively were found.
2	Digester roof	Mechanical	Emission found on the exhaust of the digester's main PRV. Maximum methane concentration of 2995 ppm found.
3	No PRV emissions found.	Liquid	N/A
4	Upgrader PRV Vent	Mechanical	Emission found on outlet of a PRV vent stack from the BUU. Maximum methane concentration of 87383 ppm was found.
5	No PRV emissions found.	Liquid	N/A
6	No PRV emissions found.	Liquid	N/A
7	Multiple digester roofs, Digesters 3,6 and 7.	Mechanical	Emissions found on multiple digester PRVs. Maximum methane concentration as follows; D3(1) = 42920 ppm, D3 (2) = 26988 ppm, D6 = 3665 ppm, D7 = 1200 ppm.
8	Digester 3	Liquid	Emission found on outlet of PRV. Maximum methane concentration of 1133 ppm was found.

* This table identifies only PRVs that were found to be a source of methane emissions, so on sites where no PRV leaks were identified (3, 5, 6) no specific PRVs are listed.

Table A3: Off-Gas Methane Emissions at Upgraders

Site	Upgrader Type	Methane Composition			Calculated Flowrate (NM^3/hr)	Average Methane Emission Quantification (NM^3/hr)
		Avg. %	High %	Low %		
1	Membrane	1.82	1.93	1.72	393.1	7.15
2	Membrane	0.97	1.37	0.00	368.8	3.58
3	Membrane with off-gas sent to LCO2 module for Cryogenic Separation	9.05	12.04	0.00	452.00	40.91
4	Membrane	0.91	11.60	0.00	373.19	3.40
5	Pressurised water separator	0.32	3.18	0.26	530.00	1.70
6	Membrane	0.8	0.87	0.72	195.01	1.56
7	Pressurised water separator	0.13	0.18	0.00	245.00	0.32

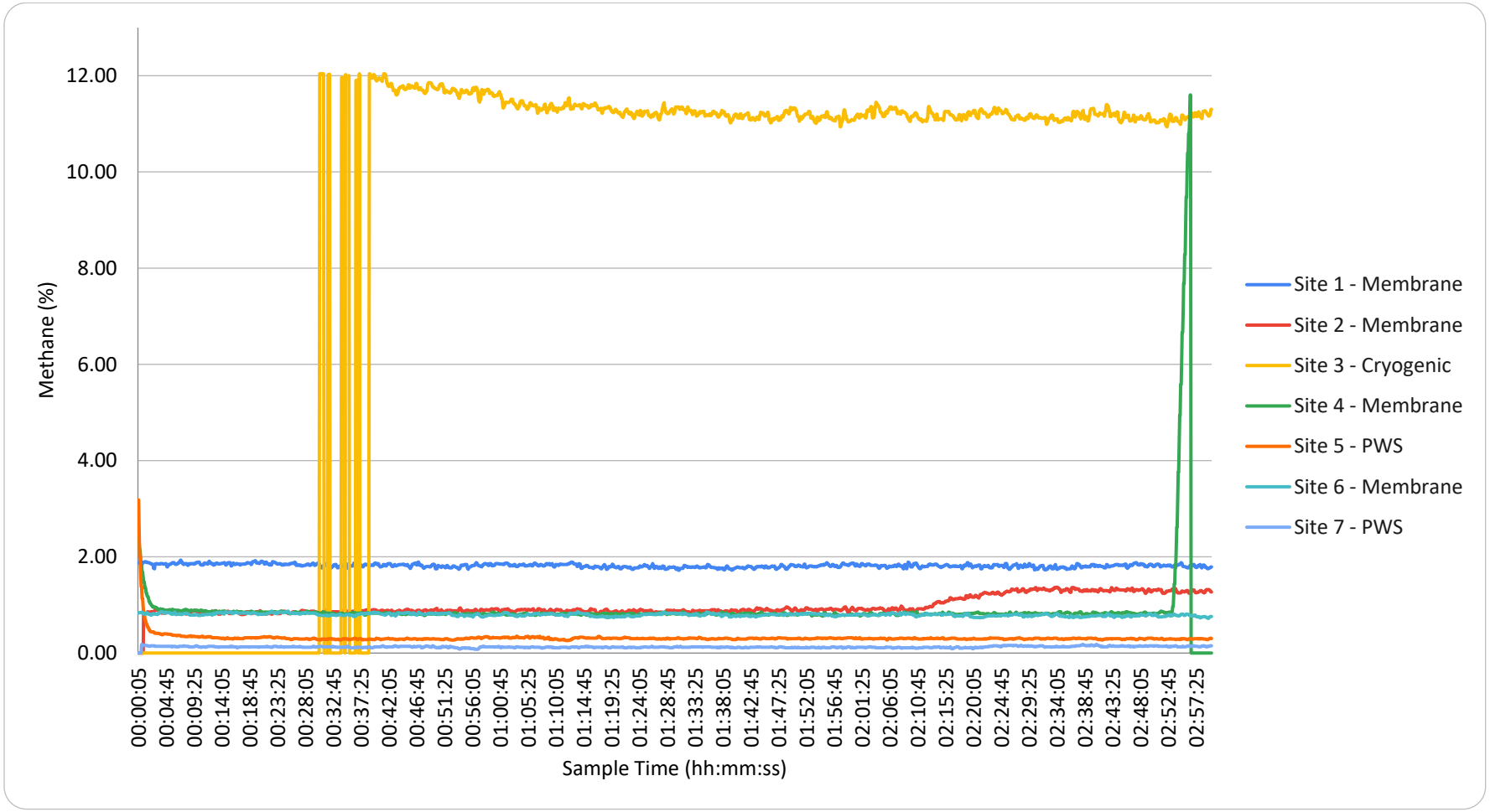


Figure A1: Biogas Upgrader Off-Gas Composition Comparison Graph[13]

[13] Given only one cryogenic site was available for sampling during this study, it is not possible to draw conclusions on this technology based on available evidence.

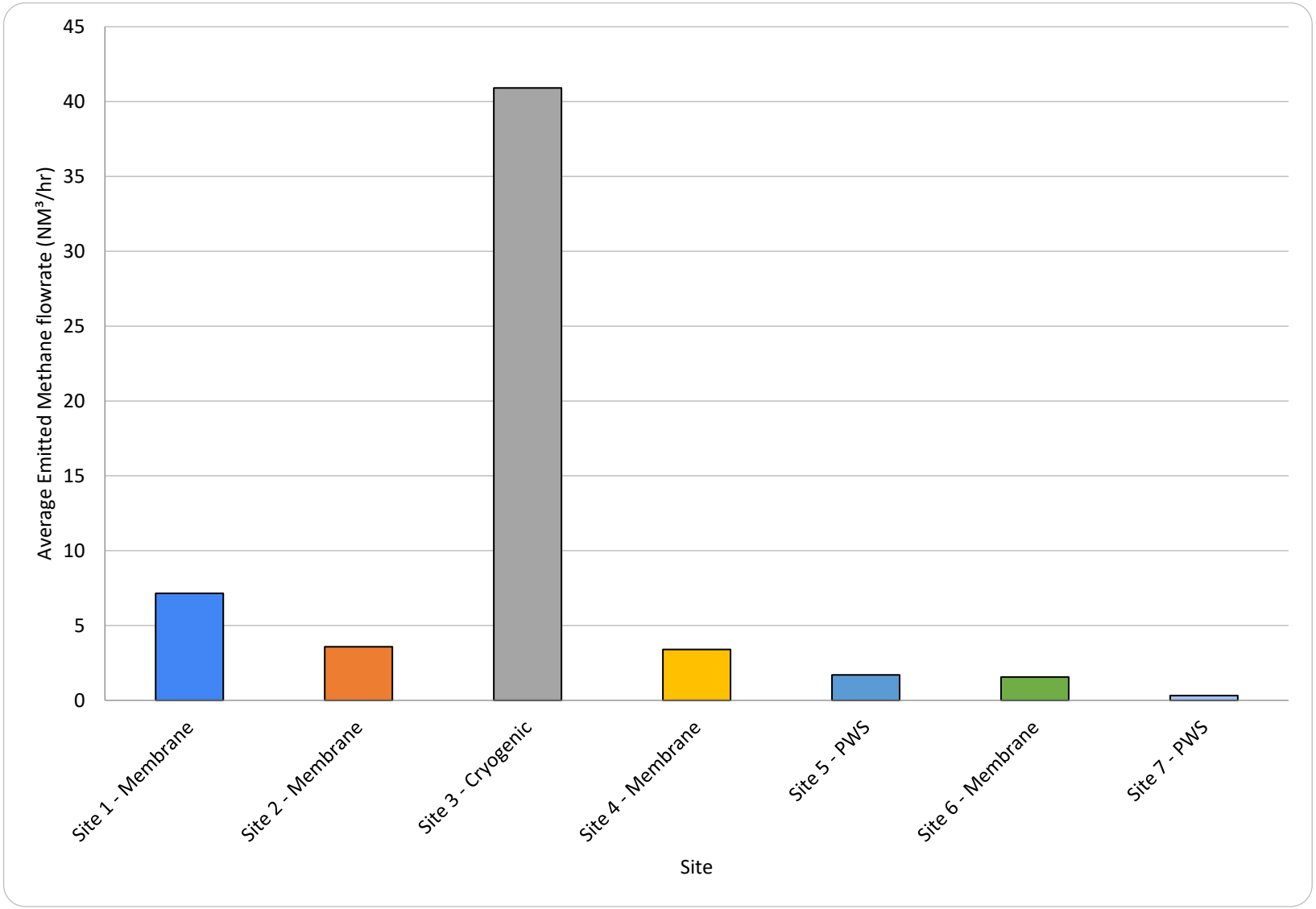


Figure A2: Biogas Upgrader Average Emitted Methane Flowrate

Appendix B – Site Selection

Market insight was used to inform site selection for the sampling of point source emissions at AD plants across the UK. Site selection focussed on BtG facilities, given that biomethane grid injection is now the preferred end use of biogas by UK AD policy, meaning that BtG deployment is expected to dominate the AD sector going forward.

Initially 10% of the UK's biomethane market was targeted for sampling. Sites were considered based on:

- **Size** (ranging from large to medium scale BtG)
- **Age** (recently commissioned and older facilities)
- **Site ownership model** (those operating under group/corporate ownership compared to individually owned and operated sites)
- **Feedstock type** (waste-fed, farm-fed or sewage treatment feedstocks).
- **Asset type** (where possible sites were selected with variable asset types e.g., upgrader types)

The full profile of sites selected for sampling is summarised below. The sites demonstrate a reasonable spread in terms of site size, age, ownership model and feedstock type, offering a fair representation of the sector in terms of the types of sites considered. Furthermore, with regards to the upgraders used at each of these sites, the majority used membrane separation biogas upgrading processes, while two used water wash upgrading technologies. This is in line with the current spread of upgrader types presently used by the BtG market in the UK.

Table B2: Profile of sites selected for point source emissions sampling.

Site	Plant Size	Feedstock Type	Upgrader Type	Commissioning Date	Ownership/Operation
A	**Medium** kWe: 3,176; Nm3/hr: 850	**Waste-fed** (50,000 tpa)	Membrane	2011	Individually owned Individually operated
B	**Large** kWe: 495; Nm3/hr: 1,200	**Farm-fed** (110,000 tpa)	Membrane	2012	Individually owned Individually operated
C	**Large** kWe: 6,400; Nm3/hr: 1,026	**Sewage** (396,000 tpa)	Water wash	2012 BtG in 2014	Individually owned Individually operated
D	**Medium** kWe: 440; Nm3/hr: 495	**Farm-fed** (22,500 tpa)	Membrane	2014	Group owned Group operated
E	**Medium** kWe: 4,500; Nm3/hr: 250	**Farm-fed** (20,000 tpa)	Membrane	2016	Group owned Group operated
F	**Medium** kWe: 500; Nm3/hr: 375	**Waste-fed** (50,000 tpa)	Water wash	2016	Individually owned Individually operated
G	**Medium** kWe: 500; Nm3/hr: 750	**Farm-fed** (51,000 tpa)	Membrane	2021	Group owned Group operated
H	**Large** kWe: 499; Nm3/hr: 1,000	**Waste-fed** (95,000 tpa)	Membrane	2022	Group owned Group operated

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