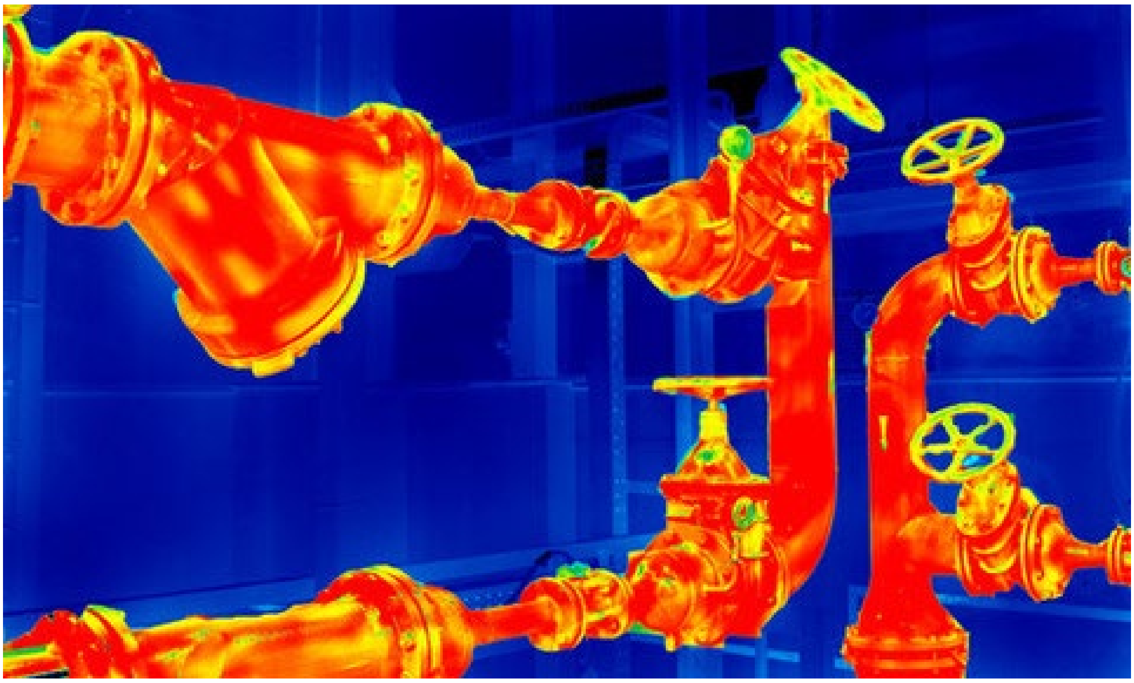
FUGITIVE EMISSION STRATEGY 2022

REGULATED INDUSTRY



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Executive Summary

This strategy sets out recommendations to reduce fugitive emissions to air of methane and Non-Methane Volatile Organic Compounds (NMVOCs) across Environment Agency regulated industrial facilities. The benefits gained from the recommendations made in this strategy will contribute towards meeting targets set by the Global Methane Pledge and Clean Air Strategy[1] of reductions of methane and NMVOCs by 30 % and 39 % by 2030.

Methane is a compound with a significant global warming potential, 1 tonne of methane is equal to the same impact as 27 - 30 tonnes of Carbon Dioxide (CO2) over 100 years[2] depending on if the methane is of fossil or non-fossil origin. However, methane has a much shorter atmospheric lifetime than CO_2 at 12 years and that means any action taken now to reduce methane in the atmosphere will have a quick and significant effect on keeping global temperatures below 2° C as agreed in the 2015 Paris Agreement. A United Nations Environment Programme (UNEP) study has identified that cutting methane by 45 % this decade would avoid 0.3°C of global warming by the 2040s[3] .

Additionally, methane plays a significant role in the creation of tropospheric photochemical ozone (O_3), a secondary pollutant that acts as a short-term climate forcer, and moreover significantly impacts the human respiratory system and increases the mortality of plants. NMVOCs are a group of compounds (excluding methane) controlled by the National Emissions Reduction Commitments Directive (EU 2016/2284) for their deleterious effect on human health but also as an important precursor pollutant to the production of tropospheric Ozone (O_3) mentioned above. Therefore, it is an Environment Agency priority to ensure the continued reduction of fugitive emissions of NMVOCs and methane from EA regulated facilities.

The chemical sector and crude oil refineries are key contributors of NMVOCs with 11.9 Kt and 8.6 Kt (as of 2019), the latter of which are known fugitive NMVOC contributions. Regulated anaerobic digestion is the regulated activity associated with the highest methane loss totalling 39.8 Kt including wastewater treatment (19 Kt), “other anaerobic digestion” (8.5 Kt) and food waste associated anaerobic digestion (12.3 Kt). With the addition of methane contributions from unregulated facilities, this total methane loss figure could be much higher. However, fugitive emissions as defined by BS: EN 15446 may compose a small percentage of this overall methane loss and therefore caution should be taken on how these figures are understood. Regulated gas activities are associated with small fugitive emission contributions and more data is needed to understand the role of gas terminals in fugitive emissions.

LDAR is an effective tool to help reach national and global commitments in the reduction of methane and NMVOCs. Quarterly LDAR surveys can reduce fugitive

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[1] Defra (2019). Clean Air Strategy 2019. The Clean Air Strategy.
[2] IPCC (2021). Sixth Assessment Report. [online] www.ipcc.ch. Available at: https://www.ipcc.ch/report/ar6/wg1/.
[3] UNEP. (2021). New global methane pledge aims to tackle climate change. [online] Available at: https://www.unep.org/news-and-stories/story/new-global-methane-pledge-aims-tackle-climate-change.

emissions by 80 % in smaller facilities and OGI may conduct LDAR surveys 24 times faster than sniffing. 92 % of emissions originate from less than 1 % of components in large facilities therefore a targeted approach is needed to find the "super emitters". The use of OGI and sniffing in combination is effective in larger facilities and may allow for more frequent and targeted LDAR surveys. Some refineries are not meeting BAT regarding LDAR and basic estimation techniques are being used for the estimation of fugitive emissions in the absence of detailed facility component information. Large Volume Organic Chemical (LVOC) facilities are undertaking LDAR, further detail than this was not available to input into this strategy. Chemical facilities that do not fit the LVOC bracket are known to be not undertaking LDAR, although smaller facilities, these facilities could be contributing significant emissions of fugitive NMVOCs. Wastewater treatment is historically associated with aged components and poor LDAR programmes of associated AD facilities however this is changing with the EA review of 120 sites and implementation of LDAR once a year.

A recommended approach to the general application of LDAR is advised with a risk-based approach to be piloted in larger facilities such as refineries and LVOC facilities. The application of annual LDAR whole-site surveys has been recommended for smaller chemical facilities and if this is not feasible, then the risk-based approach recommended in this strategy is to be applied. The use of advanced estimation techniques will have a dual positive effect on regulated industry. Their use will make the fugitive picture clearer by providing accurate data that can be inputted into the NAEI but also necessitating the identification of all pressurised components within a facility and rigorous monitoring. The internal use of OGI as part of an EA task-force to perform "spot checks" has been recommended which gives the EA the opportunity to make immediate headway on reducing fugitive methane and NMVOCs. The strategy also includes other less impacting recommendations and areas where further study can increase EA knowledge.

Defining fugitive emissions

The term "Fugitive Emissions" is defined differently by different sources and fugitive emissions are often wrongly referred to under the term "diffuse emissions". Although both share similarities, there are important differences, these are shown in the box below:

Table 1: Emission definitions

Emission type	Definition	Examples
Diffuse Emissions	Defined by BS EN:17628[4] as: Emissions to atmosphere from an identified site or facility, not specifically directed to identified stack emission points	Typical sources include: exposed-to-air area sources such as landfill heaps, storage ponds and open tanks.
Fugitive Emissions	Defined by BS EN:15446[5] as: Emission to the atmosphere caused by loss of tightness of an item which is designed to be tight.	Malfunctioning pressurised equipment components associated with closed-to-air processes.

Within this strategy where an industrial activity has the potential to generate fugitive emissions as defined by BS:EN 15446, it has been explored within this document.

Out of Scope

Table 2: Activities omitted from scope of strategy

Topics	**Reason for being excluded from scope**
Flaring and venting	Does not fit the strategy definition for fugitive emissions.
Solvents	Largely diffuse in nature.
Agriculture	Not EA regulated.
Landfill	Diffuse in nature.
Composting	Diffuse in nature.
Mechanical biological treatment of waste	Only biological treatment through anaerobic digestion considered within this process.
Open emission sources such as storage ponds or lagoons	Diffuse in nature.
Offshore processes	Not EA regulated.
National Transmission System and low and medium distribution pipeline	Not EA regulated.
Coal Activities	Not EA regulated.

[4] British Standards (2021). BS EN: 17628 - Fugitive and diffuse emissions of common concern to industry sectors - Standard method to determine diffuse emissions of volatile organic compounds into the atmosphere. British Standards, pp.1–33.

[5] British Standards (2008). 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. British Standards, pp.5–22.

Onshore oil loading	Diffuse in nature. Controlled by vapour recovery units.
Refinery Drainage	Mainly diffuse in nature if from open drains.

1. Legislation and other commitments

1.1. Commitments specific to Non-Methane Volatile Organic Compounds (NMVOCs)

1.1.1. United Nations Geneva Convention on Long Range Transboundary Air Pollution (CLRTAP)[6]

The Convention was adopted on 13th November 1979 by a high-level meeting within the framework of the Economic Commission for Europe on the Protection of the Environment and now includes the involvement of 51 parties. Parties are to develop policies and strategies that endeavour to limit as far as possible, reduce and prevent air pollution including long-range transboundary pollution. This is undertaken through the use of exchanges of information, consultation, research and monitoring.

1.1.2. Gothenburg Protocol

The 1999 Gothenburg Protocol (Multi-pollutant protocol) is an extension to the CLRTRAP and sets emission ceiling targets for the 51 parties associated with the CLRTRAP for sulphur dioxide (SO_2), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and ammonia (NH_3) to be achieved 2020 (present revision) to reduce acidification, eutrophication and ground-level ozone. Annex 6 of the Protocol for volatile organic compounds (VOCs) is the relevant provision to this strategy.

1.1.3. National Emission Reduction Commitments Directive (2016/2284/EU) (NEC Directive)[7]

Introduced in 2016, this directive transposes the reduction commitments for 2020 agreed by the EU and its Member States under the 2012 revised Gothenburg Protocol. The Directive sets ambitious reduction commitments for the five main air pollutants of NO_x, NMVOCs, SO_2, NH_3 and $PM_{2.5}$ as well as CO (carbon monoxide) to be achieved by 2030 from a 2005 baseline and in addition to this, the Directive requires that Member States draw up National Air Pollution Control Programmes. The Directive sets a reduction target of 39 % for NMVOCs for the UK to be achieved by 2030 from a 2005 baseline.

1.1.4. The Clean Air Strategy 2019

The Clean Air Strategy reiterates reduction targets for the “five pollutants of concern” set by the NEC Directive: NO_x, NMVOCs, SO_2, NH_3 and $PM_{2.5}$ by 2030 from their respective 2005 values. The strategy aims to cut overall NMVOC emissions by 39 % by 2030 and looks at emission contributions from road transport, maritime, rail, aviation, freight, Non-Road Mobile machinery (NRMM), domestic use (including burning), agriculture and industry.

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[6] treaties.un.org. (n.d.). United Nations Treaty Collection. [online] Available at: https://treaties.un.org/Pages/ViewDetails.aspx?src=IND&mtdsg_no=XXVII-1&chapter=27&clang=_en.

[7] European Environment Agency (2016). National Emission Ceilings Directive (2016/2284/EU) — European Environment Agency. [online] www.eea.europa.eu. Available at: https://www.eea.europa.eu/themes/air/air-pollution-sources-1/national-emission-ceilings.

1.2. Commitments Specific to Methane

1.2.1. Climate Change Act 2008[8]

Introduced in 2008, the act sets out to reduce the UK impact on climate change from commercial business, domestic waste and the industrial sector and also provides provisions on renewable transport fuel obligations and carbon emissions reduction targets. As part of this, the Act sets reduction targets on six greenhouse gases (GHGs) including methane, the act stipulates emissions of methane must be included within an annual GHG inventory and commits the UK government by law to reducing methane and other GHG emissions by 100 % from 1990 levels by 2050 achieving a net zero status.

1.2.2. Methane Pledge November 2021[9]

Following the annual United Nations Climate Change Conference of the parties (COP26) in November 2021, the joint "Methane Pledge" agreement was reached between the European Union and the United States which aims to cut global methane emissions by 30 percent by 2030 from the 2021 baseline in order to keep global temperature rise below 2°C as agreed by the Paris Agreement in 2015. UNEP has discovered that in achieving a global cut of methane emissions by 45 % by 2030, this would avoid a global increase in temperatures by 0.3°C by the 2040 and each year prevent 255,000 premature deaths, 775,000 asthma related hospital visits, 73 billion hours of lost labour from extreme heat and 26 million tonnes of crop losses globally[10], by reducing the formation of the secondary pollutant, ozone.

1.3. Legislation specific to Fugitive Emissions

1.3.1. Industrial Emissions Directive (2010/75/EU)[11]

The Industrial Emissions Directive (IED), applied through the Environmental Permitting (England and Wales) Regulations, 2016, as amended, is the main EU legislative instrument for regulating pollutant emissions from industrial installations. It combines an integrated approach to controlling emissions from all media for Annex 1 activities (most polluting activities). IED measures are enforced through permit conditions, the measures include emission abatement measures and technologies to keep emissions from a facility at a minimum. Abatement measures are based on the Best Available Techniques (BAT) (listed within the Directive). "Best" being the most effective, "Available" where access to most recent technology allows and "Technique" includes both the technology used and the way the installation is designed, built and maintained. For certain activities, the IED sets emission limit

[8] UK Government (2019). Climate Change Act 2008. [online] Legislation.gov.uk. Available at: https://www.legislation.gov.uk/ukpga/2008/27/contents

[9] www.globalmethanepledge.org. (n.d.). Homepage | Global Methane Pledge. [online] Available at: https://www.globalmethanepledge.org/.

[10] UNEP (2022). New global methane pledge aims to tackle climate change. [online] UNEP - Climate Action. Available at: https://www.unep.org/news-and-stories/story/new-global-methane-pledge-aims-tackle-climate-change [Accessed 7 Mar. 2022].

[11] European Commission (2010). The Industrial Emissions Directive - Environment - European Commission. [online] Europa.eu. Available at: https://ec.europa.eu/environment/industry/stationary/ied/legislation.htm.

values for selected pollutants. The industrial installations that adhere to the standards set within the IED are listed in Annex I of the IED[12].

A Commission organised exchange of information exists between Member States, representatives from industry and environmental organisations to define BAT and the BAT-associated environmental performance at EU level. The results of this are the BREF (BAT Reference Documents) specific to each regulated industry which include the “BAT conclusions”, these prescribe the appropriate BAT measures specific to the industrial activity. It is within these BAT conclusions where the IED specifically regulates fugitive emissions from industry.

BAT conclusions for the Refining of Mineral Oil and Gas[13] prescribe the following measures to be used in relation to the regulation of fugitive emissions of NMVOCs and methane:

- BAT 6 – To monitor diffuse VOC emissions to air from the entire site by using the following techniques: a combination of sniffing and OGI supported by calculations of chronic emissions based on emission factors are obligatory. DIAL and SOF are recommended.
- BAT 18 – In order to prevent or reduce diffuse VOC emissions, BAT is to apply techniques in relation to plant design, plant installation and plant operation.

The BAT conclusions for Waste Treatment[14] prescribes the following measure in relation to the control of fugitive emissions of methane and NMVOCs:

- BAT 14 – In order to prevent or, where that is not practicable, to reduce diffuse emissions to air, in particular of dust, organic compounds and odour Section 6.2. continues in more detail regarding LDAR on the use of sniffing and OGI.

The BREF document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector[15] prescribes the following BAT measures (that also apply to Large Volume Organic Compounds) regarding fugitive emissions:

- BAT 5 – Periodically monitor diffuse VOC emissions to air from relevant sources by using an appropriate combination of or all of: sniffing, OGI and emissions calculations based on emissions factors, periodically validated (e.g. once every 2 years) by measurements; and

[12] Europa.eu. (2010). The Industrial Emissions Directive - Environment - European Commission. [online] Available at: https://ec.europa.eu/environment/industry/stationary/ied/legislation.htm.
[13] EEA (2014). BAT conclusions for the refining of mineral oil and gas. Best Available Techniques, p.307/49.
[14] EEA (2018). Best Available Techniques conclusions for waste treatment. Best Available Techniques, p.30.
[15] European Commission (2016). Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment Management Systems in the Chemical Sector.

- BAT 19 – In order to prevent or where that is not practicable, to reduce diffuse VOC emissions to air, BAT is to use a combination of techniques related to plant design, plant techniques and techniques related to plant operation.

1.3.2. EPR Regulations 2016[16]

A "Regulated Facility" is a collective term used to describe an industrial facility that requires a permit as defined by the Environmental Permitting (England and Wales) Regulations 2016, as amended. Part A1 of Part 2 of Schedule 1 to the Regulations lists activities which are Environment Agency regulated and specified in Annex 1 ofthe overarching Industrial Emissions Directive, these are listed within Appendix A.

Permit conditions relating to the control of fugitive emissions are proposed within the permit pre-operational phase. Existing conditions for a development can be revised once an installation is operational and these improvement conditions can be set by the regulator to improve practices. Improvement conditions are a useful tool to improve upon a facility's existing measures to reduce fugitive emissions.

1.4. Guidance and Standards

Table 3: National and international standards and guidance on fugitive emissions

Standard	Description
BS: EN 15446	Applies to the measurement of fugitive emissions of volatile organic compounds (VOCs) from process equipment through use of OGI and sniffing.
EPA Leak Detection and Repair A Best practice Guidance	An in-depth guide to the undertaking of Leak Detection and Repair.
Energy Institute - Protocol for the Estimation of Petroleum Refinery Process Plant Fugitive VOC Emissions 2010	Includes guidance on the undertaking of a Leak Detection and Repair survey for refineries and estimating VOC emissions from refineries.
NTA 8399:2015 en	Air Quality – guidelines for detection of diffuse emissions with optical gas imaging.
ISO 15848-1:2015	Measurement, test and qualification of Industrial Valves (Part 1).
ISO 15848-2:2015	Measurement, test and qualification of Industrial Valves (Part 2).
API 2000:2014	American standard on the venting from low-pressure storage.
ISO:28300:2008	Venting of atmospheric and low-pressure storage tanks. Does not apply to external floating-roof tanks.
EPA: Protocol for Equipment Leak Emission Estimates (1995)	Includes methodologies for estimating emissions, emission factors and instruction on conducting an

[16] Gov.uk, 2022. The Environmental Permitting (England and Wales) Regulations 2016. [online] Legislation.gov.uk. Available at: <https://www.legislation.gov.uk/uksi/2016/1154/contents/made> [Accessed 29 March 2022].

	LDAR survey through the use of the sniffing technique.
Landfill Gas: Industry Code of Practice – The management of Landfill Gas	This document provides guidance on all stages of the landfill gas management process.
Method 21 – Determination of Volatile Organic Compound Leaks	EPA produced instruction on the use of equipment associated with the “sniffing” monitoring method.

2. What are Fugitive Emissions and where do they arise?

Fugitive emissions, as defined by this strategy, originate from closed processes through pressurised equipment components and have the potential to emit polluting compounds to air such as methane and NMVOCs. Fugitive emissions escape through a point of seal within the component that has failed, therefore these releases are unintentional which can be challenging to control and regulate. Actual emission data for fugitive emissions is therefore not readily available and the knowledge of fugitive emission contributions largely rely on estimations, based on emission factors, often for equipment in a good state of repair. Equipment components include but are not limited to: valves, flanges, connectors, sampling connections, pump, agitator and compressor seals, pressure relief devices and open-ended lines. Within an industrial facility such as a refinery they typically number in the tens of thousands therefore leak detection can prove difficult occasionally resulting in significant leaks of pollutants to the atmosphere. It has been found that 91.9 % of a facility's emissions released through leaks will occur from 0.2 – 0.4 % of the facility's components[17] which makes the identification of all pressurised components and the detection of leaks a crucial exercise.

All equipment components are expected to leak and typically annual fugitive emissions from a facility are estimated from monitoring and the application of individual equipment component emission factors. These factors have been calculated by the EPA from historical leak data and are based on the premise that all equipment components will leak small amounts of emissions annually, however as most leaks originate from a small amount of components, this indicates that some components will leak significantly more than emission factors predict. Therefore, a rigorous LDAR programme is essential in locating these "super emitters". Aside from the design of the facility and the installation of high-integrity equipment components and associated equipment, the primary method in reducing leaks within a facility once operational is a Leak Detection and Repair Programme (LDAR). The deterioration of equipment components or associated equipment results in leaking equipment components and deterioration occurs for a combination of or all of the following reasons:

- environmental conditions;
- poor maintenance; and
- lower quality (lower control efficiencies) equipment components.

The inherently difficult-to-find nature of fugitive emissions combined with the fact that fugitives are an issue across all industry sectors further compounds their environmental impact. Fugitive emissions from onshore oil and gas activities related to production and refining are better understood compared to other activities and according to NAEI data, in 2019 fugitive emissions from these facilities were

[17] Ke, J., Li, S. and Zhao, D. (2020). The application of leak detection and repair program in VOCs control in China's petroleum refineries. Journal of the Air & Waste Management Association, 70(9), pp.862–875.

equivalent to 0.74 % and 4.7 % of total emissions of methane and NMVOCs from all regulated industry.

In comparison, fugitive emission data from waste treatment activities are limited, currently research papers provide the best estimate for fugitive emission losses from waste sector processes. Waste facilities produced 79 % of total methane emissions from all EA regulated facilities in 2019 equivalent to 677 Kt and 84 %[18] of these emissions originated from landfill. The majority of emissions from waste treatment processes such as landfill and composting are diffuse in nature and as such are not relevant to this strategy. Landfill emissions in particular are a well understood area and as such continuous improvements to the emission control practice are reducing emissions consistently year on year. However, the growing practice of anaerobic digestion (AD) has been estimated to have high methane loss and both regulated and unregulated facilities could account for 3.8 % of total UK methane emissions[19] equivalent to 73.3 Kt in 2019. The regulation of this activity in regards to the control of fugitives is a continuously evolving process and as such there is potential to improve practices here. The chemical sector was responsible for 12.5 % of total UK NMVOC emissions in 2019[20] from all regulated industry. The production of chemicals often involves large facilities associated numerous potential leak sources and potential fugitives of NMVOCs from this sector could be significant, therefore this area requires greater understanding in regards to fugitive emissions.

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[18] Department for Environment, F. and R.A. (Defra) webmaster@defra gsi gov uk (n.d.). UK emissions data selector - Defra, UK. [online] naei.beis.gov.uk. Available at: https://naei.beis.gov.uk/data/data-selector?view=air-pollutants.

[19] Bakkaloglu, S., Lowry, D., Fisher, R.E., France, J.L., Brunner, D., Chen, H. and Nisbet, E.G. (2021). Quantification of methane emissions from UK biogas plants. Waste Management, 124, pp.82–93.

3. Study Species

Fugitive emissions are controlled due to the polluting gas compounds they contain and the impact these gases have on the environment and human health. The compounds that fugitive emissions contain vary depending on the industrial activity producing them. This strategy will focus on two species: NMVOCs and methane.

3.1. NMVOCs

NMVOCs are a group of pollutants that include a list of over 600 different compounds. The list of compounds is identical to the list defined under VOCs (Volatile Organic Compounds) with one important difference, the former definition excludes methane. The pollutants within this group vary widely in terms of chemical composition but are grouped together because they behave in a similar way in the atmosphere, they are released into the atmosphere from solvent use and industrial sources.

Typical NMVOCs associated with fossil fuels include compounds within the hydrocarbon groups: alkanes, alkenes and the aromatics. Typical NMVOCs associated with solvents are: butane, ethanol, methanol, toluene, aldehydes and acetone but include many more. In general terms, alkenes, aromatics and aldehydes have higher Photochemical Ozone Creation Potential (POCP) per molecule than alkanes, alkynes, alcohols or chlorinated compounds[21]. Certain VOCs are classified as being carcinogenic, mutagenic or toxic for reproduction (CMR 1A, 1B or 2) as defined under Commission Regulation (EC) No. 790/2009. Emissions of NMVOCs in the UK are controlled under the EU Emissions Reduction Directive as air pollutants due to their deleterious effects on human health and the environment but also their role as important precursors in the creation of tropospheric Ozone (O_3) from sunlight-initiated oxidation in the presence of Nitric Oxide (NO), this formation is particularly prevalent in the presence of aldehydes. Tropospheric ozone (O_3) is a secondary compound and acts as a short-lived greenhouse gas which can adversely affect the human respiratory, cardiovascular and central nervous systems and has been found to impact overall mortality rates. Ground level ozone also damages plants by entering into leaves through stomata and oxidising plant tissue through respiration, this effect reduces survival in plants.

Individual NMVOCs have a different reactivity in the atmosphere and therefore a different propensity to forming ozone and organic aerosols. In general terms: alkenes, aromatic hydrocarbons and aldehydes have higher Photochemical Ozone Creation Potential (POCP) per molecule than alkanes, alkynes, alcohols or chlorinated compounds[22]. The direct impact on human health and their role as an

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[21] AIR QUALITY EXPERT GROUP Non-methane Volatile Organic Compounds in the UK h Prepared for: Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of Agriculture, Environment and Rural Affairs in Northern Ireland. (n.d.). [online] Available at: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2006240803_Non_Methane_Volatile_Organic_Compounds_in_the_UK.pdf [Accessed 29 Apr. 2022].

[22] AIR QUALITY EXPERT GROUP Non-methane Volatile Organic Compounds in the UK h Prepared for: Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of Agriculture, Environment and Rural Affairs in Northern Ireland. (n.d.). [online]

important pre-cursor makes the control of NMVOCs crucial to regulating pollution within the atmosphere

3.2. Methane

Methane is a compound with a significant Global Warming Potential (GWP) due to its positive radiating forcing effect and is therefore controlled under the Climate Change Act 2008. Methane has a much shorter atmospheric lifetime than CO_2 at 12 years, however due to its positive radiating force, 1 tonne of methane has the same global warming impact as 27-29.8 tonnes of CO_2 over 100 years. Aside from indirect impacts upon human health as a result of climate change, methane is not typically considered a classical air pollutant in the sense that it does not directly impact the health of humans and ecological systems. However, it is an important precursor to ozone (O_3) when methane breaks down in the lower atmosphere in the presence of hydroxyl radicals (OH). This process forms methenium (CH_3) which is oxidised rapidly to yield O_3 in the presence of oxides of nitrogen (NO_x) and carbon monoxide (CO)[23]. Methane is responsible for the majority of the ozone formation in the troposphere in this way, ozone causes 1 million premature deaths per year therefore indirectly methane has a significant impact upon human health[24].

Available at: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/2006240803_Non_Methane_Volatile_Organic_Compounds_in_the_UK.pdf [Accessed 29 Apr. 2022].

[23] Isaksen, I., Berntsen, T., Dalsøren, S., Eleftheratos, K., Orsolini, Y., Rognerud, B., Stordal, F., Søvde, O., Zerefos, C. and Holmes, C. (2014). Atmospheric Ozone and Methane in a Changing Climate. Atmosphere, 5(3), pp.518–535. doi:10.3390/atmos5030518.

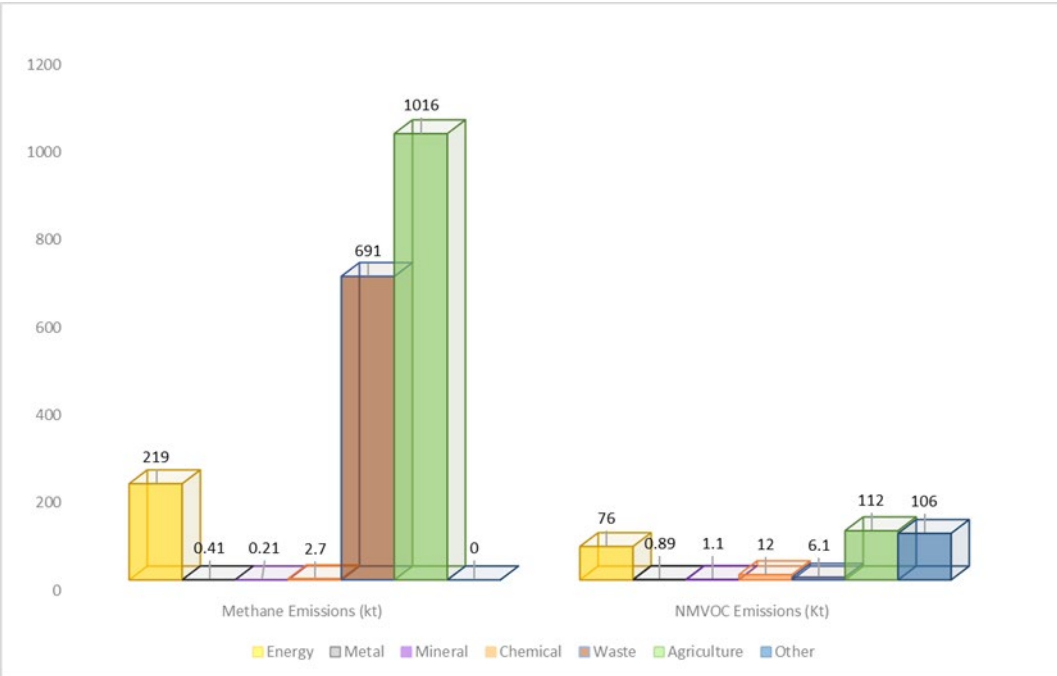
[24] McArthur, J.-A. (2021). Methane emissions are driving climate change. Here's how to reduce them. [online] UNEP. Available at: https://www.unep.org/news-and-stories/story/methane-emissions-are-driving-climate-change-heres-how-reduce-them.

4. Which sectors are significant contributors of NMVOC and methane emissions?

Emission data within this section has been gathered from publicly available NAEI data from the year 2019 (the most recent data year available). This section represents overall emission data for NMVOCs and methane for both regulated and unregulated facilities. NAEI data has large uncertainties attached to it because of the way the data is generated and therefore any emission data values should be viewed as an indication rather than the actual value.

Emissions of NMVOCs from EA regulated facilities have reduced by 37% from 2005 and emissions of methane from EA regulated facilities have reduced by 71 % from 1990. Industry types and their contributions of emissions of NMVOCs and methane are shown in the figure below, agriculture although not regulated has been included as a reference point.

Figure 1 Methane and NMVOC contributions by industry



* All data gathered from NAEI website

** Industry has been categorised according to industries defined by Annex I of the Directive

Agriculture was the main contributor of emissions of methane producing 1016 kt of methane in 2019, the majority of emissions in this industry originate from enteric sources. Excluding agriculture, 72 % of methane emissions in 2019 originated from waste management processes with 691kt of methane being produced annually. The Energy industry contributes the second largest amount of methane emissions with 28 % (269.6kt) followed by the chemical industry (2.7kt), the metal industry (0.41kt) and mineral industry (0.21kt).

The industry category of "other" dominates NMVOC emission contributions from regulated facilities producing 106 Kt annually which includes solvent activities. The energy industry is the second most important contributor of NMVOC emissions from regulated facilities with 76 Kt followed by the chemical industry with 12 Kt and the waste industry with 6.1 Kt.

5. Which regulated activities are significant contributors of methane and NMVOCs?

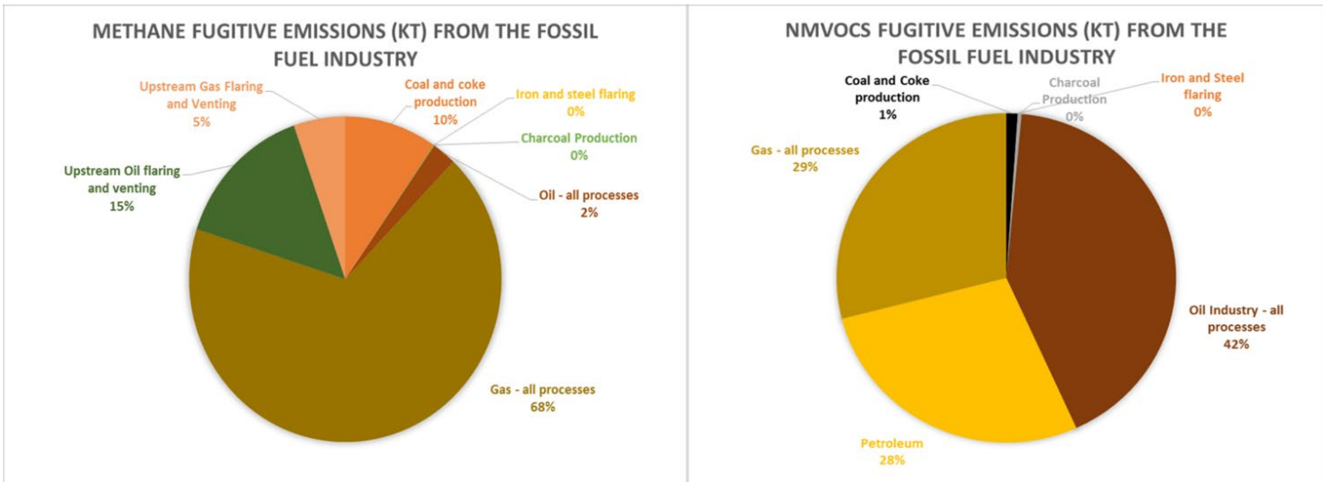
5.1. Fugitive emissions from the energy sector

Within the energy industry, in 2019 92 % (199 Kt) of methane was emitted as fugitive emissions from the fossil fuel (FF) industry. The remaining 8 % (16 Kt) of methane emissions originated from the result of combustion processes across industry.

24 Kt of NMVOCs were emitted from combustion processes and 75 Kt of NMVOCs were emitted from the fossil fuel industry as fugitive emissions.

The pie charts below represent a breakdown of fugitive methane and NMVOC emissions from the fossil fuel industry.

Figure 2: Showing Fugitive emissions of NMVOCs and methane from FF Industry



<u>Methane</u>

Onshore and offshore gas exploration, production and refining processes (including venting and flaring are responsible for the majority of fugitive methane emissions (147 Kt). Onshore and offshore crude oil processes are still responsible for significant amounts of methane fugitives (34.03 Kt) however the majority here originate from flaring and venting (29Kt). Coal and coke production produced 10 Kt of methane fugitives. Much smaller amounts are contributed by iron and steel flaring and charcoal production.

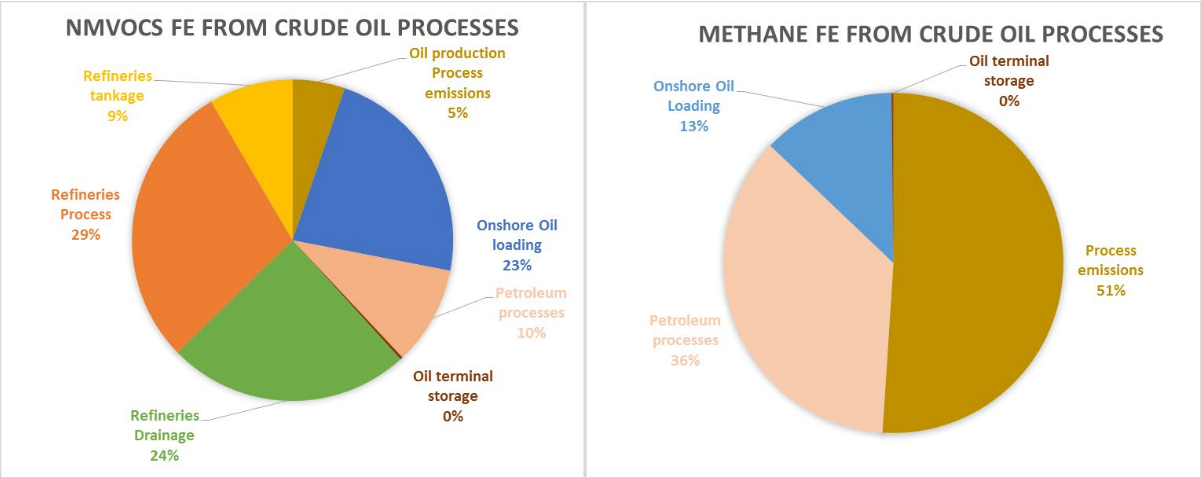
<u>NMVOCs</u>

In 2019, fugitive emissions of NMVOCs mainly originated from crude oil processes (29 Kt) followed by gas processes (21.5 Kt). The distribution and transportation of petrol produced significant fugitive NMVOC emissions (20 Kt) and coal and coke production processes produced under 1 Kt of fugitive NMVOC emissions.

5.1.1. Fugitive emissions from regulated crude oil and petroleum activities

Fugitive emissions from crude oil processes are dominated by emissions of NMVOCs with smaller contributions of methane, this is because in downstream facilities, most methane has been removed from oil at this stage of the process.

Figure 3: Showing fugitive emissions of NMVOCs and methane from crude oil processes



<u>NMVOCs</u>

In 2019 the majority of fugitive emissions of NMVOCs originated from refinery process emissions (8.6 Kt). Petroleum processes contributed 2.97 Kt followed by refinery tankage (2.52 Kt) and upstream oil production process emissions (1.57 Kt).

<u>Methane</u>

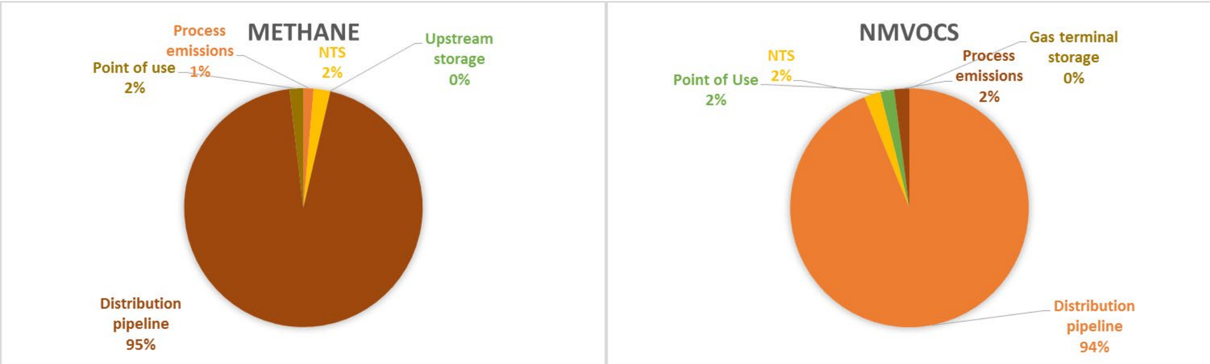
The majority of fugitive emissions of methane originated from process emissions (1.6 Kt) followed by petroleum processes (1.13 Kt), onshore oil loading (400 t) and oil terminal storage (50 t). Total VOC emissions from 23 onshore oil production sites totalled 0.5 tonnes in 2021.

It has been estimated that liquid hydrocarbon storage is responsible for 40 % of a refinery's total VOC emissions. Leaks from storage can largely be controlled by the prescription of equipment with better control efficiencies e.g. the installation of external floating-roof tanks with secondary seals and the addition of internal floating-roof tanks to fixed-roof storage tanks as prescribed by European Directive 94/63/EU[25].

[25] eippcb.jrc.ec.europa.eu. (n.d.). Refining of Mineral Oil and Gas | Eippcb. [online] Available at: https://eippcb.jrc.ec.europa.eu/reference/refining-mineral-oil-and-gas-0.

5.1.2. Fugitive emissions from regulated gas activities

Figure 4: Showing Methane and NMVOC fugitive emissions from gas industry processes



NMVOCs

Fugitive emissions within the gas industry are largely composed of methane emissions however there are still significant NMVOC releases although these are predominantly originating from the low and medium pressure distribution pipeline equivalent to 20.1 kt per annum. Fugitive emissions of NMVOCs from the NTS, process emissions, point of use and gas terminal storage were each equivalent to under 500 t in 2019.

Methane

The majority of fugitive methane emissions originated from the low and medium pressure distribution pipeline (129 Kt) followed by the high-pressure National Transmission System (NTS) (3 Kt). Leaks from point of use accounted for 2.56 Kt followed by upstream process emissions (1.8 Kt). Fugitive emissions of methane originating from upstream storage accounted for less than 50 t.

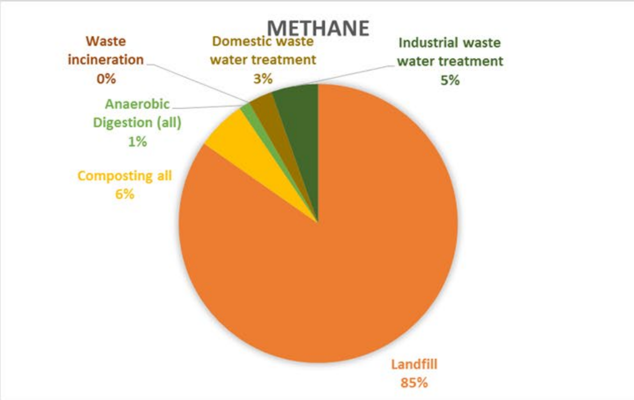
NAEI estimates for fugitive emissions of methane from the unregulated NTS could be underestimated, a recent study found the NTS to be leaking 66 Kt of methane a year[26], the study also identified significant leaks from compressor stations which are partly regulated by the EA from a combustion standpoint in relation to the gas turbine. In 2020, 279 tonnes of fugitive methane escaped from National Grid controlled compressor stations.

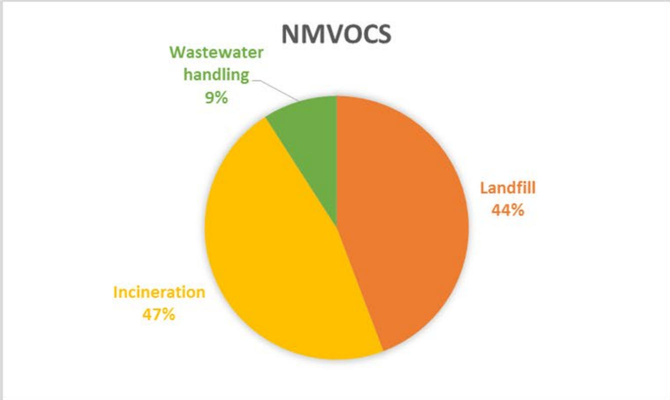
[26] Boothroyd, I., Almond, S., Worrall, F., Davies, R. and Davies, R., 2018. Assessing fugitive emissions of CH4 from high-pressure gas pipelines in the UK. *Science of The Total Environment*, 631-632, pp.1638-1648. [Accessed 4 January 2022]

5.2. A breakdown of total emissions from the waste treatment sector

Specific fugitive emission data for the waste industry is not available on the NAEI and is mixed in with diffuse emissions and emissions from other waste treatment sources. Therefore, overall emission data for methane and NMVOCs originating from all waste management processes has been presented to understand where in the industry the largest releases of emissions are being produced.

Figure 5: Showing NMVOC and methane general emission data from waste management processes





Methane

Landfill is the most important contributor of methane from waste treatment processes and produced 573.6 Kt of methane and 2 Kt of NMVOCs in 2019. However, the majority of emissions from the landfill source itself are diffuse and as such are not categorised as fugitive. Composting produced 39 Kt of methane in 2019 followed by industrial waste-water treatment (37 Kt) domestic waste-water treatment (19 Kt), anaerobic digestion (8.5 Kt) and waste incineration (0.064 Kt).

NMVOCs

Incineration processes produced 2.15 Kt of NMVOCs in 2019, followed by landfill (2.04 Kt) and wastewater handling (0.42 Kt).

As mentioned previously, specific fugitive emission data is absent and it is therefore difficult to discern where significant fugitive emissions are arising from within the waste treatment sector. In respect to this, processes that are closed to air and have the potential to release fugitive emissions of methane or NMVOCs as defined by BS EN:15446 have been considered.

Within wastewater treatment, the majority of the 19 Kt of methane produced originates from the digestion process as loss. The amount of methane emissions from this that fit the definition of fugitive is unknown. From industrial wastewater treatment, methane emissions arise from the following industries: alcohol refining, beer & malt, coffee, dairy products, fish processing, meat and poultry, organic chemicals, petroleum refineries, soap and detergents, plastics and resins, pulp and paper, starch production, sugar refining, vegetable oils, vegetables/fruits and juices and wine and vinegar. It is not known if methane emissions from these industries are originating from anaerobic digestion processes.

5.2.1. Fugitive Emissions from Landfill gas extraction

It is estimated that landfill gas utilisation systems (a requirement of the Landfill Regulations 2002) extract 75 % of a typical landfill facility's methane within a closed-to-air system. A landfill gas utilisation system will normally consist of a number wells dug into the landfill gas pile with a vacuum system that channels collected gas from the wells at low pressure through a pipeline (40mm diameter maximum) to a gas collection centre where it is treated and injected into the grid or if not possible, flared. Only a landfill of considerable size (over 200,000 tonnes) that produces a gas consisting of at least 50 % methane and emits gas at a flow rate of 600 – 750 m^3/hour can be considered for landfill gas extraction and treatment for re-injection back into the grid[27]. When the vacuum system is operational, if any leaks are present, air will be drawn into the system rather than expelled from the pipework but once the pump that channels gas into the system is stopped, leaks may occur although these will be at low pressure and thus the gas will be emitted at low leak rates. Further study on fugitive emissions from landfill gas extraction facilities is recommended.

5.2.2. Anaerobic Digestion

Anaerobic digesters (AD) use anaerobic digestion for the treatment of waste including sewage sludge, crops, animal slurry and food waste in order to produce two valuable outputs: biogas or digestate. Biogas is composed of up to 75 % methane, the energy from biogas can be used to provide heat, generate electricity or the gas can be cleaned to pump back into the grid. Digestate is used to spread on agricultural land as fertiliser.

AD is a growing industry in the UK particularly agricultural AD facilities[28] however not all AD plants are regulated, AD plants not included in the scope include those AD plants that fit the following exemption definitions as defined by the EPR regulations 2016:

- The anaerobic digestion of up to 1,000 m^3 of waste for recovery – at the place of waste production/where digestate is to be used/at any place occupied by the waste;
- A plant burning biogas as a fuel in any appliance with a net thermal input of up to 0.4 megawatts; and

[27] GOV.UK. (n.d.). *Management of landfill gas: LFTGN 03*. [online] Available at: https://www.gov.uk/government/publications/management-of-landfill-gas-lftgn-03 [Accessed 21 Feb. 2022].

[28] https://wrap.org.uk/resources/report/anaerobic-digestion-and-composting-latest-industry-survey-report-new-summaries

- An AD plant used for the spreading of digestate on agricultural land at a rate of up to 250 tonne/hectare/ year – digestate must be from anaerobic treatment of source segregated bio-degradable waste.

In addition to this, any AD plant that grows crops specifically for digestion to produce energy is not a waste and therefore does not require a permit. Agricultural AD facilities that use manure and slurry as feedstock materials as well as AD facilities using food waste, human waste and animal waste all need a permit as these feedstocks are classed as wastes.

5.2.2.1. Methane Loss from anaerobic digestion

NAEI data cannot be relied upon to give an accurate estimation of fugitive losses from regulated sites as the data includes a mix of both regulated and unregulated sites, therefore journals and other sources have been consulted to estimate fugitive losses. NAEI data representing the 19 Kt of methane emissions originating from wastewater treatment is largely attributed to methane loss associated with the anaerobic digestion of sewage sludge. A proportion of this will be fugitive emissions According to a study conducted by ADBA 26.9 Kt[29] of methane was lost from UK "farm biogas" plants in 2019 (assumed to be largely unregulated) and 12.3 Kt of methane was lost from regulated food waste biogas sites equivalent to methane emission factors (percentage of total annual methane production of plant) of 4.8 % and 2.1 %[30]. Important to note these are total methane losses and may not represent releases that fit the BS EN:15446 definition of fugitive emissions only.

It is evident then, both regulated and unregulated anaerobic digestion are associated with significant methane loss. Currently when reporting fugitive methane emissions to the Greenhouse Gas Inventory, operators are required to use a default value of 1% of total annual methane production to represent losses[31]. There is debate as to whether this figure accurately represents loss from AD in the UK as several studies have revealed higher methane losses (including those used for the research of this strategy) from AD plants. Environment Agency internal data has revealed that losses can total as much as 10 % for smaller AD plants.

Estimated values of methane loss (usually a percentage out of the total annual production of a facility) vary widely according to the research paper being consulted. The estimated values of these losses are based on the limited findings of several studies. It is also important to understand what is meant by methane loss as these values represent losses through all of but not limited to the following emission sources: venting, methane slip, associated diffuse sources and fugitive emissions as

[29] Bakkaloglu, S., Lowry, D., Fisher, R.E., France, J.L., Brunner, D., Chen, H. and Nisbet, E.G. (2021). Quantification of methane emissions from UK biogas plants. Waste Management, 124, pp.82–93.
[30] Bakkaloglu, S., Lowry, D., Fisher, R.E., France, J.L., Brunner, D., Chen, H. and Nisbet, E.G. (2021). Quantification of methane emissions from UK biogas plants. Waste Management, 124, pp.82–93.
[31] ee.ricardo.com. (2019). Understanding methane leakage from AD installations - a new methodology. [online] Available at: https://ee.ricardo.com/news/understanding-methane-leakage-from-ad-installations-a-new-methodology [Accessed 28 Mar. 2022].

defined by BS: EN 15446. Therefore, losses solely attributed to fugitive emissions may not be accurately reflected.

The reasons for high methane losses in AD plants are numerous and cannot be attributed to one factor alone however the following all contribute to methane losses in AD:

- poor maintenance and implementation of LDAR;
- type of feedstock used;
- environmental factors;
- individual processes and how they are managed;
- design of plant; and
- the employment of low-integrity equipment.

It has been found that smaller AD sites are associated with higher losses of methane, this could be due to two factors: lack of stringent controls as a result of no regulation and larger plants may have the necessity to be better organised due to more processes involving a larger area[32].

Some studies attempt to categorise methane loss at AD plants by the type of feedstock used and these are shown in Table 4. The reasons for methane loss are likely more complex than this one reason, as AD plants are not uniform in their conditions and processes and have many differing variables to consider.

Table 4: Methane loss associated with different types of feedstock[33]

Feedstock	Methane losses relative to methane production
Sewage sludge from wastewater treatment	3.1%
Municipal waste	1.7 %
Industrial Waste	0.2 %
Manure/energy crops/agricultural waste/slaughterhouse/food waste (agricultural)	2.4 %[34]
Food industry waste (alcohol/residuals/thin stillage/fat/slaughterhouse)	0.8 %[35]

[32] Bakkaloglu, S., Lowry, D., Fisher, R.E., France, J.L., Brunner, D., Chen, H. and Nisbet, E.G. (2021). Quantification of methane emissions from UK biogas plants. Waste Management, 124, pp.82–93.
[33] Jonerholm, K., Lundborg, H. and Environment, S. (2012). Baltic Biogas Bus - Methane Losses in the b. [online] Baltic Biogas Bus Project. Available at: https://docplayer.net/29996723-Methane-losses-in-the-biogas-system.html [Accesed 9 Feb. 2022].
[34] Scheutz, C. and Fredenslund, A.M. (2019). Total methane emission rates and losses from 23 biogas plants. Waste Management, 97, pp.38–46.
[35] Close
Holmgren, M.A., Hansen, M.N., Reinelt, T., Scheutz, C., 2015. Measurements of methane emissions from biogas production: data collection and comparison of measurement methods. Energiforsk report 2015:158, Energiforsk AB, Stockholm, Sweden. https://doi.org/10.13140/RG.2.1.1007.4087.

However higher methane loss from AD associated with wastewater treatment is widely acknowledged and methane losses have been found to be higher from wastewater treatment biogas plants than agricultural biogas plants (7.55 % compared with 2.4 %)[36].

A more relevant factor in determining methane loss from an AD facility may be to take into account methane loss from individual processes that occur at the plant. Different Processes and their associated methane loss values are shown in the table below:

Table 5: Showing plant process and associated methane loss

Process	Methane Loss
Upgrading Units (methane slip)	0.81 %[37]
Exhausts of CHP (co-generation units)	0.40 – 3.28 %[38]
Open storage of digestates (diffuse emissions)	0.22 – 11.2 %[39]
Gas storage	0.2 %[40]
Pasteurisation (animal slurry and food waste only)	0.5 %[41]
Pressure Vacuum Relief Valves (PVRVs)	1.8 %

In a biogas plant, leaks can occur through any component of the plant in sections that contain the biogas[42]. Methane can be released in any of the following areas associated with a biogas AD plant:

- the biogas production area; and
- the biogas utilisation area.

Within the biogas production area, methane fugitives are released from the digestion, gas storage, pasteurisation processes and leaks from pipework and associated components.

[36] Bakkaloglu, S., Lowry, D., Fisher, R.E., France, J.L., Brunner, D., Chen, H. and Nisbet, E.G. (2021). Quantification of methane emissions from UK biogas plants. Waste Management, 124, pp.82–93.
[37] Kvist, T. and Aryal, N. (2019). Methane loss from commercially operating biogas upgrading plants. Waste Management, 87, pp.295–300.
[38] Liebetrau, J., Reinelt, T., Clemens, J., Hafermann, C., Friehe, J. and Weiland, P. (2013). Analysis of greenhouse gas emissions from 10 biogas plants within the agricultural sector. Water Science and Technology, 67(6), pp.1370–1379.
[39] Liebetrau, J., Reinelt, T., Clemens, J., Hafermann, C., Friehe, J. and Weiland, P. (2013). Analysis of greenhouse gas emissions from 10 biogas plants within the agricultural sector. Water Science and Technology, 67(6), pp.1370–1379.
[40] Ricardo (2019). Understanding methane leakage from AD installations - a new methodology. [online] ee.ricardo.com. Available at: https://ee.ricardo.com/news/understanding-methane-leakage-from-ad-installations-a-new-methodology.
[41] Ricardo (2019). Understanding methane leakage from AD installations - a new methodology. [online] ee.ricardo.com. Available at: https://ee.ricardo.com/news/understanding-methane-leakage-from-ad-installations-a-new-methodology.
[42] IEA Bioenergy, 2017. Methane emissions from biogas plants. [online] Ieabioenergy.com. Available at: <https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf> [Accessed 28 March 2022].

In the biogas utilisation area, fugitive emissions arise from methane slip (CHP plants) and the upgrading units (biogas-to-grid plants) particularly CO_2 recovery units. The "upgrading process" in biogas to grid (BtG) plants is where bio-methane is treated before it is reinjected into the grid, this process involves CO_2 removal and significant losses of methane to air are possible during this process.

The amount of methane lost in the CO_2 removal process depends on the technologies used for CO_2 removal, their associated methane loss values and their prevalence in UK AD plants is included in the table below:

Table 5: CO_2 removal technologies and associated loss values[43]

	Membrane	Water wash	Amine absorption
Methane Loss (%)	0.56 %	1.97 %	0.04 %
Number of UK plants (2015)[44]	34	13	3

The membrane technology is the most common CO_2 removal technology used in BtG AD plants and the second most prone to leaks. Water wash is the second most commonly used technology and the most prone to leaks, amine absorption is the least used technology and has the lowest methane loss attributed to it.

Unnecessary venting of the pressure relief valve due to an absence of quality testing at the production stage and incorrect calibration once operational is also a major contributing factor to overall methane loss from AD facilities however this issue is covered in more detail in section 8.2.2.

5.2.2.2. Fugitive emissions from AD

A summary of three studies on leaks from biogas plants found that leaks can occur from any component associated with the containment of biogas and the prevalence of leaking for several types of component is shown in the figure below:

[43] Kvist, T. and Aryal, N. (2019). Methane loss from commercially operating biogas upgrading plants. Waste Management, 87, pp.295–300.

[44] Methodology to Assess Methane Leakage from AD Plants Part I: Report on proposed categorisation of AD plants and literature review of methane monitoring technologies. (n.d.). [online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/786756/Methodology_to_Assess_Methane_Leakage_from_AD_Plants_final_report_part1.pdf [Accessed 25 Apr. 2022].

Figure 6: Showing numbers of leaks from equipment components, data gathered from three studies[45]

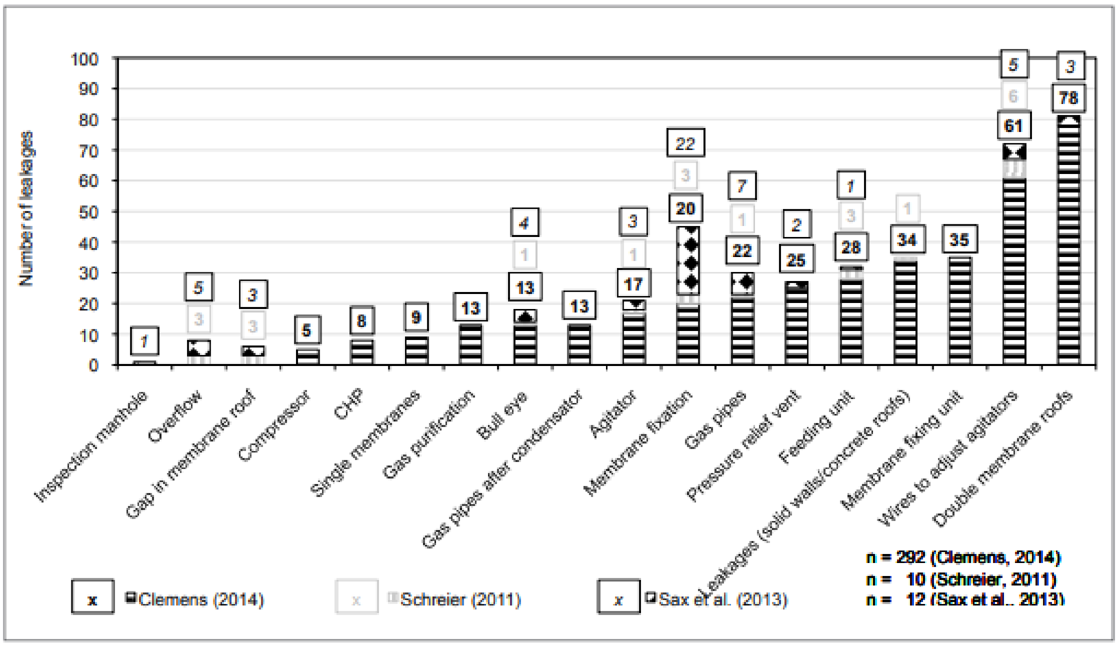


Figure 26: Identified leakages from biogas plants in Germany and Switzerland, data from (Schreier, 2011, Sax et al., 2013, Clemens, 2014)

Leaks were therefore most common occurrences in double membrane roofs, agitator wires, membrane fixing units, leakages through solid concrete walls and roofs, feeding units and pressure relief valves.

Leaks of methane solely originating from equipment components as defined by BS EN:15446 could be much smaller percentages. The combined studies (referred to in Figure 6) found that leaks from equipment and associated components in most cases were small and with low flow rates, leak data gathered from the studies were found to account for between 0.001 and 0.055 % of the total annual methane production of a facility. This is therefore a much smaller contribution of methane fugitives from AD than most studies would suggest[46].

5.3. Emissions of methane and NMVOCs from the chemical sector

Fugitive emission data for methane and NMVOCs originating from chemical processes is not available on the NAEI so general emission data has been displayed on the pie charts below:

[45] IEA Bioenergy, 2017. Methane emissions from biogas plants. [online] Ieabioenergy.com. Available at: <https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf> [Accessed 28 March 2022].

[46] IEA Bioenergy, 2017. Methane emissions from biogas plants. [online] Ieabioenergy.com. Available at: <https://www.ieabioenergy.com/wp-content/uploads/2018/01/Methane-Emission_web_end_small.pdf> [Accessed 28 March 2022].

Figure 6: Showing NMVOC and methane general emission data from waste management processes

The chemical industry contributes far larger amounts of NMVOCs (12.9 Kt in 2019) than methane (2.723 Kt in 2019). The majority of methane emissions originate from process emissions from chemical processes (2.34 Kt) followed by ethylene production processes (0.32 Kt), OPG production processes (0.048 Kt), ammonia production processes (0.01 Kt) and Acrylonitrile production processes (0.005 Kt).

The majority of emissions from NMVOCs in the chemical sector originate from chemical industry processes (11 Kt) followed by storage handling and transport (1.9 Kt).

6. Target regulated activities and their emission contributions

Table 6: Showing targeted activities for each sector and their associated fugitive emissions

Sector	Activity targeted	Emissions of methane 2019 (Kt)	Emissions of NMVOCs targeted (kt)
Crude Oil Sector	Oil refinery Process		8.6
	Petroleum processes	1.13	2.97
	23 onshore oil production facilities		0.0005 (VOCs including methane as of 2021)
	Refinery tankage	2.52	
	Oil terminal tankage		0.05
Gas Sector	Upstream Process Emissions	1.8	
	Upstream storage	0.05	
	Compressor Stations	0.279	
Waste Treatment	AD from WWT	19	
	Regulated food waste biogas sites	12.3	
	Other AD	8.5	Not known
Chemical Sector (general emission data)	Process emissions	2.34	11
	Ethylene Production	0.32	
	OPG	0.048	
	Ammonia Production	0.01	
	Acrylonitrile	0.005	
Total emissions targeted as of data from 2019		48.3	22.6

7. A key tool in reducing fugitives – Leak Detection and Repair

The detection of leaks from equipment in an industrial facility is undertaken through the implementation of one or more LDAR surveys normally on an annual basis using the monitoring techniques as prescribed in the BAT conclusions and BREF documents of the IED. The oil and gas sector, chemicals sector and waste treatment sector are required to have an LDAR programme in place by law. The BAT measures taken from the BAT conclusions for the refining of mineral oil and gas, waste treatment and the BREF document for the chemical sector (as mentioned in Section 1.1.3.1) prescribe LDAR in relation to monitoring technique only and these are shown in the table below:

Table 7: Showing BAT measures for the three targeted sectors in relation to LDAR

Sector document	BAT measure
Waste Treatment	BAT 9 – To monitor diffuse emissions or organic compounds to air from the regeneration of spent solvents, the decontamination of equipment containing POPs with solvents, and the physico-chemical treatment of solvents for the recovery of their calorific value using sniffing methods, optical gas imaging, solar occultation flux or differential absorption.
	BAT 14 – Reduce diffuse emissions to air by implementing a an LDAR programme using a risk-based approach considering the design of the plant and the amount and nature of organic compounds concerned using sniffing and optical gas imaging methods.
Refining of Mineral Oil and Gas	BAT 6 – To monitor diffuse VOC emissions to air from the entire site using following techniques: sniffing associated with correlation techniques, OGI methods and calculations of chronic emissions based on emission factors periodically validated by measurements. SOF and DIAL not required but recommended
Chemical Sector BREF	BAT 5 – To periodically monitor diffuse VOC emissions to air using all the techniques of: sniffing (EN 15446), optical gas imaging methods,= and calculations of emissions based on emission factors periodically validated (once every 2 years). Complementary techniques of SOF and DIAL.

	BAT 19 and associated section 4.6.2 in relation to LDAR.

Currently the British Standard – BS EN: 17628 is the official and most recent UK guidance on the use of sniffing/OGI as part of an LDAR survey and provides guidance on the survey method and use of the monitoring equipment only. The US EPA - LDAR: Best Practice Guide builds on this standard to give best practice recommendations to all stages of the LDAR process.

The success of an LDAR programme is dependent on the following:

- The quality of the record keeping system;
- The competency of the operator;
- The type of monitoring equipment used;
- The amount and type of components monitored;
- The frequency of surveys over an annual period; and
- How quickly repairs are being made.

The BAT conclusions in relation to the refining of mineral oil and gas, waste treatment and chemical sectors prescribe the monitoring technique to be used for the LDAR survey however no other elements are advised upon. The BAT Reference (BREF) document for the refining of mineral oil and gas expands into more detail regarding the LDAR process and gives the examples to be used for certain elements of an LDAR programme which are described in the table below:

Table 8: Showing examples given for some elements of an LDAR programme as prescribed in the BREF document for the refining of mineral oil and gas

Element of LDAR programme	Examples given by BREF
Leak definition concentration (sniffing technique)	500 ppm
Frequency	Twice a year
Types of components to be surveyed	Pumps/valves/heat exchangers/connectors/flanges
Service type to be included	Gas and light liquid

However these are examples and are not prescribed specifically therefore the control of most of the elements of the LDAR process remains up to the discretion of the facility.

7.1. Super emitters and their importance

A rigorous LDAR programme that identifies and surveys all pressurised components that have the potential to leak is crucial to ensuring all leaks within a facility are detected. This is because, a study on Chinese refineries found that only 0.2 % to 0.4

% of all components were responsible for 91.9 % of fugitive VOCs[47]. The small population of components that release the majority of VOC fugitive emissions in a facility are known as "super emitters". Super emitters account for highly skewed leak-size distributions and are responsible for strongly influencing emissions reduction potential[48]. In a larger facility, it becomes cost effective for the operator to have an LDAR programme that targets these super emitters.

7.2. The formation of a master component inventory

The recording of components within a master component inventory provides the foundation for a thorough LDAR programme. The BREF reference document for the Refining of Mineral Oil and Gas recommends that the first step of an LDAR programme is to create a component inventory and once all pressurised components that have the potential to leak within the facility are identified, these are entered into the inventory. The components must be identified in line with up-to-date pipeline and inventory diagrams (P&ID)[49]. The Leak Detection and Repair Best Practice Guide identifies that a common problem for facilities when building the master component inventory is that not all components are identified. The guide builds on advice provided by the BREF document and advises that every component should be given a unique code, the components should be physically located within the facility and tagged with the code and recorded on the Pipeline and Inventory Diagram (P&ID)[50]. The replacement of equipment should also be noted promptly within the inventory

7.3. Frequency of LDAR

Frequency of a survey is a key factor in the effectiveness of an LDAR programme, the BAT conclusions and BREF reference documents do not provide direct instruction on the frequency of LDAR surveys. However, the BREF document for the refining of mineral oil and gas does provide an example for the frequency of an LDAR survey at a refinery of twice a year and provides evidence of a Swedish refinery implementing this. However this is an example rather than instruction and as such is not enforceable on this basis.

The frequency of surveys is therefore at the discretion of the facility. In every campaign 10 – 20 % of leaks found represent newly discovered leaks and this is an important reason for the frequent undertaking of surveys[51]. EPA produced research has found that introducing one whole site LDAR survey per year to small onshore oil and gas facilities, including well sites and boosting stations, from a baseline where

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[47] Ke, J., Li, S. and Zhao, D. (2020). The application of leak detection and repair program in VOCs control in China's petroleum refineries. Journal of the Air & Waste Management Association, 70(9), pp.862–875.

[48] https://iopscience.iop.org/article/10.1088/1748-9326/aa6791/meta

[49] eippcb.jrc.ec.europa.eu. (n.d.). Refining of Mineral Oil and Gas | Eippcb. [online] Available at: https://eippcb.jrc.ec.europa.eu/reference/refining-mineral-oil-and-gas [Accessed 22 Mar. 2022].

[50] EPA, 2022. Leak Detection and Repair: A Best Practices Guide | US EPA. [online] US EPA. Available at: <https://www.epa.gov/compliance/leak-detection-and-repair-best-practices-guide> [Accessed 11 February 2022].

[51] Datta, P., 2020. How effective LDAR Campaigns Contribute to Minimising Methane Emissions. OnePetro, p.Abstract.

no LDAR programme was being undertaken can reduce fugitive emissions by 40 %[52]. Further to this, increasing the frequency of whole site surveys to a quarterly basis can reduce fugitive emissions by 80 %. Similarly, the BAT Reference document for Common Waste Gas Management and Treatment Systems in the Chemical Sector states that LDAR applied in several cycles can reduce fugitive emissions by 90 %[53]. Building on this, a more detailed study revealed that quarterly OGI surveys reduced the mean leakage of components from 0.5 g/s to 0.15 g/s at gas-well site facilities[54].

7.4. The cost of LDAR

Frequency is restricted by one main constraint: the cost of undertaking a survey. UK published information on LDAR is not readily available therefore costs have been derived from U.S. studies and regulations. Whether a facility decides to implement LDAR using a third-party operator or do it in-house can make a large difference in cost with the latter proving more costly. Initial start-up costs incur the most cost and this stage can total over £200,000 depending on the monitoring equipment bought, OGI being more expensive, and the implementation of the record keeping system. However in most facilities where LDAR is required by BAT, the initial costs should already be accounted for. In terms of labour cost, a worst-case of £95 an hour can be assumed, this is a conservative estimation which is based on an operator managed LDAR programme rather than third-party and includes costs such as supervision, overhead, travel, recordkeeping and reporting[55]. Based on this estimate, a whole-site survey for a smaller facility such as an AD plant could cost £960. For a refinery or chemical plant where a risk-based approach may be employed to target populations of components multiple times a year, it is more difficult to estimate the cost. However, according to a publication produced by IMPEL in 1999, a whole-site survey of a refinery may cost £40,000[56], however this will be based on using the sniffing technique only and therefore with the combined use of OGI and sniffing, costs may prove cheaper.

7.5. Time-taken to undertake a survey

One way to reduce the cost of an LDAR programme is to reduce the amount of time taken to undertake the survey. The time taken to undertake a survey can be

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[52] Pembina Institute, 2022. https://www.pembina.org/reports/edf-icf-methane-opportunities.pdf. [online] Pembina.org. Available at: <https://www.pembina.org/reports/edf-icf-methane-opportunities.pdf> [Accessed 12 January 2022].
[53] European Commission (2019). Best Available Techniques Reference Document for Common Waste Gas Management and Treatment Systems in the Chemical Sector. European Commission. Page 22
[54] Ravikumar, A.P. and Brandt, A.R. (2017). Designing better methane mitigation policies: the challenge of distributed small sources in the natural gas sector. Environmental Research Letters, 12(4), p.044023.

[55] Economic Analysis of Methane Emission Reduction Opportunities in the Canadian Oil and Natural Gas Industries. (2015). [online] Available at: https://www.pembina.org/reports/edf-icf-methane-opportunities.pdf.
[56] https://www.envirotech-online.com/white-paper/air-monitoring/6/cem/impel-guidelines-onnbspdiffuse-voc-emissions-middot-emission-estimation-methods-middot-emission-reduction-measures-middot-licensing-and-enforcement-practice/61

significantly reduced by two factors: the monitoring equipment used and how it is applied and an increase in the number of operators. Optical Gas Imaging (OGI) is associated with a similar level of detection accuracy to the more commonly used method of “sniffing” but allows a survey to be completed quicker. A survey using OGI can survey up to 2100 components an hour compared with sniffing which can survey up to 700 components a day[57] and this therefore allows the implementation of more frequent surveys without incurring the cost and time-taken if “sniffing” only was used. OGI should not be a replacement for sniffing as the two techniques should be used as an effective combination where OGI is used to first scan an area of components for leaks. Once the leak is visualised, sniffing is used to provide an indication of the leak value.

7.6. Repair

Potential issues with the repair process include the absence of a plan and timetable for repairing components, a delay in repair and the lack of recording of leaking components within an inventory. Repairs are often coordinated with process shutdowns and this risks that the leak could remain un-repaired for a significant amount of time. Repairs can be split into two categories: first attempt repairs and structural modifications. First attempt repairs are usually conducted within 5 days of leak detection and involve the application of simple measures to fix less complex leaks such as pressing the valve packing gland or adjusting flange bolts[58]. Structural modifications involve the replacement of the seal or in extreme cases where repair is not possible, the replacement of the component. Structural modifications are usually undertaken within 15 days[59]. Some leaks require process shutdowns to be repaired and therefore in these instances, the leaking component is put into a delay of repair system. Once a leak is repaired, their re-monitoring is essential as 80-90 % of emitting sources found consist of previously identified leaking sources[60]. The EPA advises all leaks to be repaired within 15 days and their re-monitoring is suggested within one month[61].

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[57] EPA, 2015. Oil and Natural Gas Sector: Standards for Crude Oil and Natural Gas facilities. Background technical support Document 40 CFR Part 60, subpart OOOOa, pp.60-70.

[58] Ke, J., Li, S. and Zhao, D., 2020. The application of leak detection and repair program in VOCs control in China’s petroleum refineries. Journal of the Air & Waste Management Association, 70(9), pp.862-875.

[59] Ke, J., Li, S. and Zhao, D., 2020. The application of leak detection and repair program in VOCs control in China’s petroleum refineries. Journal of the Air & Waste Management Association, 70(9), pp.862-875

[60] Ke, J., Li, S. and Zhao, D., 2020. The application of leak detection and repair program in VOCs control in China’s petroleum refineries. Journal of the Air & Waste Management Association, 70(9), pp.862-875.

[61] EPA, 2022. Leak Detection and Repair: A Best Practices Guide | US EPA. [online] US EPA. Available at: <https://www.epa.gov/compliance/leak-detection-and-repair-best-practices-guide> [Accessed 11 February 2022].

8. Equipment Components and Emission Factors

8.1. The installation of high-quality equipment components

The quality of the sealing system and the equipment design of pressurised components are factors that influence how likely an equipment component is to leak. The employment of high-integrity components (higher control efficiencies) is a direct way to prevent leaking within a facility. Aged equipment components will typically be present in large quantities in an average facility that has been operational a long time. The BREF document in relation to the refining of mineral oil and gas recommends that aged leaking equipment components are to be replaced only where a repair to a fault is not possible. Directly replacing all lower quality equipment components with high-integrity equipment components may not be a feasible exercise in most operational facilities due to the cost, size or need to shut down operations in order to undertake the replacement. Instead, the installation of high-integrity components is better considered during the design phase of the facility pre-operation.

High-integrity equipment components are listed and recommended within BAT 14, Section 1.20.6 and Section 4.6.2 of the BAT conclusions in reference to waste treatment, the BAT conclusions in relation to oil and gas and the BAT Reference Document for Common Waste-water and Waste Gas Treatment. High-integrity components have much higher control efficiencies. For example, installing seal-less pumps and valves can achieve control efficiencies of 100 % although leaks are still possible, their likelihood is vastly reduced. Welding connectors (threaded fittings) together achieves a similar control efficiency. Installing a cap, plug or second valve can completely solve leaking from open-ended lines and therefore once upgraded, LDAR does not need to be a consideration for these components.

Within a facility, the following equipment component types have the potential to produce fugitive emissions: agitator seals, compressor seals, connectors, diaphragms, drains, dump lever arms, flanges, hatches, instruments, loading arms, meters, open-ended lines, polished rods, pressure relief devices, pump seals, valves and vents.

Where faults occur that release fugitive emissions depend on the equipment component, and these are given in the table below:

Table 9: Equipment component types and where they are likely to leak

Equipment component type	Where leaks occur
Valves	Seal between the stem and housing
Bolted fittings	Threaded connection and gasket interface and circumference of the connector
Seals for compressors, pumps and agitators	Occur at the seals.
Pressure relief valves	Sealing seat, disc gasket
Open-ended lines	Point of the line open to the atmosphere
Sampling Connections	Purging the sampling line

Emissions from sampling connections only occur when the line is purged and exposed to air therefore emissions from this component cannot be categorised as fugitive as defined by BS EN:15446.

8.2. Emission Factors

Environmental Protection Agency (EPA) emissions factors for equipment components have been derived from equipment component leak rate data gathered from a range of industrial facilities including refineries and chemical process units. Emission factors predict the average leak rate of a component based on equipment component type and in the absence of monitoring data are a useful tool in estimating annual fugitive emissions from equipment component populations. Emission factors differ for the process involved and whether an emission factor is applicable to another process depends on the following factors: process design, process operation parameters (temperature and pressure), types of equipment used and types of material handled. The refinery assessment study conducted by the EPA found that the two parameters of: phase of the process stream and the relative volatility of liquid streams were defining factors that influenced mass emission rates. This has resulted in the definition of three defined service types:

- Gas/vapor – material in a gaseous state at operating conditions;
- Light liquid – material in a liquid state in which the sum of the concentration of individual constituents with a vapor pressure over 0.3 kilopascals at 20°C is greater than or equal to 20 weight percent; and
- Heavy liquid – not in gas/vapor service or light liquid service.

It is UK oil refinery industry practice to exclude equipment components associated with heavy liquid service from an LDAR survey as advised by the EI protocol.

The emission factors for SOCMI (Synthetic Organic Chemical Manufacturing Industry) and petroleum industry equipment components are given below, higher emission factors indicate an increased likelihood of leakage. Equipment components and their associated emission factors are given below.

Table 10. Equipment components with associated Emission Factors for refineries and SOCMI and amounts within a typical refinery or chemical plant[62]

Equipment Type	Service	Emission Factor (kg/hr/source)	Average no. large petroleum facility/chemical plant	Percent of total emissions
Flanges and non-flanged connectors	Petroleum Industry	0.00025	12000	31
	Gas	0.636		Not given

[62] EPA, 2022. Leak Detection and Repair: A Best Practices Guide | US EPA. [online] US EPA. Available at: <https://www.epa.gov/compliance/leak-detection-and-repair-best-practices-guide> [Accessed 11 February 2022].

Compressor Seals	SOCMI	0.228	Depends on number of compressors	
Pump seals	Light Liquid	0.0199	100	3
	Heavy Liquid	0.00862		
Valves	Gas	0.00597	7400	62
	Light Liquid	0.00403		
	Heavy Liquid	0.00023		
Open Ended Lines	All	0.0017	560	1
Pressure Relief Valves	Gas	0.16	90	1
Sampling Connections	All	0.0150	80	2

According to EPA produced Emission Factors compressor seals, pressure relief valves, pump seals, and valves are the most likely equipment components to leak over a year in that order. This is because these components are for the most part not static components and will be expected to move as part of their operation. However pumps, compressors, agitators, pressure relief valves all constitute a small proportion of a refinery's components (0.3%) and are therefore easier to target than more numerous components. Flanges and connectors are some of the least likely equipment components to leak but the most numerous within a large facility.

According to a Chinese study[63], non-flanged connectors constitute the majority of components within a refinery (55%) followed by flanges (28 %), valves (15%) and open-ended lines (2.3%). The same study concluded that valves, open-ended lines and flanges emit a high quantity of VOC's accounting for 45.4 %, 29.8 % and 18.6 % respectively. Open-ended lines were also found to have the highest leak rate (3.0%) and non-flanged connectors the lowest (0.12 %). It is important to note that open-ended lines have a higher leak rate in Chinese refineries because their capping is not mandatory by law as in the U.S. In U.K. refineries it is required by the "management systems condition" of the EPR 2016 and "all measures necessary of COMAH that the "adequate isolation" of redundant pipeline is undertaken. Adequate isolation could include a double block and bleed valve assembly, the installation of a blanking plate between flanges or the capping at the end of the line. Therefore, the leaking of open-ended lines should not pose an issue within U.K. refineries.

8.2.1. A risk-based approach

For some facilities such as refineries and chemical plants, a whole-site survey that targets all pressurised components is not feasible therefore a risk-based approach targeting those components most likely to leak, the "super-emitters", is needed.

[63] Ke, J., Li, S. and Zhao, D. (2020). The application of leak detection and repair program in VOCs control in China's petroleum refineries. Journal of the Air & Waste Management Association, 70(9), pp.862–875
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Based on emission factors and evidence presented above, components have been organised in terms of their risk and this is shown in the table below:

Table 11: Component types and their allocated risk

Component	Non-flanged connector	Flange	Valve	Open-ended lines/seals/PVRVs
Risk	Very-low	Low	Medium	High

In UK Oil and gas facilities, pipes are allocated risk based on their diameter. The thought process being: the larger the diameter of the pipe, the larger the VOC throughput and therefore if any component associated with that pipe was to leak, the larger the potential for a significant leak (e.g. above 10000 ppm). This is shown in the table below:

Table 12: Diameter of pipework and allocated risk

Pipe Diameter (mm)	$\leq$ 50	50 – 100	>100
Risk	Low	Medium	High

These two tables are then combined to show overall risk based on pipe diameter and the likelihood of the equipment component type to leak shown in the table below:

Table 13: Combined risk of above two table to give overall risk to component type and associated pipework diameter

Pipe Diameter	$\leq$50 mm	50 – 100 mm	> 100 mm
Component type			
Non-flanged connector	Low	Low	Medium
Flange	Low	Low	Medium
Valve	Medium	Medium	High
Open-ended line	Medium	High	High
Seals	Medium	High	High

These component types can then be targeted in terms of their risk, with the undertaking of multiple annual surveys for high-risk components for example. It is important to note that these tables have been based upon data associated with oil and gas facilities, however a similar risk-based approach can be applied to the chemical sector due to the similarities in their emission factor values as demonstrated in *Table 8*.

8.2.2. Pressure Relief Valves in Anaerobic Digesters

Pressure relief valves (PVRVs) are a protection device located on the top of fixed roof storage tanks associated with anaerobic digesters. Their purpose is to allow the tank to vent when pressure fluctuates in the tank as part of normal operations to prevent an exceedance of operating pressure and any subsequent accidents arising from this. PVRVs have been estimated to have an average methane emission factor of 1.2 % in ambient conditions but this may rise to as high 8 % in summer (from the total expected annual methane production of a plant). The study found that short temperature amplitudes specifically were the cause of increasing emissions from PVRVs rather than just a temperature increase[64].

Typically the valve will begin to vent in smaller quantities at 75 % of the set point, the set-point is the value near or equal to the maximum pressure of the tank. The set-point of the valve needs to be calibrated accurately to the operating pressure of the tank otherwise there is a risk that PVRVs will vent more than necessary. In addition to this, 90 % of pressure relief valve manufacturers do not perform a leak or functionality test on the valve before dispatch therefore there is a risk that the component could have inherent faults and leak[65]. Once operational, it is therefore difficult to distinguish whether a PVRV is functioning as intended or not. There are two international standards: API:2000 and ISO:28300 which specify production testing criteria for PVRVs and these should be followed before the dispatch. However, the standards were published for PVRVs in the oil and gas industry and therefore there is no regulation stipulating adherence to these standards for permitted AD facilities. A 12” valve that is not API:2000 compliant can leak 7575.6 m^3/yr equivalent to 6.6 tonnes a year compared to a 12” valve compliant with API: 2000 (7.44 m^3/yr)[66]. This is evidently a significant difference and further study into this is recommended.

8.3. Estimating fugitive emissions

A rigorous LDAR programme increases the detection of leaks, but the knowledge of every leak in a facility is not possible due to the unpredictable nature of leaks. Estimations based on emission factors allow a facility to predict leaks with varying degrees of accuracy, depending on the approach, in the absence of complete leak data normally provided by monitoring. These estimations are then fed back into the national Pollution Inventory and GHG inventories. Estimations do not reduce fugitive emissions but they do play a critical role in understanding whether existing policy on LDAR is working in reducing fugitive emissions. The employment of the tier 2 and 3 estimations (used in refineries) also improves the LDAR process due to the necessity to gather more monitoring data from a facility’s equipment components in order to undertake the estimation.

There are two industry accepted estimation techniques to determine process VOC fugitives from refineries defined by the US EPA protocol. The same methods are

[64] Reinault, T. and Liebetrau, J. (2019). Monitoring and Mitigation of Methane Emissions from Pressure Relief Valves of a Biogas Plant. Chemical Engineering and Technology, 42, pp.6–11.
[65] Reinault, T. and Liebetrau, J. (2019). Monitoring and Mitigation of Methane Emissions from Pressure Relief Valves of a Biogas Plant. Chemical Engineering and Technology, 42, pp.6–11.
[66] Assentech, Specialists in Tank Storage & Process Safety. [online] Available at: http://www.assentech.co.uk/ [Accessed 22 Apr. 2022].

also provided by the Energy Institute: Protocol for the Estimation of Petroleum Refinery Process Plant Fugitive VOC Emissions 2010. The first method uses the following tiered approaches to estimating fugitives (Tier 1 being the least accurate):

- Tier 1 – Based on average emission factors only, no monitoring required;
- Tier 2 - Applies average emission factors based on leak/no leak criteria determined through VOC monitoring of equipment components. A leak is defined once the screening value of the monitoring equipment (FID or PID) returns a value above the leak definition concentration set by the operator; and
- Tier 3 – Similarly to Tier 2, this method requires VOC monitoring undertaken at each fitting, however after the leak has been detected, it applies correlation factors to the leak values based on the pegged emission rate and equipment type.

Tier 3 is the most accurate and recommended method of the estimation of fugitive process emissions from a refinery, the Tier 1 approach is the least accurate and will typically overestimate VOC process fugitive emissions.

The second approach assumes that fugitive VOC emissions from plant and pipework represent 0.03 wt % (0.02 % recommended by EI protocol) of the actual material processed in the refinery and therefore applies the following calculation: 0.03 x annual refinery throughput (tonnes). This method should only be used in the absence of a refinery inventory detailing the number of equipment components.

BAT 20 of the Common Waste Gas Management and Treatment Systems in the Chemical Sector[67] recommends the use of emission factors, mass balance or thermodynamic models for the estimation of fugitive emissions from chemical facilities.

[67] European Commission (2022). Common Waste Gas Management and Treatment Systems in the Chemical Sector. European Commission BREF.

9. Monitoring Techniques

Four monitoring methods to be used in an LDAR survey are prescribed by the BAT conclusions and these include:

- Sniffing (method 21);
- Solar Occultation Flux (SOF);
- Differential Absorption Lidar (DIAL); and
- Optimal Gas Imaging (OGI).

A combination of or the individual use of sniffing and OGI is prescribed by the BAT conclusions for the chemical, waste treatment and refineries sectors. The use of DIAL or SOF is recommended where possible to support existing LDAR programme but their use is not practical as part of a continuous LDAR programme

9.1. SOF and DIAL

Solar Occultation Flux is a remote sensing method based on measuring infrared intensity spectra of the sun from a moving vehicle and therefore needs cloudless sky and intense sunlight to perform to high levels of accuracy. There are also a finite number of these specially adapted vehicles. This technique therefore may not be practical for facilities located within the northern hemisphere.

DIAL uses a laser source of tuneable wavelength transmitted over the measurement region, a small fraction is scattered back by the aerosols and particulates and this is collected with a telescope and a fast sensitive detector. The equipment associated with this technique is extensive, there are currently only two machines worldwide capable of undertaking this technique and the analysis of the associated data is a lengthy process requiring the need for specialists, the process is not intuitive.

9.2. Sniffing (Method 21)

The sniffing technique utilises a handheld hydrocarbon detector probe: flame ionisation (FID) , photo-ionisation detector (PID), non-dispersive infrared camera or combustion analyser) and is held to the equipment component closely to detect a potential leak. The instrument must be able to detect leaks to +/- 2.5 % of the specified leak definition concentration. The FID or PID is calibrated for the detection of the reference compound e.g. methane or other VOCs and a leak definition concentration (ppm) is set for that compound. A leak definition concentration is the local VOC concentration at the surface of a leak source that indicates a VOC emission is present and is an instrument reading based on the reference compound. When the equipment is held closely to the leaking equipment component, a screening value is returned by the device, if above the leak definition concentration, the component is identified as leaking. Typically a leak definition concentration of 1000 – 10000 ppm is set for methane by refineries and 100 ppm for biogas and anaerobic digester facilities, however the choice of the value to set is normally decided by the operator.

Sniffing has historically been the most favoured technique for the monitoring of equipment components in an LDAR survey as it can provide an indication of the leak concentration (ppm) unlike OGI. The technique although effective is slower than more modern techniques. The following are the main advantages and disadvantages associated with this technique:

- the technique reduces accessibility to hard-to-reach components due to the way in which is it operated and it cannot detect leaks from insulated components;
- the equipment can be less effective in detecting large leaks (>10000ppm); and
- leaks can be detected to a minimum limit of 1ppm which is where sniffing provides a more accuracy.

A key factor in increasing the efficiency of surveys undertaken using sniffing is to set a lower leak definition concentration. The Leak Detection and Repair: A Best Practices Guide recommends setting the leak definition concentration for the surveying of all equipment components in oil and gas facilities to 500 ppm which results in a control effectiveness (% reduction) of 95 % for valves in light liquid and gas service and 88 % reduction in leaks from flanges[68]. Applying this to surveys has been shown to be more efficient in reducing leaks than performing monthly surveys. This measure is not explicit in application to refineries and can be applied at other industrial facilities.

9.3. Optical Gas Imaging

Optical Gas Imaging consists of a handheld thermal imaging camera that uses infra-red light to capture and visualise leaks on a screen. The background to the leaking component (whether ground, equipment-level or sky) as well as the component itself both have the potential to emit infrared radiation therefore it is important that the camera is calibrated so that the difference between the background temperature and the hydrocarbon plume is visible, this is called the “Delta-T”.

OGI is an effective visualisation tool and allows a wide range of leaks to be visualised in the form of “white smoke” and its application is significantly quicker than sniffing because of this. Depending on the type of OGI camera used, leaks can be detected to a minimum of 0.2 – 10 g/h[69] depending on the hydrocarbon and Delta-T however the 90 % probability of detection is 13g/h which makes OGI more effective at detecting larger leaks[70]. In addition to this 80 % of VOC emissions detected by an OGI camera are detectable at a distance of 10 m[71]. These two attributes make OGI an effective tool for the efficient scanning of areas or “flow-lines” that contain

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[68] EPA, 2022. Leak Detection and Repair: A Best Practices Guide | US EPA. [online] US EPA. Available at: <https://www.epa.gov/compliance/leak-detection-and-repair-best-practices-guide> [Accessed 11 February 2022].

[69] Concawe (2015). Techniques for detecting and quantifying fugitive emissions - results of comparative field studies. [online] Available at: https://www.concawe.eu/wp-content/uploads/2017/01/rpt_15-6.pdf.

[70] Zimmerle, D., Vaughn, T., Bell, C., Bennett, K., Deshmukh, P. and Thomas, E., 2020. Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions. Environmental Science & Technology, 54(18), pp.11506-11514.

[71] Ravikumar, A., Wang, J. and Brandt, A., 2016. Are Optical Gas Imaging Technologies Effective For Methane Leak Detection?. Environmental Science & Technology, 51(1), pp.718-724.

numerous components within large facilities. LDAR surveys can therefore be conducted much quicker than surveys undertaken using sniffing and OGI can survey up to 2100 components an hour[72]. This allows the fast detection of “super-emitting” sources as well as allowing the undertaking of multiple annual LDAR surveys of a facility which for large facilities such as refineries and chemical plants may not have previously been possible using “sniffing”. OGI is now the primary LDAR method for detection of VOC leaks in U.S. oil and gas facilities[73], refineries in the UK are also using this as a key method where OGI is used to scan an area for leaks and sniffing to quantify the leak once found.

There are several pitfalls with OGI however and these need to be taken into account when planning an LDAR survey. It cannot quantify leaks once detected, it cannot be operated in weather conditions consisting of high wind, fog or rain. It is less efficient with uniform temperatures; it has a high minimum detection limit therefore may be less effective in detecting smaller leaks. It’s detection of methane in particular may be less effective compared to the detection of other VOCs (depending on the study consulted), a 50 % detection likelihood of methane was demonstrated to be at an emission rate of 20g/h and an imaging distance of 6 m[74].

Due to its comparatively high minimum detection limit compared with “sniffing”, its application for the undertaking of LDAR surveys on facilities operating at low pressures (such as AD plants) and subsequent low emission rates must be called into question. However, it would seem that this assumption would depend on the equipment used, the “FLIR GF320” OGI camera is well suited to detecting CH_4 emissions at well below 1g/s according to a study quantifying leaks from anaerobic digesters[75]. Therefore, the extended use of OGI in AD facilities when conducting LDAR is still recommended

Another key consideration where OGI is applied, is the competency of the operator, highly experienced OGI camera operators have been shown to take more time to screen major equipment units. In addition to this, less-experienced surveyors have more difficulty discerning leaks from certain backgrounds[76] or where the Delta-T is less pronounced, and this can lead to the incorrect categorisation of leaks.

However despite these pitfalls, the application of OGI in an LDAR survey in combination with sniffing is an essential aspect of a modern LDAR programme.

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[72] PA, 2015. Oil and Natural Gas Sector: Standards for Crude Oil and Natural Gas facilities. Background technical support Document 40 CFR Part 60, subpart OOOOa, pp.60-70.

[73] Zimmerle, D., Vaughn, T., Bell, C., Bennett, K., Deshmukh, P. and Thomas, E., 2020. Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions. Environmental Science & Technology, 54(18), pp.11506-11514.

[74] Ravikumar, A., Wang, J. and Brandt, A., 2016. Are Optical Gas Imaging Technologies Effective For Methane Leak Detection?. Environmental Science & Technology, 51(1), pp.718-724.

[75] Tauber, J., Parravicini, V., Svardal, K. and Krampe, J. (2019). Quantifying methane emissions from anaerobic digesters. Water Science and Technology.

[76] Zimmerle, D., Vaughn, T., Bell, C., Bennett, K., Deshmukh, P. and Thomas, E., 2020. Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions. Environmental Science & Technology, 54(18), pp.11506-11514.

Due to the ease at which leaks can be visualised using the camera, a unit consisting of several equipment components can be monitored quickly and leaks can be determined immediately. Once detected this allows for sniffing to be used to provide an indication of the leak value (ppm), the value from which can then be fed into component and repair inventories as well as aiding with annual fugitive emission estimations. In addition to this, as OGI does not rely on a leak definition concentration, it is therefore not constrained by a set value and can potentially detect smaller leaks than if sniffing had been undertaken. Therefore this provides the opportunity for all leaks, including those lower than a specified leak definition concentration, to be entered into a repair programme. Using a combination of the two allows a wider range of leaks to be detected and the frequency of surveys conducted annually to be increased.

10. Conclusions from the analysis of LDAR practices across EA regulated facilities

10.1. LDAR across Refineries

Six UK refineries were recently audited, the notes on the LDAR programmes were compiled and the observations of which have been summarised below:

- Method 21 and BS: EN 15446 (which invokes Method 21) are being referred to when conducting monitoring;
- All refineries are using the EI protocol when following guidance on the estimation of fugitive emissions. All six refineries are using the most basic estimation technique of: 0.02 x annual throughput, this demonstrates that refineries do not have complete inventory of components;
- In five refineries, OGI is being combined with sniffing as a monitoring technique when undertaking LDAR, however in one refinery OGI is being used alone as a technique which is not in accordance with what BAT conclusions advise;
- In all refineries, only part of the total amount of equipment components within the facility are being monitored, valves and seals are being prioritised and static components such as flanges and other bolted fittings are being excluded from surveys. Components are prioritised on the definition of light liquid service in most cases and once refinery is not considering undertaking LDAR on components with a diameter less than 2 inches. In one refinery, only one unit in the entire refinery is being monitored and at infrequent intervals;
- The LDAR programmes for four refineries are undertaken on a rolling programme where the components and units identified for LDAR are taking 2 – 5 years to undertake the surveys. It is important to note that the programmes are not covering the whole site within this time. Two refineries are conducting LDAR surveys very infrequently;
- One refinery is using an out of date P&ID diagram (produced over 20 years ago) when conducting LDAR surveys. All refineries are using P&ID diagrams and PFDs when undertaking surveys;
- Most refineries are only considering leaks over 10000 ppm and in one case 20000 ppm (when leaks are quantified with sniffing) when looking at immediate repair. Leaks under this concentration are being noted but it is unclear if they are being put into a repair programme. In all refineries leaks under 10000 ppm are not entered into annual fugitive estimations; and
- In 4 out of 6 refineries, LDAR surveys are being conducted by third party operators.

10.2. LDAR across onshore crude oil production facilities

From analysing the LDAR plans from 23 onshore oil production facilities comprising , the following is known about their LDAR programmes:

- Leaks under 1000 ppm are being logged for repair but not featured in site/annual emission estimate;

- Where significant leaks >10000 ppm are encountered from components classified as high risk or very high risk, repair effected within 7 days;
- Where less significant leaks encountered <10000 ppm, repair effected within twenty eight days;
- Every potential leak location is surveyed unless inaccessible;
- For sites in production stage, an annual LDAR survey will be undertaken, after the first year the frequency is doubled until the proportion of leaking components has been verified as having been reduced to less than 5 % of total;
- Sites in exploration stage, a single annual LDAR survey will be undertaken; and
- LDAR survey undertaken in accordance with EN15446:2008.

Table 14: Showing stepped LDAR process for onshore crude oil production facilities

Stage	Detail
1	Undertake site-specific health & safety risk assessment
2	Ensure required equipment and supplies are available, and where required, correctly calibrated/tested.
3	Review site schematic, LDAR registry and LDAR plan to understand site process and potential leak locations to be surveyed.
4	Liaise with site staff to ascertain whether any infrastructure changes or significant process upsets have occurred since previous LDAR survey.
5	Note prevailing wind and weather conditions which may affect survey.
6	Undertake site perimeter walkover to identify background levels (Methane & TVOC), noting any elevations observed or distinct discrepancies between upwind and downwind measurements.
7	Undertake systematic survey of each potential leak location starting at the upstream end of the onsite process (typically at a wellhead) working progressively downstream until the full onsite process has been surveyed (typically at a storage tank or the permit boundary). Each potential leak location to be surveyed systematically taking account of the measuring instrument's response time.
8	For every leak detected, record the location and result observed. Wherever possible, verify the precise leak location using leak detection fluid or equivalent. A confirmed 'Known leak' tag should be applied to the leaking component to aid later identification and repair.
9	Where possible, brief an onsite staff member on the locations of any leaks detected before vacating site.
10	Report any leaks identified in writing to the relevant site supervisor at the earliest opportunity following the completion of the LDAR survey.

10.3. LDAR across Compressor Stations

After liaising with the National Grid, their LDAR programme has been summarised below:

- Surveys are conducted once every four years with those stations which have a prior history of leakage prioritised first over this period;
- Third party operator conducts the survey;

- Survey undertaken for 80 % of components, the remaining 20 % of components are above ground and inaccessible. This may be improved with the future use of OGI;
- Sniffing undertaken presently however OGI is planned to be brought into the LDAR programme within the next two years;
- Once a leak is detected, a high-flow sampler is used to quantify the leak;
- A leak definition concentration of 10000 ppm is used; and
- All leaks are repaired but they are prioritised on their leak value, leaks over 10000 ppm are fixed within 28 days if a first-attempt is unsuccessful.

10.4. LDAR across AD treatment of sewage sludge in wastewater treatment

After internal consultation with the wastewater regulating team, the situation regarding LDAR across the sector has been summarised:

- Only the treatment of sewage sludge within WWT is regulated and all other activities fall under the Waste-water treatment directive;
- Currently some permitted sites are not monitoring fugitive emissions at all and only when the equipment or component is shown to be obviously failing through the SCADAR system are repairs enacted. Therefore because of this, leaking components could be emitting fugitives to air for a significant amount of time before the component is fixed;
- The majority of the equipment used in the treatment of sewage sludge is aged and inspection and maintenance of this equipment is questionable;
- Very little in terms of LDAR has been undertaken up to this point however this is beginning to change as a permit review of 120 AD sites is being undertaken with a view to implement LDAR once a year;
- LDAR will be conducted in accordance with BS EN: 15446 using the “sniffing” technique;
- Pressure-relief valves are not being calibrated correctly and therefore there could be significant and unnecessary venting of methane to atmosphere;
- The overriding issue is that there is no system in place to monitor water companies and their practices in regards to the treatment of sewage sludge.

10.5. LDAR across the chemical sector

Large Volume Organic Chemical facilities are undertaking LDAR, details about the LDAR programmes have not been possible to obtain for this strategy. There is an absence of pollution inventory reporting from the majority of chemical facilities including annual fugitive emission estimations.

11. Conclusions

Table 15: Fugitive emission conclusions from regulated industry separated into the species of concern

NMVOCs	Methane
NAEI fugitive emission data is not complete enough to provide the full picture for the majority of regulated activities. Fugitive emission data is dependent on the data derived from estimation techniques and the accuracy of this process depends on which estimation techniques facilities are using when estimating annual fugitives, which in most cases is the most basic approach, and how these are being reported.	
The chemical sector is the largest contributor of fugitive NMVOCs with 11.9 Kt however the amount of these emissions that can be categorised as fugitive is unknown. There is a lack of reliable data regarding fugitive emissions in the chemical sector and this is reflected in available NAEI data.	Anaerobic digestion is the regulated activity with the highest associated losses of methane. 19 Kt of methane released from wastewater treatment (majority associated with AD of sewage sludge). 8 Kt of methane is being lost from other regulated AD. Methane loss from the AD of food waste totals 12.3 Kt.
Crude oil refineries are the largest contributors of fugitive emissions of NMVOCs from regulated activities with 8.6 Kt.	Regulated anaerobic digestion is a significant contributor of methane emissions. However fugitive emissions of methane as defined by BS EN: 15446 from regulated AD facilities may be smaller than previously thought as this is a small constituent of overall methane loss values.
Based on the data and audit results of the 6 refineries in the UK, some refineries are not meeting BAT on LDAR. Significant improvements can be made to refinery LDAR programmes.	Regulated gas activities including compressor stations are associated with small fugitive contributions of methane (2.13 Kt). However, the bigger picture is not clear as there is an absence of data regarding fugitive losses from gas terminals and fugitive emissions could therefore be significant from these sources.
Of the 23 Igas onshore crude oil exploration and production sites, fugitive emissions of VOCs (methane and NMVOCs combined) are small and equivalent to less than half a tonne.	The majority of fugitive emissions of methane in the gas industry is originating from the unregulated low and medium distribution pipeline (129 Kt) and NTS. Leaks from the NTS are also underestimated with a study estimating that 66 Kt of methane is released as leaks.
The unregulated low and medium distribution system and National Transmission System have high NMVOC losses associated with them.	Absence of production testing and incorrect calibration of pressure relief valves (anaerobic digesters) once

	operational is leading to unnecessary venting of methane.
LDAR is not being undertaken in facilities that are not categorised as LVOC facilities	Crude oil refineries are also responsible for large fugitives of methane from tanks (2.52 Kt).
	Fugitive methane emissions from associated pipework of landfill gas extraction facilities when operational may not be an issue due to a vacuum effect. However when vacuum is not in effect and non-operational, low pressure leaks have the potential to occur.

Table 16: Conclusions regarding LDAR

Conclusions regarding LDAR
The strict application of LDAR could prove an effective tool in reducing fugitive methane emissions quickly to help meet global climate change commitments.
The use of OGI to scan areas for leaks and once leak is detected, quantification using sniffing is becoming standard practice for refineries.
Seals associated with moving equipment, open-ended lines and valves are associated with a higher likelihood of leaking than flanges and connectors.
Combining emission factors of components with annual throughput of associated pipe in a risk based approach could be an effective method to target the surveying of high-risk components.
OGI is more frequently used in the crude oil industry as a monitoring technique for LDAR compared to other sectors.
Over 90 % of fugitive emissions within large facilities originate from less than 1 % of total components.
According to differing reports, OGI can survey components up to 24 times faster than sniffing.
The distance from the component where OGI proves less effective in detecting VOCs is uncertain and differs according to different studies.
Quarterly LDAR surveys can result in reductions of up to 80 % from smaller facilities.
Reducing the leak definition concentration to 500 ppm for sniffing can result in a control efficiency of up to 95 % from valves.
LDAR is being performed at Large Volume Organic Chemical plants, the frequency of these programmes and other elements are unknown due to absence of data. LDAR may not be being performed at smaller chemical plants.
Sniffing is the primary monitoring technique used to conduct LDAR surveys in AD facilities.
Within Wastewater, LDAR of AD associated with sewage sludge has been non-existent up to this point. However this is changing as LDAR will be implemented once a year from 2023. The majority of the equipment used in the treatment of sewage sludge is aged, inspection and maintenance of this equipment is questionable.

Currently it is not justifiable to increase the frequency of LDAR for onshore oil exploration and AD facilities based on the data that is available.

12. Recommendations

12.1. Main Recommendations

Table 17: Main recommendations

Recommendation	Targeted pollutant
The risk-based approach to LDAR outlined in section 13 is recommended to be piloted within larger facilities, particularly refineries but also LVOC chemical facilities, as an improvement to existing LDAR programmes.	Mainly NMVOCs
Stipulate the use of more advanced estimation techniques (where available) when estimating annual fugitive emissions for all regulated activities.	NMVOCs and Methane
Introduce an annual whole-site LDAR survey to those chemical facilities that are not categorised as LVOC (if possible), if not, then apply risk-based approach mentioned in "recommendation no. 1".	NMVOCs
Use OGI camera via EA small task group to identify both fugitive and other emissions and trial OGI as a scanning tool for areas containing multiple components e.g. explore the distance at which the camera remains effective. To be undertaken at a selection group of sites in target sectors: refineries/AD/WWTP, onshore oil and gas/landfill.	NMVOCs and Methane

12.2. Other Recommendations

0. The EA should investigate the nature of fugitive emissions in regards to landfill gas extraction facilities. (methane)
1. Review the situation with LDAR in AD facilities when results of BEIS led study quantifying fugitive emissions from AD have been released. (methane)
2. Encourage the use of OGI in AD facilities. (methane)
3. Initiate a study to understand if petroleum and SOCMI emission factors are relevant for the biogas sector. (methane)
4. It is recommended that the Environment Agency work with external partners to initiate and help with the development of a UK recognised standard for the testing of PVRVs specifically for use within the biowaste treatment sector. (methane)

13. Recommended LDAR approach

Based on the evidence compiled within the strategy, the following approach to LDAR is recommended to be followed for all facilities. A risk-based approach outlined in section 13.3. is advised to be followed for large facilities such as refineries and LVOC facilities in addition to other advice.

13.1. Guidance

Guidance to be followed is advised within the table below:

Table 18: Showing Advised guidance and standards for different parts of the LDAR process

Facility	LDAR record keeping process	Survey using OGI and Sniffing	Fugitive emission estimation
Refinery/terminal	EPA Leak Detection and Repair: A Best Practice Approach	BS EN:15446 for both sniffing and OGI EPA Method 21 for sniffing BS EN:17628 for OGI or sniffing	EI Protocol EPA VOC protocol
Onshore oil and gas production facilities	EPA Leak Detection and Repair: A Best Practice Approach	BS EN:15446 for both sniffing and OGI EPA Method 21 BS EN:17628	EI Protocol EPA VOC protocol
Anaerobic Digesters	EPA Leak Detection and Repair: A Best Practice Approach	BS EN: 15446 EPA Method 21	

13.2. Master Component Inventory

The following steps should be applied when setting up an LDAR master component inventory:

- Every pressurised component within the facility to be identified (in crude oil facilities, only applies to equipment components associated with light liquid service as defined in EI Protocol) and grouped into component types;
- Assign risk to each component type based on Step 1 of process outlined in 13.3.
- Assign each component a unique code, physically tag the component with a code and identify on up to date pipework and inventory diagram; and
- Enter the unique component code into a digital master inventory detailing component type, last survey date, leak/no leak (value if leaking) and repair date (if needed).

Refer to LDAR: A Best Practices Guide when doing this.

13.3. Risk-based Approach for refineries, LVOC chemical facilities and other large facilities

Apply the following qualitative process to target sources most likely to leak:

Step 1: Identify all components within a facility and assign their risk based on component type as defined in table below

Component	Non-flanged connector	Flange	Valve	Open-ended lines/seals/PRVs
Risk	Very-low	Low	Medium	High

Step 2: Categorise risk of leak of component based on associated pipework diameter as defined below

Pipe Diameter (mm)	≤ 50	50 – 100	>100
Risk	Low	Medium	High

Step 3: Combine information from above two tables to determine overall risk of component

Pipe Diameter	≤50 mm	50 – 100 mm	> 100 mm
Component type			
Non-flanged connector	Low	Low	Medium
Flange	Low	Low	Medium
Valve	Medium	Medium	High
Pressure Relief Valve			
Open-ended line	Medium	High	High
Seals	Medium	High	High

Step 4: Apply LDAR intervals to each component based on its risk of leakage as defined in table below

Leak risk of component	Low	Medium	High
Specified interval	One survey every two years	Two surveys per year	Three surveys per year

13.4. Undertaking the Survey

All surveys to be conducted by accredited third party operator that meet the competency specifications in BS EN:15446 where possible and must adhere to the following:

- For sniffing and OGI equipment calibrated as advised in BS EN:17628;
- Sniffing to be conducted as advised by BS EN:17628 or Method 21. OGI survey to be conducted as advised by BS EN:17628.

- Surveys are to be conducted with a combination of both the techniques within refineries, onshore oil production facilities and : sniffing and OGI, a suggested method for larger facilities (refineries and chemical plants) is to use OGI to scan components when particularly numerous from a distance of up to 6 m. Once a leak is visualised on the OGI camera, sniffing used to quantify this leak.
- Surveys to be conducted to the frequencies given in Section 11.1.3.
- Survey to be conducted in favourable weather conditions (low windspeed, no rain or fog);
- Survey to follow pipelines from an up to date Process Flow Diagram or Piping and Instrumentation Diagram (produced in the previous 5 years preferred);
- The survey is recommended to be carried out with a plant engineer present;
- When quantifying leak using sniffing, procedure to follow Section 6 of BS EN:15446;
- All leaks detected by OGI are to be logged into a repair programme; and
- The leak shall be recorded within the Master Inventory including date and a time set for repair also logged;

13.5. Repair

Research has shown that repair is normally coordinated with facility shutdowns in EA regulated facilities, with some leaks this may be a necessary approach. However during a survey, it is advised that plant engineers are involved in the process to make quick repairs where possible, this is currently being employed within refineries. The leak and repair date should always be logged even if repaired and if further repair is needed this should be allocated a date within the master inventory.

All leaks should be addressed immediately and repaired within a period of at least 10 – 15 days, however it is understood this is not always possible. Therefore a table advising the duration for repairs to take place based on the leak value of the source has been given below.

Table 19: Repair duration

Leak value (ppm)	Advised duration for repair
> 10,000	Leak to be repaired within 10 – 15 days.
> 5000	Leak to be repaired within 10 – 15 days. Where not possible a permanent fix must be applied within 1 month of leak detection.
< 5000	Leak to be repaired within 10 – 15 days. Where not possible a permanent fix must be applied within1 – 3 months of leak detection.

Once a leak is repaired, component should be re-monitored again within 1 month using “sniffing” or “bagging” approach and a leak definition concentration set to 500 ppm.

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