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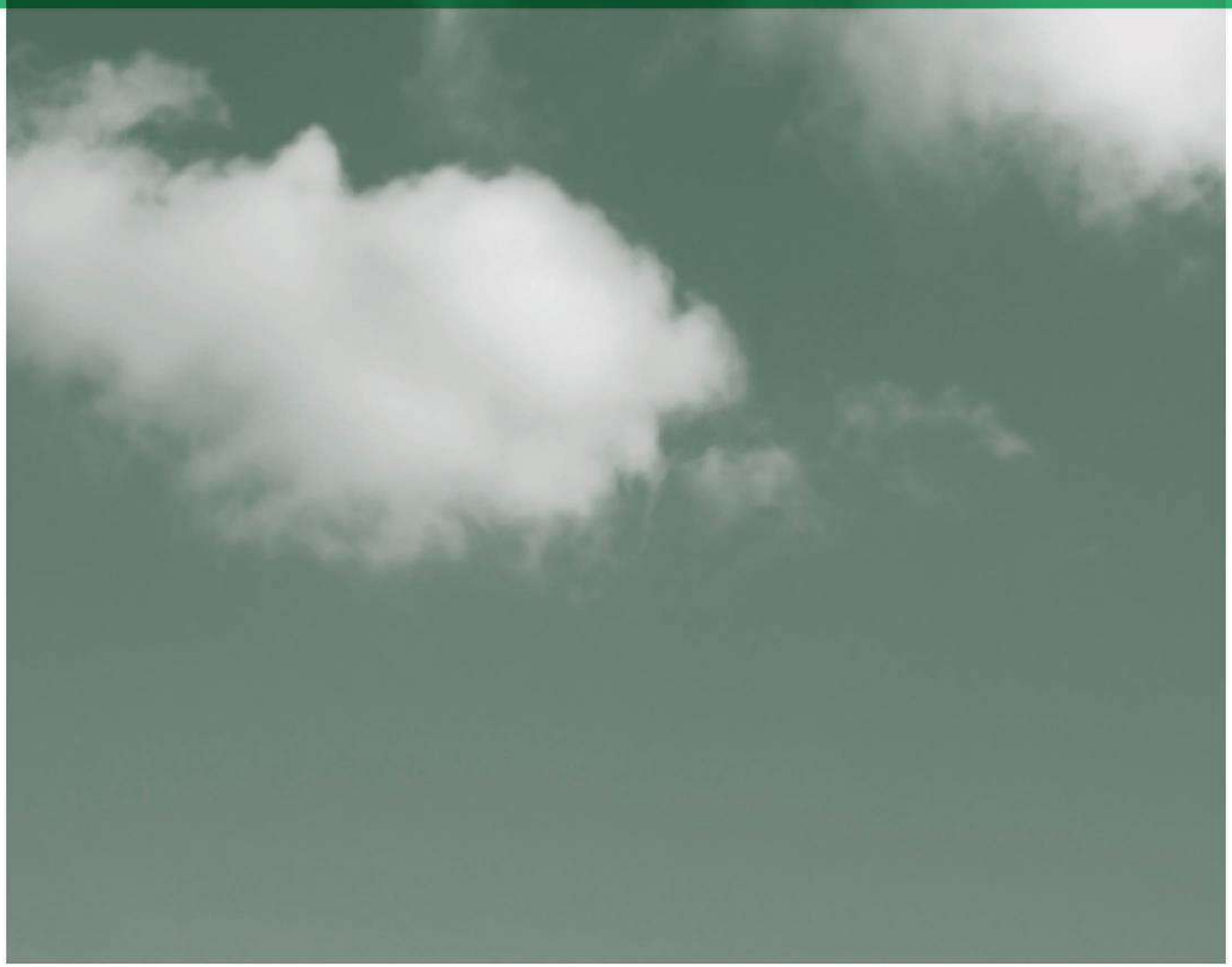
Overview of methane detection and measurement technologies for offshore applications

Final report 23 June 2020



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Project title:
Overview of methane detection and measurement technologies for offshore applications

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Carbon Limits works with public authorities, private companies, finance institutions and non-governmental organizations to reduce emissions of greenhouse gases 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 in the design and implementation of climate and energy policies and regulations.

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Acronyms and Abbreviations 3
Executive Summary 4
1. Introduction 10
1.1 Methane emissions from Norwegian offshore installations 10
1.2 Scope and objectives of this document 11
1.3 Structure of this document 12
2. Overview of new technologies and methods 13
2.1 Techniques and usage 13
2.2 New developments: Satellites 18
2.3 New developments: Aircraft 34
2.4 New developments: Drone 41
2.5 New developments: Offshore mobile surface-based sensing 49
2.6 New developments: Handheld and fixed sensors 53
3. Case studies from use of new technologies offshore 64
3.1 Sea-based measurements – experience from Netherlands 64
3.2 Drone-based measurements – experience from UK 65
3.3 Plane based measurements – experience from Norway 66
4. Conclusions and summary 67
5. References 72
Annex 1 Emissions from Norwegian offshore installations 74
Annex 2: Wind conditions offshore 75

Acronyms and Abbreviations

BVLOS	- Beyond Visual Line of Sight
CH_4	- Methane
CO_2	- Carbon dioxide
DIAL	- Differential Absorption Laser
EUR	- European Euro
GPS	- Global Positioning System
IEA	- International Energy Agency
LDAR	- Leak Detection and Repair
LIDAR	- Light Detection And Ranging
N_2	- Nitrogen
N_2O	- Nitrous Oxide
OGI	- Optical Gas Imaging
SWIR	- Short Wave Infrared
TDLAS	- Tunable Diode Laser Absorption Spectroscopy
TIR	- Thermal Infrared
UAS	- Unmanned Aircraft Systems
UNFCCC	- United Nations Framework Convention on Climate Change
USD	- US Dollars
VLOS	- Visual Line of Sight
VOC	- Volatile Organic Compounds

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.

Most of the available solutions are developed for use on land. However, there are few studies on the new technologies' applicability offshore. The purpose of this report is to systematically assess newer developments of methane detection and measurement technology, and their potential for use on Norwegian offshore oil and gas installations.

Compared to methane detection and measurement onshore, there are several elements which make detection and measurement offshore more challenging. The conditions in the northern latitudes of the Norwegian continental shelf are harsh, with constant wind and waves, seasonal cold and darkness, and vast areas of oceans between installations. The facilities themselves have been designed to use best available technologies, and have low emissions of methane, representing a challenge from an emission threshold perspective. The offshore platforms are highly compact and complex industrial facilities, and operations on board a platform are subject to strict health and safety requirements. Each of these factors affects which methods and technologies for methane detection are relevant for use on Norwegian offshore installations.

High wind levels decrease the performance of almost all methane technologies since any plume will rapidly disperse and result in lower atmospheric concentration levels. Wind and waves also limit when seaborne and airborne operations can be performed, and limit the operational window to certain times. The high latitudes and dark winters also restrict when it is possible to use satellites and airborne measurements, and also limit certain measurement techniques. Surrounding waters also strictly limit which types of technologies can be used. Remote sensing, which is based on methane absorption of infrared light reflected off a surface, works poorly over water due to low reflectivity. While there are techniques which can be used to overcome these limitations, by placing the sensor in the area where water reflects light as a mirror, such techniques result in operational constraints. 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.

The safety requirements are strict, to avoid situations which could increase risk to health and safety. The installations themselves are tightly spaced and have little open access, limiting the possibilities of drones to observe components, line-of-sight of fixed sensors, and the possibilities to set up a fixed array of sensors to capture all emissions from the site.

The relatively low emissions from each facility poses a challenge to the sensitivity of the technologies, which are compounded by the other factors above.

However - a number of technologies are available and have proven their applicability for offshore measurements. In-situ measurement sensors, which do not suffer from reduced performance when used over water, have been used on ships, drones and aircraft to measure and quantify emissions. The distance between platforms and low variability in background methane concentration rates make estimation calculations of emission rates simpler.

The report is structured to give insight into how the technologies work, and to explain why some approaches are more relevant for offshore use. 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 determines what can be measured and under which conditions. There are many different approaches for using a sensor to detect a concentration of methane, under 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. 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.

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. Measuring equipment can be handheld, fixed on site, mobile on the surface, airborne in drones or aircraft, and in different space orbits. The placement determines the spatial and temporal resolution of what the sensor is able to detect.

The calculation technique determines the flow rate and the uncertainty based on different types of models. To determine flow rates, the model is used to calculate backwards towards the emission point, based on measurement data and factors such as wind, atmospheric conditions, and background methane concentration. Uncertainties in the calculations can arise from multiple factors, including sensor precision, the quantity and spatial extent of measurement data, micrometeorological conditions, and background concentration variability.

The report gives an overview of the methane detection and quantification capabilities of satellites, planes, drones, ships, fixed sensors, and handheld sensors.

Satellites can be used for frequent, low-cost measurements over large areas. Several satellites relevant for methane detection are either in operation or planned for launch in the next few years. In addition to traditional satellites launched primarily for research purposes, a handful of organizations are launching satellites to be able to target specific industrial sites for commercial purposes. While future satellite capabilities are expected to improve rapidly, there are three extra challenges when considering satellites' usefulness on emissions from Norwegian offshore installations. The challenges to detection are low average emission rates of offshore installations, the satellites' poor performance over water and the high latitudes of the Norwegian continental shelf. Each of these challenges could be overcome, but together they strictly limit the possibilities of satellite measurements on Norwegian offshore facilities

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. Detection performance over ocean water is reduced for certain technologies (remote sensing techniques) while in-plume techniques perform at least as well as over land. In-plume techniques are therefore the preferred option for offshore measurements, and can be used for emissions estimations resulting in low uncertainty levels.

Drones equipped with sensors are available for offshore use but are currently limited 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 the drone. Another promising development is the availability of long-range drone systems which are launched and piloted from land. This would greatly reduce the risk and cost of transportation of dedicated personnel to and from a platform and would also allow for multi-site measurements. However, this solution is currently limited by flight safety regulations.

Sea surface-based measurement campaigns using ships such as supply vessels or fishing vessels are an available option for measurements. Currently, the campaigns have been research-grade missions which have required a significant amount of instrumentation and crew to be undertaken. Much has been learned through these campaigns, and multiple techniques have been tested. The emission quantifications have had a relatively high level of uncertainty, due mostly to unknown parameters such as the micrometeorological conditions.

There are already extensive efforts on Norwegian offshore installations using handheld instruments such as optical gas imaging cameras for leak detection and repair. Furthermore, the large number of fixed sensors on board ensure that larger leaks are identified quickly for action. New developments in instruments could supplement these efforts. Multiple companies can provide handheld and fixed sensors which provide detection and measurement capabilities at costs competitive to the instruments used onboard today. Some of the instruments also allow for quantitative imaging to derive a leak rate. Some of the new available solutions, such as handheld ultrasound sensors or quantitative optical gas imaging, are already in use on Norwegian onshore facilities, and experience from these could be useful to assess application offshore. New developments in robotic systems are also being tested offshore and could supplement personnel for leak detection and repair campaigns in the longer term.

Three case studies from 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.

In 2018, atmospheric measurements by ship were performed on methane emissions from Dutch offshore installations. The study concluded that emission levels from the measured installations were similar to the operator-reported emission levels at the time of measurement. Important lessons were learned on the behavior of methane plumes over cold water, the importance of meteorological conditions, measurement heights and distances. The experiences from the Dutch campaign could be used for designing a similar campaign on Norwegian offshore installations.

In 2019, a trial was performed in the UK for use of beyond visual line of sight (BVLOS) fixed wing drone flights launched from shore to perform methane emission surveys. 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 an offshore platform, and to acquire in-situ methane concentration measurements requires to determine facility level emission rates. 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.

In 2019, a campaign based on single-engine aircraft performed methane measurements on Norwegian offshore installations. 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. 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. 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. Since the background methane levels offshore were quite constant, the measurement had a better signal-to-noise ratio and allowed for more accurate measurements compared to over land.

In order to complement and verify bottom-up methods which are used for emission reporting (using e.g. handheld instruments and process-specific calculations), and give representative results, top-down measurement campaigns (using e.g. aircraft or drones), need to be supplemented by relevant technical process information on the operational status of the installation during the campaign’s limited time window. If this is not done properly, it may result in under- or overestimation of the emissions from the installation. Extensive communication between the measurement campaign operators and the installation before, during, and after the campaigns is essential in order to achieve the objective.

Sammendrag

Etter hvert som det har blitt rettet mer oppmerksomhet mot metanutslipp, har det blitt utviklet nye metoder og teknologier som kan måle og kvantifisere utslipp. I dag finnes det en rekke kommersielle løsninger for metandeteksjon og -måling.

De fleste tilgjengelige løsninger har blitt utviklet for bruk på land, imidlertid finnes det kun få studier av deres anvendbarhet offshore. Formålet med denne studien er å vurdere den nyere utviklingen innen teknologier for metandeteksjon og -måling på en systematisk måte, og teknologienes potensial for bruk på norske olje- og gassinstallasjoner offshore.

Sammenlignet med metandeteksjon og -måling på land, er det en rekke elementer som gjør det mer krevende offshore. Både de nordlige breddegradene til norsk kontinentalsokkel, med vind, kulde og mørke, samt avstandene til havs, bidrar til dette. Installasjonene har blitt designet til å benytte beste tilgjengelige teknologier med lave metanutslipp, som utfordrer teknologienes minste deteksjonsnivå. Plattformene er i seg selv kompakte og komplekse industrianlegg, og aktiviteter om bord er gjenstand for høye HMS-krav. Hver og en av disse elementene har virkning på hvilke metoder og teknologier som er relevante for bruk på norske offshoreinstallasjoner.

De høye vindstyrkene forringer ytelsen til nesten alle metandeteksjonsteknologier, på grunn av at utslipp vil spres i luft og gi lave målte konsentrasjonsnivåer. Videre vil vind og bølger kunne begrense når målinger fra luft- og sjøfartøy kan foretas, i noen tilfeller til kun deler av året. De nordlige breddegradene begrenser også når det er mulig å benytte satellitter og flybaserte målinger, og begrenser videre enkelte målemetoder hele året. I tillegg medfører plattformenes plassering i havet sterke begrensninger i hvilke typer sensorteknologi som kan brukes. Fjernmålinger, som er basert på at metan absorberer visse bølgelengder infrarødt lys reflektert fra en overflate, lider av sterkt redusert ytelse over vann. Selv om det kan benyttes enkelte metoder for likevel å kunne fjernmåle, for eksempel ved å plassere sensoren i punktet hvor vannoverflaten speiler lyset, medfører dette uhensiktsmessige operasjonelle begrensninger. Sammenlignet med anlegg på land, er offshoreinstallasjoner krevende å komme til. Mens det på landbaserte anlegg er relativt lett å måle fra kjøretøy i nærheten, fly en drone fra utsiden av et anlegg eller sette opp faste sensorer på avstand, er disse alternativene krevende å gjennomføre på åpent hav.

Sikkerhetskravene offshore er strenge, for å minimere HMS-risiko. Installasjonene er kompakte, med få åpne områder. Dette begrenser mulighetene for droner å kunne måle fra komponenter og faste sensorers siktlinjer. Videre begrenser dette mulighetene til å ha et system av sensorer utenfor installasjonen som kan måle den samlede mengden utslipp på avstand. De relativt lave utslippsnivåene fra hver plattform utfordrer teknologienes sensitivitetsnivåer for metanmålinger, noe som også forsterkes av de øvrige begrensningene beskrevet ovenfor.

Likevel finnes det en rekke tilgjengelige teknologier som har demonstrert sin anvendbarhet offshore. Sensorer som måler metankonsentrasjoner direkte, innenfra metanskyen, har god ytelse over vann. Disse sensorene har blitt benyttet fra skip, droner og fly for å måle og kvantifisere utslipp. Avstanden mellom plattformer og lave variasjoner i metankonsentrasjoner i bakgrunnen forenkler beregningene av utslippsestimater.

Denne rapporten er strukturert for å gi innsikt i hvordan teknologiene fungerer, og for å forklare hvorfor enkelte tilnærminger er mer relevante for bruk offshore. Måling og kvantifisering av metan er avhengig av en metansensor, dens plassering for å kunne måle utslipp og en metode for å beregne et utslippsnivå som skiller kilden fra bakgrunnskilder.

Sensortypen og dens design bestemmer hva som kan måles og under hvilke forhold. Det er flere ulike tilnærminger for metanmåling ved hjelp av sensorer, fordelt på to hovedgrupper: direktemålinger og fjernmålinger. Direktemålinger innebærer målinger med et instrument i og rundt en metansky, mens fjernmåling innebærer måling fra avstand uten kontakt med metanskyen. Noen sensorteknologier kan kun benyttes direkte, siden metanmolekyler må være i kontakt med sensor for å kunne gi utslag. Andre sensorteknologier, basert på deteksjon av for eksempel infrarødt lys fra solen eller en laserstråle, kan avhengig av instrumentets design, benyttes både for direktemålinger og fjernmåling.

Plasseringen bestemmer hvor innenfor eller rundt metanskyen målinger foretas, og hvor mye data som innhentes, i tillegg til målinger av relevante meteorologiske forhold. Måleutstyr kan være håndholdt, fastmontert, overflatebasert på skip, luftbårent på droner eller fly, eller befinne seg i ulike satellittbaner. Plasseringen bestemmer den geografiske og tidsmessige oppløsningen av hva sensoren er i stand til å måle.

Beregningsmetodene for å bestemme utslipps- og usikkerhetsnivåene er basert på ulike typer modeller. For å bestemme utslippsnivåene, benyttes en modell for å beregne bakover mot utslippspunktet, basert på målte data og faktorer som vind og øvrige atmosfæriske forhold og bakgrunnskonsentrasjoner av metan. Usikkerheter i beregningene kan stamme fra ulike faktorer, herunder sensorens nøyaktighet, antallet datapunkter og geografisk oppløsning, mikrometeorologiske forhold og variasjoner i bakgrunnskonsentrasjoner.

Denne rapporten gir en oversikt over ulike teknologiers muligheter for metandeteksjon og -kvantifisering fra satellitter, fly, droner, skip, fastmonterte sensorer og håndholdte instrumenter.

Satellitter kan bli benyttet til jevnlige målinger over store områder til en lav kostnad. En rekke satellitter relevante for metandeteksjon er enten i drift eller planlegger oppskyting i løpet av de neste par årene. I tillegg til de tradisjonelle forskningssatellittene, arbeider flere organisasjoner med kommersielle satellitter som kan siktes inn mot bestemte anlegg for metandeteksjon. Mens fremtidige satellitter forventes å ha betydelig bedre kapasitet for måling, er det imidlertid tre ekstra utfordringer knyttet til måling av metan fra norske offshoreinstallasjoner. Disse er forbundet med relativt lave gjennomsnittlige utslipp fra norske installasjoner, forringet ytelse ved måling over vann og norsk sokkels beliggenhet på den nordlige halvkule. Hver og en av disse utfordringene kunne isolert sett ha blitt håndtert, men sammen medfører de at det er svært krevende å måle metanutslipp fra norske offshoreinstallasjoner med satellitter.

Målekampanjer med fly er en tjeneste som i dag er kommersielt tilgjengelig, med mulighet til å dekke større områder med relativ høy presisjon. En flygning kan dekke flere installasjoner om gangen. Deteksjonsytelsen over hav blir forringet for enkelte typer sensorteknologier (fjernmåling), mens direkte målemetoder har minst like god ytelse som over land. Direkte målemetoder er derfor den foretrukne metoden offshore, og kan gi utslippsestimater med relativt lave usikkerhetsnivåer.

Droner utstyrt med metansensorer er tilgjengelig for bruk offshore, men er avhengig av en operatør om bord på plattformen eller på et fartøy i umiddelbar nærhet. Dette øker målekampanjens kompleksitet og krever reise enten med helikopter eller skip, samt akseptable værforhold for flygning. En annen lovende utvikling er muligheten for langtrekkende dronesystemer, som flyr fra land. Dette vil kunne redusere risiko og kostnad knyttet til transport av operatører til plattform, og vil kunne muliggjøre målinger fra flere installasjoner om gangen. Imidlertid er en slik løsning begrenset av dagens luftfartssikkerhetsforskrifter.

Sjøbaserte målekampanjer ved hjelp av supply- eller fiskefartøy er også en tilgjengelig mulighet. Hittil har målekampanjer fra skip vært gjennomført som forskningsbaserte operasjoner, og har krevet en betydelig innsats i instrumentering og personell. Disse målekampanjene har gitt mye kunnskap, og flere metoder har blitt prøvet ut. Imidlertid har kvantifiseringen av utslipp hatt relativt høye usikkerhetsnivåer, i stor grad på grunn av at de mikrometeorologiske faktorene i høyden ikke kan måles direkte fra havoverflaten.

Det legges i dag betydelig innsats på målinger ved hjelp av håndholdte instrumenter som OGI-kameraer (optical gas imaging) på norske offshoreinstallasjoner for lekkasjedeteksjon og reparasjon. Videre er det et høyt antall fastmonterte sensorer om bord på installasjonene, som sikrer at større lekkasjer blir identifisert og håndtert raskt. Den nyere utviklingene på instrumentsiden kan supplere denne innsatsen. Flere selskaper tilbyr håndholdte og fastmonterte sensorer til konkurransedyktige priser. Noen av disse kan kvantifisere utslippsrater ved hjelp av kvantitativ bildebehandling. Noen av disse nye instrumentene er allerede i bruk i dag på norske olje- og gassanlegg på land. Nyere utvikling innenfor robotikk-systemer blir også testet offshore og vil på lengre sikt kunne supplere målinger med personell om bord.

Tre eksempler fra målekampanjer offshore har blitt identifisert: skipbaserte målinger i Nederland, målinger med langdistansedrone i Storbritannia, og flybaserte målinger i Norge.

I 2018 ble det gjennomført atmosfæriske metanmålinger fra skip på nederlandske offshoreinstallasjoner. Studien konkluderte med at de beregnede utslippsnivåene var på linje med nivåene rapportert fra operatørene samtidig som målingene pågikk. Den ga viktig innsikt om hvordan metanskyer oppfører seg over kaldt vann, viktigheten av meteorologiske forhold, målehøyder og -avstander. Det er mulig å benytte erfaringene fra den nederlandske kampanjen i lignende kampanjer på norske anlegg.

I 2019 ble det gjennomført en testflygning i Storbritannia ved bruk av en langdistansedrone med BVLOS (beyond visual line of sight). Flygningen ble gjort fra land og var under kontroll av en pilot fra land. Dronen fløy autonomt ved hjelp av en forhåndsdefinert GPS-rute og målte metankonsentrasjoner underveis. Formålet med flygningen var å demonstrere muligheten for å kunne fly til en offshore plattform, og direktemåle metandata for å kunne kvantifisere utslippene fra anlegget. Det ble demonstrert at langdistansedroner kunne gjennomføre offshoremålinger med nøyaktighet og geografisk oppløsning nødvendig for å kunne beregne utslippene fra anlegget.

I 2019 ble det gjennomført en målekampanje på norske offshoreinstallasjoner fra et småfly. På grunn av værforholdene ved måletidspunktet, tok det 27 dager å gjennomføre ti flygninger. På hver offshoreinstallasjon, ble det gjennomført målinger i sirkel med 1 kilometer radius over ulike høyder. Utslippsnivåene ble beregnet ut fra målingene, hvor bakgrunnskonsentrasjonene ble sammenlignet med målingene inne i metanskyen. Siden det var relativt lite variasjon i bakgrunnskonsentrasjonene offshore, medførte det at målingene kunne gi mer presise beregninger av utslippsnivåene, sammenlignet med på målinger på land.

For at «top-down» metoder som benyttes i målekampanjer (for eksempel med fly eller droner), skal kunne supplere og verifisere «bottom-up» metoder som benyttes i forbindelse med utslippsrapportering (for eksempel ved bruk av håndholdte instrumenter eller prosessrelaterte beregninger) og kunne gi representative resultater, er det viktig at resultatene sammenstilles med relevant teknisk prosessrelatert informasjon om installasjonens operative status i det begrensede tidsvinduet kampanjen pågår. Dersom dette ikke gjøres, kan det resultere i under- eller overestimering av utslippene fra installasjonen. Det er viktig med god kommunikasjon mellom fly- eller droneoperatør og installasjonen før, under og etter kampanjen er gjennomført dersom målet med kampanjen skal oppnås på en god måte.

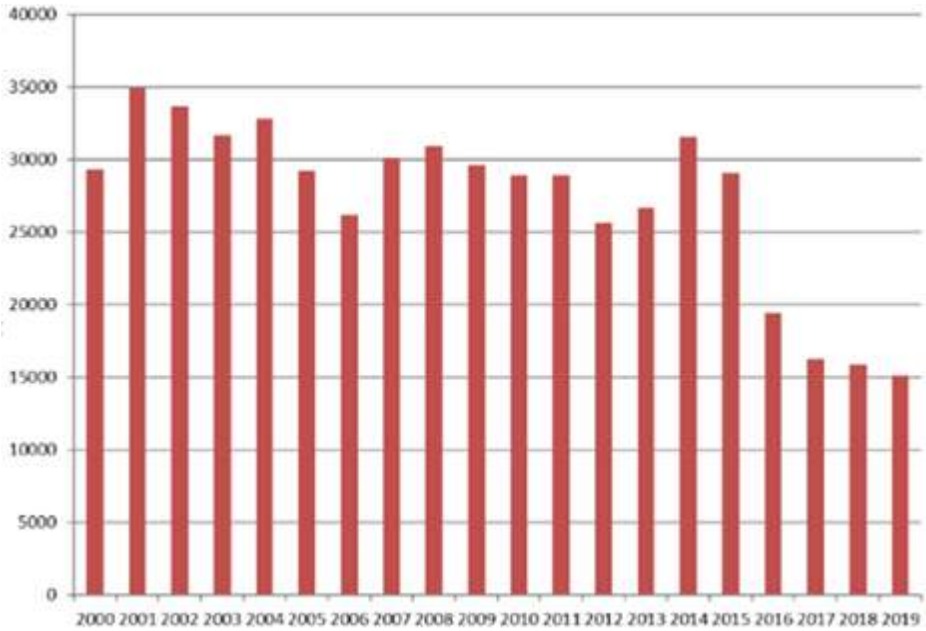
1. Introduction

1.1 Methane emissions from Norwegian offshore installations

With about 21 thousand metric tons of methane per year[1], methane emissions from offshore and onshore oil and gas activities in Norway are very low in international comparison. The Norwegian emissions represents less than 0.025 percent of global oil and gas methane emissions[2] while Norway's share of global oil and gas supplies is about 2.4 per cent.

About 15 thousand tons of methane are emitted from offshore oil and gas operations. Despite being a small source of GHG emissions, 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)[3] 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 at the Norwegian Continental Shelf for 2017.

Figure 1 – Reported methane emissions from Norwegian offshore activities, (2000-2019, tons CH_4)[4]



Emissions are quantified in accordance with the guidelines, specific for each source or process using different methods, including factor-based, measurements/sampling, process simulation, recorded measurement data, and supplier data. Generic quantification methods are primarily used, with the exception of some complex sources or less-common processes, which use facility-specific quantification methods.[5]

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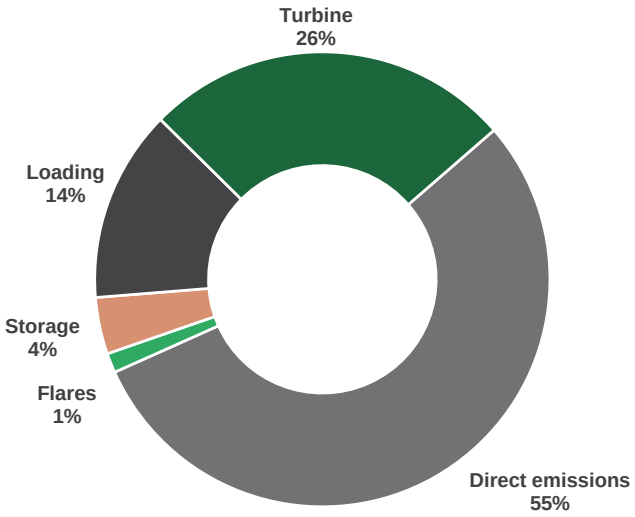
[1] National Inventory Reports 2018 available on the UNFCCCC website.
[2] Global methane emissions from Oil and gas systems are estimated to be 82 MtCH4 (IEA Methane tracker – 2019)
[3] https://www.norskoljeoggass.no/contentassets/cd872e74e25a4aadac1a6e820e7f5f95/044--guidelines-for-discharge-and-emission-reporting_ver17_2019.pdf and https://www.norskoljeoggass.no/contentassets/cd872e74e25a4aadac1a6e820e7f5f95/044---appendix-b-voc-emmissions-guidelineline.pdf
[4] Source: Norwegian Oil and Gas Association
[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. https://www.environmentagency.no/globalassets/publikasjoner/M511/M511.pdf

The companies operating on the Norwegian Continental Shelf 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 other leaking components. This report is part of the ongoing effort by the industry to improve the understanding of the emissions and to leverage the best technology and approaches to reach this goal.

Figure 2. Methane fugitive and venting emissions by main source (share of emissions in percent), 2019 (Source: NOROG).



Methane emission sources on the Norwegian continental shelf can be cataloged based on the emission points where the direct emissions are released to the atmosphere. For the purpose of measurement of methane emissions, the emission point is an important factor. With regard to bottom-up approaches, they determine which measurement or estimation techniques can be used. For top-down measurements, the location and height of the emission points determines the distance and techniques which may be used. The main emission points are:[6]

1. From dedicated atmospheric common vents. Facilities that direct emissions from multiple sources into a concentrated point, which ease metering and safe disposal to the atmosphere. Gas composition can vary significantly in common vents, because other gas such as N_2 can be released via the same vent.
2. From local dedicated vents in the installation. Compared to the dedicated atmospheric common vents, this emission point is linked to one emission source. These types of emission points are found mainly in liquid storage tanks.
3. Combustion of gas (turbines and flaring). The most common source of emissions are uncombusted gas from turbines and flares, emissions from flare ignition, extinguished flares, non-combustible flare gas and an open flare purged with inert gas.
4. Fugitive emissions (directly from equipment and components). All emissions (leaks and spills) that come from equipment components and that are unintentional.

1.2 Scope and objectives of this document

In broad terms, there are two categories of methane emission estimations: bottom-up and top down methods. Bottom-up inventories are generally “based on direct measurements, engineering calculations, manufacturer data and emissions factors for emissions sources/activities, compiled to develop an account of emissions discharged to the atmosphere from a facility (e.g. compressor

[6] Indirect emissions from e.g. ignited flare and turbines, as well as emissions from loading operations, represent other source categories that were not directly covered in the study.(https://www.miljodirektoratet.no/globalassets/publikasjoner/m664/m664.pdf).

station) or a geographic area (e.g. basin, state, region)"[7]. Globally, an increasing number of operators have been applying this type of methodology to estimate and report their emissions. Since emission estimates using bottom-up methods can be allocated to specific sources, this enables the prioritisation of methane emission reduction from an abatement cost perspective.

Top-down estimates are generally derived from measuring concentrations of methane in the atmosphere using sensors at a distance. These methods use measurement of ambient methane concentration and models to infer total emission rates from specific sites or from an entire region. They often do not allow identification of the specific equipment that is the source of the emissions, and therefore would not replace bottom-up methods for the purpose of abatement, maintenance or repair. Top-down estimates provide the total emission of a given facility/site at a given point of time, or during a restricted time window.

As methane emissions have received more attention, new techniques and technologies are being developed to measure and quantify emissions. The size and weight of high precision sensors have been reduced, allowing them to be mounted on drones or small satellites. New instruments have been developed with focus on reducing costs while maintaining high performance. Methods for calculating an emission estimate from a concentration measurement have been improved and tested. 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.

Most of the available solutions are developed for use on land. However, there are few studies on the new technologies' applicability offshore. The purpose of this report is to systematically assess newer developments of methane detection and measurement technology, and their potential for use on Norwegian offshore oil and gas installations.

The conditions in the northern latitudes of the Norwegian continental shelf are harsh, with constant wind and waves, seasonal cold and darkness, and vast areas of oceans between installations. The facilities themselves have been designed to use best available technologies, and have low emissions of methane, representing a challenge from an emission threshold perspective. The offshore platforms are highly compact and complex industrial facilities, and operations on board a platform are subject to strict health and safety requirements. Each of these factors affects which methods and technologies for methane detection are relevant for use on Norwegian offshore installations.

1.3 Structure of this document

The numerous technologies for methane detection and measurement operate in different ways with different capacities. This report is structured to give insight into how the technologies work, and to explain why some approaches are more relevant for offshore use. In section 2.1, we introduce the techniques and uses by illustrating three dimensions of estimation: the sensor type, the placement of the sensor, and the emission rate calculation method. Each estimation approach has a combination of these three dimensions, which determines its capabilities. Section 2.2 gives an overview of satellites capabilities, explaining the three major challenges for satellite detection of methane from Norwegian offshore installations, followed by an overview over relevant present and future satellite missions. Section 2.3 gives an overview over methane detection from aircraft, including the different measurement techniques and their performance over water. Their relevance for offshore use is discussed, followed by an overview over two companies providing methane measurement services from planes. In section 2.4, we give an overview over different types of drones and their capabilities, including the new developments in fixed-wing long range drones, followed by an overview over four companies providing drone services. Surface based measurements from ships, and their possibilities and limitations, are discussed in section 2.5. Fixed sensors and handheld instruments for monitoring specific components or areas on board are discussed in section 2.6, followed by an overview over different solutions. As a result of interviews with industry and service providers, in section 3 we have identified three case studies where new technologies have been applied offshore: a ship-based

[7] Source: IPIECA, 2018. Methane glossary

measurement initiative in the Netherlands, a demonstration of long-range drone measurements in the UK, and a measurement campaign from Norwegian offshore installations. Finally, summary and conclusions are presented in section 4.

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 determines 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.

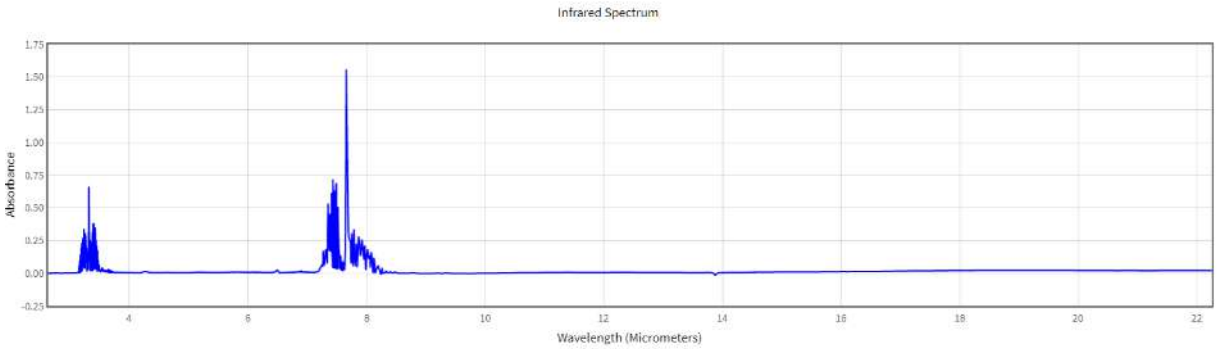
The sensor dimension – sensor types

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 3 - Infrared absorption spectrum of methane[8]



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.

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

[8] Source: https://webbook.nist.gov/cgi/cbook.cgi?ID=C74828&Units=SI&Type=IR-SPEC&Index=1#IR-SPEC

Table 1 - Sensor groups and principles[9]

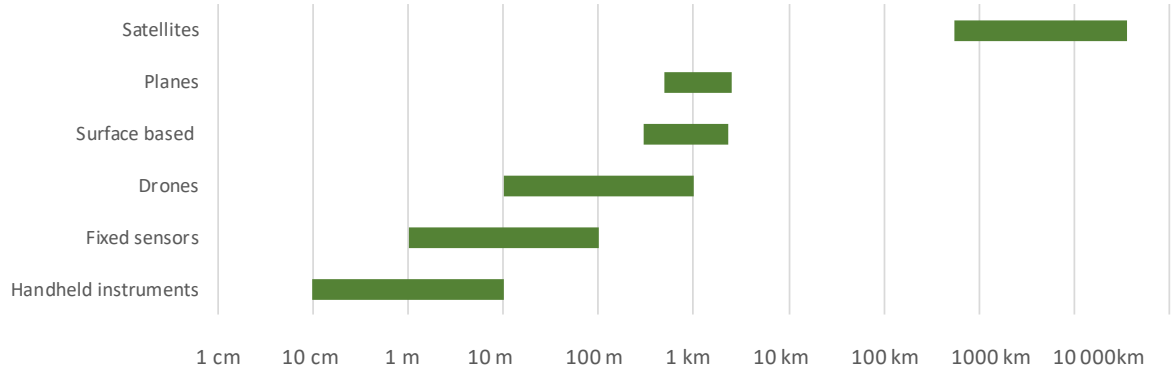
Group	Sensor technique	Applications
Metal-oxide semiconductors (in-situ only)	Electric circuits that are doped with oxide materials to react with the target gas, where tin dioxide is commonly used for methane and VOC detection. Gas particles react with the oxide material and result in change in measured 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 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 use a narrow range of the IR 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.
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

[9] Source: https://methane-1.itrcweb.org/

The 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 is able to detect.

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



Also, the placement of the sensor determines whether a method for estimation is bottom-up or top-down. There are various definitions of bottom-up and top-down methods. In this report, bottom-up refers to techniques to directly measure or estimate emissions at the source/activity level, while top-down refers to techniques to measure ambient air concentrations of methane, calculate methane flux based on atmospheric conditions, and attribute emissions to a facility or region.

Table 2: Overview of the placement option

Group	Distance and spatial/temporal resolution	
Handheld instruments	Very close proximity (10 cm – 10 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.	Bottom-up
Fixed sensors	Close proximity (1-100 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	Bottom-up
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.	Top-down
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.	Top-down

Group	Distance and spatial/temporal resolution	
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.	Top-down
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.	Top-down

Calculation dimension

Most methane sensors are designed to determine the concentration of methane in the area surveyed.[10] The placement of the sensor determines the perspective and the spatial resolution. To estimate a flow rate, concentration data and a model for calculation is used. To determine flow rates, one must in addition use a model to calculate backwards towards the emission point, based on factors such as wind, atmospheric conditions, and background methane concentration.

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 precision, 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 estimates. Single-blind studies (Ravikumar et al. 2019) of different top-down methods, 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 for 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, basically that by 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 flux	Unlike dispersion methods, tracer flux methods do not require knowledge of micrometeorological conditions such as turbulence and exact wind conditions.

[10] 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

Group	Approach
	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.

2.2 New developments: Satellites

Over the past few years, a great deal of important research on satellite sensing of methane has been published. Satellites can be used for frequent, low-cost measurements over large areas. They can be used to identify super-emitters and monitor facilities over time. Several satellites relevant for methane detection are either in operation or planned for launch in the next few years. In addition to traditional satellites launched primarily for research purposes, a handful of organizations are launching satellites to be able to target specific industrial sites for commercial purposes.

Satellite sensors measure methane in the total atmospheric column, 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.

The orbit type determines the geospatial and temporal coverage of a remote sensing satellite. Most methane-capable satellites 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 and the latitude of the site, these satellites have a site revisit frequency 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 one planned geostationary satellite with methane detection capabilities will not be able to observe above latitudes of 50° N/S.

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

At least four satellites are currently able to detect surface methane from space and are used for various applications including monitoring emissions from point sources. A number of additional new satellites are planned in the next few years, each having specific characteristics and capabilities on emissions over land.

While there have been large amounts of research on satellite capabilities onshore, relatively little has been published on detection and measurement from offshore point sources. To assess satellite capabilities on Norwegian offshore facilities, numerous papers have been reviewed to assemble a broad overview. The consultants have identified three extra challenges when considering satellites' usefulness on emissions from Norwegian offshore installations.

1) Relatively low emission rates.
2) Low reflectivity of water
3) High latitudes

Each of these challenges are significant and can potentially be showstoppers for certain types of satellite measurements. The challenges are discussed below, including how they can be overcome.

Emission rate thresholds:

The minimum detection levels of satellites 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.

The satellites currently in operation have minimum detection rates much higher than the average expected emissions from a Norwegian offshore installation. The four satellites currently available are GOSAT and GOSAT-2 (Japan Aerospace Exploration Agency), Sentinel 5P (European Space Agency) and GHGSat-D (GHGSat). The first three are research satellites with broad swaths of coverage, while GHGSat is a commercial company which can target individual sites as a paid service. The nominal detection thresholds for the different satellites have been estimated by Jacob et. al (2016). At wind speeds of 5 meters per second, they have estimated thresholds between 1000 kg/h[13] and 7100 kg/h. The two GOSAT satellites have a pixel resolution of 10 x 10 km, with a sensitivity 0.7 % and 0.4%, giving detection rates of 7100 and 4000 kg CH_4 per hour. The Sentinel 5P with the TROPOMI instrument has the capability of measuring at a spatial resolution of 7x7 km with a precision of 0.6 %, and an estimated threshold of 4200 kg/h. The GHGSat satellite in operation has a pixel resolution of 50x50 meters, but with a precision of 9-19%, with a detection threshold over 1000 kg/h.

These detection rates are much higher than are expected to be observed from an offshore installation in Norway, even without the challenges of low reflectivity and high latitudes discussed below. Based on the unlikely assumption that emissions from installations were evenly distributed over the year, the average methane emission from a platform was 39 kg/hour, with the highest emitting platform emitting 245 kg/hour on average.[14] Furthermore, satellites with low resolution are 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)[15]. Satellite remote sensing retrieves the column concentration of methane, which are commonly reported in satellite data as an enhancement relative to the local background concentration. There are multiple calculation methods to infer an emission rate from the concentration data. Information on surface winds are necessary to perform the calculation, but must be provided from

[13] After launch, GHGSat-D experienced lower sensitivity performance than expected, and therefore has been estimated to have detection rates in the range of 1000 kg/h using averaging from multiple passes.
[14] Se Annex 1 for calculation of "average" emissions.
[15] See Annex 2 for wind data.

other sources than the satellite. If not actually measured at the site, it can be estimated from a meteorological database, but results in higher uncertainty levels. Varon et al. 2018 proposed two new calculation methods for estimating point-source emissions from high-resolution satellite data. One method infers the source rate from the total detected methane mass in the plume pixels and effective wind speeds, while the other infers the source rate from methane plume transects at different distances downwind as far as plume pixels can be detected. The researchers calculated retrieval uncertainty using these methods, dependent on the satellite precision. For each level of precision, the standard errors are relatively close to the corresponding minimum nominal detection levels, resulting in high uncertainty (i.e. ± 200-290 kg/h for a 250 kg/h minimum detection level) when close to the detection limits. For sources with flow rates higher than 1 500 kg/h, retrieval standard errors were calculated to less than 25% for a minimum nominal detection level of 250 kg/h.

The nominal detection rates of satellites are not necessarily applicable in practice, even when observing over land. Uncertainty ranges are also high when based only on a single observation. Researchers (Varon et al. 2019) have analyzed emissions from an oil and gas field in Turkmenistan, using single-pass retrieval data from the TROPOMI instrument on Sentinel 5P and from GHG-Sat-D. Methane enhancements were identified in 54% (GHGSat) and 90% (TROPOMI) of observations with suitable conditions, i.e. clear skies and sufficient winds. Three emission sources were identified using GHGSat's higher spatial resolution, with the researchers estimating the weakest source to have emissions at 3.6 ±3.2 tons CH_4/h based on a single observation. The other two sources were estimated to have emissions in 9.9 ± 6.8 to 43.3 ± 12 tons CH_4/h. The TROPOMI instrument with lower spatial resolution provided retrieval of the sum of the three sources, with estimated emissions ranging between 5 tons CH_4/h (uncertainty range 0-73 t/h) and 169 tons CH_4/h (uncertainty range 80-237 t/h).

The same researchers (Varon et al. 2020) demonstrated that averaging observations from GHGSat-D from three coal mines over time could reduce uncertainty (to about 40%) and allow for detection and quantification of sources above 1000 kg CH4/h, and that this technique could be used on future satellite instruments with similar spatial resolution but improved precision.

To estimate the sensor properties of the future generation of satellites, launched until 2025, other researchers (Ayasse et al. 2019) investigated the NASAs Jet Propulsion Laboratory's AVIRIS-NG sensor, which is currently being used in aircraft-based measurements. The researchers used the AVIRIS-NG sensor properties to estimate future satellite sensor capabilities, by changing the spectral sensitivity, spatial resolution, and signal-to-noise ratios. The researchers concluded that the next generation of satellite imaging spectrometers should be able to detect plumes as small as 100 kg/h under land-based conditions.

Commercial satellite companies are also planning to launch multiple satellite missions with high sensitivity. Bluefield, for example plans to launch a satellite fleet with capability of detecting plumes as small as 70 kg/hour. GHGSat plans for launch of their second and third satellites with improved performance, estimated to have a minimum detection level in the range of 70-250 kg/hour (Varon et al. 2018).

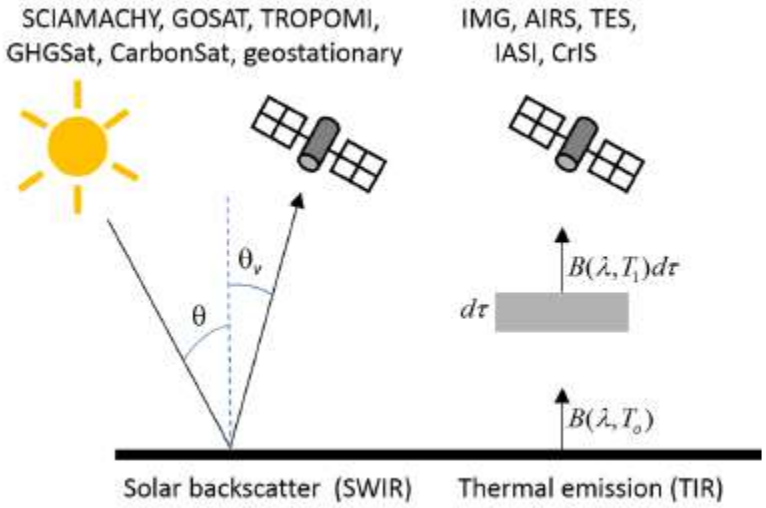
For the next generation of satellites, it is therefore expected that the minimum detection levels will decrease. Even so, on average only a small fraction (18 %) of offshore platforms have "average" emissions[16] high enough to be detected under optimal conditions, with a minimum detection threshold of 70 kg/hour. These 18% of platforms represent 58% of annual emissions. Due to wind conditions offshore, and the next challenge of low reflectivity offshore, it is assumed that even the next generation of satellites would be inadequate to estimate total offshore emissions.

[16] For the purpose of this report, hourly emission rates calculated from the annual reported emissions from each offshore facility have been used as a proxy to assess relevance of the different detection technologies. See Annex 1 for further details.

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.

Figure 5::Passive sensor observation technique, illustration from (Jacob et al. 2016)



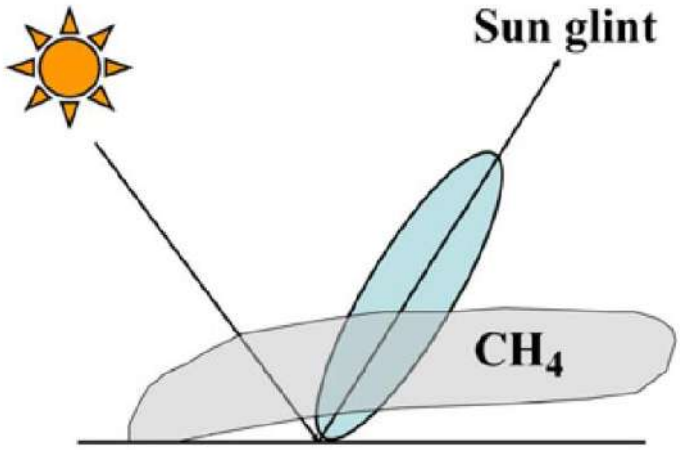
The detection of methane, and other absorbing gases, over water is a challenging issue for passive systems because one is seeking to detect an absorbing gas over an absorbing surface. Passive remote sensing using short wave infrared spectrum suffers from weak reflectivity over water. Thermal infrared sensing suffers from disproportionate levels of detection from the high atmosphere and low sensitivity at the surface (Jacob et al. 2016). 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.

Cusworth et al (2019) also examined the potential of next-generation spaceborne imaging spectrometers for methane detection. This new generation of imaging spectrometers in the shortwave infrared (SWIR) range are expected for launch in satellite projects between 2019-2025. These instruments have a spectral resolution of 7-10 nm in the 2200-2400 nm band, which would allow detection of methane. The researchers investigated different scenes using a simulation tool with superimposed methane plumes, using estimates of precision and detection rates and signal-to-noise ratios. The researchers considered four different scenes, consisting of a grassy scene, an urban scene, a desert scene, and a water scene. One of the central differences between the scenes was the surface reflectivity, and the water scene had very low reflectivity in the spectrum of interest. With the new generation of sensors, the study indicated that for moderate winds of 3.5 m/s, methane emission rates of 500 kg/h could be detected over a grassy scene and 900 kg/h could be detected over an urban scene. However, the water scene was consistently unsuccessful and was not discussed further by the researchers. For the purpose of this study, we can conclude that detection of methane from offshore sites in a normal observing mode will not be possible even for the next generation of passive sensor research satellites.

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 use of sun glint to overcome the weak reflectivity of water when remote sensing from satellites was proposed by researchers (Stamnes 2006). By positioning the satellite sensor to measure the sun mirroring off water (the glint point), one can increase the signal to noise ratio in the measurement and increase measurement of the absorbing gas. This technique has been successfully used in aircraft measurement of methane anomalies in multiple studies (Roberts et al. 2010), (Gerilowski et al. 2015) and discussed in section 2.3.

Figure 6 - Illustration of sun glint detection from (Roberts et al. 2010)



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 and are planned for a future data release.[17] MethaneSAT is being designed to be able to use sun-glint geometry, as are satellites from Bluefield.

A study by some researchers (Ayasse et al. 2018) investigated the properties of NASAs Jet Propulsion Laboratory's AVIRIS-NG sensor, used to assess future satellite capabilities, on detection over water. While the study confirmed that mapping methane sources over water bodies with AVIRIS-NG will remain challenging, the study concluded that detection of sun glint reflected off the surface of water can be used, and that the results are fairly accurate. Sun-glint geometry is however 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. 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.[18] The actual detection capabilities of sun-glint retrieval will therefore vary from satellite to satellite, and no information has been identified on the minimum detection levels of methane associated with sun-glint observation. The possibilities of sun-glint detection will have to be tested from each satellite.

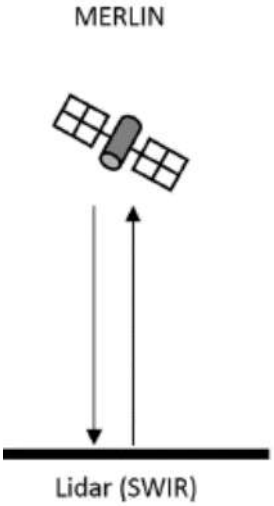
Low reflectivity offshore – active sensors

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. Only one future satellite mission is known to have an active sensor, MERLIN, to be launched in 2024. This French-German mission plans launch of a satellite to detect methane based on an Integrated Path Differential Absorption light detecting and ranging instrument. The main scientific objective of MERLIN is to provide measurement of atmospheric methane at all latitudes throughout the year with small enough systematic errors to improve knowledge of methane sources. While passive sensors

[17] https://sentinel.esa.int/documents/247904/3541451/Sentinel-5P-Methane-Product-Readme-File
[18] Dependent on the sensor type, if it is pointable or fixed.

based on SWIR rely on backscattered sunlight and can only be used in clear sky conditions, the laser-based system can measure in a broader range of conditions, including total darkness.

Figure 7: Active sensor measurement technique - illustration from (Jacob et al. 2016)



The satellite's integrated path differential absorption lidar can use the laser light backscatter from the Earth's surface to derive the column content of atmospheric gases. The IPDA technique relies on DIAL (Differentiated Absorption Laser) measurements based on a pulsed laser emitting at two frequencies around 1.64 µm. One laser wavelength is absorbed by CH_4, while the other is selected to have a negligible CH_4 absorption and is used as reference. From the difference of the two signals the total column of methane is calculated. The laser spot size on the ground is planned to have a diameter of 100 m, with a sampling distance of about 350 m. The measurements are planned to average over samples of 50 km, with a specification requirement of 3.7 ppb methane measurement error. The MERLIN satellite will have a revisit time om 28 days with spacing between two subsequent tracks of about 100 km at the equator (Ehret et al. 2017).

Since the satellite laser is positioned to measure at nadir (directly below), over water surfaces it will continually view the backscatter at the glint point, resulting in a strong signal. However, the strength of a laser backscatter depends on waves and surface winds. While a flat water surface would behave as a mirror, waves reduce the backscatter towards the sensor (Kiemle et al. 2014). Calculations of MERLIN's performance at prevalent wave and wind conditions, the researchers estimated that globally, land surface reflectivity would be about twice as much as sea surface reflectivity. MERLIN is expected to have a monthly precision of approximately 1.5 percent in the area of the Norwegian continental shelf, over a grid of 50x50 km (Kiemle et al. 2014). Due to its low resolution it is not expected to be able to provide measurements which may be used for estimation of emissions from point sources.

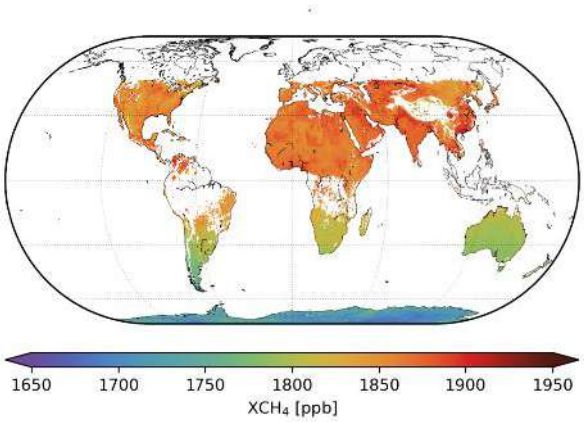
High latitudes

The high latitudes of the Norwegian continental shelf also pose a challenge for measurements from satellites. First, 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 an orbit to be geostationary, it must be directly over the equator and rotate synchronously with the earth. From a geostationary position, measurements at high latitudes towards the poles becomes impossible. For NASA's GeoCarb mission to measure greenhouse gases (including methane), the observing field is restricted to below 50 degrees north and south as a hard constraint, since higher latitudes would result in too high observing angles (Nivitanont, Crowell, and Moore III 2019).

Second, for other orbits including the near-earth orbits, remote sensing satellites 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. The TROPOMI methane measurements, for example, are typically filtered out at a solar zenith angle (the angle between the zenith (straight up) and the sun) of 70 degrees. At a latitude of 58 degrees, this would mean that observations are not useful between mid-October to mid-February[19]. An example is illustrated in the figure below, showing TROPOMI averaged data from November 28th, 2018 to January 16th, 2019. Note that data from the northern latitudes are filtered out in the period.

Figure 8 - TROPOMI CH4 data from November 2018 to January 2019[20]



For measurements from Norwegian offshore installations, this means that satellites would not be able to measure during several months of the year.

Third, 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 such as 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.[21]

Since active sensors do not rely on sunlight for measurement, such as in the planned MERLIN satellite mission, high latitudes do not represent a challenge, and would be able to provide information year-round.

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 satellite capabilities for point source detection are expected to improve by an order of magnitude. Due to their low emissions, high latitudes and surrounding ocean waters, Norwegian offshore sites are likely the most challenging oil and gas production sites in the world for methane satellite measurement. Methane detection and quantification from satellites has multiple advantages. The satellite service companies could provide competitively low-cost monitoring of total emissions over time, which for most other relevant technologies would require multiple deployment of

[19] Calculated using https://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html

[20] Image from https://sentinel.esa.int/documents/247904/2476257/Sentinel-5P-TROPOMI-ATBD-Methane-retrieval

[21] 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.

ships, drones, or planes. In the case of MethaneSat, monitoring and quantification of emission rates would be freely available at no cost.[22]

For satellites to be a preferred method of detecting and measuring methane from Norwegian offshore installations, they must be able to have low detection limits over water with sufficient temporal coverage in the northern latitudes of the Norwegian continental shelf. At present, no existing or planned satellite fulfils these criteria. The main challenge is the ability to measure over water. The one proposed satellite mission with active sensors (MERLIN) could measure over water but is not expected to be able to have the sensitivity to measure low enough emission flows to be relevant for offshore installations. Passive sensor satellites with high sensitivity and spatial resolution may be able to detect and quantify emissions from some sites, if they are able to use sun-glint geometry or if their resolution allows to observe directly over the platforms and accurately quantify based only on this data. Before they are in operation, however, their actual capabilities to do this are not known.

Even in the most optimistic case, before 2025 satellite detection limits are not expected to be improved enough to be able to monitor “average” emissions from more than a handful of Norwegian offshore installations.

Table 4- Current satellites overview table



Name	Year	Pixel size	Minimum detection level	Sensor performance over water	Share of installations covered (*)	Share of emissions covered (**)	Offshore site feasibility
GOSAT	2009	10 x 10 km	7100 kg/hr	Greatly reduced performance over water	0%	0%	
GHGSat-D	2016	50 x 50 m	1000 kg/hr	Greatly reduced performance over water	0%	0%	
Sentinel 5P Tropomi	2017	7 x 7 km	4200 kg/hr	Greatly reduced performance over water	0%	0%	
GOSAT-2	2018	10 x 10 km	4000 kg/hr	Greatly reduced performance over water	0%	0%	

(*) Share of installations covered is calculated from the technologies’ lowest minimum detection level per hour, and how many percent of offshore sites would have emissions over this level (cf. Annex 1).

(**) Share of emissions covered is calculated from the technologies’ lowest minimum detection level per hour, and how many percent of emissions from offshore sites would have emissions over this level (cf. Annex 1).

The low “average” emission rates of Norwegian offshore installations (cf. Appendix 1) require that a sensor to be very sensitive and accurate for the possibility of detecting enhanced methane concentrations from space. No satellite in operation would be able to detect these levels of emissions. Passive remote sensing requires the sun to be high to be able to measure. The low sun at high latitudes of Norwegian sector limit the operational window of these satellites to certain times of year.

[22] 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.

Table 5 - Future satellites overview table



Name	Year	Pixel size	Minimum detection level	Sensor performance over water	Share of installations covered (*)	Share of emissions covered (**)	Offshore site feasibility
GHGSat-C1	2020	< 50 x 50 m	70 - 250 kg/hr	Greatly reduced performance over water	0 - 18%	0 - 52%	
Bluefield technologies	2021	20 x 20 m	70 kg/hr	Greatly reduced performance over water (Sun glint capable)	18%	58%	
MethaneSat	2022	100 x 400 m	200 kg/hr	Greatly reduced performance over water (Sun glint capable)	3%	15%	
GeoCarb	2022	4 x 5 km	4000 kg/hr	Greatly reduced performance over water	0%	0%	
MERLIN	2024	Pencil track	Not able to estimate point source emissions	Reduced performance over water	0%	0%	

(*) Share of installations covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of offshore sites would have emissions over this level (cf. Annex 1).

(**) Share of emissions covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of emissions from offshore sites would have emissions over this level (cf. Annex 1).

Future satellites will have significantly improved detection rates, in the range of 70-250 kg/per hour. While still high, this would approach a range which could be relevant for "average emissions" from some installations (cf. Appendix 1). Passive remote sensing using short wave infrared spectrum suffers from weak reflectivity over water. Sun-glint geometry measurements, where the sun reflects off the water's glint point, may overcome reflectivity issues. Future satellites using active sensors, such as LIDAR, are able to observe over ocean. Active sensors would be able to measure at all latitudes year round since they are not dependent on solar radiation for measurements.

Satellite - GHGSat-D “Claire”

GHGSat is a Canadian company which launched its first satellite in 2016 for monitoring methane and carbon dioxide emissions from industrial and environmental sources. The demonstration satellite is named GHGSat-D “Claire”. The company offers global services including monitoring of targeted sites and emission rate estimation. Its primary instrument, Wide-Angle Fabry-Perot (WAF-P), is an advanced miniature hyperspectral SWIR imaging spectrometer for monitoring targeted greenhouse gas emitters with a spectral range is in the short-wave infrared (SWIR) at 1600-1700 nm

Availability
GHGSAT-D was launched in 2016
Available as a service provider

www.ghgsat.com

Cost and hours

Cost for one measurement campaign
GHGSat offers services on a per customer basis

Cost for measurement over time
Subscription service available

Time for measurement of one platform:
No costs for further analysis necessary

Multi-platform survey possible:
Yes, subscription service

Offshore relevance



Due to the high flow rate threshold, GHGSat’s first satellite is not relevant for measurements offshore

Capabilities/experience

After launch, GHGSat-D experienced lower than expected sensitivity levels, and therefore later has been estimated to have a detection threshold in the range of 1000 kg/h.

No information is available on the possiblity for sun glint measurements over water.

Quantification and identification

Quantification
Yes, as column concentration and calculated emission rates.

Quantification of total emissions of site:
Yes.

Component level identification:
No.

Measurement over time:
Revisit every 14 days

Can isolate site emissions from background:
Yes

Technical specifications

Satellite – low earth orbit

Sensor:
Hyperspectral SWIR imaging spectrometer

Pixel resolution
50 x 50 m

Flow rate threshold:
1000 kgh (3)

Detection levels:
Not expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Sensitive to winds

Low infrared reflectivity of water reduces the signal-to-noise ratio.

Image source: www.ghgsat.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Satellite - European Space Agency - Sentinel 5P TROPOMI

The Copernicus Sentinel 5P is a Copernicus mission in collaboration between the European Space Authority, the European Commission, and the Netherlands Space Office. The satellite was launched in 2017 and carries the tropospheric monitoring instrument (TROPOMI).

The mission's main objective is to perform atmospheric measurements at high resolution. The instrument allows for measurement of a range of atmospheric gases, including the total column concentrations of methane.

Availability
Available. Concentration data is published about 5 days after sensing.

https://sentinel.esa.int/web/sentinel/missions/sentinel-5p

Cost and hours

Cost for one measurement campaign
Data is publicly available

Cost for measurement over time
Not relevant

Time for measurement of one platform:
Not relevant

Multi-platform survey possible:
Not relevant

Offshore relevance



The satellite is unable to detect methane from offshore sites due to low spatial resolution and high detection threshold.

Capabilities/experience

The TROPOMI instrument has the capability of measuring at a spatial resolution of 7x7 km with a precision of 0.6 %. Research reported in Jacob et al. (2016) indicate a minimum detection level for a point source with a flow rate of 4 200 kg per hour.

Currently, TROPOMI only provides data on fraction of methane measurements from observations over land. Retrievals for observations from ocean observations over sunglint geometries are possible for the TROPOMI instrument, and are planned for a future data release

Quantification and identification

Quantification
Methane concentration data available. Requires analysis to infer emission rates.

Quantification of total emissions of site:
No, too large pixel size

Component level identification:
No.

Measurement over time:
Revisit daily

Can isolate site emissions from background:
No.

Technical specifications

Satellite – low earth orbit

Sensor:
Multispectral imaging spectrometer in the shortwave infrared spectrum of 2310–2390

Pixel resolution
7x7 km

Flow rate threshold:
4200 kg/h (3)

Detection levels:
Not expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Sensitive to winds

Low infrared reflectivity of water reduces the signal-to-noise ratio.

Image source: www.wikipedia.org

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Satellite - GHGSat-C1 “Iris”

GHGSat is a Canadian company which launched its first satellite in 2016 for monitoring methane and carbon dioxide emissions from industrial and environmental sources. The company has plans on launching two new satellites. The first one GHGSAT-C1 (Iris) in 2020.

With a two-satellite constellation, revisit times would be 7-8 days for a two-satellite constellation and 4-5 days for a 3-satellite constellation. GHGSat has announced that it is securing the next round of investment for a constellation of 10 satellites.

Availability
GHGSAT-C1 is planned for launch in 2020.

www.ghgsat.com

Cost and hours

Cost for one measurement campaign
GHGSat offers services on a per customer basis

Cost for measurement over time
Subscription service available

Time for measurement of one platform:
No costs for further analysis necessary

Multi-platform survey possible:
Yes, subscription service

Offshore relevance



Even with improved performance, measurement over water is a challenge in normal observing mode. No information is available on the possiblity for sun-glint measurements over water.

Capabilities/experience

GHGSat’s two planned satellites C1 and C2 are expected to have similar design as the first demonstration satellite, while applying critical lessens to improve performance. GHGSat expects an order-of-magnitude performance increase. Researchers have calculated that GHGSat could measure flow rates between 70-250 kg/hour. (3)

Quantification and identification

Quantification
Yes, as column concentration and calculated emission rates.

Quantification of total emissions of site:
Yes.

Component level identification:
No.

Measurement over time:
Revisit every 7-8 days

Can isolate site emissions from background:
Yes

Technical specifications

Satellite – low earth orbit

Sensor:
Hyperspectral SWIR imaging spectrometer

Pixel resolution
<50 x 50 m

Flow rate threshold:
70-250 kg/h (3)

Detection levels:
Not expected to be applicable for “average” emissions from Norwegian offshore sites.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Sensitive to winds

Low infrared reflectivity of water reduces the signal-to-noise ratio.

Image source: www.ghgsat.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Satellite - Bluefield Technologies

Bluefield Technologies is a company based in San Francisco, California, which plans to launch a fleet of microsatellites for tracking methane emissions. The satellites will have a sun-synchronous orbit at altitude of 550 km and have global coverage. The company has developed a sensor based on a gas filter technique, miniaturized for use in satellites.

The company will provide measurement data and operational information through a subscription-based data portal.

Availability
Planned launch of first satellite in late 2021.

Subsequent satellites planned launched from 2022-2024

https://bluefield.co/

Cost and hours

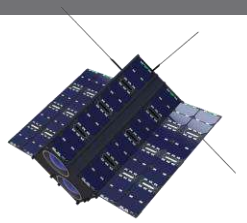
Cost for one measurement campaign
Subscription based service

Cost for measurement over time
Subscription based service

Time for measurement of one platform:
No costs for further analysis necessary

Multi-platform survey possible:
Yes, subscription service

Offshore relevance



The high spatial resolution of the sensor and the low flow rate threshold could in theory enable the satellite to measure emissions directly over the platform surface. Sun-glint reflection over ocean is a planned capability.

Capabilities/experience

The sensor is developed to absorb a complete methane spectral signature. Bluefield's approach is to split the incoming signals in two, one passes through a methane-filled capsule which filters out all methane spectral lines, and one empty container where the methane signals are preserved. The technique is developed to enable accurate detection of smaller leaks and emissions.

The instrument will have the capability to be pointed at areas of interest.

Bluefield has tested prototypes of the sensor from helicopters and high-altitude balloons at 100,000 feet. (1)

Quantification and identification

Quantification
Yes, through Bluefield's machine vision algorithm, providing a flow rate.

Quantification of total emissions of site:
Yes.

Component level identification:
No.

Measurement over time:
Retrieval over North Sea 4 times per year (one satellite) or 12 times per year (constellation of satellites) (1)

Can isolate site emissions from background:
Yes

Technical specifications

Satellite – low earth orbit

Sensor:
Hyperspectral SWIR imaging spectrometer

Pixel resolution
20 x 20 m

Flow rate threshold:
70 kg/h (1)

Detection levels:
Not expected to be applicable for "average" emissions from Norwegian offshore sites.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Sensitive to winds

Low infrared reflectivity of water reduces the signal-to-noise ratio.

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Image source: www.bluefield.co

Satellite - MethaneSAT

MethaneSAT is being 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.

Ball Aerospace has been tasked with developing the high-performance spectrometer-based sensing system.

The satellite will operate in target mode covering most sites every ten days

Availability
Currently planned launch in late 2022

www.methanesat.org

Cost and hours

Cost for one measurement campaign
Free access to data and quantification.

Cost for measurement over time
Free access to data and quantification.

Time for measurement of one platform:
No costs for further analysis necessary

Multi-platform survey possible:
Yes, free access to data and quantification.

Offshore relevance



The satellite will be able to operate in sun glint mode and observe over water, but will likely have too high detection threshold to measure most site emissions.

Capabilities/experience

MethaneSAT is planned to both map emissions over large areas and be able to measure from specific sites, using both a very high precision sensor and with a relatively small pixel size.

MethaneSAT plans to have provide open access to its measurement data, not only total column concentration data but also calculated emission rates from each point source.

The satellite will have the possibility to observe from sun-glint geometry. (1)

Quantification and identification

Quantification
Yes, will provide emission flow rates and total column concentration.

Quantification of total emissions of site:
Yes.

Component level identification:
No.

Measurement over time:
Revisit every 10 days for most sites, uncertain frequency over North Sea due to high latitudes) (1)

Can isolate site emissions from background:
Yes

Technical specifications

Satellite – low earth orbit

Sensor:
Two SWIR spectrometers

Pixel resolution
400 x 100 m

Flow rate threshold:
200 kg/h (1)

Detection levels:
Not expected to be applicable for "average" emissions from Norwegian offshore sites.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Sensitive to winds

Low infrared reflectivity of water reduces the signal-to-noise ratio.

Image source: www.methanesat.org

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Satellite - NASA - GeoCARB

GeoCARB is a NASA Earth Science mission with the goal to measure greenhouse gases and vegetation health from space using a geostationary satellite at an altitude of 35 786 km above the equator.

The scan blocks of the geostationary satellite are restricted to land between 50 degrees north and 50 degrees south as a hard constraint due to larger sensor viewing zenith angles at the higher latitudes.

Availability
Currently planned launch in 2022.

Will only be available for measurements over land in continental United States and South America

https://www.nasa.gov/feature/jpl/geocarb-a-new-view-of-carbon-over-the-americas

Cost and hours

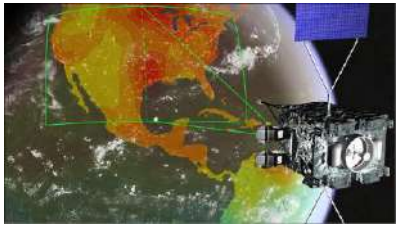
Cost for one measurement campaign
Not relevant

Cost for measurement over time
Not relevant.

Time for measurement of one platform:
Not relevant

Multi-platform survey possible:
Not relevant

Offshore relevance



It is not designed to observe the oceans, as reflectivity over the oceans is too low to provide useful data. (3)

Capabilities/experience

The GeoCarb instrument views reflected light from Earth through a narrow slit. When the slit is projected onto Earth's surface, it sees an area measuring about 2,700 km from north to south and about 5.2 km from east to west. GeoCarb stares at that area for about 4-1/2 seconds, then the slit is moved half a slit width - 3 km - to the west, allowing for double sampling.

With this technique, GeoCarb can scan the entire continental United States in about 2-1/4 hours, and from Brazil to South America's West Coast in about 2-3/4 hours. (3)

Quantification and identification

Quantification
Yes, total column methane concentrations. Requires analysis to infer emission rates

Quantification of total emissions of site:
No

Component level identification:
No.

Measurement over time:
Continuous measurement, with a single pass every 2-8 hours

Can isolate site emissions from background:
No

Technical specifications

Satellite – geostationary orbit

Sensor:
Imaging spectrometer

Pixel resolution
4 x 5 km(3)

Flow rate threshold:
4000 kg/h (3)

Detection levels:
Not relevant for offshore usage.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Sensitive to winds

Image source: www.nasa.gov

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Satellite - MERLIN

A mission by the German Space Agency and French Space Agency to launch a satellite to detect methane based on Integrated Path Differential Absorption light detecting and ranging instrument. The main scientific objective of MERLIN is to provide measurement of atmospheric methane at all latitudes throughout the year with small enough systematic errors to improve knowledge of methane sources. While passive sensors based on short wave infrared absorption rely on backscattered sunlight and can only be used in clear sky conditions, the laser based system can measure in a broader range of conditions.

Availability
Currently planned launch in 2024

https://merlin.cnes.fr

Cost and hours

Cost for one measurement campaign
Not relevant

Cost for measurement over time
Not relevant.

Time for measurement of one platform:
Not relevant

Multi-platform survey possible:
Not relevant

Offshore relevance



While expected to detect methane over water and at high latitudes, the detection rates are expected to be too high for offshore relevance and the grid area will be too large to measure site emissions.

Capabilities/experience

The IPDA technique relies on DIAL (Differentiated Absorption Lidar) measurements based on a pulsed laser emitting at two frequencies around 1.64 µm. One laser wavelength is absorbed by CH4, while the other is selected to have a negligible CH4 absorption and is used as reference. From the difference of the two signals the total column of methane is calculated. The laser spot size on the ground is planned to have a diameter of 100 m, with a sampling distance of about 350 m.

Data will be averaged and reported over a 50 km x 50 km grid. (3)

Quantification and identification

Quantification
Yes, total column methane concentrations. Requires analysis to infer emission rates

Quantification of total emissions of site:
No

Component level identification:
No.

Measurement over time:
Revisit every 28 days with spacing between subsequent tracks of about 100 km.

Can isolate site emissions from background:
No

Technical specifications

Satellite – low earth orbit

Sensor:
IPDA Lidar

Pixel resolution
Pencil track of 100 m
50 x 50 km pixel averaging (3)

Flow rate threshold:
Not capable to measure site emissions, only regionally (3)

Detection levels:
Not expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Sensitive to winds

Image source: directory.eoportal.org, CNES, DLR

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

2.3 New developments: Aircraft

Manned aircraft such as planes and helicopters are another means of placing a sensor in the atmosphere for methane detection and measurement. 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.

The major advantage of planes 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 from a single emission source. Their long range allows for flights offshore to multiple installations, and there are therefore significant returns to scale compared to single-site campaigns.

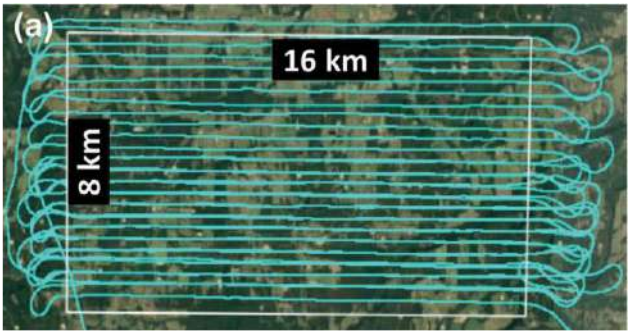
All types of sensors can be mounted in these aircraft, allowing for extremely precise instrumentation of multiple atmospheric gases, and for atmospheric sampling for further inspection in a laboratory. Both in-situ sensors and remote sensing instruments including hyperspectral imaging and Lidar are used.

For application offshore, there are extra considerations which limit the applicability of different techniques. Not all remote sensing technologies perform well over water. The following few paragraphs review the applicability of different categories of sensors mounted on aircraft for offshore applications.

Spectral imaging – relevance and challenges offshore

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. The approach has however difficulties when applied offshore. As an example, Kairos Aerospace, is flying at altitude of 3000 feet above ground level to survey below the flight path. Kairos' system uses sensors based on infrared spectrometer combined with an optical camera to create a surface map of the surveyed region from one flyover.

Figure 9 - Kairos measurement approach. Image source (Schwietzke et al. 2019)

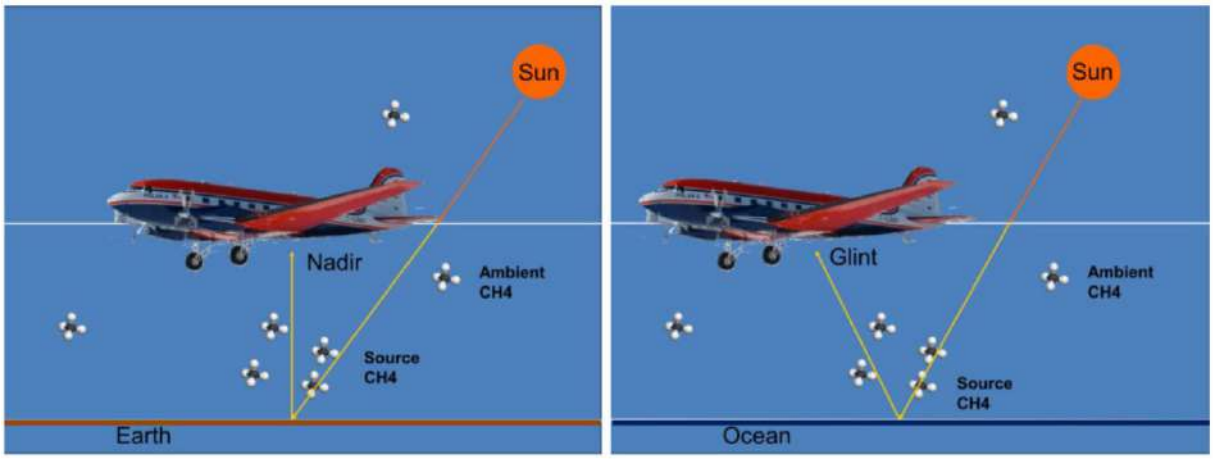


The sensor relies on sunlight reflected from the Earth's surface and measurement of specific wavelengths that methane absorbs strongly. The technology requires sufficient solar illumination, and heavy cloud cover can interfere with solar illumination the technology relies on. Since ocean water is a strong absorber of the infrared radiation in the technology's area of interest, the offshore relevance of this type of technology is greatly diminished.[23] Another example is the highly sensitive AVIRIS-NG sensor used for measurements from aircraft, which researchers found to not be usable over lake water when used in normal mode (Ayasse et al. 2018).

[23] Kairos was selected to be one of the 12 teams in the Stanford/EDF methane measurement challenge in 2018, but was not able to participate at that time due to rice field flooding in the surrounding areas of the test site. Liquid water absorbs nearly all infrared radiation in the technology's area of interest; therefore, the spectrometer would be unable to image methane over lakes and flooded fields, according to supplementary information of (Sherwin et al. 2020).

One way to overcome the difficulty of remote sensing over water is to position an aircraft at the reflection point of the sun where the ocean surface acts as a mirror. This may be achieved by positioning the sensor on a gyro-stabilized platform, so that it tracks the glint angle. The aircraft must then be maneuvered in a straight track so that the glint area is at the source of interest. A grid scan can be performed by flying multiple tracks with parallel lines over an area. The study on the capabilities of the AVIRIS-NG sensor found that high accuracy could be achieved using sun glint observation (Ayasse et al. 2018).

Figure 10 - Illustration of nadir and sun-glint geometry measurements. Illustration image from (Gerilowski et al. 2015)

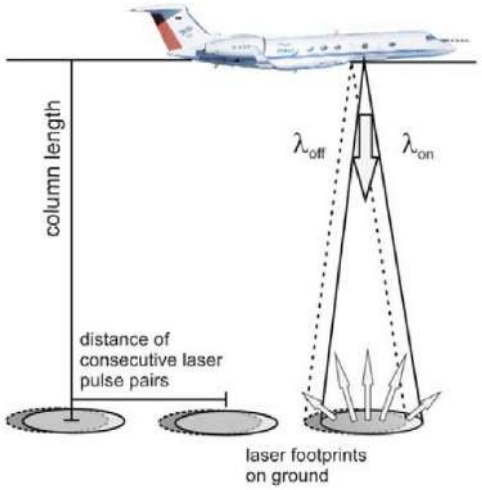


This technique has been used to measure methane emissions with research aircraft from natural marine seeps on the California coast (Thorpe, Frankenberg, and Roberts 2014), and from the 22/4b blowout area in North Sea (Gerilowski et al. 2015). Both these campaigns were designed to measure emission rates 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 tons CH_4/year to 5 000 tons 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.

LIDAR – Relevance and challenges offshore

Aircraft can also be equipped with lidar sensors, such as the CHARM-F instrument. Lidar would utilize the same infrared spectral range as other remote sensing techniques, and therefore suffers at the same low reflectivity of water. However, lidar measurement from a directly vertical (nadir) position allows for still surface water to act as a mirror (the glint point).

Figure 11 - Illustration of airborne measurements with Lidar. Image source: (Amediek et al. 2018)



CHARM-F has been demonstrated over Italian sea waters with comparable, but with consistently higher, standard errors on concentration measurements than over land (Amediek et al. 2018). While the instrument has been demonstrated to also be able to measure point sources with high emission rates such as a coal mine with approximately 9 000 tons CH_4 per year, individual measurements still show deviations compared to in situ measurements (Amediek et al. 2017).

In situ measurements – offshore relevance

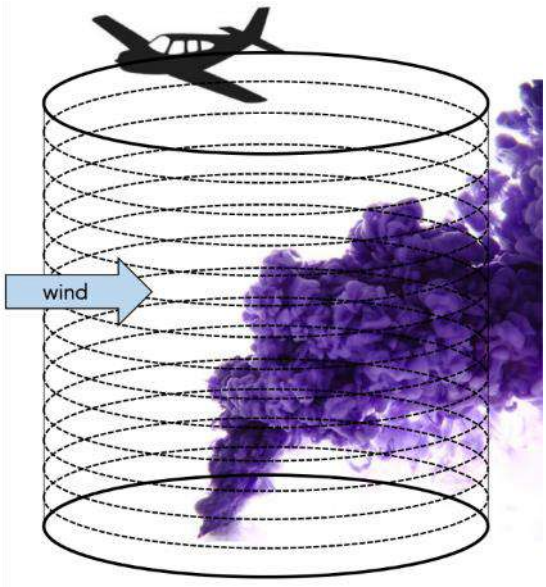
In situ measurements from aircraft require flight into a methane plume. Ambient air is sampled through an intake in the aircraft and measured in-flight using a laser spectrometer and/or sampled for subsequent analysis. The aircraft can be equipped with very precise instruments with frequent measurements, 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 is 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 with 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 one can directly measure the micrometeorological conditions which are relevant for estimation. 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, 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 ground). 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 accounted for. 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%.

Figure 12 - Scientific Aviation measurement approach. Image source: www.scientificaviation.com



Relevance for Norwegian offshore installations

Like drones, 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. Also depending on the sensor, it is possible to use supplementary techniques such as ethane measurement or sampling for isotopic analysis.

While not able to detect as small flow rates as drones (due to further distance from the source), planes using in situ measurement sensors have demonstrated the possibility to detect emission rates between 2-5 kg per hour, which is sensitive enough to measure from 83-90 percent of installations and 99% of "averaged" emissions (cf. Annex 1). As with measurements from drones and ships, since plane-based campaigns by design only measure for a short period, events that happen only under certain circumstances are less likely to be detected.

Plane measurements do not require personnel to access a platform. Planes can also easily measure from multiple installations in one flight, giving significant returns to scale.

To a higher extent than drones, planes 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 planes. The operation window would likely be between May and October.

Plane operations incur costs of aircraft usage and require commercially trained pilots. Availability of specialty aircraft and suitable operators may be limited. In the section 3.3, a case study with plane measurement is presented for the North Sea.

[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 Annex 2 for further details.

Table 6 - Overview over planes



Name	Sensor type and performance over water	Minimum detection level	Share of installations covered (*)	Share of emissions covered (**)	Share of suitable wind speeds (***)	Relative quantification accuracy over water (****)	Offshore applicability
Kairos Aerospace	Hyperspectral imaging Greatly reduced performance over water	46 – 52 kg/hr at 5 m/s	20 – 25%	61 – 68%	48 – 61%		
Ball Aerospace	LIDAR Reduced performance over water	9 – 12 kg/hr	73 – 78%	97 – 98%	73 – 78%		
Scientific Aviation	In situ laser spectrometer. Improved performance over water	5 kg/hr	85%	99%	73 – 78%		

(*) Share of installations covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of offshore sites would have emissions over this level (cf. Annex 1).

(**) Share of emissions covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of emissions from offshore sites would have emissions over this level (cf. Annex 1).

(***) Share of wind conditions applicable for measurement is calculated from the technologies' wind constraints, and the percentage of daily winds below this level at three offshore sites in 2019 (cf. Annex 2).

(****) Relative quantification accuracy has been estimated by the consultant and ranked between the assessed technologies based on available research papers and information from suppliers.

Plane - Kairos Aerospace

Kairos Aerospace is a company based in Mountain View, California. It has developed a system called LeakSurveyor, which is a hyperspectral methane imaging system mounted on a small aircraft.

Flying at altitude of 3000 feet above ground level, the system uses sensors based on infrared spectrometer combined with an optical camera to create a surface map of the surveyed region from one flyover. The sensor relies on sunlight reflected from the Earth's surface and absorption of specific wavelengths that methane absorbs strongly.

Availability
Available as a service provider

http://kairosaerospace.com

Cost and hours

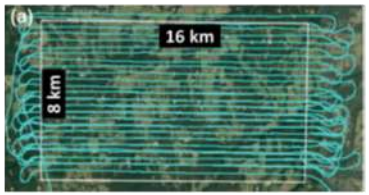
Cost for one measurement campaign
Day rate of plane (3)

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
Travel time plus time for overpasses

Multi-platform survey possible:
Yes

Offshore relevance



Kairos' hyperspectral imaging technology has reduced performance over water, and is therefore not considered to be relevant for offshore use.

Capabilities/experience

The LeakSurveyor system produces images based on GPS coordinates with an overlay of a colored plume image based on detected methane in the atmosphere between the aircraft and the ground.

Kairos was selected to be one of the 12 teams in the Stanford/EDF methane measurement challenge in 2018, but was not able to participate at that time due to rice field flooding in the surrounding areas of the test site. Liquid water absorbs nearly all infrared radiation in the technology's area of interest, Therefore, the sensor would be unable to image methane over lakes and flooded fields. (3)

Quantification and identification

Quantification
Yes, wind normalized rate.

Quantification of total emissions of site:

Component level identification:
No.

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:
Yes

Technical specifications

Plane

Sensor:
Hyperspectral imager

Detection distance
Altitude of 3000 feet

Flow rate threshold:
52 kg/h at 5 m/s (3)

Detection levels:
Not expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
No

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
2-7 meters per second

Image source: Schwietzke et al. 2019

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Plane - Scientific Aviation

Scientific Aviation is a company based in Boulder, Colorado, which operates a fleet of planes and drones and specializes in atmospheric science measurements . Scientific Aviation uses in situ analyzing instruments, which capture atmospheric samples from air inlets on the aircraft. 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 ground). This results in approximately 15 to 20 circles up to the highest extent of the methane plume.

Availability
Available as a service provider. The company currently has a single-engine aircraft available for European operations

www.scientificaviation.com

Cost and hours

Cost for one measurement campaign
Day rate of plane (1)

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
30 minutes plus travel time

Multi-platform survey possible:
Yes, estimated up to five installations per flight. (1)

Offshore relevance



Since the background methane levels offshore were relatively constant compared to onshore, the measurement had a better signal-to-noise ratio and allowed for more accurate measurements

Capabilities/experience

Scientific Aviation performed a methane measurement campaign on Norwegian offshore installations in August and September 2019. 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. For each offshore site, the aircraft circled at about a kilometer away 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.

Quantification and identification

Quantification
Yes.

Quantification of total emissions of site:
Yes

Component level identification:
No.

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:
Yes. The instruments can also measure different atmospheric gases.

Technical specifications

Plane

Sensor:
In plume ring spectroscopy

Detection distance
1 km

Flow rate threshold:
2 kg/h offshore (1)
+/ 12% accuracy (1)

Detection levels:
Relevant for offshore usage.

Offshore criteria

Previously used offshore:
Yes

No approval necessary for offshore use

Requires access to platform:
No

Wind sensitivity:
Stable winds 2-10 m/s required

Flight conditions, no precipitation

Image source: www.scientificaviation.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

2.4 New developments: Drone

Unmanned Aircraft Systems (UAS) or drones allow for atmospheric measurements in three dimensions. While surface-based measurements will always have the uncertainty of the vertical mixing of the plume, drone-based measurements can actually 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.

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. Methane detection and measurement sensors can be equipped on standard commercially available drones, but specialized drones built 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. Drones can be outfitted with sensors of different types, including in-plume sensors and remote sensing instruments. The limitations to measuring methane over water discussed in the sections above, also apply to drones. In-situ sensors, such as laser spectrometers, would therefore be the preferred sensor technology when used on offshore installations.

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 flow rates of different sizes. The study found that in general, quantification methods are in need of improvement.[25] Many of the flow rate estimates 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, which is a well-known issue in a broader range of atmospheric sciences. Close-range methane plumes, when sampled over short periods, are often not dispersed as the Gaussian models would predict (Barchyn, Hugenholtz, and Fox 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. According to the researchers, purely on theoretical grounds, it is unlikely that any mobile screening technology could offer a perfect detection likelihood.

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, since drone measurements by design only last for a short period, events that happen only under certain circumstances are less likely to be detected.

[25] Many of the systems described in the study were under active development, and have since testing in 2018 undergone changes. (Ravikumar et al. 2019)

Most drones are built as battery powered multicopters 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, flight directly over a platform should be avoided.

Drone operation is limited to clear, daylight conditions without precipitation, and is typically limited to wind speeds below 10 meters per second.

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. 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[26] includes requirements on registration and competence of the drone operator.

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 required at all times 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.

FlyLogix is a drone company based in the UK, with the goal of providing oil and gas operators drone services remotely. By using long-range, fixed-wing drones, they launch from an onshore airstrip or open surface and fly out to offshore sites. The drones operate mostly 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. The FlyLogix drone has a stated range of up to 800 km with up to a 5 kg payload, and can be equipped with different types of sensors, including FLIR cameras, optical cameras, LIDAR, radar, and gas sensors. The company states that the drone can fly in wind speeds up to 13 meters per second.[27] The section 3.2 provides a more detailed description of the experience from a test launch in UK.

[26] https://lovdata.no/dokument/SF/forskrift/2015-11-30-1404
[27] https://flylogix.co.uk/about/

Relevance for Norwegian offshore installations

Drones are increasingly becoming 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 able to measure at a closer range than 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.

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 10 grams per hour, and are therefore expected to be able to detect and quantify emissions from all Norwegian sites.

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 precipitation and 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.[28] To the consultants' knowledge, no such operations have been undertaken on Norwegian offshore facilities, and the regulatory and safety issues should be investigated.

[28] https://lovdata.no/forskrift/2015-11-30-1404/§64

Table 7 - Overview of drones



Name	Sensor type and performance over water	Minimum detection level	Share of installations covered (*)	Share of emissions covered (**)	Share of suitable wind speeds (***)	Relative quantification accuracy over water (****)	Offshore applicability
SeekOps	In situ laser spectrometer. Improved performance over water	22 g/hr	100%	100%	73 – 78%		
Scientific Aviation	In situ laser spectrometer. Improved performance over water	10 g/hr	100%	100%	73 – 78%		
Baker Hughes	In situ laser spectrometer. Improved performance over water	61 g/hr	100%	100%	73 – 78%		

(*) Share of installations covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of offshore sites would have emissions over this level (cf. Annex 1).

(**) Share of emissions covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of emissions from offshore sites would have emissions over this level (cf. Annex 1).

(***) Share of wind conditions applicable for measurement is calculated from the technologies' wind constraints, and the percentage of daily winds below this level at three offshore sites in 2019 (cf. Annex 2).

(****) Relative quantification accuracy has been estimated by the consultant and ranked between the assessed technologies based on available research papers and information from suppliers.

Drone – SeekOps

SeekOps is a company based in Texas, USA, which uses a microsensor for methane measurement developed at NASA's Jet Propulsion Laboratory. The SeekIR sensor is based on laser absorption spectrometry, and measures in-plume methane concentrations.

The SeekIRsensor mobile-monitoring technology is capable of detecting, localizing and quantitating methane emissions when coupled with SeekOps machine learning algorithms and data analytics. The drone is paired with SeekOps software and offers localized, quantified emissions leak data for field operations.

Availability
Available as a service provider. Offshore availability planned in 2020.SeekOps plans for their sensor to be drone-agnostic, giving the ability to choose off-the-shelf drones. For offshore usage, this would allow for using a more robust drone.
In addition to being a service provider, SeekOps plans for sales of the sensor while providing analytics services.

www.seekops.com

Cost and hours

Cost for one measurement campaign
Day rate. Additional costs for transport.

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
30 minutes plus travel time to platform

Multi-platform survey possible:
No, requires multiple campaigns

Offshore relevance



SeekOps sensor technology, using in-plume sensors, should be able to detect equivalent flow rates as over land.

Capabilities/experience

SeekOps participated in the Stanford/EDF single-blind methane challenge. The SeekOps team successfully identified include results from the multiple leaks per pad scenarios, demonstrating the ability of Seek Ops algorithms to distinguish multiple closely-spaced emissions sources. The team did not have any false positive detection and detected 100% of leaks in all leak classes. The researchers estimate that their detection limit is lower than 22 g/h.

However, the uncertainty of the quantification was higher than the technical specifications, with an estimated uncertainty range 18-59 g/h and a bias towards overestimation. (3)

Quantification and identification

Quantification
Yes

Quantification of total emissions of site:

Component level identification:
The company states that component level detection is available

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:
Yes

Technical specifications

Drone

Sensor:
Laser spectrometer

Detection distance
3- 300 meters (1)

Flow rate threshold:
22 g/h (3)
Estimated uncertainty range 18-59 g/h and bias toward overestimation (3)

Detection levels:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
The sensor has been used, but not the SeekOps drone

Requires approval for offshore use

Requires access to platform:
Yes

Wind sensitivity:
2-10 m/s

No precipitation conditions

Image source: www.seekops.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Drone – Baker Hughes

Baker Hughes has developed a drone named Lumen Sky, which uses both optical gas imaging (OGI) and tunable diode laser (TDLAS) technologies for detection of methane. The software allows for quantification of leak rate, leak concentration and leak location, with an integrated digital platform which assists with back office operations and automatic reports.

Availability
Unknown. No information received from the provider.

https://www.bakerhughesds.com/measurement-sensing/lumen

Cost and hours

Cost for one measurement campaign
Unknown

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
Unknown

Multi-platform survey possible:
No, requires multiple campaigns

Offshore relevance



The BHG Lumen Sky drone, using its in-plume sensors, should be able to detect equivalent flow rates as over land.

Capabilities/experience

Baker Hughes participated in the Stanford/EDF mobile monitoring challenge with a drone and a methane specific sensor based on laser absorption spectroscopy. The drone flew concentric circles around equipment for measurement.

In the study, the BHG drone reliably detected leak rates greater than 162 g/hr with 100 % detection probability, and had a detection probability of 50% for leaks below 61 g/hr, which was in line with the Baker Hughes team's reported detection limits.
For quantification, the BHG team underestimated the leak sizes, with estimated rates at 35% of the actual leak rates.

Quantification and identification

Quantification
Yes

Quantification of total emissions of site:

Component level identification:
The company states that component level detection is available

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:
Yes

Technical specifications

Drone

Sensor:
TDLAS laser and OGI

Detection distance
From 5-10 meters

Flow rate threshold: (3)
61 g/h

Quantification in field testing biased toward underestimation (3)

Detection levels:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
Unknown

Requires approval for offshore use

Requires access to platform:
Yes

Wind sensitivity:
No specific information, assumed sensitivity similar to other drones

No precipitation conditions

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Image source: www.bakerhughes.com

Drone – Scientific Aviation

Scientific Aviation is a company based in Boulder, Colorodo, which specializes in atmospheric science measurements.
In addition to plane based services, the company also offers drone based measurements.

Using DJI quadcopter and hexacopter platforms equipped with a set of meteorological instruments and a methane/ethane analyzer, the drones can measure and quantify emissions from point sources. An app solution controls the flight path, and allows for upload of data for emission calculations as a service.

Availability
Available as a service provider

www.scientificaviation.com

Cost and hours

Cost for one measurement campaign
Day rate. Additional costs for transport.

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
30 minutes plus travel time

Multi-platform survey possible:
No, requires multiple campaigns

Offshore relevance



Scientific Aviation's drones, using in-plume sensors, should be able to detect equivalent flow rates as over land.

Capabilities/experience

Scientific Aviation collaborated with ConocoPhillips in field-testing drones in Texas.

Quantification and identification

Quantification
Yes

Quantification of total emissions of site:

Component level identification:
The company states that component level detection is available

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:
Yes

Technical specifications

Drone

Sensor:
Laser spectrometer and air sampling canisters

Detection distance
1 meter to 20 meters

Flow rate threshold:
10 g/h (1)

Accuracy 20 -50% (2)

Detection levels:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
No

Requires approval for offshore use

Requires access to platform:
Yes

Wind sensitivity:
2-10 meters per second

No precipitation conditions

Image source: www.scientificaviation.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Drone - FlyLogix

FlyLogix is a drone service company based in the UK, which provides drone survey services to the oil and gas industry. Their fixed wing, long range drone operates from land to survey offshore sites, using beyond visual line of sight monitoring. The drone operates autonomously from a preprogrammed GPS track, but is under remote control by pilots onshore.

The drone can carry a payload of up to 5 kg, with a range of up to 800 km, and can be fitted with different types of sensors.

Availability
Available as a service provider

https://flylogix.co.uk

Cost and hours

Cost for one measurement campaign
Unknown

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
Dependent on measurement technique

Multi-platform survey possible:
Yes.

Offshore relevance



The drone service has the potential to provide competively priced, low risk routine measurements of methane offshore. Air safety regulations for BVLS operations are currently a barrier for routine service.

Capabilities/experience

In 2019, BP tested an approach using a fixed wing drone with long range launched from onshore to perform methane measurements on an offshore installation. FlyLogix provided and operated the drone, which was paired with a sensor from SeekOps. The drone was launched and remotely controlled from a three-pilot crew onshore but managed itself autonomously once airborne.

The drone flew from the island of Papa Stour to the Clair 1 Platform, and performed a series of orbits with in-situ measurements. This was the longest commercial beyond visual line of sight flight performed in the UK.

Quantification and identification

Quantification
Yes, based on sensor type

Quantification of total emissions of site:
Yes

Component level identification:
No

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:
Yes, technique depends on sensor

Technical specifications

Fixed wing drone

Sensor:
Multiple types of sensors including laser spectrometry and OGI

Detection distance
Dependent on sensor.

Flow rate threshold:
Dependent on sensor

Detection levels:
Relevant for offshore usage.

Offshore criteria

Previously used offshore:
Yes

Requires approval from aviation authorities

Requires access to platform:
No

Wind sensitivity:
2-10 meters per second,
Operational to 13 m/s

No precipitation conditions.

Image source: www.flylogix.co.uk

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

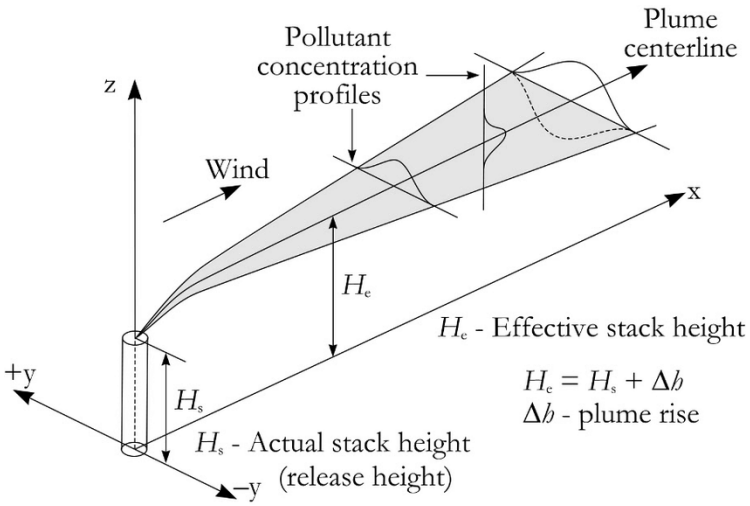
Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

2.5 New developments: 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 13 - Illustration of a Gaussian plume model. Illustration 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, Tacoma, and Verhoef 2019), (see case study further described in the section 3.1). 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, Daube, and Herndon 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 Norwegian continental shelf 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, Tacoma, and Verhoef 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.[29] 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

[29] However, measurement distance from an installation can have an effect on detection of emissions at different heights, and therefore may identify the source.

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.[30] 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.

Table 8 - Overview of ship-based measurement



Name	Sensor type	Share of installations covered (*)	Share of emissions covered (**)	Share of suitable winds (***)	Relative quantification accuracy (****)	Offshore applicability
Ship-based measurement	In situ sensor, multiple types	100%	100%	96 – 99%		

(*) Share of installations covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of offshore sites would have emissions over this level (cf. Annex 1).

(**) Share of emissions covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of emissions from offshore sites would have emissions over this level (cf. Annex 1).

(***) Share of wind conditions applicable for measurement is calculated from the technologies' wind constraints, and the percentage of daily winds below this level at three offshore sites in 2019 (cf. Annex 2).

(****) Relative quantification accuracy has been estimated by the consultant and ranked between the assessed technologies based on available research papers and information from suppliers.

[30] https://www.seabrokers.no/wp-content/uploads/Seabreeze-April-1.pdf

Sensor - Aeris Technologies Inc. - MIRA PicoMobile

Aeris Technologies focus on providing natural gas leak detection systems with highly sensitive point sensors. The MIRA PicoMobile, is a compact laser absorption spectrometer that provides real-time and geo-localized measurements, from its built-in GPS. The device is portable and weighs under 3 kg, while containing a built-in battery that provides 6 hrs of continuous use.

The MIRA also has a WiFi interface and cellular modem for remote access.
The MIRA is intended for usage with mobile leak detection systems.

Availability

Available for purchase

Cost: 35 000 USD, 39 800 USD for ultra version

http://aerissensors.com/

Cost and hours

Cost for one measurement campaign
Not applicable

Cost for measurement over time
Not applicable

Time for measurement of one platform:
Not applicable

Multi-platform survey possible:
Not applicable

Offshore relevance



The Mira PicoMobile could be used as a sensor for future ship-based measurement campaigns, with high sensitivity and competitive price.

Capabilities/experience

The ARPA-E MONITOR initiative financed the Aeris Technologies' efforts to develop a miniaturized laser point sensor for methane and ethane. The result is the MIRA PicoMobile, which is designed for mobile measurement campaigns.

The sensor could be used for surface mobile applications, e.g. mounted on vessels for ship-based measurements.

No independent information available

Quantification and identification

Quantification
Sensor only delivers concentration data, quantification depends on method of use

Quantification of total emissions of site:
Depends on method of use

Component level identification:
Depends on method of use

Measurement over time:
Dependent on method of use

Can isolate site emissions from background:

Technical specifications

Fixed sensor

Sensor:
Laser absorption spectrometer

Detection distance
Dependent on method of use

Flow rate threshold
Dependent on technique
0.02 ppm to 10 000 ppm. (1)
Sensitivity of 1 ppb (per second) for both methane and ethane (1)

Detection levels:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
Not known.

Certified to be used in explosive atmospheres

Requires access to platform:
No

Wind sensitivity:
Dependent on measurement technique

1 Hz sampling rate (1)

Image source: www.aerissensors.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

2.6 New developments: Handheld and fixed sensors

Handheld sensors

Handheld sensors such as optical gas imaging cameras 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.

Since 2017, handheld optical gas imaging cameras have been an integral part of leak detection and repair (LDAR) campaigns and maintenance Norwegian oil and gas platforms. 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. 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.[31] The OGI cameras used are typically a FLIR or Opgal EyeCGas, which are certified for usage in hazardous environments.

As with other measurement technologies, weather conditions must be taken into account when performing LDAR using handheld instruments. High wind conditions make it more difficult to detect leaks (Ravikumar, Wang, and Brandt 2017), but actual performance on board is dependent on the actual wind exposure at the point of measurement. 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. Detecting methane with OGI cameras requires sufficient training and experience, and speed and accuracy of detection is operator-dependent. 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.

This bottom-up approach, however, has two main limitations: since detection campaigns by design only provide a snapshot, events that happen only under certain circumstances are less likely to be detected. In addition, on offshore installations only fugitive emission sources are measured by handheld instruments. Other emissions, such as from vents, gas turbine exhaust and from offshore loading operations are quantified using other methods. Handheld instruments are therefore not used to estimate total emissions.

New developments within hand-held methane detection instruments include the possibility to quantify emissions directly on site by using Quantitative Optical Gas Imaging (QOGI) solutions. These solutions quantify flow rates based on an algorithm to correlate the camera signal an empirically derived calibration curve to determine a release rate. One of the solutions has been tested onshore in Norway and compared with the bagging method for quantification. Another new development is a handheld acoustic leak detector camera, which has been tested onshore in Norway on other gases than

[31] https://www.norskoljeoggass.no/contentassets/19cf6f3a9415400ebff20d0c40436f6a/088-anbefalte-retningslinjer-for-felles-modell-for-arbeidstillatelser.pdf

methane. In addition, lower cost handheld optical gas imaging cameras have been identified, though little information has been identified on real world field experience from these new cameras.

In the longer term, there is a possibility that robotics systems could supplement personnel for LDAR campaigns. Prototypes have been tested onshore using OGI cameras.[32] Aker BP and Cognite are currently testing[33] the quadruped robot Spot, developed by Boston Dynamics, for autonomous inspection on the Skarv offshore installation. The robot will use a set of sensors and cameras and could be able to detect gas leaks.[34]

Fixed sensors

Since the quantity of methane emissions can vary greatly over time, it is interesting to consider technical options to perform continuous measurement. To sufficiently understand the time variability, either repeated measurement campaigns must be undertaken, or fixed sensors can be put in place.

The very high emphasis on safety on Norwegian offshore installations has resulted in the development of standards for the principles and design requirements of technical safety[35]. The standard includes requirements of gas detection coverage using fixed gas sensors. 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 are 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. Gas detection systems are designed to detect all dangerous leaks and should be optimized to detect smaller leaks, typically 0.1 kg/s. 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.

Emissions from vents may be variable, with low pressures and low flow rates. In addition, the gas mixtures may be variable due to hydrocarbon composition and other gases such as N_2 used as purge- or blanket gas. While there are techniques using handheld instruments, which can reliably quantify emission rates from accessible vents onshore, offshore vents are less accessible. Continuous measurements with flowmeters, i.e. ultrasonic meters or differential pressure meters are used offshore, but the challenge of measuring gas composition remains. The consultants have not identified new technologies which enable more precise measurements of gas compositions to resolve this issue.

On land, arrays of fixed sensors have been used in areas downwind of a site to measure and estimate total emissions. While this could be possible at an offshore facility, it would require a set of sensors, ideally anchored at a distance sufficient to ensure atmospheric mixing of a plume such that it is measurable from the surface, and sensors which are able to withstand harsh offshore conditions without significant maintenance. No such developments have been identified, however a low-cost solution for quantifying emissions using a five-sensor array on board an offshore platform is planned for testing outside of Norway.

For continuous bottom-up measurements onboard 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 emission events that happen over time. Fixed sensors may also be placed in areas where it is not possible to use handheld instruments.

Fixed sensors would be able to detect and, in some cases, quantify emissions from specified larger components. The models identified are all stated to be able to detect emissions from up to 100 meters,

[32] https://www.flir.com/discover/instruments/gas-detection/remote-detection-and-localization-of-gas-leaks-with-autonomous-mobile-inspection-robots-in-technical-facilities/
[33] https://www.akerbp.com/exploring-the-potential-of-robotics-in-the-oil-and-gas-industry/
[34] https://e24.no/olje-og-energi/i/Jo4BL8/robothunden-spot-har-fatt-fast-jobb-pa-skarv-feltet
[35] NORSOK S-001, https://www.standard.no/no/Nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=981001

and when used with software from the manufacturer have the capability to quantify leaks through a quantitative imaging technique. Quantitative imaging is based on a method for statistical comparison of measurements to a model based on known leak rates. Different statistical methods are used by different vendors, though no information has been identified on results from field use. Based on information from the different providers, the quantitative imaging is highly sensitive to wind and distance from the source of emissions.

Some of the camera models can also be used for multiple purposes, and allow for automatic fire detection and video surveillance. The cameras also have the ability to pan and rotate the viewing angle to multiple components. Since it would be unreasonably costly to install fixed sensors with ability to cover all components with risk of emissions, fixed sensors would not be able to replace handheld instruments for leak detection and repair but would rather supplement them for measurements on certain types of equipment.

Fixed sensors must be explosion certified to be installed, and the installation would require a power source and network connection. A camera-based fixed sensor also would require line-of-sight proximity to emissions sources. In addition to requirements for explosion certification, fixed sensor instruments would have to be able to both be durable and usable under North Sea conditions. No information on experience from offshore use has been identified.

An overview over the identified handheld and fixed sensor solutions is presented over the following pages.

Handheld - Distran

Distran is a company based in Switzerland whcih specializes in advanced acoustic sensors for industrial applications. The company's sensors spatially filter background sounds present in industrial environment, allowing to detect leaks or discharges. Ultra M is capable of detecting leaks of compressed gases, but is not able to distinguish between different gases. The technology is based on ultrasonic microphones that are capable of detecting the differences on the arrival time of different sound signals that are then converted into a visual image that show the source.

Availability

Available for purchase or lease on monthly or annual basis.

Cost approximately 30 000 EUR for one camera. (1)

https://www.distran.ch/ultra-m

Cost and hours

Cost for one measurement campaign
Requires inspection of all components. Transport and accommodation in addition.

Cost for measurement over time
Measurement over time requires multiple campaigns.

Time for measurement of one platform:
Assumed to be similar to OGI, 48 hours average.

Multi-platform survey possible:
No, requires multiple campaigns

Offshore relevance



While the technology is not known to have been tested offshore, the technology has been used on Norwegian onshore facilities on other gases than methane.

Capabilities/experience

The camera/sensor is stated to be able to detect all leaks that are covered by its field of view. It can detect up to 40 meters away, with a typical measurement distance of 4-6 meters away from the source. The flow rate threshold is stated to be 2-10 liters per hour, dependent on the noise levels at the facility. The sensor overlays video images and acoustic information, and emissions are seen on screen

The company states that it is relatively easy to use, and that training consists of 3 hours theory and practice finding a simulated leak.

Quantification and identification

Quantification
No.

Quantification of total emissions of site: No

Component level identification:
Yes

Measurement over time:
Intertemporal measurement requires recurring campaigns

Can isolate site emissions from background:

Technical specifications

Handheld instrument

Sensor:
Ultrasonic microphone

Detection distance
30 cm – 40 meters (1)

Flow rate threshold: (1)
Quiet environment: 2 L/h
Industrial environment 10 L/h

Detection levels for offshore sites:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
Not known to be used offshore, but used onshore in Norway.

No details on explosion rating

Requires access to platform:
Yes

Wind sensitivity:

The autonomy of the device is 2 hours; however, an extra pack of batteries are provided, therefore a total of 4 hrs are expected (1)

Image source: www.distran.ch

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Handheld - FLIR/ Providence Photonics

Providence Photonics specializes in optical gas imaging technology for several applications, including leak detection, leak survey validation, autonomous remote leak detection, and flare combustion efficiency monitoring.

By combining the GF320 optical gas imaging camera from FLIR with Providence Photonic's QL320 handheld tablet, the system allows quantification estimations of emission rates, through quantitative imaging.

Availability

Available for purchase.

Investment costs:
Approximately USD 100 000 for tablet, FLIR GF320 is an additional cost

https://www.flir.com/products/ql320/
https://www.providencephotonics.com/leak-quantification

Cost and hours

Cost for one measurement campaign
Requires survey of all components, QOGI requires more time than OGI. Transport and accommodation in addition.

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
Average time for OGI 48 hours, QOGI would be more time-consuming.

Multi-platform survey possible:
No, requires multiple campaigns

Offshore relevance



The tablet from Providence Photonics allows for quantitive imaging based on the FLIR camera signal is then correlated to an empirically derived calibration curve to the to determine a release rate.

Capabilities/experience

The solution from Providence Photonics is not known to have been tested in a peer-reviewed academic paper. (3)

Field experience where the estimates from the QOGI tablet were compared to measurements from a Hi-Flow Sampler, showed significant differences. Some users reported good performance on leaks close to the camera, but important uncertainty on larger point sources further away from the camera. (2)

Quantification and identification

Quantification
Quantitative imaging based on camera images

Quantification of total emissions of site:
No, only per component

Component level identification:
Yes

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:

Technical specifications

Handheld instrument

Sensor:
Based on FLIR OGI

Detection distance
Up to 64 meters (1)

Flow rate threshold:
Not specified

Accuracy +/- 1% for temperature range of 0-100 C (1)

Detection levels for offshore sites:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
Not known to be used offshore, but used onshore in Norway.

Hazardous environment version available

Requires access to platform:
Yes

Wind sensitivity:
Quantitative imaging is sensitive to wind rates

Image source: www.providencephotonics.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Handheld - Sensia – Caroline Y

Sensia provides multiple solutions for methane detection and measurement. Caroline Y is an OGI camera designed to detect methane and leaks. The camera, meant as a portable device, is designed to use a smartphone or tablet as an attached processing unit.

The solution allows for data transfer via WiFi and Bluetooth, and to geolocate emission sources.

Portable OGI for LDAR, requires tripod to quantify leak rate.

Availability

Available for purchase

Cost 36 000 EUR

https://sensia-solutions.com/caroline-y/

Cost and hours

Cost for one measurement campaign
Requires inspection of all components. Transport and accommodation in addition.

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
48 hours average.

Multi-platform survey possible:
No, requires multiple campaigns

Offshore relevance



The Caroline Y is a comparatively low-cost OGI camera for methane Leak Detection and Repair, which requires a smartphone or tablet for use.

Capabilities/experience

Sensia demonstrated detection distances of a camera at Total's Lacq facility in 2017. (3)

No other independent information available.

Quantification and identification

Quantification
At component level, based on Smart LDAR and Method 21 protocols

Quantification of total emissions of site:
No, only component level

Component level identification:
Yes

Measurement over time:
Requires multiple campaigns

Can isolate site emissions from background:

Technical specifications

Handheld instrument

Sensor:
OGI camera

Detection distance
Up to 100 meters (1)

Flow rate threshold: (1)
1,08 kg/h at 50 meters
1.8 kg/h at 100 meters

Detection levels for offshore sites:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
Not known

The camera is certified to work in explosive atmospheres

Requires access to platform:
Yes

Wind sensitivity:
No information available, but the technology is sensitive to wind.

Image source: www.sensia-solutions.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Handheld - Sensia – Mileva 33 Ex

Sensia provides multiple solutions for methane detection and measurement. The Mileva 33 Ex is a Sensia's OGI camera with higher sensitivity to methane. The camera, meant as a portable device, uses a cooled infrared sensor.

When used with a tripod, the camera can be used for quantitative optical gas imaging, and can estimate flow rates using Sensia's RedLook software.

Availability

Available for purchase

Cost: 85 000 EUR

https://sensia-solutions.com/mileva-33-ex/

Cost and hours

Cost for one measurement campaign
Requires inspection of all components. Transport and accommodation in addition.

Cost for measurement over time
Requires multiple campaigns

Time for measurement of one platform:
48 hours average, quantification would require more time.

Multi-platform survey possible:
No, Requires multiple campaigns

Offshore relevance



Mileva 33 Ex is Sensia's high performance handheld OGI camera for methane detection, which also allows for QOGI.

Capabilities/experience

Sensia demonstrated detection distances of a camera at Total's Lacq facility in 2017. (3)

No other independent information available

Quantification and identification

Quantification
Yes, at the component level using quantitative optical gas imaging

Quantification of total emissions of site:
No, only per component

Component level identification:
Yes

Measurement over time:
Measurement over time requires multiple campaigns

Can isolate site emissions from background:
Yes

Technical specifications

Handheld instrument

Sensor:
Optical gas imaging

Detection distance
up to 100 m

Flow rate threshold:
0.8 g/h (1)

Detection levels for offshore sites:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
Not known

The camera is certified for work in explosive environments

Requires access to platform:
Yes

Wind sensitivity:
No information available, but the technology is sensitive to wind

Image source: www.sensia-solutions.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Fixed sensor - Rebellion Photonics - Mini GoGCI

Rebellion Photonics is a company based in Houston Texas, which provides a solution for detecting and quantifying gas emissions in industry, including the oil and gas industry. The company provides hardware, analytics and software. Their technology is based on hyperspectral imaging technology which captures both the visible light spectrum and infrared video. The Gas Cloud Imaging system is capable of identifying and quantifying methane emissions in real time, and also allows for fire detection and video surveillance.

Availability

Available for purchase and installation.

No information on cost from supplier

https://rebellionphotonics.com/products.html

Cost and hours

Cost for one measurement campaign
Not applicable, only fixed installation

Cost for measurement over time
Continuous measurement

Time for measurement of one platform:
Not applicable

Multi-platform survey possible:
Not applicable

Offshore relevance



The Mini GoCGI has capabilities to monitor emissions from components or areas continuously, in addition to safety applications.

Capabilities/experience

Utilizes algorithms to detect and quantify gas leaks in real time. The images are processed in real time to identify, quantify and track the gas plume, and operators are automatically notified and can respond to the situation, if it is a gas leak or security or fire event. Detection levels are stated to be 250 ppm per meter (1)

No independent information available

Quantification and identification

Quantification
Yes, quantification of components through quantitative imaging.

Quantification of total emissions of site:
No only components or areas.

Component level identification:
Yes, multiple components can be monitored.

Measurement over time:
Continuous monitoring

Can isolate site emissions from background:

Technical specifications

Fixed sensor

Sensor:
Hyperspectral imaging technology to both capture visible spectrum and infrared video

Detection distance
100 meters (1)

Flow rate threshold: (1)
0.159 kg/hr (3.4 meters distance)
0.283 kg/hr (5.9 meters distance)
at 4.5 m/s winds

Detection levels for offshore sites:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:
Not known to be installed offshore, but is in use on OG facilities onshore.

EX-certified version available

Requires access to platform:
Yes, requires installation.

Wind sensitivity:

Image source: www.rebellionphotonics.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Fixed sensor - Sensia - Caroline FY

Caroline FY is an OGI camera from Sensia for continuous methane detection. The camera's technology is based on uncooled infrared sensors that monitor the presence of multiple gases, including methane.

When paired with Sensia's RedLook software, the camera has capabilities to monitor emissions and health/security events. The camera is stated to be capable of both detecting and quantifying emissions from leaks/vents, in addition to CCTV and fire detection.

Availability

Available for purchase and installation.

Cost: 36 000 EUR plus installation costs

www.sensia-solutions.com

Cost and hours

Cost for one measurement campaign
Not applicable, only fixed installation

Cost for measurement over time
Continuous measurement

Time for measurement of one platform:
Not applicable

Multi-platform survey possible:
Not applicable

Offshore relevance



The Caroline FY has capabiities to monitor emissions from components or areas continuously, in addition to safety applications.

Capabilities/experience

Sensia demonstrated detection distances of a camera at Total's Lacq facility in 2017. (3)

No other independent information available.

Quantification and identification

Quantification
Yes, quantification of components through quantitative imaging.

Quantification of total emissions of site:
No only components or areas.

Component level identification:
Yes, multiple components can be monitored.

Measurement over time:
Continuous monitoring

Can isolate site emissions from background:

Technical specifications

Fixed sensor

Sensor:
Optical gas imaging

Detection distance
100 meters (1)

Flow rate threshold: (1)
1 kg/h (at 50 meters)
1.8 kg/h (100 meters)

Detection levels for offshore sites:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:

Certified to be used in explosive atmospheres

Requires access to platform:
Yes, requires installation.

Wind sensitivity:
No information available, but the technology is sensitive to wind.

Image source: www.sensia-solutions.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Fixed sensor - Sensia – Mileva 33-F

Sensia Mileva 33-F is Sensia's more sensitive OGI camera for fixed installation. The camera's technology is based on cooled infrared sensors that monitors the presence of methane and other gases.

When paired with Sensia's RedLook software, the camera has capabilities to monitor emissions and health/security events. The camera is stated to be capable of both detecting and quantifying emissions from leaks/vents, in addition to CCTV and fire detection

Availability

Available for purchase and installation.

Cost: 72 000 EUR plus installation costs

https://sensia-solutions.com/mileva-33-f/

Cost and hours

Cost for one measurement campaign
Not applicable, only fixed installation

Cost for measurement over time
Continuous measurement

Time for measurement of one platform:
Not applicable

Multi-platform survey possible:
Not applicable

Offshore relevance



The Mileva 33-F is Sensia's more sensitive OGI camera for fixed installation, wtih capabiities to monitor emissions from components or areas continuously, in addition to safety applications.

Capabilities/experience

Sensia demonstrated detection distances of a camera at Total's Lacq facility in 2017. (3)

No other independent information available.

Quantification and identification

Quantification
Yes, quantification of components through quantitative imaging.

Quantification of total emissions of site:
No only components or areas.

Component level identification:
Yes, multiple components can be monitored.

Measurement over time:
Continuous monitoring

Can isolate site emissions from background:

Technical specifications

Fixed sensor

Sensor:
Optical gas imaging

Detection distance
100 meters (1)

Flow rate threshold: (1)
0.35 g/h

Detection levels for offshore sites:
Expected to be relevant for offshore usage.

Offshore criteria

Previously used offshore:

Certified to be used in explosive atmospheres

Requires access to platform:
Yes, requires installation.

Wind sensitivity:
No information available, but the technology is sensitive to wind.

Image source: www.sensia-solutions.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

Fixed sensor – Scientific Aviation - SOOFIE

Scientific Aviation offers a continuous emissions monitoring system – SOOFIE (Systematic Observations of Facility Intermittent Emissions). The system is based on a system of sensors surrounding an installation, which measures methane enhancements and uploads data for off-site quantification. The system can be monitored from an online dashboard application.

Availability

Available for purchase or lease

Cost: 5 500 USD plus installation costs (up to 6 sensors)

www.scientificaviation.com

Cost and hours

Cost for one measurement campaign
Not applicable, only fixed installation

Cost for measurement over time
Continuous measurement

Time for measurement of one platform:
Not applicable

Multi-platform survey possible:
Not applicable

Offshore relevance



The SOOFIE is a low-cost system for continuous monitoring and quantification of methane emissions. The system is planned for testing offshore.

Capabilities/experience

The SOOFIE system has been demonstrated under real-world conditions at an oil and gas facility in the United States, where it successfully detected large emission rates, identified to come from a flare on an adjacent well pad.

It is planned to be tested at an offshore facility using an array of 5 sensors mounted on the platform.

Quantification and identification

Quantification
Yes.

Quantification of total emissions of site:
Dependent on distance from emission points and plume mixing

Component level identification:
Dependent on distance from emission points.

Measurement over time:
Continuous monitoring

Can isolate site emissions from background

Technical specifications

Fixed sensor

Sensor:
Metal-oxide semiconductor

Detection distance
Up to several hundred meters (1)

Flow rate threshold: (1)
1 kg/h

Detection levels :
Expected to be applicable for "average" emissions from Norwegian offshore sites.

Offshore criteria

Previously used offshore:
Planned for testing

Certified to be used in explosive atmospheres:
Not known

Requires access to platform:
Yes, requires installation.

Wind sensitivity:
No information available

Image source: www.scientificaviation.com

Costs per installation - Key

Below 3000 USD
3000-5000 USD
Above 5000 USD
Not applicable

Source of information – Key

(1) Information from the technology provider
(2) Field experience from an independent party
(3) Research paper or other independent source publicly available

3. 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.

3.1 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 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.

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

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.

3.2 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.

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[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.

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

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.

3.3 Plane based measurements – experience from Norway[40]

Scientific Aviation 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.

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

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[39] https://flylogix.co.uk/newsreleases/opening-north-sea-airspace-for-unmanned-aircraft/
[40] Source: This paragraph is developed based on an interview with Scientific Aviation
[41] Personal communication with Steven Conley.

4. Conclusions and summary

Over the past few years, a large amount of work has been ongoing to improve methane emissions detection and quantification led by a number of actors including operators, research groups, and technology companies. As a result, there is now a wide offering of technical solutions to identify emissions and to quantify them. This report provides a systematic mapping of these technologies and assess their applicability to Norwegian offshore oil and gas production facilities. There are specific challenges which methane detection technologies must overcome, to be applicable for Norwegian installations:

Weather conditions offshore are demanding. High wind levels decrease the performance of almost all methane technologies since any plume will rapidly disperse and result in lower atmospheric concentration levels. Wind and waves also limit when seaborne and airborne operations can be performed, and limit the operational window to certain times. When choosing technologies and techniques to be applied offshore, wind conditions should be taken into account. The high latitudes and dark winters also restrict when it is possible to use satellites and airborne measurements, reducing the operational window and also limit certain measurement techniques.

Surrounding waters also strictly limit which types of technologies can be used. Remote sensing, which is based on methane absorption of infrared light, works poorly over water due to low reflectivity. While there are techniques which can be used to overcome these limitations, by placing the sensor in the area where water reflects light as a mirror, such techniques result in operational constraints. This, in combination with the limitations of high latitudes, may be very difficult to overcome for satellites.

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.

The safety requirements are strict, to avoid situations which could increase risk to health and safety. The installations themselves are tightly spaced and have little open access, limiting the possibilities of drones to observe components, line-of-sight of fixed sensors, and the possibilities to set up a fixed array of sensors to capture all emissions from the site.

The relatively low emissions from each facility poses a challenge to the sensitivity of the technologies, which are compounded by the other factors above.

However - a number of technologies are available and have proven their applicability for offshore measurements. In-situ measurement sensors, which do not suffer from reduced performance when used over water, have been used on ships, drones and aircraft to measure and quantify emissions. The distance between platforms and low variability in background concentration rates make estimation calculations of emission rates simpler. Ships, planes, and long-range drones are able to navigate freely and perform measurements. While there is still uncertainty in quantification estimates, quantification methods have been tested in single-blind studies and are being improved. Handheld instruments and fixed sensors are becoming more capable and less costly.

In order to complement and verify bottom-up methods, which are used for emission reporting, and give representative results, top-down measurement campaigns, using e.g. aircraft or drones, need to be supplemented by relevant technical process information on the operational status of the installation during the campaign’s limited time window. If this is not done properly, it may result in under- or overestimation of the emissions from the installation. Extensive communication between the measurement campaign operators and the installation before, during, and after the campaigns is essential in order to achieve the objective.

The following few paragraphs presents the key conclusions for each group of technology and describe possible next steps which could be considered for the most relevant set of technologies.

Satellites

Satellite measurement of methane from Norwegian offshore installations is much more challenging than just about anywhere else, due to low average emission rates, poor performance over water and high latitudes. Each of these challenges could be overcome, but together they strictly limit the possibilities of satellite measurements. For example, detection levels could be reduced by frequent measurements, 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 but is limited by high latitudes and high cloud cover. Active sensors could measure over water and in all latitudes but are limited by low sensitivity and measurement frequency. It is possible, however, that the right combination of sensor technology and observation technique (e.g. a highly pointable sensor with high sensitivity and spatial precision, which performs well at sun-glint mode, or some future active sensor with multiple points with high precision at point sources) could overcome the challenges. It is also possible that a satellite with high spatial precision could observe concentrations directly above the surface of a platform and calculate from this. The real-world performance of each individual satellite mission is uncertain and can to a certain degree be optimized through data analysis and operational settings. It is recommended that the actual capabilities are tested as each new satellite enters into service.

- **Satellite methane detection will likely continue to be challenging from Norwegian offshore installations. However, interested satellite operators could be given the opportunity to demonstrate their capabilities.**

Plane-based measurements

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. Detection performance over ocean water is reduced for certain technologies (remote sensing techniques) while in-plume techniques perform at least as well as over land. In-plume techniques are therefore 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.

- **The Norwegian plane-based campaign has been undertaken as a part of Climate and Clean Air Coalition Methane Studies. When published, results from the campaign should be analyzed for detailed comparison with the other top-down technologies used offshore.**

Drone based measurements

When compared to ship-based measurements, a drone allows for measurement in all three dimensions, allowing for more precise quantification with lower uncertainty levels of the flow rate. Drones equipped with sensors are available for offshore use but are currently limited 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 the drone. The returns to scale of multiple-site measurements are therefore low. 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 safely and systematically operate the drone 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.

Potential next steps towards short-range drone-based measurement:

- **Drones can be used for measurements from offshore installations, but the logistics of transporting equipment and personnel to each site are a challenge. Planning of a deployment strategy must take into account the limitations by weather conditions.**

- **For available drone technologies and given the deployment challenges, it could be investigated what would be the most robust and cost-effective deployment strategy for**

example to have personnel onboard, or already scheduled for onboard tasks, to operate drones for methane measurement.

Another promising development is the availability of long-range drone systems which are launched and piloted from land. This would greatly reduce the risk and cost of transportation of dedicated personnel to and from a platform and would also allow for multi-site measurements. However, this solution is limited by flight safety regulations. In the UK, flight clearance for a flight plan requires months of preparation. For this to be a viable option, these types of services must be available on demand and with short lead times. 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 offered as a routine service.

Potential next steps towards long-range drone-based measurement:

- **The potential for beyond-visual-line-of-sight drone operations could be mapped for Norwegian offshore installations.**
- **If considered a cost-effective solution, the industry could work in cooperation with the Norwegian aviation authorities to analyze the safety and risks of beyond visual line-of-sight operations. In light of this assessment, review whether aviation safety regulations are balanced to ensure the possibility of safe BVLOS operations offshore.**

Ship-based measurements

Sea surface-based measurement campaigns using ships such as supply vessels or fishing vessels are an available option for measurements. Currently, the campaigns have been research-grade missions which have required a significant amount of instrumentation and crew to be undertaken. Much has been learned through these campaigns, and multiple techniques have been tested. The emission quantifications have had a relatively high level of uncertainty, due mostly to unknown parameters such as the micrometeorological conditions.

For ship-based campaigns to be a method for measuring emissions regularly over time, more research is necessary for more accurate modelling of the meteorological conditions over cold North Sea conditions. Measuring techniques and instrumentation could be more standardized to reduce costs of the campaigns. It could even be imagined that supply vessels running routine operations could be fitted with lower cost sensors with a simpler user interface to measure on a more routine basis, while analysis be performed by service providers onshore.

Potential next steps towards operational ship-based measurement:

- **Further research is necessary to adapt wind dispersion modelling to relevant offshore conditions, to ensure validation and accuracy of sea surface-based measurements.**
- **With experience, the logistics of deploying an operation should be reduced, such that costs of a measurement campaign become more competitive.**

Handheld and fixed sensors

There are extensive efforts today using handheld instruments for LDAR on offshore installations. The large number of fixed sensors on board ensure that larger leaks are identified quickly for action. New developments in instruments could supplement these efforts. Multiple companies can provide handheld and fixed sensors which provide detection and measurement capabilities at costs competitive to the instruments used onboard today. Some of the instruments allow for quantitative imaging to derive a leak rate. Some of the new solutions, such as handheld ultrasound sensors and quantitative optical gas imaging, are already in use on Norwegian onshore facilities, and experience from these could be useful to assess application offshore. New developments in robotic systems are also being tested offshore and could supplement personnel for LDAR campaigns in the longer term.

For direct measurements of emissions from vents, there are challenges related to precise quantification of flows with variable composition of gases. The consultants have not identified any new developments with improved performance

- **Real-world experience from new solutions with potential for improved performance or reduce cost should be disseminated industry-wide.**
- **More precise continuous quantification of methane from vents with variable gas compositions requires new developments in fixed sensors. More emphasis could be placed on developing cost-efficient fixed sensors which reliably quantify these sources.**

Reconciliation between top-down and bottom-up estimates:

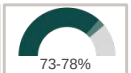
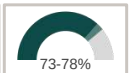
The analysis has demonstrated that a number of technologies are promising to perform top-down emission estimates offshore. Top-down emissions estimates provide the total emission of a given facility/site at a given point of time, ensuring that all the emission sources (at the time of the measurement) are captured. Top-down approaches have also, as presented in this report, some limitations in terms of uncertainty of the estimates, implementation challenges and the generally short duration of the measurements. In this context, top-down approaches can be considered only as a complement to bottom up emissions estimates as currently performed by operators on the Norwegian continental shelf. As such, they can verify the total emissions reported by bottom-up techniques, supplement with measurements over time, and provide further insight into emission sources which are difficult to measure by other means.

Deployment of top-down technologies for deriving methane emissions estimates thus raise a number of methodological considerations, in particular:

- **Reconciliation between top-down and bottom-up estimates**: Once top-down and bottom-up measurements and estimations have been conducted, it is important to match, or reconcile, the data from both approaches. For reconciliation, ideally top-down and bottom-up campaigns should be coordinated so they are able to compare data from the same time period. Comparison allows to identify any potential oversight when one or the other estimation methodology was applied. The benefits of one method also allow to balance out the drawbacks of the other and vice versa, providing a more complete, but also more detailed picture of methane emissions. This reconciliation presents some challenges, in particular due to the relative short time of the top-down campaign.
- **Sampling approach:** The definition of a relevant sample for top-down estimates is an important step to maximize the value of the top-down estimates while managing incremental costs. The sample should be driven by the variability of the facilities but also the accuracy of the reconciliation between the two approaches, with an objective to achieve an acceptable reconciliation on a representative sample of sites.
- **Timing and frequency:** As emissions can vary significantly over time, the timing of the deployment has a significant impact on the results of a specific survey and it may be interesting to deploy measurements at different times representing different “operating modes” with different emissions patterns. This requires extensive cooperation with the installation operator, and combines information from measurements with information on specific processes and operational status. As for the point above, the objective can be to achieve an acceptable reconciliation on a sample which is temporally representative.

In this context, it is recommended to develop a common methodology which provides a robust basis for the considerations above independently on the measurement approach selected.

Figure 14 - Overview of the technologies' relevance for offshore usage

	Name	Total emissions quantification	Component level detection	Measurement over time	Share of sites covered by minimum detection level (*)	Relative quantification accuracy (**)	Wind conditions (***) and other weather constraints	Approximate costs per offshore site (****)	Conclusion
	Handheld and fixed sensors	✗	✓	✓	 100%	Accuracy varies between technologies.	 14-99% Sensitivity varies	 Handheld: operator hours + transport. Fixed: high costs.	Several new handheld and fixed sensors which could supplement existing solutions
	Ship-based measurement	✓	✗	✗	 100%	 Low without tracer (-90, +1000%).	 96-99% Safe sea conditions	 Operators and day-rate for ship. Dependent on number of sites.	Measurement from ships is still at the research stage, and has required a dedicated PSV. Costs and complexity could be reduced.
	Drones	✓	✗	✗	 100%	Accuracy +/-20%	 73-78% No precipitation	 Day-rate for drone and operator, plus transport.	High detection sensitivity and can be used in offshore conditions, but require on site teams. Future BVLOS drones could be competitive.
	Aircraft	✓	✗	✗	 85%	 Accuracy +/- 12%	 73-78% No precipitation	 Day-rate for plane Dependent on number of sites	Aircraft measurements are currently a competitive option when used on multiple sites, primarily with in-plume sensors.
	Satellites	✓	✗	✓	Not expected to be relevant offshore	Not expected to be relevant offshore	Not expected to be relevant offshore	Not expected to be relevant offshore	Satellite sensing is very challenging on Norwegian offshore installations, due to reflectivity, low emission rates and latitude.

(*) Share of sites covered is calculated from the technologies' lowest minimum detection level per hour, and how many percent of offshore sites would have emissions over this level (cf. Annex 1).
(**) Relative quantification accuracy has been estimated by the consultant and ranked between the assessed technologies based on available research papers and information from suppliers.
(***) Share of wind conditions applicable for measurement is calculated from the technologies' wind constraints, and the percentage of daily winds below this level at three offshore sites in 2019 (cf. Annex 2).
(****) Costs are only estimates performed by the consultant on the basis of available information. Costs may change over time. Company internal costs are not included. Approximate costs per offshore site are grouped into green (below 3000 USD per site), yellow (3000-5000 USD per site), and red (above 5000 USD per site).
Fixed and handheld sensors: measurement over time only possible for fixed sensors.
Operators of drone-, plane- and ship-based measurement services may have the possibility to identify and detect emissions from areas or certain components.

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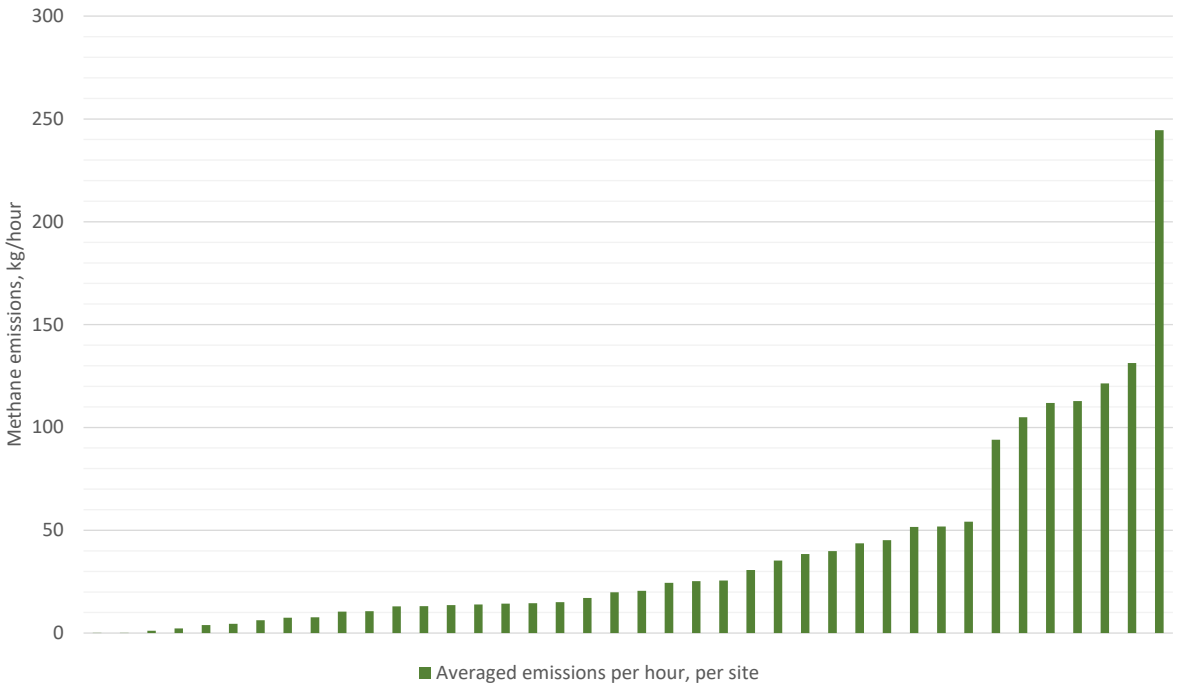
Annex 1 Emissions from Norwegian offshore installations

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.

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 are calculated. Since actual hourly flow rates will vary widely with operational conditions, these averages should be used with caution. For the purpose of this report, they are used as a proxy to evaluate the relevance of different measurement technologies', and to what extent they would be able to detect emissions from the sites.

Figure 15 - Calculated average hourly methane emissions from each offshore installation, in kg CH_4 per hour.- 2018

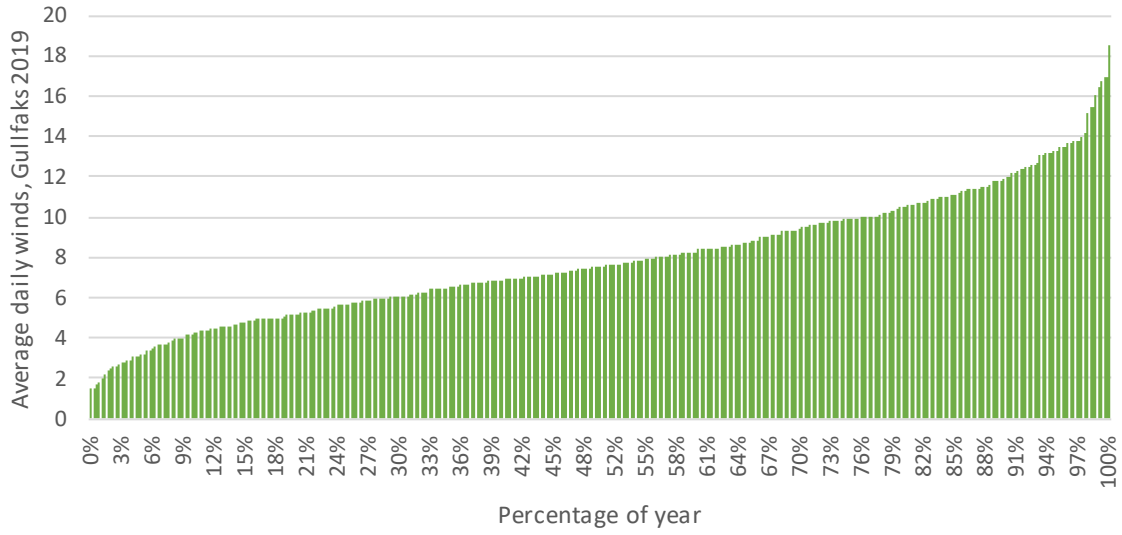


As illustrated in the figure above, there is a wide variation between the emissions of Norwegian oil and gas facilities. About 75 percent of the facilities have an *average* low emission rate between 0 and 50 kg per hour. On average, only 15% of the installations had higher emissions than 100 kg/hr. Due to their higher share of emissions, these six installations represent 52% of reported emissions in 2018.

Annex 2: Wind conditions offshore

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 Norwegian continental shelf (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 16 - Average daily winds measured at Gullfaks in 2019



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.