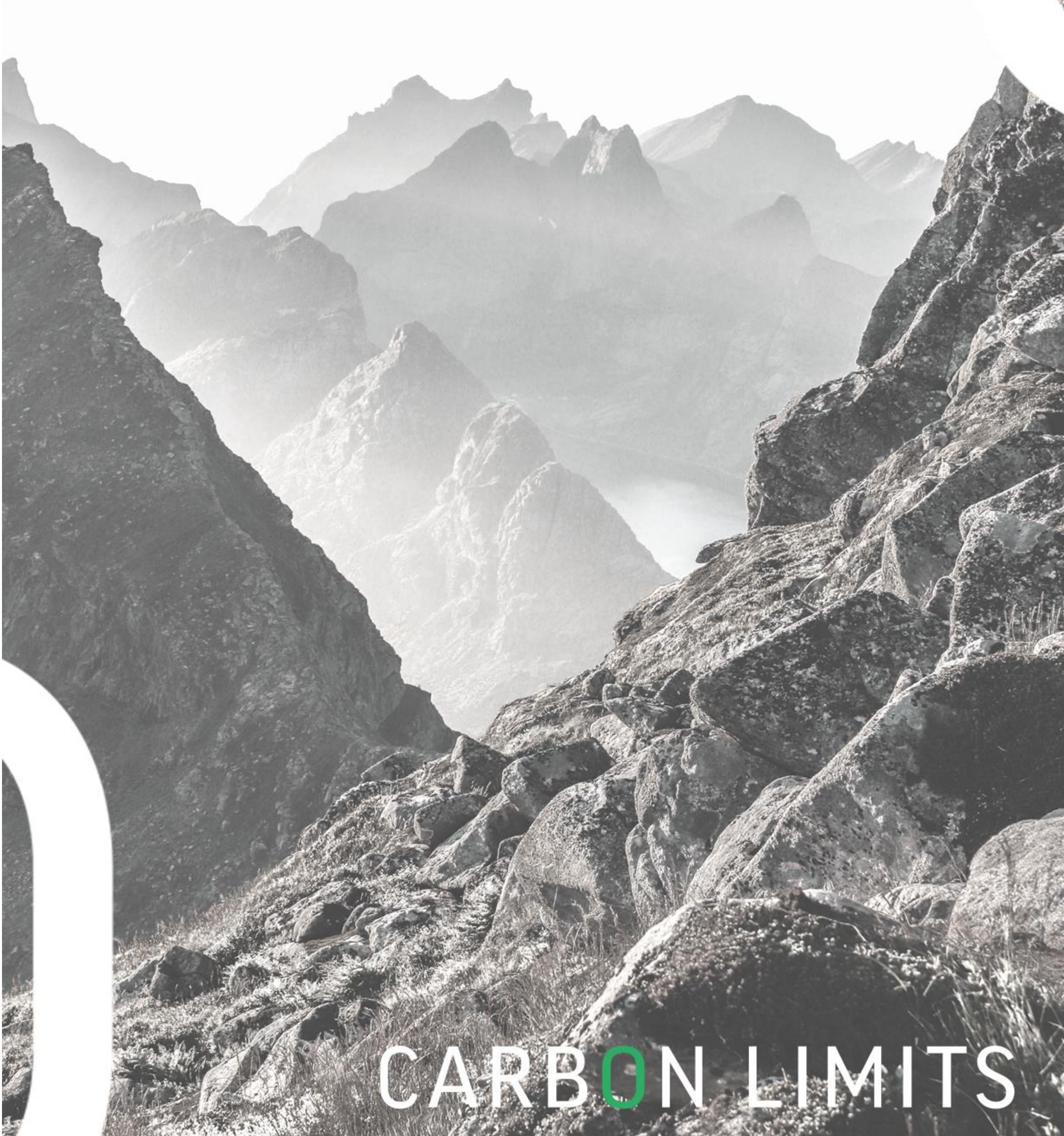
Overview of methane detection and quantification technologies for offshore applications

Update of the 2020 report “Overview of methane detection and measurement technologies for offshore applications”

January 2024



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Carbon Limits works with public authorities, private companies, finance institutions and non-governmental organizations to reduce greenhouse gas emissions from a range of sectors. Our team supports clients in the identification, development, and financing of projects that mitigate climate change and generate economic value, in addition to providing advice on the design and implementation of climate and energy policies and regulations.

This report was prepared by Carbon Limits AS for Offshore Norge

Project title:

Overview of methane detection and quantification technologies for offshore applications

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Report title:	Overview of methane detection and quantification technologies for offshore applications
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Disclaimer

This document was developed based on available data at the time of its preparation, and in dialogue with technology providers, academics and oil and gas operators. In addition, academic publications were reviewed. This report reflects the review of such information sources and is as accurate and robust as the data provided and to the extent of Carbon Limit's knowledge.

This report might not reflect the views of technology providers, and oil and gas operators that have been consulted during its preparation. For further information on their views, it is suggested direct contact with such persons or companies. Methane emissions detection and quantification technologies is a fast-evolving field, and this report does not intend to cover all subsea methane detection and quantification technologies. This report relies on data, technology, and research available to Carbon Limits at the time of its preparation, is prepared on a commercially best effort basis, and has no intention of being exhaustive. The report and technology template may need to be updated from time to time to include additional findings.

The project that resulted in this report has been conducted under the supervision of Offshore Norge. However, Carbon Limits has made the assessment independently and all precautions were taken to avoid any infringement of competition laws and to comply with best practices. No cost elements of the different technologies were shared by or to the participants of the different Offshore Norge members.

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This document has been developed as a follow up of the project and the report titled Overview of Methane Detection and Measurement Technologies for Offshore Applications performed for Offshore Norge and published in 2020[1]. To ensure that this report can be read as a standalone document, some sections of the original report have been included in this document.

Acknowledgements

This Report was prepared by Carbon Limits AS under the supervision of Offshore Norge. Carbon Limits is grateful to the input provided by member organizations of Offshore Norge and technology providers for their input, participation and feedback during the development of this report.

1

Executive Summary

As methane emissions have received more attention, new techniques and technologies are being developed to measure and quantify emissions. A significant amount of research on the detection capabilities of the different solutions has been done. Numerous commercial solutions now exist for methane detection and measurement.

This report is an update of the June 2020 report titled “Overview of methane detection and measurement technologies for offshore applications”[2], prepared by Carbon Limits. for Offshore Norge. It also builds upon the IOGP-Ipieca-OGCI Report 661 “Recommended practices for methane emissions detection and quantification technologies – upstream”, prepared by Carbon Limits[3]. The report provides an overview of techniques and methods for methane detection and quantification for offshore applications, within the specific context of the Norwegian continental shelf (NCS). Recognizing that these technologies are often developed for use on land at onshore oil and gas facilities, technologies are assessed for current capabilities, and their relevance and/or limitations for offshore applications on the NCS. The report builds upon the 2020 report by both identifying technological updates and capabilities of previously included technologies and assessing more recent technologies, to track the progress of methane detection and quantification technologies over the past 3 years. Furthermore, increased focus on third party evaluations of technology performance for detection and quantification has driven the reliance on controlled release testing using standardized test protocols, which provide an evaluation of how technologies would perform when deployed, which moves beyond best-use-scenarios that may be marketed.

Satellite technologies provide global coverage of methane emissions. The effectiveness of measurements depends on the orbit type, geographical latitude, cloud cover and reflectiveness of the view. However, measurements are limited in offshore applications, particularly in the NCS. Low water reflectivity reduces measurement capabilities. Sun glint measurements, where reflected sunlight is measured in the forward viewing plane, is a new development and an ongoing area of research, but currently increases the minimum detection threshold. The challenge is intensified at high latitudes, due to orbital limitations and low solar angles. Current, optimal minimum detection thresholds of best-in-class satellites range from 160 kg/h to 950 kg/h (dependent on latitude, time of year and viewing angle), any may be on the order of many tonnes per hour for other satellites. While ongoing technological advancements and the launch of new satellites hold promise, comprehensive monitoring of offshore methane emissions on the NCS with satellites remains a complex task.

Aircraft-based measurements can cover large distances and fly at various altitudes. They enable both site level measurements and potential for identification of specific sources within facilities. Aircraft can be equipped with a range of sensors, including in-situ instruments and remote sensing devices such as hyperspectral imagers or LiDAR. The methods faces challenges when applied offshore due to the reflectiveness of water. Although it has not been formally assessed for offshore platforms, it is an area of ongoing research. In contrast, in-situ measurements are relevant for offshore applications, and offer the advantage of precise instruments. Flights may necessitate low altitudes, so safety must be considered. Further research and technological advancements will continue to enhance their effectiveness in addressing methane emissions for offshore oil and gas facilities.

Drones are valuable technologies for detection and quantification of methane. They can be used to cover larger areas, eliminating the need for personnel to access challenging locations. Drones can be maneuvered in three dimensions and can carry multiple sensor types. Commercial adoption of drones for methane measurement has gained momentum, both onshore and offshore, driven by advancements in

[2] https://www.carbonlimits.no/projects/overview-of-methane-detection-and-measurement-technologies-for-offshore-applications
[3] https://www.iogp.org/bookstore/product/recommended-practices-for-methane-emissions-detection-and-quantification-technologies-upstream/

lightweight, precise sensors. Drones are remotely operated in line-of-sight distance by trained operators to measure site-level measurements and, in some cases, pinpointing emitting equipment or individual components. Controlled release testing of drones has been conducted, establishing wind speed and direction criteria for optimal accuracy. A trade-off exists between plume dispersion, distance of detection and concentration levels. Drones must also be operated in suitable weather conditions, and in accordance with all safety requirements.

Handheld sensors are useful instruments for bottom-up detection and quantification of methane emissions. Technologies can be used to identify both large and small emissions from individual equipment and components. However, like satellites, aircraft, and drones, they only provide a snapshot of emissions, potentially missing larger/intermittent emissions. Technology performance depends on various factors such as operator ability, observation distance, the wind speed impact on plume dispersion, and in the case of OGI, temperature differences between the emitted plume and background scene. Despite these challenges, OGI cameras and complementary handheld technologies, such as high-flow samplers and tunable diode laser spectroscopy (TDLAS) devices, continue to be instrumental in leak detection and repair (LDAR) efforts on Norwegian offshore installations. They are systematically used for quantifying fugitive methane and NMVOC emissions, both by in-house personnel and third-party contractors, typically on an annual basis. OGI cameras have started integrating quantification in-camera, while the emergence of next-generation high volume samplers enhances quantification accuracy potential. Handheld technologies may also be used in combination, first to detect and then to quantify separately, to better characterize methane emissions.

Continuous monitoring solutions have made recent developments as a useful tool for methane emission detection and quantification, offering real time, continuous surveillance, above and beyond "fenceline" and gas sensors for safety already deployed at offshore platforms in the NCS. Solutions range from in-situ measurements to imaging-based systems that monitor either whole site emissions or from specific emission sources. Recent advancements have shed light on the performance of continuous monitoring solutions. Controlled release testing shows technologies have a range of detection thresholds and quantification accuracy. Research has identified the importance of finding a balance between technology sensitivity and false positive detections. Safety standard for Norwegian offshore installations require additional considerations for explosive atmosphere safety, power requirements and robustness of technologies to withstand harsh conditions on the NCS. Controlled release testing shows promise. Recent research has shown that relying on quantification of emissions from these devices may be premature, but this will also drive improved performance. Nonetheless, the technologies enhance methane emission measurements, and ongoing research and development will continue to refine these strategies.

Analysis of individual technologies reveals the smaller pool of available technologies for deployment at offshore oil and gas facilities. Furthermore, there is an absence of a "one-size-fits-all" approach for a universally applicable technology in all scenarios. All deployment methods have unique advantages and limitations, and even from technology to technology. Deployed technologies should be well understood to create emissions monitoring strategies specific to any facility. Employing combinations of different technologies is essential to provide a more holistic approach to methane detection and quantification. Technology can be used in tandem with process-related information to better understand emission sources, patterns, and intermittency.

An analysis of test protocols for conducting controlled release testing on the NCS for offshore methane detection and quantification technologies has also been conducted by Carbon Limits and is included in this report. This was based on assessment of existing, available test protocols to be able to harmonize procedures and create a more globally applicable standard for controlled release testing. The analysis revealed several insights and considerations. First, offshore-specific safety certifications like ATEX must be a priority for equipment used in potentially explosive atmospheres. Second, complex marine boundary layers pose challenges, necessitating meteorological considerations and optimal testing conditions. Wind speed measurements need relevant measurements at representative heights to capture accurate data. Facility-specific conditions like power and space constraints must be integrated into testing plans. Accurate replication of offshore equipment layouts is essential. First prioritizing testing at non-operating platforms to better understand technologies in representative environments will provide insights into technology performance. Testing on active platforms (or with simultaneous controlled releases) will provide the most representative conditions but are more challenging and requires additional safety and logistical planning. Moreover, harsh environmental conditions require technology resilience. Caution is advised with spectrometric methods over reflective water and should be well understood. Including specific offshore emission sources enhances accuracy.

Figure 1 Summary of technologies assessed, with included datasheets

Technology Type	# Datasheets	Continuous/ Periodic	Sensor Type	Offshore Applicability	Lower Detection Threshold	Site level / Source level (equipment/ component)
Satellites	4	Periodic	Active sensors	✗		
			Passive sensors	✓	160-950 kg/h	Site Source
Aircraft	1	Periodic	Remote sensing	✗		
			In situ	✓	10 kg/h	Site Source
Drones	3	Periodic	Remote	✗		
			Fixed Wing	✓	<1 kg/h	
			In situ	✓		Site Source
Continuous Monitoring Solutions	10	Continuous	Open path	✓	0.1 kg/h	Site Source
			Imaging	✓	<0.1 – 3kg/h	
			In situ	✓	<0.1 – 3.5kg/h	
Handheld sensors	7	Periodic	OGI	✓	<1 g/h	Site Source
			High volume samplers	✓	<5 g/h	
			Spectroscopy	✓	~1ppm	

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Abbreviations

BVLOS	Beyond Visual Line Of Sight
CCAC	Climate And Clean Air Coalition
VOC	Volatile Organic Compounds
DCS	Distributed Control System
EMIT	Earth Surface Mineral Dust Source Investigation
EU	European Union
ATEX	Explosive Atmosphere
FPSO	Floating Production Storage And Offloading
DLR	German Aerospace Center
IR	Infrared
ISS	International Space Station
LDAR	Leak Detection And Repair
LiDAR	Light Detection And Ranging
METEC	Methane Emissions Technology Evaluation Center
NMVOC	Non-Methane Volatile Organic Compounds
NASA	North American Space Agency
NCS	Norwegian Continental Shelf
OIM	Operations Installation Manager
OGI	Optical Gas Imaging
PV	Photovoltaic
PoD	Probability Of Detection
RGB	Red-Green-Blue
SWIR	Shortwave Infrared
SCADA	Supervisory Control And Data Acquisition
TRL	Technology Readiness Level
TDLAS	Tunable Diode Laser Spectroscopy
UN	United Nations
UAS	Unmanned Aircraft Systems
VZA	Viewing Zenith Angles
IFR	Instrument Flight Rules
FAAM)	Facility For Airborne Atmospheric Measurement
NAEI	National Atmospheric Emission Inventory
CSU	Colorado State University
PERL	Experimental Research In Lacq
TADI	Total Energies Anomaly Detection Initiatives

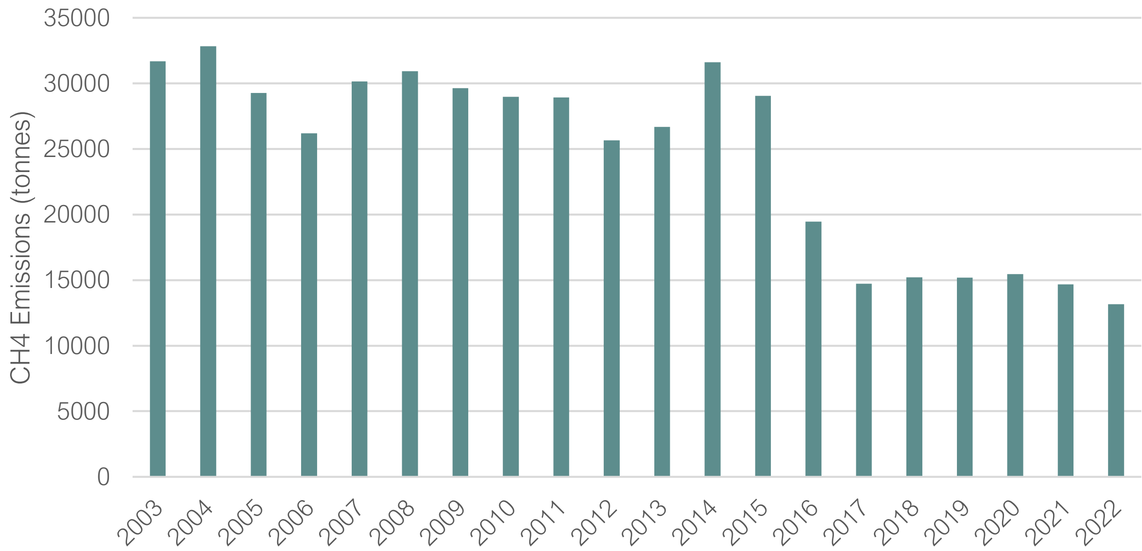
1. Introduction

1.1. Methane emissions from Norwegian offshore installations

In 2021, approximately 13,000 tCH4 were emitted from offshore and onshore oil and gas activities in Norway. This value is very low in international comparison. The Norwegian emissions represents less than 0.02% of global oil and gas methane emissions while Norway's share of global oil and gas supplies are about 2% and 3% per cent, respectively. Since the 2020 report, emissions have fallen by 14%, while total oil equivalent production has remained consistent, 215 MMboe in 2019 compared to 233 MMboe in 2022.

Oil and gas sector methane emissions attracted considerable attention in Norway from 2015 and onwards, with a particular focus in improving the methodologies and practices for quantification of methane emissions from oil and gas installations. This effort resulted in the development and deployment of new quantification methodologies and guidelines for reporting of methane and non-methane volatile organic compounds (NMVOCs) Husdal et al., (2016) which are used by all companies in their emission reports to the authorities. The result was a downward revision of almost 50% in methane emissions from direct emission sources on offshore installations on the Norwegian continental shelf (NCS) for 2017.

Figure 2 – Reported methane emissions from Norwegian offshore activities, (2003-2022, tonnes CH4)



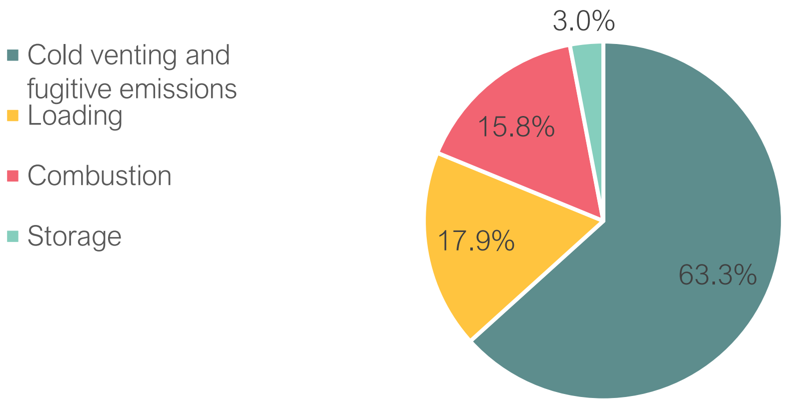
Source: Offshore Norge (2023)[4]

Annual emissions of methane are reported in accordance with methods and emission factors determined jointly by the Norwegian Environment Agency and the industry. Emissions are quantified for each source or process using different methods, including factor-based, measurements and sampling, process simulation, recorded measurement data, and supplier data. Generic quantification methods are primarily used, except for some complex sources or less-common processes, which use facility-specific quantification methods[5] Husdal et al. (2016)

[4] https://info.offshorenorge.no/klimaogmiljorapport23/sec/6/2/4#navto_3117

[5] An overview of emission estimates and quantification methods can be found in Cold venting and fugitive emissions from Norwegian offshore oil and gas activities, Sub-report 2 Emission estimates and quantification methods.

Figure 3. Methane fugitive and venting emissions by main source (share of emissions in percent), 2022



Source: Offshore Norge (2023)[6]

Operators on the NCS are continuing their efforts to improve methods for quantifying emissions. The focus has recently been on improving methods for quantifying methane emissions from gas turbines, flares, and leaking components. This report is part of the ongoing effort by the industry to improve the understanding of emissions and to leverage the best technology and approaches to reach this goal. Methane emission sources on the NCS are summarized based on emission sources where direct emissions are released to the atmosphere. According to the 2023 Climate and Environmental Report by Offshore Norge (2023), the main emission sources are:

- Planned or unplanned emissions to the atmosphere, either due to cold venting or fugitive emissions. Facilities may direct emissions from multiple sources into a common vent to improve metering and safe disposal of emissions to the atmosphere or vented individually through a dedicated vent line. Conversely, fugitive emissions are planned or unplanned , small emissions arising from equipment and components, rather than large, acute leaks. Fugitive emissions are commonly screened through leak detection and repair (LDAR) programs.
- Incomplete combustion from flares and turbines. The most common source of emissions is incomplete combustion of gas from turbines and flares, emissions from delayed flare ignition, extinguished flares, non-combustible flare gas and an open flare purged with inert gas.
- Emissions associated with oil storage, and
- Loading and offloading of crude oil

1.2. Scope and Objectives

As methane emissions have received more attention globally, new techniques and technologies are being developed to measure and quantify emissions. A significant amount of research on the detection capabilities of the different solutions has been performed, through technology performance demonstrations, single blind, controlled release testing, providing quantitative assessments of oil and gas systems or basins, and numerous commercial solutions now exist for methane detection and quantification.

This report is intended to present an update of the June 2020 report titled “Overview of methane detection and measurement technologies for offshore applications”, prepared by Carbon Limits (2020) for Offshore Norge. This report is meant to build on the 2020 report by:

[6] https://info.offshorenorge.no/klimaogmiljorapport23/sec/6/2/4#navto_3117

- Assessing technologies for offshore applications, within the specific context of the NCS
- Identifying technological updates between 2020 and the date of publication of this report to track the progress of methane detection and quantification technologies over the past 3 years, both through the update of previously identified technologies and the development of new technologies which have since entered the market.
- Assessing test protocols for methane detection and quantification technologies in the context of the NCS, to identify synergies or gaps between current practices and what would be required to assess technologies and develop test protocols suitable for the NCS.

Certain sections of the document will also contain information originally addressed in the 2020 report, where changes were assessed but determined to still be valid at the point of update. Where applicable, these sections will be noted.

The report is organized in four sections in addition to this introduction:

Section 2 provides an overview of new technologies and methods for methane detection and quantification technologies. It provides information about deployment methods and sensor types, identifies the relevance of these technologies for Norwegian offshore applications, as well as the updates in the technologies since 2020.

Section 3 provides case studies for use of methane detection and quantification technologies offshore. Case studies are drawn from academic literature. These case studies provide concrete examples of implementation of technologies and the benefits they could present, as well as other important criteria and considerations.

Section 4 presents an overview of existing test protocols for evaluation of methane detection and quantification technologies. Existing test protocols are reviewed, along with interviews with technical experts that either a) operate testing facilities or b) experts on technology testing have been interviewed to identify criteria that is important to consider for developing test protocols. Based on this, an analysis is performed to identify gaps between existing protocols and what would be required for test protocols to be developed for the NCS. These gaps are identified in a series of recommendations that would have to be considered for potential future testing that could occur.

Section 5 presents a summary of the technologies assessed, how technologies have evolved since 2020, as well as a summary of case studies presented and test protocol recommendations.

2. Overview of new technologies and methods

2.1. Techniques and usage

Measurement and quantification estimation of methane emissions is dependent on a methane sensitive sensor, its placement in a position to measure emissions, and a technique which allows for calculation of a flow rate which isolates the source from background emissions. The sensor type and design determine what can be measured and under which conditions. The placement determines where in, or around, the plume measurements take place and how many data points are captured, in addition to capture of relevant meteorological data. The calculation technique determines the flow rate and the uncertainty based on different types of models. The following section provides a brief overview of each of these dimensions.

Sensor Dimension – sensor types[7]

There are many different approaches to determine methane concentration. There are two main groups: in-situ measurement and remote sensing. In situ-measurements involve measurements with an instrument in and around a methane plume, while remote sensing involves measurements from a distance without contact with the methane plume.

The sensor groups and sensor principles are briefly summarized in Table 1.

Table 1 – Sensor groups and principles (Source: (Interstate Technology & Regulatory Council (ITRC), 2018)

Group	Sensor technique	Applications
Metal-oxide semiconductors (in-situ only)	Electric circuits that are doped with oxide materials to react with the target gas, where tin dioxide is commonly used for methane and VOC detection. Gas particles react with the oxide material and result in change in measured electrical resistance.	Handheld sensors, fixed sensors.
Printed nanotube sensors (in-situ only)	Can be designed to detect a range of atmospheric gases, including methane or ethane. The gas molecules change the electrical response of the carbon nanotube sensors, which can be detected and converted to a methane concentration.	Handheld sensors, fixed sensors.
Gas chromatography (in-situ only)	Used to separate different species of gases which are then detected via other detection technologies. A gas passes through a separator column, and the molecular weight of the gases determines the time it takes to pass. The timing of the peaks indicates the type of gas, and gas sensors in combination with the technique can therefore determine presence of ethane or other gases.	Can be used in laboratory on samples from mobile measurements such as ships, tankers or planes.
Mass spectrometry (in-situ only)	Mass spectrometers are used to identify molecules by ionization of the sample and measuring the mass to charge ratios. Mass spectrometer systems may be able to determine isotopes and therefore be used to distinguish between thermogenic and biogenic methane.	Can be used in laboratory on samples from mobile measurements such as ships or planes.
Laser absorption spectroscopy (both in-situ and remote sensing applications)	The technique utilizes the wavelength-dependent absorption of laser light to quantify the concentration of any gas in a mixture. Furthermore, the amount of light depends on the specific gas, gas concentration, wavelength, and total path length over which this light goes through air. There are several methods of magnifying the optical path length to improve the sensitivity of these sensors. This technique is extremely versatile, and several variants of this technique have evolved over time. Typical wavelengths for methane are in the infrared spectrum between wavelengths 1.6µm and 3.3µm.	Used in multiple sensor types, including in drones, planes, ships, satellite
Optical Gas Imaging (remote sensing)	Optical gas imagers (OGI) are specialized infrared cameras using a narrow range of the infrared spectrum which methane and other hydrocarbons absorb. OGI cameras can visualize gas plumes, with leaks appearing as “smoke” in the image. The cameras are not able to distinguish between specific gases, such as methane and propane.	Used in multiple applications, mostly handheld instruments, and fixed sensors.

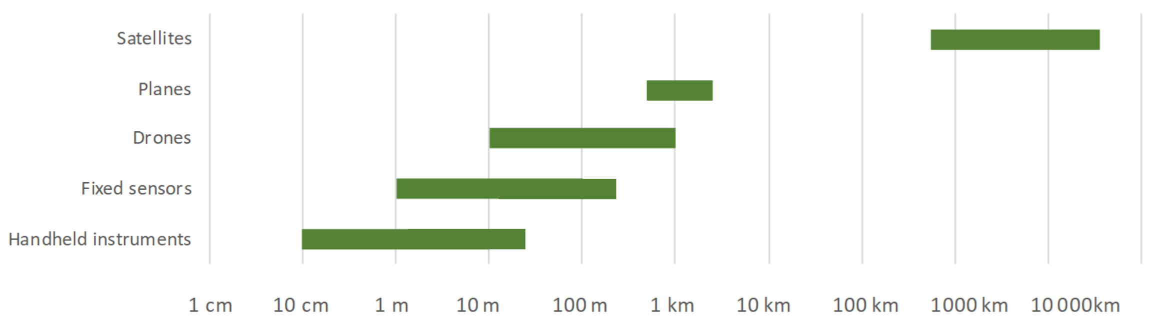
[7] This section is a shortened version from the one published in 2020, which has been included in Appendix D.

Multispectral- and hyperspectral imaging (remote sensing)	Spectral imaging sensors consists of many different techniques to image multiple bands across the electromagnetic spectrum, that go beyond the RGB-bands of visible light. Spectral imaging sensors may have the capability to distinguish between different gases based on their specific wavelength absorption properties. For the purpose of measuring methane, the infrared band is commonly used. The terms spectral imaging, imaging spectrometry, imaging spectroscopy are used without a common distinction. Multispectral imaging is commonly used for systems which capture few, spaced wavelengths, while hyperspectral imaging is used for systems which capture many or continuous wavelengths.	Used in multiple sensor types and techniques for visualization including fixed sensors, airborne and satellites
Dual Frequency Comb Spectroscopy	Dual-comb spectroscopy is a spectroscopic tool that exploits the frequency resolution, frequency accuracy, broad bandwidth, and brightness of frequency combs for ultrahigh-resolution, high-sensitivity broadband spectroscopy. By using two coherent frequency combs, dual-comb spectroscopy allows a sample's spectral response to be measured on a comb tooth-by-tooth basis rapidly and without the size constraints or instrument response limitations of conventional spectrometers.	Fixed sensors

Placement Dimension

The sensor placement determines from where a methane concentration is measured, and therefore what data can be used to calculate emission flow rates. Measuring equipment can be handheld, fixed on site, mobile on the surface, airborne in drones or aircraft, and in different space orbits. Measuring distance from the source varies from a few centimeters in the case of a hand-held instrument, to over 35 000 km in the case of a geostationary satellite. The placement determines the spatial and temporal resolution of what the sensor can detect.

Figure 4 - Measuring distance of sensor from emission point, logarithmic scale



The placement of the sensor also determines whether a method for estimation is at the source level or site level. There are various definitions of source level and site level methods. In this report, source level refers techniques that estimate emissions from individual emission sources in a system and add them together to determine total emissions. Site level measurements refer to estimates that combine numerous individual sources but may not be able to resolve them to individual sources.

Table 2: Overview of the placement option

Group	Distance and spatial/temporal resolution	Estimation Method
Handheld instruments	Very close proximity (10 cm – 30 meters) to individual components and sources. For measurement of full-site emissions all possible emission sources must be surveyed. Per-component resolution, at only short periods of time.	Source Level
Fixed sensors	Close proximity (1-500 meters) to individual components and sources. Measurement of full-site emissions would require monitoring of all possible emission sources. Per component/source resolution with continuous measurement	Source or Site Level
Surface mobile	Measuring distance of downwind methane plume concentrations from ship, typically 500 meters -2 km downwind. Can only measure concentrations from the surface, not in the vertical column of the methane plume. Resolution depends on sensor measurement frequency and travel path, typically distance/time of sailing on a cross-section of the downwind plume.	Site Level
Drones	Possibility to measure full-site emissions in all three dimensions, both in very close proximity (10 meters) and from a distance (up to 1 km). Normally full-site emissions, but depending on measuring distance, individual areas with emissions can be identified. Resolution depends on sensor type/measurement frequency and flight path, typically flying for a half-hour period.	Source or Site Level
Planes	Possibility to measure full-site emissions in all three dimensions, from a distance (500 meters to a couple of kilometers). Measurement of full-site emissions, but depending on sensor type, individual areas with emissions can be identified. Resolution depends on sensor type/measurement frequency and flight path, typically flying for a half-hour period.	Source or Site Level
Satellites	Possible to measure full-site emissions with relative high frequency. Measurement is a vertical atmospheric column in two dimensions. For near-Earth orbits this is retrieved from 500 km-2000 km above the site. For geostationary orbits, this is retrieved from 35 786 km directly above the equator. Resolution depends on sensor type, pixel size and sensitivity, in addition to orbit type.	Site Level

Calculation Dimension

Many methane sensors are designed to determine the concentration of methane in the area surveyed.[8] To estimate a methane emission rate, several calculation methods are available and presented in Table 3. Methane concentration data, along with other auxiliary data, such as wind speed, temperatures, and measurement distance (among others), are required to quantify emissions.

It is important to emphasize that the quantification methods only give estimates, and that there are multiple factors which contribute to uncertainty. Uncertainties in the calculations can arise from multiple factors, including sensor characteristics, the quantity and spatial extent of measurement data, micrometeorological conditions, and background concentration variability. Even with well-designed measurement campaigns, using precise instruments under ideal conditions, there is an uncertainty range in the quantification

[8] At a component level, direct flow measurement may be done though other techniques such as bagging, temporary flowstacks with meters or high-volume dilution sampling

estimates. Single-blind studies (e.g., (Bell et al., 2023.; Conrad et al., 2023; Johnson et al., 2021; Rutherford et al., 2023; Sherwin et al., 2021a, 2023), of different site level or source level methods (Bell et al., 2023), where different technologies and teams have performed measurements on controlled releases of methane, have found that there are significant uncertainty levels. In addition, since most techniques only measure during a short period of time, they may or may not be representative of emissions over time. Measurement campaigns can supplement the measurement information with relevant technical process information from the installation operator, which would allow for better understanding of emissions over time.

Table 3: Calculation methods

Group	Approach
Mass balance	A mass balance approach is based on the law of conservation, whereby accounting for methane entering and leaving a system, emission flows from the system can be measured. By measuring the concentration and wind speed and direction at many altitudes and positions around an emission source, a mass balance can account for net methane emitted from the control volume.
Inverse dispersion modelling	Inverse dispersion modelling is based on downwind methane concentrations measurements. By using meteorological parameters and models to calculate how a plume would disperse downwind to result in a concentration as measured, the emission rate is estimated. The meteorological parameters are either based on measured or assumed wind fluxes in the different layers of atmosphere and turbulence/stability.
Downwind tracer method	Unlike dispersion methods, tracer flux methods do not require knowledge of micrometeorological conditions such as turbulence and exact wind conditions. Tracer measurements involve access to a site for controlled releases of known amounts of tracer gases, such as nitrous oxide, near emission sources, and mobile measurements downwind to measure the enhancements and ratios of tracer gas to methane. Since the emission rate of the tracer is known, methane emissions are calculated by multiplying the integrated methane concentration enhancement by the tracer ratio. Multiple tracer gases can be used in combination to infer emissions from different point sources. The tracer flux correlation approach is a highly accurate method for quantifying site emissions and has been used to assess other methodologies. Disadvantages include the need for onsite tracer release.
Quantitative imaging	For technologies using hyper-, multispectral or optical gas imaging, quantification can be done by using the image data and to derive a leak rate from the images by using a method to measure and control all the variables and derive quantitative results. Background concentration, temperature of gas and background, wind speed, measuring distance are important variables. The camera signal is then correlated to an empirically derived calibration curve to the to determine a release rate.

Technology Detection and Quantification

In general, the closer the methane sensor is to a source, the higher the chance of detection. However, it requires that all sources are screened in to ensure emission sources are not missed, whereas detections conducted from further away will provide a more holistic view, but may, in general, result in a lower detection threshold.

All technologies that are capable of quantification will inherently be able to detect. However, a detection technology may not be able to quantify reliably. Concentrations may be available, but further processing is required (if not performed by the technology through processing or analytics using a method described in Table 3) to determine a quantitative value. Analysis and plume modelling should consider the atmospheric conditions of the marine boundary layer and potential complexities associated with them in comparison to above land. This can be done by using meteorological stations that measure as an example, wind speed and direction, temperature, pressure, humidity (non-exhaustive list) at heights representative of the release heights.

2.2. Performance Evaluation

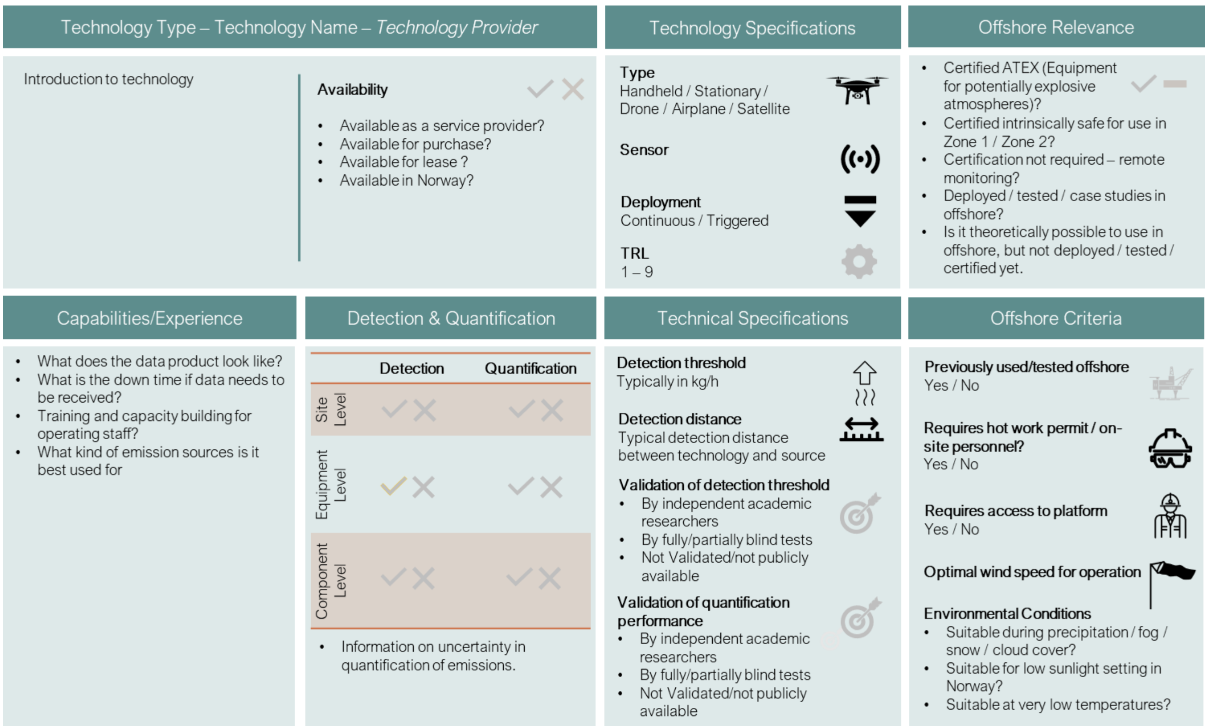
In the following sections, a series of data sheets have been developed for identified technologies applicable for methane detection and quantification at offshore installations on the NCS.

Section 2.1 provides an overview about all technologies that can be used for methane detection and quantification for offshore installations.

Technologies are often well documented, and information is readily available in the public domain, and as shown further on in this report as part of the technology datasheets. However, from a practical standpoint, the question remains on how these technologies can be evaluated and selected for deployment at offshore oil and gas facilities on the NCS.

The datasheets provide detailed information using data gathered from publicly available sources, including academic papers, as well as interviews with technology providers and with expert input from operators. In this updated version of the report, only datasheets for technologies where the providers responded to the request to participate have been included, both to provide a balance between objectiveness and subjectiveness, and the lack of publicly available information that would otherwise present challenges in assessing the technologies without technology provider expertise. Figure 5 shows the technology datasheet template used for presenting information about methane detection and quantification technologies suitable for offshore installations in NCS. The subsequent sections describe the categories presented in the datasheet.

Figure 5: Technology datasheet template



Source of information (will be provided for each field)
(1) Information from interview with technology provider / research on technology provider's website:
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Other references

Table 4: Description of categories presented in the technology datasheet[9]

Category	Description
Introduction to technology	Description of the technology and the technology provider, with information such as placement of technology at the facility, detectable gases and sensor used in the technology.
Availability	Specifies if the technology is available for: • Purchase: instruments are purchased and used by the operator's staff. • Lease: instruments are leased by the operator for a specific duration of time. • Service provider: the technology is deployed or installed by the technology provider, who subsequently provides emission detection and quantification analysis/reports to the operator. This section also specifies if the technology is available in Norway. Indicator colour description: Green tick: if technology is available for lease/purchase/as service and available in Norway. Orange tick: if technology is either available for lease/purchase/as service or available in Norway. Red tick: if technology is not currently available in Norway.
Technology Type	Specifies deployment methods including handheld units, equipment mounted on drones, airplane, fixed sensors permanently installed on site, and satellite-based technology. This can be important if certain deployment methods are challenging for a given facility, for example, plane-mounted solutions will not be possible for a no-fly zone.
Sensor	Description of sensor type used in the technology – sensor for detecting and quantifying methane range from metal oxide semiconductors to laser-based methods, such as tuneable diode laser spectroscopy, laser dispersion spectroscopy (which measures methane along a laser beam), to fixed optical gas imaging (OGI) cameras that allow natural gas (and therefore, methane) visualization. Methane quantification will vary depending on the sensor type, ranging from dispersion-modelling to image-processing.
Deployment	Technologies can be classified as follows: • Continuous monitoring: This could be at site level, equipment level or component level. Continuous monitoring can be affected by gaps in network connectivity or environmental conditions, leading to downtime of the system. • Triggered monitoring: This concerns technologies such as handheld devices and aerial monitoring, which may require assistance in deployment. The actual frequency is then selected by the operator.

[9] The categories presented in this table and their description are based on technology datasheets prepared for onshore methane detection and quantification report prepared by Carbon Limits for IOGP: "Recommended practices for methane emissions detection and quantification technologies – upstream", https://www.iogp.org/workstreams/environment/environment/methane-emissions-detection-and-quantification/. For the sake of consistencies, the description of the categories has been kept similar to the description presented in the onshore report.

TRL (Technology Readiness Level)	Presenting the maturity of technologies. The TRL presented is the readiness level for onshore sites, since most of the technologies presented as part of this report have been deployed onshore. Readiness level for offshore deployment depends on whether the technology has been tested/deployed offshore. TRL 1 to 3 signifies technology is in early development phase. TRL 4 to 6 signifies intermediate developments and TRL 7 to 9 signifies advanced development and deployment of technology. TRLs follow those as set by NASA and the EU[10]. Indicator colour description: Green: TRL 7 – TRL 9 Orange: TRL 4 – TRL 6 Red: TRL 1 – TRL 3
Offshore Relevance	Offshore relevance in the datasheets have been assessed on 3 factors (1) sensor capability to monitor offshore (2) certification of technology for use in explosive atmosphere and (3) prior testing or use at offshore facilities. For some technologies, the capability to monitor offshore facilities depends on sensor type. Some perform worse over water than on land. On certification, technologies may require explosive atmosphere (ATEX) rating, or intrinsically safe rating for class 1, division 1 for deployment at offshore facilities. Technologies have been presented as “technically feasible” if it is suitable for offshore monitoring (i.e. the technology has been developed with intrinsic safety I mind) but pending certification of testing at offshore facilities. Indicator colour description: Green tick: If technology has required certification (or does not require certification, such as the case for airplanes and satellites), AND has been previously tested or used at offshore facilities. Orange hyphen: If technology is technically feasible to deploy at offshore facilities but is pending certification or testing at offshore facilities.
Capabilities and experience	This category presents some of the key aspects of the technology relevant for the operators such as: 1. What does the data product look like? Some providers offer online platforms or other tools to help assess and use the output. The operator will need to consider how actionable these deliverables are, measured against its needs. For example, an operator that is trying to identify components that need to be mitigated may require an output that includes clear and precise localization of the methane plume, whereas figures for methane concentration downwind could be sufficient for an operator that is trying to prioritize efforts across several sites. 2. What is the down time if data needs to be received? Some technologies quantify emissions real-time to provide data almost instantly to the operators, while some technologies might need a few days down time for quantification of emissions. In some cases, network connectivity and lack of sunlight (for PV operation) could also affect the information provided by the technology. 3. Training and capacity building required for staff. Training required for deployment is likely to be closely associated with the business model of the technology provider. Some providers handle everything from installation to post-processing of data. In such cases, the operator would receive the estimated emissions data from the provider, so little training

[10] https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

	would be required for the staff of the oil and gas operator. On the other hand, some providers train the operator to use their handheld devices, drones or other equipment. Time required will vary, depending not only on the equipment but, for example, on staff experience and field/site characteristics. 4. What kind of emission sources is it best used for? Depending on the technology deployment and sensor type, technologies are capable of detecting different emission sources. Small handheld devices such as OGI cameras are best suited for component level emission detection, while stationary fenceline technologies are suitable for detecting methane emissions at site level. Depending on the operator's requirements, a combination of technologies could be required for adequate methane monitoring and quantification.
Detection and quantification	Technologies detecting methane emissions can attribute emissions at site level, equipment level or component level. The table in this category captures whether a technology can detect an emission source and attribute it at site level, to a piece of equipment (for example a tank, a flare, or a compressor) or to a component (for example a valve or a flange on a separator). One of the purposes of detecting methane emissions at component level is to identify leaking or malfunctioning components, typically during leak detection and repair (LDAR) campaigns, where the goal would be to identify emitting components and ensure mitigation. Detection at component level can also be used for inventory: some inventory methodologies require the operator to determine the number of leaking and non-leaking components to estimate fugitive methane emissions. Quantification methods often involve measuring methane concentrations in flows of gases or ambient air but could also include a variety of other measurements, calculations, and modelling. Quantification of methane emissions in this category requires presenting the methane emissions in flow rate (kg/h or m3/h) estimates. Both detection and quantification can be attributed to site, equipment or component level. While a sensor may be highly precise, the quantification method using that sensor may be more uncertain. Technologies with stated uncertainties consider quantification algorithms, environmental conditions, and emission rates. Quantification uncertainty may be reported in terms of a confidence interval of 1σ or 2σ uncertainty (68% and 95% confidence intervals, respectively), and in relative or absolute values. As the uncertainty of the method indicates how accurately the quantification is performed, care should be taken when evaluating uncertainties. Closeness of installed equipment on site, environmental conditions such as wind speeds, cloud cover etc and number of sensors installed across site affect both the detection and quantification aspects. More details on this have been presented in Section 2.1.4 and in the category description for "Detection threshold" and "Validation of quantification performance" below. Indicator colour description: Green tick: Emissions can be accurately and reliably detected at said level. Orange tick: Emissions may be detected at the said level, but it may be challenging to assess this in some cases (for example when site is very large, or if sites are closely spaced) Red cross: Not suitable to detect or quantify at this level
Detection threshold	Detection threshold is the minimum amount of methane that is reliably detectable. While the detection threshold can be presented in several forms (for example,

	concentration, concentration vs distance, volume emission rate, mass emission rate), detection thresholds in this report are stated in kg/h, where possible. Detection threshold depends on the type of emissions to detect. For instance, given the skewed distribution of emission rates, a higher detection threshold will encourage focus on higher-emitting components. It should be noted that the detection threshold is a function of the distance between the emission source and the detection technology, as well as the environmental conditions at the time, notably wind. Some technologies have begun producing probability of detection (PoD) curves to document these relationships.
Validation of detection threshold	Validation of detection and quantification thresholds refers to the ability to correctly detect the smallest amount of methane that is claimed by the provider. In most cases, detection thresholds mentioned in the technology data sheets are supplied by the technology provider and may not have been validated by a third party. Validation status and the source of this information is presented in this category. Probabilities of detection (PoDs) are ideally based on fully blind test results and consider sensor performance as well as environmental variables that can affect measurements, offering the closest conditions to the field. The following categorizations have been presented in the datasheet: • Validated by independent academic researchers: The information comes from a peer-reviewed paper prepared by independent academic researchers and may include results from fully or partially blind testing (see below). • Validated by partial/fully blind tests: Validation can be done using partially or fully blinded tests performed with a third party such as academics, independent researchers or by oil and gas operators. For fully blind tests, the presence, location, and size (if any) of the controlled test release(s) were unknown to the technology provider at the time of the test. This is the closest approximation of field conditions, with the least amount of inherent bias. For partially blind tests, the technology provider was aware that controlled release testing was taking place but was unaware of the size or location of the release. Partially blind tests offer improved validation of technology performance over scenarios where the emission source size was known but may still introduce bias. For instance, the operator performing the test may have taken more proactive steps than normally to detect or quantify emissions. • Not validated / not publicly available: Testing may have already been performed, but the results not yet made public. Information about such cases, where known, are indicated in the technology data sheets. The technology will still be considered “not validated,” since the results were not publicly available at the time of publication. This does not imply anything regarding performance, but only the availability of the information. In some other cases, some validation may have been performed, but there are no plans to make the results public. In such cases, the technology has been classified as “not validated”, even if the results of such validation were communicated orally. This does not imply anything regarding detection capabilities, but only the availability of the information. Indicator colour description: Green: Validated by academia Orange: Validated by fully/partially blind tests

	Red: Not validated
Validation of quantification performance	Quantification performance refers to the ability to give measurement values for the emission rate that match the actual emissions. Quantification performance may be described by comparing measurements to true emission rates. Ideally, the linear regression between measurements and actual emissions is a unit-slope line. Quantification performance may be based on emission rates, wind speeds, and/or distances of measurement technology from the source, all of which can impact quantification performance. Robust, defined, and publicly available analyses increase transparency regarding the abilities. Technologies that have published results for these parameters offer a more reliable indication of performance than those for which results are not publicly available. The categorizations and indicator colour description for validation of quantification performance are same as those presented for the validation of detection threshold.
Previously used/tested offshore?	Indicates if the technology has previously been tested or used at offshore facilities. Offshore locations have different density of equipment arrangements as compared to onshore facilities, and some sites may have additional safety requirements (such as no fly zones) compared to others. Testing at offshore is required before full scale deployment for ideally assessing the suitability of technology. Indicator colour description: Green: Previously tested / used at offshore sites Red: Not tested or used at offshore sites
Requires permit / on-site personnel?	Some technologies, such as handheld analysers, require the site to be manually assessed for emissions with on-site personnel. Depending on safety certifications, this could require obtaining hot work permits. In the case of aerial monitoring, such as with drones or airplanes, the safety of the pilot and the site operators must be considered. This could require permits, as well as significant coordination on the part of the operator. These requirements differ by country. For satellites, deployment depends on the orbital path of the satellite and on environmental conditions, such as cloud cover.
Requires access to site?	Some technologies, such as handheld analysers and fixed monitors could require access to the offshore platform for monitoring of emissions, or for installation of the device at the site. Since offshore platforms could typically be run without any personnel on site, this parameter is important to note for operators.
Optimal wind speed for operation	Wind speed is one of the dominant factors causing uncertainty in detection and quantification of methane emissions. While many of the technologies reviewed as part of this project require the presence of at least some wind to transport methane from the source to the sensor, they usually will not perform equally well at all wind speeds. Wind speed and direction are important for use around the site. Wind can be impacted by obstacles, such as equipment or buildings, which can affect uncertainty.
Environmental Conditions	Some technologies, such as shortwave infrared sensors, measure spectrally resolved back-scattered solar radiation to detect methane emissions. These cannot be used at night because they require ample sunlight. Cloud cover reduces observational ability, for example, by reducing the reflected sunlight that passive sensors use to detect methane, while also increasing uncertainty. This issue specifically applies to aerial technologies. Cloud cover could also affect continuous monitoring that requires solar power. This must be anticipated to have enough power backup (e.g., batteries) to operate when the meteorological conditions are not ideal.

	Snow will impact reflectivity, affecting some laser-based technologies, for example by increasing detection thresholds and/or the uncertainty levels for quantification. This can affect both aerial and fence-line monitoring. Snow can also affect continuous monitoring systems that use solar panels, as the snow can cover the panel and prevent the charging of the battery. Water droplets will scatter light and reduce instrument sensitivity, potentially reducing the ability to detect or quantify emissions. Precipitation may also increase the level of uncertainty in quantification, particularly for laser-based solutions. Rain or snow at the time of detection can also affect the methane plume itself, including its direction and concentration. Quantification could then result in a higher level of uncertainty.

2.3. New developments: Satellites

Satellite sensors measure methane in the total atmospheric column, which is the entire vertical column of air between the surface and the satellite. They therefore must have a very high sensitivity to be able to distinguish a surface methane plume from the background methane concentrations in the atmosphere. Since they are generally not able to identify the distribution of emissions *within* the total column, (i.e., the vertical extent of a plume), they provide information only in two dimensions. However, depending on their orbit, they allow for continuous or frequent measurement, and therefore add a time dimension. Most satellites typically operate from a low earth orbit, with an altitude between ~500 and 1000 km above Earth. At a low orbit altitude, the pull of gravity is almost as much as on the Earth's surface. To sustain altitude in a low orbit satellite speeds must be relatively high and orbit the earth at least 11.25 times per day. [11] Depending on the satellite's field of view, latitude of the site and number of satellites in a constellation, most satellites have a site revisit frequency capability between 1 and 14 days.

A low Earth sun-synchronous orbit places a satellite in a path where it passes above Earth at the same solar time on each path. This orbit is useful for remote sensing instruments because every time that the satellite is overhead, the illumination angle on the surface is nearly the same. This consistent lighting is a useful characteristic for remote-sensing instruments that require sunlight.

In contrast, a geostationary orbit is at an altitude of 35,786 kilometers directly above Earth's equator and follows the direction of Earth's rotation. All geostationary satellites must be located on this ring. Since geostationary satellites are positioned in the same place, they (in theory) have the possibility to monitor areas continuously. The requirement to space these satellites apart means that there are a limited number of orbital slots available, and thus only a limited number of satellites can be operated in geostationary orbit. As the latitude increases, the possibility of measurement becomes more difficult due to the observation angle. At latitudes above about 81°, geostationary satellites would be below the horizon and could not be seen at all.[12] The previously mentioned geostationary satellite, GEOcarb, was cancelled in 2020, and replaced by the EMIT (Earth Surface Mineral Dust Source Investigation) program which can measure methane from the International Space Station (ISS). EMIT data is available through the Carbon Mapper data portal[13]. However, no emissions from the NCS have been identified at the time of writing. Data from this satellite is likely not relevant due to relatively low emission rates (below the minimum detection threshold of the satellite) from offshore operations on the NCS, geographical latitude, and low reflectivity of water (see below for more information), and therefore have not been included as part of this report.

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[11] https://en.wikipedia.org/wiki/Low_Earth_orbit
[12] https://en.wikipedia.org/wiki/Geostationary_orbit
[13] https://carbonmapper.org/data/

Since satellites measure the concentration of methane in the vertical atmospheric column, additional calculations are required to infer an emission rate from concentration data of both point source and area imaging satellites. Briefly, methods are summarized by Jacob et al., (2022) as:

1. Fitting to a Gaussian plume, local mass balance for near-source pixels
2. Local mass balance for near-source pixels
3. Gauss theorem with integration to the outward flux along a closed contour s,
4. Cross sectional flux integral,
5. Integrated mass enhancement with independent wind speed information,
6. IME with wind speed inferred from the plume angular width θ,
7. Machine learning applying a convolution neural network to the plume image.

Successful methods to determine point source emission rates from methane concentration observances using satellites are using the CSF method, where the source rate is inferred from the product of the methane enhancement and the wind speed integrated across the plume width, and the integrated mass enhancement (IME) method where the total mass enhancement in the plume is related to the magnitude of emission with a parameterization dependent on wind speed (Jacob et al., 2022).

Clouds are an important factor in preventing sunlight from reaching the surface of the Earth, and also impacts a satellite's ability to measure methane emissions. The higher the cloud cover and subsequently the larger number of missing pixels, the lower the probability that a detection can be made. For example, TROPOMI data will be rejected with a cloud fraction higher than ~8-15% (Hasekamp et al., 2019).

The following sections describe several characteristics of satellites that must be considered for the deployment and use on the NCS.

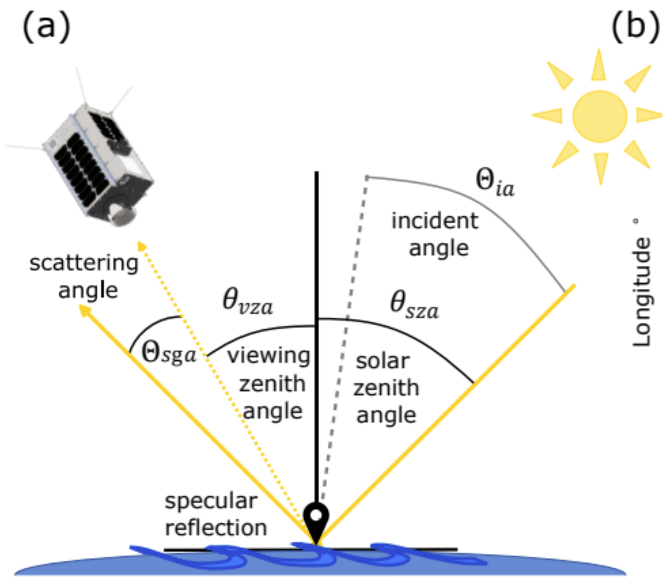
Low reflectivity offshore – passive sensors

Satellites observational capabilities are defined by their ability to identify a methane specific signal through the background noise of each measurement. All satellites in operation, and the vast majority of planned satellites, are based on observation of background radiation such as infrared light, reflected off the Earth's surface, so called passive sensors. Passive sensors in satellites include short wave infrared (SWIR) sensors which measure the backscatter from sunlight on the Earth's surface and thermal infrared sensors, which measure thermal emissions. The sensors are passive in the meaning that they do not emit radiation themselves but rely on ambient radiation for measurement. Satellites require clear skies without cloud coverage. Retrievals may also fail if the surface is too dark, such as over water or forest canopies. Observations of methane emissions from offshore oil and gas operations is more difficult due to this low reflectivity of water in the SWIR.

The detection of methane, and other absorbing gases, over water is a challenging issue for passive systems because one is seeking to detect an absorbing gas over an absorbing surface. Passive remote sensing using short wave infrared suffers from weak reflectivity over water.

However, development of measurements over water have increased the potential coverage to measure methane emissions from offshore oil and gas industry, relative to several years ago using sun glint measurements. Sun glint, the area of a satellite image where the water surface acts as a mirror to sunlight, is generally something avoided when remote sensing from satellites, as the bright areas interfere with measurements and may saturate the imaging pixels. However, the "sun glint" method can be used to enhance the signal over water. In this configuration, the sensor captures the specular reflection of solar off water. Sun glint observations can be achievable by pointing the sensor in the sun-surface forward scattering direction, or by instruments with a large field of view, such that a large part of the swath falls in the forward scattering direction.[14]

Figure 6: Cross-section of the satellite viewing geometry for offshore sun glint observations. The satellite viewing zenith angle, θvza, and solar zenith angle, θsza, are measured with respect to the target normal (black solid line). Incoming solar radiation imp



Source: Maclean et al., 2023

The low reflectivity of water presents challenges for measurements at offshore oil and gas facilities. Currently, Sentinel 5P TROPOMI only provides data on methane measurements from observations over land. Retrievals for observations from ocean observations over sun glint geometries are possible for the TROPOMI instrument using a recent update of the TROPOMI data product implemented a posteriori correction that is fully independent of reference data and accurate enough to correct for low surface albedo scenes (such as over water) and detect methane concentrations in these scenarios (Lorente et al., 2021). GHGSAT has been able to perform glint measurements during the last couple of years, the most notable one measuring the one in a lifetime event on Nordstream's-2 methane leak with an emission rate of 79 tCH_4/h(GHGSat, 2022). Irakulis-Loitxate et al., (2022) have also demonstrated the ability to detect three large methane plumes (111,000 ± 45,000 kg/h, 92,000 ± 40,000 kg/h, 94,000 ± 38,000 kg/h) from offshore platforms in the Gulf of Mexico using sun glint retrievals from WorldView-3 and Landsat- 8. A full physics model for the retrieval of sun glint methane concentration measurements using the Sentinel 5P TROPOMI satellite has also been recently developed to validate retrievals over the ocean to within a precision and accuracy of 1% (Lorente et al., 2022).

However, sun-glint geometry is more technically difficult, as clouds and specific ocean surface conditions such as waves and wind will influence the retrieved signal, and there may be a risk of saturating the sensor pixels. For example, Furthermore, since sun-glint geometry only can be used in certain subsets of the satellites' observational field, the frequency of sun-glint retrieval over specific sites may be significantly lower than observations under normal circumstances[15]. The actual detection capabilities of sun-glint retrieval will

[14] Jacob
[15] Dependent on the sensor type, if it is pointable or fixed.

therefore vary from satellite to satellite. The possibilities of sun-glint detection will have to be tested from each satellite.

Low reflectivity offshore – active sensors

Satellites equipped with active sensors are also possible. Active sensors have the advantage of emitting radiation, as for example a laser, and therefore do not rely on sunlight for measurement. Active sensors may also overcome the weak reflectivity of water. The 2020 report identified the MERLIN satellite, a French-German mission planned to launch in 2024, as a potential satellite with active sensor to monitor methane emissions. However, the launch date of MERLIN has been pushed back from 2024 to February 2028. Therefore, it has been determined that the satellite is not relevant for the current analysis of methane detection and quantification technologies. More details can be found in Section 2.2 of the 2020 report.

High latitudes

The high latitudes of the NCS also pose an additional challenge for measurements from satellites. The high latitude limits the type of orbit which a relevant satellite can be placed in. Geostationary orbits allow for near-continuous measurements over a certain area of the Earth and can improve detection through averaging measurements with frequent intervals.

For other, near-earth orbits, measurements at high altitudes (or VZA, Viewing Zenith Angles) can result in less reliability due to a longer travel path through the earth's atmosphere, higher probability of scattering and absorption of the light before it reaches the satellite sensor, and lower signal to noise ratios. Near-earth orbiting satellites also have certain limitations on their solar zenith angle, (the angle between the sun and the sensor) to avoid noise in the measurements. The satellites observe in a nadir position (directly downwards towards earth), usually at some solar time around mid-day when the sun is at its highest. At high latitudes, the sun is at a lower angle compared to lower latitudes. In the winter months, due to low angle sun, satellite sensing angles may become too high to retrieve data.

Sun-glint geometry observations occur when sunlight reflects off the surface of the ocean at the same angle that a satellite is viewing the surface. At high latitudes above 60 degrees north, solar elevation is never much higher than 50 degrees at its highest point in summer. For sun-glint observation to be possible for a satellite, it would require the ability to observe at an off-nadir point of over 40 degrees (by pointing its sensor towards the glint point) to be able to observe at sun-glint geometry at high latitudes. In addition, high viewing angles would require the solar radiation to travel a much longer path through the atmosphere, making calibration more difficult. Since the solar elevation is lower most parts of the year, even sun-glint observations would be more challenging at high latitudes.[16]

Minimum Detection Threshold

The minimum detection threshold of a satellite determines which emissions can be detected under optimal conditions. Satellite detection capabilities depend on their pixel resolution and sensitivity, and there is a tradeoff between these two metrics. Each pixel is a measurement of the total atmospheric column of methane in an area. As a methane plume flows downwind from a site, the background concentration falls rapidly with dispersion. For a given sensitivity rate of the sensor (total column concentration in parts per billion) a larger pixel size requires a higher emission rate to "fill up" a pixel. A large pixel size of 10x10 km (equal to 100 km^2 pixels) therefore requires a much higher sensitivity rate than a small pixel size of 25x25m (equal to 625 m^2) to be able to measure the same emission flow rate.

[16] GOSAT can observe in sun glint geometry, but since its sensor can only point 20 degrees off-nadir, data over the ocean are limited to latitudes within 20° of the sub-solar latitude. This results in GOSAT retrieval of sun glint observations as far north as Spain.

Several satellites, both commercial and public, are available, and summarized by Jacob et al. (2022). Detection thresholds range from 100kg/h up to 25,000kg/h. Detection thresholds are often presented under optimal conditions, which include measurements onshore, no cloud cover and with optimal wind speeds less than 5m/s. However, measuring methane emission from offshore installations in Norway presents additional challenges, due to the low reflectivity of water and the high latitudes, as described above. Similarly, satellites with low resolution are also highly sensitive to wind speeds, and Norwegian offshore winds are seldom below 5 m/s (14%, 16%, and 24% of the days have an average wind speed below 5 m/s at offshore platforms Sleipner, Gullfaks and Heidrun, respectively)[17]

A recent preprint by Maclean et al., (2023) demonstrates that the detection threshold of offshore glint measurements using the GHGSat constellation will vary significantly based on the time of year as well as the latitude, which impacts the amount of reflected light available. 25th and 75th percentiles of detection thresholds vary from 170 to 240kg/h (in summer at latitudes between 0-30 degrees), to 280 to 620 kg/h in winter at latitudes between 30-60 degrees). Overall, detection thresholds in the 5th and 95th quantiles range from between 160kg/h to 950kg/h. GHGSat may be conservatively viewed as a best-case scenario for satellites currently available, meaning that detection thresholds of other satellites would only be as good (but not improved), compared to these numbers.

Furthermore, satellite measurements of methane emissions can also have high uncertainty associated with them. Sherwin et al. (2023) performed single blinded evaluations of 5 satellites. 49 tests were performed in the desert in Arizona, with 35 (71%) being correctly identified. The following table summarizes the test results. Detections were found to be as low as ~200kg/h (GHGSat). Tests were performed in the open desert in clear skies during daylight hours. Even in these ideal conditions, often measurements were not possible due to cloud coverage. Should be noted that these single blind tests were not meant to test minimum detection thresholds, but to assess quantification accuracy of the satellite. Total errors are also highly dependent on satellite and on the team who conducted the analysis to determine emission rates. These conditions are very different than for offshore, and should not be viewed as comparable, rather to identify the existing challenges in quantifying methane emissions using satellites in general.

Table 5: Summary of single blinded evaluation of onshore satellite-based measurements of CH_4 emissions

Satellite	Coverage	Emission Rates Tested (kgCH_4/h)	1σ Error
GHGSat-C2	Targeted	200-4400	-4% (-17/+13%)
WorldView 3	Targeted	1600-4000	-29% (-57%/7%)
PRISMA	Targeted	2300-7300	27% (-20%/110%)
Landsat-8	Global	1800-4000	7% (-48%/103%)
Sentinel-2	Global	1100-7300	-32% (-68%/3%)

Source: Sherwin et al. (2023)

Due to the limitations of the technology, availability of publicly available measurements and research for offshore oil and gas installations are far less than for onshore, where numerous academic papers have been published on the topic. Researchers have applied satellite measurements to quantify methane emissions from offshore oil and gas. Irakulis-Loitxate et al. (2022) have also demonstrated the ability to detect three large methane plumes (111,000 ± 45,000 kg/h, 92,000 ± 40,000 kg/h, 94,000 ± 38,000 kg/h) from offshore platforms in the Gulf of Mexico using sun glint retrievals from WorldView-3 and Landsat- 8.

[17] See Annex 2 for wind data.

TotalEnergies and GHGSat also launched a new initiative to monitor offshore methane emissions by satellite in 2021[18].

Relevance for Norwegian offshore installations

Satellites have the potential to provide frequent monitoring of methane emissions from individual sites on land. In the next few years, several satellites are expected to be launched (e.g., MethaneSAT or Merlin) that will increase coverage of point source detection.

Methane detection and quantification from satellites has multiple advantages. The satellite service companies could provide competitively large-scale monitoring of total site level emissions over time, which for most other relevant technologies would require multiple deployment of ships, drones, planes or on-the-ground teams using handheld sensors. In the case of MethaneSAT, monitoring and quantification of emission rates will be freely available at no cost.[19]

Detection thresholds of certain satellites are currently on the order of magnitude of 100kg/h in optimal conditions over land. As an example of the potential for satellites to be used for the detection and quantification of methane, Jacob et al. (2022) assessed the possibility for point-source imaging satellites to observe in 5 US basins. Cumulative distribution functions were derived for these five basins using aircraft-derived measurements. To briefly summarize, they determined that 71 observations per year (roughly 5 d return time, assuming 30 % clear skies, using a satellite with a detection threshold of 100kg/h) would be required to estimate annual point source emissions with a high intermittency (emission persistency of 24%) within 50 %, and 145 observations per year to estimate point source emissions within 35% precision. Emissions distributions in the onshore US oil and gas sector are incomparable to offshore oil and gas on the NCS, but the comparison provides an example of the limitation to observe total emissions using satellites alone.

Due to their low emissions, high latitudes and surrounding ocean waters, this will likely be more challenging for Norwegian offshore sites. Even as sensor technology improves and the sensitivity of the sensor increases, remote sensing over water from satellites with passive sensors is still expected to be difficult. A recent article in pre-print by Gao et al. (2023) evaluated the observational coverage of country-by-country onshore oil and gas sectors using the TROPOMI satellite. The median 3-year average number of consecutive days and gap days with valid observations was calculated for all countries. For example, 0% coverage was determined for onshore oil and gas facilities in Norway. This would not be expected to increase for offshore platforms, as previously described above. As mentioned previously, realistic, current minimum detection thresholds of currently available satellites range from 160kg/h to 950kg/h (5^{th} and 95^{th} percentiles), which is highly dependent on latitudes and seasons.

Satellite based services from the European Maritime Safety Agency (EMSA)[20] are currently available that provide visual, routine observations of maritime events related to offshore oil and gas operations, including oil spills and other potential malfunctions or emergency events. While they may be able to detect large emission events quickly, they are not methane-specific, and are used for environmental protection rather than for the identification of methane emissions.

For satellites to be applicable for methane detection and quantification, they must be capable of a low detection threshold over water using sun glint retrievals. They must also have sufficient temporal coverage in the northern latitudes of the NCS. While more research and testing has been performed, with better understanding of satellites for methane over water, no existing or planned satellite fully fulfils these criteria. Passive sensor satellites with high sensitivity and spatial resolution may be able to detect and quantify

[18] https://totalenergies.com/media/news/press-releases/totalenergies-and-ghgsat-launch-new-initiative-monitor-offshore-methane

[19] Data from the TROPMI instrument are also freely available, but are provided as measured concentration enhancements, and must be used in a calculation model to infer flow rates.

[20] https://emsa.europa.eu/we-do/surveillance.html

emissions from some sites, providing large, intermittent emission sources are present at the time of satellite observance.

Updates of the technology review since 2020

13 satellite technologies were initially identified as potentially relevant. However, satellites with release dates much further in the future (e.g. Merlin) and area-imaging satellites (e.g., TROPOMI, Sentinel-2, EMIT, Landsat-8) with large area coverage but with much higher minimum detection thresholds, were not included as relevant technologies. The full list can be found in Appendix D. A similar number of technologies are available, many of which may not be applicable for the reasons covered in the above sections.

There have been technological improvements in sun glint retrievals. More understanding and research have been undertaken, with the recent publication of blinded evaluations of satellite measurements of methane emissions that also evaluated quantification accuracy. There has also been demonstration to use satellites using glint measurements. More commercial satellites are being launched (e.g., several by GHGSat and Orbital Sidekick). Several satellites which are expected to launch may also improve coverage, but it is yet unclear how much coverage for the NCS will change prior to deployment.

There are still challenges for detection thresholds to meet expected emission rates. Potential for large releases to be caught, but intermittency of these potentially larger emission sources, relative to the longer return period times (between 1 and 14 days), means possibility to observe these emissions at the time they occur is minimal. The ability to perform frequent revisits will help better characterize emission sources, confirm the presence or absence of large emission sources and to provide representative measurements of annual emissions.

Similar to the 2020 report, we conclude that detection of all sources of methane from offshore sites using glint measurements will not be possible for the current generation of passive sensor research satellites. However, through periodic monitoring satellites have the potential to quantify large emission sources that may otherwise go undetected or increase confidence in the absence of these emission sources.

Satellite – *GHGSat*

Small satellites with instruments that can detect CH4 emissions and locate individual sources of CH4 from around 500 km above the Earth's surface. Patented imaging interferometer, optimized for CH4 sensing with ~25 meters resolution. Combination of fine spatial and spectral resolution enables measurement and tracking of emissions from individual sites across the world. 10 satellites in space by 2023. (1)

Availability ✓

Available as a service provider (1)

Available in Norway (1)

Technology Specifications

Type
Satellite (1)

Sensor
Fabry-Perot Spectrometer (1)

Deployment
Triggered (1)

TRL
9 (1) (2)

Offshore Relevance

Demonstrated through successful mission operation using an observation mode called "sun-glint", which measures solar radiation reflected by the water surface in the forward scattering direction. (5) ✓

For example, GHGSat has detected and quantified a very large leak from Nord Stream over the Baltic Sea (3) (6)

Capabilities/Experience

Below a non-exhaustive list of the data products available:
- Surface reflectance,
- Methane concentration,
- Methane concentration measurement error,
- Methane emission plume map
- Emission source location
- Emission source rate

- Revisit opportunity time: 1-2 days (as of Aug. 2023) (1)
- Data latency: < 2 days (1)
- Suitable for point sources from targeted locations or for extended domain area mapping. (1)
- Data available through GHGSat's SPECTRA Platform. (1)

Detection & Quantification

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✗	✗
Component Level	✗	✗

Partiality-blind test error between -17% and 13% for three onshore measurements with valid data collection. (4)

Technical Specifications

Detection threshold
Offshore: As low as 150 kg/h CH4 at 3 m/s wind speed, with methane column density precision at 2% of background (1) (4) (5) (6)
5-95th percentiles of 160-420kg/h during summer months and 220-950kg/h during winter months at latitudes between 30-60° (6)

Detection distance
~500km from earth surface
25 m-125 m spatial resolution (1) (6)

Validation of detection threshold
Validation onshore by independent academic researchers (3) (4)

Validation of quantification performance
Validation onshore by independent academic researchers (3) (4)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
No (1)

Requires access to platform
No (1)

Optimal wind speed for operation
Between 1 and 6 m/s (1)

Environmental Conditions
Suitable at high latitudes, however, detection threshold depends on latitude and season (6). Ability to detect will also be affected by cloud coverage (2)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.ghgsat.com
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Semeniuk I. "Canadian satellite captures first direct view of methane leak from Nord Stream pipelines". The Globe and Mail, https://www.theglobeandmail.com/world/article-nord-stream-methane-leak/
(4) Sherwin E, et al. "Single-blind validation of space-based point-source methane emissions detection and quantification". Sci. Rep 13:3836. 2023, https://www.researchgate.net/publication/369066273_Single-blind_validation_of_space-based_point-source_detection_and_quantification_of_onshore_methane_emissions
(5) Ayasse A, et al. "Methane remote sensing and emission quantification of offshore shallow water oil and gas platforms in the Gulf of Mexico". Environmental Research Letters. 17:8. 2022, https://iopscience.iop.org/article/10.1088/1748-9326/ac8566
(6) Maclean, JPW et al. "Offshore methane detection and quantification from space using sunglint measurements with the GHGSat constellation". EGUsphere [preprint]. 2023, https://egusphere.copernicus.org/preprints/2023/egusphere-2023-1772/

Satellite – Maxar – Worldview 3 – *DigitalGlobe*

Commercial Earth observation satellite by DigitalGlobe. Data is offered for research and application development, prototype, and test projects, for users in European Space Agency (ESA) Member States (including Canada) and in the European Commission Member States. Maxar can also be tasked to monitor locations and will provide high-resolution imagery and emission rates. (1)

Availability

Available as a service provider (1)

Available in Norway, but little to no coverage expected (2)

Technology Specifications

Type
Satellite (1)

Sensor
Short-wave Infrared (SWIR) spectrometer (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Could be applicable using an observation mode called "sun-glint", that other satellites have demonstrated measuring solar radiation reflected by the water surface in the forward scattering direction (2), (6)

Capabilities/Experience

Satellite imagery from Worldview3 are available as part of the Maxar Standard Satellite Imagery products and are distributed by European Space Imaging (EUSI). (7)
Technology has been used to monitor large emissions offshore in the Gulf of Mexico (6), but detection threshold is much higher than for onshore measurements. No emission detections have been observed in the NCS in publicly available information (2).
Based on the high detection threshold and low expected emissions from offshore O+G on the NCS, observational capabilities may be limited. (2)

Detection & Quantification (2)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✗	✗
Component Level	✗	✗

Mean error of -32% from metered emissions and 1-sigma uncertainty of 50% for emission sources of 4000 kg/h (4), which are much higher than stated detection threshold of controlled release testing (1).

Technical Specifications

Detection threshold
100 kg/h CH4 (5)
Emissions of ~100kg/h and above from oil and gas fields in Algeria and Turkmenistan, and from coal mines in China. 1500kg/h for offshore emissions in Gulf of Mexico (6)

Detection distance
~600km from earth surface
3.7x3.7m pixel size, with a 66.5x112km^2 swath (5)

Validation of detection threshold
Validated onshore by independent academic researchers (2)

Validation of quantification performance
By independent academic researchers (2)

Offshore Criteria

Previously used/tested offshore
Yes (6)

Requires hot work permit / on-site personnel?
No (2)

Requires access to platform
No (2)

Optimal wind speed for operation
Not Specified (2)

Northern latitude of Norway, cloud coverage, reflectiveness of water and likely means that observational coverage of satellite will result in little to no positive detections (2)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: http://worldview3.digitalglobe.com/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Ayasse A, et al. "Methane remote sensing and emission quantification of offshore shallow water oil and gas platforms in the Gulf of Mexico". Environmental Research Letters. 17:8. 2022, https://iopscience.iop.org/article/10.1088/1748-9326/ac8566
(4) Jacob D, et al. "Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane", Atmospheric Chemistry and Physics 22:14. 2022. p. 9617–9646, https://acp.copernicus.org/articles/22/9617/2022/
(5) Sherwin E, et al. "Single-blind validation of space-based point-source methane emissions detection and quantification". Sci. Rep 13:3836. 2023
(6) Sánchez-García E, et al. "Mapping methane plumes at very high spatial resolution with the WorldView-3 satellite". Atmospheric Measurement Techniques. 15:6. 2022, https://amt.copernicus.org/articles/15/1657/2022/
(7) Irakulis-Loitxate I, et al. "Satellites Detect a Methane Ultra-emission Event from an Offshore Platform in the Gulf of Mexico". Environmental Science & Technology Letters. 9. p. 520-525. 2022. https://pubs.acs.org/doi/pdf/10.1021/acs.estlett.2c00225
(8) European Space Agency. "Worldview-3 full archive and tasking". https://earth.esa.int/eogateway/catalog/worldview-3-full-archive-and-tasking

Satellite – Spectral Intelligence – *Orbital Sidekick, Inc*

Satellite constellation with hyperspectral intelligence, surveying worldwide. Constellation captures over 500 bands of light and reflectance features in the visible and infrared light spectra. Orbital Sidekick utilizes the data gathered by the satellite constellation to provide methane (anomalies) detection and quantification (1)

Availability

Available as a service provider (1)

Data collection in progress. Services for operators to begin in fourth quarter of 2023 (1)

Technology Specifications

Type
Satellite (1)

Sensor
Optical Hyperspectral Sensor (1)

Deployment
Triggered (1)

TRL
9 for onshore detection (1) (2)

Offshore Relevance

Currently the same process is used for observing over land and water, there may be a correction applied of the reflection over water. (1)

Could be applicable using an observation mode called "sun-glint", that other satellites have demonstrated measuring solar radiation reflected by the water surface in the forward scattering direction, (2) (3)

Capabilities/Experience

- Re-visit time for satellite based on operator requirements. Could re-visit within a few days to a few weeks.
- Targeted observations (2 to 4 days required for initial setup). Establishing initial account activation requires targets/shapefile of location(s) to be provided.
- Satellite tasking is done by the provider and is transmitted to the spacecraft constellation for the next available, or scheduled, collection cycle.
- Images with latitude and longitude of potential emission sites and quantification estimates along with wind speeds are sent to the customer via a dashboard. (1)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✗	✗
Component Level	✗	✗

90+% confidence for detecting emissions higher than 200 kg/hr, over land. Uncertainty is leak-rate dependent, lower leak rates correspond to higher uncertainty (1)

Technical Specifications

Detection threshold
Over 100 kg/h CH4 (1)
Will likely be higher for measurements over water (2)

Detection distance
~500km above ground level (1)

Validation of detection threshold
Not validated (1)

Validation of quantification performance
Not validated (1)

Validation of results in collaboration with operators in progress (1)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
No (1)

Requires access to platform
No (1)

Optimal wind speed for operation
Better observation at low wind speeds, less than 5 m/s (1)

Environmental Conditions
Observation affected by thick cloud, precipitation and reflection due to snow cover. Observations could be difficult at high altitude and in winter months. (2)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.orbitalsidekick.com/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Ayasse A, et al. "Methane remote sensing and emission quantification of offshore shallow water oil and gas platforms in the Gulf of Mexico". Environmental Research Letters. 17:8. 2022, https://iopscience.iop.org/article/10.1088/1748-9326/ac8566

Satellite – *EDF* – MethaneSAT

MethaneSAT is developed by a subsidiary of the Environmental Defense Fund. The satellite is designed to provide regular monitoring of emissions from more than 80 percent of global oil and gas production, with enough detail to identify location and emission rates. (1)

Availability

Available as a service provider (1)

Available in Norway/globally (1)
Planned launch of MethaneSAT is January 2024 (information as of 2022) (2).

Technology Specifications

Type
Satellite (1)

Sensor
Short-Wave Infrared (SWIR) spectrometer (1)

Deployment
Triggered (2)

TRL
6* *MethaneAIR, precursor to MethaneSAT was tested in 2021 using the same spectrometer wavelengths, spectral sampling, and resolution (1)

Offshore Relevance

Could be applicable using an observation mode called "sun-glint", that other satellites have demonstrated measuring solar radiation reflected by the water surface in the forward scattering direction, (2)

Detection at higher latitudes (like Norway) could be difficult for satellite systems (2)

Capabilities/Experience

- The satellite will also be capable of measuring CO_2 to be able to correlate potential CH_4 emissions from oil and gas. Data will be publicly available
- Based on the high detection threshold and low expected emissions from offshore O+G on the NCS,cloud coverage, reflectiveness of water and observational capabilities, coverage may be limited. (2)

Detection & Quantification (4)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✗	✗
Component Level	✗	✗

Technical Specifications

Detection threshold
500 kg/h CH4 (3)

Detection distance
~500km from earth surface
400m x 100m resolution (1)

Validation of detection threshold
Not Validated (2)

Validation of quantification performance
Not validated (2)

Offshore Criteria

Previously used/tested offshore
No (2)

Requires hot work permit / on-site personnel?
No (2)

Requires access to platform
No (2)

Optimal wind speed for operation
Not Specified (2)

Source of information
(1) Information from interview with technology provider / research on technology provider's website: www.methanesat.org
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Ayasse A, et al. "Methane remote sensing and emission quantification of offshore shallow water oil and gas platforms in the Gulf of Mexico". Environmental Research Letters. 17:8. 2022, https://iopscience.iop.org/article/10.1088/1748-9326/ac8566
(4) Jacob D.J., "Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane", Atmospheric Chemistry and Physics, 2022, https://acp.copernicus.org/articles/22/9617/2022/

2.4. New developments: Aircraft[21]

Manned aircraft such as planes and helicopters can be used detect and quantify methane emissions from offshore oil and gas facilities The size of the aircraft ranges from larger multi-engine research planes to small single-engine general aviation aircraft. Aircraft based measurements are commercially available and have been used for numerous applications. Aircraft may be used to perform both site level measurements, and in some cases differentiate between emission sources to identify emission locations within a facility.

The major advantage of aircraft for methane measurement is that they can fly at all altitudes and have a long range. This allows both for high altitude overview flights over large areas, as well as low altitude flights for detection and measurement at closer proximities. Their long range allows for flights offshore to survey multiple installations from land, and there are therefore significant returns to scale compared to single-site campaigns.

Many types of sensors can be mounted in these aircraft, allowing for extremely precise instrumentation of multiple atmospheric gases, and for atmospheric sampling for further inspection in a laboratory. Both in-situ sensors and remote sensing instruments including hyperspectral imaging and LiDAR are used.

Plane measurements do not require personnel to access a platform. Aircraft operations require commercially trained pilots. Availability of specialty aircraft and suitable operators may be limited.

For application offshore, there are extra considerations which limit the applicability of different techniques. The following few paragraphs review the applicability of different categories of sensors mounted on aircraft for offshore applications.

Spectral imaging

Aircraft equipped with spectral imaging cameras have been successfully used for onshore methane measurement campaigns and can provide mapped images with an overlay of a colored methane plume image based on concentration in the atmosphere between the aircraft and the surface. It is then possible to calculate flow rates based on atmospheric modelling.

In 2021, spectroscopic measurements using the Global Airborne Observatory aircraft (an airborne research laboratory) were conducted over 150 shallow water production platforms in the Gulf of Mexico (Ayasse et al., 2022). Flights were conducted so that the sensor mounted on the aircraft would equal the SZA, and the glint spot was centered on the target. Therefore, the glint area would be able to detect emissions from the targeted platform. Mean measured emission rates ranged from 213 ± 78 kg/h (attributed to wells) to 906 ± 327 kg/h (attributed to tanks). Generally, a grid scan is performed by flying multiple tracks with parallel lines over an area.

[21] This section has been updated from the 2020 report, with both similar and updated information presented, where relevant.

Figure 7 – Illustration of nadir and sun-glint geometry measurements.

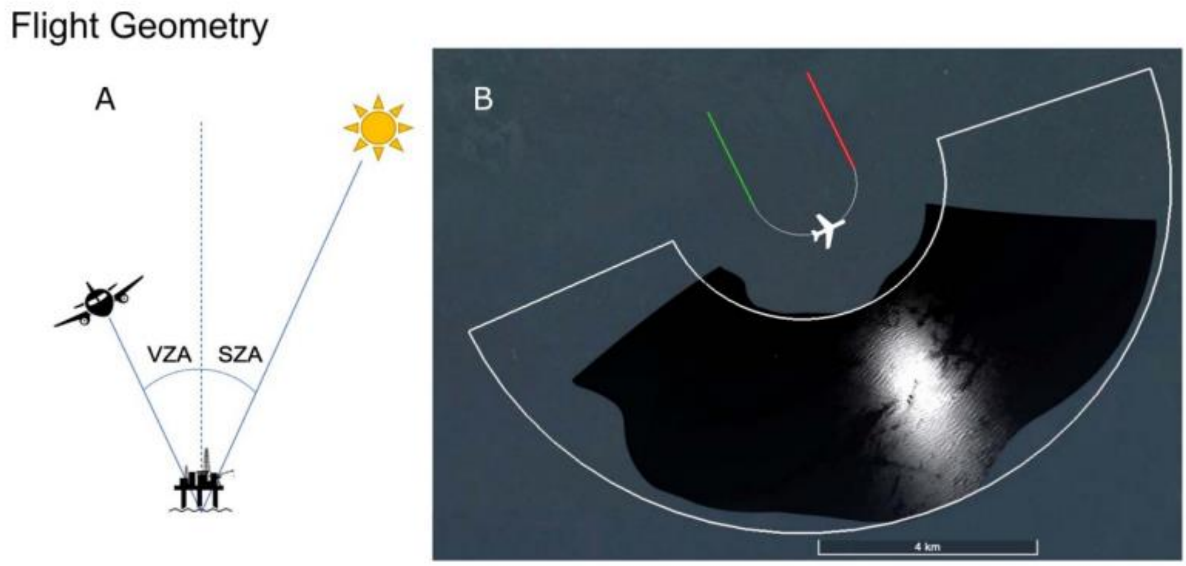


Figure 1. Panel (A) shows a cross section of the sun-target-plane arrangement for the glint collects. The VZA is the view zenith angle and the SZA is the solar zenith angle. Panel (B) show a top-down view of the plane's flight path, the projected collection area, and the actual collected image. The green line is where the plane enters the bank (note airplane not to scale), the red line is where the plane exits the bank, and the white outline is planned collection area. An example red–green–blue (RGB) image of the flight line collected by GAO is included under the planned collection area. The bright spot near the middle of the image is the glint spot. The small dot in the glint spot is the target platform. Although this method targets a single platform, the area surrounding the platform is also illuminated and any infrastructure within the glint spot is surveyed.

Source: Ayasse et al. (2022)

Other research identified in the 2020 report are still relevant to consider for spectral imaging using aircraft[22]. Similar to in the 2020 report, the approach has difficulties when applied offshore. The 2020 report identified Kairos Aerospace and the AVIRIS-NG operated by NASA JPL, as two spectral imaging sensors which rely on reflected sunlight to perform methane measurements. Due to the reflectiveness of infrared wavelengths over ocean water, capabilities of aircraft deploying these sensor types are greatly diminished, which was initially noted in the 2020 report. Current capabilities are expected to be similar, and given the commercial unavailability of these technologies (which are predominantly focused on the US onshore oil and gas sector), technology datasheets were not completed for these technologies.

LIDAR – Relevance and challenges offshore

In the past few years, there has been a large improvement in the capabilities of LiDAR (Light Detection and Ranging). LiDAR is a laser-based technology used to create imagery from a remote distance using pulsed laser or continuous-wave lasers to image gas concentrations. Companies like Bridger Photonics have deployed LiDAR solutions, predominantly onshore in North America.

The technology was assessed using a controlled release study by Bell et al. (2022) to determine a 90% probability of detection of 0.25kg/h/(m/s wind speed) at a flight altitude of 125 m (0.75kg/h at 3m/s wind

[22] Spectral imaging has been used to measure methane emissions with research aircraft from natural marine seeps on the California coast (Thorpe et al., 2014), and from the 22/4b blowout area in North Sea (Gerilowski et al., 2015). Both these campaigns were designed to measure emission rates much higher than expected from Norwegian offshore installations. Even with the sun-glint method, minimum detection levels from these campaigns were relatively high. The latter measurement campaign did not detect heightened emissions from the UK 22/4b area, at an emission rate estimated to be in the range of 10 000 tonnes CH_4/year to 5 000 tonnes CH_4 per year, equivalent to between 1141 kg and 570 kg per hour. While more precise sensors could increase the signal-to-noise ratio and improve sensitivity to lower emission rates, sun-glint geometry limits the flight operations to a more complicated flight pattern in comparison to in situ methods.

speed and 2.25kg/h at 9m/s wind speed). The quantification accuracy of these controlled release rates ranged from -64,1% to 87%, with an aggregate quantification error of +8.2%.

However, plane-based LiDAR measurements are not relevant for measurements over water. Similar to satellites, measurements over water can be performed using sun glint measurements. To this point, the technology has not been formally assessed at offshore platforms but is an ongoing area of improvement. Therefore, it is not currently expected to be applicable for offshore application to reliably perform surveys.

In situ measurements – offshore relevance

In situ measurements from aircraft require flight into a methane plume. Ambient air is sampled through an intake in the aircraft and measured in-flight using a laser spectrometer and/or sampled for subsequent analysis. The aircraft can be equipped with very precise instruments with frequent measurements, allowing for a large dataset for analysis. Since in situ measuring is no more challenging over water than over land, the technique is suitable for offshore measurement. Because estimation and quantification are dependent on the background variability, campaigns using in situ measurement instruments may actually be easier offshore than on onshore, where agriculture, industry or other emission sources could contribute to more background variation which must be corrected for.

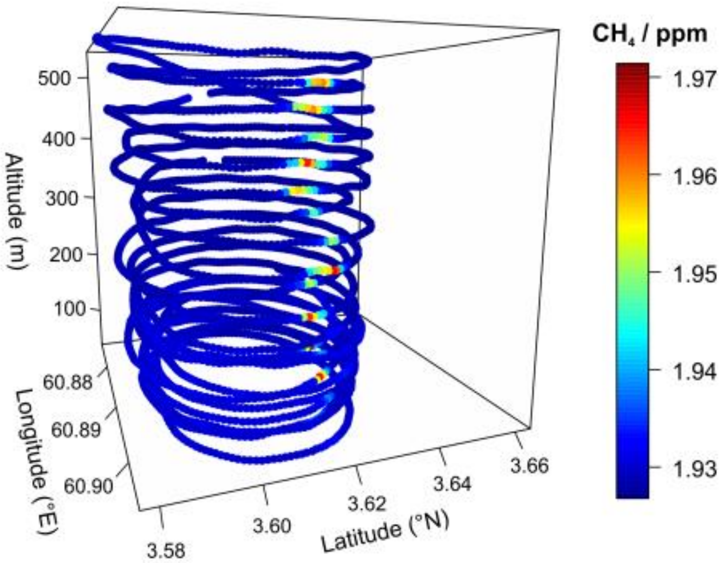
A disadvantage of in-plume measurement from aircraft is that point-source measurement involves at least some flying at low altitudes and in proximity to the sources. Low level flight involves an inherent risk to flight safety, as any unexpected flight situations (such as engine failure or loss of control over aircraft) will leave less time for the crew to handle them. The high focus on safety onboard offshore platforms also means that flights ideally should be cleared by or planned with platform managers.

There are multiple measurement techniques which may be used when performing in situ measurements from aircraft. Since the aircraft can operate in all three dimensions, measurement of meteorological conditions can also be conducted to assist with emission estimation (such as wind speeds, temperatures, pressures etc.) One approach involves flying at a cross-section of a downwind plume, measuring the methane concentration enhancements associated with the plume, possibly at multiple altitudes. Other techniques including variations such as flying both upwind and downwind, at single or multiple altitudes, or a "screen" on the downwind face of the box (Conley et al., 2017). The airborne method described by Conley et al. involves flying around the source investigated at concentric circles at multiple altitudes. This in effect creates a virtual cylinder, observing horizontal wind and trace gas concentrations. The approach relies on flying the aircraft around an emission site in circles approximately 1-2 kilometers in diameter at multiple altitudes from the safest lowest flight level (approximately 200 feet above sea level). This results in approximately 15 to 20 circles up to the highest extent of the methane plume. For a 2 km diameter circle, this is equivalent to a flight path for measurement of about 95 - 125 km, with approximately 30 minutes of flight time per site. By integrating the outward horizontal fluxes at each point along the circular flight path, the emissions from the enclosed source can be determined. The paper described testing of the method on real-life estimation of emissions and compared to controlled natural gas releases of 14 kg/h, with an average difference between estimated emissions and calculated flow rates of 13%. A visual representation of the sampling method is described in Figure 8. Since the 2020 report, this method has also been used in other studies of methane emissions from offshore oil and gas platforms in research by Gorchov Negron et al. (2020), Yacovitch et al. (2020), Ayasse et al. (2022) and Foulds et al. (2022).

Other offshore research campaigns have also been documented. For example, a campaign in 2020[23] was conducted by DLR scientists to measure methane emissions from offshore oil and gas off the Central African Coast. 15 research flights were performed. However, work is ongoing to process and analyse the data to publish results of the campaign and used to compare with operator data from monitored facilities.

[23] https://www.dlr.de/pa/en/desktopdefault.aspx/tabid-2342/6725_read-81464/

Figure 8 Figure B3 from "Quantification and assessment of methane emissions from offshore oil and gas facilities on the Norwegian continental shelf" showing a 3-dimensional map of a light pattern of ChampionX aircraft sampling a CH_4 plume from an offshore O&G facility.



Source: Foulds et al. (2022)

Research part of the United Nations Climate & Clean Air Coalition (UN CCAC) Methane Studies identified in the 2020 report also provides insight into aircraft measurements (France et al., 2021). Methane emission from UK and Dutch offshore oil and gas installations were conducted using a Twin-Otter aircraft to both identify installations that emit significant CH4 and improve flux estimation methodologies for quantification of emissions in the complex meteorology of the marine boundary layer. Researchers noted that in the North Sea, potential temperature profiles of the boundary layer structure can often be partly stratified, with complex layering and increase of potential temperature with height, causing large scale wind circulations around central areas of high atmospheric pressure (anticyclonic behavior) with low wind speeds and poorly defined airflow. This can crease difficulties determining emission source locations and causing emissions to become trapped in vertically thin filaments, and can be missed when flying stacked legs of varying altitude due to gradual increase of CH4 emissions with altitude. In cases like these, researchers determine some particle dispersion models used to calculate emission rates may be inappropriate to use. Contrastingly, conditions in a well-mixed boundary layer result in clear CH4 concentration increases at discrete altitudes. Therefore, it is essential that any modelling undertaken to determine emission rates must have adequate understanding of the atmospheric conditions at the time of measurement, both to optimize measurement effectiveness and improve quantification accuracy.

Relevance for Norwegian offshore installations

Piloted aircraft can measure atmospheric methane concentrations around an offshore installation. Depending on the sensor, the aircraft can maneuver in or above the plume, allowing for measurement and quantification. It is also possible to use supplementary techniques such as ethane measurement or sampling for isotopic analysis.

Plane measurements, like other site level measurements, provide a measurement of emission from offshore oil and gas installations to quantify total site level emissions. Depending on the technology, sensor, flight pattern, site layout, flight altitude and distance from the platform, they may also be able to detect potential emission sources within a facility. Therefore, the emissions they detect are highly dependent on the operating conditions of the platform at the time, and are a “snapshot” of emissions, and may not be representative of annual emissions, without performing multiple measurements per year.

While more precise spectral imaging sensors could increase the signal-to-noise ratio and improve sensitivity to lower emission rates, sun-glint geometry limits the flight operations to a more complicated flight pattern in comparison to in situ methods. Spectral imaging sensors are likely not relevant for Norwegian offshore installations.

Aircraft can be limited by offshore weather conditions. Due to the longer flight times from shore to the offshore sites, and multiple site measurements, operational windows must last longer with less likelihood for unforeseen weather events. Although each flight is planned and executed in cooperation with flight control under instrument flight rules (IFR), the measurements must be performed under visual flight rules (VFR), including minimum requirements for visibility. Based on data wind data for three Norwegian offshore sites in 2019[24], only 42-50 percent of days had lower peak winds than 10 meters per second. In addition, low clouds and precipitation would impede measurement from aircraft. The operation window would likely be between May and October. From a safety perspective, operators on the NCS may have requirements that multi-engine aircraft be used when performing flights for measurement campaigns. Therefore, small single-engine aircraft may not be permitted for use in performing measurements in some scenarios.

Aircraft using in-situ measurements demonstrate the possibility to detect emission rates as low as approximately 10 kg/h. As with measurements from satellites and drones, plane-based campaigns by design only measure for a short period where intermittent emission sources that only occur under certain circumstances are less likely to be detected.

Updates of the technology review since 2020

Two aircraft-based technologies were identified in 2020, both of which have also been included in this report. In the current analysis, 4 aircraft-based methane measurement technologies were initially identified as potentially relevant, which included both spectral-imaging sensors and in-situ techniques. The full list of technologies can be found in Appendix D. Several new research articles were identified since 2020, with other ongoing research being conducted on the NCS and elsewhere.

Aircraft deploying spectral imaging sensors like Bridger Photonics, Kairos Aerospace and AVIRIS-NG rely on similar sun glint methods to satellites to be able to measure methane over water. While technology performance over land is very good, and have been widely commercialized, measurement capabilities over water are currently reduced. While ongoing research into the performance of these technologies continues to occur, no commercially available technologies were identified and relevant for the offshore installations on the NCS at the time of this report.

In-situ based technologies are also available, where site level emissions are quantified by performing mass balance approaches by flying around facilities. One commercially available, aircraft-based measurement technology was identified, by ChampionX. Technology performance is similar to in 2020, with the ability to measure site level emissions without requiring access to the platform. However, there may be restrictions on single-engine aircraft being used for flights, due to safety concerns.

Repeated measurements over time will help to improve quantification estimates of facility level emissions (see Section 3.1).

[24] Measured wind data from three Norwegian offshore sites in 2019 have been used as a proxy for weather conditions, to assess the operational limitations of different measuring technologies. See Appendix C for further details.

Aircraft – Manned Aircraft– *ChampionX*

The ChampionX fleet consists of three Mooney aircrafts, each with slightly different features. Aircrafts feature avionics and navigational systems and can be customized for mission requirements. Measurements can be made using CH_4, C_2H_6, CO_2 and N_2O sensors for single facilities or entire regions(1)

Availability

Available as a service provider (1)

Available in North America, Europe (past deployments) Could be deployed in other regions in the future (1)

Technology Specifications

Type
Airplane (1)

Sensor
Laser Absorption Spectrometer (1)

Deployment
Triggered (1)

TRL
9 (1) (2)

Offshore Relevance

Applicable offshore because access to site is not required. (1) (2)
May be restrictions on flights using single engine aircraft due to safety concerns (6)
Has been used extensively and successfully for offshore quantification. (1) (4)

Published reports from testing in North Sea and Gulf of Mexico (4), (5)

Capabilities/Experience (1)

- **Data product:** Spreadsheet of emissions with uncertainties for each site. Raw data text files with winds, GPS location, methane concentrations for the entire flight. Kml files colored by chemical species available.
- **Data availability:** Actionable preliminary data (spreadsheet of emissions estimates with uncertainties for each site) available same day as measurement. Typically 2 to 4 weeks for a final report/final numbers.
- **Training and capacity building for operating staff:** Pilots part of service have commercial license and are trained on source quantification flights in-house.
- **Best used for isolated facilities** (no other facilities or obstructions within ~1 km of facility)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✗	✗
Component Level	✗	✗

Typically 10 - 30% uncertainty on quantification depending on wind variability (1) (3)

Technical Specifications

Detection threshold
Around 10 kg/h CH4 (1) (3)

Detection distance
1 km (1)

Validation of detection threshold
By fully/partially blind tests (4)

Validation of quantification performance
By fully/partially blind tests (3) (4)

Offshore Criteria

Previously used/tested offshore
Yes (1) (4), (5)

Requires hot work permit / on-site personnel?
No (1)

Requires access to platform
No (1)

Optimal wind speed for operation
2 m/s to 10 m/s (1)

Environmental Conditions
Not suitable for snow on the ground. Can fly in low sunlight, but not night/total darkness. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.championx.com/products-and-solutions/emissions-technologies/aerial-surveys/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Erland B, et al. "Comparing airborne algorithms for greenhouse gas flux measurements over the Alberta oil sands". Atmospheric Measurement Techniques 15. 2022. p. 5841-5859, https://amt.copernicus.org/articles/15/5841/2022/
(4) Conley S, et al. "Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases" Atmospheric Measurement Techniques,https://www.researchgate.net/publication/319684246_Application_of_Gauss's_theorem_to_quantify_localized_surface_emissions_from_airborne_measurements_of_wind_and_trace_gases
(5) Foulds A, et al. "Quantification and assessment of methane emissions from offshore oil and gas facilities on the Norwegian continental shelf" Atmospheric Chemistry and Physics, 2022, https://acp.copernicus.org/articles/22/4303/2022/
(6) Operator input

2.5. New developments: Drones

This section has been updated from the 2020 report, with both similar and updated information presented, where relevant.

Unmanned Aircraft Systems (UAS) or drones allow for atmospheric measurements in three dimensions. Drone-based measurements can observe the concentrations in the vertical column. In addition, they can be used to calculate wind speed and direction in the different layers of the atmosphere, enabling more data for calculations.

Similar to aircraft, they can provide measurements over larger areas more efficiently than traditional methods. Use of drones can also avoid exposing personnel to confined spaces, and to monitor emission sources at elevation that would be challenging or impractical for personnel to access. Drones are also maneuverable in three dimensions, while not requiring direct access to sites. Multiple sensor types (such as IR cameras or in-situ sensors such as TDLAS) can be deployed on drones which allow for flexibility in the deployment.

However, similar to aircraft deployed spectral sensors such as LiDAR, there are limitations for these sensors deployed on drones.

Multicopter close range drones

The drone's flying pattern can be adjusted to use different types of measurement techniques, such as mass balance or inverse dispersion modelling. Since drones can maneuver freely in all three dimensions, hover still, and fly much closer to the emission source than other types of airborne instruments, they also can be positioned to be able to identify heightened emissions from sub-areas or even specific components.

Drones are being used in numerous commercial applications, including on offshore installations. Smaller, lighter, and more precise sensors have allowed drones to be competitive platforms for methane measurement, as the payload of a drone is often a limiting factor for flight durations and capabilities to fly. Methane detection and measurement sensors can be equipped on standard commercially available drones, but specialized drones built by technology providers for methane detection and measurement are also commercially available. Drones are remotely controlled from a line-of-sight distance by a trained operator, allowing the drone to fly around the installation at a distance, but also close to specific areas when needed. This allows both for top-down measurements with quantification of full site emissions but can also in some cases allow for identification of the area of emission or even identification of an individual component.

The detection and quantification capabilities of different drone solutions have been evaluated by researchers in single-blind tests, where the capabilities have been tested on methane emissions with known emission rates. Ravikumar et al. (2019) tested several teams using drones at two sites in California and Colorado, which were designed to assess the technologies' ability to locate and detect leaks and quantify emission rates of different sizes. Many of the flow rate estimates from different teams had significant errors in their estimates, leading to average or systematic errors in quantification. According to the researchers, this is due to the fundamental issue of quantification of leakage rates in from detected concentrations in downwind plumes.

Close-range methane plumes, when sampled over short periods, are often not dispersed as simple Gaussian plume models would predict (Barchyn et al., 2019). This can lead to small areas of high concentration, which can be overcome by averaging over time (minutes to hours). By time-averaging, the spatial pattern can be closer to the prediction of the Gaussian distribution. However, since most mobile measurement techniques move rapidly and measure at the sub-minute level, they can pass through where a plume is expected to be (given a certain flow rate) but measure a higher or lower concentration than expected.

The methane plume mixes as it flows downwind, giving less variability, but at the same time the concentration level decreases, reducing the detection probability for a given sensor. There is therefore a tradeoff between the two, resulting in condition-dependent optimal distances for measurement. As with other mobile measurement techniques, drone measurements present a “snapshot” of emissions for a finite time, intermittent events that only happen under certain circumstances are less likely to be detected.

Controlled release testing of drone-based CH4 measurements was performed in 2020 by researchers in Switzerland over land (Morales et al., 2022). A mass balance approach was used. A minimum wind speed of 2.3m/s, a maximum wind direction variability of 33.1°, and a maximum downwind measurement distance <75m was recommended, as higher absolute error in measurements were observed at lower wind speeds or higher wind variability. Linked to the findings by Barchyn et al. (2019), they recommend multiple measurement passes to be performed to average out short samples, which will provide better quantification of the turbulent plume.

Most drones are built as battery powered multicopter with four or more rotors and have the advantage of the possibility to be controlled precisely in any direction, as well as hover stabile in one position. The energy requirements and weight limitations of batteries typically give 30-40 minutes of flight time before a battery change, which is sufficient for a typical offshore installation. Drone operations require a suitable landing area either on an offshore platform or on a nearby vessel, and it is up to the OIM (Operations installation manager) to decide whether a drone can be operated from the platform. For safety reasons, flights directly over a platform should be avoided. Drone operation is limited to clear, daylight conditions with minimal precipitation, and is typically limited to wind speeds below 10 meters per second.

While analysis of the measurement data can be done off-site, operating personnel must have suitable training to maneuver the drone in accordance with the measuring technique. Companies are developing software such that the drone operation can be more automated, requiring less training for the operators. Fully autonomous drone operations are not allowed under current regulations, and a human pilot is always required to be able to intervene and take control over the drone.

Fixed wing long-range drones

Fixed wing drones have the advantage of more efficient aerodynamics. This provides the advantage of longer flight durations at higher speeds, in addition to the possibility of heavier aircraft and payload. Fixed wing drones therefore can survey larger areas per flight. However, they do not have the capability of hovering in one position or closely inspecting components, since they need a continuous airflow over the wing to stay airborne. Launching and landing for fixed-wing drones is more demanding than for multicopters, and they are therefore not considered relevant for launch from offshore installations. For fixed-wing drones to be relevant for offshore, they must have a sufficient range to be able to carry out their operations from land.

All conventional drone operations are conducted within line-of-sight, meaning the operator must be able to visually control the drone by looking directly at it without optical or digital aids. This, along with the limited flying time of multicopter drones, constrains the possibility of multi-platform or from-shore measurement campaigns. A new development is the possibility to fly drones at long distances beyond visual line of sight (BVLOS). This type of drone operation has the potential to reduce operational costs and risk to personnel when compared to both manned flight operations and onboard drone operations.

Long-range, fixed-wing drones may be launched from an onshore airstrip or open surface and fly out to offshore sites. These drones may be operated autonomously from a preprogrammed flight plan but are under the command of pilots who are able to remotely monitor and take control of the drone at any time. Similar to multicopter drones, the flight range is dependent on payload (heavier weights resulting in reduced flight range) and can also be equipped with different types of sensors, including IR cameras, optical cameras, LIDAR, radar, and gas sensors.

Relevance for Norwegian offshore installations

Drones offer a competitive option for detection and measurement of methane. They are easy to transport and set up, and the necessary operation time for a site measurement is low. A drone can access areas inaccessible for personnel, while also being able to measure at a closer range than an aircraft. Several different solutions are commercially available, employing a range of different techniques and sensors. Some drone solutions also offer the possibility of measurement of ethane for isolation from background methane emissions.

One main disadvantage to using drones offshore, is due to their limited flight range and requirements for line-of-sight operations. This therefore requires that the drone and flight operator must be on board the platform or on a nearby vessel. In addition, high-capacity lithium-ion batteries have an inherent fire risk which must be taken into account, such that they must also not enter any areas that require intrinsic safety or explosive atmospheres. Flight patterns over the platform itself is generally avoided, due to the risk of damage to personnel or equipment from a malfunctioning drone. Flights must also not pose any risk to other air traffic, and therefore must be undertaken at times clear of helicopter transportation. The Norwegian regulation on unmanned aerial vehicles includes requirements on registration and competence of the drone operator (Ministry of Transportation, 2022).

Drones using in-situ measurement sensors have demonstrated that they have the possibility to measure low methane flow rates and are able to quantify emissions down to well below 1kg/h. It should be noted that detection and quantification are heavily dependent on the distance between the drone and the source (due to plume dispersion), emission rate and wind conditions. The configuration of the site layout is important. Since no drones are ATEX certified, they must only fly at distances outside of explosive atmospheres. Therefore, performance will depend on a case-by-case basis.

There are also technical and logistical considerations for drone operations. Operation from a platform requires suitable landing areas and permission from the head of platform. Operators must pilot the drone at line-of-sight distances, and this requires transport to and from each offshore platform. Campaigns over multiple installations would therefore be transport intensive, as also measurement at different times would be. Helicopter transport to and from Norwegian offshore installations requires at minimum a health certificate and a safety course, which could limit the availability of drone service providers. Drone operations from a ship are also a possibility, and ship-based drone operations have been performed on Norwegian offshore sites. This would simplify campaigns over multiple installations but would incur additional costs for ship and crew. Offshore weather conditions can be limiting to drone operation, and most drones are limited to operations at winds below 10 meters per second, which represented 73-78 percent of annual average day-wind conditions in 2019. In addition, operation is not possible in high levels precipitation or low visibility conditions. It is therefore likely that operators must wait onboard for weather conditions and that measurements can be performed only at suitable windows of flight conditions.

The possibility of using long-range, beyond visual line of sight drones for measurement has a significant potential reduce the costs and transport intensity of drone operation. In Norway, there are strict regulations on beyond visual line-of-sight operations. By default, they are prohibited above 120 meters above surface, and in controlled airspace. In special cases, and provided that flight can be performed safely and without hindrance to other traffic, flight clearance may be given (Ministry of Transportation, 2022).

Updates of the technology review since 2020

6 drone-based measurement technologies were identified as part of this report. Of these, three technology datasheets were included as part of this report. Two technologies are no longer in operation or in transition, while one did not respond to request for participation. Technology datasheets for drone operations include products from Explicit, ChampionX and SeekOps. The full list of technologies can be found in Appendix D.

With the increasing relevance of methane measurements, more service providers are entering the market to perform methane measurements of the oil and gas sector. Often, this is through the purchase of, for example, an OGI camera from companies like FLIR, Sensia or Sierra Olympic, packaged with a commercially available drone and inhouse analytics to perform quantification and source attribution of detected emissions.

FlyLogix, a provider of fixed-wing drones that provide CH_4 measurements and identified as part of the 2020 report, is no longer in operation, partly due to complexities of operations in a heavily regulated space[25]. FlyLogix deploys the sensors developed by SeekOps. However, alternative third-party service providers for drone flights may be identified by SeekOps to continue measurements using fixed wing drones. In discussions with operators, there is potential for FlyLogix operations to resume, however the timeline of this is unclear, and as such they were not included in the report. To the consultants' knowledge, no other measurements using fixed wing drones have been undertaken on Norwegian offshore facilities.

In general, there is an increasing testing of drone-based measurement campaigns are being conducted by operators for offshore measurements, with work currently ongoing. TotalEnergies has implemented a worldwide drone-based campaign across its oil and gas assets using an an-house technology called AUSEA[26]. In 2021, Neptune Energy and EDF launched a drone-based campaign across Neptune Energy's UK assets[27].

Many of the conditions highlighted in 2020 are still valid. Safety and flight regulations and requirements are similar to 2020. Similarly, transport requirements and logistical challenges of drone-based measurements are not expected to have changed. Detection threshold for all drones identified are less than 1kg/h. All technologies provide site level measurements and may be able to attribute specific emission sources to equipment, although this is highly dependent on distance of measurement, emission rate, and equipment layout. Attribution of these emission sources may require additional follow-up.

[25] https://www.energyvoice.com/oilandgas/north-ea/497542/flylogix-bp-backed-drone-firm-lands-in-administration/
[26] https://www.pipeline-journal.net/news/totalenergies-implements-drone-based-detection-campaign-reduce-methane-emissions
[27] https://www.neptuneenergy.com/media/press-releases/year/2021/neptune-energy-and-edf-complete-first-its-kind-methane-study-uk

Drone – *Explicit*

Explicit ApS is an engineering company monitoring emissions using drones. The company offers inspection and verification services to operators looking to document their emissions and comply with OGMP 2.0. Explicit provides site level quantification and is accredited for its methods as an independent laboratory under ISO/IEC 17025. (1)

Availability ✓ ✗

Available as a service provider (1)

Available in Norway (1)

Technology Specifications

Type
Drone (1)

Sensor
Tunable diode laser absorption spectroscopy (TDLAS) (1)

Deployment
Triggered (1)

TRL
9 (1) (2)

Offshore Relevance

Not certified as intrinsically safe, or for use in ATEX (Equipment for potentially explosive atmospheres) (1)

Suitable for offshore environments, multiple case studies already performed in the North Sea (1)

Capabilities/Experience (1)

- Explicit is the inventor and provider of the Drone Flux Measurement (DFM) method, a quantitative top-down technique to establish emission rates at site level.
- Drone are equipped with gas and wind sensors to map a cross section of the drifting plumes from a site in so-called vertical 'flux walls'.
- Data is transmitted in real-time to an online (e)lab with results reported in kg/h including detailed map visualizations of the emissions to support source localization.
- Must be flown at safe distances from platform that are outside of explosive atmospheres, and in coordination with platform/operators (2)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✓	✓
Component Level	✗	✗

Max. ± 20 % uncertainty on quantification above 0.5 $kgCH_4/h$ averaged over min. 3 flux walls. (1)

Technical Specifications

Detection threshold
Around 0.3 kg CH_4/h at site level (1)
Threshold may be optimistic and higher based on offshore conditions (4)

Detection distance
From 50-100 meters subject to source intensity (1)

Validation of detection threshold
Third party evaluation performed at TADI, but not publicly available (3)

Validation of quantification performance
Third party evaluation performed at TADI, but not publicly available (3)

The technology has been tested at METEC in 2023, the results are not public as of September 2023. (1) (2)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes (2). If personnel and drone are launched from platform

Requires access to platform
Yes, if launched from the platform. and No, if launch from helipad or supply vessel (2)

Optimal wind speed for operation
Between 1 and 10 m/s (1)

Operational range from -10 to +40 C. Not suitable heavy precipitation/rainfall. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.explicit.dk/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) The DFM method has been independently validated. Documentation available upon request.
(4) Operator Input

Drone – Multi-RotorDrone – *SeekOps*

SeekOps is a sensor technology and data analytics company. Their sensor solution, SeekIR, is a Tunable Diode Laser Absorption Spectroscopy (TDLAS) sensor mounted on drones. DJI M300 drones are typically used with a 40-45min flight time and the SeekIR solution is used to do the quantification of emissions. (1)

Availability ✓ ✗

Available as a service provider (1)

Available in the North Sea. Deployments also possible in North America, South America, Europe, Middle East, Africa, Asia-Pacific, Australia (1)

Technology Specifications

Type
Drone (1)

Sensor
Tuneable Diode Laser Absorption Spectroscopy (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

ATEX (Equipment for potentially explosive atmospheres) certification not required – remote access to site (1)

Can fly around the platform but requires maintaining a certain distance from the infrastructure. Applied offshore in the North Sea, Gulf of Mexico, West Africa, Southeast Asia, Brazil, Australia, etc. (1)

Capabilities/Experience

- The data product consists of both tabular emissions quantification and detailed report with graphics.
- Reports are typically delivered within a few weeks of the completion of the operation, depending on the complexity of the operation, the lead time can be shorter. Trained and qualified regional services partners are used for data acquisition. (1)

Detection & Quantification (1,2)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✓	✓
Component Level	✗	✗

Flying perimeter polygons resulted in an absolute error of less than a 36% difference and an average error of 16.2%, (3) (4)
Equipment level detection can be challenging in densely packed facilities. (2)

Technical Specifications

Detection threshold
Around 1 kg/h CH4 (1) (3)
Threshold may be optimistic and higher based on offshore conditions (5)

Detection distance
<500m from offshore infrastructure (1)

Validation of detection threshold
By independent academic researchers (3) (4)

Validation of quantification performance
By independent academic researchers (3) (4)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes (1). If personnel and drone are launched from platform
Requires access to platform
Yes, if launched from the platform. and No, if launch from helipad or supply vessel (1)

Optimal wind speed for operation
Between 1 and 15 m/s (1)

Environmental Conditions
Technology is suitable in low temperature environments (-20C) and not dependent on sunlight for measurement (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://seekops.com/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Corbett A, Smith B. 2022. "A Study of a Miniature TDLAS System Onboard Two Unmanned Aircraft to Independently Quantify Methane Emissions from Oil and Gas Production Assets and Other Industrial Emitters" Atmosphere. 13:804. 2022, https://www.mdpi.com/2073-4433/13/5/804
(4) Ravikumar A, et al. "Single-blind inter-comparison of methane detection technologies – results from the Stanford/EDF Mobile Monitoring Challenge". Elem Sci Anth. 7:37. 2019, https://online.ucpress.edu/elementa/article/doi/10.1525/elementa.373/112505/Single-blind-inter-comparison-of-methane-detection
(5) Operator Input

Drone – DJI Matrice – *ChampionX*

For lower altitude and near-field point source quantification, Scientific Aviation provides drone platform solutions using DJI Matrice drones. The drones are equipped with anemometers, temperature and a methane analyzer. Custom-built iPad app controls the drone flight path, with real-time data and camera views. (1)

Availability

Available as a service provider (1)

Available in North America, Europe, Australia. Could be deployed to Asia, Middle East with some planning (1)

Technology Specifications

Type
Drone (1)

Sensor
Laser absorption spectrometer (1)

Deployment
Triggered (1)

TRL
9 (1) (2)

Offshore Relevance

Not certified ATEX (Equipment for potentially explosive atmospheres) (1)

Technology has been tested offshore, with EDF UK Neptune site (1)

Has been deployed on a platform in the North Sea, but data not published yet.

Capabilities/Experience (1)

- Spreadsheet of emissions with uncertainties for each site measured. Kml files of drone flight path colored by methane, showing methane hotspots downwind of emissions sources.
- No down lead for data to be received and analyzed. Preliminary data products available within 1-2 days.
- Drone pilots included in service, are trained and hold a part 107 license.
- Best used for any source that can be accessed by the drone pilot. Sources of <1 km diameter in size (limited by flight time). (1)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✓	✓
Component Level	✗	✗

Technical Specifications

Detection threshold
Around 0.02 kg/h CH_4 (1)
Threshold may be optimistic and higher based on offshore conditions (3)

Detection distance
Recommended flying between 10m and 500m downwind of sources (1)

Validation of detection threshold
Not validated (1)

Validation of quantification performance
Not validated (1)

Blind controlled release testing from METEC, 2023, currently in progress (1)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes (2). If personnel and drone are launched from platform

Requires access to platform
Yes, if launched from the platform. and No, if launch from helipad or supply vessel (2)

Optimal wind speed for operation
Between 2 and 10 m/s (1)

Environmental Conditions
Able to operate down to -10 degrees Celcius. Very low temperatures not suitable (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.championx.com/products-and-solutions/emissions-technologies/drone-surveys/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Operator Input

2.6. New developments: Offshore mobile surface-based sensing

No updates on offshore mobile surface-based sensing techniques have been identified since 2020. The text from the 2020 report on ship-based measurements can be found in Appendix D. (France et al., 2021) also noted that due to meteorological conditions on the NCS demonstrate complex boundary layer dynamics and impacts on plume dispersion, that require full understanding of meteorological conditions of the marine boundary layer across the entire layer. They note that this presents a significant limitation of ship-based measurements that are unable to resolve the vertical structure of a plume in the marine boundary layer and will rely on potentially idealized models of plume dispersion to detect and quantify emissions. Similar to conclusions in the 2020 report, ship-based measurements are difficult and effort-intensive, and predominantly research-based. Moving beyond research-based applications would require that cost of implementation and more market demand to develop an economically feasible business model for the development of commercially available ship-based measurements of methane emissions from offshore oil and gas facilities in Norway. Therefore, ship-based measurements will not be further assessed as part of this report.

2.7. New developments: Handheld sensors

Handheld sensors such as optical gas imaging (OGI) cameras or in-situ measurements of methane concentration, can be used to identify methane emissions from individual components and sources at facilities. Each component with a likelihood of emissions must then be screened. This bottom-up approach allows for detection and identification of very small emissions and gives basis for mitigation actions. Similar to aircraft, airplanes and drones, the limitation of handheld sensors is they only provides a snapshot of emissions, where events that happen only under certain circumstances are less likely to be detected.

OGI cameras (such as models by FLIR, Sensia, or other OGI cameras with a detection limit of <3g/h) are used to screen leaking components. OGI cameras can also be used to quantify emissions using a quantitative aspect, often referred to as QOGI. This allows OGI cameras to move beyond regulation requirements of performing LDAR for fugitive emissions, to quantification of other, process-related emission sources. This can be done through a connected tablet where processing and analytics can be done at the time of OGI measurement, integrated directly into the camera, or saved to the camera directly, with post-processing occurring after the campaign. QOGI cameras can be used to both detect and quantify leaks.

While handheld sensors were originally used to identify smaller, fugitive emissions that are unintentional, they can also be used to quantify process emissions (i.e. intentional emission sources such as vents).

The capabilities of handheld OGI cameras are a function of several parameters. First observation distance will impact the ability to observe emissions, with larger distances reducing the relative image size and pixel count that observes a plume. Atmospheric dispersion of the plume by wind speed will also cause more challenges, with stronger winds dispersing a plume more quickly, thus reducing concentrations. Apparent temperature difference between the emitted plume and background scene (ΔT) will also impact abilities, with stronger temperature differences allowing for a more visible plume, typically greater than 5 degrees Celsius, but on a sliding scale.

While not conducted recently, a 2017 report by Concawe evaluated the quantification abilities of OGI camera systems (FLIR QL100 QOGI tablet with a FLIR GF 300/320 series camera). Where leak rate quantification was achieved with the QOGI system, the differences between the values determined and the known release rates were within a range of -23% to 69%, with an average difference of 6% (Caico et al., 2017). While the technologies are likely outdated now, it presents the challenges with quantification using OGI cameras.

A more recent preprint evaluated several anonymized technologies for quantification of midstream emissions in 17 controlled release tests (Liu et al., 2023). Two QOGI cameras had absolute errors of 63 and 74%, were able to quantify within 0.5-2x the release rate 36-and-25% of the time, and within 0.1-10x within 79-and-69% of the time, covering a total of 94%-and-82% of the released volumes. One OGI camera was also not able to measure a source due to the height of the release point, which also highlights the importance of distance of detection in the ability of an OGI camera both to detect and quantify emissions.

A more thorough analysis of OGI cameras was also conducted in 2020 (D. Zimmerle et al., 2020). 488 controlled release tests were performed at METEC over a 10 month period. The study showed important implications for detection rate, where more experiences operators were able to detect 1.7x more leaks than operators who had performed fewer surveys. While this is not indicative of the technology itself, it shows the importance of operator experience and motivation to be able to detect and quantify leaks.

As with other measurement technologies, weather conditions must be taken into account when performing LDAR using handheld OGI cameras. High wind conditions make it more difficult to detect leaks but actual performance on board is dependent on the actual wind exposure at the point of measurement (Ravikumar et al., 2018). At wind speeds over 10 m/s, it is not suitable to measure some exposed areas. Precipitation is also a limitation. Even though the OGI cameras have a weather-proof rating, water evaporating from warm components interferes with gas visualization on the OGI cameras. Measurement campaigns are therefore typically performed between March and September.

Methane detection using handheld instruments requires close access to all components and is time consuming. Small emission sources can be difficult to detect, and one component may require measurement from multiple angles to classify with high certainty. On an offshore platform, thousands of points must be inspected carefully. Depending on the size of the platform, a campaign can take between 40 and 180 hours, with an average platform typically requiring 48 hours of measurement. Each identified emission point is recorded, tagged, and reported.

While the LDAR campaigns are motivated primarily by a high emphasis on offshore safety and are basis for maintenance and repair, the results from the campaigns are used as basis for subsequent quantification. To quantify the results, statistically derived emission factors are assigned to each component based on the industry "Leak/no leak" method, which sums individual leaks together to report cumulative values at the asset level.

Handheld solutions such as OGI cameras are widely used for LDAR, detecting leaking components. They may also be used to screen other venting sources, which are not typically covered in an LDAR program. The technology can be used periodically to monitor for emissions. Companies are familiar with the technology.

Apart from OGI cameras, other complementary, handheld technologies exist. For example, three new high flow sampler technologies have also been developed, which replace the discontinued Bacharach High Flow Sampler. High flow samplers were tested at Colorado State University, with results published in an open report in 2022 (D. Zimmerle et al., 2022). High flow samplers measure emission directly from the source. However, they are typically accompanied by detection technology such as an OGI camera that can screen sources much quicker. Other handheld technologies that employ tunable diode laser spectroscopy (TDLAS) are also commercially available. These technologies are similar in practice to US EPA Method 21 (which has traditionally been performed using flame ionization detection of photoionization detection), and can be used to screen for leaks prior to quantification using an alternate method.

Relevance for Norwegian offshore installations

Since 2017, handheld optical gas imaging cameras have been an integral part of leak detection and repair (LDAR) campaigns and maintenance on Norwegian oil and gas platforms. Detection and quantification, for environmental reporting purposes, of small gas leaks is performed through the OGI leak/no leak method (Offshore Norge, 2022). The quantification method is based on a database of facility components with leak potential, updated over time based on a quantitative risk assessment[28]. They are systematically used as basis for quantification of fugitive methane and NMVOC emissions. Both in-company personnel and service providers are used for LDAR campaigns. Typically, the inspections are performed on an annual basis, with one trained operator transported by helicopter to an installation to perform a systematic inspection of all components, area by area. Other handheld technologies are also available for leak detection, while high flow samplers are available for quantification for accurate measurements as follow-ups.

Handheld instruments require explosion proof certification to be operated on an offshore installation, or else a work permit for "Hot work class B" must be issued (Offshore Norge, 2022). The assessed technologies are largely ATEX-certified and can be used by operator personnel or third-party contractors.

Updates of the technology review since 2020

The availability of OGI cameras and handheld detection devices has increased, with more technologies for use in ATEX environments. Minimum detection thresholds are similar to in 2020, being able to detect even small leaks. Quantification has begun to be integrated directly into OGI cameras. However, there is still uncertainty in the accuracy of these technologies to accurately quantify leak rates. One major development is the new availability of next-generation high volume samplers, which can be used as a follow up to detection that will provide more accurate quantification. There is better understanding of the technology capabilities, highlighted by the dependence on operator ability to detect all emission sources accurately and reliably.

[28] Quantification is also performed using LEL sensors. This additional measurement is performed for safety considerations, rather than for quantification from an environmental impact perspective.

Handheld – GFM 2.0 – *Addglobe*

Designed as a replacement for the obsolete Bacharach Hi-Vol Sampler, this second generation of the device provides sample flow rate and natural gas concentration of samples. (1)

Availability ✓

Available for purchase (1)

Europe, Canada and United States (1)

Technology Specifications

Type
Handheld (1) High Flow Sampler

Sensor
Nondispersive infrared sensor (NDIR) NDIR Optic Sensor tuned to Methane. (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Certified as intrinsically safe, or for use in Class 1 Div 2 (UL)/Zone 2 ATEX (Equipment for potentially explosive atmospheres) (1) ✓
Currently being used in offshore platforms in Trinidad (1)

Technically possible to use but not tested yet. (1)

Capabilities/Experience (1)

- Data saved and displayed on phone by date. Measured and Calculated Values saved to Date/Time Stamp/Location/Leak Rate provided as part of the set. .
- Training time on GFM 2.0 is approximately 1 hour. Support and Application Videos under development.
- Backpack included

Detection & Quantification (1)

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✗	✗
Component Level	✓	✓

GFM 2.0 is capable of detection in theory, but is most commonly used as a follow up to quantify emissions after detection using another device (e.g., OGI camera) (2)

Technical Specifications

Detection threshold
Less than 1 kg/h CH4
0.25 Standard Liter Per Minute (SLPM) (3)

Detection distance
Directly at source (1)

Validation of detection threshold
By partially/fully blind tests (3), (4)

Validation of quantification performance
By partially/fully blind tests (3), (4)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes (1)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not Applicable- measurements capture entire plume (2)

Rated for -20° C. Battery however could be affected by lower temperatures (2). Ingress Protection 68 (water resistant in fresh water to a maximum depth of 1.5 meters for up to 30 minutes and are protected from dust) incorporated. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://addglobe.com/product/gfm-2-0/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Zimmerle D, et al. "Open-Source high Flow Sampler for Natural Gas Leak Quantification". 2022. https://energy.colostate.edu/wp-content/uploads/sites/28/2022/08/FACF_High_Flow_Final_Report_ada.pdf
(4) Tim Vaughn, "AddGlobe GFM 2.0 Assessment". 2022. Available at https://addglobe.com/product/gfm-2-0/ (requires creation of account to access).

Handheld – Flow Sampler – *HETEK*

The Hetek Flow Sampler is a gas leak quantification device. It quantifies the leak by sampling at high flow rate(s) to capture all the gas leaking from the component along with surrounding air. By measuring the flow rate of the sampling stream and the natural gas concentration within that sample stream, the natural gas leak rate is calculated. (1)

Availability

Available for purchase (1)

US, Canada, Europe, Middle East (Predominant clients fall in these regions. Hetek could ship to other countries, subject to supply chain restrictions) (1)

Technology Specifications

Type
Handheld (1) High Flow Sampler

Sensor
Catalytic oxidation and thermal conductivity (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Certified intrinsically safe for use in Zone 1 / Zone 2, and has ATEX certification (Equipment for potentially explosive atmospheres) (1)

Not tested or deployed at offshore platforms. (1)

Theoretically possible to use in offshore, but not tested yet. (2)

Capabilities/Experience (1)

- Device displays quantified leaks (in lpm for cfm. CSV file can be obtained after surveying. Calibration records also available in csv format
- Basic product operation training takes about 1-day – provided by HETEK or distributors of technology.
- Best suited for component level emission estimation, in combination with OGI camera to do the initial detection.
- Portable, usually in a bag (1)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✗	✗
Component Level	✓ (partial)	✓

Detection is often performed with OGI camera prior to quantification using Hetek flow sampler. Theoretically, Hetek is also capable of detection at component level. (1)

Technical Specifications

Detection threshold
Less than 1 kg/h CH_4
0.127 lpm CH_4 = 4.95 g/h(1) (3)

Detection distance
Directly at source (2)

Validation of detection threshold
By fully / partially blind tests (3)

Validation of quantification performance
By fully / partially blind tests (3)

Newer tests being planned in 2023 to assess detection threshold (1)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes (1) – no hot work permit required

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not Applicable (2)

Operating temperature between -20 C to 40 C, at low temperatures, battery life is impacted. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.hetek.com/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Zimmerle D, et al. "Open-Source high Flow Sampler for Natural Gas Leak Quantification". 2022. https://energy.colostate.edu/wp-content/uploads/sites/28/2022/08/FACF_High_Flow_Final_Report_ada.pdf

Handheld – Mileva 33– *SENSIA*

Mileva 33 is SENSIA's latest model of Quantitative Optical Gas Imaging (QOGI) for the detection of fugitive emissions of hydrocarbon gases (HxCx). It integrates a spectrally optimized high-resolution cooled detector that increases the detection sensitivity for leaks down to 0.35 g/h of CH4(1)

Availability ✓ ✗

Available for purchase (1)

Available worldwide (1)

Technology Specifications

Type
Handheld (1)

Sensor
Cooled Optical Gas Imaging (OGI) (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Certified ATEX Zone 2 (Equipment for potentially explosive atmospheres) (1) ✓ –

Camera platform has been previously used on offshore platforms, but not in North Sea (1)

Capabilities/Experience (1)

Data output: .mp4 and radiometric videos, generatable reports and .json quantification files.

SENSIA offers 2 days of training (1 theoretical and 1 practical) for use. Performance is operator-experience dependent (2)

Can be used for traditional LDAR and operational emissions quantification.

Quantification done in camera (no external tablet etc.), Requires the use of a tripod for a stable image.

Detection & Quantification (1)

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✓	✓
Component Level	✓	✓

±30%, but higher uncertainty at high wind conditions (1)
Distance to component does impact ability to detect and quantify emissions, while also dependent on the camera lens (1), size of the source, wind, and ΔT. (3)

Technical Specifications

Detection threshold
Around 0.35 g/h CH4 (1)

Detection distance
2-10m for LDAR, further distances for larger emission sources (operational emissions/vents, etc.) (1)

Validation of detection threshold
Meets US EPA OOOOa requirements (1)

Validation of quantification performance
Not Validated (1)

METEC testing has been done, but the results are not public yet. (1)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes – no hot work permit required (2)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Below EPA specified value for LDAR surveys. (1)

Environmental Conditions
Suitable for low sunlight setting in Norway. Operating temperature -20C to +50C (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://sensia-solutions.com/mileva-33/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Zimmerle, D, et al. "Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions". Environmental Science & Technology 54:18. 2020. p.11506–11514.

Handheld – Gx320, Gx620, G620 – *Teledyne FLIR*

Gx320, Gx620 and G620 are cooled OGI cameras with integrated quantification for immediate in-field results. FLIR launched this technology in 2005 which is the basis for many regulations tied to LDAR globally. The Gx320 detector is built with the same sensitivity as the previous FLIR OGI cooled cameras (GFx320, GF320, GF620). (1)

Teledyne FLIR also produces the GF77, a handheld, uncooled optical camera with a filter at the lens level that allows for interchangeable lenses for Methane (LR) and Ammonia/Ethylene (HR) (1). The GF77 provides detection at equipment and component level, but not quantification. (2)

Availability ✓

Available for purchase (1)

Available globally (1)

Technology Specifications

Type
Handheld (1)

Sensor
Cooled Optical Gas Imaging (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Gx320, Gx620: Certified for use in ATEX Zone 2 environments (Equipment for potentially explosive atmospheres) (1) ✓

G620: Not certified as intrinsically safe, or for use in ATEX

Camera has been previously deployed on offshore platforms and in North Sea (1)

Capabilities/Experience

- The handheld cameras are sensitive to methane alone. The cameras can be used for viewing live leaks on camera screen and videos can be exported to an SD card.
- Cloud and WiFi storage options are also available.
- Technology provider has an internal training division for operators (1)
- Performance of the camera is technician dependent, where more experienced operators will be able to detect more leaks and at greater speeds (5)
- Quantification using QOGI is still developing, with potentially high measurement errors relative to actual leak rates (2)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✓	✓
Component Level	✓	✓

Distance to component does impact ability to detect and quantify emissions, while also dependent on the size of the source, wind, and ΔT. (5)

Technical Specifications

Detection threshold
Less than 1 kg/h CH_4 (1) (3)
The quoted specification on sensitivity is 100 ppm*m (4)

Detection distance
Typically 1-10m (5)

Validation of detection threshold
Via 3rd party research and validation (6)

Validation of quantification performance
By partially blind tests (3)
QOGI able to quantify of 1-1000 g/h with errors of -23/+69%. Required ΔT between leak and background of at least 5°C to quantify, compared to 1-2°C to detect.

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes (1)

Requires access to platform
Yes (1)

Optimal wind speed for operation
0 - 10m/s (2) (5)

Environmental conditions
Operable in day/night applications, in all conditions where the equipment is visible by the operator using the camera, operable camera temperature range is –20°C to +50°C (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.flir.com/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Caico. C. et. Al., *An evaluation of an optical gas imaging system for the quantification of fugitive hydrocarbon emissions*, 2017, https://www.concawe.eu/publication/an-evaluation-of-an-optical-gas-imaging-system-for-the-quantification-of-fugitive-hydrocarbon-emissions-report-no-2-17/
(4) FLIR, "FLIR GF77 supporting document", 2022, https://support.flir.com/DsDownload/Assets/85201-0102-en-US.html
(5) Zimmerle, D, et al. "Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions". Environmental Science & Technology 54:18. 2020. p.11506–11514.
(6) FLIR OGI Operating Envelope Report https://flir.netx.net/file/asset/12465/original/attachment

Handheld – Detecto-Pak Infrared+ (DP-IR+) – *Heath Consultants*

Heath Consultants offers several products and services for detection of natural gas. DP-IR+ is a hand-held leak detection device using an infrared optical gas detection system with sample gas pumped into the instrument through a probe. It is designed to detect natural gas/methane only and will not trigger a false alarm on other gases. (1)

Availability ✓

Available for purchase (1)
Available for lease in the US (1)

Available worldwide (1)

Technology Specifications

Type
Handheld (1)

Sensor
Infrared (IR) Controlled Interface Polarization Spectrometer (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Certified intrinsically safe for use in ATEX Zone 1 / Zone 2 (1)

Not tested or deployed at offshore platforms (1)

Capabilities/Experience (1)

- Concentration displayed on screen in ppm-m, but does not perform quantification. Can connect to external device APP to store the readings and sound alarm if threshold is crossed. Audible alarm can be set when concentration is over the threshold.
- Training for technology use can be provided in an hour, in-person or online training.
- Once a leak it detected, a device capable of quantification would then need to be used (2)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✓	✗
Component Level	✓	✗

Technical Specifications

Detection threshold
Less than 1 kg/h CH4 (1)
1 ppm (1)

Detection distance
Close to source,
within ~1m (2)

Validation of detection threshold
Approved for use by CARB for use following US EPA Method 21 (3)

Validation of quantification performance
Not applicable (2)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes (1)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not Applicable (2)

Environmental Conditions
Has been tested in high snow conditions, with little effect on the instrument. Ideal operating temperature between -17 C and 50 C. Only battery life is affected in very low temperatures. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://heathus.com/gas-products/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) CARB, "Letter about DP-IR+", 2018. Available upon request

Handheld – Remote Methane Leak Detector – *Heath Consultants*

Remote Methane Leak Detector – Complete Solution (RMLD-CS) is a handheld, portable, light-weight instrument, capable of detecting leaks from remote distance using Tunable Diode Laser Absorption Spectroscopy (TDLAS) technology with combined emitter and receiver. The RMLD-CS makes it possible to detect leaks without having to travel the entire length of a pipe. (1)

Availability ✓

Available for purchase (1)
Available for lease in the US (1)

Available worldwide (1)

Technology Specifications

Type
Handheld (1)

Sensor
Tunable Diode Laser Absorption Spectroscopy (TDLAS) (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Certified intrinsically safe for use in Zone 1 / Zone 2 (1) ✓

Used in offshore platforms in the US (1)

Capabilities/Experience (1)

- Concertation displayed on screen in ppm-m, but does not perform quantification. Can connect to external device APP to store the readings and sound alarm if threshold is crossed. Audible alarm can be set when concentration is over the threshold.
- Training for technology use can be provided in an hour, in-person or online training.
- Once a leak it detected, a device capable of quantification would then need to be used (2)

Detection & Quantification

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✓	✗
Component Level	✓	✗

Technical Specifications

Detection threshold
Less than 1 kg/h CH4
Detection Alarm level: 1 – 999 ppm-m (parts-per-million-meter) (1)
50,000 ppm-m max detection threshold

Detection distance
<30m (1)

Validation of detection threshold
By partially/fully blind tests (3) but not in public domain

Validation of quantification performance
Not applicable (2)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes (1)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not Applicable (2)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://heathus.com/gas-products/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) METEC, "RMLD-CS Survey Emission Detection and Quantification Final Report", 2021. Available upon request

Handheld – LM Smart/LMm – *Pergam Suisse*

Pergam-Suisse is a company that designs and manufactures equipment for natural gas (methane) leak detection and provides services in that space. The basis of Pergam-Suisse's technologies is Tunable Diode Laser Absorption Spectroscopy (TDLAS). LM Smart / LMm (Laser Methane mini) is a handheld methane detector. (1)

Availability

Available for purchase (1)

Available worldwide (1)

Technology Specifications

Type
Handheld (1)

Sensor
Diode laser spectroscopy with open path technology (1)

Deployment
Triggered (1)

TRL
9 (2)

Offshore Relevance

Certified intrinsically safe for use in Zone 2 but technology is capable of detecting emissions in Zone 0 and Zone 1 from Zone 2. (1)

Applicable offshore if handheld in classified zones by an operator or outside classified zones carried by a drone (1)

Not tested on offshore platforms (1)

Capabilities/Experience

- Data provided includes leak detection info, leak time, concentration in the methane cloud shows on the screen.
- 0.1 sec response time of the detector
- Training and capacity building for operators can be completed within 1 hour. (1)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✓	✗
Component Level	✓	✗

±10% uncertainty on quantification of ppmxm reading (1)

Technical Specifications

Detection threshold
5 ppm×m at 30m(1)

Detection distance
0.5 - 30 m (1)

Validation of detection threshold
Not Validated (1)

Validation of quantification performance
Not applicable (2)

Tested at METEC but results not published yet. (1)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes (1)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not Applicable (2)

Environmental Conditions
Operating Temperature: -17C to up to 50C. Technology is not affected by sunlight and has been used in regions with high snow cover previously. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://pergam-suisse.ch/
(2) Carbon Limits Assessment based on the interview and other publicly available information

2.8. New developments: Continuous Monitoring Solutions

Continuous monitoring solutions are sensors placed downwind of operations to detect CH_4 enhancements, and hence fugitive emissions, and can be placed on or near facilities. Fenceline monitoring uses multiple instruments fixed at the boundary of oil and gas operations to continuously measure gas concentrations[29]. Fenceline monitors can also be considered as continuous monitoring solutions, but continuous monitoring solutions also includes a broader range of applications. These continuous monitoring solutions included in this report differ from fixed gas sensors employed for safety standards for Norwegian offshore installations, which may be placed around platforms to provide concentration readings and alarms for detection and alerts of toxic or flammable gases. However, they may not be directly used for environmental purposes (installations are designed such that emissions from vents do not trigger alarms).

Continuous monitoring solutions may be placed to monitor emission sources in areas where it is not possible to use handheld instruments, either at heights or in confined spaces. Continuous monitoring sensors may use in situ-methods, where atmospheric movement is required to transport the methane plume into contact with the sensor. Imagery based solutions may also be used, which will “visualize” the plumes, and thus do not require direct contact with the plume to detect or quantify emissions. Imagery-based technologies can also be installed on pan-and-tilt gimbals that allow for observing multiple fields of view, increasing the potential coverage of a single sensor.

For continuous source level detection and quantification at an offshore facility, sensors such as optical gas imaging or hyperspectral imaging cameras can be permanently installed. This allows for continuous monitoring within the camera’s field of view and the opportunity to detect and/or quantify emission events that occur over time. Some imagery-based solutions can also be used for multiple purposes, such as safety-related fire detection, PPE, spills or tank liquid level monitoring, as well as methane emission detection. Technology providers and third-party providers have also developed analysis software using artificial intelligence (AI) trained to detect and quantify these emissions automatically.

Advances in continuous monitoring solutions have been made recently. In a recent published paper (Bell et al., 2023), 11 continuous monitoring solutions were tested at the METEC facility in Colorado USA. The testing was the first-of-its-kind study of continuous monitoring/fixed sensors using a consensus-developed testing protocol (D. Zimmerle, 2020).Technologies used either point sensor networks or imaging solutions to detect and quantify controlled releases at the testing center. Testing included determination of probability of detection (PoD) curves for all sensors, that specify a detection limit at which a solution would be able to correctly identify a potential leak with 90% probability. The paper also evaluated the ability to quantify these leaks, and report relative quantification errors. While solutions were anonymized, they still offer a range of single-estimate detection and quantification. Solutions had detection limits ranging from 2.7 $kgCH^4/h$ (95% CI of 0-17.3 $kgCH^4/h$) up to 30.1$kgCH_4/h$ (95%CI of 0-NA $kgCH_4/h$). Mean, relative quantification errors ranged from -43.6% (-92.6%-141.4%) to over 500% (-96.7%-2078.7%) for controlled releases ranging from 0.1$kgCH_4/h$, and from -39.5% (-99.9% - 242.4%) to 92.2% (-99.1% - 448.3%) for controlled releases greater than 1$kgCH_4/h$. In general, quantification estimates would improve with higher controlled release rates.

The researchers also highlighted the importance of balancing the technology sensitivity (detection thresholds) with a low false positive rate (false positives would arise when a solution would detect an emission that was not released). This will also have implications for follow-ups. If a solution has a high false positive rate, it may be more prone to alarm, triggering operator personnel to investigate the potential source of emissions to quantify or perform corrective actions to mitigate, and may generally reduce trust in the solution (sometimes called “alarm fatigue”). The ability to attribute emissions to a specific source will

[29] Fenceline Monitors Parameters - Energy Institute (colostate.edu)

also determine follow-up procedures. For example, if an emission source from a process emission (intentional release of methane) is attributed as an unintentional leak, it may trigger unnecessary follow-up.

Relevance for Norwegian offshore installations

The high emphasis on safety on Norwegian offshore installations has resulted in the development of standards for the principles and design requirements of technical safety (*NORSOK S-001:2020+AC:2021*, 2021). The standard includes requirements of gas detection coverage using fixed gas sensors (not specifically to methane alone). A combination of spaced point sensors and open path line sensors, typically based on infrared absorption, are used. In addition, acoustic sensors based on ultrasound are used for early warnings. On each platform, there may be hundreds of sensors. The placement of the sensors is based on design assessments of gas leak scenarios and gas dispersion, and are primarily in process areas or well areas, where they are placed 5-7 meters apart. Their role is to detect presences of toxic or flammable gases, including methane, alerting personnel to react or automatically controlling safety actions. The gas detection systems are designed to detect leaks to allow action from a safety viewpoint, and not from an environmental viewpoint, and the installations are designed such that emissions from vents do not trigger safety alarms, but would likely catch a large emission event (super-emitter) in the rare event it occurs.

Continuous monitoring technologies must be explosion certified to be installed, and the installation would require a power source and either a network connection or potentially connection to a control room for integration. A camera-based continuous monitoring sensor also would require line-of-sight proximity to emissions sources. In addition to requirements for explosion certification, continuous monitoring solutions would have to be able to both be durable and usable under North Sea conditions.

Continuous monitoring solutions that use in-situ detection and quantification of methane plumes are subject to wind speed and direction. Therefore, adequate understanding of wind conditions is necessary to select optimal placement of one or more sensors to be able to monitor emissions, which will be done on a case-by-case basis.

Technologies will generally require network communications for cloud-based analytics and data availability. Otherwise, data can be integrated with existing DCS or SCADA. Power requirements are also necessary. Technology providers will typically install solar panels at onshore facilities. However, this may not be practical at offshore installations, so connection with platform power system is necessary, and a logistical consideration to be made. Site access is required for installation of these systems, which may require hot work permits. Maintenance may also be necessary, which can be done either by the technology provider or operation personnel, given the challenges with providing transport for additional, non-operation staff on the platform.

To address the relevance of continuous monitoring of CH_4 using continuous monitoring solutions, the results presented in the paper by Bell et al. (2023) suggest that the results of monitoring using continuous monitors should be used with caution. The detection limits, probability of detection, source localization and quantification may not be applicable for all scenarios. It is important to note that METEC is a testing centre that is most relevant for an onshore US oil and gas industry. Results may vary, especially when comparing the onshore testing centre to an offshore oil and gas facility on the NCS. One potential limitation of continuous monitoring solutions is the placement. Offshore installations are typically quite condensed, with multiple potential emission sources in proximity. This may be more challenging for continuous monitoring sensors to differentiate emission sources, and to inform subsequent follow-up activities. There may be limitations for where the technologies may be permanently deployed in a reasonable, safe manner due to explosive atmospheres. Continuous monitoring solutions may also use atmospheric modelling to back calculate emission rates and source identification. Atmospheric conditions will vary greatly from onshore to offshore, and thus any technology would require modelling that accurately captures the atmospheric environment of an offshore platform.

Unfortunately, there is no way to quantitatively address these differences at this point, with no other publicly available controlled release testing, or testing otherwise, currently available for continuous monitoring solutions at offshore platforms.

However, if the performance of a technology is well understood and performance is robustly documented, the technology can provide invaluable information. For example, most technologies will likely detect larger emissions with higher probability, and faster than survey methods such as handheld, drone, airplane or satellite technologies. However, relying on quantification from these solutions may be premature at this point (Bell et al., 2023). Therefore, additional follow-up may be required using an alternate, more precise quantification method.

Updates of the technology review since 2020

19 continuous monitoring technologies were identified as part of this report, compared to 4 in the 2020 report. Of these, 10 technologies have been included in 9 datasheets in this report. Technology providers that did not respond to requests to participate were not included Technology datasheets for continuous monitoring solutions were created from companies such as Teledyne FLIR, CleanConnect AI, Longpath Technologies, Project Canary, Providence Photonics, Sensia and Sensirion Connected Solutions. The full list of technologies can be found in Appendix D.

The availability of these technologies has increased, both remote sensing and in-situ based technologies more widely available. Many of the technologies have been designed for use in ATEX environments or installed in explosive atmosphere-safe enclosures. Minimum detection thresholds are similar to in 2020, being able to detect emissions down to the order of 1-10kg/h. Technologies can be used with third party integration of analytics software that are becoming available for automated detection and quantification. The recent publications of testing of continuous monitoring have greatly increased the understanding of continuous monitoring solutions capabilities. The results of the recent paper by Bell et al. (2023) state that the performance of continuous monitoring solutions have changed substantially, with increased testing performed. This has been attributed to pressure for regulatory purposes, financial penalties, and company-internal emission mitigation efforts, which has increased interest in deploying continuous monitoring solutions. This has driven “rapid and dramatic … need for quality testing, critical review of solution performance, and a clear understanding of uncertainties for all result types reported by these methods”. They also note reliance on quantification may still be premature, thus requiring additional quantification to be performed as a follow-up to detection, for example for reporting requirements. Therefore, they may be seen as a supplemental technology.

Stationary – Mileva 33F– *SENSIA*

Mileva 33F is the latest model of Optical Gas Imaging for micro-leaks detection of Volatile Organic Compounds (VOC's) and hydrocarbon (HxCy) gases. Mileva 33F performance lets RedLook to enable exhaustive monitoring and real-time alerting. (1)

Availability

Available for purchase (1)

Available worldwide (1)

Technology Specifications

Type
Stationary (1)

Sensor
Fixed Point Cooled OGI (1)

Deployment
Continuous (1)

TRL
9

Offshore Relevance

Certified ATEX Zone 1 (Equipment for potentially explosive atmospheres) (1)

Camera platform has been previously deployed on offshore platforms, but not in North Sea (1)

Capabilities/Experience (1)

- Data Output: compressed and radiometric video, images, quantification data over time for individual sources of interest, alarming system.
- Detection using autonomous, AI-based analytics. Can be used for safety and environmental purposes (emission detection, quantification and reporting)
- Training and capacity building for operating staff. (1 day)
- Data can be integrated with DCS, SCADA. Communication through Modbus or OPC, email notifications and data available through a web-based platform.
- Can be deployed on a pan and tilt for multiple fields of view. (1)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✓ (partial)	✓ (partial)
Component Level	✗	✗

Uncertainty of quantification: ±15% (after commissioning and Scenario Based Tuning with ground truth calibration), but higher uncertainty at high wind conditions.(1)

Technical Specifications

Detection threshold
Around 0.7 kg/h CH4 (1)

Detection distance
125 m for flow rates >1.1 kg/h
250 m for flow rates >1.8 kg/h
(1)

Validation of detection threshold
Not Validated (1)

Validation of quantification performance
Not Validated (1)

METEC testing has been done, but the results are not public yet. Future tests at METEC have also been planned.

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not Specified (1)

Environmental conditions
Operating Temperature: -20 to 50C

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://sensia-solutions.com/mileva-33f/
(2) Carbon Limits Assessment based on the interview and other publicly available information

Stationary – GF77a, G300a – *Teledyne FLIR*

Teledyne FLIR produces several cooled and uncooled optical gas imaging (OGI) cameras. GF77a is a fixed uncooled camera. It has filter at the lens level and is not as sensitive as FLIR's cooled OGI camera for hydrocarbons. FLIR has combined this camera with an environmental enclosure, alarming analytics and a VMS software for a continuous methane monitoring solution
Teledyne FLIR also produces the G300a, a fixed, uncooled OGI camera for hydrocarbons, which does not provide quantification. (1)

Availability ✓ ✗

Available for purchase (1)

Available globally (1)

Technology Specifications

Type
Stationary (1)

Sensor
Uncooled Optical Gas Imaging (1)

Deployment
Continuous (1)

TRL
9 (2)

Offshore Relevance

Fixed solution and can be installed in Ex enclosures (Equipment for potentially explosive atmospheres) (1)

Theoretically possible to use in offshore, but not deployed yet (1)

No testing done at offshore platforms or in the North Sea (1)

Capabilities/Experience (1)

- Fixed OGI camera designed to visualize methane gas. Camera can be viewed in visual, IR or HSM mode. The camera can be installed for fixed, continuous monitoring in intrinsically safe enclosures. (1)
- Image streaming with radiometric and 8-bit video to be used for alarming analytics (1)
- Imagery can be linked offsite via mobile network, but requires network communications (1)
- GF77a provides quantification in ppm*m and flow rate (not available for G300a). (2)
- The fixed cameras may also be used by 3rd party providers using analytics to provide automatic detection/quantification (1), or detect multiple plumes for site level measurements (2)

Detection & Quantification (2)

	Detection	Quantification
Site Level	✓ ✗	✓ ✗
Equipment Level	✓ ✗	✓ ✗
Component Level	✓ ✗	✓ ✗

Detection and quantification at equipment and component level dependent on infrastructure. Requires line of sight to attribute to sources, which may be more challenging at offshore installations (2)

Technical Specifications

Detection threshold
Less than 1 kg/h CH4 (1) (2)
Detection threshold may increase to up to 3.5kg/h at 80m distance (1)

Detection distance
Typically <100m (1)

Validation of detection threshold
Via 3rd party research and validation (3)

Validation of quantification performance
Not available (1)

Distance to component does impact ability to detect and quantify emissions, while also dependent on the size of the source, wind, and ΔT. (4)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (2)

Optimal wind speed for operation
1-10m/s (2) (4)

Environmental conditions
Operable in day/night applications (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.flir.com/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) FLIR OGI Operating Envelope Report https://flir.netx.net/file/asset/12465/original/attachment
(4) Zimmerle, D, et al. "Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions". Environmental Science & Technology 54:18. 2020. p.11506–11514.

Stationary – Autonomous 365 – *Clean Connect AI*

Cleanconnect AI offers a suite of AI finished solutions that enables automation of methane monitoring and quantification. It is broken down into three different bundles based on sensor type. (1)

Availability ✓ ✗

Available as a service provider (1)

Available worldwide (1)

Technology Specifications

Type
Stationary (1)

Sensor
Fixed optical gas imaging (OGI) (1)

Deployment
Continuous

TRL
6 (2)

Offshore Relevance

Certified ATEX (Equipment for potentially explosive atmospheres) for Zone 2 (1) ✓ –

No testing done at offshore platforms or in the North Sea (1)

Theoretically possible to use in offshore, but not tested yet. (1)

Capabilities/Experience

- The data tracked can be used for EPA Subpart W, OGMP 2.0, and other regulatory reporting (1)
- Typically 2-8 hours training for an operator to become proficient. (1)
- Communication network required – ethernet (0 connectivity issues), Starlink WAP – no connectivity issues either. 3G and 4G can have connectivity issues. (1)
- Detection and quantification capabilities may vary from onshore capabilities based on platform setup, equipment setup and potentially dense site configurations (2)

Detection & Quantification (1,2)

	Detection	Quantification
Site Level	✓ ✗	✓ ✗
Equipment Level	✓ ✗	✓ ✗
Component Level	✓ ✗	✓ ✗

Tech provider states "Yes" for detection and quantification at all scales. However, it has not been tested offshore and dense equipment setup and variability of offshore operations may impact capabilities. Requires line of sight to attribute to sources or to see total site, which may be more challenging at offshore installations

Technical Specifications

Detection threshold
~3 kg/h CH4 at 100m distance (2.86 kg/h at 91m distance) (1)

Detection distance
Not specified

Validation of detection threshold
Validated (3) for CDPHE AIMM program (onshore)

Validation of quantification performance
Validated (3) for CDPHE AIMM program (onshore)

Offshore Criteria

Previously used offshore
No (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not specified (2)

Environmental Conditions
Camera enclosure (PT unit) rated to operate between -30C and 60C. Technology has worked well in extreme cold, rain, wind, hail, snow during a testing conducted in Colorado (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.cleanconnect.ai/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) https://cdphe.colorado.gov/oil-and-gas-and-your-health/approved-instrument-monitoring-method-aimm-for-oil-gas

Stationary – Soofie – *Scientific Aviation*

SOOFIE is a stand-alone real-time leak detection system. Powered by the sun with enough battery backup to survive a week of thick overcast, It is a pole-mounted continuous monitoring system for site-level leak detection, emission rate quantification, and automated alerting. (1)

Availability

Available as a service provider (1)
Available for purchase (1)

Available in North America, Europe, Middle East and Asia (1).

Technology Specifications

Type
Stationary (1)

Sensor
Metal-oxide semiconductor sensor (1)

Deployment
Continuous (1)

TRL
9 (2)

Offshore Relevance

Not certified as intrinsically safe, or for use in ATEX (Equipment for potentially explosive atmospheres) (1)

Theoretically possible to use in offshore, but not certified yet. (1)

No testing done on offshore platforms (1)

Capabilities/Experience

- **What does the data product look like?** SOOFIE Dashboard displaying near real-time CH_4 concentrations, emissions, and alerts status.
- **What is the down time if data needs to be received:** 15 minutes
- Needs cellular or wifi communications (1)
- **Training and capacity building for operating staff:** Provide training for users and field operators. (1)
- **What kind of emission sources is it best used for:** Intermittent emissions of 1 kg/h or greater. (1)

Detection & Quantification (1,2)

	Detection	Quantification
Site Level	✓ (green)	✓ (green)
Equipment Level	✓ (yellow)	✓ (yellow)
Component Level	✗ (red)	✗ (red)

±30% uncertainty in quantification - primarily determined by uncertainties in dispersion modeling. (1) Quantification performance may have high error, useful for leak alerts (2)

Technical Specifications

Detection threshold
Around 0.4 kg/h notional detection limit (fence line estimate) (1)

Detection distance
3 m to 250 m away from source (1)

Validation of detection threshold
METEC validation down to 0.3 kg/h or higher – not publicly available. (1)

Validation of quantification performance
METEC validation down to 0.3 kg/h or higher-not publicly available. (1)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (2)

Optimal wind speed for operation
Between 1 and 20 m/s (1)

Environmental Conditions
Shown to operate at temperatures as low as -30 degrees Celsius. Some sun required for solar panel charging. (1)
Requires network communication (2)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.scientificaviation.com/soofie/
(2) Carbon Limits Assessment based on the interview and other publicly available information

Stationary – G2301 Gas Concentration Analyzer– *Picarro*

Provides simultaneous measurement of carbon dioxide and methane at ppb and water vapor at (ppm) sensitivity. Sensor is used to for determining the decay time of light in an optical cavity filled with the gas stream to be analyzed. Device is stationary in an enclosure and continuously pumps in sample to measure concentration. Alternatively, device can be mounted on mobile vehicles (such as drone, airplane) for inspection. (1)

Availability

Available for purchase (1)
Available for leasing (1)

Available worldwide (1)

Technology Specifications

Type
Stationary (1)

Sensor
Cavity Ring Down Spectroscopy (CRDS) (1)

Deployment
Continuous (1)

TRL
9 (2)

Offshore Relevance

Not certified as intrinsically safe, or for use in ATEX (Equipment for potentially explosive atmospheres) (1)

Theoretically possible to use offshore, but not yet. (1)
No testing done at offshore platforms or in the North Sea (1) Used on research vessels in North Sea (1)
Must be placed in an enclosure to protest from rain and snow. Must ensure tube has no condensation. Device corrects for humidity and water presence. (1)

Capabilities/Experience (1)

- Data provided: Concentration measurements every 2 to 5 seconds. (1)
- Post-processing of this data to estimate emissions rate could be possible, not done by analyzer directly. (2)
- Anemometer attached to device, will help with detecting the course of emissions in post-processing (2)
- Minimal training required for equipment operation. 2 to 4 hours of online training with the first instrument. (1)

Detection & Quantification (1)

	Detection	Quantification
Site Level	✓	✗
Equipment Level	✓	✗
Component Level	✗	✗

Device is capable of detecting emissions if concentration of CH4 is higher than the typical concentration in ambient air, but operator must use OGI to detect the exact location of leak. (2)

Technical Specifications

Detection threshold
<1.5 ppb (5 sec)
<0.66 ppb (5 min) (1)

Detection distance
Extractive plume sample (3), distances close enough to measure concentrations before dispersion (2)

Validation of detection threshold
Not Applicable (2)

Validation of quantification performance
Not Applicable (2)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (1)

Optimal wind speed for operation
Not Applicable (1)

Environmental conditions
Operating Range: 10C to 35C, sample temperature between -10C to 45C. Must be housed in an enclosure below this temperature (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.picarro.com/technology/cavity_ring_down_spectroscopy/brief_technical_description_of_crds
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Ravikumar A. et al. "Single-blind inter-comparison of methane detection technologies – results from the Stanford/EDF Mobile Monitoring Challenge". 2019. https://online.ucpress.edu/elementa/article/doi/10.1525/elementa.373/112505/Single-blind-inter-comparison-of-methane-detection

Stationary – Nubo Sphere – *Sensirion Connected Solutions*

Continuous monitoring system to localize and quantify methane emissions. Comes with hardware, solar PV panels for power requirements, and wind meter incorporated in the system. Has two exchangeable sensor cartridges that allow for easy maintenance and sustainable upgrades to the latest sensor technology. The methane quantification system uses plume modelling to back calculate emissions rate. (1)

Availability

Available as a service (1)
Available for purchase (1)
Available for lease (1)

Available in North America and Europe (Predominantly sold in these regions, however, can be made available in other regions as well) (1)

Technology Specifications

Type
Stationary (1)

Sensor
Laser spectroscopy (1)

Deployment
Continuous (1)

TRL
9 (1) (2)

Offshore Relevance

Not certified as intrinsically safe, or for use in ATEX (Equipment for potentially explosive atmospheres) (1)

Research in progress to develop a version of the product that will be certified ATEX (Zone 2). Expected to launch mid 2024. (1)

No testing done on offshore platforms (1)

Theoretically possible to use in offshore, but not certified yet (2)

Capabilities/Experience

- When an emission is detected, the system suggests the location of the source, but an engineer can override the localization.
- The provider is currently testing an algorithm to send an alert directly to the operator for large emission sources.
- For deployment, multiple devices can be installed per hour. Number of devices installed depends on operator requirements and size of facility. A mounting mast is required for mounting the device.
- System is installed by the operator following system manual.
- Long-Term Evolution (LTE) is required for communication (1)

Detection & Quantification (1,2)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✓ (partial)	✓ (partial)
Component Level	✗	✗

Quantification uncertainty can vary from 2% to 50% depending on, number of sensors, wind speed and topology. (1) (3)

Detection at equipment level: METEC ADED testing found 12% of emissions were localized to within 1m of actual source (4)

Technical Specifications

Detection threshold
90% PoD at 7.8 g/h is the lowest detected emissions rate at ADED 2023 testing. (1)(4)

Detection distance
10m to 100m (1)

Validation of detection threshold
By fully/partially blind tests (1)(4)(6)

Validation of quantification performance
By fully/partially blind tests (1)(4)
0.1-1 kg/h: -43.6% mean error
>1 kg/h: -39.5 % mean error

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (2)

Optimal wind speed for operation
Between 0.5 m/s and 15 m/s (1)

Environmental Conditions
An average uptime of 84% in weather conditions between -40C and 0C, improved in warmer conditions. (3) Downtime predominantly due to battery life being affected by low temperatures. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://sensirion-connected.com/solutions/nubo-sphere/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Sensirion, 2023, "Canadian Winter 2022 / 2023: A performance report of NuboSphere", https://admin.sensirion-connected.com/media/media/file/2FABA738/647D8E6D/SCS_NuboSphere Report_CanadianWinter.pdf
(4) Sensirion, 2023, 'NuboSphere's performance in ADED 2023", https://www.sensirion-connected.com/forms/whitepaper-metec-aded-2023

Stationary – Canary X – *Project Canary*

Project Canary deploys continuous on-site environmental monitoring IoT devices (Canary X) that record emissions in real time via the cloud to provide continuous monitoring solutions and actionable data using all weather sensors. Includes Sensirion Nubo Sphere and Aeris sensor integration into Project Canary, while also allowing operators to purchase other sensors and integrate into the system (1).

Availability

Available as a service provider (1)

Operating in North America predominantly (1)

Technology Specifications

Type
Stationary (1)

Sensor
Tunable Diode Laser Absorption Spectroscopy (1)

Deployment
Continuous (1)

TRL
9 (2)

Offshore Relevance

Not certified as intrinsically safe, or for use in ATEX (Equipment for potentially explosive atmospheres) (1)

Stationary equipment not yet tested at offshore facility as quantification could be tricky due to differences in atmospheric conditions for offshore used in modelling/analytics. (2)

Capabilities/Experience (1)

- Data provided via a dashboard, quantified at 15-minute intervals. Quantification is currently being optimized. Network connectivity required for communication.
- Around 4 weeks of data is to be fed into the system to train machine learning models to quantify and attribute emissions to specific pieces of equipment with time weighted averages. Data available every minute as it is uploaded to the server.
- Installation of equipment can be completed within a single day. Depending on sensor, density of each facility and their locations, multiple sites can be completed in a day.

Detection & Quantification (1,2)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✓ (partial)	✓ (partial)
Component Level	✗	✗

Quantification uncertainties vary based on emission size, with larger uncertainties for larger sources. (4), (5)
Time to detection and attribution depends on wind speed and direction (2)
Tech provider states "Yes" for detection and quantification at site and equipment level. However, not been tested offshore and dense equipment setup and variability of offshore operations may impact capabilities. (2)

Technical Specifications

Detection threshold
90% PoD 0.6 kg/h CH_4 (5)
Lowest threshold at METEC: 0.007 kg/h (1)

Detection distance
<50m (5)

Validation of detection threshold
By fully/partially blind tests (3)

Validation of quantification performance
By fully/partially blind tests (5)

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes – for installation (1)

Requires access to platform
Yes (2)

Optimal wind speed for operation
Not specified (2)

Environmental Conditions
Technology requires power either from grid or with an independent solar PV system. Low sunlight conditions could affect operation if connected to an independent solar PV system. (1) (3)

Source of information
(1) Information from interview with technology provider / research on technology provider's website: https://www.projectcanary.com/solutions/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Project Canary, 2021, "Round 3 METEC Testing Results Abstract", https://www.projectcanary.com/wp-content/uploads/2021/12/Project-Canary-Abstract_Sci-Paper_2_v1.4_AS_Na.pdf
(4) Project Canary, 2021, "METEC Testing Results August 2021", https://www.projectcanary.com/wp-content/uploads/2021/08/METEC-Project-Canary-Abstract9.pdf
(5) Project Canary, 2021, "A Quantitative Overview to Continuous Monitoring of Methane Emissions", https://www.projectcanary.com/wp-content/uploads/2021/09/METEC_ProjectCanary_Sept2021_Quantification_Final.pdf
(6) Project Canary, 2023, "Event-based analysis of performance by project canary's continuous monitoring systems", https://www.projectcanary.com/blog/event-based-analysis-of-performance-by-project-canarys-continuous-monitoring-systems/

Stationary – LongPath Laser System – *LongPath Technologies*

Single laser continuous monitoring device, monitoring facilities within a 2.5+ mile radius (7.5+ sq miles). Each facility only requires passive mirrors.
Central node with telescope and passive mirrors are placed on site for monitoring emissions. Integrated line sensors, each measurement gives full visibility of the site. Open-path laser spectroscopy measures time-resolved gas absorption to provide time resolved, quantified and localized emission rates. (1)

Availability

Available as a service provider (1)

Predominantly US and Canada. Deployment in more regions in the foreseeable future (1)

Technology Specifications

Type
Stationary (1)

Sensor
Open-path laser spectrometer (1)

Deployment
Continuous (1)

TRL
9 (2)

Offshore Relevance

Not certified as intrinsically safe, or for use in ATEX (Equipment for potentially explosive atmospheres) (1)

Theoretically possible to use in offshore, but not certified yet. Monitoring from near-shore/floating platforms is possible, can be connected to independent solar PV system for energy needs. (1)

No testing done at offshore platforms or in the North Sea (1)

Capabilities/Experience (1)

- Data is available near-real time. Time taken to connect to cloud and sync device could be the only source of delay. Requires network for communication (2)
- Dashboard with live data is available as web app or API and can be exported as CSV into local system
- Alarms on detected emissions are available via web, text, mail and is customizable based on needs
- Technology has 97% uptime which adds to low latency for data. Hardware realignment (mirrors) and connection to cloud affect the uptime
- Installation and setup of technology could take up to 4 days. Dashboard training for operators can be done remotely and could take less than 1 day for training. (1). Durations based on onshore installation, may take longer offshore (2)

Detection & Quantification (2)

	Detection	Quantification
Site Level	✓	✓
Equipment Level	✓	✓
Component Level	✗	✗

Quantification uncertainty onshore is roughly ±27% for single steady leaks and ±40% for multiple intermittent leaks. LongPath cites quantification accuracy with 0% bias ±30% on individual readings. (1). Spatially condensed sources offshore can make attribution to specific equipment difficult. (2)

Technical Specifications

Detection threshold
Down to 0.1 kg/h CH4 (1) (3)

Detection distance
Not specified (1)

Validation of detection threshold
By academic researchers (3) (4)

Validation of quantification performance
By academic researchers (5)

Note: Academic paper was co-authored by the technology provider

Offshore Criteria

Previously used/tested offshore
No (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (2)

Wind sensitivity:
1 m/s minimum wind required (1)

Environmental conditions
Light source and laser are generated by technology, hence there is little influence of sunlight, wind, cloud or ground cover. Observations could be affected during blizzards and low visibility conditions (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: www.LongPathtech.com
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Alden et al., 2020, "Temporal Variability of Emissions Revealed by Continuous, Long-Term Monitoring of an Underground Natural Gas Storage Facility", Environ. Sci. Technol., 54, 22, 14589–14597 (2020), https://doi.org/10.1021/acs.est.0c03175
(4) Coburn et al., 2020, "Long Distance Continuous Methane Emissions Monitoring with Dual Frequency Comb Spectroscopy: deployment and blind testing in complex emissions scenarios". Retrieved from: https://arxiv.org/ftp/arxiv/papers/2009/2009.10853.pdf
(5) Alden et al., 2019, "Single-Blind Quantification of Natural Gas Leaks from 1 km Distance Using Frequency Combs", Environ. Sci. Technol., 53, 5, 2908–2917 (2019), https://doi.org/10.1021/acs.est.8b06259

Stationary – Mantis Flare Monitor – *Providence Photonics*

The Mantis Flare Monitor is based on the patented Video Imaging Spectral Radiometry (VISR) method. It is capable of continuous monitoring of flare combustion efficiency (CE), smoke index, flame stability, flame footprint, and fractional heat release. Mantis is used to quantify emission rate (combined with flow measurement either by conventional flowmeter or by Mantis itself). (1) The technology is specifically catered to Flare units. (2)

Availability ✓

Available as a service provider (1)
Available for purchase (1)

Available worldwide (1)

Technology Specifications

Type
Stationary (1)

Sensor
Multi-spectral radiometry imaging system (1)

Deployment
Continuous (1)

TRL
9 (2)

Offshore Relevance

Not certified as intrinsically safe, or for use in ATEX (Equipment for potentially explosive atmospheres) (1) ✓

Used offshore more on more than 20 installations, including five in the North Sea. (1) Hot work permits are required if set up in an area of the platform or vessel that requires hot work permit. Can also be installed at an external platform for monitoring (1).

Capabilities/Experience (1)

Mantis provides following data:

- Real time, continuous flare performance metrics with no latency
- Five performance metrics provided
  - Combustion Efficiency (DRE)
  - Smoke Index
  - Fractional Heat Release
  - Flare Footprint
  - Flare Stability
- One second data interval or in 1-, 5- or 15-min averages.
- Results immediately available, allows for tuning or testing of multiple flare conditions
- Measurement is remote, no integration with control systems.

Detection & Quantification

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✓	✓
Component Level	✗	✗

±0.49% for combustion efficiencies - 95% to 100%, ±0.67% between 90% to 95% and ±1.79% between 0% to 85%. (3). Individual quantification errors ranged from 0.1% at a combustion efficiency of 100% to 13.61% at a combustion efficiency of 59.99% (3) (4) Combustion efficiency helps determine the methane emissions, hence the uncertainty is important to note (2)

Technical Specifications

Detection threshold
Not applicable

Detection distance
100–500 m – typical flares
50–100 m – smaller flares
Up to 1000 m – large flares (1)
Entire flare must be captured in camera view (2)

Validation of detection threshold
By fully/partially blind tests (4)

Validation of quantification performance
By fully/partially blind tests (3)
Meets US EPA requirements (5)

Offshore Criteria

Previously used/tested offshore
Yes, more than 20 offshore installations. (1)

Requires hot work permit / on-site personnel?
Yes- for installation (2)

Requires access to platform
Yes (2)

Optimal wind speed for operation
Not specified (2)

Environmental conditions
Suitable for day/night, all sunlight conditions, all temperature conditions. Heavy snow, rain or fog could temporarily prevent measurement. (1)

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://www.providencephotonics.com/
(2) Carbon Limits Assessment based on the interview and other publicly available information
(3) Zeng Y., Morris J., Dombrowski M. "Validation of a new method for measuring and continuously monitoring the efficiency of industrial flares". 2015. https://www.tandfonline.com/doi/full/10.1080/10962247.2015.1114045
(4) Morris J., Zeng Y., Srikanth M. " Inspection of Industrial Flares Using the Video Imaging Spectral Radiometry (VISR) Method". 2019. https://downloads.regulations.gov/EPA-HQ-OAR-2017-0357-0049/attachment_3.pdf
(5) Based on US EPA 40 CFR (Code of Federal Regulation) 63.670 and (US EPA 40 CFR 60.18) requirements

Stationary – Agni – *SENSIA*

SENSIA proposes monitoring solutions based on infrared imaging. SENSIA's RedLook Technology combines AI powered infrared cameras and software. Agni is one of the RedLook cameras, specially designed for the surveillance of pilot flames and flared gases. (1)

Availability ✓

Available for purchase (1)

Available worldwide (1)

Technology Specifications

Type
Stationary (1)

Sensor
Bi-spectral cooled OGI (1)

Deployment
Continuous (1)

TRL
9 (1)

Offshore Relevance

Certified ATEX Zone 1 (Equipment for potentially explosive atmospheres) (1) ✓

Camera has been previously deployed on offshore platforms, but not in the North Sea (1)

Capabilities/Experience (1)

- Training requirement for operators of <1d, setup takes a few hours
- Technology is designed for flare monitoring. Outputs flare destruction removal efficiency (DRE) over time.
- Can monitor multiple flares either mounted on pan and tilt or several flares in a single field of view.
- Data can be integrated with DCS, SCADA. Communication through Modbus or OPC, email notifications and data available through a web-based platform.

Detection & Quantification (1)

	Detection	Quantification
Site Level	✗	✗
Equipment Level	✓	✓
Component Level	✗	✗

Technical Specifications

Detection threshold
Not applicable (1) – flare monitoring technology
Flare CH4 DRE 0-99.9%

Detection distance
30m from any angle. 500m if camera placed at height (1)

Validation of detection threshold
Not Validated (1)

Validation of quantification performance
Not Validated (1)

Validation work currently ongoing, but not currently available (1)

Offshore Criteria

Previously used/tested offshore
Yes (1)

Requires hot work permit / on-site personnel?
Yes – for installation (2)

Requires access to platform
Yes (2)

Optimal wind speed for operation
Not specified/applicable* (1)

Environmental Conditions
*Wind orientation more important than wind speed. The influence can be minimized with a proper commissioning.
Operating temperature -20 – +50C
Extreme precipitation/fog will reduce transmittance of energy from flare to camera.

Source of information

(1) Information from interview with technology provider / research on technology provider's website: https://sensia-solutions.com/agni/
(2) Carbon Limits Assessment based on the interview and other publicly available information

3. Case studies from use of CH_4-measurement technologies offshore

Three case studies from top-down measurement campaigns from offshore facilities have been identified: each of these gives new insight into the challenges and opportunities of offshore measurements of methane[30].

To summarize the case studies, methane emissions from offshore O&G facilities are present a challenging environment to quantify. Throughout the case studies, different technologies were mentioned to detect, quantify, and attribute methane emissions from offshore facilities. Some of these technologies are plane-based and ship-based measurements using remote sensing imaging spectrometers and further process with a gaussian plume model. Methane emissions can be reported by operators using bottom-up approaches for inventory purposes. However, bottom-up estimates require a high level of granularity and transparency to ensure consistency and reliability. This can result in bottom-up approaches underestimating or overestimating methane emissions from certain sources. Top-down measurements may vary from operator-reported emissions, due to the spatial and temporal variability of emissions over time when compared to annual averages. Understanding facility, operational status, emission sources present at facilities and emission persistence is crucial to reconciling top-down measurements with bottom-up estimates. Therefore, multiple top-down surveys and revisits are needed to capture the temporal and spatial variability of the emissions and to validate bottom-up estimates.

3.1. Plane based measurements and comparison with facility-level reporting – experience from Norway

A recently published paper by Foulds et al. (2022) presents CH_4 emission fluxes from 21 offshore O&G facilities collected in 10 offshore O&G fields over two regions of the NCS in July, August, and September of 2019. Measurements during 13 aircrafts surveys, resulted in emissions which ranged from 2.6 to 1200 tonnes per year (mean of 211 tonnes per year). These measurements were later compared to aggregated operator-reported facilities emissions for 2019, which end up in excellent agreement with the mean aircraft measured fluxes only 16% lower than those reported by operators.

The technology used during the measurements were survey flights from the UK's Facility for Airborne Atmospheric Measurement (FAAM) BAe-146 atmospheric research aircraft and from ChampionX Mooney aircraft. Over the course of this campaign, 21 offshore O&G facilities were surveyed by both aircraft plus repeats at some facilities (for a total of 34 surveys). Detection thresholds were estimated to be 2 kg/h for FAAM and unspecified for SA.

Measurements of the 21 offshore O&G facilities were compared with facility-level reported emissions. Mean measured fluxes (as an aggregate of the 21 facilities studied) were 16% lower than equivalent operator reported data but agreed within uncertainty. The result showed that measurements may be able to replicate facility-level reported emissions with enough surveys, whilst also confirming that facility-level reporting procedures can provide accurate emission estimates for the incorporation into inventories, since they contain an increased level of granularity concerning operational emissions and sources.

However, the authors noted facility operation status over time would improve the results of surveys of individual facilities, as many measured emission rates did not agree with reported emission rates, and understanding operational status will help inform mitigation activities. It was also mentioned that measured emission rate confidence intervals did not agree with reported emissions on a site-by-site basis. They also noted that the extrapolation of measurements to other production fields would not be reliable and would

[30] Three case studies were also identified in the 2020 report, which provide valuable insights. They have been included in Appendix D

require unique measurements for validation using top-down measurements. They noted that a key for accurate quantification of estimates requires repeated, randomized surveys of facilities (either for single facilities or on a regional level) which will improve estimates regardless of operational status.

3.2. Methane remote sensing and emission quantification- experience from the Gulf of Mexico

Ayasse et al. (2022) studied CH_4 emissions from shallow water offshore oil and gas platforms in the Gulf of Mexico using a 432-band visual and short-wave infrared imaging spectrometer with a 34 degrees field of view mounted on the Global Airborne Observatory (GAO) research aircraft to capture sun glint reflection from the water directly surrounding the target areas.

Around 150 unique platforms and surrounding areas were targeted, with 3 or more observations for 40 of these platforms. The main target were platforms which had already been previously measured, as they represent a higher probability for positive CH4 detection and therefore could be used as a test for CH4 glint mode retrievals, also a few similar platforms which had not been previously measured. The offshore, shallow sources measured in this study tend to be more persistent than their onshore counterparts, with an average persistence of 63% of the time. It was found that emissions mostly come from tanks and vent stacks, and that their emissions exhibit a super emitter behavior. In contrast, Yacovitch et al. (2020) performed measurements in deep water in the Gulf of Mexico who found that despite higher production rates, emissions in deep water were much less than for shallow waters (which were often unmanned platforms).

The paper shows the ability to use remote sensing imaging spectrometers and glint targeting to efficiently observe offshore infrastructure, quantify methane emissions, and attribute those emissions to specific infrastructure types. It was also found that methane emissions from most measured sources tend to be very persistent and exhibit super emitter behavior compared to measurements in the Permian Basin in the USA. In the context of the NCS, however, results from shallow water measurement campaigns may not be applicable to the NCS, which are manned, deepwater offshore platforms. Lastly, it also shows the validity of using glint enabled measurements using satellites, which will improve the understanding of the emissions from a critical and largely unmeasured methane sector.

3.3. Methane emissions from oil and gas platforms in the North Sea – experience from the UK

In a paper by Riddick et al. (2019), ship-based measurements of methane mole fractions were conducted at eight oil and gas production platforms on the North Sea, which were neither flaring gas nor loading oil. Measurements were performed during the summer of 2017. Meteorological models were later used in a Gaussian plume model to estimate methane emissions from each platform.

Oil and gas platforms in the UK waters are located between 30 and 500 km from the UK, most located to the east in the North Sea. The technology chosen for the measurements was Los Gatos Research Ultra-portable Greenhouse Gas Analyzer[31], which is a lased absorption spectrometer that measures methane mole fractions in the air. It reports methane mole fractions every second, with a stated precision of < 2 ppb (1σ at 1 Hz) over an operating range of 0.1 to 100 ppm. Calibration was performed before and after deployment using low, target, and high mole fraction calibrated gases. Meteorological data were sampled and recorded at 1 min intervals and included wind speed, wind direction, air temperature at 2m, relative humidity, rain rate, irradiance, and air pressure. The Gaussian plume model used in the study calculates the mole fraction of a gas as a function of distance downwind from a point source.

[31] UGGA; http://www.lgrinc.com/

It was found that all platforms emitted methane during normal operation, and that the median emission was 24.5 kg h^{-1}, corresponding to a median loss of 0.23 % of gas production. They also compared their results with the UK National Atmospheric Emission Inventory (NAEI), which relies on emission factors reported by the industry, and found that the NAEI emissions were mainly due to flaring and oil loading activities, which were not observed during their measurements. This suggests that there is a large missing source of methane emissions from offshore oil and gas operations in the UK inventory. The authors argue that direct measurements of emissions are preferable to emission factors, which may underestimate total emissions if not all sources are identified.

The study highlights the importance of measurements: if measured methane emissions are low, it can improve consumer confidence in oil and gas extraction activities, while higher than reported emissions are observed, it provides the opportunity to operators for improved efficiency of platforms, thus potentially increasing profits from extracted gas. They conclude that more measurements of offshore oil and gas production platform operations are needed to better inform leakage estimates and to improve the UK and global methane emission inventories.

4. Test Protocols

Test protocols are documents that describe the specific testing activities and procedures for verifying that a system meets the established requirements, in this case, methane detection and quantification (Ofni Systems, n.d.). Test protocols are important for several reasons. First, they help to ensure that the testing is consistent, comprehensive, and effective. Second, they provide a clear and detailed record of the testing process and results, which can be used for documentation, communication, training, and troubleshooting purposes. Lastly, they enable the replication and validation of the testing outcomes, which can support compliance with legal and regulatory standards.

Several controlled release tests have been performed in the previous few years for satellites (Sherwin et al., 2023), aircraft (Bell et al., 2022; Conrad et al., 2023; Johnson et al., 2021; Rutherford et al., 2023; Sherwin et al., 2021b), drones ((Morales et al., 2022; Ravikumar et al., 2019), continuous monitoring technologies (Bell et al., 2023; Ravikumar et al., 2019; Singh et al., n.d.) and handheld technologies (Bell et al., 2020; Ravikumar et al., 2018, 2019; D. Zimmerle et al., 2020; D. J. Zimmerle et al., 2020). However, the results of these academic publications for controlled release tests are limited to onshore oil and gas, predominantly in North America. Therefore, there is a need to perform testing in representative conditions that simulate field deployment of methane detection and quantification technologies at offshore oil and gas facilities. This section identifies existing test protocols and relevant criteria for developing test protocols for offshore deployment. Based on this, a gap analysis is performed between currently available test protocols, and what would be required to perform controlled release testing safely and accurately at offshore oil and gas facilities on the NCS.

Currently, there are several test protocols. Methane Emissions Technology Evaluation Center (METEC)[32], operated by the Energy Institute through Colorado State University (CSU), have developed several publicly available test protocols for both survey and continuous monitoring technologies (D. Zimmerle, 2020, 2022). They perform leak detection and quantification using single blind controlled release testing over a range of environmental conditions and controlled emission rates. Their testing facilities are in the state of Colorado, US. It includes several different equipment layouts to perform testing in different settings that replicate oil and gas facilities in North America. METEC performs technology evaluations and continuously improves their test protocols. At the date of publication, METEC have limited controlled release testing protocols to onshore operations, and have not conducted tests in offshore locations such as the nearby Gulf of Mexico.

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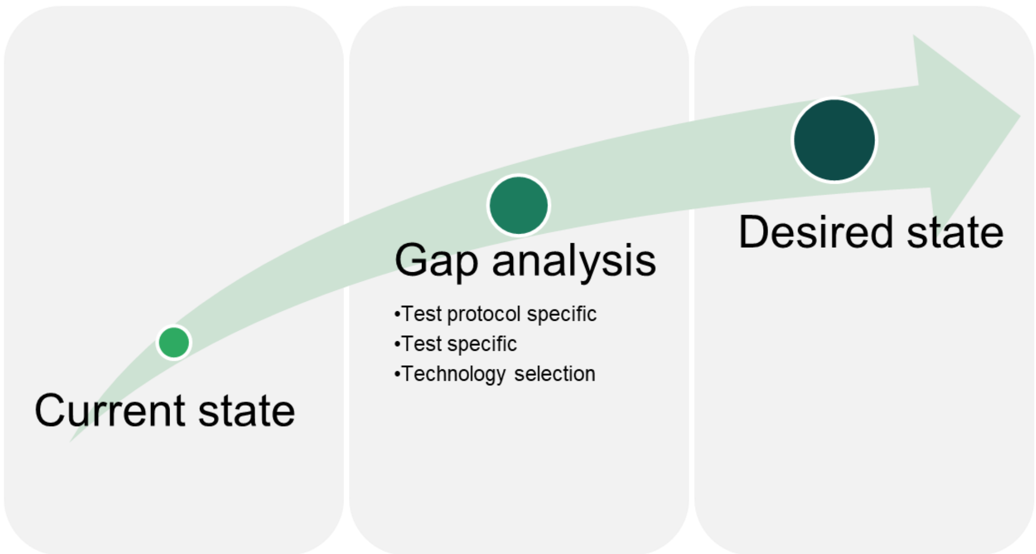
[32] METEC - Energy Institute (colostate.edu)

Another controlled release testing facility is operated by TotalEnergies. TotalEnergies performs controlled release testing at their "Total Energies Anomaly Detection Initiatives" (TADI) facility for detection and quantification at their facility for Experimental Research in Lacq (PERL) in Lacq, France. TADI is the only testing infrastructure of its kind in Europe for the detection and quantification of gas emissions, dedicated to safety (prevention of major accidents) and the environment (reduction of emissions), and a robotics development platform[33]. TADI is divided into two platforms, with controlled release testing with a lower bound of capable controlled release rates similar to METEC but also for higher controlled release rates (up to ~1000 kg/h). Since 2016, METEC and TADI have built up strong scientific collaboration covering developing common testing protocols and exchanging expertise and staff. In 2023, METEC and TADI have jointly prepared a scope of work titled, "Developing a Path Toward International Standards for Leaks Detection Standards for Leak Detection and Quantification Solutions". The scope of work outlines the need to develop one set of standards that: (1) Certifies the accuracy, detection limits, and operational restrictions of measurements methods used for GHG accounting and (2) develops a consensus method for comparing measurements of varying duration with long-duration inventory reporting of GHG, and other emissions. (D. Zimmerle et al., 2023)

A gap analysis was performed following the end goal, which is to have a standardization on protocols to test technologies on methane detection and quantification and with the purpose of building towards performing testing on the NCS.

Figure 9 presents the evaluation of controlled release testing of methane detection and quantification technologies in an offshore environment using test protocols. To perform the gap analysis, the current state of testing protocols is evaluated using interviews with personnel from both METEC and TADI, as well as publicly available documents such as METEC test protocols on survey and continuous monitoring. Secondly, a gap analysis is performed to understand what is required to include in test protocols, what can be drawn upon to ensure standardization of methodologies (where possible), and potential challenges to perform test protocols in an offshore environment, specifically in the NCS.

Figure 9: Gap analysis for test protocols and performing controlled release testing of methane detection and quantification technologies in an offshore environment



Source: Carbon Limits Assessment

[33] PERL Lacq : Pôle d'étude et de recherches de Lacq (Sud-Ouest) (totalenergies.fr)

Existing test protocols are used as the baseline to build from a standardized format, rather than creating a test protocol from scratch for assessment of relevance for offshore controlled release testing. At the point of publication, only METEC test protocols for survey technologies and continuous monitoring were available.

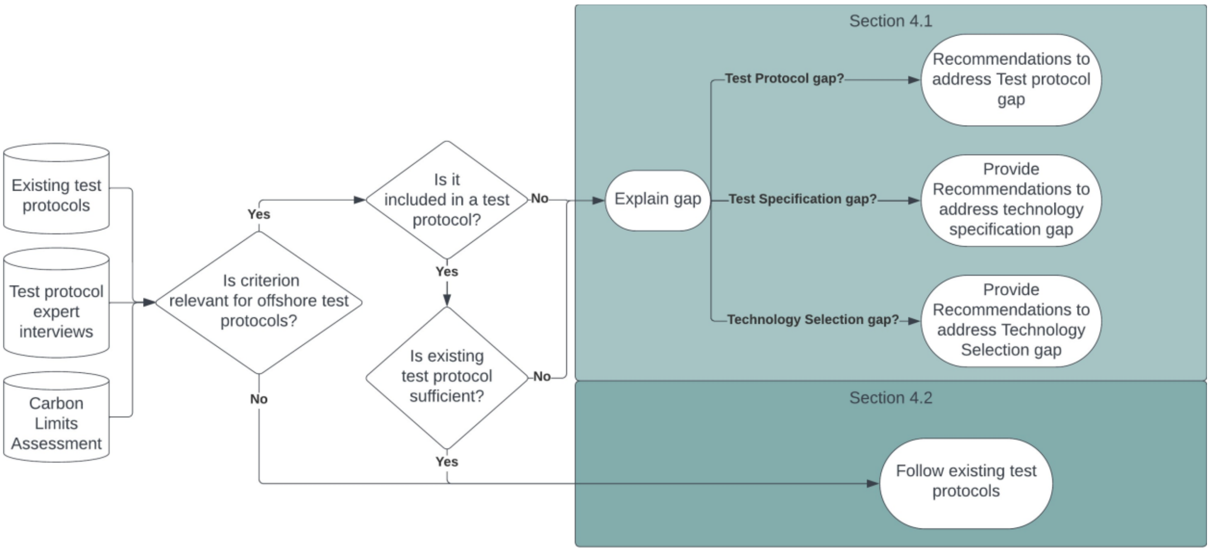
Test protocols were supplemented by interviews with personnel from METEC and TADI, which provided valuable insights into potential considerations for performing controlled releases in an offshore environment. This was also supplemented by Carbon Limits assessments, which are based on literature review of offshore measurements.

Figure 10 describes the decision process for identifying relevant criteria from existing test protocols for methane detection and quantification technologies. Information from test protocols, interviews and assessments of peer-reviewed literature was used to identify a list of potential criteria that are relevant for offshore test protocols. For each criterion, it was assessed whether it had implications for offshore tests, if it was considered in an existing test protocol, and if the existing test protocol was sufficient. If the criterion was not relevant for offshore test protocols, or if it was AND the existing test protocol was sufficient, the recommendation is to follow existing test protocols, and can be found in Section 4.2 below. If the criterion is relevant for offshore testing and is either not included in a test protocol OR included but not sufficient for offshore testing, a gap is identified and explained. The gap was then assessed whether it was one of three options:

- Test protocol: Items that may be necessary to consider as part of including in a standardized test protocol, for which there might be an impact on performing controlled release tests on the NCS.
- Test specification: Items that may be necessary to consider for deploying technologies for controlled release testing offshore on the NCS, which are test specific and could have an impact on controlled release testing.
- Technology selection: Items out of the scope of a test protocol or test specification, but which should be considered for technology selection for testing and subsequent deployment in offshore settings on the NCS.

Recommendations are then provided based on the type of gap identified, which can be found in Section 4.1

Figure 10. Decision tree for performing the gap analysis on test protocols for methane detection and quantification



Source: Carbon Limits Assessment

4.1. Test Protocols Gaps and Recommendations

For criteria that are relevant for offshore test protocols, and either not included in an existing test protocol, or are addressed but additional gaps exist, these are summarized in Table 6 below. Gaps are identified in terms of test protocols, technology specifications and technology selection.

Testing should clearly define the controlled release testing layout, including potential emission sources that are representative of what is found at offshore oil and gas facilities, including release rates. Offshore oil and gas facilities are often more limited with space and can result in emission sources being limited, and creating complex wind profiles, such that attributing emission sources to specific pieces of equipment could be more challenging. Emission sources specific to offshore conditions, such as FPSO or oil loading, should also be tested. Emission rates tested should be representative of expected rates in real scenarios. Generally, controlled release testing and developed test protocols should be as representative as possible to what would be encountered in “real-world” technology deployments, which will offer a better evaluation of technology capabilities.

Testing and subsequent measurements should consider the conditions of the complex marine boundary layer. Testing coordinators should have a clear understanding of meteorological conditions at the time of controlled release testing through measurements of wind speed, direction, temperature, humidity, precipitation. Complex marine boundary layers may result in plumes acting in ways that modelling may not predict without adequate measurement of meteorological conditions. Meteorological measurements such as wind speed should be monitored at emission source heights, while also testing at wind speeds expected to be applicable during real field deployments. These parameters should be measured at the testing location and at the time of measurements, as they may directly affect the performance of a technology in detecting and quantifying methane.

Some criteria were categorized as relevant for technology selection for controlled release testing. These may not directly apply to test protocols but play an important role in determining performance in offshore environments. ATEX certification or any other type of safety certifications which are required in an offshore facility should be adhered to. Technologies that use spectrometric methods and rely on reflectiveness of the background are limited by the low reflectiveness of water. These technologies could still be evaluated but should be treated with a high degree of caution. Performing controlled release tests of these technologies will also be able to benchmark performance while also being able to assist with technology improvement in the future. Lastly, during interviews one of the constantly persisting perspectives from operators and technology providers is that offshore oil and gas platforms are complex. Physical space is limited, personnel capacity is limited, transport to and from platforms presents logistical challenges, and weather conditions are highly variant varied. This created challenges in holding testing windows and should be considered when performing testing offshore.

Table 6. Gap analysis for methane detection and quantification testing performed in an offshore environment

#	Relevant criteria for offshore test protocols	Included in existing test protocols?	Explain Gap	Recommendations for how to address gap		
				Test Protocol	Test Specification	Technology Selection
1	**Offshore specific requirements & certifications (Such as ATEX)** Offshore oil and gas safety carry a high risk of explosive atmospheres. ATEX certification is required for all equipment which needs to be used at offshore platforms.	No	METEC test protocols mainly cover the procedure while testing in facility. No mention of ATEX safety requirements	Define realistic zones requiring ATEX safety as part of testing protocol	Technologies should be positioned in locations applicable for their ATEX rating.	Prior understanding of technology to be tested and zones in which the testing will occur. ATEX certification requirement should be checked before.
2	**Complex marine boundary layers** Boundary layers proved to be important influence on observed CH4 mixing ratios. (1) it is difficult to determine which enhancements are from installations and require further investigation. (2) emissions being actively released can become entrained in complex turbulent air structures, which can be easily missed.	No	Measurements in conditions with multiple residual boundary layers makes interpretation difficult and pin-pointing emissions especially challenging, as emission plumes can easily be missed when they are trapped in thin filaments, increasing the uncertainties of measurement-based emission flux calculations.	Testing coordinators should have a clear understanding of meteorological conditions at the time of controlled release testing through measurements of wind speed, direction, temperature, humidity, precipitation etc. at testing location	For tested technologies, wind speed and direction should be included in measurement and reporting by technologies, where relevant. Technologies should be tested in weather conditions representative of offshore environments (i.e. not only optimal measurement conditions)	Similar recommendations to test specifications.

3	**Wind speeds & height of emissions sources** Average wind speed in offshore locations tends to be higher than in onshore locations. For the case of the NCS, wind speeds average over 10m/s at a height of 10m, while wind speed may vary significantly in the boundary layer depending on meteorological conditions. Methane plumes and modelling are highly dependent on wind speed measurements to determine emission rates. Higher wind speeds can result in higher dispersion.	Yes	Wind speed measurement is part of METEC protocol. However, METEC protocol does not specify the height of the measurement, while wind speed can vary significantly with height. METEC protocol for continuous monitoring requires installations to be suitable to withstand winds of up to 50m/s.	Include specification on the height of wind speed measurements. Consider several heights representative of different emissions points.	Testing should be performed at wind speeds and heights representative of offshore environments. Testing should be performed in wind speeds that ensure safe conditions as relevant for offshore health and safety requirements.	Carefully consider technologies beforehand which have specifications that limit operation in wind speeds below most common wind speed on NCS.
4	**Facility specific such as: Network connectivity, power supply, tight space constraints, etc.** Some measurement technologies, mostly continuous monitoring ones, need external network connectivity, power supply and may have a minimum footprint size.	Yes	According to test protocols (Installations 5.1), performers are encouraged to provide their own power and network connectivity as it would be deployed in field. Offshore platform personnel might need to use locations resources as there might be space constraints.	METEC provides 120V/60Hz power distribution at all mounting positions for continuous monitors. Offshore testing protocols should document procedures for realistic scenarios which consider both tight space constraints,	Facility specific conditions should be assessed beforehand and considered during the planning of offshore testing. Testing should be done as would be deployed in field.	Technology requiring network connectivity and power should be suitably assessed to determine there is limitations that would result in data losses or

				and power availability at specific locations		
5	**Equipment layout** Depending on site layout and proximity of equipment and emission sources to one another, it can provide challenges for localization and source attribution. i.e., if there are several sources with intermixing plumes, it can be mixed and detected as one plume.	Yes	Offshore platforms equipment layout varies very significantly from onshore layout, as space constraint increases, equipment tends to be grouped together in tighter spaces.	METEC test protocol defines emission surveys through facility boundary, equipment groups and equipment. Refer to S7 of test protocols. Offshore testing should also consider this.	Control release testing should be representative of what would be expected in an offshore deployment, including representative emission rates and intermittency. Multiple releases from multiple equipment sources, or sources in proximity may be most representative, and pose additional challenges to technologies, which could be considered in addition to controlled release testing with single release rates.	Technologies should be evaluated using equipment layout representative of offshore deployments, with potential plume mixing and equipment in proximity
6	**Other environmental conditions** Environmental conditions are generally rough in an offshore environment. Specific parameters of note may include low sunlight conditions, high salinity, low temperature.	Yes	Although, METEC already includes requirements to report several environmental conditions, it is worth to mention how the environment can vary form onshore locations.	Conditions should be summarized in the report and considered at the time of controlled release testing.	Similar recommendation for Gap #2, technologies should be tested in weather conditions representative of offshore environments (i.e. not only optimal measurement conditions)	Technology should be able to withstand environmental conditions.
7	**Reflectiveness of water** Water has a high reflectance, which can impact spectrometric-based measurements (e.g., satellites or planes	No	METEC section on Technology is being tested over land, soon should be tested offshore. Reflectiveness of water is not considered in test protocol	Test protocols should be developed such that technologies that use spectrometric-based measurements are not excluded from	Reflectiveness of water should be considered during testing in such a way that it would be representative in real	Consider current limitations due to reflectiveness of water. Current capabilities are limited over water and should be treated

	either passive or active sensing technologies) and create challenges in performing measurements.			participation, regardless of current effectiveness	scenarios (i.e., using glint measurements)	with high degree of caution at this time for controlled release testing and deployment.
8	Specific Sources Potential emitting sources offshore vary to onshore emissions sources. Other type of sources which are present in offshore environments could include FPSO, Oil loading, among others.	No	METEC includes potential emissions sources which are present Onshore in US upstream production/transmissions segments.	Specific emission sources should be documented, which would represent emission sources found at offshore oil and gas facilities. Controlled release rates along with a number of predetermined controlled releases, that may include blanks (zeros), steady, unsteady or intermittent rates (inc. 95% confidence intervals) with gas compositions representative of each specific source should be recorded by the facility	Controlled releases should be representative of emission sources expected in an offshore deployment.	Technologies should be evaluated for emission sources representative in an offshore deployment.
9	Site location Testing location must be selected to perform the controlled releases. Options could include, operating platforms, non-operating platforms, or on a vessel.	Yes	METEC testing performed at a non-operating facility that is specifically designed for controlled release testing. Controlled release testing is also planned for the future in actively producing regions.	Test location should be documented and if other potential emissions sources are present.	Testing would first ideally be performed at a non-operating platform, which would be the more representative compared to ship-based measurements, which would be challenging to present representative conditions for an offshore	No gap identified for site location

					platform). Following future developments and increased understanding of controlled releases at offshore platforms, it would be essential to perform controlled releases at producing platforms to best determine capabilities, safety-permitting	
10	**Offshore Logistics** Logistics when going offshore have an added complexity. Some complexity which are added to offshore activities include but are not limited to higher cost, certifications to go offshore for both equipment and personnel, weather dependency, etc.	No	Publicly available testing protocols mainly cover the procedure while testing in facility. Logistics are not included and can be highly complex in practice.	Test protocols should define logistics for including a maximum survey time for manned technologies (e.g. handheld or drones), and time for deployment of continuous monitoring solutions pre-testing. Required continuous monitoring maintenance should be scheduled between tested technologies and testing coordinators.	Consider logistics of travel to and from testing facility, For example, maximum number of personnel to install or deploy technologies prior to testing, for maintenance. Personnel limits if multiple technologies deployed according to health and safety.	Logistics should be considered as potential challenges and maintenance/ should be accordingly planned.

4.2. Standardization with Existing Test Protocols

Identified criteria that may not be specific to offshore oil and gas facilities on the NCS or are important but are covered by an existing test protocol were not exclusively included in the gap analysis in Section 4.1. Current facilities such as METEC and TADI have both developed test protocols and performed controlled release testing of methane detection and quantification technologies, both onshore and offshore. Furthermore, their collaboration on developing standardized test protocols is a step towards a globally consistent approach that will allow for more direct comparison between controlled release testing performed in different jurisdictions or areas. This will enable industry stakeholders to participate in the development and advancement of methane detection and quantification technologies. Where possible, it is recommended to perform controlled release testing following existing test protocols as much as possible, and to identify opportunities to collaborate with test protocol stakeholders such as METEC and TADI.

5. Conclusions and summary

This report provides an overview of the availability and capability of methane detection and quantification technologies for offshore use on the NCS. The report is an update of the 2020 report titled “Overview of methane detection and measurement technologies for offshore applications”. Methane emissions from Norwegian offshore oil and gas facilities were assessed, including total emission rates and common emission sources.

Measurements at offshore oil and gas facilities on the NCS provide several challenging environmental limitations, including northern latitudes, weather conditions such as seasonal cold and darkness, and meteorological conditions such as high variability of wind speed in the marine boundary layer. Reflectiveness over water restricts remote sensing technologies used in satellites, aircraft, and drones. Performance of these technologies is reduced when compared to deployment at onshore oil and gas facilities. Methane absorption of infrared light reflected off the water surface is poor due to this reflectively While there are techniques which can be used to overcome these limitations using glint measurements, there is still ongoing work to overcome these limitations compared to measurements over land.

Offshore oil and gas facilities on the NCS also have varying logistical constraints when compared to other producing regions, particularly when compared to onshore oil and gas facilities. Logistical constraints include facility access and strict health and safety constraints. More technologies are available that have ATEX certification. The logistical constraints deploying technologies with explosion proof requirements is subject to operator safety requirements and is more challenging in practice than at onshore facilities. Space is constrained in densely packed offshore oil and gas platforms, with limited open access that can limit technology deployment and operating areas. Compared to facilities on land, offshore installations are difficult and costly to access. Whereas at land-based installations one can relatively easily drive along nearby roads, fly a drone from outside the perimeter or set up a fixed array of sensors in the areas around, these options are much more challenging to do in the open sea.

To assess potential technologies relevant for deployment on the NCS, interviews were conducted with technology providers. A number of technologies are available and were identified for applicability for methane measurements at offshore oil and gas facilities. In total, 28 datasheets were developed for technologies potentially relevant, which were created based on technology provider input, internal assessment and feedback from industry and operator experts. Datasheets were created for satellites, aircraft, drone, handheld and continuous monitoring technologies. Each of these deployment methods are further described in the sections below.

A gap analysis of existing test protocols was also performed. The goal of this was to identify potential challenges, limitations, and synergies of current test protocols developed for measurement of emission from onshore oil and gas, and what may be required for developing a test protocol for controlled release testing offshore on the NCS. Gaps were assessed based on test protocols, technical specifications, and technology development, that can be used to better inform successful controlled release testing.

5.1. Satellites

Satellite measurements of methane emissions from Norwegian offshore installations are most suited to performing top-down, site level measurements. Satellite measurements are more challenging than other areas, due to low average emission rates, reduced performance over water, high latitudes and cloud coverage. Each of these challenges could be overcome, but together they strictly limit the possibilities of satellite measurements. For example, higher detection thresholds could be mitigated by more frequent satellite observations, but high latitudes limit the operational window and makes continuous monitoring from geostationary satellites impossible. Poor performance over water could be overcome by sun-glint geometry observations. Methods to perform these glint measurements have been improved, but there are still limitations, with higher detection thresholds. Satellites have been demonstrated to detect large emission sources from offshore oil and gas platforms and pipelines. Satellites are best suited to detect large, intermittent emission sources that may otherwise be missed. They should have adequate pixel resolution to be able to determine that the emission source can be attributed to a specific platform. Shorter return periods will help include temporal coverage and can also be used to confirm absence of these large emission sources. The real-world performance of each individual satellite mission is still uncertain, but vast improvements have been made in the past few years. While ongoing technological progress and the introduction of new satellites show promise, achieving comprehensive monitoring of methane emissions originating from offshore sources on the NCS using satellites remains a complex endeavor. It is recommended that the actual capabilities are tested as each new satellites enter service.

5.2. Aircraft

Measurement campaigns using small planes are a commercially available option which allows for coverage over large areas with relatively precise estimation. One flight can cover multiple sites and can reduce the per-site cost of measurement. Aircraft can be used to perform top-down site level measurements, that may be able to provide whole site measurements (in-situ and remote sensing techniques) and to detect emissions from specific equipment or emission sources (remote sensing techniques). Detection performance over ocean water is reduced for remote sensing technologies, while in-plume techniques perform at least as well as over land. Therefore, in-plume techniques are still the preferred option for offshore measurements and can be used for emissions estimations resulting in low uncertainty levels. Unsuitable weather conditions for flight offshore were a challenge for the measurement campaign over the Norwegian offshore installations, resulting in many days of waiting for an operational window. Therefore, aircraft-based measurements of methane emissions from Norwegian offshore installations are most suited to performing top-down, site level measurements.

5.3. Drone based measurements

Drones equipped with sensors are available for offshore use and can be used to perform top down, site level measurements, as well as identifying specific emission sources. The maneuverability of drones helps assess emission sources in proximity that may otherwise be missed, such as elevated sources. There are still logistical challenges for drone-based measurements. This includes limitations to being flown by an operator who is onboard the platform or on a ship in the immediate area. This adds complexity to a campaign, requiring travel to a platform by helicopter or ship, suitable weather conditions for flight, and clear-access areas for take-off and landing of the drone. One option to reduce costs could be either to combine drone measurements with other onboard services such as leak detection and repair personnel, training them to operate the drone safely and systematically for measurements. Another option could be to have a drone available onboard a platform, and train onboard personnel to be able to use it for routine measurement. Multirotor drones are the most common drone-based measurement. Fixed wing drone technologies have been available, but there are still logistical and regulatory challenges for flying drones beyond visual line of sight. If such operations are deemed safe and regulations allow for a simpler method of achieving clearance for a flight plan, long-range drone operations could be a feasible measurement technique.

5.4. Handheld Sensors

Handheld sensors are bottom up, source level detection and (in some cases) quantification devices that can be used to identify specific emission sources. There are extensive efforts today using handheld instruments for LDAR on offshore installations on the NCS. Technologies can be operated by both facility personnel or third party contractors. An important indicator of handheld sensors performance is operator ability, where more experienced operators will be more effective at identifying and quantifying leaks. Several technologies can be used for quantification of emission sources. OGI cameras are capable of quantification but are ideally paired with a separate device for quantification, such as a high volume sampler.

5.5. Continuous Monitoring Solutions

Continuous monitoring solutions have made recent developments as a useful tool for methane emission detection and quantification, offering real time, continuous surveillance, above and beyond "fenceline" and gas sensors for safety already deployed at offshore platforms in the NCS. More technologies have become available since 2020 and are potentially relevant for offshore platforms in the NCS. Technologies may be an array of sensors that provide site level measurements or can be fixed on specific emission sources to provide source level quantification. Technologies should be suitable for use in ATEX environments, and optimal placement of sensors should be considered on a case-by-case basis to best detect and quantify emissions. They offer quicker detection and quantification of emissions that periodic measurements using satellites, aircraft, drones, or handheld sensors. Recent research has shown that relying on quantification of emissions from these devices may be premature, but this will also drive improved performance. Currently, they may be best suited to identify potential emission sources. However, they can be an important aspect of a monitoring, reporting, and verification program. Measurements with continuous monitoring solutions may require follow-up with a more accurate quantification device to inform mitigation actions.

5.6. Combination of Technologies

Different deployment methods for methane emissions detection and quantification offer different benefits and limitations. Based on the assessments of different deployment methods, no one technology could definitively measure all emissions from offshore oil and gas facilities. Combinations of different technologies may be employed, that offer various advantages of different methods that complement the limitations of others. However, even with selecting combinations of technologies, there is no one-size fits-all approach that will always provide a complete measurement of all methane emissions from oil and gas facilities, whether they are onshore or offshore. All facilities and associated emission sources will vary, thus varying the requirements for measurements. Different emission sources may exhibit different characteristics and patterns, which include emission rate, intermittency, or variability in rates.

Recent research by Wang et al. (2022) that present a quantification, monitoring, reporting, and verification framework using a tiered approach of different deployment methods to detect and quantify methane emission from oil and gas. The framework uses both periodic monitoring with top-down measurement techniques such as satellites, aircraft, and drones, with more frequent periodic monitoring helping to provide a less biased estimate of total emissions. This can be supplemented with bottom-up techniques using systematic detection surveys using audio, visual and olfactometry, US EPA Method 21 and OGI detection. This can be combined with continuous monitoring using fixed sensors. The use of these periodic measurements along with continuous monitoring can be paired together to capture both intermittent and short-duration events that are missed by periodic monitoring, to increase confidence in measurement-based inventories.

6. References

Ayasse, A. K., Thorpe, A. K., Cusworth, D. H., Kort, E. A., Negron, A. G., Heckler, J., Asner, G., & Duren, R. M. (2022). Methane remote sensing and emission quantification of offshore shallow water oil and gas platforms in the Gulf of Mexico. *Environmental Research Letters*, *17*(8). https://doi.org/10.1088/1748-9326/ac8566

Barchyn, T. E., Hugenholtz, C. H., & Fox, T. A. (2019). Plume detection modeling of a drone-based natural gas leak detection system. *Elementa*, *7*. https://doi.org/10.1525/elementa.379

Bell, C., Ilonze, C., Duggan, A., & Zimmerle, D. (2023). Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol. *Environmental Science and Technology*, *57*(14), 5794–5805. https://doi.org/10.1021/acs.est.2c09235

Bell, C., Rutherford, J., Brandt, A., Sherwin, E., Vaughn, T., & Zimmerle, D. (n.d.). *Single-blind determination of methane detection limits and quantification 1 accuracy using aircraft-based LiDAR 2*.

Bell, C., Rutherford, J., Brandt, A., Sherwin, E., Vaughn, T., & Zimmerle, D. (2022). Single-blind determination of methane detection limits and quantification accuracy using aircraft-based LiDAR. *Elementa: Science of the Anthropocene*, *10*(1), 1–12. https://doi.org/10.1525/elementa.2022.00080

Bell, C., Vaughn, T. L., & Zimmerle, D. J. (2020). Evaluation of next generation emission measurement technologies under repeatable test protocols. *Elementa: Science of the Anthropocene*, *8*(1), 32. https://doi.org/10.1525/elementa.426

Brown, P. F., Saunier, S., Simon, M., & Heras Cruz, B. (2020). Carbon Limits. *Overview of methane detection and measurement technologies for offshore applications*.

Caico, C., Fragu, L., Gonzalez, L., Juéry, C., Kangas, P., Lawson, C., Negroni, J., Roberts, P., Smithers, B., Tupper, P., & Vaskinen, K. (2017). *An evaluation of an optical gas imaging system for the quantification of fugitive hydrocarbon emissions*. www.concawe.org

Conley, S. A., Faloona, I., Mehrotra, S., Suard, M., Lenschow, D. H., Sweeney, C., Herndon, S., Schwietzke, S., Pétron, G., Pifer, J., Kort, E. A., & Schnell, R. (2017). Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases. *Atmospheric Measurement Techniques*, *10*, 3345–3358. https://doi.org/10.5194/amt-10-3345-2017

Conrad, B. M., Tyner, D. R., & Johnson, M. R. (2023). Robust probabilities of detection and quantification uncertainty for aerial methane detection: Examples for three airborne technologies. *Remote Sensing of Environment*, *288*, 113499. https://doi.org/10.1016/j.rse.2023.113499

Foulds, A., Allen, G., Shaw, J. T., Bateson, P., Barker, P. A., Huang, L., Pitt, J. R., Lee, J. D., Wilde, S. E., Dominutti, P., Purvis, R. M., Lowry, D., France, J. L., Fisher, R. E., Fiehn, A., Pühl, M., Bauguitte, S. J. B., Conley, S. A., Smith, M. L., … Schwietzke, S. (2022). Quantification and assessment of methane emissions from offshore oil and gas facilities on the NCS. *Atmospheric Chemistry and Physics*, *22*(7), 4303–4322. https://doi.org/10.5194/acp-22-4303-2022

France, J. L., Bateson, P., Dominutti, P., Allen, G., Andrews, S., Bauguitte, S., Coleman, M., Lachlan-Cope, T., Fisher, R. E., Huang, L., Jones, A. E., Lee, J., Lowry, D., Pitt, J., Purvis, R., Pyle, J., Shaw, J., Warwick, N., Weiss, A., … Young, S. (2021). Facility level measurement of offshore oil and gas installations from a medium-sized airborne platform: Method development for quantification and source identification of methane emissions. *Atmospheric Measurement Techniques*, *14*(1), 71–88. https://doi.org/10.5194/amt-14-71-2021

Gao, M., Xing, Z., Vollrath, C., Hugenholtz, C. H., & Barchyn, T. E. (2023). *Global observational coverage of oil and gas methane sources with TROPOMI*. https://doi.org/10.21203/rs.3.rs-2681923/v1

Gerilowski, K., Krings, T., Hartmann, J., Buchwitz, M., Sachs, T., Erzinger, J., Burrows, J. P., & Bovensmann, H. (2015). Atmospheric remote sensing constraints on direct sea-air methane flux from the 22/4b North Sea massive blowout bubble plume. *Marine and Petroleum Geology*, *68*, 824–835. https://doi.org/10.1016/j.marpetgeo.2015.07.011

GHGSat. (2022, September 30). *GHGSat measures its largest emission from a single source ever from Nord Stream 2 leak*. https://www.ghgsat.com/en/newsroom/ghgsat-nordstream/

Gorchov Negron, A. M., Kort, E. A., Conley, S. A., & Smith, M. L. (2020). Airborne Assessment of Methane Emissions from Offshore Platforms in the U.S. Gulf of Mexico. *Environmental Science and Technology*, *54*(8), 5112–5120. https://doi.org/10.1021/acs.est.0c00179

Hasekamp, O., Lorente, A., Hu, H., Butz, A., Aan De Brugh, J., & Landgraf, J. (2019). *Algorithm Theoretical Baseline Document for Sentinel-5 Precursor Methane Retrieval*.

Husdal, G., Osenbroch, L., Yetkinoglu, Ö., & Østebrøt, A. (2016). *Kaldventilering og diffuse utslipp fra petroleumsvirksomheten på norsk sokkel Delrapport 2 Utslippsmengder og kvantifiseringsmetodikk Utarbeidet for Miljødirektoratet*.

Interstate Technology & Regulatory Council (ITRC). (2018). *Evaluation of Innovative Methane Detection Technologies*. https://methane-1.itrcweb.org/4-technology/

Irakulis-Loitxate, I., Gorroño, J., Zavala-Araiza, D., & Guanter, L. (2022). Satellites Detect a Methane Ultra-emission Event from an Offshore Platform in the Gulf of Mexico. *Environmental Science & Technology Letters*, *9*(6), 520–525. https://doi.org/10.1021/acs.estlett.2c00225

Jacob, D. J., Varon, D. J., Cusworth, D. H., Dennison, P. E., Frankenberg, C., Gautam, R., Guanter, L., Kelley, J., McKeever, J., Ott, L. E., Poulter, B., Qu, Z., Thorpe, A. K., Worden, J. R., & Duren, R. M. (2022). Quantifying methane emissions from the global scale down to point sources using satellite observations of atmospheric methane. *Atmospheric Chemistry and Physics*, *22*(14), 9617–9646. https://doi.org/10.5194/acp-22-9617-2022

Johnson, M. R., Tyner, D. R., & Szekeres, A. J. (2021). Blinded evaluation of airborne methane source detection using Bridger Photonics LiDAR. *Remote Sensing of Environment*, *259*, 112418. https://doi.org/10.1016/j.rse.2021.112418

Liu, Y., Paris, J.-D., Broquet, G., Roy, V. B., Meixus Fernandez, T., Andersen, R., Berlanga, A. R., Christensen, E., Courtois, Y., Dominok, S., Dussenne, C., Eckert, T., Finlayson, A., Fernández De La Fuente, A., Gunn, C., Hashmonay, R., Hayashi, J. G., Helmore, J., Honsel, S., … Bousquet, P. (2023). *Assessment of current methane emissions quantification techniques for natural gas midstream applications (pre-print)*. https://doi.org/10.5194/amt-2023-97

Lorente, A., Borsdorff, T., Butz, A., Hasekamp, O., Aan De Brugh, J., Schneider, A., Wu, L., Hase, F., Kivi, R., Wunch, D., Pollard, D. F., Shiomi, K., Deutscher, N. M., Velazco, V. A., Roehl, C. M., Wennberg, P. O., Warneke, T., & Landgraf, J. (2021). Methane retrieved from TROPOMI: Improvement of the data product and validation of the first 2 years of measurements. *Atmospheric Measurement Techniques*, *14*(1), 665–684. https://doi.org/10.5194/amt-14-665-2021

Lorente, A., Borsdorff, T., Martinez-Velarte, M. C., Butz, A., Hasekamp, O. P., Wu, L., & Landgraf, J. (2022). Evaluation of the methane full-physics retrieval applied to TROPOMI ocean sun glint measurements. *Atmospheric Measurement Techniques*, *15*(22), 6585–6603. https://doi.org/10.5194/amt-15-6585-2022

Maclean, J.-P. W., Girard, M., Jervis, D., Marshall, D., Mckeever, J., Strupler, M., Ramier, A., Tarrant, E., & Young, D. (2023). *Offshore methane detection and quantification from space using sun glint measurements with the GHGSat constellation (pre-print)*.

Miljødirektoratet. (n.d.). *Norske Utslipp*. Retrieved September 22, 2023, from https://www.norskeutslipp.no/no/Komponenter/Utslipp/Metan/?ComponentType=utslipp&ComponentPageID=55

Morales, R., Ravelid, J., Vinkovic, K., Korbeń, P., Tuzson, B., Emmenegger, L., Chen, H., Schmidt, M., Humbel, S., & Brunner, D. (2022). Controlled-release experiment to investigate uncertainties in UAV-based emission quantification for methane point sources. *Atmospheric Measurement Techniques*, *15*(7), 2177–2198. https://doi.org/10.5194/amt-15-2177-2022

NORSOK S-001:2020+AC:2021. (2021).

Offshore Norge. (2022). *Guideline 044 - Offshore Norge Recommended guidelines for discharge and emission reporting*. https://offshorenorge.no/en/guidelines/guidelines/environment/044--norwegian-oil-and-gas-recommended-guidelines-for-discharge-and-emission-reporting-new-revision-23022017/

Offshore Norge. (2023). *Klima og miljørapport 2023*. https://info.offshorenorge.no/klimaogmiljorapport23

Ofni Systems. (n.d.). *Test Protocols and Test Plans*. Retrieved September 23, 2023, from https://www.ofnisystems.com/services/validation/test-protocols/#:~:text=Test%20Protocols%20are%20collections%20of,acceptance%20criteria%20for%20the%20test.

Ravikumar, A. P., Sreedhara, S., Wang, J., Englander, J. G., Roda-Stuart, D., Bell, C. S., Zimmerle, D. J., Lyon, D. R., Mogstad, I., Ratner, B., & Brandt, A. R. (2019). Single-blind inter-comparison of methane detection technologies – results from the Stanford/EDF Mobile Monitoring Challenge. *Elementa: Science of the Anthropocene*, *7*(1), 37. https://doi.org/10.1525/elementa.373

Ravikumar, A. P., Wang, J., McGuire, M., Bell, C. S., Zimmerle, D. J., & Brandt, A. R. (2018). “Good versus Good Enough?” Empirical Tests of Methane Leak Detection Sensitivity of a Commercial Infrared Camera. *Environmental Science & Technology*, *52*(4), 2368–2374. https://doi.org/10.1021/acs.est.7b04945

Riddick, S. N., Mauzeral, D. L., Celia, M., Harris, N. R. P., Allen, G., Pitt, J., Staunton-Sykes, J., Forster, G. L., Kang, M., Lowry, D., Nisbet, E. G., & Manning, A. J. (2019). Methane emissions from oil and gas platforms in the North Sea. *Atmospheric Chemistry and Physics*, *19*(15), 9787–9796. https://doi.org/10.5194/acp-19-9787-2019

Rutherford, J., Sherwin, E., Chen, Y., Aminfard, S., & Brandt, A. R. (2023). *Evaluating methane emission quantification performance and uncertainty of aerial technologies via high-volume single-blind controlled releases*.

Samferdselsdepartementet. (2022). *Forskrift om luftfart med ubemannet luftfartøy i åpen-og i spesifikk kategori (BSL A 7-2)*. https://lovdata.no/dokument/SF/forskrift/2020-11-25-2460

Sherwin, E. D., Chen, Y., Ravikumar, A. P., & Brandt, A. R. (2021a). Single-blind test of airplane-based hyperspectral methane detection via controlled releases. *Elementa*, *9*(1). https://doi.org/10.1525/elementa.2021.00063

Sherwin, E. D., Chen, Y., Ravikumar, A. P., & Brandt, A. R. (2021b). Single-blind test of airplane-based hyperspectral methane detection via controlled releases. *Elementa: Science of the Anthropocene*, *9*(1). https://doi.org/10.1525/elementa.2021.00063

Sherwin, E. D., Rutherford, J. S., Chen, Y., Aminfard, S., Kort, E. A., Jackson, R. B., & Brandt, A. R. (2023). Single-blind validation of space-based point-source detection and quantification of onshore methane emissions. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-30761-2

Singh, D., Barlow, B., Hugenholtz, C., Funk, W., Robinson, C., & Ravikumar, A. P. (n.d.). *Non-peer reviewed pre-print submitted to EarthArXiv Field Performance of New Methane Detection Technologies: Results from the Alberta Methane Field Challenge*.

Thorpe, A. K., Frankenberg, C., & Roberts, D. A. (2014). Retrieval techniques for airborne imaging of methane concentrations using high spatial and moderate spectral resolution: Application to AVIRIS. *Atmospheric Measurement Techniques*, *7*(2), 491–506. https://doi.org/10.5194/amt-7-491-2014

Wang, J. L., Daniels, W. S., Hammerling, D. M., Harrison, M., Burmaster, K., George, F. C., & Ravikumar, A. P. (2022). Multiscale Methane Measurements at Oil and Gas Facilities Reveal Necessary Frameworks for Improved Emissions Accounting. *Environmental Science and Technology*, *56*(20), 14743–14752. https://doi.org/10.1021/acs.est.2c06211

Yacovitch, T. I., Daube, C., & Herndon, S. C. (2020). Methane Emissions from Offshore Oil and Gas Platforms in the Gulf of Mexico. *Environmental Science and Technology*, *54*(6), 3530–3538. https://doi.org/10.1021/acs.est.9b07148

Zimmerle, D. (2020). *Continuous Monitoring Protocol METEC Controlled Test Protocol: 2 Continuous Monitoring Emission Detection And Quantification*.

Zimmerle, D. (2022). *Survey Protocol METEC Controlled Test Protocol: 2 Survey Emission Detection And Quantification*.

Zimmerle, D., Bénassy, M.-F., & Marcarian, X. (2023). *Developing a Path Toward International Standards for Leak Detection and Quantification Solutions*.

Zimmerle, D. J., Vaughn, T. L., Bell, C., Bennett, K., Deshmukh, P., & Thoma, E. (2020). Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions. *Environmental Science & Technology*, *54*(18), 11506–11514. https://doi.org/10.1021/acs.est.0c01285

Zimmerle, D., Vaughn, T., Bell, C., Bennett, K., Deshmukh, P., & Thoma, E. (2020). Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions. *Environmental Science and Technology*, *54*(18), 11506–11514. https://doi.org/10.1021/acs.est.0c01285

Zimmerle, D., Vaughn, T., Cody, K. B., Slr, R., Harrison, M., Wilson, A., & Johnson, C. (2022). *Final Report: Open-Source High Flow Sampler for Natural Gas Leak Quantification*. https://energy.colostate.edu/wp-content/uploads/sites/28/2022/08/FACF_High_Flow_Final_Report_ada.pdf

Appendix A. Technology Assessment Summary

Table 7: Summary of technologies assessed, categorized based on deployment method

Deployment Method	Count of Technologies Identified		Technically Relevant	Included in 2023 Report
	2020	New (2023)		
Handheld	3	12	15	10
Stationary	4	15	18	9
Drone	3	4	7	4
Plane	2	1	1	1
Satellite	5	8	5	4
Total	**13**	**40**	**46**	**28**

Table 8: Summary of presented datasheets, compared to the datasheets presented in 2020 report

Company	Technology	Deployment Method	Technically Relevant	Report identified	Included (Yes/no)	Reason if No	Previously deployed offshore
Explicit	Emissions monitoring	Drone	Yes	2023	Yes		X
FlyLogix (SeekOps)	Fixed wing drone	Drone	Yes	2020	No	Out of business/in transition	
ChampionX	DJI Matrice	Drone	Yes	2020	Yes		X
SeekOps	Multi-rotor drone	Drone	Yes	2023	Yes		X
Sierra Olympic	Ventus OGI	Drone	Yes	2023	No	No response	
Baker Hughes	Lumen Sky	Drone	Yes	2020	No	Not in operation	
AddGlobe	GFM 2.0	Handheld	Yes	2023	Yes		X
Distran	Ultra M	Handheld	Yes	2020	No	No response	
Heath Consultants	Detecto-Pak Infrared+ (DP-IR+)	Handheld	Yes	2023	Yes		
Heath Consultants	Remote Methane Leak Detector (RMLD-CS)	Handheld	Yes	2023	Yes		X
Hetek	HETEK flow sampler	Handheld	Yes	2023	Yes		
Opgal	EyeCGas 2.0	Handheld	Yes	2023	No	No response	
Pergam-Suisse	LM Smart/LMm	Handheld	Yes	2023	Yes		
Picarro	G4301 Gas Concentration Analyzer	Handheld	Yes	2023	Yes		
Providence Photonics	QL320 handheld tablet	Handheld	Yes	2020	No	Integrated in other Teledyne FLIR technologies	
Sensia	Caroline Y	Handheld	Yes	2020	No	Replaced new model	
Sensia	Mileva 33	Handheld	Yes	2023	Yes		x
Sensors Inc	Semtech Hi Flow Sampler 2	Handheld	Yes	2023	No	No response	
Teledyne FLIR	GFX320	Handheld	Yes	2023	Yes		x
Teledyne FLIR	Gx620	Handheld	Yes	2023	Yes		x

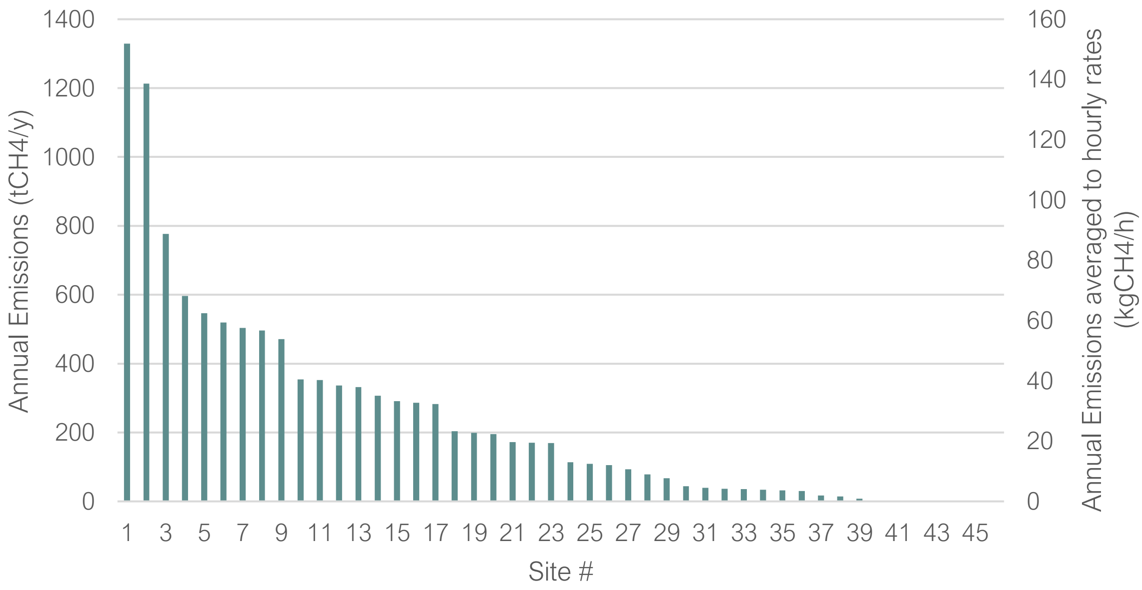
Teledyne FLIR	G620	Handheld	Yes	2023	Yes		x
Bridger Photonits	GML	Plane	No	2023	No	Not relevant	
Kairos Aerospace	LeakSurveyor	Plane	Yes - report only	2020	No	Not relevant	
NASA JPL	AVIRIS-NG	Plane	Yes - report only	2023	No	Not relevant	
ChampionX	Manned Aircraft	Plane	Yes	2020	Yes		x
ASI	PRISMA	Satellite	No	2020	No	Not relevant	
Bluefield Technologies		Satellite	No	2020	No	Out of business/in transition	
Carbon Mapper / Planet	Carbon Mapper	Satellite	Yes	2023	No	No response/not relevant	
DigitalGlobe	Maxar - WorldView 3	Satellite	Yes	2023	Yes		x
Environmental Defense Fund	MethaneSAT	Satellite	Yes	2020	Yes		
ESA	Sentinel 2	Satellite	No	2020	No	DL too high	
ESA	TROPOMI	Satellite	No	2020	No	DL too high	
French-German	Merlin	Satellite	No	2020	No	Future Release	
GHGSat	GHGSAT - Constellation	Satellite	Yes	2020	Yes		x
NASA	GeoCARB	Satellite	No	2020	No	Cancelled	
NASA	EMIT	Satellite	No	2020	No	DL too high	
NASA/USGS	Landsat-8	Satellite	No	2020	No	DL too high	
Orbital Sidekick, Inc.	Spectral Intelligence	Satellite	Yes	2023	Yes		
Aeris Technologies Inc.	MIRA PicoMobile	Stationary	Yes	2020	No	No Response	
Atmosfir	D-fenceline	Stationary	Yes	2023	No	No response	
Clean connect AI	Autonomous 365	Stationary	Yes	2023	Yes		
Honewell	Rebellion Photonics - Mini GoGCI	Stationary	Yes	2020	No	No Response	
Kuva	Kuva daylight	Stationary	Yes	2023	No	No response	
Longpath Technologies	Longpath Laser System	Stationary	Yes	2023	Yes		
Mirico	ORION	Stationary	No	2023	No	Not relevant	
NevadaNano	MPS Methane Gas Sensor	Stationary	Yes	2023	No	No response	
Picarro	G2301	Stationary	Yes	2023	No	Replaced new model	
Project Canary	Canary X	Stationary	Yes	2023	Yes		
Providence Photonics	Mantis Flare Monitor	Stationary	Yes	2023	Yes		x
Qube	Axons	Stationary	Yes	2023	No	No response	
ChampionXChampion X	Soofie	Stationary	Yes	2020	Yes		
Sensia	Caroline FY	Stationary	Yes	2020	No	Replaced new model	
Sensia	Agni	Stationary	Yes	2023	Yes		x
Sensia	Mileva 33F	Stationary	Yes	2023	Yes		x
Sensirion Connected Solutions	Nubo Sphere	Stationary	Yes	2023	Yes		
Teledyne FLIR	G300a	Stationary	Yes	2023	No	Replaced new model	
Teledyne FLIR	GF77a	Stationary	Yes	2023	Yes		

Appendix B. Emissions from Norwegian offshore installations

For methane detection and measurement technologies to be relevant for Norwegian offshore installations, the individual technologies' minimum detection threshold must be lower than the emission level expected to be measured. To investigate the size of the total emission rates for each site, official data from the Norwegian Environment Agency are used, based on annually reported emissions in 2022 (Miljødirektoratet, n.d.) and shown in Figure 11. Reported emission rates vary from 1328 tCH_4/y to less than 1t/y (0.525 tCH_4/y). 15% of facilities reported less than 10 tCH_4/y, and 41% reported less than 100 tCH_4/y. The largest 6 contributors accounted for 50% of total reported emissions in 2022.

While it is apparent that emission rates may vary significantly over time, more detailed times-series data is not available. Based on the annual reported data, hourly average emissions may in practice also be calculated. However, emission rates will vary significantly with operating conditions throughout the year, and are not representative to use in the current analysis, particularly for evaluating technology capabilities to measure these emissions. In theory, the minimum detection threshold of the site level measurement technologies such as satellites, aircraft and drones could be compared to average hourly emission rates as a proxy to determine what portion of total emissions they would be able to detect. However, the time variability mentioned previously means that it would not be practical to make assumptions, when instantaneous emission rates could vary significantly. For bottom-up quantification methods such as handheld and fixed technologies, comparison to site level emission rates would need to be accompanied by equipment counts of potentially emitting sources and emission rates distributed between them. This level of granularity is not currently available. However, the data can be used to perform a qualitative assessment of technology capabilities at offshore installations on the NCS, and is noted in the report as relevant.

Figure 11: Calculated average hourly methane emissions from each offshore installation, in kg CH_4 per hour (2018)



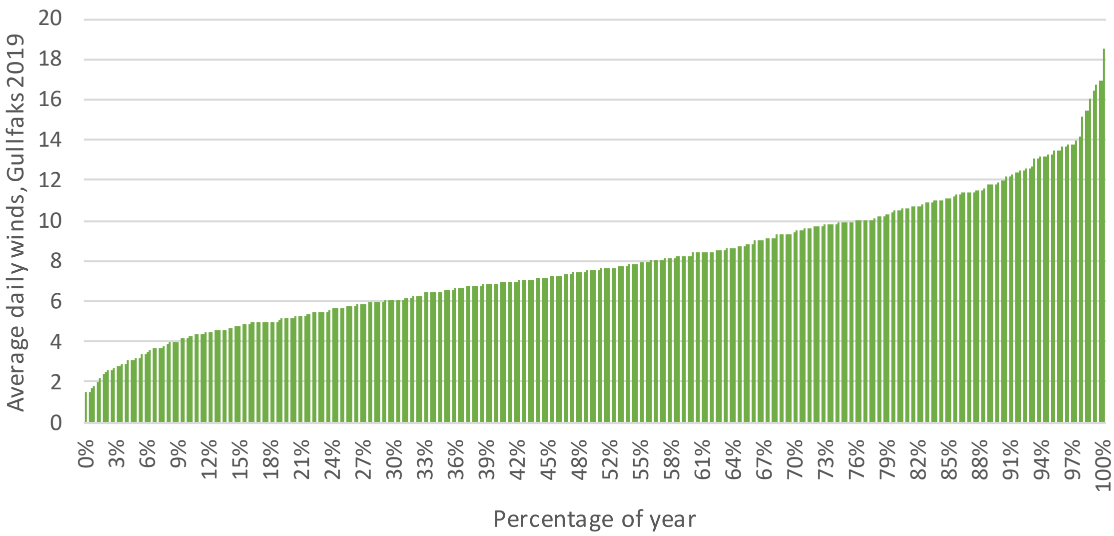
Source: (Miljødirektoratet, n.d.)

Appendix C. Wind conditions offshore

This section was originally presented in the 2020 report. It is presented in the 2023 report as updated information was not identified. Given atmospheric conditions are not expected to vary over this time period, it is presented again in this report.

Since almost all sensor types measure the atmospheric concentration of methane, winds have a significant effect on the possibility to measure emissions. While some wind is necessary for methane to develop into a plume, high wind conditions are challenging for most measurement techniques. Daily average and peak wind data from offshore installations in three different areas of the NCS (Gullfaks, Sleipner and Heidrun) in 2019 have been used as a proxy to analyze the extent that wind conditions are a limiting factor for the specific measuring technologies. Many methane detection techniques have specified detection and quantification at different wind speeds, and a commonly used metric is 5 meters per second. Offshore sites experience windy conditions year-round, with only a relatively small percentage of days with average winds below 5 meters per second, as illustrated below.

Figure 12 - Average daily winds measured at Gullfaks in 2019



Source: Carbon Limits, 2020

Wind impacts measurements in two ways. High winds disperse a methane plume quickly, and a given flow rate will result in lower ambient methane concentrations, reducing the possibility of detection for certain techniques and technologies. In addition, high wind conditions will restrict the possibility for airborne and sea-based measurements, due to flight- and sea safety constraints. When planning a measurement campaign offshore, each of these conditions must be planned for, to avoid unnecessary delays or inadequate results.

Appendix D. Sections from the 2020 report

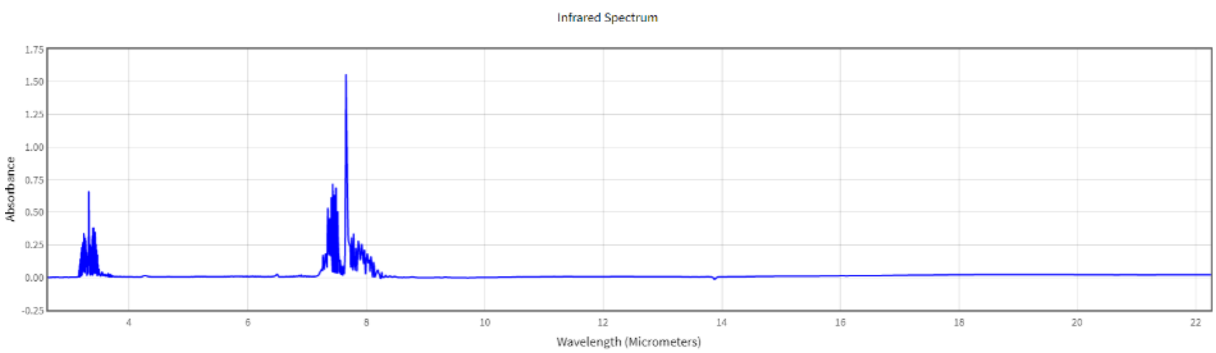
Section 2.1.1 from 2020 report – The Sensor Dimension – sensor types

There are many different approaches to detecting a concentration of methane. There are two main groups: in-situ measurement and remote sensing. In situ-measurements involve measurements with an instrument in and around a methane plume, while remote sensing involves measurements from a distance without contact with the methane plume. Passive sensors measure changes in background energy, such as reflected sunlight, caused by the presence of methane. Active sensors transmit bursts of energy in the direction of interest, e.g. a laser beam, and record the origin and strength of the backscatter.

Some types of sensor technologies can only be used in a methane plume since methane molecules must be in contact with the sensor for chemical or physical interactions. Other sensor technologies based on detection of an electromagnetic signal, typically infrared light from the sun or a dedicated laser, can be used both in-situ and or remotely, depending on the design of the instrument. When electromagnetic radiation such as visible or infrared light passes through the atmosphere, specific wavelengths are absorbed by different molecules. Each molecule has a specific absorption signature. Several different sensing instruments, including optical gas imaging and laser absorption spectroscopy, take advantage of these absorption features of methane for detection and measurement.

Methane absorbs at a range of wavelengths but is a particularly strong absorber of infrared radiation at certain wavelength regions. CH_4 has absorption features along the infrared spectral range (0.75–14 µm). Other atmospheric gases such as CO_2, CO, O_3, N_2O and water vapor also have their unique absorption signature which partially overlap certain absorption waves of methane, and instrument systems must be designed to take this into account when attempting to isolate a methane signal from other noise.

Figure 13 - Infrared absorption spectrum of methane



Source: National Institute of Standards and Technology (NIST) Chemistry WebBook, SRD 69

Most measurement techniques for methane rely on measuring enhancements of methane concentrations compared to background concentrations, involving e.g. measurement upwind and downwind of a site, and calculating the difference. In some cases, it can also be useful to identify whether a methane concentration originates from oil and gas production (thermogenic sources) or natural processes (biogenic sources). There are two techniques which may be used to analyze, ethane measurement and isotopic analysis.

Hydrocarbon reservoirs typically contain a mixture of different compounds, typically ethane in combination with methane in a site-specific concentration. Biogenic sources of methane do not have associated ethane emissions. Ethane measurements can therefore be used to distinguish emissions from thermogenic sources from biogenic sources. For technologies that can respond to and distinguish among multiple gases, two general approaches are used: spectroscopy and mass spectrometry. Spectroscopy relies on the unique electromagnetic radiation absorption spectra of individual gases; this can involve measuring individual absorption bands that differ between commonly occurring gases or a hyperspectral approach that compares the full spectra. Mass spectrometry identifies gases by comparing their mass-to-charge ratio. Since many gases have similar ratios, mass spectrometry may be coupled with a separation technique such as gas chromatography to first separate gases based on their molecular properties. Unlike spectroscopy, which can work remotely by measuring infrared absorption, mass spectrometry requires the gas to physically enter the detector.

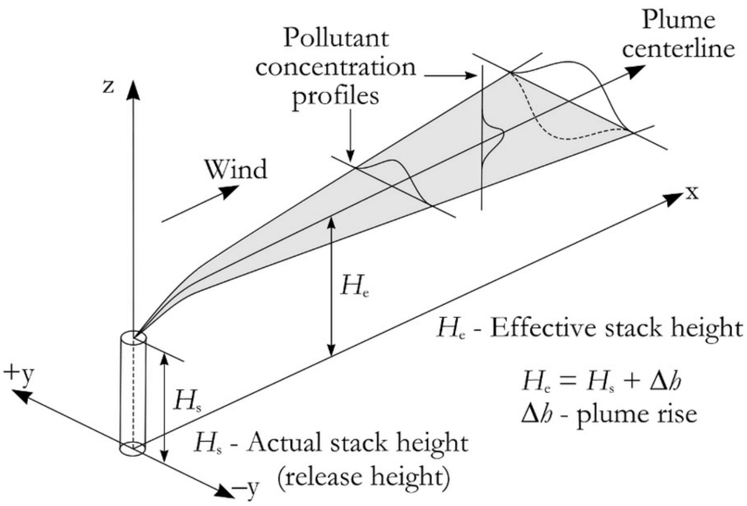
In nature, carbon exists as two stable, nonradioactive isotopes: carbon-12, carbon-13, and the radioactive isotope carbon-14. Carbon-14 has a half-life of about 5,730 years, and therefore gradually decays. Since carbon-14 is constantly being produced in the atmosphere from cosmic radiation, the same proportion is also taken up in plants and animals while they live. When they die, they cease to exchange carbon, and the carbon-14 starts to decay at a known rate. The proportion of carbon-14 to carbon-12 can therefore be used to determine the age of a sample, and it can be used to identify biogenic or thermogenic methane through isotopic analysis.

Section 2.5 from 2020 report

Offshore mobile surface-based sensing

Ground based mobile surveys are a relatively common top-down technique for estimating emissions from onshore sites. The process usually involves a vehicle equipped with methane sensors and instruments to determine the precise meteorological conditions while measuring. Emissions are located by downwind, drive-by inspection where concentration measurements are mapped by GPS coordinates. The sensors measure heightened methane concentrations when the vehicle enters the downwind intersection of the plume. Based on the assumed height of the emissions source, the wind direction and speed, and assumptions about the dispersion of the plume between the source and the measurement are modeled inverse dispersion models such as a Gaussian plume model. The model can use the measured enhancements of concentration levels to calculate a flow rate at the source.

Figure 14 - Illustration of a Gaussian plume model



Source:(Leelőssy et al. 2014)

The vertical dispersion of the methane plume is an important uncertainty factor for surface-based measurements, as concentrations above the surface cannot directly be observed. Suitable atmospheric conditions, taking into account the height of emissions, are therefore important when conducting surface-based measurements. Wind speed and wind direction, atmospheric turbulence, ambient air temperature, and height of an inversion layer are all meteorological conditions which are important.

Onshore mobile surveys are generally limited by the available roads downwind from the site of interest, and therefore may not be able to access the points of optimal measurements. In addition, other methane emissions from agriculture or other facilities nearby can make source identification more complicated. Sea-based campaigns have the advantage of being able to conduct measurements irrespective of wind direction. Since Norwegian offshore installations are widely spaced, it is comparatively simple to attribute emissions to a single location.

There is currently relatively little experience with surface-based measurements from offshore oil and gas installations. In 2019, two ship-based campaigns investigated emissions from North Sea platforms in the Dutch sector (Hensen et al., 2019). In 2018 ship-based measurements were performed in the Gulf of Mexico (Yacovitch, Daube, and Herndon 2020) and in 2017 a fishing vessel was used to measure emissions from eight platforms the UK sector of the North Sea (Riddick et al., 2019)

In the Gulf of Mexico, researchers installed a suite of meteorological equipment onboard a research vessel to investigate methane emissions from 103 platforms. A TDLS laser absorption spectroscopy instrument was used to measure methane from an air inlet tube placed 10 meters over the sea surface. For the sites investigated in depth, the sampling strategy was to intercept the methane plume in a zig-zag pattern at a range of distances from 1-10 kilometers downwind.

There are potentially large errors/biases stemming from the methodology itself. Land-based tracer-release studies of the Gaussian dispersion methodology have found that the method itself has a 95% confidence interval within a factor of 3.17 (Yacovitch et al., 2015). In their campaign in the Gulf of Mexico, the researchers (Yacovitch et al., 2020) set a 95% confidence interval at a factor-of-10 on all estimates, i.e., that estimates of flow rates are between 10% and 1000% of the actual flow rate. This higher uncertainty level is partly due to uncertainties related to the emission release height and location, and partly due to the researchers' method to determine the atmospheric stability above sea waters.

Source height is a particularly important factor when conducting surface-based measurements. Measurement intake heights in the Gulf of Mexico campaign were 10 meters above the sea surface, while emission sources varied between 7 and 30 meters. Measurement heights in the Dutch campaign were 10 to 35 meters. Emission sources from platforms on the NCS can be quite high, and measurement campaigns must be designed carefully to take this into account.

For ship-based measurements, weather conditions must be suitable both for measurements and calculations to be conducted properly, but also to ensure safety and well-being of the crew. In each of the campaigns, wind speeds above 2 meters per second were required for measurement, and wave height for the Gulf of Mexico campaign was limited to 2-meter waves. In the Dutch campaign, wind speeds of over 20 meters per second were specified as a quite high upper limit, to avoid failure of scientists or their instruments (Hensen et al., 2019).

So far, ship-based measurements have been conducted as dedicated research missions on research-, supply-, or fishing vessels equipped with research-grade measurement instruments. These missions require a significant amount of preparation time, in addition to the time for actual operation. Under suitable atmospheric conditions, and with properly designed instrumentation and measurements, such missions can measure and quantify emissions. However, since the vertical dispersion is not known when measuring from the surface, uncertainties from ship-based measurements when quantifying emissions using inverse dispersion calculations will remain.

Relevance for Norwegian offshore installations

Ship-based measurement allows for emissions from all sources on an offshore installation to be measured and estimated but does not generally allow for individual components or sources to be identified.[34] Ship based measurements would also only be able to measure emissions at one point in time, and intertemporal events are therefore likely to not be detected. Ship-based measurements are well suited for measurement campaigns over multiple installations since they can navigate directly from site to site.

Ship-based measurements can use highly sensitive sensors, and the previous campaigns have been able to detect and quantify very low emission rates from offshore facilities. A well-designed measurement campaign should be able to measure emissions relevant for all Norwegian offshore facilities. Since only surface concentrations are measured, the uncertainty levels are quite high when not using a tracer gas method. Improvement and validation of the dispersion models for calculation of methane plumes are necessary for more precise calculations. As with measurements from drones and planes, since sea-based campaigns by design only last for a short period, events that happen only under certain circumstances are less likely to be detected.

Surface based measurements are also sensitive to wind and weather conditions. Some winds (approximately 2 meters per second) are required to develop a methane plume. Since surface-based measurements are sensitive to atmospheric mixing, weather conditions related to inversion layers and meteorological conditions must be taken into account. Sea based operations are possible under conditions with higher winds (up to 20 m/s) than airborne operations, and can be undertaken in darkness and precipitation.

Since the offshore measurements so far have been undertaken as research missions, the costs of the campaign itself, for personnel and instrumentation, are relatively high. In addition, the costs of a ship-based measurement campaign would be dependent on the day rates for a suitable vessel.[35] For ship-based measurements to be a competitive option for quantification from Norwegian offshore installations on a regular basis, costs and complexity of the campaigns must be reduced

Section 3 from the 2020 report: Case studies from use of new technologies offshore

Three case studies from top-down measurement campaigns from offshore facilities have been identified: ship-based measurements in Netherlands, fixed-wing drone measurements in the United Kingdom, and plane-based measurements in Norway. Each of these give new insight into the challenges and opportunities of offshore measurements of methane.

Sea-based measurements – experience from Netherlands[36]

In 2018, TNO performed atmospheric measurements by ship on methane emissions from Dutch offshore installations for the Netherlands Oil and Gas Exploration and Production Association (NOGEPA). The purpose of the initiative was to independently assess the emissions reported from each site.

Two measurement campaigns were undertaken, each lasting three days, using supply ships for measurement. Meteorological conditions over sea are different from over land, and there is relatively little experience with mobile plume measurements over sea. The campaign was therefore designed to use N_2O tracer gas releases from a subset of the platforms, which allowed for “calibration” of the inverse dispersion model for dispersion of methane plumes over sea. It was the first time a tracer gas had been used offshore for this purpose. Simultaneously with the ship measurements, a team was on the two platforms conducting methane measurements from equipment with handheld instruments.

The campaigns used two identical offshore supply ships with instruments in a mobile container laboratory to detect methane ethane and N_2O using a spectrometer. The atmospheric gases were collected at inlets fixed at the top of the ship (a 30 meter top-inlet and two 10-meter inlets on starboard and portside for the first campaign, a 35 meter top-inlet at the second campaign).

To ensure successful measurements, the wind speed needed to be between 2 and 20 meters per second. The lower range is necessary for methane plumes to form, while the upper range was determined for sea and equipment operation. In addition, atmospheric conditions such as an atmospheric boundaries and temperature inversion heights could make measurements and calculations more difficult. The study found

[36] Source: This paragraph is developed based on (Hensen, Tacome, And Verhoef 2019) and interview with NOGEPA and TNO

that the inverse dispersion modeling using a Gaussian plume model predicts that plumes spread out more widely than they actually measured, due to lack of thermal convection over cool surface and absence of objects like trees and houses which create turbulence. The researchers modified the Gaussian model to provide narrower plumes which were more consistent with the tracer gas measurements, making the calculation of the methane emissions more reliable.

In the first campaign in July 2018, the measurements indicated methane and ethane plumes downwind of the platforms, but data showed variables results from the tracer gas. A reevaluation of the meteorological data after the campaign showed that the problem was a low atmospheric inversion layer with heights as low as 30-100 meters. This meant that there was a two-layer build up in the atmosphere, and where methane and tracer gas were released above the inversion layer height, they did not reach the surface altitude at which the measurements were done. The 3-day campaign allowed 35 platforms to be visited, but for 10 platforms it was impossible to make emission estimates.

The second campaign was undertaken in November 2018 with an identical vessel, measuring emissions from 22 offshore installations. Tracer gas releases were used on 5 offshore installations, though no simultaneous measurements on board took place during the second campaign. Before the campaign there was more emphasis on prediction of the inversion layer height, to ensure that conditions were suitable for measurement. At the time of measurement, there was no inversion layer below 200 meters. In addition, the sample inlet height on the supply vessel was raised to 35 meters using a mast on top of the ship mast.

Prior to the measurement gas plume release from different heights were simulated, and it was found that plume releases at 80 meters could be completely missed at measuring distances closer than 500[37] meters from the platform. Above 2000 meters distance, dilution of the plume could make it difficult to identify elevated concentrations above background emissions. TNO concluded that distances of 1000 to 2000 meters downwind from a platform were best for measuring total emissions, which the measurements confirmed. Closer measurement allowed for assessment on a subset of individual lower-level plumes from areas lower on the platform.

During the interpretation of data, it was concluded that large heat sources, such as exhausts from gas turbines and cooler banks, can interfere with the ‘cold’ methane and tracer gas plumes. This interference was not incorporated in the Gaussian plume model, but can have a major impact on the plume behavior and thus on the measurement results.

The study concluded that emission levels from the measured installations were similar to the operator-reported emission levels at the time of measurement, and confirmed that emissions from Dutch oil and gas per unit of production were compared to the international average reported by IEA (factor 10). The researchers estimated an uncertainty in their measurements of 10-40% random error, and a potential non-random error of +/- 50%. The unsuccessful tracer experiments in the first campaign showed that a mismatch in measured and modeled plumes could easily lead to a very high uncertainty at the order of a factor 10, indicating that this method should be designed very carefully and verified.

The experiences from the Dutch campaign could be used for designing a similar campaign on Norwegian offshore installations. Careful design of the campaign, including planning of logistics such as availability of a vessel, instrumentation and prediction of suitable meteorological conditions and sea conditions makes measurement campaigns complex with a relatively high amount of preparation time.

[37] Both Dutch and Norwegian installations have a safety zone of 500 meters, in which it is prohibited to navigate unless the head of platform grants access to the ship captain.

Drone-based measurements – experience from UK[38]

Conventional rotary drone-based operations have the disadvantage of requiring offshore transportation of personnel and equipment to platforms, with them the inherent risks of lithium-ion batteries, restrictions in accommodating personnel, along with costs of measurement. For measurements on multiple installations, equipment and personnel must be transported again. An alternative to transporting people and equipment offshore is to host resident drones. This however involved the training of individuals to become drone operators capable of performing methane surveys and carries the associated effort and cost of purchasing and maintaining equipment.

In 2019, a trial was performed for use of beyond visual line of sight (BVLOS) fixed wing drone flights launched from shore to perform top down methane emission surveys. The project combined a highly advanced sensor technology originally designed by NASA for the Mars Curiosity Rover combined with a fixed-wing remote piloted air system (drone) provided by FlyLogix. The drone was launched onshore and remotely controlled by a pilot from a ground control station. The drone flew autonomously following a predefined GPS flight path to the platform and performed monitoring under pilot surveillance.

The objective of the project was to demonstrate the capability to fly the drone from a remote onshore location in the Shetlands Island to the Clair 1 Platform, and to acquire in-situ methane concentration measurements requires to determine facility level emission rates.

The drone flew for approximately 2 hours and covered a total distance of over 185 km, establishing a record for the longest commercial drone flight in the UK. Methane concentration measurements were acquired throughout the flight path. On location the drone circled the Clair platform at a radius of approximately 500 meters and at various heights to resolve the platforms emission plume downwind. The trial successfully demonstrated the use of fixed wing long-distance drone flights to acquire offshore methane concentrations emissions at detection levels and spatial resolution necessary to determine facility level emission rates. During the trial, an interruption to the drones primary communications link was experienced resulting in the operational decision to safely return the aircraft. This shortened the intended flight and limited the amount of data recorded.

It should be noted that the drone system is restricted to flight operating conditions, including winds below 13 meters per second, which are likely to limit the operational window in the North Sea to between May and October.

The process to obtain necessary flight clearance for the unprecedented unmanned flight took about three months. Currently, work is being conducted to overcome the challenges and allow commercial operators of unmanned aircraft easier access to UK controlled airspace for BVOS of sight operations. Flylogix Limited is currently developing and testing a concept that would allow operators to launch flights within hours of a request and enable routine BVLOS operations.[39]

The potential of such a drone service for methane detection and quantification is promising. The deployment solution can be paired with different sensors available on the market, and flight pattern and quantification method adapted to the sensor. For a system to be a competitive option, it must be available as a routine industry service where operators could request a flight at a relatively short notice and receive an emission rate estimate. Repeated measurements could be done based on operational conditions and provide more insight into emissions over time, ether during routine and abnormal asset operating conditions. This knowledge can be used to validate calculated emission data. For such a service to be commercially viable, it requires sufficient demand from oil and gas operators.

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[38] Source: This paragraph is developed based on information from https://flylogix.co.uk/category/newsreleases/ and an interview with BP.

[39] https://flylogix.co.uk/newsreleases/opening-north-sea-airspace-for-unmanned-aircraft/

Plane based measurements – experience from Norway[40]

ChampionX performed a methane measurement campaign on Norwegian offshore installations in August and September 2019. This was the company's first measurement campaign in Europe, and the company flew a Mooney single-engine aircraft from the United States to Norway before the campaign. Due to Norwegian weather conditions at the time of the campaign, the ten research flights required a total time period of 27 days to be completed. Measurement flights could not be carried out in active precipitation and require stable winds between 2-10 meters per second. For the measurement operations over the offshore installations, visual flight conditions without low clouds are necessary.

For each offshore site, the aircraft circled at about a kilometer away from each installation and spent approximately a half hour circling the site to measure emissions, flying consecutive loops at different altitudes upwards from 200 feet above the surface to create a virtual vertical cylinder. The height of the offshore platforms allowed the methane plumes to be higher than 200 feet even with limited vertical mixing of the methane plumes over cold water. Emission rates are calculated from the measurements while flying in the vertical cylinder, where background methane levels are compared to the measurements in the emission plumes. Onshore, many sources can contribute to methane emissions. Since the background methane levels offshore were quite constant, the measurement had a better signal-to-noise ratio and allowed for more accurate measurements. According to the company, this gave a detection level as low as 2 kg per hour, compared to 10 kg per hour for a typical measurement onshore. Uncertainty levels of the quantification were estimated to +/- 12 %, depending on the variability at different laps. [41]

The offshore installations in the North Sea are located far enough away from each other such that there are no issues related to attribution of methane emissions to each installation. Flight time from the onshore airport to offshore platforms could take approximately one hour, but up to five installations could be measured during each flight.

ChampionX currently has stationed an aircraft in Europe which is available for operations.

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[40] Source: This paragraph is developed based on an interview with ChampionX
[41] Personal communication with Steven Conley.

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