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Methodology to Assess Methane Leakage from AD Plants

Part I: Report on proposed categorisation of AD plants *and* literature review of methane monitoring technologies

Final Report

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1 Introduction

Government Energy Statistics[1] show that the use of anaerobic digestion (AD) has increased significantly since 2011. Installed electrical generation capacity has increased from 71 MW in 2011 to 286 MW in 2015. For the same period, the RHI has increased the generation of heat (to around 1110 GWh/year in 2015) and the injection of biomethane into the gas grid. According to the Renewable Energy Association (REA) there were around 50 biomethane-to-grid (BtG) projects at the end of 2015[2], injecting approximately 2.5 TWh/year into the gas grid. The 2016 statistical report from the European Biogas Association (EBA), states that the number of BtG plants in the UK increased to 80 plants at the end of 2016 injecting around 74 Mm^3/year. This demonstrates that AD producing biogas can play a significant role in the UK, with potential to contribute to the renewables target for 2020 and the subsequent Carbon Budget 4 (2027) and Carbon Budget 5 (2032).

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. Estimates by the Department for Business, Energy and Industrial Strategy (BEIS) of Greenhouse Gas (GHG) savings from biomethane and biogas are sensitive to the assumed levels of methane leakage, which is currently assumed between 0.05% and 2.5%.

A study by Börjesson and Berglund in 2003[3] reported that, in order to maintain positive lifecycle GHG savings, the maximum allowable methane emissions from the production and upgrading of biogas can be in the range 8-26% depending on the type of feedstock (highest for manure, 22-26% followed by organic waste, 12-17%). In addition, IPCC Guidelines (2006)[4] state that emissions of CH_4 from AD facilities due to unintentional leakages during process disturbances or other unexpected events will generally be between 0 and 10% of the amount of methane generated and that a default value of 5% can be assumed in the absence of data.

Several factors influence the level of methane leakage from an AD plant. These include the type of feedstock or mixture of feedstocks on site, the practice in storing the feedstock and feeding it to the digesters, the design of digester and gas storage area and nature of the digestion process, the practice in storing the digestate and the processes involved in the final use of the biogas (combustion in combined heat and power (CHP) / boiler or upgrade and injection into the grid).

The literature on methane leakage from AD plants is relatively recent and is limited. Studies in the literature are focussed on identifying sources of leakage and evaluating methane leakage for specific sites. Studies have been conducted in Germany, Denmark, Austria, Sweden Switzerland, France and Canada. These studies are usually based on different assumptions, site parameters, monitoring technologies and boundaries and so are not easily comparable. Extensive literature is, however, available on methods for monitoring technologies for methane technologies.

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. This report forms the first phase of a project aimed at monitoring methane emissions from AD plants in the UK.

The objectives of Phase I of the 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,

[1] https://www.gov.uk/government/statistics/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes

[2] REA, http://www.r-e-a.net/blog/review-2016-biomethane-to-grid-is-heating-up-14-06-2016

[3] From the Swedish Voluntary system for control of methane emissions published by IEA Bioenergy Task 37

[4] Volume 5, Chapter 4 (Biological treatment of solid waste), available at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html

(ii) define counterfactuals and developing 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 of a biomethane monitoring methodology and test it on a pilot plant

This report is one of two deliverables for the Phase I project and is aimed at addressing (i) - (iii) above. As part of this project we have also produced a **second report** that details the biomethane monitoring methodology which will be used under the large scale field trial. The two reports are meant to be stand-alone but are cross-referenced where necessary.

The **main overall objective of this first report** is to recommend a methodology for categorising existing AD plants in the UK, in terms of factors that may influence potential biomethane leakage. This will allow the general monitoring methodology to be tailored for, and consequently applied to, each of the categories.

Structure of the report
The report is in two parts. The first part (Section 2) is focussed on developing a methodology for classifying AD plants in the UK and defining the boundaries and counterfactuals related to the defined classifications. The second two (Section 3) is focussed on a literature review of biomethane monitoring technologies.

Our approach to classifying AD plants in the UK is first summarised in Figure 1. This presents the criteria that have been taken into account in classifying AD plants. Section 1.2 discusses sources of methane leakage from different process areas within AD plants. Section 2 presents our methodology for categorising AD plants and discusses boundary issues which need to be taken into account for each of these categories. Section 2 also discusses counterfactuals and the considerations that need to be taken into account for each of the different categories. Section 3 then presents a detailed review of the available literature on biomethane monitoring technologies.

Methane leakage from gasification and pyrolysis
Biomethane leakage could potentially arise from gasification and pyrolysis plants as well as AD plants. While the methane content in biogas from AD is in the range 50-70% depending on the type of feedstock, the content of methane in syngas from gasification is around 5-10%. The number of biomass and waste gasification plants in the UK is much smaller than AD plants. Furthermore, currently there are no plants in the UK that produce biomethane from gasification / pyrolysis process (i.e. via syngas methanation). The focus in this report will be on biomethane leakage from AD plants.

1.1 Overall approach to plant classification

Biogas and biomethane plants can have many variations depending on, for example, the type of feedstock, type of AD process, nature of the end-use of the biogas produced and type of upgrade plant. Different types of AD plants will have different sources and levels of leakage. The monitoring programme under the large scale field trial will deploy the monitoring methodology (see Methodology Report) to a wide range of AD plants to allow comparison and to possibly develop benchmarks for different categories. The objective of the classification of AD plants described in this report is thus to facilitate the process from which plants will be selected under this subsequent phase.

Different types of AD plants in the UK generally consist of the same core process areas, as shown in Figure 1. Each of these areas has potential to contribute to biomethane leakage and will be examined in the classification proposed in this report. This section considers the variations of each of these main process areas that are important to take into account in the classification of AD plants. AD plants can be classified in several ways, depending on the specific design of each of these areas. We have summarised the key aspects to be taken into account for each of the process areas in Table 1.

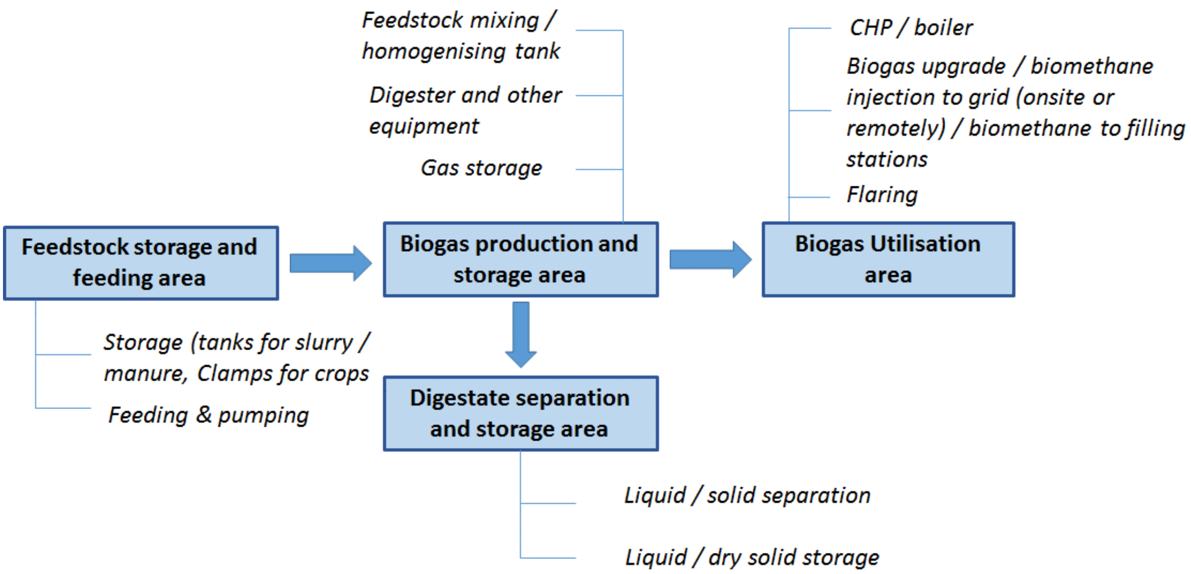

Figure 1: Main areas of an AD plant

In categorising AD plants according to the variations discussed in Table 1, the dataset of all AD plants in the UK has been considered. It was ensured that a statistically-representative dataset is available to select sites for a potential large scale field trial. This will ensure that the estimates made for a given category are based on several plants from that category. Data on the type of digestion process or on whether, for example, the liquid digestate is stored on site or transported offsite for immediate spreading may not always be available. Such data may, however, be collected as part of the site survey that will be conducted as part of the monitoring exercise.

Another consideration for categorisation is the applicability of the monitoring methodology. The categorisation of plants needs to ensure that the biomethane monitoring methodology (see Methodology Report) is applicable to as many plants as possible. However, as discussed above there will always be variations amongst plants for which the methodology will need to be tailored. The monitoring methodology developed needs to be applicable to a wide range of AD plant categories. To meet these requirements the monitoring methodology developed consists of general principles and procedures applicable to all types of plants (see Methodology Report). However, there will be specific aspects that the monitoring methodology needs to address, e.g. pumping the liquid digestate from sewage plants for storage in open lagoons away from site. The categorisation of plants, on the other hand, needs to ensure that plants are grouped in such a way as to cover all possibilities whilst at the same time ensuring that the monitoring methodology does not become unnecessarily cumbersome and difficult to apply.

Table 1: Main considerations in classification of AD plants

Process area	Main considerations in classification of AD plant based on a review of the literature
Feedstock storage and feeding area	• **Type of feedstock**: Key categories include (i) agricultural waste including animal slurry, manure and purpose-grown crops (e.g. maize, silage, grain, straw), (ii) municipal and commercial waste including kitchen waste, (iii) sewage sludge resulting from wastewater treatment plants after primary and secondary treatment. • **Method of storage**: depends on feedstock (clamps for purpose-grown crops; tanks for slurry, manure and sewage sludge).
Biogas production area	• **Feedstock mixing tank**: For plants taking mixed feedstocks, a tank for mixing feedstocks is required to ensure feedstock composition is homogeneous. This is a key source of leakage and is typical for agricultural plants where slurry is mixed with crops before admitting to the digesters. • **Biogas storage**: Depending on design, digesters can either be integrated with gas storage or can be a separate tank from gas storage. Integrated digester / biogas storage systems can either have a floating roof or an expanding roof for holding the biogas. Leakage from the biogas production area mainly results from safety valves and venting areas. Whether gas storage is separate or integrated with the digester will influence the design, length of pipes and location of safety valves and so a key factor to consider for categorisation. • **Size and age of plant**: Integrated digester / gas storage is typical for large AD plants and for plants recently developed in the UK and so size and age of plant is an important categorisation factor. • **Temperature:** Depending on the type of digestion process and specifics of the feedstock, the digestion process can be thermophilic (higher temperature digestion, around 57-58 ^{o}C), mesophilic (36 - 37 ^{o}C) or both thermo- and mesophilic. • **Dry or wet digestion**: The fermentation process can either be dry (15% solid content) or wet (solid content less than 10%), • **Pasteurisation:** Some systems, depending on feedstock (slurry, manure or kitchen waste) will require pasteurisation (which can be post- or pre-digestion). • **Residence time:** The residence time influences the methane content in the digestate.
Digestate separation and storage area	• **Separation of liquid and solid streams:** Digestate is separated into liquid and solid streams either mechanically or through drying • **Storage of liquid digestate:** Depending on size of plant, seasonal conditions and other factors (e.g. whether spreading of digestate on land is allowed), liquid digestate may be stored on site for further transport or it may be removed off site immediately after separation, • **Storage of dry residues**: The dry solid part of the digestate could be main source of methane. Storage on site prior to disposal / spreading, can be covered or un-covered, on site prior to disposal/spreading.
Biogas utilisation area	• **Combustion:** Biogas can either be used to generate heat, electricity or both by combustion in boilers or cogeneration units. Methane leakage could be as a result of incomplete combustion. This part of the plant is usually monitored to ensure safety. • **Upgrading:** Biogas can be upgraded for injection in to the grid (onsite or off-site at main gas network entry points) or for use in transport. Different designs and types of plant are available for upgrade. • **Off-gas:** The off-gas from the upgrade plant can either be vented to the atmosphere (this can be a large source of fugitive methane emissions depending on the CO_2 removal technology used) or it can be combusted or flared. • **Flaring:** Biogas can also flared (this is mainly a safety measure during breakdown /maintenance of the energy recovery system or during period of high biogas production with no storage availability and no demand for the biogas).

1.2 Sources of leakage from biogas and biomethane plants

1.2.1 Sources of leakage

The literature on sources of biomethane leakage from AD plants was reviewed. The main sources of leakage in each of the process areas described in Figure 1 are summarised in Table 2 below.

Table 2: Sources of biomethane emissions in an AD plant as reported in the literature

Process area	Sources of methane emissions
Feedstock storage and feeding area	Fugitive emissions occur primarily when there have been delays in delivery or processing. These emissions are leaked into the environment before biogas production. Fugitive methane emissions can be seen as negligible for this stage. Fugitive emissions could also arise from the pumping of slurry and delivery of feedstock to feeders. These emissions are also minimal. ***The Baltic Biogas Bus project[5] reported that the range of methane emissions from feedstock storage and feeding for existing plants is around 0 - 0.1%.***
Biogas production area	**The digestion process** It is expected that no methane losses should occur in the digester. Some methane leakage will occur from gas safety release valves. The valves are designed to open when the container experiences too much internal pressure. When the valves are not calibrated correctly to match normal chamber pressure, they can become significant fugitive emission sources, releasing at lower pressures than the chamber can handle. Uncalibrated valves can also cause damage to chambers leading to leakage at seams or, in the case of sealed membrane digesters, puncture to the container. Another large potential source of biogas release is during maintenance of the chamber. **Gas storage** Gas holders are designed to store gas and prevent leakage. Poorly-maintained units with leakages have the potential to be large continuous emitters. Depending on the design of the AD plant, gas storage units may be separate from the digester itself or integrated with it. This leads to different methane leakage into the atmosphere. ***The Baltic Biogas Bus project reported that the range of methane emissions from the digestion stage, including gas storage, for existing plants is around 0 -0.2%.*** **Pasteurisation** Pasteurisation is required for food waste and animal slurry and is a legal requirement to avoid the risk of spreading disease. A high temperature of 70ºC inhibits methane-producing bacteria. However, there is a risk of methane production as the heat increases to optimal temperature. Diluting the substrate with reject water from digestate post digestion chamber will increase the potential for methane leakage. ***The Baltic Biogas Bus project reported that the range of methane emissions from pasteurisation processes for existing plants can be around 0 -0.5%.*** **Gas equipment and pipework** Pipework and equipment can become a source of emissions if not maintained properly. Leaks may occur at seals, flanges, safety valves or manual valves. As in the digester, gas safety valves will release biogas into the atmosphere to avoid pressure build-up. Some gas analysis instruments use tributary flows that release small amounts of biogas continuously into the atmosphere.
Digestate separation and storage area	The digestate leaving the digester is either separated into solid and liquid parts mechanically using a dewatering unit or dried. Dewatering units are commonly open to the atmosphere and so diffuse methane emissions will be inevitable.

[5] Katarina Jonerholm, Hans Lundborg, Sweco Environment AB Methane Losses in the Biogas system, Baltic Biogas Bus, 2012.

	Liquid digestate storage The potential for methane loss post-digestion is related to the degradation ratio of the substrate and consequently the residence time on the digester. Depending on the design of plant and residence time in the digester, a proportion of the digestate will always be undigested. Undigested substrate will continue to release methane after it exits the digester. Some plants counteract this by also collecting biogas in the digestate tank. Some larger wastewater treatment plants digestate tanks function as dewatering/thickening units that are open to the atmosphere and therefore have a high risk of being continuous methane emission sources. **Solid digestate storage** Solid digestate will result from mechanical dewatering or through drying and is then stored on site for future spreading on land. Fugitive emissions released in the solid digestate storage unit are from undigested material. The dewatering process can lower the probability of leakage by aerating and cooling down the digestate. Methane emissions will depend on whether mechanical dewatering or dying is used. It will also depend on whether the storage is open or closed to the atmosphere.
Biogas utilisation area	**Biogas combustion in CHP units and boilers** Combustion of biogas in cogeneration units or boilers may lead to emissions leakage as a result of incomplete combustion. **Upgrading units** In general, biomethane-to-grid (BtG) plants consist of several steps including (i) the removal of water from biogas through drying, (ii) the removal of hydrogen sulphide from biogas through activated carbon adsorption or filtration or via chemical or biological scrubbing (iii) the removal of carbon dioxide from biogas either using physical or chemical absorption, physical or chemical adsorption, membranes or cryogenic processes, (iv) the addition of propane to the resulting biomethane to increase its calorific value to gas network standards and (v) injection into the grid or delivery to filling stations for use as transport fuel. The main differentiator in the design of biomethane-to-grid plants is the type of CO_2 removal technology used. The most common processes in BtG plants in the UK are membranes followed by water wash (chemical absorption process) and amine chemical absorption. Methane losses could vary from one site to another depending on the technology used for CO_2 removal. Membrane processes require compression of the biogas to high pressures before entering the membrane which could lead to higher methane leakage than with absorption processes which are performed at atmospheric pressures. Also, different technologies have different methane recovery efficiencies (>96-99.9% for amine absorption, 95-98% for water wash, 80-95% for membranes). Methane losses are highest for membrane technologies and lowest for amine absorption. **Utilisation of biomethane** All 80 biogas upgrade sites in the UK inject the resulting biomethane into the grid. Two of these sites, inject the biomethane at high pressures (250 bar) into High Pressure Multiple Element Gas Container (MEGC) Trailers for transport and injection into the gas network at remote locations. It is very likely that in the near future biomethane generated in the UK will also be transported to fuel filling stations for use in road vehicles. **Off-gas** The off-gas from the CO_2 removal process may be combusted or vented directly into the atmosphere which could be a major source of fugitive methane emissions. **Flaring** In the event that biomethane cannot be injected into the grid, the biogas produced by the AD plant can be stored, utilised by the CHP plant if available on site or it can be flared. Methane leakage may occur if the biogas is not fully combusted as a result of no ignition in the torch or as a result of using dated flare technology. Biogas may be allowed to vent from a gas holder into the atmosphere for safety reasons but this

	should be minimised for economic and environmental reasons. In such cases, the pressure relief vent is usually equipped with a flame or detonation device.

An early commitment to reducing biomethane leakage from AD plants was the "Swedish voluntary Initiative", which was started in 2007 by the Swedish Waste Management Association. The initiative committed biogas and upgrading plant owners to identify and decrease methane emissions in their facilities and to develop an inventory of emissions.

The Baltic Biogas Bus project (referred to in the table above) summarised emissions from different types of AD plant with CHP based on results collected through the Swedish Voluntary Initiative (Table 3). For upgrade plants, methane losses are reported by the same project as 0.4% for plants with amine absorption, 1.5% for plants with pressure swing adsorption and 3.1% for plants with water wash.

Table 3: Methane leakage from AD plants with different types of waste (Baltic Biogas Bus project)

Feedstock	Methane losses relative to methane production
Sewage sludge from wastewater treatment	3.1%
Municipal waste	1.7%
Industrial waste	0.2%

Some studies reported high methane emissions from upgrade units, depending on the CO_2 removal technology used. The GreenGasGrid project[6] reported methane recovery rates for different types of upgrade technologies with membrane separation having lowest recovery rates and potentially high methane leakage. Table 4 presents a comparison of methane leakage from different types of upgrading plants. New membrane technologies installed in the UK (Haffmans Pentair[7]) claim higher methane recovery rates.

Table 4: Methane leakage from BtG plants with different CO_2 removal technologies (from GGG project based BiogasPartner - Biogas Grid Injection in Germany and Europe, Fraunhofer Umsicht, 2009**)**

	Membrane	Waterwash	Amine absorption	Pressure swing adsorption
Required pressure, bar	>15	4 – 7	0.05 – 0.5	4 – 7
Required temperature, °C	Environmental	10 - 25	10 – 15	10 – 20
Methane recovery, %	80 – 95%	95 – 98%	96 – 99.9%	95 – 98%
Methane loss, %	5 – 15%	1 – 2%	0.1 – 0.5%	1 – 10%
Number of UK plants (end of 2015)	34	13	3	0

Membrane technology for CO_2 removal from biogas streams is more common in the UK due to its lower capital and operating costs. The higher methane losses in BtG plants with membranes are due to the lower recovery efficiencies for membranes and so more methane is likely to escape with the off-gas than with other technologies. In addition, membrane separation is performed at higher pressures than with other technologies and so the likelihood of methane escaping the process (e.g. from the compression process) is higher. The amount of methane recovered from the off-gas can be increased

[6] http://www.greengasgrids.eu/fileadmin/greengas/media/Downloads/Workshop_Development_of_biomethane_in_Europe/Measures_to_reduce_GHG_emissions_in_the_Biomethane_supply-chain_-_William_Mezullo.pdf

[7] https://foodandbeverage.pentair.com/en/products/haffmans-biogas-upgrading-technology

by passing the gas through several membrane stages thus reducing methane leakage. Based on these results, in order to compare methane leakage from different designs of upgrade plants, it is necessary to include upgrade plants as a separate category, as is discussed in Section 3.

Operational patterns and seasonality
A study by Flesch et al.[8] showed that reduced methane emissions during periods of maintenance as a result of halting feedstock loading. During these periods, gas was still produced and combusted to generate electricity but at a lower rate. It was concluded that a major source of fugitive emissions was the loading hopper as it was the only substantive difference between normal operation and maintenance periods during initial operation periods. The same study also highlighted the fact that the production of biogas from the same feedstock differs from one season to another depending on the feedstock composition. Lower methane production rates during spring were attributed to non-ideal feedstock material (high protein content is required for optimum decomposition).

1.2.2 Review of recent studies

The literature on measuring and quantifying methane emissions from AD plants is relatively recent. Results in the literature are not easily comparable because they are based on different types of feedstocks, boundaries, assumptions, systems design and plant-specific parameters, and monitoring technologies with different uncertainties.

The report by Energiforsk reviewed results from studies in several countries[9]. A recent project in **Austria** (Klimoneff project) focussed on the quantification of fugitive methane emissions from five agricultural biogas plants using remote sensing. The project focussed on the analysis of digestate. The results from seven days of data collecting gave a median value of 4 % loss of the produced methane when the open digestate storage tanks were filled.

In **Denmark, under the project, "Methane Emission from Danish Biogas Plants"** funded by Energinet.dk under the ForskEL programme, a biomethane monitoring methodology was developed and subsequently applied to ten biogas plants. Around 50 leakages were identified representing 4.2% of the total methane production at the studies sites. In a different study in Denmark nine total methane measurement campaigns were implemented on wastewater treatment plants using the tracer dispersion method. It was found that total methane emissions ranged from 5 to 92 kg/hr (2 – 33% of total methane production). It was reported that the highest emission of methane was measured during a period with foaming problems in the anaerobic digesters.

In **France**, measurement campaigns were carried out in three farm installations on emissions from engines. Results showed that methane emission from engines are in the range of 1.7– 3.2 % of methane production.

In **Germany**, IR cameras and hand-held methane lasers were used to identify sources of leakage from 10 agricultural AD plants. Eight plants had an overall number of 22 leakages and seven of them evaluated as serious leakages (loose wires to adjust agitators, leakage in double membrane roof of digester). Membrane leakage occurrences from CHP were found to be small in comparison to the digester area but are still possible.

In a different study in Germany, ten agricultural AD plants were tested for methane leakage. Seven of these were based on wet fermentation and three on dry fermentation. The methane emissions were determined by an on-site method. A plant survey was conducted to identify the emission spots and in the second step the emissions were quantified. The silage storage, the feeding units (e. g. screw

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[8] T.K. Flesch, R.L. Desjardins and D. Worth, Fugitive methane emissions from an agricultural biodigester. Biomass and Bioenergy 35 (2011), 3927-3935.
[9] Energiforsk, Measurement of methane emissions from biogas production, 2015: http://www.sgc.se/ckfinder/userfiles/files/EF2015-158+methane+emissions+measuring.pdf

conveyor, mixing tank) and the digestion (e. g. leakages, methane diffusion in the supporting air of double membrane roofs) were investigated by means of an open chamber system. The methane emissions from the open digestate storages were determined by a closed chamber. Covered storages and digestate storage tanks were investigated by means of the air injection method. The emissions from the gas utilization were directly measured in the exhaust pipe. Methane emissions from open digestate storage tanks ranged from 4 to 20 g CH_4/kWh_e (but based on two single measurements only). The emission factors from the CHPs varied from 1 to 6 g CH_4 / kWh_e1 (0.6 – 3.3 % CH_4 loss) for the single CHP units. These methane emissions were caused by incomplete combustion in the engine. The methane leakage from the upgrading unit (measured for two plants) amounted to around 10 and 2 g CH_4 / kWh_e (5.3 and 1.2 % CH4 loss) which were caused by a defective or missing post combustion.

In **Sweden**, measurements between 2007 and 2009 on several biogas upgrade plants showed methane leakage of 2.7% relative to the produced amount of produced gas.

A study in **Canada** investigated a biogas plant over a whole year. An average of 3.1 % CH_4-loss during normal operation was measured using a remote sensing method.

It should be noted that, in addition to the reasons given above, most of these studies are not comparable because they employ different methodologies and so are each associated with different uncertainties that are not always reported. A summary of two studies where meaningful comparison can be drawn is given in Table 5 which provides results from Austria and Germany for agricultural plants.

Table 5: Comparison of methane leakage for agricultural AD plants (summarised based on different studies as indicated)

Country	Focus of study and boundaries	Results
Austria	• Studies based on agricultural waste • Boundaries include CHP but not biomethane to grid • Focus on emissions from digestate storage • Used remote monitoring (Laser technology) for methane concentration measurement combined with dispersion modelling and anemometers for wind speed and turbulence parameter measurement • Other studies [10] within the project also used direct measurement onsite.	• Methane loss of 4% relative to methane produced • A specific study[10] reported 1.8% methane loss for CHP, 1.2% methane loss from open digestate tanks and 0.1 – 0.2 % from silage storage.
Germany	• For agricultural feedstock with CHP and biomethane to grid plants • On-site monitoring (open chamber for feedstock storage and digesters, closed chamber for open digestate storage, air injection methods for closed storage tanks, and in-pipe measurements for CHP and upgrade plant)	• Digestate: methane loss around 2.4 – 10.6% relative to methane produced • CHP: 0.6 – 3.3% • Upgrade: .2 – 5.3%
France	Studies specifically targeted emissions from CHP	1.7 – 3.2% methane loss relative to methane production

[10] http://conference.sgc.se/ckfinder/userfiles/files/Hrad(1).pdf

2 Proposal for AD plant categorisation

We have researched AD market data from Waste and Resources Action Programme (WRAP)[11], Renewable Energy Association (REA) Biogas[12] and Biogas Info (The Official Information Portal on Anaerobic Digestion, developed and is maintained by NNFCC[13]). Incorporating and merging information from all of these reports into a single document has produced an extensive list of AD plants in the UK, coupled with the data from their usage and size. A summary by type of feedstock and end-use of the biogas is shown in Table 6.

Table 6 shows the number of plants in our database of 565 and a mix of differing waste streams and uses from the gas produced. Some plants use multiple methods of gas usage, for example “electricity and biomethane to grid” or “electricity and heat”. The number of sites that inject biomethane into the grid and have CHP on site is 23.

The majority of plants use a single type of feedstock, while 28 plants use a mixture of feedstocks. These are mostly agricultural feedstock-based plants co-digesting one other type of feedstock with one plant (a brewery) using industrial, municipal and commercial waste. Industrial waste used in AD plants is mainly from distilleries, breweries and the food industry. The four biomethane-to-grid plants which use only industrial waste are composed of two distilleries, one creamery and one sugar production site.

Considering availability of data, the differentiators which are available for sites in the list are

- site name, location, developer, operator, AD technology supplier, whether the plant is operational and year of first operation (i.e. age of plant)
- the type of feedstock
- the end-use of the biogas
- the size of plant (electrical capacity for CHP, heat capacity for boilers and m^3/hr for Biomethane-to-grid) and also size in terms of the feedstock us (tonnes / year)

We have used the available data on existing AD plants in the UK to categorise AD plants. We have also considered the significance of each of the parameters above in terms methane leakage from AD sites. The literature review shows methane leakage may vary significantly depending on the type of feedstock and whether the site utilises the biogas for power and heat generation only or for injection into the grid.

Operational factors may also influence methane leakage from a plant. It is usually considered that larger plants (such as BtG CHP plants registered with incentive schemes) are more likely to have a monitoring plan and a maintenance regime in place than smaller farm plants. In general, small-scale plant operators may not have the necessary resources, knowledge and equipment to do so but this is not always the case. As a result, it is expected that the size and nature of plant and consequent the operating modes of the site will influence the level of leakage. This leads us to recommend (as highlighted in Section 2.2) that the size of plant is considered an important factor.

Based on the number of plants in each of the feedstock end-use groups, we categorised AD plants in the UK to form groups with statistically-representative datasets (Table 7). The number of sites in the

[11] http://www.wrap.org.uk/content/operational-ad-sites
[12] http://www.biogas.org.uk/plants
[13] http://www.biogas-info.co.uk/resources/biogas-map/

last column represent the maximum number of plants to choose from. Some site (i.e. sites with mixed feedstocks and sites with both CHP / boiler and BtG injection) are included in all relevant categories.

The number of plants where the biogas is used in boilers is small and so this group was combined with the CHP category, as whether the biogas is combusted in a boiler or a CHP will require the application of similar monitoring techniques and will not make material difference to the monitoring methodology.

Table 6: Breakdown of AD plants in the UK by type of waste and end use of biogas

Feedstock (total sites)	Total	CHP	Boiler-only	Biomethane-to-grid (BtG)
Sewage sludge (159)	0	✓	✓	✓
	0	✓	✓	
	9	✓		✓
	0		✓	✓
	150	✓		
	0		✓	
	0			✓
Agriculture (273)	1	✓	✓	✓
	13	✓	✓	
	9	✓		✓
	2		✓	✓
	200	✓		
	8		✓	
	41			✓
MSW & Commercial (69)	0	✓	✓	✓
	4	✓	✓	
	2	✓		✓
	0		✓	✓
	55	✓		
	0		✓	
	8			✓
Industrial (36)	0	✓	✓	✓
	2	✓	✓	
	2	✓		✓
	0		✓	✓
	30	✓		
	0		✓	
	2			✓
Agricultural & MSW (23)	0	✓	✓	✓
	1	✓	✓	
	1	✓		✓
	0		✓	✓
	16	✓		
	0		✓	
	5			✓
Agricultural & Industrial waste (4)	0	✓	✓	✓
	0	✓	✓	
	0	✓		✓
	0		✓	✓
	2	✓		
	0		✓	
	2			✓
MSW & Industrial (1)	0	✓	✓	✓
	0	✓	✓	
	0	✓		✓
	0		✓	✓
	0	✓		

Feedstock (total sites)	Total	CHP	Boiler-only	Biomethane-to-grid (BtG)
	0		✓	
	1			✓

Plants where the feedstock is **sewage sludge** resulting from primary and secondary wastewater treatment are all combined with CHP for electricity and /or heat generation onsite. Some of these (9) plants added BtG injection in recent years. All sewage sludge plants are grouped into a single category regardless of whether the end-use is only CHP or CHP combined with BtG injection. This gives a total of 159 AD plants.

Plants using **industrial waste** were categorised in a single category regardless of end use due to the specific issues that need to be considered as part of the monitoring methodology.

Table 7: Proposed main AD plant categories based on feedstock type and end use of biogas

Category	Category	Number of AD plants to choose from in the database
1	Agricultural waste AD plants for **electricity and / or heat** production (including mixed feedstock sites and including BtG with CHP and / or boiler)	253
2	Municipal or Commercial waste for **electricity and / or heat** production - – including sites with mixed feedstocks	79
3	Agricultural waste AD plants with **BtG injection** (including mixed feedstocks and including CHP and / or boiler sites with BtG injection)	61
4	Municipal or Commercial waste with **BtG injection** – including sites with mixed feedstocks	17
5	All sewage AD (electricity and / or heat production, and / or BtG)	159
6	All Industrial waste AD (electricity and / or heat production, and / or BtG) including sites with mixed feedstocks	41

Recommendations regarding additional categorisation of the groups identified above are discussed in the following sections.

2.1 Plant age

We have managed to determine age data for almost half (251 plants) of the plants on our database (Figure 2). The data supports our hypothesis of the recent increase in anaerobic plants. A large proportion of AD plants in the UK have been constructed relatively recently, stimulated by Government incentives, and thus the majority of plants are similar in design and in the first stage of their life[14]. Based on the available age data, around 90% of the plants have been constructed since 2010.

Taking this data into account, we do not think that the age of the plants can be used as a differentiator to measure methane leakage due the disparity in the age of the plants. The main issue with the age of AD plants will only be significant when maintenance quality is poor; this is likely to be a function of factors such as perishable parts that require regular replacement (such as seals, valves, pumps).

We do recommend that the age of the plant be recorded during any biomethane leakage assessment as a matter of course, especially in terms of older facilities such as sewage treatment works that

[14] If properly maintained, AD plants can have a lifespan of 25 years.

maybe significantly older facilities, and the degree of maintenance be recorded and considered a cause of leakage in the assessment. However, we do not regard age as a separate category to be accounted for in the categories in the sector.

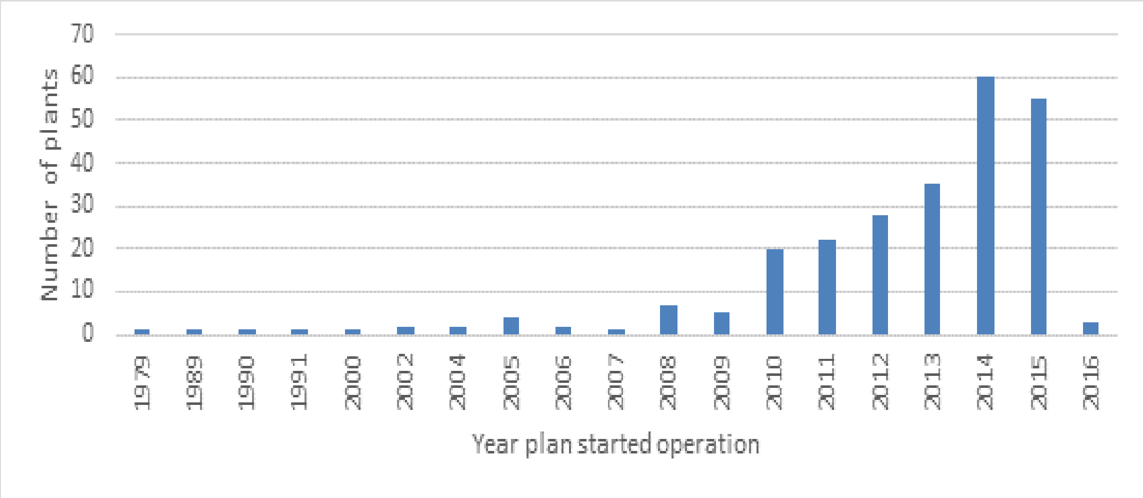

Figure 2: Categorisation of plants based on year of operation

2.2 Plant size

The size of a plant will have a determining factor on the design, maintenance and degree of control day-to-day over the operations. Small AD plants (<25,000t feedstock/year) usually have different operating models to those of large plants. For example, a small farm AD plant may be unmanned and only fully utilised at certain periods of the year, whereas a large-scale plants (>50,000 tonnes feedstock/y) will have full time staff working on the plant 24hrs per day to ensure maximum throughput and gas production. Smaller AD plants are not likely to have a monitoring and maintenance regime in place while for larger AD plants the operation and maintenance of the plant is likely to be carried out regularly by specialist companies, thus reducing the probability and risk of leakage. The range of size of plants does vary, although the distribution of scale follows a typical normal distribution.

Taking this into account, it is recommended to assess the range of plants in one of the groups shown in Figures 3 and 4. It is appropriate to use the agricultural plants with electricity and / or heat production (264 sites) to investigate biomethane leakage linked to size, due to the large number and breadth of scale within these plants as shown in Figure 3. Considering different sizes of plants is likely to capture different operating models. It is also recommended to assess a small size AD plant where maintenance and basic monitoring regimes are not in place. This can be established as part of the site survey.

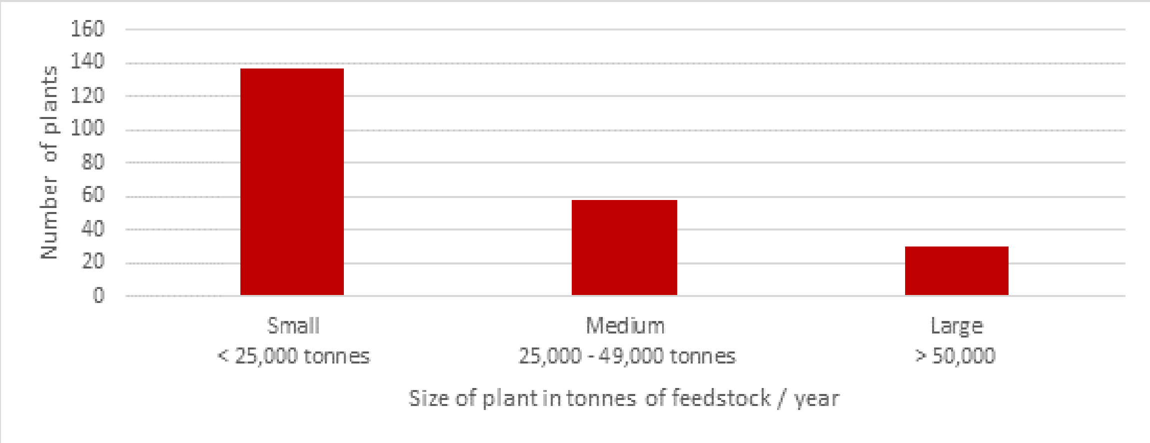

Figure 3: Variation of size for agricultural AD plants in the UK (based on available data for 225 plants)

However, not all plants have tonnage throughput data. Alternatively, we can assess the plants by electrical capacity (Figure 4). This chart shows that there are many smaller plants and only a handful of very large plants.

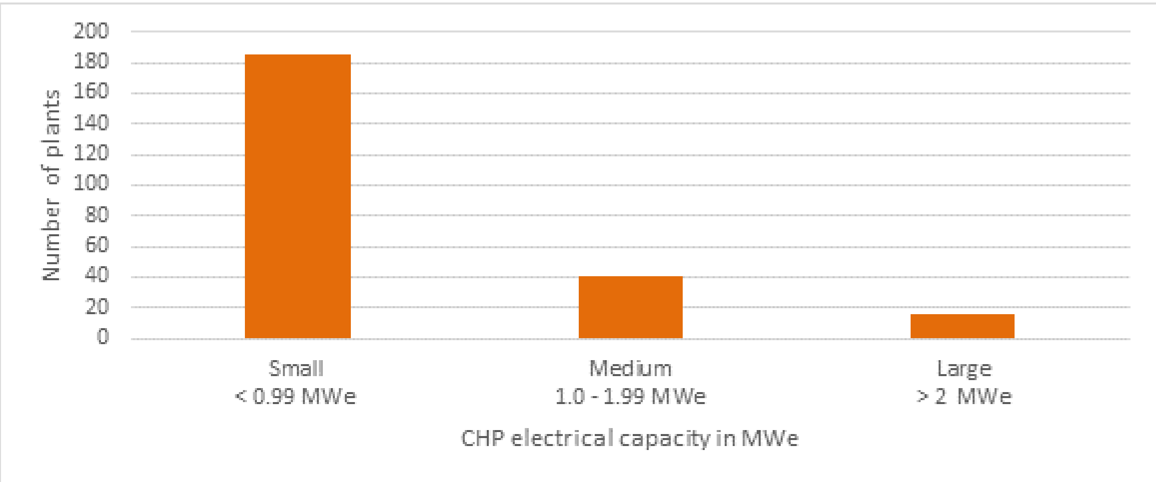

Figure 4: Variation of size for agricultural AD plants with CHP (based on data for 242 sites)

2.3 Types of Digesters and Gas Holders

2.3.1 Type of Digestion

There are two main types of anaerobic digestion; thermophilic and mesophilic – the primary difference between them being the temperatures reached in the process. Thermophilic processes reach temperatures of up to 60 °C and mesophilic normally runs at about 35-40 °C. Some existing plants use both thermo- and mesophilic processes. The choice of system depends mainly on the feedstock to be processed. For example, 'high solid materials', such as a garden and food waste mixture, tend to be processed at a thermophilic temperature and 'low solid materials', such as animal slurry mixed with industrial and municipal food wastes, are more likely to be processed at lower temperatures. Because the feedstock will ultimately decide the type of digestion used, this difference will be covered by categorising AD plants by feedstock above and does not need to be further categorised by this category.

2.3.2 Types of Digesters

The digestion of waste and collection of gas in AD plants should be performed in a completely closed environment with no oxygen present; therefore, the leakage of methane should be controlled in this area. However, there is a potential for leakage that might occur due to pressure relief valves, hydraulic seals and overflow pipes. This will be mostly down to poor design/operation or lack of maintenance. This section will consider the design and construction of digesters and gas collection and examine whether there differences need to be categorised differently. The design of this equipment can be categorised into two main layouts:

1. Separate digesters and gas holders; and
2. Joint digesters and gas holders.

2.3.3 Separate digesters and gas holders

Figure 5 shows a typical plant design comprising 2 tanks; a mixing tank for feedstock homogenisation and storing the feedstock prior to digestion and the digester itself. The digester tank and mixing tank will both be fixed volume sealed vessel (normally a mix of concrete base and steel/concrete side and a steel top). The gas produced by the digester is pumped to a separate gas storage holder. The gas holder is normally an expanding double skinned container where the gas will be kept prior to treatment or use. This expands to help control pressure of the gas.

Figure 5: Separate digester and gas holder

2.3.4 Joint digesters and gas holders

Joint digester / gas storage designs are the most common plant type in the UK and are typical for large AD plants. There are two main designs for a join digester and gas holder, a floating roof and an expandable roof. The expandable roof gas holder is essentially added directly on top of the digester. The advantage of this design is reduced footprint of the plant, although it does restrict the design and operation of the digester. The floating roof gas holder is where a floating roof is able to move up and down to change the volume of the vessel (this is a metal roof structure that floats on the digester contents and rides vertically on steel guide members and roller mechanisms). The expandable roof normally consists of a membrane cover that spans the tank and moves based on the quantity of biogas stored under this cover), as shown in Figure 6.

The different designs of digester may result in leaks from different parts of the process, either from a single location (joint storage and digester system) or possibly two locations (separate storage and digester system). However, the anticipated areas where leaks may occur (joints, seals, pumps and valves) will be the very similar, and because of the method storage are designed to not allow any escape of gas it should only be design faults and poor maintenance that result in any biomethane leakage.

Therefore, it is recommended to include at least one of the 3 different joint digester and gas holder designs. The sewage sector is most likely to have a number of reference plants covering all of these designs.

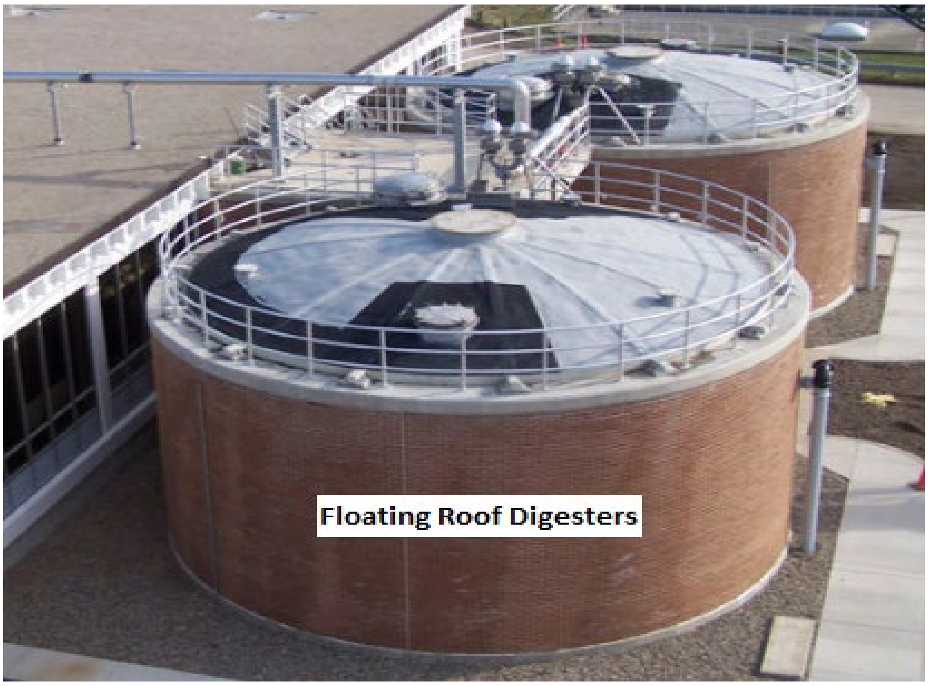

Figure 6: Expanding and floating roof digesters

2.4 Type of fermentation (dry vs. wet fermentation)

The types of fermentation for AD "wet or dry", will be simply dependent on the water content of the material in the digester. The "dry" AD process typically utilities feedstocks of solids content 15-40% as opposed to <15% for wet AD. Dry AD tends to be cheaper to run as there is less water to heat, there are higher gas yields per unit feedstock (and consequently higher probability of methane leakage), and dry AD is associated with lower capital costs. However, wet AD is by far the most prevalent and proven system for AD and accounts for the majority of plants. Also, while the design and operation of a dry AD plant is very different from a wet process, the stages of each process are normally very similar. Furthermore, data on dry vs. wet fermentation is not usually collected and so is not available in the database. This data can be collected as part of the site survey which is a pre-requisite for the implementation of a monitoring methodology. For the reasons above, we recommend that the type of fermentation process within the digester is not used for categorising AD plants.

Dry digestion is more suitable to the processing of co-mingled food and green waste, contaminated food waste and even the biological fraction of MSW, and thus the choice of a dry AD process is helped by the waste type. The main difference with dry AD is that it is generally not feasible to pump dry waste, so the waste is typically moved mechanically, by loading shovels or conveyors/screws rather than a liquid/sludge pumped through pipes. The movement of materials in this manner means that there may be different areas where leakage might occur. This will be addressed in the monitoring methodology by categorising pants according to the type of feedstock used.

2.5 Types of upgrade plants (membrane, water wash, amine chemical absorption)

The general design principles of upgrade plants are the same. Upgrade plants mainly consist of (i) drying equipment for removal of water from the biogas, (ii) carbon filters for removal of H_2S, (iii) a CO_2

removal process, (iv) a step for adding propane to the treated biomethane stream and (v) a step for injection into the grid (grid entry unit).

The main difference amongst biomethane-to-grid plants is the choice of the CO_2 removal technology. While pressure swing adsorption is the technology of choice for most biomethane upgrade plants in other country, the prevalent technologies in the UK are membranes (70%), water wash (25%) and amine absorption (5%).

An upgrade plant is usually designed to ensure minimal leakage. The methane purity varies for different CO_2 removal technologies and so the amount of methane escaping to the atmosphere with the CO_2 stream is likely to vary depending on the technology of choice. It is recommended to consider different designs of upgrade plants with agricultural BtG plants.

2.6 Categorisation summary

Taking account of all the factors mentioned above, Table 8 lists 12 categories recommended for testing the monitoring methodology on 20-30 sites in the UK. The monitoring methodology will be developed to address the variations resulting from these categories.

For agricultural waste plants, a range of sizes, corresponding to varying operational and maintenance regimes, will be investigated. Furthermore, as agricultural plants are the largest group in terms of number of biomethane injection plants, they will also be used to study methane emissions from different CO_2 removal (i.e. biogas upgrade) technologies (Category 3).

Sewage sludge AD plants (with CHP /boiler and / or BtG) will be compared for different designs of digester and gas storage plant. Municipal and commercial waste plants where the biogas is used for heat and / or power generation or upgraded to biomethane will be compared.

In addition to other data, as part of the site survey, additional information should be noted and collected for each of the categories. Examples include:

- (i) whether the feedstock and digestate storage is open or closed,
- (ii) whether the off-gas from the upgrade plant is vented or combusted,
- (iii) whether grid injection is accomplished onsite or away from the site,
- (iv) whether pasteurisation exists,
- (v) whether sewage sludge is pumped offsite for treatment,
- (vi) whether biogas is sent off-site for utilisation in CHP or boilers, and
- (vii) whether digestate separation is accomplished mechanically or through drying.

As discussed in section 1.2.1, it should also be noted that biomethane leakage (as percentage of total methane production) will be influenced by the normal operating conditions of the site (periods of maintenance, flaring, shut-down). Methane emissions are expected to fall during maintenance periods and increase significantly during flaring. Seasonality will also influence the biomethane emission rates as Production of biogas is expected to vary from one season to another depending on the feedstock material. As biomethane emissions are expressed as percentage of these production rates, then a variation will be observed from one season to another. As a result, a robust methodology needs to take seasonality into account.

Table 8: Proposed AD plant categories for consideration as part of the monitoring programme

Category		Description	Number of AD plants in the database
1	a	Agricultural waste AD plants for electricity and / or heat production – Small - feedstock throughput < 25k tonnes / year)	253

	b	Agricultural waste AD plants for electricity and / or heat production – Medium - feedstock throughput: 25k – 49k tonnes / year)	
	c	Agricultural waste AD plants for electricity and / or heat production – Large - feedstock throughput > 50k tonnes / year)	
2		Municipal or Commercial waste for electricity and / or heat production	79
3	a	Agricultural waste AD plants with BtG injection – Membrane process for CO_2 removal	61
	b	Agricultural waste AD plants with BtG injection – Water wash for CO_2 removal	
	c	Agricultural waste AD plants with BtG injection – Amine process for CO_2 removal	
4		Municipal or Commercial waste with BtG injection	17
5	a	Sewage AD with electricity and / or heat production and / or BtG injection – Separate digester and gas holder	159
	b	Sewage AD with electricity and / or heat production and / or BtG injection – Joint digester & gas holder – Floating roof	
	c	Sewage AD with electricity and / or heat production and / or BtG injection – Joint digester & gas holder – Expanding roof	
6		All Industrial waste AD (electricity and / or heat production, and / or BtG)	41

2.7 Boundary considerations

It is proposed that the biomethane monitoring methodology (described in the Methodology Report) should take into account the 12 categories in Table 8. Adopting a holistic method of assessing total biomethane leakage by measuring at the site borders will simplify the methodology and make it more cost-effective. The methodology in that sense will be applicable to a wide range of categories, but still need to address specific issues related to system boundaries, the counterfactual for different process areas and monitoring of leakage from specific components and areas outside the boundary.

Adopting a holistic approach will simplify setting the boundary, although this will create additional issues in ensuring that all leaks are covered and that methane emissions outside the boundary are subtracted from the total methane emissions. This approach makes it very essential that the boundary for the site is determined carefully.

In general terms, the boundaries for the site should include all process areas highlighted in Figure 1. The exact site boundary, however, will need to be considered for the different categories described above and will need to be determined on a case-by-case basis, as each site will be different. However, in order to decide what is included in the measurement of methane leakage and what will not, we will need to ring fence the components of the plant in a certain logical manner. The components of each individual plant, while being slightly different and dependent on the type of plant, will all follow a similar pattern, and will be considered as show in Figure 7.

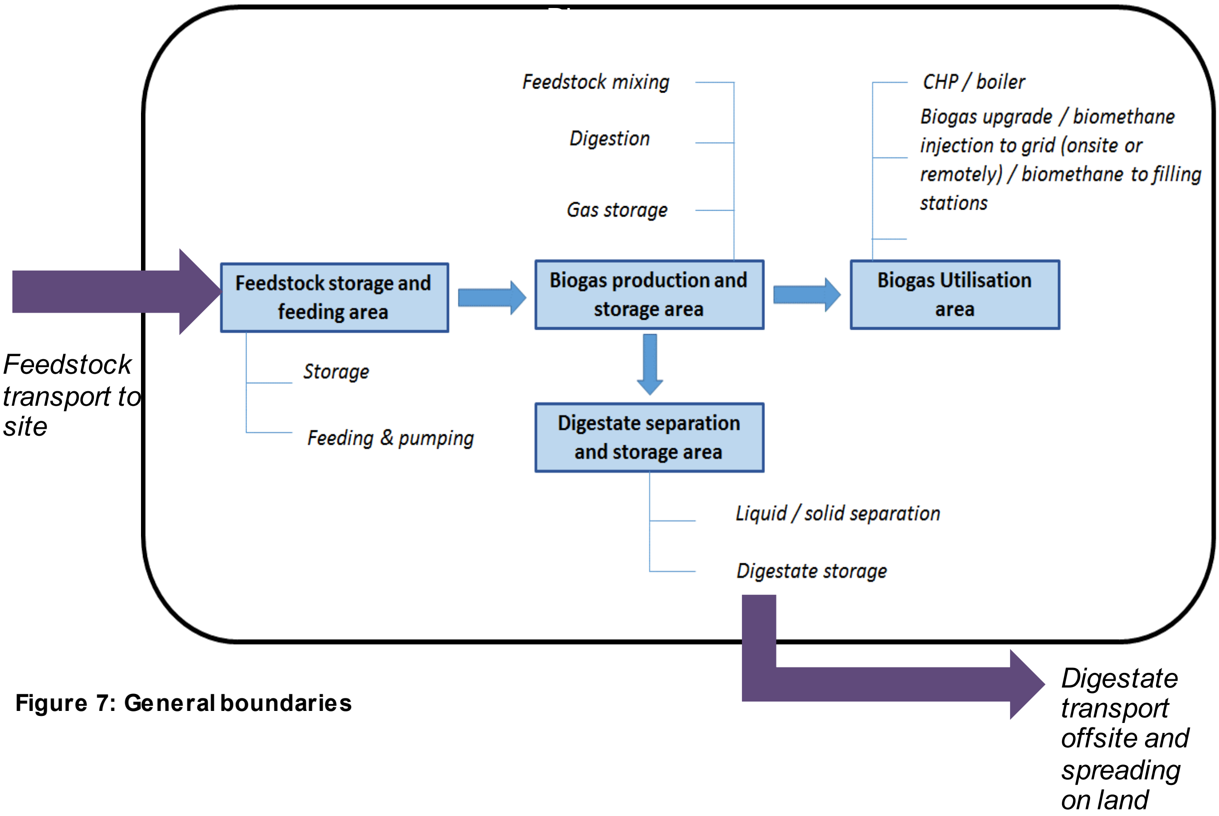

Figure 7: General boundaries

A virtual ring fence will be drawn around the key elements of the AD plant, incorporating the storage area, the anaerobic digestion & gas storage areas, the digestate processing and storage area and the gas utilisation area. It should be noted that this circumference may have to be split among multiple locations or parts of a site and this need to be accounted for multiple or segregated boundaries. The splitting of activities across a large site **is most likely with sewage treatment works** (Category 5) or large industrial processes (Category 6) and will need to be considered by the boundary used for measurement.
Specific considerations for each of the process areas for all 12 categories are given below:

Storage of feedstock and feeding

- This will be the point where waste is specifically stored on the site ready for anaerobic digestion.
- Bulking of material at other intermediate sites and transport to the AD site are outside the boundary.
- Storage and holding tanks for slurry and manure, lagoons (in case of sewage plants) or other feedstock storage facilities on site, will be included within the boundary.
- Waste (municipal & commercial) will most likely be pre-treated via either shredding, mixing or heat treatment. This will be included within the boundary.
- Purpose-grown energy crops will be transported and loaded into feeders via onsite equipment

Digesters & gas storage

- The feedstock homogenisation / mixing tank, digesters and storage of gas will be captured within the border of the study, irrespective of the design. This might account for a number of interconnecting areas of the site or simply one core location.
- In some cases, material from the digester is pumped to the mixing tank to ensure homogeneity and recycled back into the digester. These intermediate processes are part of the boundary.

Digestate storage

- The digestate liquid / solid separation process is part of the boundary.
- When liquid digestate is stored on site (whether covered or uncovered), this should be within the boundary. A site survey will clarify whether liquid digested is stored on site or transported and spread directly on land.
- Solid digested storage on site is within the boundary.

Gas Utilisation

- Gas combustion in engines or boilers is part of the boundary including biogas pipeline, valves and compression if applicable.
- In some cases, biogas may be transported through pipeline to a different site for use in CHP or boilers. This should also be part of the boundary.
- All equipment within a BtG facility should be part of the boundary. This will include the grid entry unit and the propane addition process.
- Injection of biomethane into high pressure multiple element gas container (MEGC) trailers for transport offsite and for injection into the grid at remote locations (e.g. the SGN's Portsdown Hill Entry Facility) should also be considered part of the boundary. Biomethane is compressed to a pressure of 250 bar and filled into the trailers for transport off-site. Two such plants are available in the UK and are accredited under the RHI. This approach saves costs as it eliminates the need for propane addition on site, since the gas is blended with the gas network at origin and so calorific value adjustment is not required. More BtG plants are likely to be designed in this way in the UK in the future[15].
- Biomethane injection from high pressure MEGC trailers into the grid at network entry points away from the generation site should also be within the boundary.
- Flaring on site should also be part of the boundary.
- Additional equipment used to provide heat to the upgrade process (e.g. biogas boilers, biogas CHP, etc.) should be part of the boundary.
- It is likely that the use of biomethane as fuel in vehicles will increase in the near future in the UK[16]. AD plants which inject the upgraded gas directly into biomethane filling stations (whether onsite or offsite) rather than into the gas network already exist in Sweden (48 plants), Germany (20) and Finland (6). The transport of biomethane offsite and the injection into filling stations (whether onsite or offsite) should be included in the boundary.
- The gas network is outside the boundary.

In defining the boundary, potential methane sources from neighbouring facilities (e.g. herd of cows, near-by waste storage) need to be identified and metered separately in order to be subtracted from the total methane emissions. Issues related to definition of boundary should this be discussed and addressed in detail for the different categories as part for monitoring methodology. Issues related to a situation where parts of the anaerobic digestion process cover more than one specific location should also be addressed.

Therefore, in practice, prior to implementing the monitoring methodology on a site for biomethane monitoring, a site survey will be required to address specific boundary issues. So boundary issues will be assessed on a case-by-case basis and will feed into the methodology for that particular site.

2.8 Description of counterfactuals

As part of the monitoring programme, measurements of biomethane leakage from the site, combined with other sources of GHG emissions from the biogas production lifecycle, should be compared against a counterfactual for each of the categories proposed in order to estimate GHG savings.

[15] https://www.sgn.co.uk/Our-Services/SGN-Biogas-Connections/

[16] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416002/biomethane-for-transport.pdf

The purpose of this section is to describe the procedures for calculating lifecycle GHG savings from using biogas for the generation of electricity or for biomethane gas to grid injection. It describes the counterfactuals used and quantifies their lifecycle GHG emissions. In estimating GHG emission savings, actual emissions from the biogas full life cycle are compared against the counterfactual life cycle emissions, which are defined as the "reference" GHG emissions.

2.8.1 Sustainability Criteria reporting

Guidance on sustainability criteria reporting requirements are outlined by in the non-domestic RHI sustainability self-reporting guidance[17]. The Guidance provides details on land and GHG reporting requirements.

GHG criteria are outlined in Section 5 of the Guidance. The Regulations require that sites must produce renewable heat with lifecycle GHG emissions of less than or equal to 34.8 g CO_{2-e} / MJ of heat generated, or, if they are injecting biomethane instead of producing heat, the biomethane must have lifecycle greenhouse gas emissions of less than or equal to 34.8 g CO_{2-e} / MJ of biomethane (measured as the net calorific value). For a biogas CHP plant to be judged sustainable, it should show that its GHG emissions are lower than 34.8 g CO_{2-e} / MJ of heat produced from CHP.

It should be noted that waste used in the AD plant is exempt from reporting on GHG emissions (Table 2 under Section 4 in the Guidance). Under the Sustainability Reporting, Paragraph 5.59 of the Guidance states that it is not necessary to account for methane losses from the storage of **digestate** since this is outside the scope of the methodology outlined in the Regulations. Digestate is treated as a co-product and so is considered as an output from the system, therefore the storage of digestate is not included in the calculations of GHG emissions for self-reporting to Ofgem.

According to the Renewable Energy Directive (RED)[18], GHG emissions from the production of solid and gaseous biomass fuels, before conversion into electricity, heating and cooling, shall include the total of

- emissions from the extraction or cultivation of raw materials
- annualised emissions from carbon stock changes caused by land use change
- emissions from processing
- emissions from transport and distribution
- emissions from the fuel in use, that is greenhouse gases emitted during the combustion of solid and gaseous biomass
- emission savings from soil carbon accumulation via improved agricultural management
- emission savings from carbon capture and geological storage and
- emission savings from carbon capture and replacement.

Digestate does not fall into any of the categories above. The monitoring methodology developed under this project (described in the Methodology Report) is designed to measure total methane emissions from the site including digestate fugitive emission. Methods for estimating and deducting methane emissions associated with the digestate are also described as part of the methodology. The UK Solid and Gaseous Biomass Carbon Calculator has been developed by Ofgem to calculate GHG emissions from a number of electricity and heat production routes relevant to the ROC, FIT and RHI schemes administered by Ofgem. The Calculator uses a methodology compliant with the RED and is based on UK specific information. The latest version of the Carbon Calculator includes both production of electricity from AD and production of bio-methane for grid injection from AD.

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

[18] Directive 2009/28/EC on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive

The Carbon Calculator, developed by E4Tech, and the biomethane and biogas GHG calculator developed by Ricardo Energy & Environment both include methane fugitive emissions from the digester and upgrade plant (i.e. excluding methane emissions from digestate and feedstock storage). The calculator assumes biomethane losses of 0.2 g CH_4/MJ biogas and 0.2 g CH_4/MJ biomethane. No losses are assumed from combustion and from injection into the grid.

2.8.2 Estimation of GHG savings associated with the biogas life cycle

In order to quantify GHG emission savings, total life cycle emissions (LCEs) from the biogas life cycle, including the direct methane fugitive emissions from the AD plant, should be compared against the counterfactual. The stages associated with GHG emissions resulting from both the AD plant and the counterfactual are shown in the table below. The stages were categorised in the way shown below to facilitate comparison to the stages associated with the counterfactual.

Table 9: Stages associated with GHG emissions in the biogas and counterfactuals' life cycles

	Stages in the biogas life cycle leading to GHG emissions (Total Biogas LCEs)	GHG emissions associated with the counterfactual (Total Counterfactual LCEs)**
Upstream emissions	**A.** Emissions from feedstock production and transport to the AD site (as required for reporting under the Ofgem sustainability criteria). This is entered as zero for all waste feedstocks (e.g. slurry) in the GHG calculator.	**A´**. Feedstock production and storage or utilisation (offsite, i.e. the alternative to using it in the AD plant)
Onsite emissions	**B.** Biogas production / upgrade and utilisation on site (methane leakage and fugitive emissions) • Feedstock storage on site • Digester and other methane emissions from biogas production • Methane from digestate storage • Methane leakage from combustion or injection into the grid	**B´**. Natural gas alternative • Natural gas production and processing • Gas transmission & distribution • Combustion in CHP engine (not-relevant in the counterfactual for biomethane injection into the grid)
Downstream emissions	**C.** Digestate transport offsite and spreading on land	**C´**. Fertiliser life cycle (production and spreading on land as alternative to digestate)

* Carbon dioxide, methane and nitrous oxide (N_2O) emissions should be considered. The global warming potentials (GWP) are 1 g CO_{2e} for carbon dioxide, 23 g $CO_{2,e}$ CH_4 for methane and 296 g $CO_{2,e}$ N_2O for nitrous oxide.
** It should be noted that A' and C' are not part of the Ofgem guidance for reporting sustainability or calculating GHG savings.

The biomethane monitoring methodology described in the Methodology Report aims to provide an actual measurement of methane emissions on site (total of all B emissions in the table above). The measured biomethane emissions from the AD site (B) can be combined with other emissions from the biogas life cycle to estimate total biogas LCEs. As described in section 3.1.1, this is different to the procedure adopted in the Ofgem Sustainability Guidance, which does not include elements A' (feedstock counterfactual) or C' (digestate counterfactual).

The GHG savings (%) can be calculated as

$$\frac{Total\ Counterfactual\ LCE - Total\ Biogas\ LCE}{Total\ Counterfactual\ LCE}$$

Where Total biogas LCEs = A + B + C, and Total counterfactual LCEs = A´ + B´ + C´
The counterfactuals are briefly described in the sections below. As mentioned above, the A' and C' are not part of the Ofgem guidance which only considers the fossil fuel counterfactual. The method above is not intended to replace this method of comparing measured biomethane leakage on site to the fossil fuel counterfactual. It is, however, proposed that when applying this method for the large scale field trial, the two following calculations are performed:

- Comparing site emissions (as the measured biomethane leakage) to the B' counterfactual,
- Adding metered biomethane data on site (B) to upstream and downstream emissions and comparing the total biogas LCEs to the A'+B'+C' counterfactual.

2.8.3 Primary counterfactual: the fossil-fuel counterfactual (B')

Biogas from AD plants is replacing fossil fuels and so the main counterfactual is considered to be the natural gas life cycle. The counterfactual for the production of biogas and combustion in a CHP plant is the fossil fuel alternative defined as the production of natural gas, its processing, transmission and distribution and then combustion in CHP plant.

The natural gas emissions factor (EF) assumed in the Carbon Calculator is 66.59 g $CO_{2\text{-}e}$ / MJ of natural gas (239.7 g $CO_{2\text{-}e}$ / kWh of natural gas, net CV) for the EU mix quality of natural gas and assuming 4000 km of transport. This includes all life cycle emissions from the natural gas life cycle including combustion emissions[19] and is in agreement with the figure obtained from the UK GHG Inventory[20] which quotes 204 g $CO_{2\text{-}e}$ / kWh (net CV) for combustion emissions and 28 g $CO_{2\text{-}e}$ / kWh (net CV) for upstream emissions (including 20.2 g $CO_{2\text{-}e}$/kWh for production and processing, 0.3 g $CO_{2\text{-}e}$/kWh for transmission and 7.5 g $CO_{2\text{-}e}$/kWh for distribution), as shown in the "WTT tab" of the Inventory, giving a total of 232 g $CO_{2\text{-}e}$ / kWh. Upstream emissions attributed to transmission and distribution of natural gas are estimated as 7.8 g $CO_{2\text{-}e}$ / kWh of gas (3.5% for transmission and 96.5% for distribution).

For AD plants with biogas utilisation in **CHP** / boilers (categories 1, 2 and 5 and 6, if relevant, in Table 8), the reference GHG emissions (i.e. emissions associated with the counterfactual's life cycle) for estimating GHG savings should be 239.7 g $CO_{2\text{-}e}$ / kWh of gas. It should be noted that if electricity is used on site with no export to the grid, the counterfactual in this case will be zero.

For AD plants **with biogas upgrade and injection** (categories 3, 4 and 5 and 6, if relevant, in Table 8) with injection in the distribution network at 2 bar, the reference emissions for estimating GHG savings excludes transmission emissions and so the counterfactual should be 239.4 g $CO_{2\text{-}e}$ / kWh.

2.8.4 Secondary counterfactuals

In addition to savings relative to the fossil fuel counterfactual which the biogas production and utilisation process is replacing, savings could also result from (i) utilising the feedstock in the AD plant, and (ii) spreading the digestate on land as replacement to fertiliser. These two counterfactuals are described below.

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[19] Methane and nitrous oxide emissions from NG gas engine are assumed 1.23 g $CO_{2,e}$ / MJ.

[20] http://naei.defra.gov.uk/reports/reports?report_id=902

2.8.4.1 Feedstock counterfactuals (A')

The counterfactual for each of the different categories in Table 8 will depend on what would happen to the feedstock if it were not used in the AD plant. When the feedstock is treated in AD plants, the methane produced is collected as biogas and either combusted in engines and / or, boilers, flared, or upgraded and injected into the grid or used by vehicles for transport. The biogenic methane is oxidised to CO_2 except for the proportion which leaks into the atmosphere.

The quantity of methane that would have been released into the atmosphere in the absence of AD will depend on the feedstock mix for the site and so needs to be determined on a case-by-case basis (e.g. if the feedstock is a mix between agricultural and food waste, the reference GHG emission level against which the AD plant should be compared will depend on the proportion of each of these two feedstocks).

2.8.4.1.1 Counterfactual for agricultural feedstocks

For a plant utilising agricultural waste as the main feedstock, the counterfactual is the maximum amount of methane that would be leaked out into the atmosphere if the feedstock were not used in the AD plant. The feedstock counterfactual is different depending the type of agricultural feedstock used (e.g. slurry, silage grain).

Animal slurry
The counterfactual for slurry will depend on what management system is assumed. Several slurry management systems are given in the IPCC Guidelines (2006)[21]. These include daily spread on land, drying and burning as fuel and storage for spreading on land at a later stage.

The most common practice is to collect and transport slurry for storage in tanks, ponds or lagoons onsite in the vicinity of the animal housing, for spreading on land at a later date. The storage could be in open or closed tanks and could last for several months or a year. With storage in closed lagoons, biogas can be collected and either utilised or flared releasing CO_2 to the atmosphere. This, however, may be an expensive option for many farmers. **The counterfactual for animal slurry** assumes that the storage occurs for a period of less than one year in an open tank as excreted or with minimal addition of water outside the animal housing.

IPCC Guidelines (2006) can be used to quantify methane release into the atmosphere for the two counterfactuals above (See Appendix 1). The assumptions for the manure and slurry counterfactuals and estimated reference methane emissions are given in Table 9.

It should be noted that the methane released is dependent on the composition of the slurry (methane emissions are related to the organic matter). The definition of a reference slurry composition is a difficult task as it depends on type, age and diet of the animal[22].

The total methane emissions, whether released from feedstock storage, the digester area, the digestate storage or from the biogas combustion area will not exceed the maximum methane emissions that would have been released if the feedstock had not been used in the AD plant. There is no doubt that if biogas is not produced, the management of slurry on land will lead to higher methane emissions compared to leakage from the AD plant (from digesters, digestate storage, etc.).

Purpose-grown crops

[21] IPCC Guidelines for Inventories, Chapter 10, Emissions from Livestock and manure management, 2006. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf
[22] http://www2.mst.dk/udgiv/publications/2009/978-87-92548-20-7/pdf/978-87-92548-21-4.pdf

Grass and maize silage and maize grain are grown for the purpose of generating biogas in an AD plant. If purpose-grown crops (silage, grain) are not used in AD plants, the land would have been used for growing other crops.

LCEs from maize silage are reported in a study by DEFRA in 2015[23]. The total upstream emissions are reported as 19.2 g $CO_{2\text{-}e}$/MJ of electricity generated in CHP (this figure excludes combustion emissions). The total GHG emissions from maize silage production, harvesting, processing and transport are around 55 kg $CO_{2\text{-}e}$/ tonne of maize. This compares to 73 kg $CO_{2\text{-}e}$/ tonne of maize in the Ofgem Solid and Biogas Carbon Calculator.

Table 10: Summary of counterfactuals for different types of AD plants

Feedstock	Counterfactual description and assumptions	GHG emissions kg $CO_{2\text{-}e}$/ tonne of feedstock	Comments	Reference
Agricultural				
Animal slurry	Waste is collected and transported in liquid state to tanks for storage near animal housing. Liquid is stored for less than one year. Assumes dry solids content of 8% and 4.5% respectively in fresh material for cattle and pig and 80% organic matter content in the dry matter.	- 41.4	There is a **saving** on GHG emissions if slurry is used in an AD plant instead of storing it in tanks on farm.	Calculation based on IPCC guidance (see Appendix 1)
Energy crops	Land used to grow crop which is not used in the AD plant (life cycle includes crop production, harvesting, processing and transport). Land is used to grow maize silage.	+ 55 - 73	Energy crop would not be grown if it were not used in an AD plant.	Lower limit from Ofgem GHG calculator and higher end based on the UK GHG Inventory
Food waste	Collecting and sending food waste to new landfills. Based on UK GHG inventory, current methane production rate is 192 kg CH_4 / t MSW. However, a large proportion of this still leaks even for new landfills. Assuming methane capture of 90% in new landfills and 10% oxidation of emitted methane.	- 398	There is a **saving** on GHG emissions if MSW is used in an AD plant instead of landfilling it.	Based on data from the UK GHG Inventory (Waste disposal tab in the Inventory)
Sewage sludge and industrial waste	Waste collected using a flush system and transported to lagoons for storage. AD plant exists anyway as treatment is a requirement by legislation.	NA	NA	NA

[23] Risk and Opportunities of Current and Future Maize production (available at: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=2&ProjectID=19655

2.8.4.1.2 *Counterfactual for food waste*

In the UK, around 45% of the waste generated in 2016 was recycled, composted or digested, 33% was sent to landfills and 20% was incinerated. Incineration leads to the release for CO_2 rather than methane. Composting is an aerobic process and a large fraction of biodegradable fraction is converted into CO_2. Methane is formed in anaerobic sections of the compost, but is then oxidised to a large extent in the aerobic sections of the compost.

The counterfactual for food waste assumes sending the waste to new rather than old landfill. The UK GHG inventory quotes a figure of 680 kg $CO_{2\text{-}e}$/tonne food waste sent to landfills. These are mainly from methane and equate to around 31 kg CH_4/tonne waste. The main reason for high methane emissions from landfills is the lack of energy recovery from old landfills, which still account for a large proportion of landfill sites in the UK. However, waste to AD plants is most likely to be diverted from new rather than old plants.

The GHG Inventory does not provide data on the split between old and new landfills. Based on 2014 data, methane generation rates are 192 kg CH_4 / tonne MSW with 57% used for power generation, 10% flared and the rest emitted. Of the emitted methane, 10% is oxidised. The EA Guidance on the Management of Landfill Gas [24] states that 85% methane capture rate from new landfills is achievable. According to the GasSim manual[25], capture rates above 90% are achievable from sites with permanent capping. However, that is emission from capped waste. Until fully capped there will be a period of no cap and then temporary cap, during which methane leakage can be significant. Assuming a capture rate of 90%, the methane emitted is 17.3 kg CH4/tonne MSW waste (398 kg $CO_{2\text{-}e}$ / tonne).

2.8.4.1.3 *Counterfactual for sewage sludge and industrial feedstocks*

Regulations require that sewage sludge and industrial waste are treated, using anaerobic digestion on site, to certain standards before it can be spread on land or disposed off-site. In this case, the feedstock counterfactual is the same as the digestion plant itself.

2.8.4.2 Digestate counterfactual (C')

The alternative to using digestate from the AD plant is to use fertiliser. The GHG calculator used for Ofgem reporting, uses the following parameters to estimate GHG from fertilisers.

Fertiliser production life cycle emissions	4.5678	kg $CO_{2\text{-}e}$ / kg N
Fertiliser production life cycle emissions	1.176	kg $CO_{2\text{-}e}$ / kg P_2O_5
Fertiliser production life cycle emissions	0.6356	kg $CO_{2\text{-}e}$ / kg K_2O
Nutrient content of digestate	3	kg N/ m^3
Nutrient content of digestate	0.5	kg P_2O_5/m^3
Nutrient content of digestate	2	kg K_2O/ m^3
Density of digestate	1000	kg/ m^3

These parameters are used with the amount of digestate (kg or tonnes) to estimation GHG emissions for the fertiliser counterfactual.

[24] https://www.sepa.org.uk/media/28986/guidance-on-the-management-of-landfill-gas.pdf
[25] http://www.gassim.co.uk/documents/GasSim%20User%20Manual%20v2.5.8.pdf

2.8.5 Example using the counterfactual

A site produces 1000 m^3 / h of biogas (54% methane) with 15% used in a CHP and 85% sent to an upgrade plant for biomethane production. The site used 3 tonnes / h of slurry, 3 tonnes / h of maize silage and produces 5 tonnes / h of digestate. All electricity is used on site with no export to the grid. A methane monitoring station on site, measures 10 kg/h of total methane leakage from the site.

The counterfactual

- Upstream emission: 114 kg $CO_{2\text{-}e}$ / h for slurry (savings) and zero for maize silage
- Onsite emissions: 1,070 kg $CO_{2\text{-}e}$ / h for biomethane injection to grid (zero for CHP)
- Downstream emissions: 79 kg $CO_{2\text{-}e}$ / h for digestate spreading on land instead of fertiliser.
- Total counterfactual emissions = 1,263 70 kg $CO_{2\text{-}e}$ / h

Actual life cycle emissions

- Upstream emission: zero for slurry and a 158 kg $CO_{2\text{-}e}$ / h for maize silage. No reporting is required for waste streams (i.e. slurry)
- Onsite emissions: 230 kg $CO_{2\text{-}e}$ / h
- Downstream emissions: zero for digestate (no reporting requirement for digestate)
- Total site life cycle emission: 388 kg $CO_{2\text{-}e}$ / h.

GHG savings

In comparison to the counterfactual defined above, the site provides GHG savings of 69%. This compares to a site leakage rate of 2.6% (of the total methane produced). For a leakage rate of 30 kg CH_4 / h (8% leakage), the site provides GHG savings of 33% in comparison to the counterfactual.

3 Literature review of biomethane leakage monitoring technologies

3.1 Objective of monitoring methodology

As indicated in the Introduction to this report, the purpose of this project is to define a methodology to provide improved understanding and data to quantify the methane emissions from AD operations in the UK. The methodology will be applied in a subsequent study to assess emissions from AD and inform the role of Renewable Heat Incentive (RHI) in reducing GHG emissions.

To inform the development of the monitoring methodology, a literature review was undertaken to consider the following:

- Measurement techniques for methane
- Quantification techniques for fugitive and process releases
- Leak detection and quantification
- Quantification of methane leakage from AD and other biogas plant

In the following sections, an introduction to the types of emissions which can occur at industrial processes is provided together with details of the aspects listed above.

3.2 Types of emissions from industrial processes

Methane leakage from AD plant encompasses several types of emission. Emissions to atmosphere from industrial processes can be broadly divided between closed or vented releases (generally discharged in a controlled manner from a stack or duct) and fugitive releases which can arise from a variety of activities/sources including stockpiles, materials handling, leaks from buildings, process vessels, pressure relief valves, bypass/purge vents and connecting pipe or ductwork. Work in this project is to understand 'leakage' but this encompasses both closed and fugitive releases from the AD activity. This includes releases from the biogas production plant and associated operations including, for example, on-site utilisation and storage.

There is a large body of reference and guidance material for assessing vented releases, including well-established national, European and International measurement Standards used for assessing compliance with Emission Limit Values (ELVs) and for calibration of continuous emission monitors. These have largely been developed for particulate matter and other air quality pollutants but BS EN ISO Standards have also been developed for methane measurement (Section 3.5.2). However, assessment of fugitive releases from industrial sources is not as well-defined.

3.3 Reasons for emission monitoring

Emission monitoring is undertaken for a variety of reasons including:

- Assessing or demonstrating compliance with regulatory emission limit values
- Input to air quality models
- Assessing plant performance (for example optimisation trials, acceptance testing)
- Development of emission factors (for example for use in emission inventories)

- Investigation/research (for example resolving process issues, assessing new technologies or pollutants)

The monitoring strategies for these purposes can be quite different and are also influenced by the pollutants, available measurement techniques and available resources. For example, demonstrating compliance with a regulatory emission limit may be assessed for some pollutants using continuous emission monitoring systems but with averaging periods of minutes, an hour or 24 hours. For some pollutants and other measurement purposes, short-term monitoring with discrete sampling exercises may be undertaken.

For the purposes of this study, a short-term average may not provide an adequate understanding of a representative methane leakage from AD plant. A short-term monitoring campaign will provide a snapshot of methane leakage, but discussion with operators indicates that feedstock and operation of AD plant, and hence potential for methane leakage, may change substantially over a year. This suggests a need for longer term monitoring which is consistent with the approach adopted for the ongoing BEIS survey of boilers receiving RHI support. Hence, a longer term monitoring programme is envisaged which can provide a more representative average of actual operation of AD plant.

3.4 Measurement techniques for methane

3.4.1 Discrete sampling, semi-continuous and continuous measurements, point/open-path measurements and periodic surveys

Point measurements are undertaken at a single location and several measurements at different locations may be needed to provide a representative average measurement. An open path measurement provides an average concentration along a measurement path – typically several metres or tens of metres.

Continuous measurements provide real-time analysis of gas concentration and allow identification of trends in releases. Semi-continuous measurements require a short integration period (from a few seconds to several minutes) and provide average concentrations over the integration period. Discrete sampling generally involves collection of samples, which are then analysed later to provide average data for the sampling period. This sampling period may be a few seconds, minutes, hours or days depending on the measurement technique and sampling strategy. For example, collection of air samples in a bag or canister for subsequent analysis.

The term “periodic surveys in emission sampling” refers to an occasional monitoring campaign compared to continuous monitoring. For example, one or more short-term surveys compared to monitoring being installed and operated over a full year.

Satellite data for methane are also available but these tend to be applied for regional or large area sources.

3.4.1 Semi-quantitative measurement techniques applied for methane

3.4.1.1 Safety monitoring - flammable gas detectors

Methane leakage can give rise to an explosive atmosphere and is a potential asphyxiant in a confined space. There is a wide range of monitoring equipment and techniques for flammable gases. These devices are intended to monitor the flammable gas content of atmospheres typically in and around process operations involving flammable gases and in particular enclosed or partially enclosed areas to provide warning of flammable atmospheres. They are generally not specific to methane but clearly will respond to methane if present. The devices include simple portable units for personal or area protection to fixed sensors which may be used in multiple to monitor multiple areas within an installation.

In the AD processes, identification of leaks and ensuring methane levels in equipment cabins and around key components are well below the lower explosive limit (LEL) is a priority for safe operation. An LEL meter provides the concentration of the explosive gases on a scale of 0–100% LEL (about 5% volume/volume, v/v, methane) with visible and/or audible alarms when pre-determined thresholds are exceeded.

Portable combustible gas meters can be calibrated for methane, but are designed to determine the concentration of an explosive gas mixture as a percentage of the lower explosive limit of 5 % (50,000 parts per million, ppm).

An LEL meter applied for personal or area safety is not intended to pin-point leaks but to alert staff to potentially high levels of methane. However, similar technologies are also used by gas fitters and others to monitor for leaks in pipework.

Several techniques are applied but the main detection techniques and measurements for portable units are:

- catalytic combustion (pellistor) – flammable gas,
- infrared - hydrocarbons
- thermal conductivity - flammable gas
- semiconductor - flammable gas
- flame ionisation detection - hydrocarbons.

There are international standards for the detection and measurement of combustible gases.

- BS EN 60079-29-1:2007 Explosive atmospheres. Gas detectors. Performance requirements of detectors for flammable gases
- BS EN 60079-29-2:2015 Explosive atmospheres. Gas detectors. Selection, installation, use and maintenance of detectors for flammable gases and oxygen
- BS EN 60079-29-4:2010 Explosive atmospheres. Gas detectors. Performance requirements of open path detectors for flammable gases
- BS EN 50270:2015 Electromagnetic compatibility. Electrical apparatus for the detection and measurement of combustible gases, toxic gases or oxygen

Method performance

- Measured quantity - %LEL or flammable gas concentration
- Continuous or integrated measurement - continuous
- Specific to methane – No
- Point/area/line monitoring – point
- Complexity – simple
- Deployment period – short or long term
- Price ranges (purchase cost) from less than £50 to £3,000 depending on sophistication of device.
- Availability – wide range of commercial products
- Measure in the range 1–10,000 ppm (but limit of detection and higher range boundary depends on detection technique and application).
- Catalytic technique is sensitive to low oxygen atmospheres or very high methane (greater than 12%). Catalytic, conductivity and semiconductor systems can become 'poisoned' or consumed with use.
- Certified units are suitable for use in flammable atmosphere (intrinsically safe), rugged and portable.
- Screening, area and personal protection use.

3.4.1.2 Leak detection techniques

Portable flammable gas technologies described in Section 3.4.1.1 can be applied to leak detection on individual fittings, valves, vessels and connections.

Forward Looking Infra-Red (FLIR) and infrared absorption spectroscopy (IAS) allow visualisation of leaks. The main benefit of modern FLIR is that a captured, real-time image in the visible and IR range can be displayed on a screen, allowing the operator to see the source of the leaks and methane plumes. This improves the speed of leak detection.

There will be a place for FLIR in assessing fugitive emissions as it allows (remote) screening of the production area for further detailed assessment and potentially can also be used for longer term surveillance. This equipment is used in the same way as a handheld video camera.
A hand-held infrared absorption spectroscopy (IAS) instrument uses a semiconductor laser for methane measurements. The detector measures a fraction of the diffusely reflected beam from its target point.

Method performance (FLIR, IAS)
- Measured quantity – ppm metres (IAS), intensity (FLIR)
- Continuous or integrated measurement - continuous
- Specific to methane – some devices
- Point/area/line monitoring – line (IAS), area (FLIR)
- Complexity – simple
- Deployment period – short term
- Price ranges from £1,500 (IAS) to £65,000 (FLIR).
- Availability – limited range of commercial products
- An important screening tool – FLIR qualitative but provides visualisation of the extent of a leak.
- Portable and can be used at a distance (typically a few metres to tens of metres from source).
- Certified units are suitable for use in flammable atmosphere. Requires ideal weather conditions for FLIR, although IAS is claimed to work in poor visibility.
- Claimed to provide quantification of leakage rates with suitable software.

3.4.2 Quantitative measurement techniques applied for methane

3.4.2.1 International Standards for methane monitoring

International Standards have been developed for methane measurement from stacks and vents on stationary sources:
- BS EN ISO 25139:2011 Stationary source emissions. Manual method for the determination of the methane concentration using gas chromatography.
- BS EN ISO 25140:2010 Stationary source emissions. Automatic method for the determination of the methane concentration using flame ionisation detection (FID).

In addition:
- BS EN 12619:2013 Stationary source emissions. Determination of the mass concentration of total gaseous organic carbon. Continuous flame ionisation detector method.

The latter is not specific to methane but, in the absence of other hydrocarbon components, would provide a measurement of methane. However, these are intended for application in 'closed' stacks, ducts or vents and have a relatively high measurement range than is suitable for fugitive or ambient measurements.

There are also international standards for monitoring of pollutants in ambient air – they are not specific to methane but the technologies described are suitable for measurement of methane concentrations:

- BS EN 15483:2008 Ambient air quality. Atmospheric measurements near ground with FTIR spectroscopy
- BS EN 16253:2013 Air quality. Atmospheric measurements near ground with active Differential Optical Absorption Spectroscopy (DOAS). Ambient air and diffuse emission measurements.

These are open path/long path methods providing an average concentration over the length of the measurement path.

3.4.2.2 Flame ionisation detection (FID)

The most popular methane monitoring method is flame ionisation detection. Within the sample chamber, a flame fuelled by hydrocarbon-free air and hydrogen ionises the methane and other VOCs into ionised carbon, changing the current across the chamber to an extent proportional to the VOC concentration.

The hydrogen fuel source is carried in a pressurised gas cylinder (for a fixed monitor hydrogen fuel can be generated locally from electrical decomposition of water) while the hydrocarbon-free air is supplied by either a gas cylinder or a compressor. The FID will require adjustment against a zero gas (nitrogen or air) and a calibration gas (methane) at an appropriate concentration.

All FIDs have a relative response to other hydrocarbons, although it is possible to determine ‘methane only’ in higher end methane/non-methane systems which incorporate a catalyst which can selectively destruct non-methane components (although this is not an absolute separation of the methane and non-methane components).

This is a standard approach for both methane and non-methane VOC analysis in stack emissions and some comparable landfill gas applications. Portable certified instruments for use in flammable atmospheres are available (intrinsically safe) but instruments designed for ambient measurement are not certified for use in flammable atmospheres.

Method performance

- Measured quantity – concentration, ppm propane or methane equivalent
- Continuous or integrated measurement - continuous
- Specific to methane – No
- Point/area/line monitoring – point
- Complexity – moderate
- Deployment period – short or long term
- Availability – wide range of commercial products
- Price range: the high end instruments will retail from £9,000 to £20,000. A hand-held portable system will retail from £1,600 to around £6,000.
- Measures methane via flame ionisation, typically in the range <1–10,000 ppm. Assuming proper calibration, FIDs are sensitive and accurate. Typical hand-held instruments are capable of an accuracy for methane (after calibration with zero air and 500 ppm methane gas) within ± 0.5 ppm or ± 10 per cent of actual methane concentration (0.5–2,000 ppm range).
- Fuel is hydrogen, which presents a significant hazard for the operator.
- Specific training and care in operation required.
- Oxygen synergy for 100 per cent hydrogen FIDs can be a source of interference.
- With age, a FID can become ‘temperamental’ and so the user needs to be experienced with the full operation of the system.
- Used for screening (LDAR), ambient and source assessment. Can be easily configured with internal data logging and GPS capability.

3.4.2.3 Non-dispersive infrared detection (NDIR)

Non dispersive infrared absorption (NDIR) spectroscopy uses the principle of infrared absorption of a target gas. The NDIR analyser will be set up at a particular wavelength which will be selected to be most sensitive to methane but, as far as possible, not absorbed by other species. The attenuated IR at the end of the sample cell is detected by a sensitive photo-receptor. The signal is compared to the IR source in an inert gas such as nitrogen. The attenuation of the IR signal is used to calculate the concentration of methane in the test cell.

Different compounds have unique absorption spectra. However, this measurement principle does suffer from cross interference with water vapour and carbon dioxide, and so the gas does need to be conditioned before entry to the test cell.

Advanced versions of near IR spectroscopy such as cavity enhanced absorption spectroscopy could also be used, but these are more expensive. These more sensitive systems are more commonly associated with ambient measurements and used in vehicular transects, as discussed in a subsequent section.

Method performance

- Measured quantity – concentration
- Continuous or integrated measurement - continuous
- Specific to methane – yes
- Point/area/line monitoring – point
- Complexity – moderate
- Deployment period – short or long term
- Availability – wide range of commercial products
- Price range: in the region of £6,000 to £10,000 (estimated).
- Measures methane via infrared light absorption spectroscopy but may have a limited range.
- Assuming proper calibration, NDIR is sensitive and accurate.
- Interference from moisture and carbon dioxide.
- Used for screening (LDAR), ambient and source assessment.
- Less common than FID and catalytic combustion.

3.4.2.4 Fourier Transform Infra-Red (FTIR)

FTIR spectroscopy collects spectral data across the infra-red spectrum (not at a fixed wavelength as used by NDIR). The instrument can then resolve the spectral patterns measured to identify and quantify components based on a library of stored spectra. This provides a powerful analyser capable of simultaneously monitoring for several IR-absorbing components including methane and other common pollutants. Portable instruments are available.

Method performance

- Measured quantity – concentration
- Continuous or integrated measurement – near continuous (requires a short integration period to resolve and quantify components)
- Specific to methane – yes
- Point/area/line monitoring – point
- Complexity – moderate
- Deployment period – short or long term
- Availability – a range of commercial products
- Price range: in the region of £30,000 to £45,000 (estimated).
- Measures methane via infrared light absorption spectroscopy but may have a limited LoD.
- Assuming proper calibration, FTIR sensitive and accurate.
- Interference from moisture and carbon dioxide.
- Used for screening (LDAR), ambient and source assessment.

3.4.2.5 Cavity enhanced adsorption spectroscopy (CEAS)

The CEAS method is a derivative of tuneable diode laser absorption spectroscopy (TDLAS). There are two main commercial forms of this technique:

- ‘time’ based cavity ringdown spectroscopy (CRDS)
- ‘intensity’ based integrated cavity output spectroscopy (ICOS)

A tuneable diode laser is used to introduce a near infrared beam into an absorption cell in which the laser pulse is reflected between two or more highly reflective mirrors, which creates the ‘cavity’. The path length of the light in the cavity is not the distance between the mirrors alone, but this length multiplied by the number of times the light is reflected creating virtual path lengths of tens of kilometres which allows a very low Limit of Detection.

When the source of near infrared energy is interrupted through use of a pulsed laser or chopper, the IR already in the cavity will bounce off the mirrors but will lose energy exponentially over time, as no mirror can be fully 100 per cent reflective. The time that it takes the initial IR pulse to decay to zero because of these losses is the ‘ring-down’. The IR frequency is tuned to match specific absorption bands of the target gas, so when the IR beam in the cavity passes through the target gas, the decay in the IR intensity is accelerated. The difference in time for complete extinction of the IR beam in the cavity between mirror losses alone and combined mirror and target gas absorption losses is directly proportional to the concentration of the target gas.

In ICOS, determination is by intensity of the laser pulse and is not time based as in CRDS but the basic laser and cavity cell approach are similar.

Development of CEAS systems over the last three decades has reduced measurement errors, improved stability and reduced power consumption, so that these systems are becoming much more common as field instruments.

Method performance

- Measured quantity – concentration
- Continuous or integrated measurement - continuous
- Specific to methane – yes
- Point/area/line monitoring – point
- Complexity – high
- Deployment period – short or long term
- Availability – a range of commercial products
- Price range: around £35,000 for current field portable instruments is a conservative estimate; a lab bench basic unit costs in the region of £27,000.
- Multiple operating ranges.
- Precision – 1 part per billion (ppb) or better.
- Uncertainty: <1 per cent without calibration; <0.03 per cent with calibration
- Low power consumption from 300 W down to 60 W.
- Low drift 0.8 ppb in 24 hours.
- High accuracy system for ambient assessment and not an alternative for LDAR methane leak detection screening.

3.4.2.6 Open path FTIR

Unlike the portable or fixed FTIR instruments (Section 3.4.2.4), the open path application of FTIR involves use of atmosphere as an external measurement cell which allows whole site or fenceline assessments. The approach requires a transmitter and receiver along the path of the measurement beam. These can either be separate (at each end of the path) or a combined unit in which the beam is reflected by use of a mirror placed at some distant point. The FTIR technology typically requires a path length of over 100m. Evaluation data published for VOC measurements (but not methane) suggest a LoD of <1ppm.

Method performance

- Measured quantity – concentration
- Continuous or integrated measurement - continuous
- Specific to methane – yes
- Point/area/line monitoring – line (area if scanning multiple lines in turn)
- Complexity – moderate/high
- Deployment period – short or long term
- Availability – several commercial products
- Price range: in the region of £50,000 to £80,000
- LoD 0.32ppm (Ethylene).
- Range 400-500m

3.4.2.7 Open path DOAS

Ultra-violet differential optical absorption spectroscopy (UV-DOAS) is a common open path technology applied for assessing VOC releases but is not suitable for methane. IR-DOAS is a potential technology for monitoring methane. The open path approach involves use of an external measurement cell which allows whole site or fenceline assessments. The approach requires a transmitter and receiver along the path of the measurement beam. These can either be separate (at each end of the path) or a combined unit in which the beam is reflected by use of a mirror placed at some distant point. The UV-DOAS technology typically requires a path length of over 500m. Evaluation data published for VOC measurements (but not methane) suggest a LoD at ppb level.

- Measured quantity – concentration
- Continuous or integrated measurement - continuous
- Specific to methane – no (does **not** measure methane)
- Point/area/line monitoring – line
- Complexity – high
- Deployment period – short or long term
- Availability – wide range of commercial products

3.4.2.8 Open path TDLAS

Tunable diode laser absorption spectroscopy (TDLAS) involves use of atmosphere as an external measurement cell which allows whole site or fenceline assessments. The approach requires a transmitter and receiver along the path of the measurement beam. These can either be separate (at each end of the path) or a combined unit in which the beam is reflected by use of a mirror placed at some distant point. The TDLAS technology typically requires a path length of over 250m. Evaluation data published for VOC measurements and methane suggest a LoD of <1ppm.

Method performance

- Measured quantity – concentration
- Continuous or integrated measurement - continuous
- Specific to methane – yes
- Point/area/line monitoring – line (area if scanning multiple lines in turn)
- Complexity – high
- Deployment period – short or long term
- Price range: in the region of £50,000
- LoD 0.1 ppm.
- Range to 1km

3.4.2.9 Open path LIDAR/DIAL

DIAL or Differential Absorption Lidar (Light Detection and Ranging) is a technique which allows remote sensing of pollutants (including greenhouse gases). A laser source emits a pulse of light which interacts with the pollutants which results in release of photons which can be detected allowing determination of both concentration and distance. This is a key difference from the other open path technologies which provide an average concentration over the measurement path. Although a powerful measurement technique, the cost of the system is high.

Method performance

- Measured quantity – concentration and distance
- Continuous or integrated measurement - continuous
- Specific to methane – yes
- Point/area/line monitoring – line (area if scanning multiple lines in turn)
- Complexity – high
- Deployment period – generally short term
- Price range: in the region of £200,000-500,000 (bespoke), £30-100k for single campaign up to 1 week
- LoD 50 ppb.
- Range 50m to 1km

3.5 Quantifying releases from industrial processes

3.5.1 Overview

Regulatory authorities, operators and other stakeholders have developed a wide range of techniques to identify and quantify releases from industrial processes. These include approaches such as stack/vent monitoring, leak surveys, fenceline monitoring (or more distant remote monitoring), mass balances and modelling (and combinations of these). Data from such surveys can be used to develop emission factors (for example UNFCCC 2012) which may then be applied to similar processes to estimate vented and fugitive releases however care is needed to assure that such factors are representative of installation activity and operation.

Determination of a contained emission release rate ‘E’, for example a stack or vent emission, can be relatively straightforward to obtain from an emission concentration ‘C’ and stack or vent gas flowrate ‘Q’.

$$E = C \times Q$$

However, consideration of representative sample, measurement periods are key to minimising uncertainty and covered in emission measurement Standards (Section 3.4.2.1) and also BS EN ISO 11771:2010 Air quality. Determination of time-averaged mass emissions and emission factors. General approach.

Determination of a fugitive release rate (flux) can be inherently more uncertain than for a contained release (that is a release which is discharged through a stack, duct or vent). On an industrial process, there are often multiple sub-processes and locations where material could be released.

In the case of AD plant, the main anticipated contained releases are building/vessel release vents, combustion engine exhaust, the gas upgrade release vent and, the combustion flare. Fugitive releases will arise from leaks (potentially multiple location across the AD plant), operation of relief valves and anaerobic activity in feedstock or spent digestate occurring outside the AD process units.

There are also temporal variations – these may be short-term ‘events’ (for example short term releases due to a plant failure or operation of a release vent) or longer term variation due to changes in operation particularly for batch or semi-continuous activities and where seasonal or other factors may influence emissions.

The methodology for assessing methane leakage needs to reflect the monitoring objective(s) and this should include a representative survey of plant and approach which addresses the range of operation of the activity. This would include (for example) recognition of the influence of short-term and long-term differences in emission.

For the purposes of this study, the term **bio**methane leakage is used to describe methane emissions from biogas (anaerobic digestion) activities including contained and fugitive emissions.

3.5.2 International Standard fugitive assessment procedures

There are currently no International Standards Organisation (ISO) or European Standards (CEN) for determining gaseous fugitive releases from industrial activities. CEN Working Group 38 to the Technical Committee 264 is working to elaborate a European Standard, in support of Directive 2010/75/EU on industrial emissions (IED), to determine fugitive and diffuse emissions of volatile organic compounds into the atmosphere but the draft is at committee stage and not available for public comment.

CEN Working Group 44 to the Technical Committee 264 may also be relevant and is developing a methodology to allow source apportionment of ambient concentrations of air quality pollutants to activities (including industrial sources).

There are a number of EN and ISO Standards that deal with type approval and measurement of fugitive emissions from valves for product type testing because measured concentrations and flowrates. The IED guidance on Best Available Techniques (BAT) for refineries (EIPPCB, 2014) and draft guidance on monitoring (EIPPCB, 2013) mentions the following EN Standards are relevant for assessing fugitive dust emissions and fugitive vapour emissions.

- BS EN 15445:2008 Fugitive and diffuse emissions of common concern to industry sectors. Qualification of fugitive dust sources by reverse dispersion modelling – EIPPCB comments that the Standard states that it should not be used for compliance assessment or comparison of industrial installations from the same industrial sector.
- BS EN 15446:2008 Fugitive and diffuse emissions of common concern to industry sectors. Measurement of fugitive emission of vapours generating from equipment and piping leaks.

The latter Standard includes screening (sniffing) of process valves and then encapsulating (bagging) the valves or other devices and monitoring concentration changes to quantify leak rates.

3.5.3 National methodologies for assessing fugitive emissions

Organisations in the UK, Germany and US have produced guidance for assessing fugitive emissions. A selection of the guidance is provided below, these range from general guidance to activity and/or pollutant-specific material:

- **UK**
  Environment Agency Technical Guidance Note (Monitoring) M8 - Monitoring Ambient Air
  Environment Agency Technical Guidance Note (Monitoring) M17 - Monitoring Particulate Matter in Ambient Air around Waste Facilities
  Environment Agency - Considerations for quantifying fugitive methane releases from shale gas operations
- **Germany**
  VDI 4285 – Part 1 Determination of diffusive emissions by measurement - Basic concepts
  VDI 4285 – Part 2 Determination of diffusive emissions by measurements - Industrial halls and livestock farming
- **US**
  EPA Handbook: Optical Remote Sensing for Measurement and Monitoring of Emissions Flux
  Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology
  Other Test Method 10 - Optical Remote Sensing for Emission Characterization from Non-point Sources

Other Test Method 32 - Determination of Emissions from Open Sources by Plume Profiling
Other Test Method 33/33A - Geospatial Measurement of Air Pollution, Remote Emissions Quantification (GMAP-REQ)
Guidance for evaluating landfill gas emissions from closed or abandoned facilities
Guide for Developing a Multi-Metals, Fence-Line Monitoring Plan for Fugitive Emissions Using X-Ray Based Monitors

The content of these guidance documents is wide-ranging. The Environment Agency is the regulatory authority in England for major industry and waste; it has produced monitoring guidance for ambient air which includes consideration of fugitive releases (Technical Guidance Note M8). This sets out a decision flow chart for determining a monitoring strategy (Figure 8). Although the guidance is focussed on air quality monitoring (rather than greenhouse gases), the approach is valid and does provide commentary on key aspects such as the merits of continuous monitoring and occasional sampling, temporal coverage, choosing the averaging period for data, data logging periods, directional sampling, the choice of fixed-point sampling or open path methods, sensor location. In addition, practical guidance on addressing interfering sources, topography and choice of sampling height are provided.

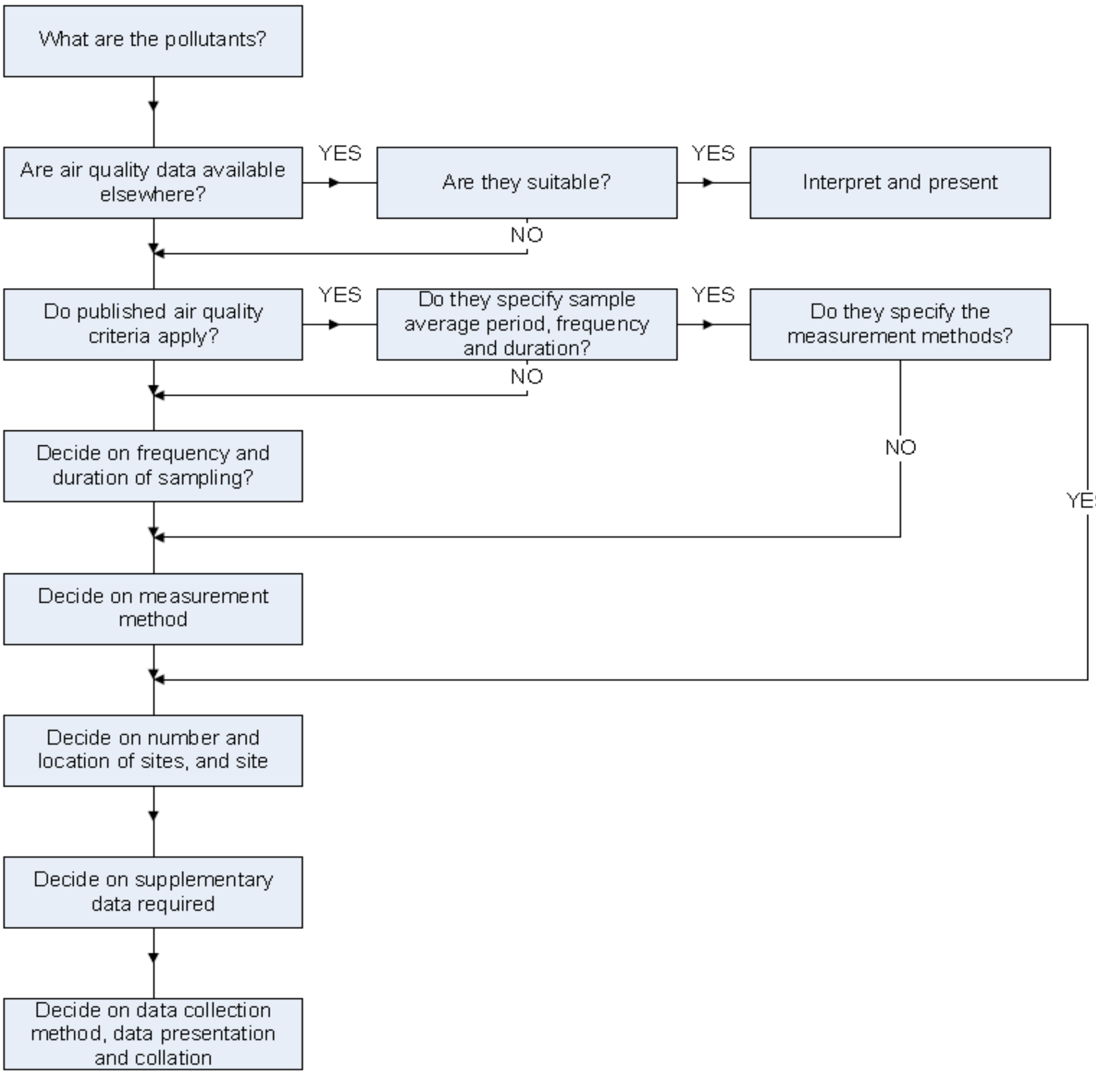

Figure 8: Environment Agency Decision tree to determine Monitoring Strategy (EA, 2011)

The Environment Agency has also produced guidance for quantifying fugitive methane releases from shale gas operations (EA, 2014). This guidance adopts a risk-based approach which includes monitoring where appropriate and provides guidance on monitoring methods:
"*..methods are presented as a hierarchy of techniques that can be used in line with the risks to the environment and the performance of an operator at a site. While more approximate and cheaper methods may be acceptable in situations with lower risks and higher performance, more detailed and costly methods may be appropriate in situations with higher risks and variable performance. The hierarchy can be used to select simpler methods for basic surveillance purposes, and more sophisticated methods for detailed studies e.g. for calibrating generic emission factors*."

The monitoring for shale gas operations is focussed on managing impacts of the activity on the local environment rather than input to national policy development required for this study. Nonetheless the monitoring methods described in the guidance are relevant to the current study and include on-site, boundary fence and off-site monitoring.

The German VDI (The Association of German Engineers) has produced general guidance for assessing fugitive emissions and specific requirements for particular activities. The US Environmental Protection Agency (US EPA) guidance includes 'other' test methods for assessment of fugitive emissions by plume sampling or downwind monitoring and there are also activity and pollutant-specific protocols. The US EPA guidance is the most detailed and the 'Other Test Methods' are directly relevant to aims of this study.

3.5.4 Literature review of fugitive monitoring approaches

A large body of scientific literature has been reviewed for the study primarily sourced from English language internet searches against appropriate search terms (see Appendix 2). The review has considered:

- Reports and guidance from UK and US regulatory bodies
- Guidance from the European integrated pollution prevention and control bureau (EIPPCB)
- Reports and guidance from other government bodies
- Reports and guidance from industry
- International and national standards
- Papers on fugitive/diffuse/area emission assessment methods
- Papers on methane measurement
- Papers on methane leakage from biogas plant

Guidance and reviews have been undertaken to summarise approaches to assessing diffuse and fugitive emissions (Holmgren 2015, Jonerholm 2012, EA 2012, USEPA 2011b, USEPA 2007, Concawe 2008 and EIPPCB 2013/2014). These generally describe the range of approaches to assessing fugitive emissions from leak detection through to methane-specific instrumentation. A range of approaches are discussed for developing emission rates from measurement of concentration measurements on and around the facility. A number of USEPA 'Other Test Methods' (OTM) are relevant including OTM 10, 32 and 33.

The approaches described include site surveys, open path measurements and classification of leaks (Leak Detection or sniffing), use of tracer gases releases, reverse dispersion modelling and plume profiling. Much of the review literature is concerned with other industries, basic leak detection methods and/or more sophisticated (and expensive) open/long path remote sensing.

The EIPPCB guidance on Best Available Techniques (BAT) for refineries summarises several approaches for assessing fugitive volatile organic compound (VOC) from EN 15446, FLIR to open path methodologies (including DIAL). Advantages and disadvantages of approaches are summarised and the guidance indicates that BAT is to monitor diffuse VOC emissions to air from the entire site by using leak detection, optical gas imaging and emission factors (validated by measurement). Further, the use of optical absorption-based techniques is described as a useful *complementary* technique.

Holmgren 2015 provides a review of methane leak detection approaches applied to biogas plant in several European Member States and also provides a comparison trial of on-site and remote monitoring at a biogas plant in Sweden. This review highlighted the variability of data from one country to another. It also highlighted that there were high and unknown uncertainties in the measurements collected due to analytical uncertainty and time variation in emissions.

International Standards – the relevant international standards are described at Section 3.5.2.. There are no international Standards for assessing leakage from a biogas facility but Standards are available for measurement of methane and assessment of fugitive releases.

Methane leakage from biogas plant and fugitive release assessment – a number of papers were reviewed including:

Reference	Summary
Biogas plants	
Groth, 2015	Open path TDL with tracer gas and meteorological measurement plus reverse dispersion modelling, measurements around AD plant for part of 1 day in Dec 2013. Used methane as a tracer.
Hrad, 2015	Open path TDL and reverse dispersion modelling. Monitoring around farm AD plant during daylight hours for 3-6hrs for 18 months, shorter campaign for 4 other plants. Assessed leakage rate from over 1 year of data. Operational and meteorological emissions differences noted. 10min average data collected, upwind data prior and after each campaign. Met data screening to exclude poor dispersion periods.
Yoshida, 2014	A mobile downwind survey at wastewater treatment plant (WWTP) using CRDS and tracer gas dilution. Study found that process configuration, as well as the operation of the WWTP, determines the rate of GHG emission for methane and nitrous oxide. Acetylene tracer used. Methane background concentration was 1900ppb with 2545ppb maximum measured downwind concentration.
Flesch, 2011	Open path TDL and reverse dispersion modelling around farm AD plant. Seasonal campaigns of several days, manual switching of lasers for up/downwind. Mainly full site assessment but also some monitoring over lagoons and other elements of plant. Seasonal differences noted, some commentary that loading hoppers are potential source of leaks. Runoff and feedstock piles low emission contribution compared to maintenance and normal operation.
Other facilities	
McBain, 2005	Field trial to demonstrate modelling by releasing methane as a tracer gas using a mass flow controller and release array at ground level and at about 1.5m. TDL set up in open area around release grid. Conclusions - works for all but low wind speeds, good measurement height about 1.3m (for this study with low height discharge), measure downwind at 25 x height of any obstruction, estimates can be improved by duplicating measurements at different sensor heights.
Babilotte, 2011	Review and comparison of methods for landfill sources. Compared flux chambers, plume mapping, tracer gas and DIAL. Flux chambers not recommended, plume mapping not recommended, tracer gas has limitations for multiple sources but DIAL and tracer gas most promising (for landfill).
USEPA, 2014	USEPA fugitive and area source group, application of next generation fixed and mobile sensors using CRDS to assessing leakage from upstream oil and gas sources.
EA, 2014	Potential for application of drones for methane measurement above/around landfills

Reference	Summary
Wong 2013	Helicopter survey over/around landfill facility using TDL to provide aerial survey
Chamber 2008	Use of DIAL system to map methane and other releases from a refinery
USEPA, 2005a/b/c	Application of open path FTIR, TDL, UV-DOAS and horizontal and vertical plume mapping at abandoned landfill sites
Innocenti, 2012	Measurements of Methane Emissions and Surface Methane Oxidation at Landfills: WR1125

3.6 Summary

Measurement of emissions arising from leakage or from area sources can be a complex process. **Measurement sensors** allow measurement of methane, flammable gas and also other pollutants with a wide range of Limit of Detection, operating range and interferents[26].

The sensor technologies allow determination of methane concentration at specific points, as an integrated (average) concentration between a sensor and transmitter (with varying path lengths of a few metres to km level) or allow mapping of pollutant concentrations within a two dimensional plane.

Sensors are available for leak detection, air quality analysis, atmospheric pollution analysis and stack emission monitoring. The cost of measurement equipment broadly increases with capability (i.e. low limit of detection, mapping and multi-pollutant capability provided by DIAL systems cost multiple orders of magnitude more than simple leak detectors which monitor flammable gas at a fixed point).

There are a variety of approaches to assess fugitive/diffuse leaks from activities, methods have evolved to reflect available measurement technologies, there is a European Standard for assessing fugitive particulate releases and there is a European Standard in development for assessing fugitive emissions from industrial activities.

However, current guidance and approaches adopted for assessing fugitive releases in literature are provided in Table 10. Satellite data for methane are also available but these tend to be applied for regional or large area sources.

Table 10: Summary of fugitive release assessment methodologies

Approach	Description	Measurement	Advantage	Disadvantage
Leak detection-based	Measurement on site with relatively low sensitivity equipment which may measure flammable gas concentration rather than methane	Methane or flammable gas	EN Standard, LDAR guidance available, cheap, portable sensors, able to assess individual components, direct monitoring of emission rate from bagging techniques.	Concentration used as an indicator of release rate, 'spot' measurement – complex sites can take long time to survey, multiple surveys needed to assess longer term emission. Bagging techniques for quantifying leaks (of valves and other process units) may not be universally applicable to all sources.
Plume profiling	Downwind monitoring of plume using fixed (or open path) sensors and meteorological data	Methane	USEPA OTM10, addresses whole site, can be applied long term.	May require additional site measurements to discount sources. Need to ensure plume is sampled. May be difficult to distinguish plume from background, need low LoD and high resolution.

[26] Common interferents relevant for monitoring AD plant are carbon dioxide and moisture, other relevant interferents may be other flammable gases.

Approach	Description	Measurement	Advantage	Disadvantage
Tracer gas	Downwind monitoring of plume using open path sensors, supported by quantified release of tracer gas and meteorological data	Methane + tracer gas	Whole site, use of tracer gas usually means short term sampling but can be applied long term. Can avoid need for using meteorological data.	Second measurement for tracer. Tracer may not be co-located with leaks – but not an issue if far enough downwind. May require additional site measurements to discount sources. Need to ensure tracer plume is sampled. May be difficult to distinguish plume from background, need low LoD and high resolution.

Approach	Description	Measurement	Advantage	Disadvantage
Reverse dispersion modelling	Downwind monitoring of plume using open path sensors, release rate determined by dispersion modelling	Methane	Whole site, may be limited where site is large with sources widely dispersed or at different heights.	May require additional site measurements to discount sources. Need to ensure plume is sampled. May be difficult to distinguish plume from background, need low LoD and high resolution.
Vertical/Radial plume monitoring	Downwind monitoring of plume using open path sensors, release rate determined by dispersion modelling	Methane	Whole site, may be limited where site is large with sources widely dispersed or at different heights.	May require additional site measurements to discount sources. Need to ensure plume is sampled. May be difficult to distinguish plume from background, need low LoD and high resolution.
Mobile system (perimeter or aerial monitoring)	Typically applies atmospheric measurement techniques with good LoD and resolution with modelling techniques to map plume(s).	Methane	Can track plume movement and cover large sites or regional emissions. Atmospheric analysis technique so good LoD and resolution	Cost of aerial surveys, may require additional site measurements to discount sources. May not be good for assessing short-term or variable releases
DIAL/Lidar	Maps pollutant concentration and in cross-section plume (not an average along the measurement path), release rate determined by dispersion modelling	Methane	Whole site, allows quantification and distance determination of plume concentrations so discharges/leaks may be picked out. Atmospheric analysis technique so good LoD and resolution	Cost. May require additional site measurements to discount sources. Need to ensure plume is sampled. Reported usage all for short term assessment.

The use of downwind fixed point sensors (as proposed in our tender) would appear to be an uncommon approach for assessing leakage from biogas plant but is the basis of a US EPA methodology. However, the project aims to establish a methodology that can be applied cost-effectively to a larger survey. The open path methods applied in the other methodologies and for published research at biogas plant seem to be used for short periods (and some methodologies are daylight only methods) which would be a limitation in assessing year-round operation.

A **potential significant constraint** in the methodology may be the need to exclude emissions from component parts of the AD facility. This can be addressed as discussed in our proposal and as highlighted in Section 3 (Boundaries) through use of a **site survey** to understand magnitude of subcomponent releases but extended monitoring of both the downwind whole site emission and subcomponents would require significant additional resources.

Appendix 1 – Applying IPCC Guidelines (2006) to determine methane leakage for the counterfactual

The amount of methane which can be released from storage is calculated based on the IPCC Guidelines (2006) as

$$CH_4\ [storage] = VS_{storage}\ [kg] \times B_0 \times 0.67 \times MCF$$

Where

VS is the volatile solid content
B0 is the biodegradability factor, 0.45 for pig slurry and 0.24 for cow slurry [m^3 methane / kg VS]
0.65 is the density for methane [kg methane / m^3] and
MCF is the methane conversion factor obtained from Table 10.17 in the IPCC Guidelines[17] and depends on the management system adopted and depends on the average annual temperature. For annual UK temperatures, MCF is 2% for solid manure storage and 17% for open tank slurry storage without crust cover.

Based on an average volatile solid ($VS_{storage}$) content of

The volatile solid content (%) is calculated based on the data below[27]

	Dry solids as % of fresh material	Organic solids as % of dry solids	$VS_{storage}$, %
Pig slurry	4.5%	80%	3.6%
Cow slurry	8%	80%	6.4%
Manure	25%	80%	20%
Municipal solid waste	35%	50%	17.5%
Sewage sludge	12%	80%	9.6%

Using the formula above,

- Methane emissions from storage of pig slurry in tanks = 1.85 kg CH_4 / tonne of pig slurry
- Methane emissions from storage of cattle slurry in tanks = 1.75 kg CH_4 / tonne of cattle slurry
- Assume an average of 1.8 kg methane per tonne of animal slurry
- This compares well with the figure which can be estimated from JRC work reported here (JRC, 2014) [28] where a figure of 1.4 kg / tonne of slurry can be estimated from the figures referred to in that report but based on 43% VS reduction.

Repeating the calculation for manure, we get methane emissions = 0.9 kg CH_4/ tonne of manure.

[27] SEAI: http://www.seai.ie/Renewables/Bioenergy/Bioenergy_Technologies/Anaerobic_Digestion/The_Process_and_Techniques_of_Anaerobic_Digestion/Gas_Yields_Table.pdf
[28] Jacopo Jiuntoli et. Al., Solid and gaseous bioenergy pathways, Input values and GHG emissions, JRC Science and Policy Reports, 2014. https://ec.europa.eu/energy/sites/ener/files/documents/Solid%20and%20gaseous%20bioenergy%20pathways.pdf

Appendix 2 – Applying IPCC Guidelines (2006) to determine methane leakage for the counterfactual

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Where

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Pig slurry	4.5%	80%	3.6%
Cow slurry	8%	80%	6.4%
Manure	25%	80%	20%
Municipal solid waste	35%	50%	17.5%
Sewage sludge	12%	80%	9.6%

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- Assume an average of 1.8 kg methane per tonne of animal slurry
- This compares well with the figure which can be estimated from JRC work reported here (JRC, 2014) [30] where a figure of 1.4 kg / tonne of slurry can be estimated from the figures referred to in that report but based on 43% VS reduction.

Repeating the calculation for manure, we get methane emissions = 0.9 kg CH_4/ tonne of manure.

[29] SEAI: http://www.seai.ie/Renewables/Bioenergy/Bioenergy_Technologies/Anaerobic_Digestion/The_Process_and_Techniques_of_Anaerobic_Digestion/Gas_Yields_Table.pdf
[30] Jacopo Jiuntoli et. Al., Solid and gaseous bioenergy pathways, Input values and GHG emissions, JRC Science and Policy Reports, 2014. https://ec.europa.eu/energy/sites/ener/files/documents/Solid%20and%20gaseous%20bioenergy%20pathways.pdf

Appendix 2 - Literature Review Sources

Reference	Authors	Source	Title	Region	AD ?	Methane ?	Plant type	Feedstock	Methodology
Alhamdani, 2016	Yousef A. Alhamdani, Mimi H. Hassim, Rex T.L. Ng, Markku Hurme	International Journal of Hydrogen Energy, 2016.07.274	The estimation of fugitive gas emissions from hydrogen production by natural gas steam reforming	Malaysia, US, Finland	No	Yes	Hydrogen reformer	Nat. gas	Emission factors
Safitri, 2011	Anisa Safitri, Xiaodan Gao, M. Sam Mannan	Journal of Loss Prevention in the Process Industries Volume 24, Issue 2, March 2011, Pages 138–145	Dispersion modeling approach for quantification of methane emission rates from natural gas fugitive leaks detected by infrared imaging technique	US	No	Yes	Gas plant	Nat. gas	Infra-red imaging + dispersion modelling
Leifer, 2013	Ira Leifer, Daniel Culling, Oliver Schneising, Paige Farrella, Michael Buchwitz, John P. Burrows	Atmospheric Environment Volume 74, August 2013, Pages 432–441	Transcontinental methane measurements: Part 2. Mobile surface investigation of fossil fuel industrial fugitive emissions	US	No	Yes	Industry		Atmospheric methane monitoring, GC-FID plus CRDS
Farrell, 2013	Paige Farrell, Daniel Culling, Ira Leifer	Atmospheric Environment Volume 74, August 2013, Pages 422–431	Transcontinental methane measurements: Part 1. A mobile surface platform for source investigations	US	No	Yes	Various		Atmospheric methane monitoring, GC-FID

Thorpe, 2013	Andrew K. Thorpe, Dar A. Roberts, Eliza S. Bradley, Christopher C. Funk, Philip E. Dennison, Ira Leifer	Remote Sensing of Environment Volume 134, July 2013, Pages 305–318	High resolution mapping of methane emissions from marine and terrestrial sources using a Cluster-Tuned Matched Filter technique and imaging spectrometry	US	No	Yes	Various		Airborne infra-red sensors
Wu, 2014	Chang-Fu Wu, Tzong-gang Wu, Ram A. Hashmonay, Shih-Ying Chang, Yu-Syuan Wu, Chun-Ping Chao, Cheng-Ping Hsu, Michael J. Chase, Robert H. Kagann	Atmospheric Environment Volume 82, January 2014, Pages 335–342	Measurement of fugitive volatile organic compound emissions from a petrochemical tank farm using open-path Fourier transform infrared spectrometry	Taiwan	No	No	Petrochem tank farm	Petrochem	Open path FTIR
Amodio, 2013	M. Amodio, E. Andriani, P.R. Dambruoso, G. de Gennaro, , A. Di Gilio, M. Intini, J. Palmisani, M. Tutino	Atmospheric Environment Volume 79, November 2013, Pages 455–461	A monitoring strategy to assess the fugitive emission from a steel plant	Italy	No	No	Steel plant		PM sampling

Aziz, 2013	Nik N.N.A. Aziz, Mimi H. Hassim, Markku Hurme	Chemical Engineering Research and Design Volume 91, Issue 8, August 2013, Pages 1373–1382	Computer aided estimation of fugitive emission rates and occupational air concentration in process design	Malaysia, Finland	No	No	Chemical processes	Various	Simulation
Hassim, 2013	Mimi H. Hassim, Markku Hurme, Paul R. Amyotte, Faisal I. Khan	Journal of Loss Prevention in the Process Industries Volume 25, Issue 5, September 2012, Pages 820–829	Fugitive emissions in chemical processes: The assessment and prevention based on inherent and add-on approaches	Malaysia, Finland, Canada	No	No	Various	Various	Simulation
Hassim, 2012	Mimi H. Hassim, Markku Hurme, Paul R. Amyotte, Faisal I. Khan	Journal of Loss Prevention in the Process Industries Volume 25, Issue 5, September 2012, Pages 820–829	Fugitive emissions in chemical processes: The assessment and prevention based on inherent and add-on approaches	Malaysia, Finland, Canada	No	No	Various	Various	Simulation
Brereton, 2012	Carol A. Brereton, Matthew R. Johnson	Atmospheric Environment 51 (2012) 46e55	Identifying sources of fugitive emissions in industrial facilities using trajectory statistical methods	Canada	No	No	Oil and gas	Various	Trajectory statistical methods combined tuneable diode laser network.

Hurry, 2016	Jacquelyn Hurry, David Risk, Martin Lavoie, Bjørn-Gustaf Brooks, Claire L. Phillips, Mathias Göckede	International Journal of Greenhouse Gas Control Volume 45, February 2016, Pages 1–8	Atmospheric monitoring and detection of fugitive emissions for Enhanced Oil Recovery	US, Canada	No	Yes	Enhanced oil recovery		Picarro Cavity Ringdown Spectroscopic (CRDS)
Bossche, 2017	Michael van den Bossche, , Nathan Tyler Rose, Stephan Franz Joseph De Wekker	Sensors and Actuators B: Chemical Volume 238, January 2017, Pages 501–509	Potential of a low-cost gas sensor for atmospheric methane monitoring	US	No	Yes			solid state sensor
Bamberger, 2014	I. Bamberger, J. Stieger, N. Buchmann, W. Eugster	Environmental Pollution Volume 190, July 2014, Pages 65–74	Spatial variability of methane: Attributing atmospheric concentrations to emissions	Switzerland	No	Yes			Tunable diode laser - fast methane anlayser
Onat, 2006	Adem Onat	Sealing Technology Volume 2006, Issue 10, October 2006, Pages 7–9	A review of fugitive emissions	Turkey	No	Yes	various		leak detection

Tiwary, 2015	A. Tiwary, I.D. Williams, D.C. Pant, V.V.N. Kishore	Renewable and Sustainable Energy Reviews 42 (2015) 883–901	Emerging perspectives on environmental burden minimisation initiatives from anaerobic digestion technologies for community scale biomass valorisation	UK, India	Yes	Yes	various AD		
Yusuf, 2012	Rafiu O. Yusuf, Zainura Z. Noor, Ahmad H. Abba, Mohd Ariffin Abu Hassan, Mohd Fadhil Mohd Din	Renewable and Sustainable Energy Reviews Volume 16, Issue 7, September 2012, Pages 5059–5070	Methane emission by sectors: A comprehensive review of emission sources and mitigation methods	Malaysia ?	Yes	Yes			
Yoshida, 2014	Hiroko Yoshida, , Jacob Mønster, Charlotte Scheutz	Water Research Volume 61, 15 September 2014, Pages 108–118	Plant-integrated measurement of greenhouse gas emissions from a municipal wastewater treatment plant	Denmark	Yes	Yes	WWTP	Sewage	mobile cavity ring-down spectroscopy (CRDS) and Tracer dilution
Boldrin, 2011	Alessio Boldrin, Trine Lund Neidel, Anders Damgaard, Gurbakhash S. Bhander, Jacob Møller, Thomas H. Christensen	Waste Management Volume 31, Issue 4, April 2011, Pages 619–630	Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE	Denmark	Yes	Yes	Bio-treatment of MSW	Various	Modelling

Hrad, 2015	Marlies Hrad, Martin Piringer, Marion Huber-Humer	Bioresource Technology Volume 191, September 2015, Pages 234–243	Determining methane emissions from biogas plants – Operational and meteorological aspects	Austria	yes	Yes	AD, co-digestion	agricultural	Open-path tunable diode laser; Inverse dispersion modeling;
Bacenetti, 2016	Jacopo Bacenetti, Cesare Sala, Alessandra Fusi, Marco Fiala	Applied Energy Volume 179, 1 October 2016, Pages 669–686	Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable	Europe	yes	yes	various	various	LCA review
Ahlberg-Eliasson, 2017	Karin Ahlberg-Eliasson, Elisabet Nadeau, Lotta Levén, , Anna Schnürer	Biomass and Bioenergy Volume 97, February 2017, Pages 27–37	Production efficiency of Swedish farm-scale biogas plants	Sweden	yes	yes	farm AD	manure	Simulation
Muha, 2015	Ivo Muhaa, Bernd Linkeb, Gabriel Wittum	Bioresource Technology Volume 178, February 2015, Pages 350–358	A dynamic model for calculating methane emissions from digestate based on co-digestion of animal manure and biogas crops in full scale German biogas plants	Germany	yes	yes	farm AD	manure and biogas crops	model for emissions from Digestate

Groth, 2015	Angela Groth, Claudia Maurer, Martin Reiser, Martin Kranert	Bioresource Technology 178 (2015) 359–361	Determination of methane emission rates on a biogas plant using data from laser absorption spectrometry	Germany	yes	yes	AD		open path remote sensing TDLAS measurement methodology, tracer gas, meteorological measurements and an backward Lagrangian stochastic (bLs) method
Flesch, 2011	Thomas K. Flesch, Raymond L. Desjardins, Devon Worth	Biomass and Bioenergy Volume 35, Issue 9, October 2011, Pages 3927–3935	Fugitive methane emissions from an agricultural biodigester	Canada	yes	yes	Farm AD	manure, effluent, offal	open path laser and reverse modelling
McBain, 2005	M.C. McBain, R.L. Desjardins	Agricultural and Forest Meteorology Volume 135, Issues 1–4, 14 December 2005, Pages 61–72	The evaluation of a backward Lagrangian stochastic (bLS) model to estimate greenhouse gas emissions from agricultural sources using a synthetic tracer source	Canada	No	yes	Methane tracer	N/A	open path TDL and reverse modelling

Adams, 2015	P.W.R.Adams, W.G.Mezzullo,M.C. McManus	Energy Policy87(2015)95–109	Biomass sustainability criteria: Greenhouse gas accounting issues for biogas and biomethane facilities	Europe	Yes	Yes	AD, biogas	Cattle manure/ slurry	Biomass sustainability
CAPP, 2014	Canadian Association of Petroleum Producers	Report by Clearstone Engineering Ltd for CAPP, report 2014-0023	Update of Fugitive Equipment Leak Emission Factors	Canada	No	no	oil and gas		literature review
USEPA, M21	US Environmental Protection agency	Code of Federal Regulations	Method 21 - Determination of Volatile Organic Compound Leaks	US	No	No	oil and gas		Leak qualification
Jonerholm, 2012	Katarina Jonerholm, Hans Lundborg	Report for the BalticBiogasBus project.	Methane losses in the biogas system	Baltic region	yes	Yes	AD, biogas	various	review
Sandsten, 2004	Jonas Sandsten, Hans Edner and Sune Svanberg	Optics Express Vol. 12, No. 7, April 2004	Gas visualization of industrial hydrocarbon emissions	Sweden	No	No	PE plant		GFC-IR
USEPA, 2011a	Eastern Research Group, Inc for US EPA AgSTAR Program		Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures	US	Yes	Yes	farm AD	Manure	Calculation

Clemens, 2012	Orbit 2012 ?	?	Leakage control of biogas plants	Germany	Yes	Yes	AD, biogas		IR Camera + sensors
FLIR	FLIR	Manufacturer literature	Thermal imaging cameras for optical gas imaging (OGI) and furnace inspections	Europe	No	Yes	Various		IR Camera
USEPA, 2014	Eben Thoma, Halley Brantley, John Albertson	CH4 Connections: September 23-24, 2014 , The Woodlands, TX	Fugitive methane assessment with mobile and fence line sensors	US	No	Yes	Oil and gas		open path, mobile
EA, 2012	Mark Broomfield, Brian Donovan	Published by: Environment Agency, Horizon House, Deanery Road, Bristol, BS1 5AH, www.environment-agency.gov.uk ISBN: 978-1-84911-278-9 © Environment Agency – August 2012	Monitoring and control of fugitive methane from unconventional gas operations	UK	No	Yes	Unconventional oil and gas		review

EA, 2014	Grant Allen, Martin Gallagher, Peter Hollingsworth, Samuel Illingworth, Khristopher Kabbabe, Carl Percival	Published by: Environment Agency, Horizon House, Deanery Road, Bristol, BS1 5AH www.environment-agency.gov.uk ISBN: 978-1-84911-329-8 © Environment Agency – July 2014	Feasibility of aerial measurements of methane emissions from landfills	UK	No	Yes	Landfill		Feasibility of using aerial unmanned vehicle to survey methane from landfill.
Concawe, 2008	M-F Bénassy, K. Bilinska, G. De Caluwé, L. Ekstrom, F. Leotoing, I. Mares, P. Roberts, B. Smithers, L. White	Concawe report 6/08, Concawe, Brussels, 2008	Optical methods for remote measurement of diffuse VOCs: their role in the quantification of annual refinery emissions	Europe	No	No	Oil and gas		Review of LDAR, remote and other techniques
USEPA, 2005a	Mark Modrak, Ram A. Hashmonay, Ravi Varma, Robert Kagann	USEPA Report EPA-600/R-05/088 August 2005 prepared by ARCADIS G&M Inc	Measurement of Fugitive Emissions at a Landfill Practicing Leachate Recirculation and Air Injection	US	No	Yes	Landfill		Open path FTIR, horizontal & vertical plume mapping

USEPA, 2005b	Mark Modrak, Ram A. Hashmonay, Ravi Varma, Robert Kagann	USEPA Report EPA-600/R-05/042 April 2005 prepared by ARCADIS G&M Inc	Evaluation of a Former Landfill Site in Fort Collins, Colorado Using Ground-Based Optical Remote Sensing Technology	US	No	Yes	Landfill		Open path FTIR, open path tunable diode laser, horizontal & vertical plume mapping
USEPA, 2005c	Mark Modrak, Ram A. Hashmonay, Ravi Varma, Robert Kagann	USEPA Report EPA-600/R-05/041 April 2005 prepared by ARCADIS G&M Inc	Evaluation of Fugitive Emissions at a Former Landfill Site in Colorado Springs, Colorado Using Ground-Based Optical Remote Sensing Technology	US	No	Yes	Landfill		Open path FTIR, open path tunable diode laser, UV DOAS, horizontal & vertical plume mapping
USEPA, 2005d	Thomas Robertson, Josh Dunbar	USEPA Report EPA-600/R-05/123a Sept 2005 prepared by Environmental Quality Management Inc	GUIDANCE FOR EVALUATING LANDFILL GAS EMISSIONS FROM CLOSED OR ABANDONED FACILITIES	US	No	Yes	Landfill		
USEPA, 2007		USEPA Report EPA-600/R-07/032 February 2007 prepared by Arcadis G&M Inc	Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology	US	No	Yes	Landfill		Various - review of methodology and sensor types

USEPA, 2013		USEPA OTM-32	Determination of Emissions from Open Sources by Plume Profiling	US	No	No	Various		Plume profiling
NPL, 1998	R A Robinson, A S Andrews, T D Gardiner, I J Uprichard, P T Woods	NPL Report COEM 13	Differential Absorption Lidar Measurements of VOC Emissions from Wytch Farm Crude Oil Gathering Station	UK	No	No	Oil and gas		DIAL
Babilotte, 2011	Antoine BABILOTTE	Report for EREF by Veolia Environment Research centre.	FIELD COMPARISON OF METHODS FOR ASSESSMENT OF METHANE FUGITIVE EMISSIONS FROM LANDFILLS	US	No	Yes	Landfill		Flux chambers, vertical plume mapping, tracer gas and DIAL

Roscioli, 2015	J. R. Roscioli, T. I. Yacovitch, C. Floerchinger, A. L. Mitchell, D. S. Tkacik, R. Subramanian, D. M. Martinez, T. L. Vaughn, L. Williams, D. Zimmerle, A. L. Robinson, S. C. Herndon, and A. J. Marchese	Atmos. Meas. Tech., 8, 2017–2035, 2015 www.atmos-meas-tech.net/8/2017/2015/	Measurements of methane emissions from natural gas gathering facilities and processing plants: measurement methods	US	No	Yes	Oil and gas		Dual tracer gas, direct-absorption quantum cascade laser spectrometers
Wong, 2013	Colin L. Y. Wong, Jeffrey Ramkellawan	Journal of the Air & Waste Management Association, 63(11):1324–1334, 2013.	Calibration of a fugitive emission rate measurement of an area source	US	No	Yes	Landfill		Aerial survey with TDL
Chambers, 2008	Allan K. Chambers , Melvin Strosher , Tony Wootton , Jan Moncrieff & Philip McCready	Journal of the Air & Waste Management Association, 2008, 58:8, 1047-1056	Direct Measurement of Fugitive Emissions of Hydrocarbons from a Refinery	Canada	No	Yes	Oil and gas		DIAL

Mellqvist, 1996	Johan Mellqvist, Bill Arlander, Bo Galle, Bjorn Bergqvist	IVL Swedish Environmental research Institute report for Akzo Nobel Surface Chemistry AB	Measurement of Industrial Fugitive Emissions bythe FTIR tracer method (FTM)	Sweden	No	No	Petrochemi cal		FTIR long path
CCME, 1993		Canadian council of Ministers of the Environmental secretariat, CCME, report CCME-EPC-73E, Oct 1993	Environmental COP for the measurement and control of fugitive VOC emissions from equipment leaks	Canada	No	No	Various		Emission factors
Macey, 2014	Gregg P Macey, Ruth Breech, Mark Chernaik, Caroline Cox, Denny Larson, Deb Thomas and David O Carpenter	Environmental Health 2014, 13:82	Air concentrations of volatile compounds near oil and gas production: a community-based exploratory study	US	No	No	Oil and gas		passive, bag samples

Haider, 2014	Sibu Thomas, Nishi Shahnaj Haider	Int. Journal of Engineering Research and Applications, ISSN : 2248-9622, Vol. 4, Issue 5(Version 4), May 2014, pp.137-143	Instruments for Methane Gas Detection	India ?	No	Yes	various		Various
Holmgren, 2015	Magnus Andreas Holmgren, Martin Nørregaard Hansen, Torsten Reinelt and Tanja Westerkamp, Lars Jørgensen, Charlotte Scheutz and Antonio Delre	ISBN 978-91-7673-158-1, Energiforsk AB	Measurements of methane emissions from biogas production Data collection and comparison of measurement methods	Europe	Yes	Yes	AD plant	Food waste, ABPR, Food industry residues	Open path and on-site point source methods compared plus reverse dispersion modelling
EIPPCB, 2013	Ralf Both, Bianca-Maria Scalet	European IPPC Bureau, Monitoring BREF	JRC Reference Report on Monitoring of emissions from IED-installations (Final Draft)	Europe	No	No	Various		Review

USEPA, 2011b	Dennis K. Mikel et al	U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Air Quality Analysis Division, Measurement Technology Group, Research Triangle, North Carolina, 27711	EPA Handbook: Optical Remote Sensing for Measurement and Monitoring of Emissions Flux	US	No	No	Various		Handbook/review
IPCC, 2012	UNFCCC CDM board	UNFCCC CDM board	Methodological Tool - “Project and leakage emissions from anaerobic digesters” (Version 01.0.0)	World	Yes	Yes	AD		Leakage methodology

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