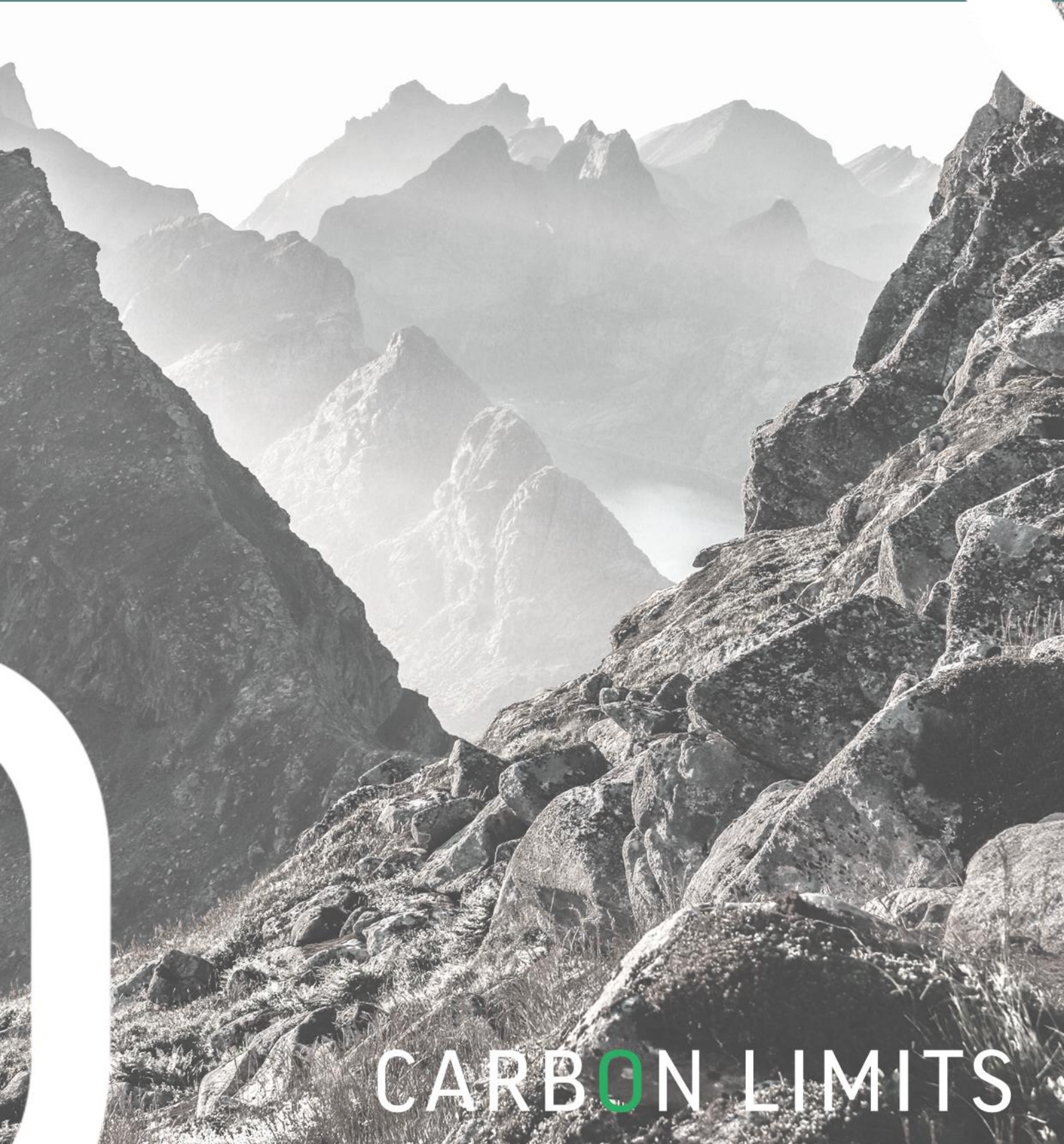


Overview of subsea methane emissions detection and quantification technologies

Technologies and Cross-cutting elements

Version 2.0 - October 2023



CARBON LIMITS

This report was prepared by Carbon Limits AS for Offshore Norge...

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Overview of subsea methane emissions detection and quantification technologies

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

Disclaimer

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

This report might not reflect the views of technology providers, and oil and gas operators that have been consulted during its preparation. For further information on their views, it is suggested direct contact with such persons or companies.

Methane emissions detection and quantification technologies is a fast-evolving field, and this report does not intend to cover all subsea methane detection and quantification technologies. This report relies on data, technology, and research available to Carbon Limits at the time of its preparation, is prepared on a commercially best effort basis, and has no intention of being exhaustive. The report and technology template may need to be updated from time to time to include additional findings.

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

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This document has been developed as a follow up of the project and the report on Recommended practices for methane emissions detection and quantification technologies – Upstream, performed for IOGP, IPIECA and OGCI which is expected to be published Q2 2023. To ensure that this report can be read as a standalone document, some sections of the original report have been included in this document.

Executive Summary

Since 2020, European institutions have been working on a proposal for methane emissions detection, quantification and mitigation in the oil and gas sector. A key feature has been an obligation for operators to perform leak detection using technologies or methods that have a defined detection threshold both for leaks to the atmosphere and below sea surface.

The aim of this document – along with its accompanying Technology Data Sheets – is to provide oil and gas operators with a technology basis to assess subsea methane emissions detection and quantification technologies for oil and gas activities, tailored to their facilities and objectives.

The first part of this report provides an overview of the criteria that operators should consider in selecting technology appropriate to their activities. This includes factors such as: type of sensor, deployment method, detection threshold, operating and environmental constraints. These characteristics are detailed for each of the 11 detection and quantification technologies from 6 technology providers reviewed as part of these project and can be found in the Technology Data Sheets. When considering the result of the assessment of subsea detection and quantification technologies, the following points can be highlighted:

- Subsea methane detection and quantification technologies are limited when compared to technologies for onshore, ambient air detection and quantification of methane emissions.
- No technologies were identified for methane quantification specifically, where methane emissions can be determined as a mass or volumetric emission rate without additional follow-up or auxiliary information.
- There is currently limited, conflicted, or no information to document minimum methane detection thresholds.
- There are currently no independent third-party testing results publicly available.

The document also presents other elements that can impact operator selection and deployment of methane detection and quantification technologies and more generally elements related to subsea methane emissions. The processes and challenges linked to quantifying the amount of anthropogenic methane released to the atmosphere from subsea emissions sources from oil and gas activities are also described.

More precisely, methane released from the seabed dissolves in the water column as the bubbles rise through the water column and part of it can be released later through water-atmosphere transfers. However, a broad range of chemical and environmental parameters affect the amount of methane released to the atmosphere. To accurately quantify the amount of methane emissions released to the atmosphere, a leak detection or quantification technology requires additional information. No available technologies considered as part of this report were found to incorporate all these aspects.

In addition, methane emissions can occur naturally from the seabed due to bacterial or geologic activity. Some of the technologies assessed as part of this project allow to isolate anthropogenic emissions from natural methane emissions, while others do not.

Recognising that there is neither a “one-size-fits-all” technology nor a “one-size-fits-all” technology combination yet, several examples of operators’ experiences with technology combinations are described, highlighting the benefits that can be provided by certain combinations. Other monitoring methods, which are not directly related to source or component subsea methane quantification technology, can be used for emissions monitoring, such as mass balance, optical camera, and optic fibre. However, detection and quantification levels associated with these methods are uncertain and have not been further assessed. Depending on the frequency, regular proactive deployment of some of the mobile-deployed techniques (e.g., from vessels) may have a non-negligible climate impact. It is recommended to evaluate the climate impact of these options.

Table of Contents

Executive Summary	3
Abbreviations.....	6
1 Introduction	7
2 Criteria for technology selection presented in the Data Sheets	8
2.1 Operator Preferences.....	9
Deployment Method.....	9
Sensor Type.....	10
Technology Development Stage	11
Business Model.....	12
Frequency of technology deployment.....	12
Sampling frequency during operation	12
Requires access to site	13
Operating Regions	13
Potential to cover multiple sites per deployment	13
Operational Since	13
2.2 Detection	13
Components Detected	13
Applicable medium	13
Detection Level	13
Detection Threshold/Precision – Natural and Anthropogenic Sources – Methane	15
Detection Threshold/Precision – Anthropogenic Sources – Methane	15
Detection Threshold/Precision – Anthropogenic Sources - . Other Components	15
Detection Threshold validation	15
Independent assessment on false positives.....	17
Possibility to distinguish anthropogenic from natural seepage/leakages	17
2.3 Quantification	17
Quantification Level	17
Quantification threshold similar or above detection threshold	18
Quantification Performance – Methane	19
Quantification Performance – Other components.....	19
Quantification performance validation	19
Uncertainty on quantification.....	19
2.4 Environmental conditions	19
Max water depth (m) and impact on uncertainty	19
Impact of Sea conditions (Tidal currents, oceanic characteristics etc.).....	19
Impact of Sound.....	20

Other environmental constraints	20
2.5 Deployment characteristics	20
Time for deployment	20
Ease of deployment.....	20
Training requirement for operators	20
Power demand and other dependencies	20
Best works on	20
3 General observations from technology review	20
4 Cross-cutting elements.....	23
4.1 Elements of subsea methane emissions	23
Natural methane emissions	23
Evolution of methane bubbles in the water column	25
Evolution of methane dissolved in water	25
4.2 Impact of natural methane seepage on measurements.....	27
4.3 Complementary technologies to Leak Detection Systems	28
4.4 Combinations of Technologies.....	29
5 Case studies	29
5.1 Methane leak detection as part of a Leak Detection System.....	30
5.2 Limitations of subsea methane technologies.....	30
6 Conclusion	31
7 Appendix A Methodology and data sources	33
7.1 Literature review	33
7.2 Interviews with operators, researchers, and standardization bodies.....	33
8 Appendix B References	34

Abbreviations

AUV	Autonomous underwater vehicle
FID	Flame ionization detector
GOR	Gas oil ratio
GWP	Global warming potential
IMR	Inspection, maintenance, and repair
LDAR	Leak detection and repair
MEUR	Million EUR
MRV	Monitoring, reporting and verification
NDIR	Non-dispersive infrared
PoD	Probability of detection
ppmv	Parts per million (volumetric)
ROV	Remotely operated vehicle
SCADA	Supervisory control and data acquisition
TDLAS	Tuneable diode laser spectroscopy
TRL	Technology readiness level

1 Introduction

Methane is a potent greenhouse gas with a global warming potential (GWP) of 82.5/29.8 over a 20/100-year period¹. Methane emissions from oil and gas are estimated to account for 61% of global methane emissions from the energy sector, and 33% of anthropogenic methane emission sources².

Recently, focus on greenhouse gases from the energy sector has prompted proposed regulations to reduce methane emissions through various, improved measures such as monitoring, reporting and verification (MRV), mandatory leak detection and repair, bans on venting and flaring, and acceptable leaks from both onshore and offshore oil and gas installations in the US, Canada and EU^{3,4,5}. To comply with new regulations, many upstream oil and gas operators are aiming to implement and/or improve methane detection and quantification at their sites^{6,7}. Monitoring of methane emissions to air using techniques such as optical gas imaging cameras and flame ionization detectors (FIDs) have been longstanding and are often required in national regulations for oil and gas operations^{8,9}. More recently, novel methane detection technologies such as drones, planes and satellites have become increasingly popular.

However, these technologies are not readily applicable to subsea methane detection and quantification. Subsea leak detection is a challenging field with many specificities related to this unique environment. First, the leaking methane will be released in seawater such that traditional air methane leak detection technologies are not applicable due to different physical properties: surface tension of water at the water-gas interface differs, methane bubbles dissolve due to solubility in water, gas exchange with oxygen and nitrogen in the water column which deplete the methane content inside the bubble as it rises through the water column, high pressure at low depths cause methane to rise to the surface due to density differences, or low-light conditions, which all vary from methane released in the atmosphere.

Fortunately, seawater also allows to develop technologies that are based on alternate physical properties. For example, a bubble can be detected using acoustics sensors that employ sonar techniques, or by performing spectroscopic analysis to determine its methane concentration. However, the conditions where the leak inspection is performed can also be a challenge when considering development of subsea leaks detection technologies. Technologies that are deployed at sites for long durations can be impacted by corrosion, salt deposits and the development of biofouling. Finally, many facilities and pipelines are remotely located and may not be easily accessible. Operators may need to deploy a vessel with experienced staff and specific equipment, such as ROVs, AUVs or any other means that allow an inspection to be carried out on installations, which requires time, economic resources, and environmental consideration.

The purpose of this document is to provide an overview of the currently available methane detection and quantification technologies for subsea oil and gas infrastructure. Therefore, technologies not specific to methane detection or not specific to subsea deployment will not be treated in detail. To have a global vision of what exists in the field of leak detection and what may be deployed on offshore oil and gas facilities (such as mass balance system or satellite detection), further studies may be required. This document and

¹ IPCC Sixth Assessment Report. <https://www.ipcc.ch/assessment-report/ar6/>

² IEA Global Methane Tracker Report, 2023. <https://www.iea.org/reports/global-methane-tracker-2023/overview>

³ US EPA Supplemental Proposal to Reduce Methane and Other Harmful Pollution from Oil and Natural Gas Operations. <https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-industry/epa-issues-supplemental-proposal-reduce>

⁴ Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on methane emissions reduction in the energy sector and amending Regulation (EU) 2019/942. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A805%3AFIN&qid=1639665806476>

⁵ Federal regulations to reduce methane emissions in the oil and gas sector. <https://www.canada.ca/en/environment-climate-change/services/canadian-environmental-protection-act-registry/proposed-methane-regulations-additional-information.html>

⁶ In the body of the report, sites are synonymous with “facilities” as “Collection of emission sources with some relation to one another within a delimited geographical area.”

⁷ Oil and Gas Methane Partnership. <https://www.ogmpartnership.com/>

⁸ US EPA 40 CFR Part 60 Subpart OOOOa <https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60/subpart-OOOOa>

⁹ AER Directive 060. <https://static.aer.ca/prd/documents/manuals/Manual016.pdf>.

accompanying set of Technology Data Sheets provide subsea oil and gas operators with an overview of the *methane* detection and quantification technologies currently available to characterize methane emissions.

The technology Data Sheets have been developed based on multiple sources, including peer-reviewed academic literature, publicly available information, and interviews with operators, academics, and technology providers. Sources for all information in the Technology Data Sheets are clearly identified. (Further information on methodology and data sources is provided in Appendix A; a list of academic papers reviewed is provided in Appendix B.)

The document and its accompanying Technology Data Sheets do not aim to recommend or impose one technology or approach over another. They have been developed to provide an overview of the available technologies to allow operators to make informed decisions on selecting and deploying the technology (or combinations of technologies) best suited to the specific circumstances of their assets, considering the objectives that the technology deployment is aiming to achieve.

Section 2 provides an overview of the criteria covered in the Data Sheets that could be useful to readers in selecting technologies appropriate to their sites. Section 3 provides a summary of observations from the technology Data Sheets for the identified subsea methane detection and quantification technologies. Section 4 provides additional information on general elements of subsea methane detection and quantification. These elements are not technology specific, but provide additional information required for an operator to consider when deploying methane detection and quantification technology to characterize emissions. Section 5 provides several examples of operators' experience in deploying technologies, highlighting the benefits and limitations of deploying subsea methane detection and quantification technologies.

2 Criteria for technology selection presented in the Data Sheets

Subsea methane detection and quantification technologies can be deployed for various purposes at sites with different characteristics. Purpose of deployment and site characteristics both play a critical role in the selection and deployment of technologies. To help the operators understand which technologies may be most suitable for their sites, a series of Technology Data Sheets have been developed and are provided in conjunction with this report¹⁰. Data Sheets are used to help an operator understand technologies with respect to their requirements for specific site(s) and purpose(s). The following sources and validation aspects were used to develop the Data Sheets.

Table 1 Sources and Validation Options used in the Data Sheets

Sources	
[1]	Information from peer-reviewed paper prepared by an independent party (such as academia)
[2]	Information from independent third party (such as operator)
[3]	Information from technology provider (including peer-reviewed paper from technology provider)
[4]	Certification against a standard
[5]	CL Assessment
Validation	
(a)	Validated by independent academic researchers

¹⁰ Note that criteria for technology presented in the Data Sheets has been adapted from a previous recommended practices document for OGCI, IOGP and Ipeca regarding on shore, ambient air methane detection and quantification technologies. There are similarities between these reports, as structures and options for the Data Sheets are similar. Criteria has been edited where applicable to apply to subsea methane detection and quantification technologies.

(b)	Validated by fully blind tests performed with third party (e.g.: operator, academia) Fully blinded tests are when the technology provider has no knowledge of controlled releases being performed and are the most representative of real-world oil and gas sector surveys.
(c)	Validated by partially blind tests performed with third party (e.g.: operator, academia) Partially blinded tests are when the technology provider is aware of controlled releases, but not of the characteristics of the release, such as the location or the magnitude.
(d)	In-house testing

This section presents the information and criteria used to develop the Data Sheets and provides the reader with background information on how to interpret them, as well as applicable options. Figure 1 presents an overview of general criteria covered in the Data Sheets.

Figure 1 Data Sheet Criteria

General information - Name - Description - Deployment method - Sensor type - TRL	Detection/Quantification - Detection/Quantification Level - Detection threshold - Detection distance - Quantification Performance - Uncertainty	Other relevant information - Operating Regions - Maturity - Ideal Utilization - R&D Developments
Environmental/Operational limitations - Max water depth - Impact of Sea Conditions - Impact of Sound - Other	Deployment - Time for Deployment - Ease of Deployment - Training requirements - Power Demand	References and additional material - Link to peer reviewed articles - Company Reports - Industry Testing

2.1 Operator Preferences

Subsea methane emissions detection and quantification technologies can take many forms and may be deployed in different ways. The nature of the technology can be selected depending on the operator’s preferences and constraints with regards to site setup, equipment present, environmental factors in the surrounding area, as well as the methane detection method of the sensor. The sections below provide details on these characteristics. Some factors have pre-defined labels that are assigned to all technologies based on interviews or other information, to simplify the comparison between different technologies. However, other factors will provide more open-ended, relevant details based on the information collected during interviews, availability online or otherwise that do not follow pre-defined options.

Deployment Method

The underwater environment imposes constraints that shape the leak detection technologies. Systems are needed that are not usually compatible with leak detection systems in open air. However, underwater environment constraints also impact the leak detection practices.

First, facilities are more difficult to access. To perform measurements for inspection or monitoring, two strategies are often applied: permanent installation of sensors at subsea infrastructure or deploying sensors to the inspected zone mainly using a remotely operated vehicles (ROV) or autonomous underwater vehicle (AUV). Both strategies have strengths and weaknesses. For stationary monitoring, no access to the facility is needed once it is installed and operational, and there is no need to work underwater. Furthermore, measurements of the surrounding waters occur continuously. One limitation of a stationary underwater sensor is it will only measure the area in proximity, and will be subject to environmental constraints, such as

currents. On the other hand, inspecting a zone using vehicles allow to use the sensors that are most suitable for the specific environment and different points can be inspected with the same vehicle. However, it will only perform measurements intermittently, every time an inspection is completed and a boat with specific and trained staff is needed (the ROV and AUV will be operated from this vessel).

Sensor Type

The characteristics of the measurement environment (underwater and of different depths), leads to a different approach than the one used in open air leak detection. Methane interacts differently with water than air, so most leak detection technologies commonly used in air are not effective underwater. However, technology development is in progress, and even if some technologies are currently deployed on offshore facilities, others are still in testing phase. An overview of the different types of sensors applicable for subsea methane detection and quantification are presented hereafter. Technology providers typically rely on one or more of these sensing methods to develop their specific technology.

Active acoustic

Active acoustics technologies are based on the same principle as a sonar. They emit a sound at a specific frequency that will be reflected by surrounding infrastructure or obstacles. Those elements can be objects or marine animals, but also bubbles. Once reflected by those elements, the returning sound will reach the emitter-receiver where it can be analysed. In the case of leak detection, this sensor will focus on detecting methane bubbles. This principle is used for two different types of technologies. The first one is a point sensor, monitoring a specific equipment or component, while the second type provides monitoring over a certain area.

The first type is typically placed on the top of key infrastructure points (large manifold, Christmas trees, etc.). A funnel placed on top of those equipment or components will collect all the bubbles that are emitted and direct them to the sensor. The sensor measures the number of bubbles and their size, which allows to estimate the leak rate, and knowing the concentration of methane of the leaking product, the amount of methane released can be evaluated.

The second type of sensor is placed in an area of interest (e.g., clusters of wellheads). By emitting high frequency sounds, it can have a range of hundreds of meters and can map the space around it. This continuous spatial monitoring allows to determine the location of the methane plume and its development in the water column, including from where it was emitted and therefore it could be possible to differentiate leaks from natural emissions.

The following technologies use this type of sensor: *Naxys Technologies Local Leak Detector*, as a point sensor and *METAS AS Active Acoustic Leak Detection* and the *Sonardyne Solstice* and *Sentry*, as area coverage sensors.

Methane sniffer

Methane sniffer sensors directly measure the methane concentration in the water using different physical principles, such as optical non-dispersive infrared (NDIR) or tuneable diode laser spectroscopy (TDLAS). The dissolved methane diffuses over a membrane into a detection chamber. Methane sniffers are point sensors, meaning they require direct contact with the leaking medium, to determine the presence or absence of methane. The methane molecules emitted and dissolved into the water must reach the close vicinity of the sensor, by diffusion or driven by the sea current to be detected. By using methane as a proxy, any leak containing methane (e.g., oil leaks), can be detected.

Even if it is reliable and precise to quantify methane, it has several limitations. For example, in areas with large natural variations of methane concentration, it can lead to false alarms or low sensitivity. Methane detection can be impacted by sea currents which either draw methane leaks towards or away from the sensor. Therefore, methane sniffers cannot detect methane that does not come into direct contact with the sensor.

The following technologies use this type of sensor: *Franatech (Mobile laser-based hydrocarbon sniffer and Hydrocarbon Leak Detector)* and *SubCtech OceanXpert Sea IR-CH₄*.

Passive acoustic

Passive acoustic sensors are similar to what is commonly known as hydrophones. They continuously “listen” to their underwater surroundings. When a leak occurs, the pressure-drop from the high-pressure pipeline into the lower pressure water makes noise that can be detected by the sensor. It can be used as a stationary sensor at key points in facilities or deployed on an ROV or AUV for leak detection over larger areas.

The following technologies use this type of sensor: *Co.l.mar Acoustic Leak Detector* and *Naxys Acoustic Leak Detector*.

Capacitance sensors

Capacitance sensors are point sensors that measure the change in the dielectric constant of the medium surrounding the sensor. The sensor is formed by two concentric, capacitor plates in the same plane. The capacitance of the sensor is directly proportional to the dielectric constant of the medium between the plates, and contact with methane will be noted by a change in the measured capacitance by the sensor.

The following technologies use this type of sensor: *Franatech METS Methane sensor*.

Multi Beam Echo Sounder (MBES)

Multi Beam Echo Sounder sensors are acoustic sensors, installed on surface vessels that allows the mapping of the seabed. The principle is very simple: an acoustic wave is sent in the direction of the seabed, where it will be reflected and sent back to the vessel. By measuring the time needed for a sound wave to go back and forth between the vessel and the seabed and knowing the speed of sound propagation, it is possible to determine the depth. By sending the wave in several directions, it is possible to determine the depth of swath instead of a single point. For the detection of hydrocarbon leaks the principle remains the same: if the calculated depth is shallower than the one expected, it means that there is something in the water column, that may be a gas or oil plume. Algorithms have also been developed that perform well in rough bathymetry and can differentiate non-static distortions like large fish shoals or diving mammals. No datasheet provided as we were not able to contact any provider.

Technology Development Stage

Technology development stage are defined based on a Technology Readiness Level (TRL) from API 17N¹¹. The following levels and descriptions are directly copied and referenced from this source as follows:

TRL 0: Concept- Basic scientific/engineering principles observed and reported; paper concept; no analysis or testing completed no design history.

TRL 1: Technology concept and/or application formulated b) Concept and functionality proven by analysis or reference to features common with/to existing technology c) No design history; essentially a paper study not involving physical models but may include R&D experimentation.

TRL 2: Concept design or novel features of design is validated by a physical model, a system mock-up or dummy and functionally tested in a laboratory environment; no design history; no environmental tests; materials testing, and reliability testing is performed on key parts or components in a testing laboratory prior to prototype construction

TRL 3: Item prototype is built and put through (generic) functional and performance tests; reliability tests are performed including reliability growth tests, accelerated life tests and robust design development test program in relevant laboratory testing environments; tests are carried out without integration into a broader

¹¹ [API 17N - Recommended Practice on Subsea Production System Reliability, Technical Risk, and Integrity Management](#)

system b) The extent to which application requirements are met are assessed and potential benefits and risks are demonstrated.

TRL 4: Meets all Requirements of TRL 3; designed and built as production unit (or full-scale prototype) and put through its qualification program in simulated environment (e.g., hyperbaric chamber to simulate pressure) or actual intended environment (e.g., subsea environment) but not installed or operating; reliability testing limited to demonstrating that prototype function and performance criteria can be met in the intended operating condition and external environment.

TRL 5: Meets all the requirements of TRL 4; designed and built as production unit (or full-scale prototype) and integrated into intended operating system with full interface and functional test but outside the intended field environment.

TRL 6: Meets all the requirements of TRL 5; production unit (or full - scale prototype) built and integrated into intended operating system; full interface and function test program performed in the intended (or closely simulated) environment and operated for less than three years; at TRL 6 new technology equipment might require additional support for the first 12 to 18 months.

TRL 7: Production unit integrated into the intended operating system, installed, and operating for more than three years with acceptable reliability, demonstrating low risk of early life failures in the field.

Business Model

Technology and service providers generally offer two main business models:

- Instruments are purchased and used by the operator's staff.
- Technologies are offered as a data product, whereby the technology is deployed or installed by the technology provider, who subsequently provides data analysis / reports.

Some technologies can be deployed using either business models, while others are only available under one of these two arrangements. A hybrid model may also be possible, including as a bespoke product. Turnaround times and specific services offered can vary significantly and have been documented in the Data Sheets when known.

Frequency of technology deployment

Technologies have been classified as one of the following:

- **Continuous monitoring:** This could be at any detection level (site, equipment or detection level), where the technology is continuously monitoring for methane. It should be noted that continuous monitoring can be affected by gaps in network connectivity or environmental conditions, leading to occasional gaps due to downtime of the system.
- **Periodic monitoring:** This relates to technologies such as ROV, AUV or other periodically performed methane measurement campaigns. Such technologies may require the operator's or provider's assistance in deployment. The actual frequency of deployment is then selected by the operator.

Sampling frequency during operation

During measurements, technologies may take samples at different time frequencies, for example more than every second, every minute, every 10 minutes etc, and can be useful information to understand how "continuous" a methane sensor is. This section will provide further information regarding the sampling frequency of a technology while it is deployed.

Requires access to site

Some technologies may require site access to perform e.g., periodic measurements around site equipment. Otherwise, site access may also be required for installation or deployment, e.g., a permanently installed sensor on a fixture that requires placement and setup. Permits may be required for some of these technologies. Other technologies can be deployed without access to the site, for example if they are remotely operated at sufficient distance from equipment. Possible responses in the Data Sheets are as follows:

- **Yes:** Site access is required for deployment or installation
- **No:** Site access is not required for deployment or installation

Operating Regions

For some technologies, providers may not have availability in all areas, due to international restrictions, lack of demand or limited personnel availability. This section of the Data Sheet covers specific areas where the technology is currently deployed or is available for use or purchase.

Potential to cover multiple sites per deployment

Some technologies can monitor and provide measurements for multiple sites or templates per deployment, which can depend on proximities from one another. This could be advantageous for the operator when, for example, performing measurements of emissions for multiple templates which are located close together, and save on e.g., operational expenses. Choices in the Filtering Tool for this factor are:

- **Yes:** The technology would be able to monitor multiple sites per deployment.
- **No:** The technology would not be able to monitor multiple sites per deployment.

Operational Since

This section of the Data Sheet presents the age of the technology. While technologies may change and improve over time, and a separate section of TRL is available and described above, this section provides an indication of the technology provider experience.

2.2 Detection

Detection is the process of identification of methane emissions from potential sources by providing a concentration level (e.g., ppmv), without the measurement of the mass quantity (e.g., flow rate in kg/h).¹²

Components Detected

Where possible, detected components are listed here. While the focus of this report is on methane, some technologies are able to detect methane, other hydrocarbons, oil, condensates or dual-phase mediums that are listed in this section.

Applicable medium

This section will list the applicable mediums that the technology will work in, and can include seawater, brine, or freshwater.

Detection Level

Detection level of a technology is split into multiple categories, described below.

¹² Adapted from <https://www.ipieca.org/resources/awareness-briefing/methane-emissions-glossary/>

Detection at site level: This criterion captures whether a technology is suitable for detecting emissions at the level of a site. In this context, a site may be classified as a group of linked equipment, such as a subsea template that could include e.g., production controls, manifolds, risers or umbilicals. It could also refer to several jumpers or sections of pipelines.

The detection threshold plays an important role in the selection of site-level technology. In addition to site attribution, a particular technology may or may not be able to attribute emissions to specific pieces of equipment or components. Note, however, that certain technologies that are used to detect emissions at the equipment or component level may not be applicable for site-level detection. This may be the case, for example, if the technology is not able to visualize methane plumes. Such technologies would be used more appropriately to identify specific pieces of equipment or components as a follow up to the use of suitable site-level technology.

Given the variability of cases and on-site experience reported by operators, the following classification has been used for the ability of a technology to detect and quantify site-level methane emissions:

- **Yes:** The technology can accurately and reliably detect emissions at site level.
- **Maybe:** The technology may be able to detect emissions at the overall site level, but it may be challenging to assess the entire site if very large, or if multiple sites are closely spaced, and it may be difficult to identify the source of the plume from one site to another.
- **No:** The technology is not appropriate for detecting emissions at site level.

Detection at equipment level: This criterion captures whether a technology can detect the presence of an emission source and attribute it to a specific piece of equipment. The technology may be able to attribute emissions to a specific piece of equipment at a site, for example a manifold or a wellhead, but might not be able to attribute the emissions further to the precise emitting component.

Given the variability of cases and of on-site experience reported by operators, the following classification has been used:

- **Yes:** The technology can detect emissions at equipment level, and accurately attribute emissions to them reliably and consistently.
- **Maybe:** The technology may be able to detect spatially isolated equipment sources, but it may be challenging to attribute emissions reliably and consistently to all equipment sources in all scenarios, for example when many sources are located close together.
- **No:** The technology does not have the right level of resolution to detect emissions at the equipment level.

Detection at component level: This criterion captures whether a technology can detect the presence of an emission source and attribute it to a specific component of a piece of equipment, for example a flange on a separator.

The main purpose of detecting methane emissions at component level is to identify leaking or malfunctioning components, typically in the context of a leak detection and repair (LDAR) campaign, where the goal would be to both identify emitting components and to ensure successful mitigation. (Some inventory methodologies simply require the operator to determine the number of leaking and non-leaking components to estimate fugitive methane emissions.)

A particular technology may be able to detect emissions from large, relatively isolated components (e.g., large pipeline flange), but prove less reliable in the case of equipment with large numbers of closely placed components. In these circumstances, the technology in question would not be considered a component-level detection technology.

Given the variability of cases and of on-site experience reported by operators, the following classification has been used:

- **Yes:** The technology can detect emissions at component level, and accurately attribute emissions to them reliably and consistently.
- **Maybe:** The technology may be able to detect components emitting, but it may be challenging to attribute emissions reliably and consistently to all component levels in all scenarios, for example when many sources are located close together.
- **No:** The technology can, for example, detect emissions at equipment level, but does not necessarily have the right resolution to detect emissions from specific components of that equipment.

Detection Threshold/Precision – Natural and Anthropogenic Sources – Methane

Detection threshold is the minimum amount of methane that is reliably detectable by the technology.¹³ While the detection threshold can be presented in several forms (e.g., concentration, concentration vs distance, volume emission rate, mass emission rate), detection thresholds in this report are stated in g/h where possible. Detection threshold of natural and anthropogenic sources is the minimum amount of methane detectable without differentiating between sources (i.e., if methane is the result of natural seepage or emitted from oil and gas infrastructure).

It should be noted that the detection threshold is typically a function of the distance between the emission source and the detection technology, as well as a function of the environmental conditions at the time, notably including background ambient noise (in the case of acoustic sensing methods) or sea conditions at the point of measurement, which, for example, may move the bubble column away from a sensor (in the case of an in-situ measurement technology). In most cases, the detection thresholds mentioned in the Technology Data Sheets are provided by the technology provider and may or may not have been validated by a third party. The validation status and the source of this information is presented in the Data Sheets. Where available, the applicable environmental conditions for the detection threshold are noted.

Since the performance of some technologies can vary significantly, depending on many different parameters, review of this criterion should be done in conjunction with careful review of validation status and other criteria provided in the Data Sheets. This criterion classifies the detection threshold and precision of a technology for detecting methane from both natural seepages of methane from the seabed floor, and from anthropogenic sources from oil and gas infrastructure.

Detection Threshold/Precision – Anthropogenic Sources – Methane

Similar to the detection threshold and precision of both anthropogenic and natural sources of methane, this criterion classifies the detection threshold and precision of a technology for detecting methane from anthropogenic sources from oil and gas infrastructure, while *differentiating* it from natural seepages of methane from the seabed floor. This criterion is of particular importance for an operator as they will be able to attribute which emissions are sources associated with operated assets, and which are naturally occurring.

Detection Threshold/Precision – Anthropogenic Sources -. Other Components

For technologies that may not be methane-specific, the detection threshold and precision of other components will also be listed in this section, for example oil, condensates, or multi-phase emissions, where applicable.

Detection Threshold validation

There is currently no international standard to measure and compare the performance of methane detection and quantification technologies. In order to improve transparency regarding existing third-party validation of technologies reviewed as part of this project, technologies have been assessed against several types of

¹³ IPIECA. *Methane Emissions Glossary*. <https://www.ipieca.org/resources/awareness-briefing/methane-emissions-glossary/>. Accessed Feb 23, 2023.

validation. This criterion may be especially useful for operators who are not planning to perform internal technology validation.

Detection threshold validation may be described using probability of detection (PoD) curves based on emission rates, environmental aspects, such as ambient noise, and distances of measurement technology from the source, all of which can have an impact on performance. Robust, parameterised, and publicly available analyses of performance increase transparency regarding the abilities of technologies. Technologies that have published results for these parameters offer a more reliable indication of performance than those for which results are not publicly available.

Probabilities of detection and quantification are ideally based on fully blind test results and consider sensor performance as well as environmental variables that can affect measurements, offering the closest conditions to those of field operation. For the purposes of this project, “validation” means that tests have been conducted with publicly available results; it does not necessarily mean that the tests found that the technology performed “as advertised”. Note that the validation criterion is completely independent from the performance criteria. Four different technology validation options are available in the Data Sheets:

Validated by independent academic researchers: The information comes from a peer-reviewed paper prepared by independent academic researchers and may also include the results from either fully or partially blind testing (see below).

Validated by fully blind tests performed with third parts (e.g.: operator, academia): Validation can be done using fully blinded tests performed with a third party such as academics, independent researchers or by oil and gas operators. For fully blind tests, both the size and presence of the controlled test release(s) were unknown to the technology provider at the time of the test. This is the closest approximation of field conditions, with the least amount of inherent bias.

Validated by partially blind tests performed with third parts (e.g.: operator, academia): Validation can also be done using partially blinded tests performed with a third party such as academics, independent researchers or by oil and gas operators. For partially blind tests, the technology provider was aware that controlled release testing was taking place but was unaware of the size or location of the release. Partially blind tests offer improved validation of technology performance over scenarios where the emission source size was known, but may still introduce bias, e.g. the operator may have taken more proactive steps than they normally would have done to detect or quantify emissions.

In-house testing: Tests may have been performed by the technology provider, either in the lab or at a subsea facility, with the presence and size of the emission source either known or unknown to the technology operator. Care should be taken when considering the conditions under which in-house testing took place, since these may not always reflect field conditions. For the purposes of this document, technologies are considered “not validated” if they have only undergone in-house testing. Technologies are also considered “not validated” if test results are not publicly available. For some technologies, testing already may have been performed, but the results not yet made public. Information about such cases, where known, are indicated in the Data Sheets. However, the technology will still be considered “not validated” for the purposes of this report, since the results were not yet publicly available at the time of publication. For some technologies, some validation may have been performed, but there are no plans to make the results public. In such cases, the technology has been classified as “not validated”, even if the results of such validation were communicated orally. This does not imply anything regarding performance, but only the validation of performance.

Not applicable for this technology: Applicable filter for technologies that can either perform detection or quantification. For example, some technologies only allow to detect methane but not to quantify it, in which case verification of quantification performance is not relevant.

Where relevant, information in the Data Sheets is provided regarding the layout of the testing site, environmental conditions, and limitations of the validation performed. The user should carefully consider the

test conditions and setup relative to those in which the technology is likely to be. For example, tests performed in shallow water depths with a single point emission source may not be relevant if the operator intends to use the technology in deep water with multiple, small sources in a complex facility layout. Validation of detection and quantification thresholds refers to the ability of the technology to correctly detect / quantify the smallest amount of methane that is claimed by the technology provider. Probabilities of detection and quantification are ideally based on fully blind test results and consider sensor performance as well as environmental variables that can affect measurements, offering the closest conditions to those of field operation.

Independent assessment on false positives

Another aspect of leak detection systems is the need for reducing unwanted warnings, or false positive detections. False positives are reports of methane detections in cases where no methane emissions occurred. False positives may lead to unnecessary follow-up and to alarm fatigue and are often generated due to natural seepage of hydrocarbons from the seabed, or high background noise from process equipment. Tests that have been conducted for false positives are reported in the Data Sheets where available. The options for validation of false positives are:

- **Yes:** Assessment of false positives are available
- **No:** Assessment of false positives are not available

Possibility to distinguish anthropogenic from natural seepage/leakages

Similar to the detection threshold and precision of both anthropogenic and natural sources of methane, this criterion classifies the detection threshold and precision of a technology for detecting methane from anthropogenic sources from oil and gas infrastructure, while differentiating it from natural seepages of methane from the seabed floor. This criterion is of particular importance for an operator as they will be able to attribute which emissions are sources associated with operated assets, and which are naturally occurring. The following options are available:

- **Yes:** The technology can accurately and consistently distinguish anthropogenic methane emissions from natural seepages in the event both sources of methane are present in an area.
- **No:** The technology is not able to distinguish anthropogenic methane emissions accurately or reliably from natural seepages in the event both sources of methane are present in an area.

2.3 Quantification

Quantification varies from detection in that it determines an emission rate, such as mass per time (e.g., g/h) or volume per time (e.g., m³/min), rather than detects the presence or absence of methane (and provides e.g., a concentration in ppmv). Quantification can be done directly through measurement of the emissions, or indirectly through estimations, calculations, and modelling based on measured parameters.¹⁴

Quantification Level

At site level:

This criterion captures whether a technology can provide information on the total emission rate for a specific site or facility. The technology may be able to identify several large sources within a site but may not necessarily have the ability to attribute emissions on a more granular scale, e.g., to specific pieces of equipment. Given the variability of cases and of on-site experience reported by operators, the following classification has been used:

¹⁴ Adapted from <https://www.ipieca.org/resources/awareness-briefing/methane-emissions-glossary/>

- **Yes:** The technology can quantify emissions at the site level. (An important caveat is that, depending on sensor placement, detection thresholds, and monitoring and emission frequency, some technologies will not necessarily be able to confirm that total emissions are quantified at a site level, e.g. some areas of the site might not be considered in the quantification.)
- **Maybe:** The technology may be able to detect emissions at the overall site level, but it may be challenging to assess the entire site if very large, or if multiple sites are closely spaced, and difficult to identify the source of the plume from one site to another.
- **No:** The technology cannot quantify emissions at site level reliably and consistently.

At equipment level:

This criterion captures whether a technology can provide information on the total emission rate for a piece of equipment, such as a wellhead or manifold.

Given the variability of cases and of on-site experience reported by operators, the following classification has been used:

- **Yes:** The technology can quantify emissions reliably and consistently at the equipment level.
- **Maybe:** The technology may be able to quantify spatially isolated equipment sources, but may not be able to attribute emissions reliably and consistently to specific equipment sources in all scenarios, e.g. when many sources are located close together or there are multiple plumes present.
- **No:** The technology may be able to quantify emissions at a more granular scale than site level but is not able to quantify emissions reliably and consistently from a single piece of equipment or equipment group; it would therefore not be considered an equipment-level quantification technology.

At component level:

This criterion captures whether a technology can provide information on the total emission rate at the component level, for example, from an individual flange on a separator.

In some cases, for example leaks, it will be necessary to first detect the emitting components before quantifying the volume of their emissions. For other components, prior detection may not be required since emissions are already known to be present, e.g., in the case of equipment that vents methane by design.

Component-level quantification technologies allow the operator to determine the volume of vented emissions more accurately, as such emissions can vary widely, over time or between similar equipment types. Given the variability of cases and of on-site experience reported by operators, the following classification has been used:

- **Yes:** The technology can quantify emissions at component level and accurately attribute emissions to them reliably and consistently.
- **No:** While the technology may be able to quantify emissions at equipment level, it does not have the correct resolution to quantify emissions from specific components. Similarly, a technology may be able to quantify emissions from large components (for example a thief hatch on a storage tank), but not from equipment with several components placed closely together; in such circumstances it would not be considered a component-level quantification technology.

Quantification threshold similar or above detection threshold

Once emissions are detected, it is often important to quantify them. Quantification provides the emission rate (e.g. as a mass rate such as g/h, or a volumetric rate such as m³/h) and uses the emission duration to estimate total emissions. Quantification methods often involve measuring methane concentrations in flows of gases or ambient air but could also include a wide variety of other measurements, calculations, and modelling. For some technologies, the quantification threshold will be the same as the detection threshold.

In some cases, however, quantification can only be done at a threshold higher than the detection threshold. Options available are:

- **Similar:** The quantification threshold will be the similar to the detection threshold.
- **Above:** The quantification threshold will be the above the detection threshold.

Quantification Performance – Methane

This section will detail performance of technologies to quantify methane. Where possible, quantification will be specified in relation of distance from the measuring technology to the leaking source.

Quantification Performance – Other components

This section will detail technology performance to quantify other non-methane components. Where possible, quantification will be specified in relation of distance from the measuring technology to the leaking source.

Quantification performance validation

Validation of detection and quantification thresholds refers to the ability of the technology to correctly quantify the smallest amount of methane that is claimed by the technology provider. The options for validation of detection and quantification thresholds are those indicated above in section “Detection Threshold validation”. For technologies that may not be methane-specific, the detection threshold and precision of other components will also be listed in this section, for example oil, condensates or multi-phase emissions, where applicable.

Uncertainty on quantification

Many factors can affect the ability of a particular technology to detect or quantify methane emissions. Therefore, technology providers that have published PoD curves typically provide a detection sensitivity at a specified emission rate with a certain probability, either under typical operational conditions or, for example, in terms of distance from the source to the measurement technology. Providing this type of information helps users better understand the performance of the technology. Where available, more details on the technology’s quantification performance are presented in the relevant Data Sheets.

2.4 Environmental conditions

Max water depth (m) and impact on uncertainty

Uncertainty of methane conversion to carbon dioxide with transport time increases with water depth. It can be challenging to estimate how much methane is released to atmosphere, and how much is degraded through natural processes, as various environmental parameters affect this process. More information on the mechanisms that could impact methane emissions to atmosphere can be found in section 0. This section documents whether the water depth is considered in determining the amount of methane that reaches the surface as a function of water depth.

Impact of Sea conditions (Tidal currents, oceanic characteristics etc.)

This section provides further details on potential sea conditions and variations, along with how this may affect the detection or quantification of subsea methane emissions using a relevant technology. The section reflects results from interviews with providers and operators with experience using the technology, however there may be other conditions not covered which could be relevant to the technology. Therefore, the details in this section should not be considered comprehensive, as conditions may vary on a case-by-case basis.

Impact of Sound

This section provides further details on potential impacts of background noise or sound. This section is specifically relevant for acoustic emissions measurement technologies and may not be relevant for all technologies.

Other environmental constraints

This section covers other environmental constraints that may impact the performance of a technology, which are not covered by the above sections. Input comes from interviews with technology providers and operators with firsthand experience.

2.5 Deployment characteristics

Time for deployment

There are several factors to consider regarding time for technology deployment. Some technologies may require significant lead time to perform measurements, which may include travel to the site, or having a vessel nearby from which to operate. Additional time must be considered for the technology to be deployed, perform measurements, as well as follow up with any potential data processing and reporting requirements.

Ease of deployment

There are several factors to consider regarding technology deployment. Depending on the safety certifications of the technology, this could, for example, require obtaining hot work permits. In the case of underwater vehicles, additional requirements could include permits, as well as significant coordination on the part of the operator.

Training requirement for operators

Consideration must also be given to any operator training required for deployment. This is likely to be closely associated with the business model of the technology provider. Some technology providers handle everything from installation to post-processing of data or integration into a control room system. In such cases, the operator would receive the estimated emissions data from the technology provider, so minimal training would be required for the staff of the oil and gas operator. On the other hand, some technology providers may train the operator to use their equipment. The training time that is required will vary, depending not only on the equipment but, for example, on staff experience and field/site characteristics.

Power demand and other dependencies

This section provides indications of the power requirements for technologies, which are helpful for both new installations and retrofits, where available power or bandwidth may be limited.

Best works on

This section provides an overview of typical equipment, sites, or potential configurations the technology would appropriately measure subsea methane emissions.

3 General observations from technology review

Figure 2 presents summary information of the technology Data Sheets. Additionally, several points can be drawn from the interviews, as summarized below.

Figure 2 Summary of Technology Data Sheets

Technologies	Sensor Type	Gas Detection?	Gas Quantification?	Methane-specific Quantification?	Threshold	Frequency	Deployment method	Sensor type	Type of sources	Performance Validation	Possible to isolate anthropogenic methane	Maturity (TRL)
SubCtech	Sniffer	✓	✗	✗	10 ppm CH ₄					✗	✗	3
Franatech METS	Capacitance	✓	✓	✗	0.01L/min CH ₄ †					✓	+	7
Franatech LMS	Sniffer	✓	✓	✗	0.01L/min CH ₄ †					✓	+	7
Franatech HLD	Sniffer	✓	✓	✗	0.01L/min CH ₄ †					✗	✓	7
Metas	Active Acoustic	✓	✓	✗	42g/h @200m range (100% CH ₄)					✓	✗	6
Naxys SALD	Passive Acoustic	✓	✗	✗	N/A					✓	✗	7
Naxys SLLD	Active Acoustic	✓	✓	✗	N/A					✗	✗	6
Wavefront Sentry IMS	Active Acoustic	✓	✓	✗	0.1L/min at 500m range					✗	+	6
Wavefront Sostice MAS	Active Acoustic	✓	✓	✗	1L/min at 100m range					✗	+	6
Colmar	Passive Acoustic	✓	✓	✗	0.1 L/min					✗	+	7
Volume Collection	Funnel	✓	✓	✗	<0.1 L/min					✗	+	NA
Key Threshold: Lowest value stated by tech providers Frequency Continuous Periodic Deployment Method Permanent Installation ROV/AUV Diver Vessel Deployed Sensor Type Point Sensor Area coverage Type of sources Site Level Yes Equipment Level No Component Level Performance validation (of any kind with publicly available information) Yes No Possible to isolate anthropogenic methane Yes Yes, with auxiliary information No Maturity API 17N 1 — 7 † Franatech detection limits based on proprietary software (not yet available)												

- **Subsea detection and quantification technologies are limited**

11 Data Sheets for detection and quantification technologies from 6 technology providers were created. A further three technologies were identified as potential technologies. Unfortunately, it was determined that the amount of obtainable information from publicly available data was not sufficient to provide a useful overview to develop Data Sheets from alone. Therefore, technologies from providers that did not respond to interview requests were not included in the Data Sheets.

- **Few methane specific technologies are currently available.**

Of the 11 Data Sheets, only 4 Data Sheets were produced for technologies for methane detection specifically (from two technology providers). To clarify, quantification technologies for subsea leaks do exist but will quantify *total* emissions that does not differentiate between methane from hydrocarbon gases, or hydrocarbon gases from oil/condensates. While several technologies may be able to detect oil or hydrocarbon gas, they would not be able to determine the amount of methane gas in the leak, and would require additional, auxiliary information such as methane content of the volume through top-side evaluation of methane content using gas chromatography, isotopic sampling or other techniques. Furthermore, no technologies were identified for methane quantification specifically, where methane emissions can be determined as a mass or volumetric emission rate. The impact of these factors may be reduced by incorporating other information from a leak detection system (e.g., process SCADA, calculated gas oil ratio (GOR) and methane content of natural gas through top-side analysis using gas chromatography or other methods) – see Section 4.3 for more information. The number of technologies is limited for subsea methane leak detection and quantification, specifically when compared to onshore/ambient air methane detection and quantification (refer to technologies tested at METEC¹⁵ or technologies applicable for MiQ certification¹⁶, where dozens of technologies are commercially available).

- **Difficulty to determine minimum detection thresholds**

During interviews, some technology providers had difficulties in presenting a value for lower detection limit to include in the Data Sheets. Beyond the limitation of determining a methane-specific leak rate, the lower detection limit of a leaking medium (i.e., not methane specific natural gas, oil, or a two-phase leak), is variable. While a technology might be effective if a leak is very close to the sensor, capabilities will be reduced with increased distance. For some technologies, favorable conditions where gas plume reaches sensor will provide excellent results, but when the current shifts and draws the leak away from a sensor, it might be unable to detect the plume. Some technology providers also stated that they would produce a performance assessment following installation to evaluate the technology, in-situ. This can be on a case-by-case scenario, based on both present infrastructure and environmental conditions, such as ambient sound. This challenge may also be alleviated by e.g., sensor placement near high-probability leak points, or combinations of technologies.

- **No verification with third party testing**

Currently, there are no protocols or standards to i) robustly test and ii) report performance of subsea methane detection and quantification technologies in a consistent format, which results in challenges to compare and deploy different technologies. Compared to onshore and ambient air methane detection and quantification technologies, where multiple blinded evaluations of technologies have been performed that determine lower detection limits, assessment of false positives and quantification performance^{17,18,19}, subsea methane technologies have not undergone

¹⁵ <https://energy.colostate.edu/metec/leak-detection-and-quantification-solutions/>

¹⁶ <https://miq.org/methane-tech-providers/>

¹⁷ Bell C, Ilonze C, Duggan A, Zimmerle D. Performance of continuous emission monitoring solutions under single-blind controlled testing protocol. ChemRxiv. Cambridge: Cambridge Open Engage; 2023; This content is a preprint and has not been peer-reviewed.

¹⁸ Conrad, B. M., Tyner, D. R., & Johnson, M. R. (2023). Robust probabilities of detection and quantification uncertainty for aerial methane detection: Examples for three airborne technologies. *Remote Sensing of Environment*, 288, 113499. <https://doi.org/10.1016/j.rse.2023.113499>

¹⁹ Sherwin, E.D., Rutherford, J.S., Chen, Y. *et al.* Single-blind validation of space-based point-source detection and quantification of onshore methane emissions. *Sci Rep* 13, 3836 (2023). <https://doi.org/10.1038/s41598-023-30761-2>

extensive verification with third party testing. Many of the technologies have been used in industry trials that are not publicly available, or research articles that were used for specific purposes that may not test the accuracy, uncertainty, or lower detection thresholds of the technologies against a known reference in e.g., controlled release testing. Where possible, testing with third parties was noted in the Data Sheets, but identifying verification with third party testing in blinded evaluations that was publicly available proved to be a challenge for this report.

- **Potential for technology combinations**

The use of proactive leak detection, quantification and repair may have significant resource requirements for mobile deployment methods. To consistently deploy these technologies requires a support vessel that will transport, for example a diver or ROV between oil and gas installations to access infrastructure. In interviews with operators in the NCS, technologies for detection and quantification of methane from subsea oil and gas infrastructure are often incorporated in a risk-based approach to detect, quantify, and repair leaks as necessary. This could involve the deployment of permanently installed technologies to provide a larger-scale monitoring program that includes other components of a leak detection system such as mass balance methods or periodic surface inspections. This is illustrated and described in more detail through case studies presented in Section 4.4.

4 Cross-cutting elements

When considering the impact of the oil and gas activities offshore and especially the impact of accidents and leaks that can occur, one must consider the fate of the methane emitted subsea. Onshore, all methane that escapes from leaks or that is deliberately released through venting or flaring will contribute to the greenhouse effect, leading to global warming. Subsea, the situation is rather different. When a leak occurs, the methane is emitted at depths ranging from less than one hundred meters to thousands of meters, in seawater, an element that will interact with methane molecules. To fully understand the impact on the environment of methane emissions underwater, it is necessary to consider specificities of the marine environment, including natural methane seepage from the seabed and marine chemistry. Note that only methane will be addressed in this section, as the presence of other toxic molecules or pollutant components is not considered. Other cross-cutting elements will be developed after that to address all aspects of underwater methane leak detection.

4.1 Elements of subsea methane emissions

Natural methane emissions²⁰

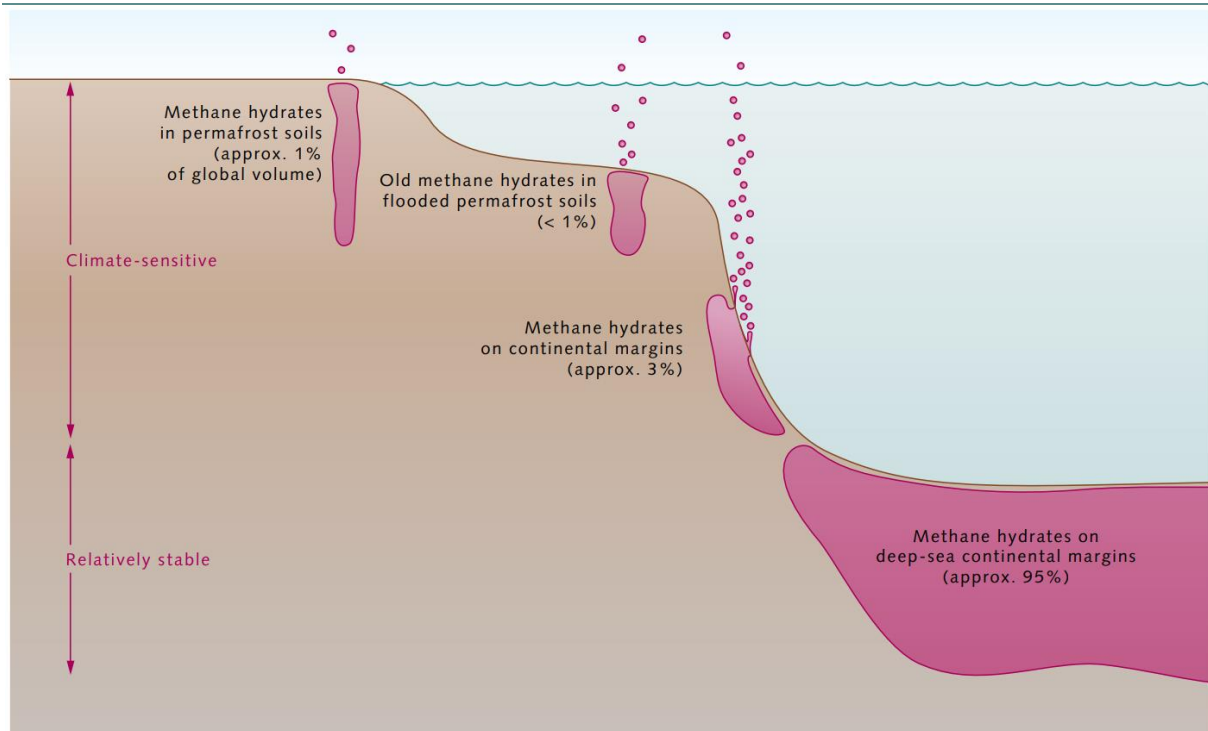
This report is focused on underwater methane emissions from subsea oil and gas infrastructure. However, those emissions are not the only ones that are emitted below the water surface, as methane can also be naturally released from the seabed. Natural seeps are non-negligible and can have a great impact on the ability to detect emissions from the operation's facilities. They are mentioned in the sensor part of this report (see Section 2.), as the fluctuation of methane concentration in the water can lead to false leak alarm or adversely impact the leak detection threshold.

The greatest possible source of natural methane from the seabed is due to the thawing of methane hydrates. Methane hydrates have the appearance of ice but are in fact methane molecules trapped in a network of water molecules. It is estimated that 10 times more methane is contained in methane hydrates than in conventional gas fields. Methane hydrates naturally develop in areas where sufficient methane is present, and in extreme conditions of high pressure and/or low temperature. These conditions are typically encountered in the frozen lands of the far north (e.g., Russia, Canada), also known as permafrost and the

²⁰ World Ocean Review 3: Marine Resources, chapter 3: Energy from burning ice; Sintef, Report: Methane seeps, a desktop study, Tor Nordam, Anusha L. Dissanayake, Odd Gunnar Brakstad.

underwater soil at great depth. Recent changes in climate put their stability at risk, especially in medium depths areas such as continental margins. When their stability is compromised, methane hydrates will thaw and release the methane they contain. When in the vicinity of the offshore oil and gas facilities, this can interfere with measurements by increasing the background methane concentration in the water and altering the water chemistry.

Figure 3 Presence of methane hydrates in the seabed²¹



The methane contained in the hydrates comes mainly from microbial degradation of organic matter. Biomass that come from dead planktonic organisms sink from the upper layer of the ocean towards the seabed, forming sediments. In this high-pressure environment, methanogenic bacteria are found, which destroy this biomass, emitting methane. More than 80% of the methane stocked in hydrates was produced this way.

Methane can also be found in gaseous form in shallow geological layers. These deposits are generally not exploited due to poor gas quality and the presence of impurities such as water, carbon dioxide or sulphur. The gas in these deposits may come from biogenic degradation of sedimentary layers rich in organic materials, or from leakages from deeper gas deposits, which are captured in shallower permeable and porous rocks. These deposits are normally stable, but some may be over-pressured, and a disruption of their stability by seismic activity in the vicinity of faults or by the exploitation of conventional offshore oil and gas deposits, mainly in the drilling phase, can lead to gas drop-out. If such events occur, large amounts of methane can be released in the vicinity of a rig.^{22,23}

Numerous natural methane emissions points from the thawing of hydrates have been detected and analysed, and the literature is extensive on this subject in the North Sea and off the coast of Svalbard. The order of magnitude of these natural leaks can be of tens of tons per year over surfaces of several km².

²¹ World Ocean Review 3: Marine Resources, chapter 3: Energy from burning ice

²² DrillingFormulas.com: Introduction to shallow gas well control (<https://www.drillingformulas.com/introduction-to-shallow-gas-well-control/>)

²³ Baird Petrophysical International: Shallow gas & near surface; there are only 6 hazards. By Ralph W. Baird (https://www.bairdpetro.com/shallow_gas.htm)

Evolution of methane bubbles in the water column²⁴

Methane is emitted from the seabed or from oil and gas facilities in the form of bubbles. A methane bubble is less dense than seawater, therefore it will move up through the water column, increasing in size due to the pressure reduction with height. Being in contact with seawater during its ascent, the methane will react and dissolve in the water. Those interactions only take place at the contact surface between the gas and the water, so only a small portion of the gas reacts at a given time. Despite this, there is sufficient contact to allow the methane to progressively dissolve into the water, reducing the size of the bubble as gas escapes (although bubble size increase due to pressure reduction has a larger impact). The methane contained in the bubble can be entirely dissolved, such that no methane will reach the surface directly. If the bubble was large enough when it was emitted, or too many bubbles were emitted, making the water saturated with methane, or methane concentration equilibrium is reached between the bubble and surrounding water, the bubble will reach the surface and the remaining methane it contains will be released into the atmosphere.

Other exchanges between seawater and a bubble can occur on its way up, involving nitrogen and oxygen entering in the bubble and changing the gas composition, so a bubble can reach the atmosphere containing a gas with a lower methane concentration than when it was emitted, or even without methane at all.

The share of methane released from the seabed that reaches the surface directly (i.e., when the bubble breaks the water surface) depends on several factors.

- The depth of the emission point, the longer the journey to reach the atmosphere is and the more methane will have dissolved into the water.
- The initial size of the bubbles and its characteristics (concentration of methane, presence of oil that may “coat” the bubble) are also key factors.
- The water composition and characteristics, such as temperature or its preliminary methane concentration will also have an impact on the dissolution.

The size of the bubbles and the depth of the emission can be measured using an ROV and image processing. The evolution of the bubbles is also a problem well known to physicists and different models have been developed to assess this. Under normal conditions that can be encountered at sea, most of the methane will be dissolved into the water. This can be nuanced if the emission is situated at a very shallow depth (less than 50 meters) or if a large amount of methane is released at once (Nord Stream pipeline rupture can be cited as an example). In these extreme situations, more methane will be released into the atmosphere and further studies might be needed to determine the amount of methane that will be directly released into the atmosphere.

Evolution of methane dissolved in water²⁵

As explained in the previous section, most of the methane initially released will be dissolved in the water column before it to a variable degree may reach the atmosphere.

Dissolved methane interacts with other elements present in the water and follows the water movements such as marine currents. In the long run, there are two possible outcomes for the dissolved methane molecules. They can be biodegraded by bacteria or reach the ocean surface, where they will evaporate to the atmosphere. The biodegraded methane will not have an impact on the atmosphere, but the portion that evaporates will contribute to the greenhouse effect even though this process does not occur instantaneously.

When near the ocean surface, methane molecules will interact with the atmosphere and evaporate. Methane evaporation can be accelerated by the natural water evaporation at the ocean's surface. All methane

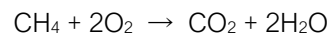
²⁴ World Ocean Review 3: Marine Resources, chapter 3: Energy from burning ice
Sintef, Report: Methane seeps, a desktop study, Tor Nordam, Anusha L. Dissanayake, Odd Gunnar Brakstad.

²⁵ World Ocean Review 3: Marine Resources, chapter 3: Energy from burning ice
World Ocean Review 1: Living with the oceans, chapter 2: How climate change alters ocean chemistry.
Sintef, Report: Methane seeps, a desktop study, Tor Nordam, Anusha L. Dissanayake, Odd Gunnar Brakstad.

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molecules can reach the upper layers if they are not biodegraded, regardless of their depth, due to the vertical turbulent mixing of sea water. These water movements are caused by temperature differences depending on water depth and are reinforced at times of strong wind in winter and autumn.

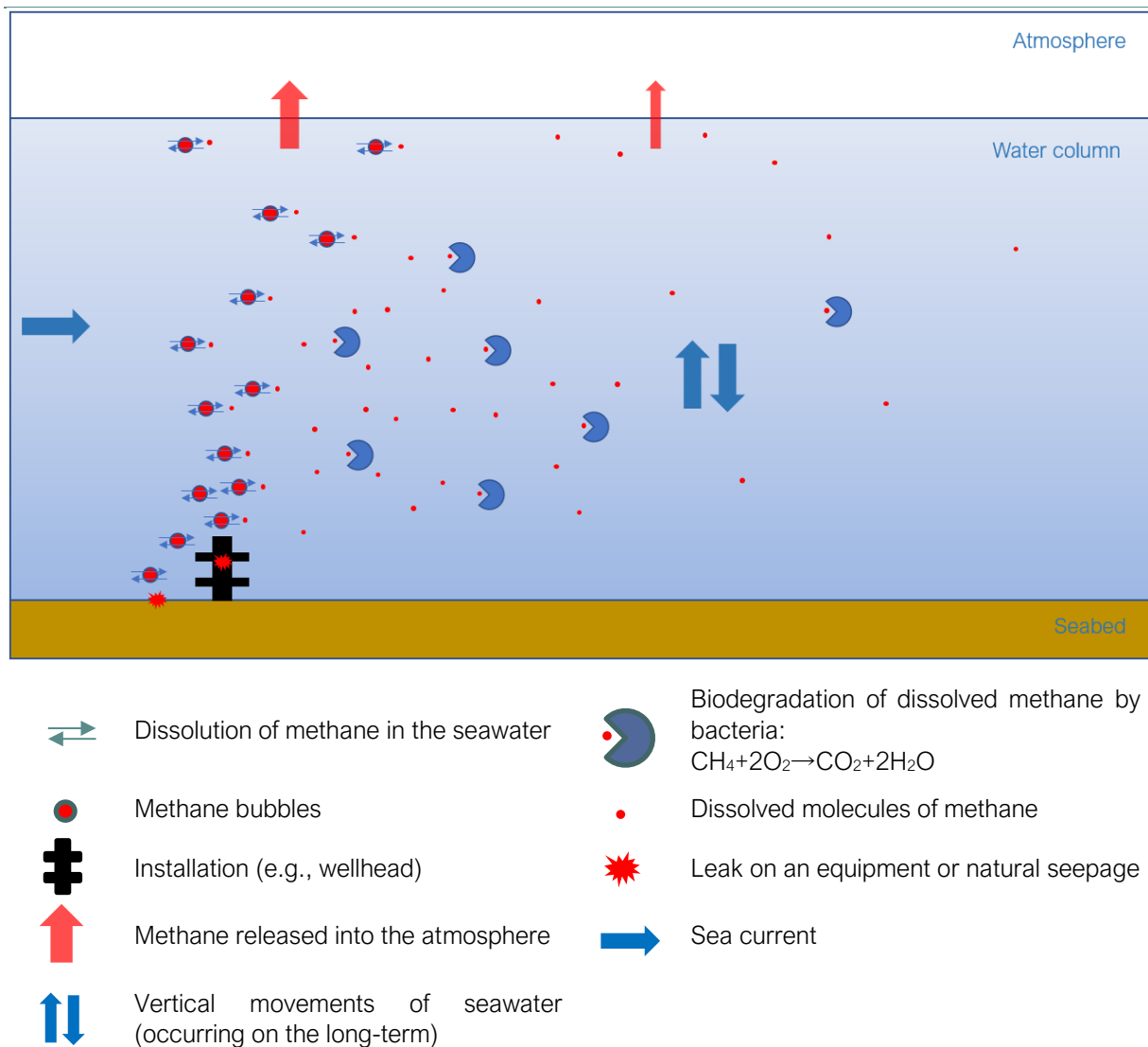
Biodegraded methane can have environmental impacts even if it does not reach the atmosphere. One molecule of methane and two molecules of oxygen react to produce a molecule of carbon dioxide and two molecules of water:



This reaction effectively reduces methane molecules that can be emitted to the atmosphere from underwater seepages, but it can also impact the chemical composition of the water. Oxygen is required for the reaction to take place which lowers, in extreme cases, oxygen concentrations in the water and negatively impacts other organisms such as fish. Furthermore, the production of carbon dioxide will lead to acidification of the ocean, although studies have shown that this acidification is negligible compared to that caused by the interaction with the atmospheric carbon dioxide.

The percentage of methane that is released into the atmosphere at the end of the dissolution cycle depends on how much methane biodegrades and how much methane reaches the upper layer of the ocean. The biodegradation is impacted by the bacteria concentration in the ocean, the amount of oxygen available, the temperature of the water and the natural methane concentration of the water. Therefore, the methane evaporation ratio depends on the geography and the seasons.

A recent study on the Norwegian Continental Shelf showed that for a leak appearing at a depth of 50 meters, 74% of the methane released from the seabed or oil and gas installations reached the atmosphere. When the methane leakage occurs at depths of more than 360 meters, only 2% of the methane reaches the atmosphere.

Figure 4 Fate of subsea methane emissions²⁶:

4.2 Impact of natural methane seepage on measurements

Methane is naturally present in seawater, with different concentrations, depending on the region considered: in nutrient-rich areas, marine life can thrive and increase the amount of methane in the water. Furthermore, methane can be naturally released from the seabed. Methane seeps from the ground as bubbles and rise through the water column. In doing so, it will eventually dissolve, changing the methane concentration of the water. The concentration of methane in water is therefore not uniform in time or space, which can make quantification more challenging.

To detect methane emissions from offshore installations, a sensor that simply measures the evolution of the methane concentration will therefore not be very reliable. To counter the false-alarm risk, the background methane concentration in the surrounding waters must first be measured, to correct the measure when in operation, and measure only the excess methane, that may come from the offshore/subsea facilities. But due to natural seepage and methane concentration evolution in time, false alarms may be triggered anyway. There is therefore a trade-off between accuracy of measurement and alarm reliability. False alarms can lead

²⁶ Photo by Carbon Limits using information adapted from:

World Ocean Review 1: Living with the oceans, chapter 2: How climate change alters ocean chemistry

World Ocean Review 3: Marine Resources, chapter 3: Energy from burning ice

Sintef, Report: Methane seeps, a desktop study, Tor Nordam, Anusha L. Dissanayake, Odd Gunnar Brakstad.

to unnecessary follow-up actions. To avoid false alarms, higher alarm thresholds may be set to a higher level of concentration, causing smaller leaks to remain undetected. It is also possible to integrate additional components of a leak detection system to complement methane detection and quantification technologies (see Section 4.3).

All these actions and choices are to be made by the operators as there are limited recommended practices and regulatory framework. That means that they must test their sensor by simulating a leak on its surroundings to see how it is going to react. They must define the threshold for the alarm triggering and define the procedure that operational staff will follow once the alarm is triggered. In the control room, a lot of information is processed. Without a procedure to follow, the alarm leak will likely be ignored by the staff, and even more so if they do not trust the system (because it wasn't test properly, or because there is a high probability of false alarms).

In practice, it can be very challenging to differentiate methane coming from offshore activities and methane coming from natural seepage without the use of optical cameras or acoustic sensors that map the entire water column. Some companies that have extensive knowledge of the oceans are developing software using machine learning or probabilistic models to interpret sensor results or deploy expert on the field to analyse the data²⁷. However, these solutions are relatively new and continuous improvements are necessary.

4.3 Complementary technologies to Leak Detection Systems

Subsea gas leaks can be detected by e.g., passive, or active acoustics, methane sniffers or capacitive sensors (see *Sensor Type* in Section 2). The size of a bubble can be measured, but the volume of methane contained within the bubble will depend on the other measurable or known parameters such as pressure (water depth), temperature, gas composition, etc. The amount of methane released to the atmosphere is also dependent on water depth, temperature, initial bubble size and water characteristics (see Section 0). To accurately detect and quantify the amount of methane emissions released to the atmosphere, a leak detection or quantification technology requires additional information. No available technologies considered as part of this report were found to incorporate all these aspects. However, additional information such as SCADA, mass balance methods, periodic visual checks, and knowledge of gas composition (either inferred or through measurements using e.g., gas chromatography) can be incorporated with the selected methane detection technology to better understand potential emission sources, atmospheric emission rate, location, patterns, and frequency of leaking sources or assessing for false positives. Throughout discussions with operators, the following complementary technologies to methane leak detection and quantification technologies were identified²⁸.

- **Mass balance:**
 - Measured natural gas flow and pressure values can be compared to simulation models which predict the expected pressure and flow in the case of “no leaks”²⁹. A large deviation between the measured and predicted values can indicate a leak in the system. A limitation of this method is that it is reserved for large emissions (for example, when deviation is over 5% of the total flow), and can be inaccurate when production volumes are fluctuating, and the steady state assumption of the mass balance is not correct, producing difficulties in interpreting the mass balance and the appropriate need for follow up to identify a potential leak.
- **Optical camera:**
 - Optical cameras (video camera) can be used for visual surveillance of a local area of subsea infrastructure. The camera system may be able to detect the presence or absence

²⁷ Most of the companies interviewed for the writing of the datasheet provide this kind of services.

For the software: METAS: <https://metas.no/>

For the expert on the field: Co.I.mar: <https://www.colmaritalia.it/> or Franatech: <https://www.franatech.com/>

²⁸ A more complete list of technologies not specifically mentioned during interviews as part of this overview can be found in DNV-RP-F302. <https://www.dnv.com/oilgas/download/dnv-rp-f302-offshore-leak-detection.html>

²⁹ Area coverage (for example of an entire pipeline system) can be conducted using instrumentation installed in the SPS.

of a leak in a limited area, but additional information may be required to identify a specific source or to quantify a leak. Since cameras are a line-of-sight technique, they are also sensitive to marine growth, water turbidity, pollution, and the available lighting in the area.

- **Optic Fiber:**
 - Another method which may be useful as part of a leak detection system is the use of fibre-optic cable installed along the entire length of a pipeline or structure. Fibre optic cables may be able to sense variations in either temperature or acoustics of an area. One limitation of this method is a limited bend radius of the cable. A trade-off exists between spatial resolution and detection sensitivity.

4.4 Combinations of Technologies

DNV Leak Detection Systems first developed a recommended practices document for offshore leak detection systems (DNV-RP-F302³⁰) in April 2010, and amended in October 2021. The RP document considers planning, design, integration, and operation of leak detection technology in offshore fields for hydrocarbon production, but not specifically for methane. The recommended practices use TRLs based on API 17N (Recommended Practice on Subsea Production System Reliability, Technical Risk, and Integrity Management). Note that the RP considers leaks in general which are the accidental loss or admittance of contents in a hydrocarbon production system content. Leaks may be either liquid (e.g., crude oil) or gas (e.g., methane, or other hydrocarbons). The document does not consider methane specifically. However, the recommended practices provide guidance on the design of leak detection systems, stating that considerations should be made for combining complementary technologies for leak detection. This combination can improve the reliability and range of a leak detection system and complement methane detection and quantification technologies. Combining technologies can compensate for respective weaknesses of individual technologies and enables indication of a leak discovered by one sensor to be confirmed by a similar positive indication from a separate technology. Consideration of several parameters include:

- reliability and performance of the sensors.
- area coverage and using a combination of point sensors and area sensors.
- qualification records of the different sensor techniques.
- data collection capacity and software to compare the output data from the different sensors.
- combination of dedicated leak detection sensors and process sensors such as flow, pressure, and temperature transmitters.
- integration possibilities (i.e., alarm decision, algorithms, and visualization).
- use of a secondary sensor to verify the function of the primary sensor.
- possible interference between the technologies, sensors, and system components.

5 Case studies

Given the relatively immature state of subsea methane detection and quantification technologies (specifically in comparison to ambient air methane monitoring technologies), there is also a need for practical, real-world examples of how they can be implemented. No “one-size-fits-all” technology has yet been identified, since the needs and requirements of operators and the conditions present at facilities need to be considered on a case-by-case basis.

This section presents several real-life examples of selecting methane detection and quantification technologies, showing the selection process and criteria, incorporating into leak detection systems, and

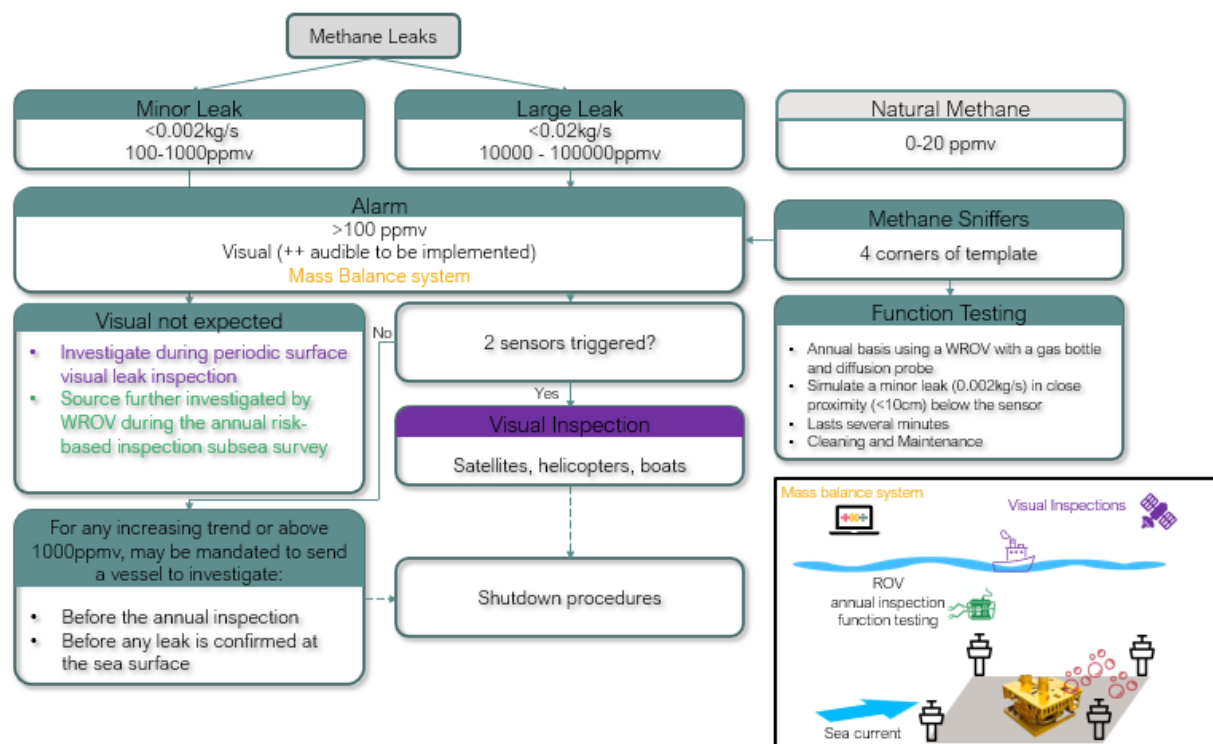
³⁰ <https://www.dnv.com/oilgas/download/dnv-rp-f302-offshore-leak-detection.html>

challenges experienced by the operators. These examples are not intended to serve as guidelines or recommendations, but to share experiences between operators regarding specific situations.

5.1 Methane leak detection as part of a Leak Detection System

One operator implemented a leak detection system at a new subsea template incorporating methane detection technologies, a mass balance system (see Section 4.6) and visual inspections. Leak detection technologies were screened based on potential for integration of the sensors into an existing subsea control system, in addition to seeking experience feedback from other Operators in knowledge-sharing exercises. The selected methane detection technology uses a methane sniffer located at each of the four template corners. The location of the sensors is expected to provide some indication of the location of any potential leakage within or external to the template footprint. In addition, Figure 4 presents how the methane leak detection system is integrated as part of a leak detection system.

Figure 4 Diagram for leak detection system in Case Study 5.1



5.2 Limitations of subsea methane technologies

Several interviewed operators stated they combine a variety of methods to detect leaks from their subsea installations. This, for example, can include mass balance systems, pressure transmitters, radar detection at the surface, and periodic ROV inspections with methane sniffer methods, or optical cameras. From the discussions it appeared that a combination of detection and quantification technologies are used to assess and optimize the need for more thorough inspection and potential repair.

Some operators that were interviewed have implemented inspection maintenance and repair (IMR) programs. This IMR program consists of sending an ROV equipped with an optical camera which will inspect the installations, including pipelines and equipment (manifolds, Christmas trees, etc.) on an annual basis. When a leak is detected during this inspection, the leak rate is estimated by counting the number of bubbles and evaluating their size. If repairs are not required (because the estimated leak rate is too low), the leak is registered and an ROV will be sent to evaluate its evolution every six months.

In cases where leaks are detected through an alarm system, some operators do not react immediately to the signal, depending on the situation. To confirm a leak once an alarm is triggered, operators may wait for:

Leak Confirmation	Limitations
Alarms above a given threshold	Requires: - Alarm thresholds and triggering the control room system are properly set. - Subsequent procedures are in place to handle them (so that alarms are not ignored by staff) - Sensor placement is set up such that it will be able to reliably detect methane leaks. - Close enough in proximity that the leak is identifiable (distance from sensor to leak is a large factor in detection capability of any sensor).
Alarms from multiple sensors are reported	- Will only occur in the event multiple sensors are deployed. - Limitations e.g., in developed fields (retrofits, limited power availability)
Another layer of the leak detection system is triggered	Mass balance system: - Will only occur in the event of a very large leak. Surface Inspection: - Small to medium leaks may not be detectable or reach the surface. ROV/AUV inspection: - Cost - Time requirement - Experienced personnel - Vessel from where the inspection is done (environmental impact) - Frequent false alarms that require vessels may result in higher emissions for deployment than for fixing a small leak or false alarm.

Some operators identified the need for a small footprint technology, low energy requirements, low cost and high accuracy that combines reliable quantification with detection that can be used for reporting requirements, and the design of systems that allow for future sensor integration.

Employing regular deployment mobile-based measurement techniques as a proactive LDAR-like technique may have a non-negligible climate impact, requiring ROV deployment from dedicated vessels to performing proactive LDAR campaigns. It is recommended to evaluate the climate impact of the option.

6 Conclusion

Technologies for detecting and quantifying subsea methane emissions from oil and gas have improved significantly over the last few years and continue to evolve. The aim of this report is to provide an overview of currently available methane detection and quantification technologies for subsea oil and gas operations. For this, a series of Data Sheets were developed in conjunction with this report, to provide a standardized and centralized overview of current capabilities of technologies. Data Sheets were created following interviews with technology providers to detail technology characteristics, strengths, and limitations. Criteria included as part of the Data Sheets are summarized in this report and include technology characteristics, operating and environmental conditions, and other considerations. Findings from the interviews and Data Sheets are summarized in the report. The report and its accompanying Data Sheets have been produced such that no one technology is recommended over others. Rather, they have been developed to provide an overview of technologies such that operators can make an informed decision when selecting based on their unique circumstances and requirements.

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11 technologies and measurement methods were identified for subsea methane leak detection and quantification as part of this report. Reported detection thresholds from providers ranged greatly and are dependent on both water depth and pressure, methane concentration, and distance of detection. For example, detection thresholds may be as low as 0.01L/min CH₄ for in-situ measurements using methane sniffers. Detection thresholds of total gas (i.e., not methane specifically) using remote measurements vary with distance of detection, for example as low as 0.1L/min at 500m to 10L/min at 1000m, or 42g/h at 200m to 1260g/h at 500 m and water depth of 100m for total gas using remote measurements. The amount of methane released to the atmosphere is dependent on bubble size, bubble release depth, methane content of the leaking fluids, and methane degradation. Further complicating factors regardless of the deployed technology including the presence of natural seepage and methane degradation. Technologies are currently available to quantify methane emissions, but require proper setup, placement and coverage that will vary on a case-by-case basis, and at this point require additional, auxiliary equipment in a combined leak detection system. Operators are currently implementing leak detection systems that produce a best-case equivalent which may use multiple layers, while technology providers are investing in research and development activities, and it is expected that along with momentum for greenhouse gas emissions reductions, technology capabilities will further progress. Depending on the frequency, regular proactive deployment, of some of the mobile-deployed techniques (e.g., from vessels) may have a non-negligible climate impact and it is recommended to evaluate the climate impact of these options.

7 Appendix A Methodology and data sources

7.1 Literature review

A thorough review of the literature was performed as a starting point to collect data and information on the performance of available detection and measurement technologies. In addition, technology providers were asked to share case studies, company reports and academic studies in which their technology had been featured. Academic papers most often covered overarching elements of methane detection and quantification and were most applicable in Section 0. The literature review was also used to inform the current understanding of methane detection and quantification practices, current best-available knowledge, successful implementation, and related challenges in detecting and quantifying subsea methane emissions at the time of the report. The complete list of reports and peer reviewed academic papers is available in Section 8. Interviews with technology providers

Interviews were conducted with technology providers. Interviews were contacted with a request to contribute to the project, and a blank Data Sheet was shared to present the information requested to cover. Providers were invited to a 1h virtual meeting, where a discussion was held to help understand the technologies and provide information to fill out the Data Sheets. Following the interviews, Data Sheets were finalized and shared with the providers to assess the accuracy and completeness of the Data Sheets. Data Sheets were then shared with Offshore Norge and a final check was performed. Data Sheets were only developed for technologies from providers that responded to requests. We would like to thank the following technology providers for contributing information to the Data Sheets and report:

- Colmar
- Naxys
- Franatech
- SubCtech
- Sonardyne
- Metas

7.2 Interviews with operators, researchers, and standardization bodies

We would like to thank the researchers and operators who accepted requests to contribute information to this report. Carbon Limits also reached out to standardization and verification bodies for subsea methane leak detection and quantification technologies. However, no relevant personnel were identified in this search, and thus have not been included in the report.

8 Appendix B

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