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OGCI Oil and Gas Climate Initiative

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REPORT 661
MARCH 2025

Recommended practices for methane emissions detection and quantification technologies – upstream

Acknowledgements

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About

This Report provides oil and gas operators with a framework and guidelines to help select and deploy methane emissions detection and quantification technologies that are tailored to their sites and objectives in the upstream oil and gas industry. It is accompanied by an online technology filtering tool, detailed technology data sheets covering over fifty technologies, and decision trees to guide deployment.

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Recommended practices for methane emissions detection and quantification technologies – upstream

Revision history

VERSION	DATE	AMENDMENTS
1.0	September 2023	First release
2.0	March 2025	Update of the Decision Trees, some technologies data sheets, and addition of 6 new technology data sheets.

Contents

Introduction

Many upstream oil and gas operators are aiming to implement and/or improve methane emissions detection and quantification at their sites[1], including in response to requirements of regulators, company practices, identification of mitigation opportunities and reporting initiatives. This document and its accompanying online tool and set of technology data sheets[2] provide oil and gas operators with guidelines for selecting and deploying methane emissions detection and quantification technologies tailored to the situation at their sites, with the aim of improving upstream methane management and emissions reporting.

Technologies for detecting and quantifying methane emissions have improved significantly and continue to evolve. Following such improvements, reporting standards have also evolved, requiring robust detection and quantification. The selection of appropriate technologies to meet these needs depends on several factors.

The technology filtering tool that accompanies this report guides the operator by asking questions related to purpose, location, prevailing weather conditions, as well as details on the detection threshold, frequency, and uncertainty required. The technology data sheets provide more nuances to the assessment and the technology filtering tool is a simplification of a complex assessment. Operators are always invited to check the technology data sheets and to contact technology providers. Next, a set of decision trees in the second part of this Report provide guidance in deployment.

At the heart of the technology filtering tool is a set of technology data sheets for over fifty technologies that are searchable according to the factors mentioned above. The independent consultancy, Carbon Limits, developed the technology data sheets based on multiple sources, including peer-reviewed academic literature, public datasets, and interviews with operators, service providers, and technology providers. Sources for all information in the technology data sheets are identified. Further information on methodology and data sources is provided in Appendix A. A list of reviewed academic papers is provided in Appendix C.

This document and its accompanying technology filtering tool and technology data sheets do not recommend one technology or approach over another. They have been developed to provide a framework of detailed technology characteristics so that operators can make informed decisions on selecting and deploying the technology (or combinations of technologies) best suited to their specific circumstances, taking into account the objectives of technology deployment.

Section 1 of this Report provides an overview of the criteria by which the technology filtering tool helps users select the technology.

Section 2 of the Report provides guidance for deployment, based on decision trees for different activities, including quantification at source level, quantification at site level, reconciliation for a single site, and reconciliation for a group of sites and/or a single site with multiple measurements over time. By answering a series of questions, an operator can obtain guidance best adapted to their unique situation.

[1] In the body of the report, sites are synonymous with "facilities": see Glossary for more information.

[2] https://www.iogp.org/workstreams/environment/environment/methane-emissions-detection-and-quantification/methane-detection-and-quantification-technology-filtering-tool/tool/

The importance of combining technologies was highlighted by many interviewees. Recognizing that there is neither a universal technology nor a universal combination of technologies, Section 3 provides recent examples of operators' experience, highlighting the benefits of certain combinations.

Section 4 covers several recommendations which emerged from interviews and discussions.

In a fast-evolving methane measurement and reporting space, new information is always available. Version 1.0 of this Report was finalized in January 2023. Version 2.0 was finalized in December 2024 and reflects the best knowledge available at the time.

1. Criteria for methane technology selection presented in the online database and technology data sheets

Purpose and site characteristics both play a critical role in the selection and deployment of methane emission detection and quantification technology. To help operators understand which technologies may be most suitable, a technology filtering tool and technology data sheets were developed and are provided with this Report.

Using the interactive technology filtering tool, the operator answers a set of questions, selecting preferences for a range of criteria, to assess which technologies would be suitable for the operator. The operator may answer only parts of the questions depending on the specific characteristics of the need. The technology filtering tool simplifies a complex assessment, and operators are invited to refer to the technology data sheets for a more detailed assessment.

Detailed technology data sheets have been prepared for each technology assessed under this project. The information used in the technology filtering tool comes from the technology data sheets, based on the filtering criteria.

The following sources and validation methods were used to develop the technology filtering tool and technology data sheets.

- Sources
  - Information from peer-reviewed paper prepared by an independent party (such as academia)
  - Information from independent third party (such as operator)
  - Information from technology provider (including peer-reviewed paper from technology provider)
  - Certification against a requirement (such as optical gas imaging (OGI), US Environmental Protection Agency (US EPA) Title 40 – Chapter I – Subchapter C – Part 60 - Subparts OOOOa and OOOOb)
  - Carbon Limits assessment
- Validation
  - Validated by independent academic researchers
  - Validated by fully blind tests performed with a third party (such as, operator, academia). Fully blinded tests are tests where the technology provider has no knowledge of controlled releases being performed and are the most representative of real-world oil and gas sector surveys.
  - Validated by partially blind tests performed with a third party (such as, operator, academia). Partially blinded tests are tests where the technology provider is aware of controlled releases, but not of the characteristics of the release, such as the location or the magnitude.
  - In-house testing[3]

[3] Technology provider's in-house testing

In some jurisdictions, regulation can influence the choices of technologies and reconciliation methods. For example, the US EPA has a process for approving alternative technologies for use in its NSPS OOOOb and EG OOOOc regulations[4] and specific methods for integrating emission observations from other large release events into regulatory reporting.[5] Another example is the EU Methane Regulation, which provides requirements for technology detection capabilities, as well as performing reconciliation approaches.[6]

The below sections (1.1 through 1.7) present the information and criteria used in the technology filtering tool and technology data sheets. Categories followed by "Tool Filter" are used as filters in the database. All criteria mentioned in this section, whether they function as filters or not, are fully detailed in the technology data sheets to provide a comprehensive understanding of each technology.

1.1 Operator preferences

Methane emissions detection and quantification technologies can be selected based on the operator's preferences and constraints with regards to site access, business model, deployment method, and the output of the sensor (visual/non-visual). The sections below detail each of these filters.

Depending on the filter questions, the operator can choose one or more options. For single option filter questions, the default is "All". In this case, technologies applying to all option types will be displayed in the final technology table. For multiple option filter questions, the user can tick or untick the boxes depending on the characteristics to be included or excluded, narrowing the technology choices that will be displayed by the technology filtering tool.

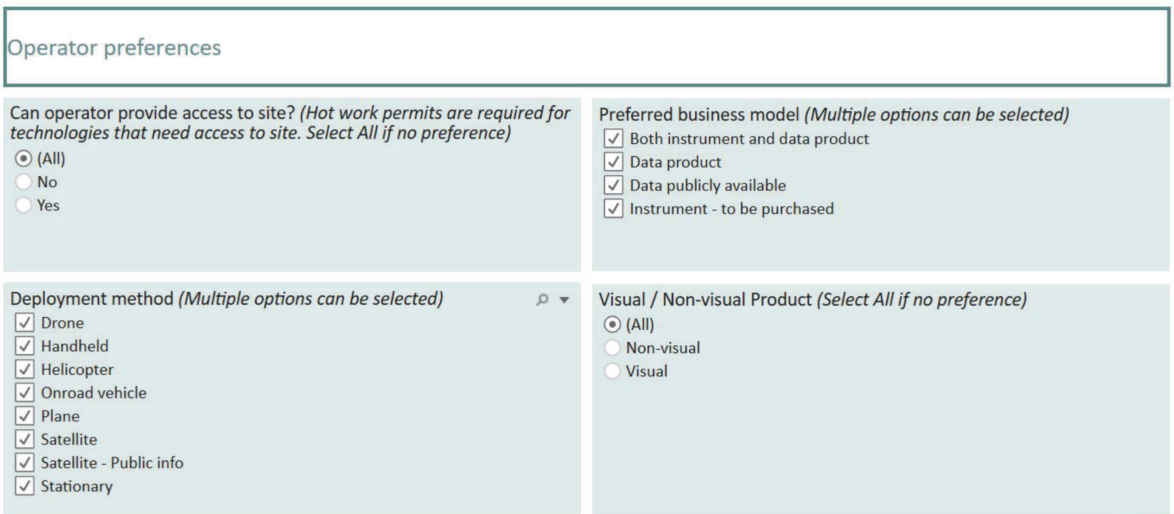


Figure 1: Operator preferences

4 https://www.epa.gov/emc/oil-and-gas-alternative-test-methods
5 United States Environmental Protection Agency, 2024, https://www.govinfo.gov/content/pkg/FR-2024-05-14/pdf/2024-08988.pdf
6 Regulation (EU) 2024/1787 of the European Parliament and of the Council, 2024

1.1.1 Access to site (tool filter)

Site access may be required for deployment or installation of technologies. Hot work permits may be required for installation or deployment, e.g., a permanently installed sensor on a fixture that requires placement and setup. Some deployments do not require access to the site.

The relevant question for this issue in the technology filtering tool asks whether to consider technologies that would require site access for deployment. The possible answers are:

- **All** - Both "Yes" and "No" options will be displayed.
- **No** - site access is not required.
- **Yes** - site access is required.

1.1.2 Business model (Tool filter)

Technology and service providers generally offer three 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.
- The data product is publicly available, for example, in the case of TROPOMI satellites.

Some technologies can be deployed using either the instrument or data product business model, while others are only available under one. A hybrid model may be possible, including as a bespoke product. Operators can choose the "both instrument and data product" option to filter providers who offer both options. Turnaround times and services offered can vary and have been documented in the technology data sheets when known.

1.1.3 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. This section will provide further information regarding the sampling frequency of a technology while it is deployed.

1.1.4 Deployment method (tool filter)

Deployment methods include handheld units, truck-based solutions, equipment mounted on drones, planes or helicopters, fixed sensors on tripods, elevated mounting systems or permanently installed on equipment, and satellite-based technology. This can be important if certain deployment methods are challenging for a given facility, for example, plane-mounted solutions will not be possible for a no-fly zone.

The technology filtering tool asks about the different deployment methods. The operator should tick all the deployment methods that they wish to consider.

1.1.5 Visual/non-visual product (tool filter)

Technologies are classified as visual or non-visual products based on the output of detection or quantification activities. A visual product may, for example, provide plume imagery overlaid on a photo. A non-visual product would not offer imagery to identify methane plumes. The type of product could affect the ability to follow-up on a specific source.

1.1.6 Sensor classification and types

Though not presented as a filter, the tool classifies sensors by type.

Technologies to sense methane range from metal oxide semiconductors to laser-based methods, such as tuneable diode laser spectroscopy or laser dispersion spectroscopy (which measures methane along a laser beam), to handheld or fixed optical gas imaging (OGI) cameras that allow natural gas (and consequently, methane) visualization.

Sensors may be classified as using in-situ or remote sensing techniques. Sensors requiring direct contact with the plume are classified as in-situ. Deployment methods could include fixed sensors for stationary continuous monitoring, or mobile sensors that use ground-based equipment, handheld monitors, or aerial solutions such as drones, planes, or helicopters. Remote sensors could employ, for example, infrared, laser-based, or spectroscopy technology. This does not mean all laser-based methods work remotely. Some laser-based techniques require direct contact with the plume (such as tuneable diode laser spectroscopy or cavity ringdown spectroscopy), so are classified as in-situ sensors in this Report.

Methane quantification approaches will vary depending on the sensor type, ranging from dispersion-modelling to image-processing. For example, a visual product with plume imagery overlaid on a photo or a non-visual product may be provided.

Figure 2 below presents a summary of the technologies assessed in this Report according to the classifications described in Sections 1.1.4 to 1.1.6.

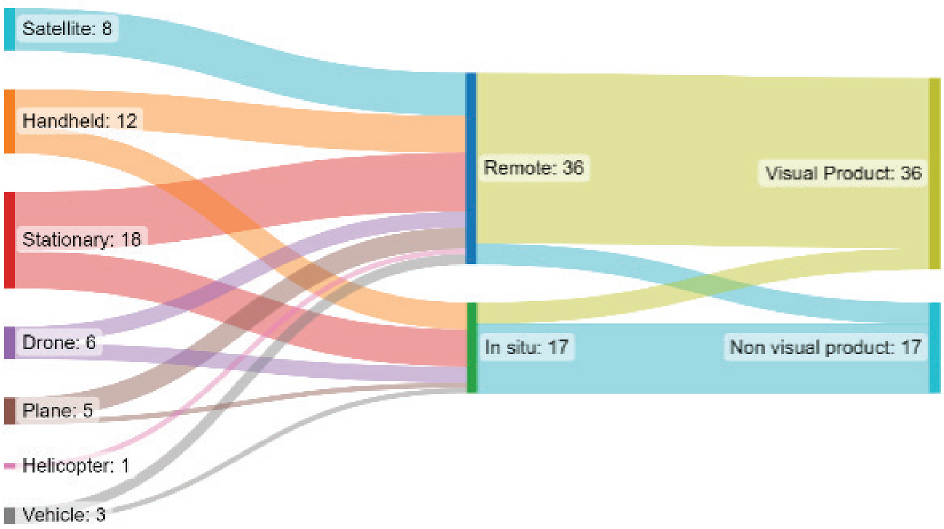


Figure 2 - Distribution of the CH_4 technologies assessed by deployment method (left), sensor type (centre) and product type (right)

1.1.7 Operating Regions

Some technology providers may not be available in all regions 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.

1.1.8 Operational Since

This section of the data sheet presents the age of the technology to provide an indication of the technology provider's experience.

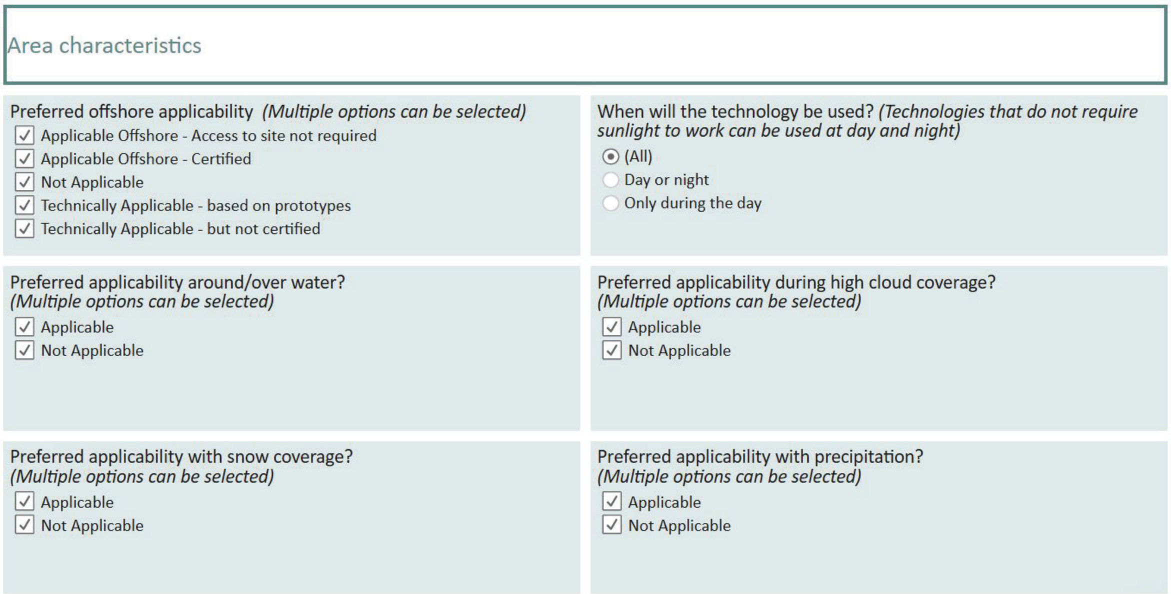
1.2 Area characteristics

These criteria allow evaluation based on conditions at the site.

The first criterion (offshore applicability) enables filtering based on suitability for offshore locations. Other criteria relate to environmental conditions. For each criterion related to an environmental condition, the technology filtering tool and technology data sheets classify according to the following options:

- **Applicable**: Performance is slightly affected or not affected by the environmental condition.
- **Not Applicable**: Performance is affected, or use is impossible in those environmental conditions.

In the data sheets, an additional criterion for "Applicable but higher detection threshold and/or uncertainty" is included and where possible, detailed, to indicate that the technology can be used in an area where the particular environmental condition applies; however, it is possible that the detection threshold is higher (it may not be able to detect values as low as its usual detection limit), its probability of detection is lower, and/or its quantification uncertainty is higher under such circumstances.


Area characteristics

Preferred offshore applicability *(Multiple options can be selected)*
- ☑ Applicable Offshore - Access to site not required
- ☑ Applicable Offshore - Certified
- ☑ Not Applicable
- ☑ Technically Applicable - based on prototypes
- ☑ Technically Applicable - but not certified

When will the technology be used? *(Technologies that do not require sunlight to work can be used at day and night)*
- ◉ (All)
- ○ Day or night
- ○ Only during the day

Preferred applicability around/over water? *(Multiple options can be selected)*
- ☑ Applicable
- ☑ Not Applicable

Preferred applicability during high cloud coverage? *(Multiple options can be selected)*
- ☑ Applicable
- ☑ Not Applicable

Preferred applicability with snow coverage? *(Multiple options can be selected)*
- ☑ Applicable
- ☑ Not Applicable

Preferred applicability with precipitation? *(Multiple options can be selected)*
- ☑ Applicable
- ☑ Not Applicable

Figure 3: Area characteristics

1.2.1 Offshore applicability (tool filter)

This criterion reflects the overall applicability to offshore conditions, which is a combination of two different factors: technical applicability and certification.

- Technical applicability to offshore conditions: For some technologies, the capability to monitor offshore facilities depends on sensor type. Some perform worse over water than on land[7]. When technically ready and certified for offshore deployment, the technology filtering tool categorizes the product as "Applicable". The tool will classify the product as "technically applicable" if the product is in the prototype phase or not yet certified, or the provider is exploring technical and computational improvements to take offshore conditions into consideration. Further details are presented in the technology data sheets.
- Certification (such as, explosive atmosphere (ATEX) rating, class 1, division 1) may be required for deployment at offshore facilities. Some technologies may be technically suitable but waiting for certification to ensure safe use. The technology data sheets, and technology filtering tool present the status of certification at the time of the publication of this Report. This is likely to evolve, so an update on certification status may be obtained from the provider. This filter should not be used if certification status is not important.

1.2.2 Access to offshore installation required

Platform access may be necessary for the deployment, installation, operation, and maintenance of technologies at offshore facilities. This might involve obtaining hot work permits and addressing logistical or safety measures, such as platform access and space constraints. However, some deployments may not require platform access. This section will provide detailed information, as specified by the technology provider or other third parties, on a case-by-case basis.

[7] Jacob D, et al, 2022.

1.2.3 Daylight (tool filter)

Some technologies, such as shortwave infrared sensors, measure spectrally resolved back-scattered solar radiation to detect methane emissions. These cannot be used at night because they require ample sunlight.

To consider technologies that can also operate at night, non-relevant technologies can be filtered out using this criterion in the technology filtering tool.

1.2.4 Readings near bodies of water (tool filter)

As noted, light may be required to reach the sensor to perform measurements. Bodies of water, such as around offshore facilities, are a dark surface and often do not provide enough reflected radiance to allow detection of methane emissions. This is typically more challenging for remote sensing technologies that require light reflection than for in-situ sensors, which are not affected. New techniques are being developed that use sun glint[8] reflected off a water surface to detect and quantify emissions. Currently early in development, this technique could improve the ability to detect and quantify methane emissions around bodies of water.

The effect of water in the technology filtering tool is considered generally in the offshore applicability filter (see above), while the technology data sheets provide additional information on the specific challenges of reflected light near bodies of water.

1.2.5 Cloud cover (tool filter)

Cloud cover reduces observational ability, for example, by reducing the reflected sunlight that passive sensors use to detect methane, while also increasing uncertainty. This issue specifically applies to aerial technologies. Cloud cover could also affect continuous monitoring that requires solar power. This must be anticipated to have enough power backup (such as batteries) to operate when the meteorological conditions are not ideal.

1.2.6 Snow cover (tool filter)

Snow will impact reflectivity, affecting some laser-based technologies, for example by increasing detection thresholds and/or the uncertainty levels for quantification. This can affect both aerial and fence-line monitoring.

Snow can also affect continuous monitoring systems that use solar panels as a power source, as the snow can cover the panel and prevent the charging of the battery.

Operators can filter out technologies affected by snow coverage. Details on how the technology is affected by snow coverage is provided in the technology data sheets.

[8] Glint is the specular reflection from the surface of water and occurs when the sun angle and view angle are equal and in the same principal plane.

1.2.7 Precipitation (tool filter)

Water droplets and fog will scatter light and reduce instrument sensitivity, potentially reducing the ability to detect or quantify emissions. Precipitation may also increase the level of uncertainty in quantification, particularly for laser-based solutions.

Rain or snow at the time of detection can also affect the methane plume itself, including its direction and concentration. Quantification could then result in a higher level of uncertainty.

1.2.8 Wind

Wind speed is one of the dominant factors causing uncertainty in detection and quantification of methane emissions. While many of the technologies reviewed as part of this project require the presence of at least some wind to transport methane from the source to the sensor, they usually will not perform equally well at all wind speeds. Wind speed and direction are important for use around the site. Wind can be impacted by obstacles, such as equipment or buildings, which can affect uncertainty.

Wind speeds affect quantification of methane emissions, depending on sensor type and deployment. Wind speed and/or direction will also impact the uncertainty of measurements. Some recent tests evaluate the Probability of Detection (PoD) at a given emission threshold depending on the wind conditions (see Section 4.5.2). When available, these results are presented in the technology filtering tool. Wind direction and speed need to be carefully considered when interpreting results.

Wind condition is not a direct filter in the technology filtering tool. However, recommended minimum and maximum wind speeds and details about the effects of wind are provided in the technology data sheets to detail the operating envelope in which the technology will be able to perform reliably.

1.3 Aim of deployment

Criteria in the technology filtering tool allow the identification of deployment objective(s). IOGP Report 661 assessed two main deployment purposes: 1) detection of methane emissions and 2) quantification of methane emissions.

Methane emissions are detected and attributed at the site, equipment, or component level, depending on the technology.

Quantification technologies estimate the rate of emissions, for example as a volume rate (such as m3/h) or as a mass flow rate (such as kg/h). For some types of events, total emissions can then be calculated by multiplying the emission rate by the duration of the event (measured or estimated). Uncertainty can increase with duration. Some quantification technologies (continuous monitoring) provide an estimated value for the total emissions, subject to the uncertainty in the system design.

Some technologies can measure the methane concentration in a plume. In this case, the data must be processed with other factors, such as wind speed and duration of the emissions, to obtain the emission rate and total emissions. In the technology filtering tool and technology data sheets, a technology with the capability to provide emission rates is tagged as a quantification technology.

1.3.1 Capacity to monitor multiple sites per deployment (tool filter)

Some technologies (notably planes, helicopters, and satellites) can monitor and provide site level estimates for multiple sites per deployment. This could be advantageous when, for example, performing reconciliation of emissions for multiple sites (refer to Section 2.6).

Choices in the technology filtering tool for this filter 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.
- **Maybe**: No preference (the technology filtering tool will not use this criterion).

1.3.2 Detection at site level (tool filter)

This criterion captures site level emissions detection suitability. The detection threshold affects the selection of site level technology (see Section 1.4.1 regarding thresholds).

In addition to site attribution, emissions may be attributed to specific equipment or components. However, certain technologies that are used to detect emissions at the equipment or component level may not be suitable 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 more appropriate to the identification of equipment or components as a follow-up to the use of site level technology.

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

- **Yes**: Emissions can be accurately and reliably detected at site level.
- **Maybe**: Emissions may be detected at the overall site level, but it may be challenging to assess the entire site if very large, or if sites are closely spaced. 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.

1.3.3 Detection at equipment level (tool filter)

This criterion captures whether a technology can detect an emission source and attribute it to a piece of equipment. The technology may be able to attribute emissions to a specific piece of equipment at a site, for example a tank, a flare, or a compressor, but might not be able to attribute the emissions to the emitting component.

The following classification has been used:

- **Yes**: Emissions can be detected at equipment level, and accurately attributed.
- **Maybe**: Spatially isolated equipment sources may be detected, but it may be challenging to attribute emissions 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.

1.3.4 Detection at component level (tool filter)

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

One of the purposes of detecting methane emissions at component level is to identify leaking or malfunctioning components, typically during Leak Detection and Repair (LDAR) campaigns, where the goal would be to identify emitting components and ensure mitigation. Detection at component level can also be used for inventory: some inventory methodologies require the operator to determine the number of leaking and non-leaking components to estimate fugitive methane emissions.

A particular technology may detect emissions from large, isolated components (such as a thief hatch on a storage tank) but prove less reliable in the case of equipment with many closely placed components. In these circumstances, the technology would not be considered a component-level detection technology.

The following classification has been used:

- **Yes**: Emissions can be detected at component level, and accurately attributed.
- **Maybe**: Components emitting may be detectable, but it may be challenging to attribute emissions 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 have the right resolution to detect emissions from specific components.

1.3.5 Quantification at basin level (tool filter)

This criterion assesses the ability to quantify (as opposed to detect) total emissions at the basin level.

The following classifications have been used and are available in the filtering tool:

- **Yes**: The technology can quantify emissions at the basin level.
- **No**: The technology cannot quantify emissions at the basin level.

1.3.6 Quantification at site level (tool filter)

This criterion captures the ability to provide the total emission rate for a specific site or facility. The technology may quantify several large sources within a site but may not be able to attribute emissions on a more granular scale, such as to specific pieces of equipment.

Quantification of methane emissions at site level is an essential input for a reconciliation exercise (the other is source level quantification). Site level quantification ensures that a major emission source is not missing from its source level inventory or has been improperly quantified.

The following classification has been used:

- **Yes**: Emissions can be quantified 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, that is, some areas of the site might not be considered in the quantification.
- **Maybe**: Emissions may be quantified 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.

1.3.7 Quantification at equipment level (tool filter)

This criterion captures whether a technology can provide the total emission rate for a piece of equipment, such as an individual tank, flare, or compressor.

The following classification has been used:

- **Yes**: Emissions can be quantified at the equipment level.
- **Maybe**: The technology may be able to quantify spatially isolated equipment sources but may not be able to attribute emissions to specific equipment sources in all scenarios, such as 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 from a single piece of equipment or equipment group. It would not be considered an equipment-level quantification technology.

1.3.8 Quantification at component level (tool filter)

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

In some cases, it will be necessary to 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, such as equipment that vents methane by design.

Component or equipment-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.

The following classification has been used:

- **Yes**: Emissions can be quantified at the component level.
- **Maybe**: The technology may be able to quantify spatially isolated components but may not be able to attribute emissions to specific sources in all scenarios, such as when many component 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 equipment level but is not able to quantify emissions from a single component. It would not be considered a component-level quantification technology.

1.4 Technology characteristics

This section presents performance criteria. It should be read in conjunction with Section 1.5 (technology validation).

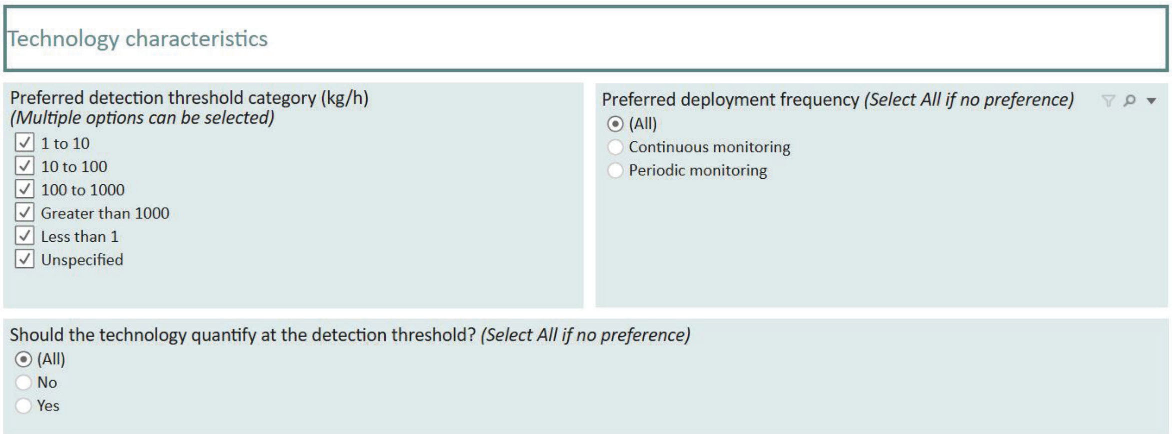


Figure 4 - Technology characteristics

1.4.1 Detection threshold (tool filter)

Detection threshold is the minimum amount of methane that is reliably detectable[9]. While the detection threshold can be presented in several forms (for example, concentration, concentration vs distance, volume emission rate, mass emission rate), detection thresholds in this Report are stated in kg/h, where possible.

Detection threshold depends on the type of emissions to detect. For instance, given the skewed distribution of emission rates[10,11] a higher detection threshold will encourage focus on higher-emitting components. Some jurisdictions set minimum detection thresholds which could influence the selected technology.

[9] IOGP-Ipieca-GIE-Marcogaz - Methane Emissions Glossary
[10] Omara M et al.,2022
[11] Zavala-Araiza D, et al., 2017

It should be noted that the detection threshold is a function of the distance between the emission source and the detection technology, as well as the environmental conditions at the time, notably wind. Some technologies have begun producing PoD curves to document these relationships. Please see Section 4.5.2 for more detail.

In most cases, detection thresholds mentioned in the technology data sheets are supplied by the technology provider and may not have been validated by a third party. Validation status and the source of this information is presented in the technology data sheets. Where available, the appropriate environmental conditions for the detection threshold are noted.

The technology filtering tool allows selection from five different detection threshold categories, ranging from less than 1 kg/hour (most sensitive) to over 1,000 kg/hour (least sensitive).

Since the performance of some technologies can vary due to many different parameters, review of this criterion should be done with careful review of validation status and other criteria in the technology data sheets.

1.4.2 Quantification at detection threshold level (tool filter)

The operator might want to quantify detected emissions for reporting purposes or to prioritize abatement measures. Quantification provides the emission rate (for example, as a mass rate such as kg/h, or a volumetric rate such as m3/h). Multiplying the rate by the duration allows the estimation of total emissions.

Quantification methods often involve measuring methane concentrations in flows of gases or ambient air but could also include a variety of other measurements, calculations, and modelling. For most 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.

The technology filtering tool allows the user to specify whether quantification is required at the same threshold as detection.

1.4.3 Frequency of technology deployment (tool filter)

The recommended frequency of deployment may be specified, though only from a technical perspective. Section 2.7 provides information on other elements that can influence choices regarding frequency of deployment.

Technologies have been classified as follows:

- **Continuous monitoring**: This could be at site level, equipment level or component level. Continuous monitoring can be affected by gaps in network connectivity or environmental conditions, leading to downtime of the system.
- **Periodic monitoring**: This concerns technologies such as handheld devices and aerial monitoring, which may require assistance in deployment. The actual frequency is then selected by the operator (refer to Section 2.7).

1.4.4 Quantification uncertainty

While a sensor may be highly precise, the quantification method using that sensor may be more uncertain. Technologies with stated uncertainties consider quantification algorithms, environmental conditions, and emission rates. Quantification uncertainty may be reported in terms of a 1σ or 2σ uncertainty (68% and 95% confidence intervals, respectively), in relative or absolute values. Care should be taken when evaluating uncertainties. Please refer to Section 4.1 for details.

1.5 Technology validation

There is no international standard to measure and compare the performance of detection and quantification technologies (see Section 4.4). To improve transparency regarding third-party validation, technologies have been assessed against several types of validation that have been presented in the datasheets. The database helps operators select technologies based on the validation performed. This criterion may be useful for operators who are not planning to perform internal technology validation.

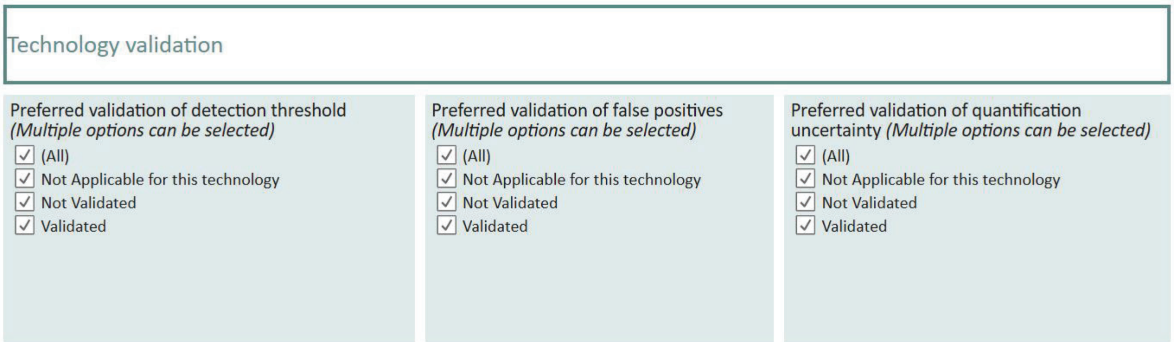


Figure 5 - Technology validation

For the purposes of this project, "validation" means that test results are publicly available. It does not necessarily mean that the technology will perform "as advertised" under all site conditions. The validation criteria are independent from the performance criteria.

Four technology validation options are available in the technology filtering tool:

- Not applicable for this technology: Filter for technologies that can perform either detection or quantification. For example, some are able to detect methane but not quantify it, in which case verification of quantification performance is not relevant.
- Not Validated: Tests may have been performed by the technology provider, either in the lab or field, 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 reflect field conditions. Technologies are considered "not validated" if they have only undergone in-house testing or results are not publicly available.

- Validated: Validation has been done by peer-reviewed papers prepared by independent academic researchers, or validation has been done using partially or fully blinded tests performed with a third party such as academics, independent researchers or by oil and gas operators.

In the data sheets, information has been provided about the type of validation. The following categorizations have been presented in the data sheets, apart from the ones specified above:

- Validated: academia: The information comes from a peer-reviewed paper prepared by independent academic researchers and may include results from fully or partially blind testing (see below).
- Validated: partial/fully blind tests: Validation can be done using partially or fully blinded tests performed with a third party such as academics, independent researchers or by oil and gas operators. For fully blind tests, the presence, location, and size (if any) of the controlled test release(s) were unknown to the technology provider at the time of the test. This is the closest approximation of field conditions, with the least amount of inherent bias. For partially blind tests, the technology provider was aware that controlled release testing was taking place but was unaware of the size or location of the release. Partially blind tests offer improved validation of technology performance over scenarios where the emission source size was known but may still introduce bias. For instance, the operator performing the test may have taken more proactive steps than normally to detect or quantify emissions.

Some validation work is ongoing. The technology filtering tool and technology data sheets should be regularly updated to account for results of new tests and research. The following cases are highlighted:

- Testing may have already been performed, but the results not yet made public. Information about such cases, where known, are indicated in the technology data sheets. The technology will still be considered "not validated," since the results were not publicly available at the time of publication. This does not imply anything regarding performance, but only the availability of the information.
- 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 availability of the information.

Where relevant, information in the technology data sheets is provided regarding the layout of the testing site, environmental conditions, and limitations of the validation. The user should consider the test conditions and setup relative to those in which the technology is likely to be used (see Section 4.5). For example, a partially blind test performed in a desert with a single point emission source may not be relevant if the operator intends to use the technology for multiple, small sources in dense foliage.

1.5.1 Validation of detection threshold/quantification threshold (tool filter)

Validation of detection and quantification thresholds refers to the ability to correctly detect/quantify the smallest amount of methane that is claimed by the 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 the field.

The options for validation of detection and quantification thresholds are those indicated above in Section 1.5.

1.5.2 Quantification performance and uncertainty (tool filter)

Quantification performance refers to the ability to give measurement values for the emission rate that match the actual emissions. Quantification performance may be described by comparing measurements to true emission rates. Ideally, the linear regression between measurements and actual emissions is a unit-slope line.

Quantification performance may be based on emission rates, wind speeds, and/or distances of measurement technology from the source, all of which can impact quantification performance. Robust, defined, and publicly available analyses increase transparency regarding the abilities. Technologies that have published results for these parameters offer a more reliable indication of performance than those for which results are not publicly available.

Providers that have published results of quantification performance typically provide a range of emission rates for which the technology is able to perform quantification and a quantification uncertainty at a specified emission rate either under typical operational conditions or, for example, in terms of wind speed. This type of information helps users understand the performance envelope of the technology.

The technology filtering tool allows selection where the presented quantification uncertainty is validated. Where available, more details on the technology's quantification performance are presented in the technology data sheets.

The options for quantification performance and uncertainty are those indicated above in Section 1.5.

1.5.3 Validation of false positives (tool filter)

False positives are reports of methane emission detection where no methane emissions occurred. False positives may lead to unnecessary follow-up and alarm fatigue. Tests for false positives are reported in the technology filtering tool and technology data sheets, where available.

The options for validation of false positives are those indicated above in Section 1.5.

1.6 Deployment aspects

Qualitative aspects to consider when selecting suitable technology include ease of deployment, time required to deploy, and training required. While these criteria are not used in the technology filtering tool, qualitative information on these and other deployment aspects is presented in individual technology data sheets.

1.6.1 Time considerations for technology deployment

This section provides detailed information about the amount of time required for initial setup, installation lead times, and other temporal aspects of the technology. This may include battery lifetime, charging time (if applicable), maintenance duration, and other relevant time-related factors.

1.6.2 Ease of deployment

Some technologies, such as handheld analysers, require the site to be manually assessed for emissions. Depending on safety certifications, this could require obtaining hot work permits.

In the case of aerial monitoring, such as with drones or airplanes, the safety of the pilot and the site operators must be considered. This could require permits, as well as significant coordination on the part of the operator. These requirements differ by country. For satellites, deployment depends on the orbital path of the satellite and on environmental conditions, such as cloud cover.

1.6.3 Training

Training required for deployment is likely to be closely associated with the business model of the technology provider. Some providers handle everything from installation to post-processing of data. In such cases, the operator would receive the estimated emissions data from the provider, so little training would be required for the staff of the oil and gas operator. However, some providers train the operator to use their handheld devices, drones, or other equipment. Training time required will vary, depending not only on the equipment but, for example, on staff experience and field/site characteristics.

1.7 Other factors when selecting technology

The following sections present additional factors that may need to be considered when selecting a methane emissions detection or quantification technology. These are not covered by the technology filtering tool, or the technology data sheets, as they do not apply globally, are not relevant for most technologies, or are unique to a particular region, operator, or site.

1.7.1 Presentation of output and results

Data generated and reported by detection and quantification technologies and services are not standardized. Output can vary significantly, including in terms of format, scale, unit, and scope.

Some providers offer online platforms or other tools to help assess and use the output. The operator will need to consider how actionable these deliverables are, measured against its needs. For example, an operator that is trying to identify components that need to be mitigated may require an output that includes clear and precise localization of the methane plume, whereas figures for methane concentration downwind could be sufficient for an operator that is trying to prioritize efforts across several sites.

1.7.2 Safety, regulation, and social responsibility

Some regulations can directly impact the technology itself, either by requiring a particular type of technology, carrier, or sensor, or by requiring technology performance standards, such as a detection threshold or PoDs (see Section 4.5.2).

Other regulations may not directly target methane emissions detection and quantification technologies but could impact deployment. This is typically the case with airborne detection and quantification. For example, flight restrictions for aircrafts, weight or altitude limits for drones, or a ban on drone flights all together, can limit deployment options.

Beyond regulation, questions of sustainability and social responsibility can come into play. The overall impact of deployment on the local population and the environment can influence the decision. This aspect can be very site-specific and cover many topics. Examples include limiting the number of aircraft flying over inhabited areas (for reasons of safety and noise pollution), limiting disruption to local flora and fauna, and avoiding increased road traffic.

1.7.3 Scalability of technologies

Operators will typically need to deploy technologies across many assets, which may be widely dispersed. In such instances, scalability is likely to be important.

Potential constraints are twofold. The first is availability, including whether the technology is available in the operator's geographic area, and the provider's manufacturing and deployment capacity.

The scale of deployment will also depend on budgetary and labour resources. For example, if the deployment of a particular technology requires months of work from a full team for a single site to obtain conclusive results, challenges will likely arise when looking to deploy this technology across all company assets, including operational and logistical constraints, such as ongoing maintenance.

1.7.4 Third-party deployment/service providers

In some cases, equipment can be deployed by either the operator or third parties, depending on aim and scale.

Hiring a third-party service provider usually means that the operator does not need to acquire the technology directly or train personnel to deploy it, and fewer employees need to be redirected (only for managing or supervising the deployment). In addition, for leak detection and repair, personnel experience plays a significant role in leak identification.[12]

On the other hand, relying on a third party for methane emissions detection and quantification implies that the operator either has a long-term contract with a monitoring service provider or hires each time the technology is deployed. This could impact the scalability of the deployment. It may also require site access for external personnel, which can increase administrative burden.

The operator may need to consider whether a service provider is able to support the deployment of the specific technology within the operator's required region(s) and timeframe(s).

[12] Zimmerle, D, et al., 2020

2. Deployment – decision trees

While the technology filtering tool uses criteria to help select appropriate technologies for use at a particular type of site for a given purpose, additional factors should be considered when it comes to deployment, such as part of a methane emissions detection, quantification, and reporting programme. This section addresses some deployment considerations using "decision trees".

The following deployment decision trees have been developed:

- **Tree 0**: A general decision tree that organizes the different processes into a coherent framework
- **Tree 1**: Screening of components and sites
- **Tree 2**: Quantification of emissions at source level
- **Tree 3**: Quantification of emissions at site level
- **Tree 4**: Reconciliation for a single site
- **Tree 5**: Reconciliation for a group of sites and/or a single site with multiple measurements over time
- **Tree 6**: Reconciliation to produce a single Measurement Informed Inventory (MII) as per the GTI Veritas protocols

The final section presents some elements of deployment frequency.

2.1 Tree 0 - General Tree

The general tree is used to identify which other tree(s) should be used, depending on the main objective of the deployment. The two main deployment objectives covered by the general tree are:

- reducing methane emissions
- reporting methane emissions, following an international standard or otherwise

The "reporting" side of the decision tree combines both objectives since most operators are also aiming to reduce the emissions they report.

In some instances, deployment will respond to a regulatory requirement. The operator is invited to use this decision tree to evaluate whether complementary technologies or processes that are not already included in the regulatory requirements should be considered, taking into account objectives and site characteristics.

2.1.1 If the objective is to reduce emissions

Where the focus of deployment is reducing emissions, the first step is to perform a screening exercise at either the site, equipment-group, or component level (refer to Section 2.2). This allows the operator to identify priority areas for resources.

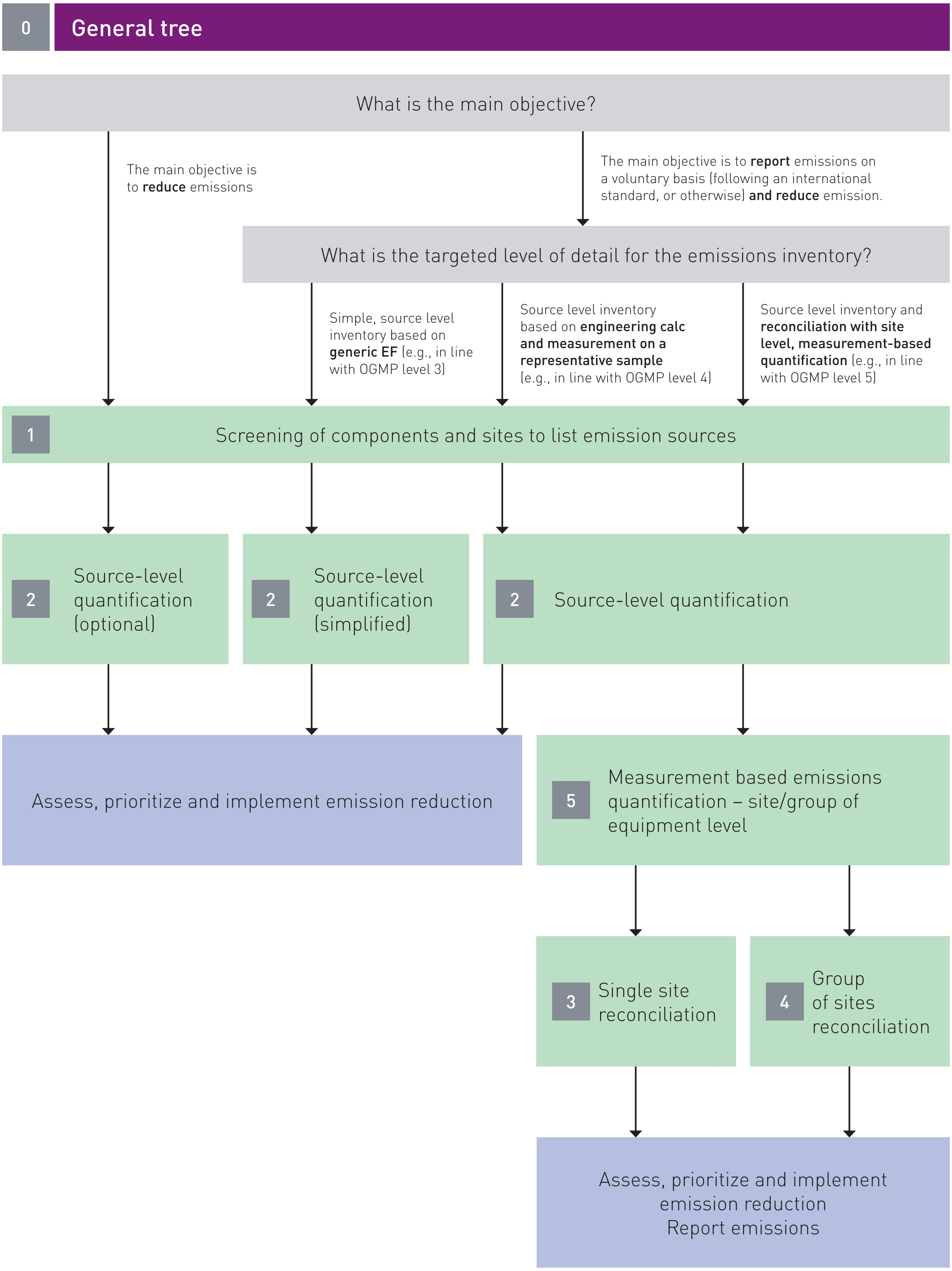


Figure 6: General tree

An optional follow-up is the quantification of emissions from the identified sources. There are several ways to quantify methane emissions at source level, as presented in the source level quantification tree (refer to Section 2.3). This step is relevant if the operator wishes to use results as part of an inventory based on detected emissions, or report emission reductions achieved through mitigation. Mitigation prioritization and implementation are not covered in this Report.

2.1.2 If the objective is to report and reduce emissions

The creation of a robust inventory of methane emissions will always require an understanding of potential emission sources and a screening of those sources (refer to Section 2.2). Inventories can have various levels of accuracy. Deployment to aid in this process depends on the targeted level of detail.

The simplest form of inventory at source level relies on generic emission factors (EF), such as in line with OGMP[13] Level 3 or the baseline inventory in the GTI Veritas[14] Source-Level and Measurement Reconciliation Protocol. Source level inventories based on generic emission factors can be a first step in assessing methane emissions (see Section 2.3).

Operators can develop a more specific source level inventory by using engineering calculations or measurements performed on a sample in place of generic emission factors, such as in line with OGMP Level 4. For such an inventory, the detailed process for implementation may be found in Section 2.3.

One option where operators can take the development of their inventory a step further is by comparing a source level inventory (see Section 2.3) with site level measurements (see Section 2.4). One purpose of site level measurement is to help ensure that source level quantification has considered all large emission sources, and that source level quantification of major sources is accurate. This process is an example of reconciliation between source and site measurements and can be done for either a single site or group of sites with similar characteristics. It can also be used for measurements of the same site over time. Decision trees are available describing the reconciliation process for each of these cases (see Section 2.5 for a single site and Section 2.6 for a group of sites). This option is the one considered for this Report and detailed in the decision trees.

Operators may also combine measurements, EFs, and engineering calculations to produce a Measurement-Informed Inventory (MII), in which both source- and site level measurements, and engineering calculations may be combined to produce a single emission inventory estimate for a group of equipment, site, or group of sites (see Section 2.7).Reconciliation and measurement-informed inventories are emerging areas, where methodological refinement is on-going around how to integrate different types of measurements into inventories over time.

2.2 Tree 1 - Screening of components and sites

Screening of methane emissions, even without quantification, can already be an important source of information. The aim of this decision tree is to guide operators through source level and site level screening.

[13] https://www.ogmpartnership.com/
[14] https://veritas.gti.energy/protocols

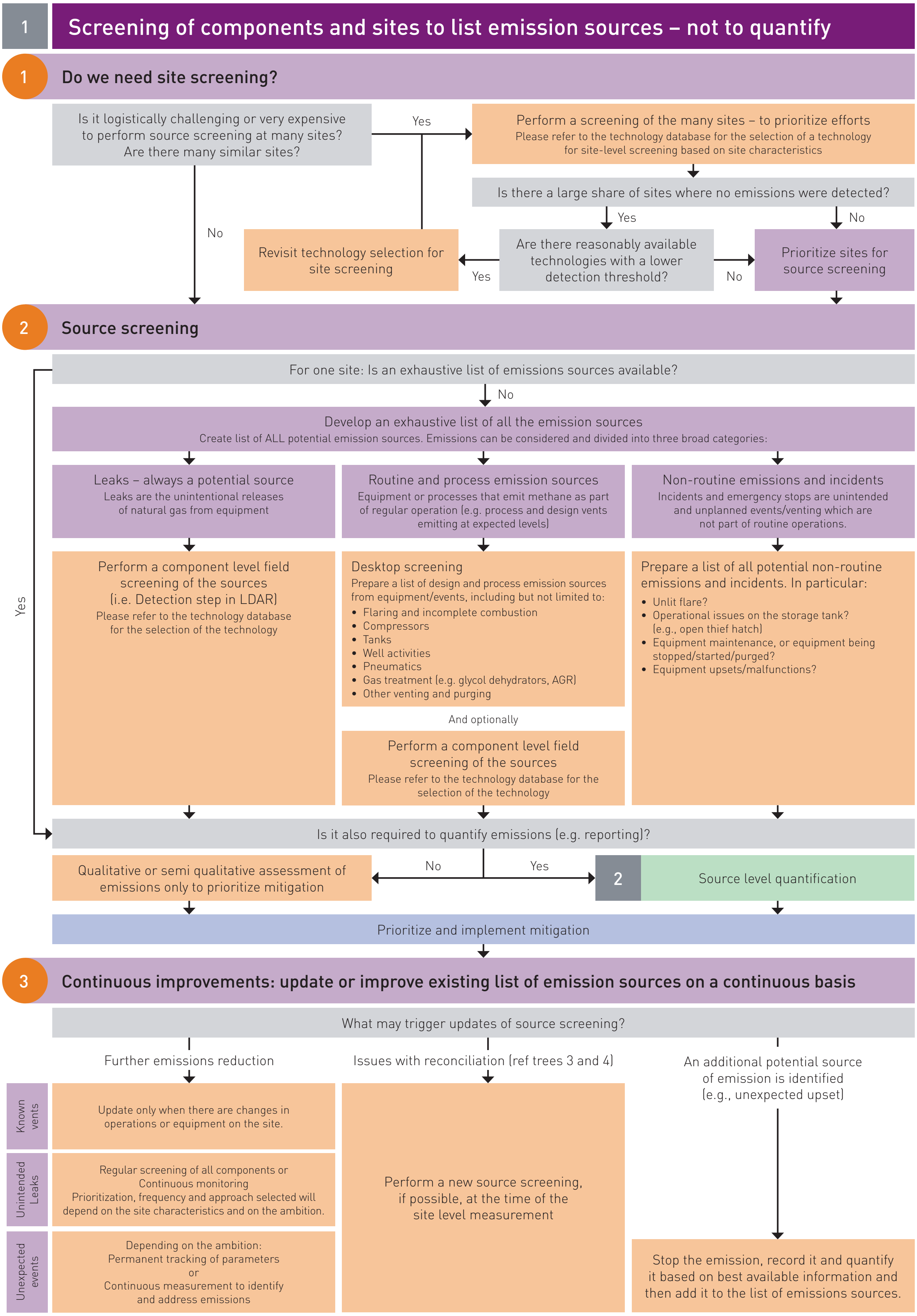


Figure 7: Screening of components and sites

2.2.1 Do we need site screening?

Source level screening should be performed at all sites. In some cases, site level screening may be used to identify the sites at which to prioritize source level screening. Site level screening is recommended where there are many similar sites and it is logistically challenging or expensive to perform source level screening, or to increase the frequency of screening.

If no emissions are detected at a large share of sites, it may be worthwhile to revisit the technology selected for site screening and determine whether one with a lower detection threshold can be used instead (this may not be necessary if the technology selected is in line with local minimum detection threshold regulations, as discussed in Section 1.4.1). If no technology with a lower detection threshold is available, sites can be prioritized for source level screening based on the small share of sites where emissions were detected or on other relevant parameters, such as number of components and age of installations.

Some site level screening technologies provide source level detection (see the technology filtering tool and technology data sheets).

2.2.2 Source screening

The first step in source level screening is to develop an exhaustive list of emission sources at each site, regardless of whether methane emissions have been confirmed.

Emission sources can be divided into three broad categories:

- Leaks (always a potential source): unintentional releases of natural gas from equipment
- Routine and process emission sources: equipment or processes that emit methane regularly
- Non-routine emissions and incidents: unintended events/venting

Since leaks can arise anywhere and at any time, a complete component-level screening for such emissions[15] is useful.

Routine and process emissions are more predictable. Sources can often be determined based on facility design and operational practices. It is recommended to start the analysis with a desktop study to prepare a complete list of all design and process emission sources from equipment and events, including but not limited to:

- Flaring and incomplete combustion from power and heat generation, such as engines, turbines, and boilers
- Compressor seals, for example, rod packing of reciprocating compressors, and wet/dry seals for centrifugal compressors
- Hydrocarbon storage tanks
- Well activities, such as liquids unloading, casinghead gas venting, well completion and workover, and well drilling and testing
- Pneumatic controllers and pumps
- Gas treatment, namely glycol dehydrators, acid gas removal (AGR)

[15] https://www.iogp.org/workstreams/environment/environment/methane-emissions-detection-and-quantification/methane-detection-and-quantification-technology-filtering-tool/tool/

- Blowdown and pressure-control releases of vessels and pipes
- Other venting and purging

Optionally, screening in the field can be performed in addition to a desktop study to ensure that all potential emission sources have been considered. A field screening may not be sufficient for some of these sources since some may be intermittent.

Finally, all potential non-routine emissions and incidents should be listed, based on equipment and operational practices on site. This could include:

- Unlit, malfunctioning, or inefficient flares
- Operational issues on the storage tank, such as an open thief hatch, typically in the case of onshore operations
- Maintenance or equipment stopped/started/purged
- Upsets/malfunctions

Since screening is also an essential first step to quantification, the operator should consider whether the objective includes quantification. If so, the exhaustive list of all emission sources can be used for source level quantification (refer to Section 2.3). If emission quantification is not required, then a qualitative or semi-qualitative assessment can be used to prioritize mitigation. This process can support mitigation action.

2.2.3 Continuous improvement: update or improve existing source level inventory continuously

Source level screening of methane emissions should not be a one-time event, but rather viewed as a snapshot of a situation that can change. Different things can trigger an update of source level screening, for example:

- Further emissions reduction, such as, the operator aiming to reduce or eliminate emission sources (in particular, leaks) following a schedule
- Inconsistencies noted from reconciliation, such as variability in emissions not captured properly at the source level inventory (refer to Sections 2.5 and 2.6)
- Identification of an additional potential source of emissions, such as an unexpected upset

When the aim of the update is to mitigate emissions, how screening should be considered depends on the category of the emission source. For known vents, for example, source screening only needs to be updated when there are changes in operations or equipment on the site, as their status tends to remain relatively consistent. This is not the case for leaks, which can arise at any moment. For this type of emission source, it is recommended, for example, to perform regular component screening (that is, the detection component of LDAR) or continuous monitoring such as for larger, more frequent events. The frequency and approach will depend on the site(s), previous screening, and the level of operator ambition to reduce methane emissions.

The objective also plays a role in the screening of unexpected events. At a first level, operators are encouraged to institute permanent tracking of relevant parameters (such as, SCADA, online meters, and so on) that could indicate when unexpected events occur. To go further, operators are encouraged to implement continuous monitoring to identify and address the source of unexpected emissions.

When source level screening is performed to resolve issues with reconciliation, all source categories may be treated in a similar way, i.e., by performing a new source level screening. This should take place at the same time as the site level measurement to provide potential explanations for emissions found at that time.

Finally, the aim of the screening may be to add a potential source to the list of emission sources at a facility. This typically only applies to unexpected events. Once the emission source has been addressed, the operator is encouraged to record it and, if relevant, quantify it.

2.3 Tree 2 - Source level quantification

Source level quantification can be done by quantifying emissions from individual sources and summing them. A list of all potential emission sources is required to perform accurate source level quantification. This should be informed by the steps presented in Section 2.2 (Tree 1) to identify all potential sources at a facility. Without this, emissions may be under- or over-estimated.

For source level, there are four methods to quantify emissions, each of which is covered in this section:

- Generic emission factors
- Measurement-based emission factors
- Engineering calculations
- Measurements

This decision tree helps operators identify the appropriate quantification method for each source at a facility.

If the goal of the inventory is a simple, source level inventory, generic emission factors (such as in OGMP Level 3) may be used. It is important to note that using generic emission factors may result in higher uncertainty or errors and may not provide accurate results. However, this approach can be used in a first, high-level assessment to develop a baseline, which can be improved by adding measurements or engineering calculations. In addition, or alternatively, this approach may be used to prioritize mitigation or to pinpoint emission sources that could represent interesting mitigation projects.

If the goal is to develop a source level inventory based on measurements or engineering calculations, or to perform reconciliation with site level, measurement-based quantification, a more detailed approach should be taken. For any emission source, an operator must first determine if the source is material, that is, if it is likely to contribute a non-negligible share of site level emissions. This can be informed by operator knowledge of site processes and previous quantification methods, such as generic emission factors. If the emission source is non-material, a generic emission factor can be used to quantify, as any error is unlikely to significantly contribute to the uncertainty of quantification for the facility. If the emission source is material, or may be material, a more conservative, source-specific quantification approach is recommended. This can involve measurements, engineering calculations, or other methods equivalent to OGMP Level 4 quantification, as presented in the OGMP technical guidance documents.[16]

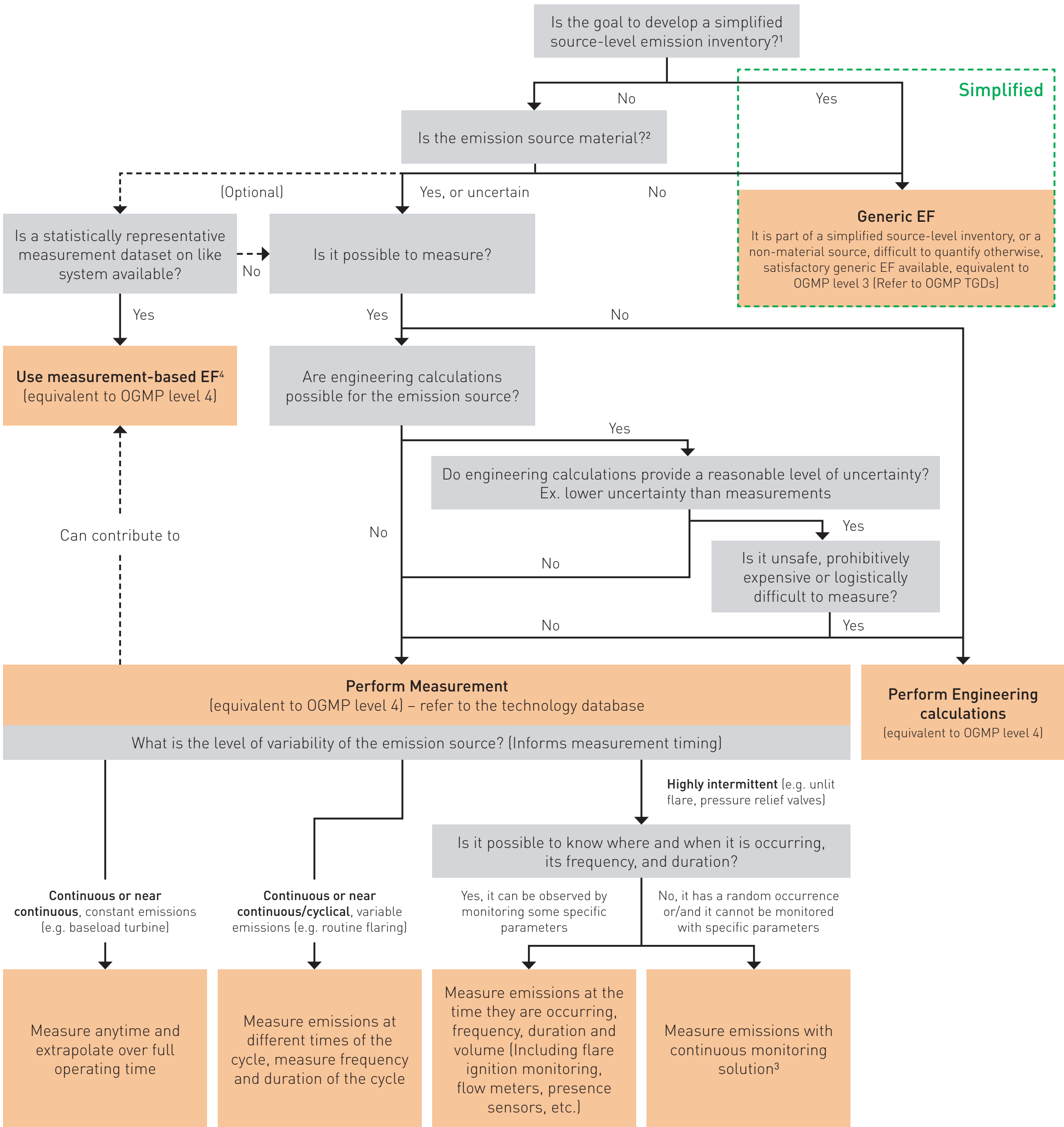
[16] https://ogmpartnership.com/guidance-documents-and-templates/

2 Emission inventory source-level quantification

Follow the tree to identify appropriate quantification methods for each emission source identified

Information required

- A list of all potential emission sources to perform a conclusive source-level quantification (See tree 1 for process to create this list)
- While no recommendations on the percentage of components to sample, it is recommended to use Measurements, Engineering Calculations or measurement-based EF where possible.



[1] If the source level inventory is a simplified, high level assessment, a user can choose the simplified source-level quantification method using generic emission factors with the knowledge that the estimates may be associated with high uncertainty or errors and may not provide accurate results, which can be improved over time with the supplementation of measurements or engineering calculations.

[2] Material emissions are estimated to contribute non-negligible emissions with respect to facility level emissions

[3] May be associated with larger emission uncertainties, which can be a function of ex. wind conditions, background methane emission sources, or emission source attribution. However, implementing continuous monitoring is better than having no measurements.

[4] Measurement-based emission factors can be developed as part of level 4 quantification for like systems. Generally, events or equipment with similar operational, environmental or design characteristics can be considered as like systems. Variations around some characteristics are acceptable, if it can be demonstrated that these do not significantly affect methane emissions.

Figure 8: Source-level quantification

If the source is material, the first question is whether it is possible to reliably measure emissions. If the methane emissions cannot be measured for technical reasons, it is recommended to rely on engineering calculations for quantification. Engineering calculations can be preferred if taking measurements could be unsafe, expensive, difficult, or results in greater uncertainty. However, this requires that engineering calculations exist, are possible, and provide a reasonable level of uncertainty for quantification at the source level.

When it is not prohibitively challenging to do so, it is recommended to measure. This Report provides general principles for measuring several different types of emission sources. Additional factors should also be considered, such as the complexity of the emissions and operations, topography, or meteorological conditions.

When measuring, variability should be considered to inform the measurement timing and to assess total emissions over the relevant timeframe. If the emission source is continuously or near-continuously emitting at the same rate, measurements can be performed anytime and extrapolated over the full period of operation.

If the source is cyclical with variable emissions, measurements should be taken at different times in the cycle and attributed to the different operating modes of the source that would reflect overall emissions.

If the source is highly intermittent or event-based, such as in the case of an unlit flare, and it is possible to know the frequency, duration and timing of such emissions, measurements should be performed to capture volume, frequency, and duration.

If the event occurs at random or is not monitorable, it is recommended to measure emissions using continuous monitoring.

An alternative, optional quantification route is to use emission factors derived from previous measurements performed on site or on other sites with similar operating conditions, though only if a representative dataset, based on similar sources, is available. In this case, measurement-based emission factors can be used, such as in line with OGMP Level 4, in place of measurements, engineering calculations or generic emission factors. Generally, events or equipment with similar characteristics – referred to as 'like systems' – can be considered representative. Variations around some characteristics are acceptable if they do not significantly affect the volume of methane emissions.

Since emissions are rarely consistent over time, source level quantification should be updated regularly, and particularly in the case of newly identified sources, modifications of site design and operations, or changes in materiality, operating conditions, or characteristics of existing sources.

2.4 Tree 3 – Measurement based emissions quantification – site/group of equipment

This section guides the selection and deployment of technologies for site level quantification. For the purpose of this report, site level quantification is defined as emissions measurement at the scale of the site and is independent of site measurements at source level. This definition is in line with the one considered in OGMP 2.0[17]. Other definitions for site level quantification have also been presented as part of other guidelines or standards, such as GTI Veritas which defines site level measurements as "Methane measurements taken at spatial scales greater than the component or equipment scale, capable of detecting and/or quantifying emissions without the knowledge of a source level inventory."[18] Tree 3 is also applicable for measurements of a group of equipment (also definable as a functional element), which may be defined as spatially separable areas related to different identified processes.[19] The decision tree below is applicable for site level measurements following the OGMP 2.0 definition, as well as for sites as defined by GTI Veritas which focuses on site level measurements for a spatially distinct set of equipment. The tree does not follow the exact structure of a decision tree since what it presents should be considered simultaneously rather than sequentially. The tree is complementary to the technology filtering tool, highlighting constraints to consider when selecting appropriate site level quantification technologies in the technology filtering tool (see Section 1).

Collecting information on site characteristics, such as location and environmental conditions, helps optimize selection and is necessary for avoiding non-applicable technologies, such as those intended for use onshore when the site is offshore.

Prior to site level quantification, it is recommended to have estimates of total site level emission rates based on source level quantification (as described in Section 2.3), including from routine and non-routine sources and ideally obtained under different operational modes. It is important to define the goal of the site level quantification, which is the entry point for the processes described in this section. The question of frequency of site level quantification is addressed in Section 2.7.6.

2.4.1 What is the aim of the site level quantification?

There are two essential parameters of the site level measurement technology to consider:

- The detection and quantification threshold, above which emissions should be measured.
- The uncertainty of the quantification.

The extent to which these criteria should be fulfilled depends on the goal of the site level quantification.

[17] OGMP 2.02022, https://ogmpartnership.com/wp-content/uploads/2023/02/OGMP-2.0-UR-Guidance-document-SG-approved.pdf
[18] https://veritas.gti.energy/protocols
[19] Innocenti et al.,2023

3 Site-level quantification measurement

The main tool for selecting site-level quantification technology is the technology database. The different aspects present in this document are to be considered simultaneously (as filters) rather then sequentially.

Information required

- Information on site characteristics (location, environmental conditions, other co-located industrial activity ...)
- Objective of site level quantification (reconciliation with source-level inventory, screening assessment for anomalous emissions...)
- Source-level assessment of total emission rates (in different operational mode, if possible) – is recommended to be done prior to site-level measurements, including knowledge of both routine and non routine emission sources – ref Tree 2

What is the objective of the site-level quantification?

	Inform inventory / validation / reconciliation (equivalent to OGMP level 5)	Monitor and address potential super emitters / unexpected sources	Build understanding of temporal variability – continuous
Threshold	Select a technology with a threshold well below expected emission rate determined by source-level inventory – within reasonable costs, logistical and labor efforts with regards to the absolute level of emissions. Very high probability of detection required for the threshold target.	Select a technology with a threshold higher than the total of continuous source, and in line with either super emitter definition for your site or proportionately large emission sources. Very high probability of detection required for the threshold target.	Select technology with quantification threshold (or alarm threshold) that does not generate alarm fatigue (i.e quality degradation due to repetition). Detection threshold can be slightly higher than the total of the continuous sources.
Uncertainty	Technologies with documented uncertainties that consider uncertainty of the sensor and of the method depending on environment conditions.	Requirement on the uncertainty of the quantification depends on whether the quantification will directly be used for inventory or whether the measurement will be combined with other estimation methods.	NA - Currently high to very high uncertainty for all technologies assessed.

Technology constraints to consider when selecting site-level quantification technology:

Validation
Documented, transparent validation of emissions (third party testing, public availability of information, controlled release testing in representative conditions).

Safety
Technologies that respect company and local safety requirements, e.g. ATEX certification, civil aviation requirements, IOGP/company aviation requirements.

Source localization
Selection of technologies that can attribute emissions to desired level (e.g. site or equipment level) and that are appropriate with respect to the facility characteristics (e.g. small/large, congested/geographically dispersed assets).

Availability
Import/export, commercial availability in-country and other restrictions and logistical constraints for technologies.

Operational data
Ensure field data collection at the time of monitoring (operational mode, events, ...) to improve the understanding of operational factors and correlate them to measured levels of emissions.

Environment
Technologies may be impacted by environmental conditions (e.g. cloud cover, snow, precipitation) that undermine their ability to monitor emissions at desired frequency.
Location offshore may also make some technologies not applicable.

Figure 9: Site-level quantification

2.4.1.1 Inform inventory, validation, or reconciliation

When the aim is to develop an inventory or to validate or reconcile emissions (for example, equivalent to OGMP Level 5 or measurement-only reconciliation pathway in the GTI Veritas Protocols[20]), the operator is encouraged to choose technologies with a minimum detection threshold that will capture the majority, such as 90% of expected emissions by the source level inventory. This increases the likelihood of obtaining accurate site level measurements.

Measurement technologies with low detection thresholds should be selected, bearing in mind costs, logistical and labour efforts relative to the level of emissions at the site. At a minimum, they must have a very high probability of detecting known emissions, based on the source level emission rates determined by the inventory, at an aggregate level.

The operator is encouraged to choose technologies for which uncertainties are well documented, including both the uncertainty of the sensor and the uncertainty of the method, which may be impacted by environmental conditions, because uncertainty analysis is at the core of the validation and reconciliation process. Where important temporal variability is proven or expected, it can be interesting to select a technology that can easily be deployed multiple times over the observation period to reduce temporal uncertainty.

2.4.1.2 Monitor and address high emitters and/or unexpected sources

Another objective could be to monitor and address super emitters and/or unexpected sources, which would correspond to a High Minimum Detection Limit (MDL) measurement technology according to GTI Veritas Protocols. Threshold requirements in this case depend on the operator's definition of a "super emitter," as well as what is considered a "large" emission source for the site. Selected technologies need an adequate detection threshold and a very high probability of detection above this threshold. If the goal is only to detect abnormally large emissions, it is recommended to choose a threshold higher than the total of known continuous emissions sources (as assessed by source level quantification).

The requirements regarding uncertainty depend on the goal of the estimates. Uncertainty requirements will differ, for example, depending on whether the quantification will also be used to develop an inventory or whether the measurements will be combined with other quantification methods, such as engineering calculations or process simulation.

2.4.1.3 Build an understanding of temporal variability – continuous quantification

Finally, operators could choose to deploy site level quantification technologies to understand temporal variability of site emissions. This is typically done through continuous site level quantification.

It is recommended to select a quantification threshold (or alarm threshold) that is low enough to measure emissions from the targeted emission sources a sufficient share of the time, but high enough to avoid alarm fatigue, that is, deterioration in the quality of the alarm follow-up due to too many alarms. Usually, the threshold can be slightly higher than the total of the continuous emissions sources.

[20] https://veritas.gti.energy/protocols

In this case, no consideration of uncertainty is required because all assessed technologies that allow for continuous quantification have a high quantification uncertainty[21]. Time series analysis of site emissions should consider this.

2.4.2 Other constraints when selecting site level quantification technology

In addition to adequate threshold and uncertainty, some constraints can impact selection. When evaluating technologies for continuous monitoring of site level emissions, operators may consider constraints regarding:

- validation
- safety
- source localization
- availability
- operational data collection
- environmental conditions

These constraints are included in the technology filters that are described in Section 1.

2.5 Tree 4 - Reconciliation for a single site

This section covers reconciliation between a source level inventory and site level measurement, from either a single site or group of equipment (reconciliation for a group of sites or for a single site with multiple measurements over time is covered in Section 2.6). Many operators have reported that it can be helpful to initially perform a reconciliation exercise on a group of equipment or a small site, as opposed to a large site, since starting small can improve understanding of the connection between source level and site level emissions.

2.5.1 Information required

Before a reconciliation exercise, it is necessary to collect methane emissions data for the target site, including:

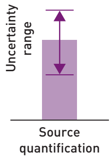
- The conclusive results of a site level measurement, namely:
  - The detection threshold of the technology, considering geographical conditions (such as high latitudes) and applicable environmental conditions (for example, high windspeeds measured at the time of the site level quantification) which may increase the detection threshold.
  - The rate of the site level quantification (if emissions are detected), e.g., 23 kg/h.
  - Uncertainty (e.g., +/- 30%) covering not only the sensors but also the method at the time of the measurement, including consideration of environmental conditions that could have an impact (refer to Section 4.1).
- A source level inventory (refer to Section 2.3 to create one) with uncertainty assessment, if relevant.

[21] See the list of technologies assessed in Appendix B

4 Reconciliation between source level inventory and site level measurement – single site or group of equipment[1] for a single point in time

1 Determine a source level inventory at the time of the site level measurement

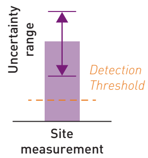
- For each emission source present in the inventory:
  - To the best ability, determine if the source was present at the time of the measurement.
  - Determine the emission rate at the time of the measurement (note that the approach is different between continuous sources and intermittent/event-based sources)
  - A detection device (e.g., OGI) present on site at the time of the site level quantification may inform if an emission source was emitting when the measurement was performed.
- Determine the expected total emission rate at the time of the site level measurement considering all continuous emissions and intermittent/event-based sources occurring at the time.



Notes:
- If step 1 is performed at an early stage, the estimate can inform the technology selection for site level measurement
- If it is not possible to determine a source level inventory at the time of the site level measurement (e.g. if inventory is limited to annual reporting), it is possible to skip and go directly to step 2. However, caution should be taken as this may result in larger uncertainties on the reconciliation performed .

Information required

- Source level inventory (refer to Tree 2)
- Conclusive result of a site level measurement including:
  - Detection threshold of the technology deployed
  - If detected, emission rate of the site level quantification
  - Uncertainty of site level quantification
  - Consideration of weather conditions and geographical site setup

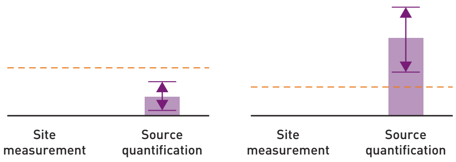


2 Comparison between source level inventory at the time of the measurement and site level measurement-based quantification

Were emissions detected during the site-level measurement? (i.e. emissions above the detection threshold of the measurement technology)

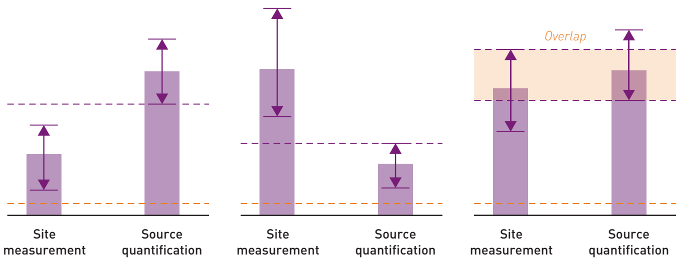
No → Is the source quantification expected to be above the detection threshold?

- **No** → Reconciliation completed – reconsider site-level measurement technology selection (e.g. lower detection threshold) Repeat exercise over time (refer to Frequency section in report)
- **Yes** → Is there a risk that the site level measurement did not capture all emission sources? Is there a potential issue with the site level quantification?



Yes → Is there an overlap between the site-level measurement and the source quantification when considering the uncertainty ranges?

- **Yes** → Reconciliation successful[2] – repeat exercise over time (refer to Frequency section in report)
- **No** → Is the source quantification at the time of site measurement greater than the measured site level emissions?
  - **Yes** → Is there a risk that the site level measurement did not capture all emission sources? Is there a potential issue with the site level quantification?
  - **No** → Are there emission sources that may be overlooked during source quantification? In particular:
    - Unlit flare?
    - Operational issues on the storage tank? (e.g., open thief hatch)
    - Equipment maintenance, or equipment being stopped/started/purged?
    - Equipment upsets/malfunctions?



Is there a risk that the site level measurement did not capture all emission sources? Is there a potential issue with the site level quantification?
- **Yes** → Reconsider site level measurement technology selection (step 3)
- **No** → Identify the emission sources which may be a source of discrepancy in the source quantification.

Are there emission sources that may be overlooked during source quantification?
- **No** → Identify the emission sources which may be a source of discrepancy in the source quantification.
- **Yes** → Perform source level quantification for relevant additional sources (step 3)

Identify the emission sources which may be a source of discrepancy in the source quantification. In particular:
- Emission sources where the quantification is based on generic EF which may not be representative of the site (level 3 in OGMP 2.0)
- Emission sources with high variability over time
- Emission sources which represent an important source of emission and have large uncertainty.

3 Recommended additional measurements/quantification

Reconsider site level measurement technology selection AND/OR Ensure source level quantification and site level measurement cover same emission sources → Repeat from step 1	Improve source level quantification with additional measurement or engineering calculations for emission sources AND/OR Review the quality of the site measurement/uncertainty range and reconsider site level measurement technology → Repeat from step 1	Perform source level quantification for relevant additional sources OR Review source quantification to ensure all emission sources are accounted for → Repeat from step 1

[1] Depending on the site level measurement technique. It is recommended to use group of equipment if possible.
[2] Consideration should be taken if the site-level measurement technology results in a large uncertainty range. In that situation, it is recommended to consider an alternate site-level measurement technology.

Figure 10 - Reconciliation for a single site

2.5.2 Source level quantification

Once the data has been gathered, the next step is determining a source level inventory at the time of the site level measurement. This will be used to calculate an expected value for the site level emission rate. This should be done in a unit that allows comparison with the actual site level measurement, for instance, both measurements might be expressed in mass of methane per hour.

For each of the emission sources in the inventory, the operator needs to:

- Determine whether the source was present at the time of the site level measurement. For example, liquids unloading may be a large source of emissions for a site over the year but may not have taken place at the time of the site level measurement. As another example, a particular compressor may not have been running at the time of the site level measurement, so should be discarded for the reconciliation.
- Determine the emission rate at the time of the site level measurement:
  - For continuous sources with limited variability, rates could be considered as constant (total of yearly emissions divided by the operational time). Or, the rate could be used directly, for example, when the flow of a specific vent is measured continuously with a flowmeter.
  - For variable, intermittent or event-based sources, such as liquids unloading, storage tank loading, equipment blowdown, gas driven pneumatic controllers and pumps, maintenance activities and well casinghead gas venting, it is important to understand if these were occurring at the time of the site level measurement. Other relevant parameters monitored using SCADA, online meters, etc., may also be leverageable and that could indicate how these sources may be emitting. The emission rate may be determined based on either the duration of the event and total emissions, or use of the emission rate directly.

With this data, the expected total emissions rate at the time of the site level measurement can be determined, considering all continuous emissions and intermittent/event-based emissions at the time. A detection device, such as an OGI camera, deployed during the site level quantification can be a helpful tool to ensure that all potential sources are in the inventory.

If the source level inventory is available from an earlier period, this can inform the technology selection for the site level measurement (refer to Section 2.4).

If it is not possible to determine a source level inventory at the time of the site level measurement, some operators have used the yearly average for the reconciliation. This may cause larger uncertainties for reconciliation if a large share of source level emissions at the site is variable, which in turn reduces the relevance of performing reconciliation.

2.5.3 Comparison between source level inventory at the time of the measurement and site level, measurement-based quantification

Once the site level quantification has been successfully performed, the next step is to determine whether any emissions were detected or whether they were below the detection threshold.

If none were detected, it is still possible to draw meaningful conclusions in some cases. For example, if site level emissions were expected to be below the detection threshold based on source level quantification, the fact that no emissions were detected at the site level would suggest that the source level inventory does not exclude a major source of emissions. In that case, reconciliation could be considered completed. It is still recommended to regularly review the appropriateness of the site level measurement technology (see Section 2.4), and repeat the exercise over time (refer to Section 2.7), since reconciliation only represents a particular moment and its validity is therefore time-limited.

If no emissions were detected at the site level, but source level quantification leads the operator to expect emissions above the detection threshold during site level quantification, reconciliation may be indicating issues with either source level or site level quantification, which would need to be assessed.

The first element to consider would be the risk that the site level measurement did not capture all emission sources, or that there is some other problem with the site level quantification. If the risk of this is high, or if another issue with the site level quantification is found, the operator may need to reconsider use of the particular site level measurement technology and/or further ensure that source- and site level measurements cover the same sources. This should be followed up by a new reconciliation exercise.

Alternatively, the operator may ensure source level quantification and site level measurement cover the same emission sources by excluding those from the source level inventory which were not covered by the site level measurement (see Section 2.5.2 above for intermittent events).

If, however, the risk that the site level measurement failed to capture all emission sources is low, and if no other issues with the site level quantification have been identified, a more detailed analysis of the source level inventory would be required. This involves identifying the emission sources which could cause a discrepancy. Priority should be given to reviewing the following types of sources, which have been shown to be more likely than others to cause discrepancies between source- and site level quantification[22,23]

- Sources for which quantification is based on generic emission factors, which may not be representative of actual emissions (ref. Level 3 in OGMP 2.0).
- Sources that are highly variable over time.
- Sources which are expected to represent an important share of site level emissions, but which have a high level of uncertainty associated with their quantification.

[22] Vaughn T, et al.,20187
[23] Zavala-Araiza D, et al.,, 2015

It is recommended to review the source level quantification, supplementing this with measurements or engineering calculations, and to review the reconciliation process from the beginning.

In addition, or as an alternative, before starting the reconciliation process from the beginning, the quality of the site level measurement or its uncertainty range could be reviewed, focusing on the measurement threshold and uncertainty range.

On the other hand, when emissions are detected and successfully quantified by site level measurement, there are three possible scenarios:

- Measured site level quantification is lower than what source level quantification would suggest.
- Measured site level quantification is higher than what source level quantification would suggest.
- Site level and source level quantification are aligned.

For the third scenario, in which there is an overlap between the uncertainty ranges of site level and source level quantification, the reconciliation exercise is considered to be successful. A one-off successful reconciliation is an indication of a satisfactory inventory at a given point in time. Nevertheless, the exercise should be repeated periodically to confirm the validity of the inventory over time and across different conditions. Elements to consider when assessing the frequency of site level measurements can be found in Section 2.7.

If the site level measurement is below the lower uncertainty range for the emissions that could be expected based on the source level inventory, reconciliation has indicated potential issues with source level or site level quantification which would need to be assessed. Like the case in which no site level emissions are detected, the first possibility is that the measurement may not have captured all sources, or that there could be some other issue with the site level quantification. If the risk of either of these is high, or if another issue is detected, an operator should review the selection of the site level measurement technology and/or ensure that source- and site level measurements cover the same emission sources. This step should be followed by a new reconciliation exercise.

However, if the risk of missing sources in the source level inventory is low and no issues with site level quantification have been identified, a detailed analysis of the source level inventory should be conducted to identify the sources which may be causing the discrepancy. As described previously, it is important to review emission sources for which the quantification is based on generic emission factors, that are highly variable over time, and which have a high level of uncertainty associated with their quantification to identify the source of the discrepancy.

It is recommended to review the source level quantification with additional measurements or engineering calculations for relevant sources, and to review the reconciliation process from the beginning. In addition, or as an alternative, the quality of the site level measurement or its uncertainty range could be reviewed by reconsidering the choice of site level measurement technology before redoing the reconciliation process.

If the site level measurement is above the upper-bound of the uncertainty range of the emissions expected from the source level inventory, the reconciliation exercise has indicated potential issues with the source level quantification. Identifying the source(s) of the discrepancy will allow the operator to improve the source level inventory and potentially reduce these emissions.

The first thing to consider when looking at potential reasons that the site level measurement is higher than expected is whether there are any emission sources which could have been overlooked during source level quantification. As mentioned in Section 2.2.2, the following sources tend to lead to large emissions but are not always captured by source level inventories:

- Unlit or malfunctioning flare, or other issues with flare ignition.
- Operational issues with storage tanks, such as an open thief hatch (typically, in the case of onshore operations).
- Maintenance, or equipment being stopped/started/purged during the site level measurement.
- Equipment upsets/malfunctions.

If large sources that could explain the discrepancies are identified, a source level quantification can be performed for the additional sources. The site level quantification should then be reviewed against the revised source level inventory, which should now include the additional sources. The alternative is to review the source level quantification to ensure that all sources are accounted for before comparing it with the site level measurement.

If no large sources that could explain the discrepancy are identified, other, smaller, sources of discrepancies should be reviewed, including the following:

- Sources for which the quantification is based on generic emission factors that may not be representative of actual emissions for the site, such as Level 3 in OGMP 2.0 or GTI Veritas bottom-up inventory methods.

- Sources that are highly variable over time.

- Sources which would be expected to represent an important share of site level emissions, and which have high quantification uncertainty.

It is recommended to review the source level quantification by supplementing with additional measurements or engineering calculations, and to review the reconciliation process. In addition, or alternatively, the quality of the site level measurement or its uncertainty range could be reviewed by reconsidering the site level measurement technology before redoing the reconciliation process.

2.5.4 Additional considerations

The relative size of the uncertainty range affects the outcome of the reconciliation exercise. When looking only at a reconciliation outcome, there is an incentive to favouring technologies with larger uncertainty ranges that may increase the chances of an overlap between the source- and site level quantification uncertainty ranges. Therefore, whether the site level measurement technology results in a large uncertainty range should be established. If so, it is recommended to select alternative site level measurement technology. In some cases, the selected technology may be the most suitable technology and is expected to be able to capture the majority of emissions, or if it is in line with local regulation minimum detection threshold requirements. It may also be recommended to perform additional measurements with the same technology within similar conditions when emissions are expected to be similar. Either of these could reduce the uncertainty of the site level measurement and increase confidence in reconciliation.

In general, there may be limitations to performing these snapshot reconciliation exercises. For example, this may be due to the challenges with deriving source level uncertainty estimates, which can be technically challenging and time consuming. Methane emissions can be highly variable over time (see Section 2.7.3), such that conducting site/facility-level measurements may result in high levels of uncertainty. The extrapolation of these measurement beyond the measured time frames will also introduce additional uncertainty. Therefore, this typically does not allow an annual inventory or reporting with a satisfactory level of certainty. Reconciliation is intended to be repeated. The main objectives are to learn from the reconciliation to improve the quality of the quantification and reporting and to achieve emission reductions. Operators can conduct site level measurements and reconciliation that cover various conditions and patterns. Reconciliations do not need to be performed using the same technologies. The process described above can be adjusted to reflect different detection thresholds and uncertainties of the site level measurement technologies used as part of the time-series analysis. Combinations of technologies can be used in measurement and reconciliation over time. For example, multiple site level measurement technologies may be combined to increase measurement coverage of site level emissions. Examples can be found in Section 3.

2.6 Tree 5 – Reconciliation for a group of sites

This section covers the decision tree for reconciliation between a source level inventory and a site level measurement from a group of sites for which there are measurements from a point in time, or from a single site with measurements over time. The aim is to understand reconciliation exercises involving many site level measurement data points (Reconciliation of a single site with site level measurement performed at a single point in time is covered by Section 2.5.). This is intended as a simplified approach, however, other approaches for reconciliation exist, such as the one proposed by GTI Veritas.

If sites are not similar, the grouping of sites should define subgroups of 'like' systems. In addition, given the loss of precision compared to single-site reconciliation, it is recommended to follow this methodology only in cases where it is challenging or expensive to perform many single-site reconciliations (refer to Section 2.5).

These multi-site measurements can provide a wealth of additional or more granular observations and interpretations. Some groups, organizations, and researchers have developed more advanced methodologies to reconcile emissions across large samples.

5 Reconciliation between source level inventory and site level measurement – multiple sites/multiple measurements[1]

1 Use this tree?

Are there many similar sites or many site level measurements of the same site? Is it logistically challenging or very expensive to perform many, single site reconciliations?

No → Perform multiple, single site reconciliations (refer to tree 3) OR Review site grouping

Yes ↓

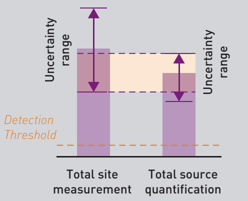
Information required

- Conclusive result of a sample of site level measurement including:
  - Detection threshold of the technology deployed
  - If detected, emission rate of the site level quantification
  - Uncertainty of site level quantification
  - Consideration of weather conditions and geographical site setup
- It is assumed that the operator has a source level inventory available for all sites in the sample

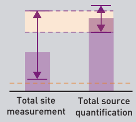
2 Compare site level and source level estimates

Source quantification for the sites	=	Average of source-level quantifications of the sites or of the site (refer to tree 2)
Uncertainty of source quantification (optional)	=	Total uncertainty or statistical analysis of the source-level quantification of the sites – Propagation of uncertainty
Site-level measurements of the sites	=	Average of site level measurements
Uncertainty of site-level measurements	=	Total uncertainty or statistical analysis[2] of the site level measurements – Propagation of uncertainty

Overlap between site- and source-level quantification?



Yes → **Large uncertainty?** The uncertainty range is very wide, the reconciliation may be successful in theory but without robust insight



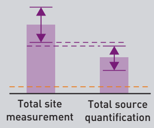
Yes → Consider an alternate site level quantification technology

No → **Reconciliation successful** Consider performing site level (tree 3) reconciliation on a few sites, which will provide additional insight

No ↓

3 Root cause analysis of discrepancies in reconciliation – source level quantification

Not capturing all emissions?
Are there emission sources that may be overlooked during source quantifications? In particular:
- Unlit flare?
- Operational issues on the storage tank? (e.g., open thief hatch)
- Equipment maintenance, or equipment being stopped/started/purged?
- Equipment upsets/malfunctions?



Yes → Add sources to source quantification (refer to tree 2) and start step 2

No ↓

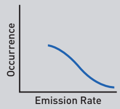
Miscalculated emission source?
Identify the emission sources which may be a source of discrepancy in the source quantification. In particular:
- Emission sources where the quantification is based on generic EF which may not be representative of the sites (e.g. level 3 in OGMP 2.0)
- Emission sources with high variability over time (liquids unloading, equipment blowdown, starts and stops, casinghead gas venting, ...)
- Emission sources which represent an important source of emission and have large uncertainty

Yes → Review existing source quantification (refer to tree 2) and start at step 2

No ↓

Root cause analysis of discrepancies in reconciliation – site level quantification

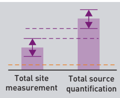
Detection threshold too high?
Missing an important share of the total distribution of emissions, including smaller emission sources. This can result in both an over- or an under-estimation of site-level measurements. If technologies with different detection thresholds are used, this can be built into the statistical analysis of the emissions curve and identified super emitters can be used to inform and improve source-level inventory.



Yes → Consider an alternate site level quantification technology

No ↓

Not capturing all emissions?
Site level measurements may not capture all the emission sources (for example an equipment a bit on the side) or the distribution of different operational modes or upsets, neighboring emission sources, intermittency etc.

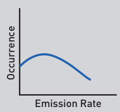


Yes → Either perform more site level measurements or exclude the emission sources missed from the source level estimate and start from 2

No ↓

Root cause analysis of discrepancies in reconciliation – sampling strategy

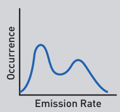
Sampling?
There is not enough points to fully understand the distribution. This can result in an unsatisfactory estimation of the average and uncertainty of the site-level measurements.



Yes → Do more site level measurements

No ↓

Grouping of sites considered as similar?
After statistical analysis, the distribution indicates that the population of initially considered similar sites may not have similar enough emission characteristics.
Note: not relevant for multiple site quantification for a single site



Yes → Review site grouping, separate the original population into two or more groups and restart from step 2 for each group

[1] The tree is presented for multiple sites – the approach is similar if the operator has performed many site level measurements for one site
[2] Where site quantification technologies with different detection thresholds are used, this should be reflected in the total uncertainty and/or statistical analysis

Figure 11 - Reconciliation between source level inventory and site level measurement

2.6.1 Required information

Before reconciling, collect methane emissions data for the target sites in the group (or for the single target site over time), including:

- The conclusive results of a site level quantification, including:
  - The detection threshold of the technology, considering geographical conditions (such as high latitudes) and environmental conditions at deployment (for instance, high windspeeds measured at the time of the site level quantification) which may increase the detection threshold.
  - The rate of the site level quantification (if emissions are detected), e.g., 23 kg/h.
  - The uncertainty of the site level quantification, covering the uncertainty of the sensors and of the method, including consideration of environmental conditions which can have an impact (refer to Section 4.1).
- A source level inventory (refer to Section 2.3) with uncertainty assessment if relevant.

2.6.2 Compare site level and source level estimates

Once measurements have been taken and results are available, the site level and source level quantifications can be compared to identify if the results are consistent.

Four different elements are required for the analysis:

- Source quantification for the sites is the average of the source level quantification exercises of the sites (or site) included in the analysis (refer to Section 2.4).
- Uncertainty of source level quantification is the total uncertainty of the source level quantification exercises of the sites, taking into consideration spread of uncertainty throughout the measurements. This parameter is optional. The analysis can be conducted without this information, which may be difficult to obtain depending on the approach. However, use of uncertainty levels increases the rigour of the analysis and the reliability of the results.
- Site level measurement of the sites is the average of all the site level measurements considered in this study, relying on statistical analysis where relevant.
- Uncertainty of site level measurements is the total uncertainty of the site level measurements, taking into consideration the spread of uncertainty throughout the measurements. Uncertainty typically decreases when the number of measurements increases. When the result of a site measurement has been inconclusive or below the detection threshold, the operator should consider this uncertainty as well. If site level measurement technologies with different detection thresholds are used, this can be reflected in the total uncertainty using statistical analysis, by considering the share of emissions potentially not captured by the site level measurements. Alternatively, two analyses can be conducted, segregating the data from the different technologies.

Once these data have been obtained, one should look for an overlap between:

- The total of site level measurements and its uncertainty range (from now on, referred to as "total site measurements").
- The source level quantification and its uncertainty range, if available (from now on, referred to as "total source quantification").

Where the total source quantification falls within the range of the total site measurements, the reconciliation exercise can be considered successful for the group of sites. For more information, one could perform single-site level reconciliation (refer to Section 2.5) for a sample of sites included in the analysis.

When total source quantification falls within the uncertainty range of total site measurements due to a very wide uncertainty range of the total site measurements, the reconciliation can, in theory, be considered successful. However, the value it provides might be limited. When this happens, it is recommended to re-evaluate the selection of the site level quantification technology, or to perform additional measurements with the same technology.

2.6.3 Root causes of discrepancies in reconciliation

This section presents possible explanations for unsuccessful reconciliation and how these can be addressed.

2.6.3.1 Root causes associated with source level quantification

Where the total source quantification is less than the total site measurements, the first potential root cause to explore is whether any emission sources were not properly captured in the total source quantification, in particular:

- Unlit, malfunctioning, or inefficient flares.
- Operational issues on the storage tank, such as an open thief hatch (in the case of onshore operations).
- Maintenance or equipment being stopped/started/purged.
- Equipment upsets/malfunctions.

If certain sources have been overlooked in the total source quantification, these should be added to source quantification (refer to Section 2.3). From there, the comparison between total site measurement and total source quantification can be re-evaluated (refer to Section 2.6.2).

If no sources have been overlooked for source level quantification, another possible cause for discrepancy between total site measurement and total source quantification is an error in the quantification of an emission source. To remedy this, identify the emission sources which may be a cause of discrepancy in the source level quantification. As noted in previous sections, sources that could cause such discrepancies include:

- Sources for which the quantification is based on generic emission factors that may not be representative of the sites (e.g., Level 3 in OGMP 2.0).
- Sources with high variability over time (such as liquids unloading, equipment blowdown, starts and stops, and casinghead gas venting).
- Sources which are expected to represent an important share of site level emissions but have a high level of uncertainty associated with their quantification.

If such sources are identified, their quantification should be reviewed (refer to Section 2.3). After this, the comparison between total site measurement and total source quantification should be re-evaluated (refer to Section 2.6.2).

2.6.3.2 Root causes associated with site level quantification

Another path to explore when looking for root causes of discrepancies between total site measurements and total source quantification is problems with the site measurement itself.

First, the operator should assess if the detection threshold for the site level measurement technology is well adapted to the sites included in the analysis. An unsuited threshold can lead to an under-estimation of site level emissions. If the detection level is high compared to the distribution of emissions across the group of sites, an important share of total emissions could be missing, including smaller sources. If statistical analysis establishes that the detection level of the selected site level technology is too high, an alternate site level measurement technology should be selected, or additional measurements can be carried out to reduce uncertainty. If several site level measurement technologies with varying detection thresholds are used, this can be included in the analysis to evaluate if a sufficient share of emissions are captured by the combination of technologies. Site level technologies can be deployed for other purposes, such as super-emitter monitoring. Where super-emitters are identified, the data can be used to improve source level inventory.

Other possible explanations for discrepancies linked to site level quantification are that the site level measurement may not have captured all emission sources, such as equipment located far from the main facility. Or, it may not have properly accounted for the distribution of the different operational modes or upsets, neighbouring emission sources, intermittency, and so on. In such situations, it is recommended to perform more site level measurements or exclude the missed emission sources from the source level estimate and review the comparison between site level and source level estimates.

2.6.3.3 Root causes associated with sampling strategy

Another root cause of discrepancies in reconciliation may be found in the sampling strategy. For example, the site level measurement sample may not have enough points to portray the distribution of site level emissions, resulting in unsatisfactory estimates for the average and uncertainty of the site level measurements. To correct this situation, additional site level measurements would be required.

The way the sites have been grouped for the analysis could provide an explanation. Statistical analysis would be required to identify whether a group of sites initially considered "similar" might not be similar enough in terms of their emissions characteristics. In such a case, the site grouping should be reviewed to separate the original single group into two or more groups, followed by a review of the site level and source level comparison for each group.

The size of the sample is dependent on several factors, including, but not limited to, the population size, the shape of the distribution, the complexity of the site, the variability of emissions and operations. Statistical analysis is required to ensure the full distribution of site level emissions is captured in the sample.

This exercise can be repeated to provide a better understanding of emissions over time (refer to Section 2.7 for frequency of reconciliation).

2.7 Tree 6 – Reconciliation to produce a single Measurement Informed Inventory (MII)

This section covers the decision tree for reconciliation to produce a single, Measurement Informed Inventory (MII) that relies on both measurements and calculations. The decision tree follows the GTI Veritas Measurement and Reconciliation Protocol. An MII is defined in the February 2024 *Source-Level Measurement and Reconciliation Protocol* for the upstream segment as follows: "An inventory that is predominantly informed by data from methane measurements of the assets and sources in the inventory, where predominantly means methane emissions quantification informed by measurement can be based on 100% sample size or based on a statistically representative subset of samples. *This definition is different from the Veritas Protocol*.[24] The aim is to develop an annual inventory estimate of total methane emissions for a group of equipment, site, or group of sites.

2.7.1 Step 1: Define Scope and Identify Emission Sources

The first step to develop an MII is to define the scope of sources to be included. The scope may be established at different levels, including:

- A single site.
- All sites within a certain production region.
- All operated sites.

Once the scope is defined, the operator should identify all emission sources within the scope boundary. Operators can refer to Tree 1 in Section 2.2 to assist in the development of a list of emission sources. Otherwise, the operator can continue to Tree 2 or another source-specific inventory protocol.

2.7.2 Step 2: Categorize and Stratify Emission Sources

All emission sources identified in Step 1 may now be categorized as one of the following:

- Best Calculated: sources whose emissions are not well characterized by snapshot measurements and/or are more accurately estimated by engineering approaches or EFs, for example:
    1) Sources whose activity is tracked, or emission times are bounded by independent means like SCADA systems or other activity records.
    2) Sources that are expected to be below detection limits of deployed measurement technologies, intermittent, and/or short in duration.
- Best Measured: sources whose annual emissions are accurately estimated using measurements. Technologies or methods for direct measurements of sources in the 'Best Measured' category can be selected by the user. Sources that combine measurements with engineering calculations can be categorized as 'Best Measured'.

The operator may also refer to Tree 2 in Section 2.3 for further guidance on determining the best method for quantifying each emission source.[25]

[24] OGMP 2.0, 2022, https://ogmpartnership.com/wp-content/uploads/2023/02/OGMP-2.0-UR-Guidance-document-SG-approved.pdf
[25] Higgins S, et al., 2024doi: https://doi.org/10.2118/219445-PA

After categorization, the operator will stratify emission sources. Stratification may assist in the development of emission distributions (Section 2.7.3) and developing sampling and measurement strategies (Section 2.7.4). Stratification can be performed using various approaches, including:

- Per emission sources that are best measured.
- Using natural groupings, such as business units or sites within discrete regions.
- By facilities or emission sources that have similar characteristics, such as the age of equipment, expected emissions, site complexity, temporal variability, or intermittency of emissions.

Stratification can be performed at different levels of granularity, such as at site, group, or equipment-level, and it is up to the operator to choose an approach based on their own operations. Since stratification is meant to influence the sampling and measurement strategy, stratification should be influenced by the emission characteristics of the Best Measured sources.

2.7.3 Step 3: Establish Initial Inventory and Expected Emissions Distribution (EED)

An initial inventory should be developed to provide an estimate of annual emissions of all emission sources included in the analysis and can be performed for each stratum created in Step 2. If this is the first year of developing an MII, an EED can be developed based on several options:

1) Publicly available datasets, such as the US EPA Greenhouse Gas Reporting Program (GHGRP), the Greenhouse Gas Index (GHGI) or the Natural Gas Sustainability Initiative (NGSI).
2) A source level inventory developed using Tree 2 or a similar program.
3) An important note is that the GTI Veritas Protocols allow an exception to constructing an EED in the first year of reporting. As there are many ways to develop an EED, it can be both time and resource-consuming for some operators, and this step may therefore be skipped in the first year.

In subsequent years of developing an MII, an EED may be developed using the previous year's MII to help inform sampling and measurement strategies. This allows an operator to have a better understanding of anticipated frequency or intermittency of emission rates for their own assets based on information specific to their sites and emission sources.

2.7.4 Step 4: Develop Sampling and Measurement Strategies

The GTI Veritas Source-Level Measurement and Reconciliation Protocol requires an MII to be based on either a 100% sample size (i.e., all of the sources are measured) or a "representative unbiased sample of all sources within an asset".

Other objectives may also be set by the operator, such as quantifying the MII with a given uncertainty, quantifying a certain percentage of emissions from high-emitting sources, improving understanding of certain emission sources, developing an MII with lower total emissions or uncertainty each year, or to screen with a sufficiently low detection limit technology such that inventories are accurate.

Based on the objectives, the operator can identify methane detection and quantification technologies that may be relevant using the technology filtering tool[26] and accompanying guidance in Section 1. Consideration should be taken regarding the ability of technologies to detect, quantify, and localize emissions. Operators may use a combination of technologies, including technologies that can detect and quantify at different levels (site, equipment, or component).

The technologies should be subsequently selected for deployment, based on the objectives defined in Step 4a, the initial inventory developed in Step 3, and Tree 2 (source level quantification).

Next, a survey plan should be established. All sites included within the scope should be surveyed at least once. Operators can also refer to Section 2.8 for elements of frequency for site level measurement. The survey plan should be documented, including a description and rationale for selection of the measurement campaign objectives, the deployment technologies, and the frequency of deployments.

2.7.5 Step 5: Deploy Technologies and Collect Data

Next, the measurement technologies should be deployed following the survey plan. During measurements, additional non-measurement data such as operational data, occurrence of emissions that are best calculated, results of follow-up investigations of leak indications or alerts, activities to support the estimation of event durations, and environmental data should be collected to analyse the data and evaluate data quality.

2.7.6 Step 6: Analyse Data and Evaluate Quality

The next step in developing an MII is to start data analysis to ensure quality measurements are being used. Reliable emissions inventories require accurate data, which can be compromised by sensor failures, transcription errors, omissions, or other issues. Before using the data, it must be checked for quality, completeness, and accuracy. As part of this process, operators should begin analysing key data properties like the number of detections, average emission rates, standard deviation, event duration, and emissions distribution.

Operators should perform data quality checks to look for unusual or untrustworthy measurements, including anomalies or outliers, or measurements of emissions that are not attributable to the operator's own sites or activities.

[26] https://www.iogp.org/workstreams/environment/environment/methane-emissions-detection-and-quantification/methane-detection-and-quantification-technology-filtering-tool/tool/

Specific environmental conditions that may influence the measurements should also be considered, including high or variable wind speeds; presence of precipitation, cloud cover, snow cover, or humidity; very high or low temperatures; complex topography; or obstructions of measurements.

The evaluation can be supported by the non-measurement data collected at the same time as measurements were performed, such as data gathered using SCADA or other continuous monitoring systems, periodic LDAR, or an OGI camera deployed at the time of measurements.

2.7.7 Step 7: Choose Reconciliation Pathway

Operators have two options to select from when performing reconciliation. The first option is the measurement-only pathway, which is based entirely on measurements. To select this pathway, operators must use a technology that is sensitive enough to detect and quantify over 90% of emissions with measurements and also provides full spatial coverage of the inventory. In the measurement-only pathway, the MII is the sum of all measurements, ERm. This option can be selected without completing cause analysis or collecting operational data. However, this option is not currently widely implemented and is therefore more intended for the future when technology capabilities improve. It is not expected that operators will select this option, and will instead use the second option, the hybrid pathway.

The hybrid pathway includes emission estimates using both measurements and calculations. Measurements can be performed with a measurement technology that supports the attribution of emissions to sources.

2.7.8 Step 8: Reconcile Inventories and Estimate Measurement Informed Inventory (MII)

For the measurement-only pathway, the MII is calculated as the sum of ERm. No additional EFs of engineering calculations are required for this pathway, and the user can proceed to Step 9.

For the hybrid pathway, emission sources are determined as one of the following:

1) If an emission source is Best Calculated, the emission is estimated using engineering calculations or engineering factors (as detailed in Tree 2 or another source-specific inventory protocol) and the emission source is defined as ERc.
2) If the emission source is not Best Calculated (i.e., it is Best Measured), the next step would be to determine if a quantification technology is able to quantify the emission rate.
    a) If so, the emission source is defined as ERm, and the measured emission rate is used.
    b) If the emission rate was not measured by the quantification technology (for example, if the emission rate was below the technology's detection threshold or not measured), the emission source is defined as ERb, and the emission rate will be determined using relevant emission factors or engineering calculations.

The MII is then calculated as the sum of all ER_m, ER_c, and ER_b.

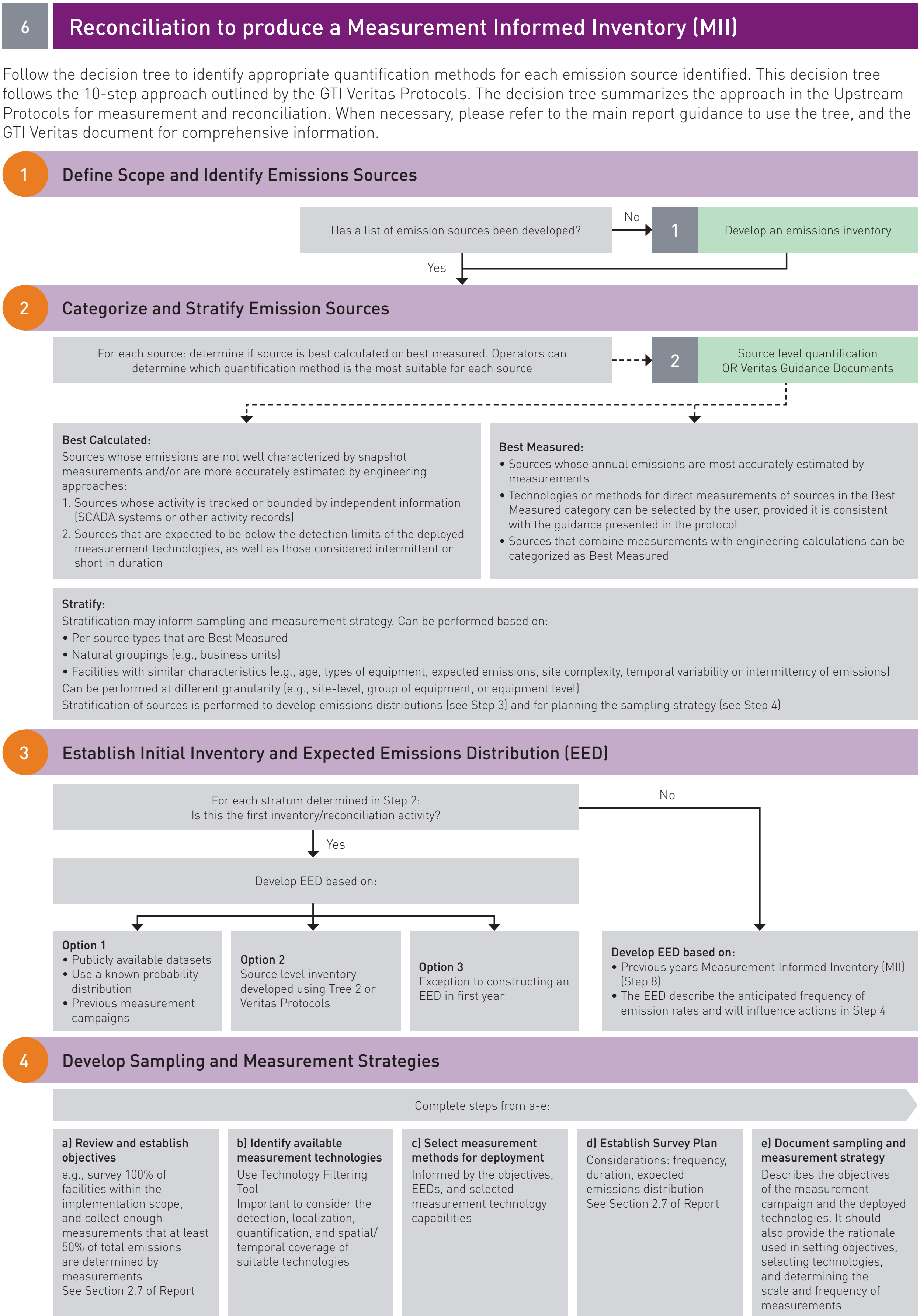


Figure 12 - Reconciliation to create a single Measurement Informed Inventory (MII)

5 Deploy Technologies and Collect Data

- Deploy measurement technologies and implement sampling plan. This can be a single technology, or combination of detection devices, source-level quantification, or site-level quantification technologies
- In addition, collect non-measurement data (operational data, occurrence of emissions that are best calculated, results of follow-up investigations of leak indications or alerts, mitigation action to support estimation of duration of events, environmental data)

6 Analyze Data and Evaluate Quality

Data quality checks, cleaning, and analysis

Consider looking for:

- Unusual observations
- Untrustworthy measurements/outliers
- Measurements that are not attributable to the operator's own operations and/or facilities

Specific environmental considerations:

- Variable wind speed/direction
- Precipitation, snow cover, and humidity
- Proximity to a body of water
- Temperature
- Cloud cover
- Complex topography, obstructions

Use of operational data to determine causes and durations:

- SCADA or continuous monitoring system data
- Periodic LDAR

7 Choose Reconciliation Pathway

Measurement-Only Pathway[1]

- Inventory based on measurements and optionally supplemented for sources below a technology detection limit
- Requires sufficiently sensitive technology to detect >90% of total emissions, provides full spatial coverage, and produces estimated emission rates for all detection events

Can be implemented without cause analysis for each source, and can be implemented without operational data

OR

Hybrid Pathway

- User will use emission estimates from both measurement and calculations
- Measurements can be performed using source level or site level measurements. If from site level measurements, cause analysis should be performed to attribute emissions to emission sources (as determined in Step 6) which requires measurement approaches with sufficient spatial resolution for source-level attribution

8 Reconcile Inventories and Estimate Measurement Informed Inventory (MII)

For Measurement-Only pathway

$$\mathrm{MII} = \sum ER_m$$

Is the emission source best calculated?

- Yes → ER_c: Determined using engineering calculations/emission factors (refer to Tree 2)
- No → Was emission rate quantified using quantification technology?
  - Yes → ER_m: Determine emission rate using Measurements as determined by Tree 2 or Veritas Protocols
  - No → ER_b: Determine emission rate using emission factors or engineering calculations as determined by Tree 2 or Veritas Protocols

For hybrid pathway

$$\mathrm{MII} = \sum ER_m + \sum ER_c + \sum ER_b$$

Note on uncertainty quantification:

ER_b: based on uncertainty associated with the frequency and/or duration of events, depending on calculation method

ER_c: based on the uncertainties associated with the underlying emissions modeling and calculations used to develop the estimate

ER_m: should be based on the uncertainty associated with emission source frequency, duration, and emission rate

As per the GTI Veritas Protocols, uncertainty estimates are optional. There is no one-case-fits-all method to determine uncertainty. Please refer to GTI Veritas Protocols for an in-depth analysis of potential methods to use to determine uncertainty

9 Evaluate Objectives

Were objectives set in Step 4a met?

- Yes → Objectives met. Repeat in next reporting period
- No → Update objectives for next reporting period

10 Develop Report: Refer to GTI Veritas Protocols

[1] Note the measurement-only pathway is not currently realistic or widely implemented. It is expected that most operators follow the hybrid pathway.

Figure 12 (continued) - Reconciliation to create a single Measurement Informed Inventory (MII)

2.7.9 Step 9: Evaluate Objectives

The results of the MII are evaluated in comparison to the objectives set in Step 4. If objectives were met, the operator is encouraged to repeat the activities in the following reporting period. If the objectives were not met, the objectives should be updated, and the same reconciliation exercise should be repeated in the following period. Reconciliation is an iterative process, and inability to meet objectives is not seen as a failure: rather, it should be used to better understand and continuously improve the emissions inventory.

2.7.10 Step 10: Develop Report

While not covered in this Report, Step 10 is to develop a report in line with the GTI Veritas Protocols. Please refer to the protocols for full report guidance.

2.8 Elements of frequency – site level measurement-based quantification

An essential question of methane emissions detection and quantification is the frequency of deployment, or how often quantification connected with reconciliation should be conducted. There is no single answer to this question, which depends on many factors including site configuration, local legislation, operational characteristics, expected emissions patterns or persistency, the type of technology used (for example, facility level vs. source level), monitoring of other parameters already in place, historical record of successful reconciliation, and the costs and benefits of technology deployment.

This section covers how to determine the frequency of reconciliation between source level and site level emissions quantification. This is different from the frequency of LDAR, which may depend on other factors such as local regulation and the emissions reduction targets and guidelines of the company. Furthermore, LDAR is a mitigation tool independent of site level measurement and reconciliation.

Frequency is linked to a cost-benefit assessment which identifies the frequency that allows the operator to maximize knowledge within acceptable costs. Interviews and literature review have highlighted several drivers that could impact a decision to change the frequency of reconciliation, notably:

- History of successful/unsuccessful reconciliation.
- The presence of potential super emitters.
- Degree of understanding of emissions variability during different operational modes and of factors that could increase variability.
- Advantages from combining detection/quantification technologies.

2.8.1 History of successful reconciliation

A history of successful reconciliation at a site or group of sites demonstrates an understanding of the variability of the methane emissions over time. It also indicates that the quantification methods have a good track record of capturing all emissions at those sites and that there are likely no continuous, unexpected emissions. In such cases, the operator may consider reducing the frequency of the reconciliation exercise.

Sites where the operator has only recently begun to investigate methane emissions reconciliation, or where they have conducted reconciliation exercises with unsatisfactory results, may require more frequent reconciliation for the operator to better understand those sites' emission sources and their variability.

2.8.2 Potential super emitters

One of the main challenges of any methane inventory is to understand the "fat-tail" distribution, i.e., the presence, likelihood, and time variability of "super emitters" or super-emitting events. Some equipment, processes, and operational practices have been documented in peer-reviewed literature to be important potential sources of super emitters or generators of super-emitting events.[27,28, 29, 30] These notably include, but are not limited to:

- Gas flares.
- Un-stabilized condensate or crude oil storage tanks.
- Upset/malfunctioning process conditions.

If equipment, processes, or operational practices that are likely to lead to super-emitting events, or to become super emitters, are present, more frequent reconciliation may be needed. Operators may also consider direct or permanent monitoring to identify the potential cause of a super emitter. For example, the operator could continuously monitor the flare ignition to ensure that unlit-flare events are tracked and understood, reducing the need for frequent site level measurements.

2.8.3 Understanding emissions variability

The time variability of emissions can be impacted by variations in operating modes, including but not limited to:

- Full operation.
- Partial operation.
- Starts and stops.

Clear understanding of how emissions vary over the different operating modes of a site or equipment reduces uncertainty related to the reconciliation exercise. The link between emissions and operating mode can provide useful input on when to perform reconciliation that most effectively covers the different operating modes. It can also help the operator demonstrate a good understanding of the time variability of emissions at the site in

[27] Zavala-Araiza D, et al., 2017
[28] Brandt A, Heath, G. A., Cooley, D., 2016
[29] Tyner D, and Johnson M., 2021
[30] Cusworth D, et al., 2021

question. This in turn helps justify performing a reconciliation exercise less often at that site than at a facility where such an understanding is more limited.

Some factors can increase the variability of emissions within an operating mode, increasing the range of conditions that reconciliation should cover. This could lead to more frequent reconciliation to ensure that such factors are properly captured. Such factors include, but are not limited to:

- Seasonal/climatic variations impacting processes.
- Variability of key processes, such as, variability of the load of the turbines, number of compressors in operation, volume of flared gas.
- Non-continuous processes, such as loading and unloading.
- Processes with operating pressure close to or above design pressure.
- History of incidents, malfunctions, or other super-emitting events.

2.8.4 Combining different technologies[31]

Factors linked to detection and quantification technologies can impact the frequency of reconciliation. For example, some technologies are better suited to detecting and quantifying smaller emission sources, while others are better at picking up larger ones. Combining different source level detection and quantification technologies can help gain a fuller picture of methane emissions throughout the site. This is important, as site level quantification is intended to capture methane emissions from all sources. If a section of the emissions distribution curve is not captured, it could lead to unsuccessful reconciliation.

A history of successful reconciliation is an important criterion to consider when determining the frequency of reconciliation. Combining technologies can increase the chance of successful reconciliation and therefore reduce the frequency of this exercise.

When source level quantification technologies are combined with continuous measurement systems, the continuous measurement systems help identify intermittent emissions events while source level quantification helps identify the expected sources of such events. This can be done alongside operational data collection, which can indicate the source of the high-emitting events. If no such combination is in place, it may be required to perform the reconciliation exercise more often to successfully capture those events in the analysis.

One source of added complexity is combining measurements from different technologies, or repeating measurements consecutively. Recent peer-reviewed research concluded that the variability of emissions from multiple site level measurements do not always agree with one another[32]. Therefore, aerodynamic effects, site layout, and unconsidered algorithm or model uncertainties may contribute to additional challenges in assessing the results of the site level measurements.

[31] Reference Section 3 below for examples of technologies combinations

[32] Brown et al., 2023

2.8.5 Large-scale reconciliation

Finally, reconciliation can be performed for a single site or a group of sites. Conducting the analysis for a group of sites can reduce the influence of operating modes and of variability within operating modes. This is because taking site level measurements of a large number of sites is likely to capture a broad range of operating modes, as well as a broad range of factors impacting emissions within different modes, such as variability of key processes and non-continuous processes. However, capturing the variety of operating modes this way will lead to limited insights at the site level, making identification of mitigation options for processes or pieces of equipment at specific sites more difficult.

Not all problems related to time variability can be reduced through this process. Factors such as climatic variations that impact processes, as well as processes operating at pressures close to or above design levels, will typically not be reflected using this approach.

2.8.6 Overview of factors influencing frequency of reconciliation

The following table summarizes qualitative factors influencing the frequency of reconciliation.

Table 1 - Qualitative factors influencing site level quantification and reconciliation.

Factors that could justify a lower frequency:	Factors that could justify a higher frequency:
There is a long history of successful reconciliation.	There is not a long history of successful reconciliation.
No equipment, processes, or operational practices are likely to become super emitters or to generate super-emitting events.	There are equipment, processes, or operational practices likely to become super emitters or to generate super-emitting events.
The operator has a good understanding of how emissions vary across the different operating modes.	The operator has limited understanding of how emissions vary across the different operating modes.
The operator has a good understanding of factors impacting the variability of emissions within operating modes.	The operator has limited understanding of factors impacting the variability of emissions within operating modes.
There is a continuous monitoring system of emissions and/or of key parameters influencing the variability of emissions.	There is no continuous monitoring system of emissions and/or of key parameters influencing the variability of emissions.
Reconciliation is performed for a group of sites.	Reconciliation is performed for a single site.

3. Technology combinations

Most methane emissions detection and quantification technologies are not well suited for every type of emission source, size, or deployment purpose. Combinations are often used to cover some shortcomings. No "one-size-fits-all" combination has been identified since the needs of operators and the conditions at facilities vary.

For example, a source with variable emissions may require more frequent measurements to properly characterize its emissions. It may require different characteristics from those required for monitoring sources with continuous emissions. Other factors impacting selection include expected emission patterns, which can inform the proper capture of the fat-tail emissions distribution.[33,34,35] Finally, the expected quantity of methane emissions from a source can affect the selection of an appropriate detection threshold.

This section presents several examples of combining technologies for methane emissions detection and quantification, showing the selection process, criteria, and challenges experienced by operators. These examples are not intended to serve as guidelines or recommendations, but to share experiences between operators regarding specific situations.

3.1 Example 1 – Framework for combination of numerous technologies

A peer-reviewed article[36] published in 2022 presents a quantification, monitoring, reporting, and verification framework that uses periodic monitoring (such as satellites, aircraft-based measurements, or drones) along with continuous monitoring of emissions to reconcile measurements with inventory estimates. The framework also considers intermittent emissions, which may have high intra-day variability.[37] A quantification, monitoring, reporting, and verification program with up to two phases is outlined:

- The first phase uses monthly, systematic detection surveys (which consider all emission sources, not just leaks) or periodic, aerial- or drone-based measurements. The addition of audio, visual, and olfactometry surveys, United States Environmental Protection Agency (US EPA) Method 21 or other techniques are used to capture intermittent emissions.
- Over time, a second phase is launched using continuous monitoring solutions to capture intermittent or short-duration events, providing real-time verification of large events that may be missed by periodic monitoring.

The article demonstrates how continuous monitoring, paired with an increased understanding of site level events, are key to an accurate accounting of short-duration, intermittent, and high-volume events that are often missed in periodic surveys and to annualize these measurements.

[33] Frankenberg, C., et al., 2016
[34] Irakulis-Loitxate I et al., 2021
[35] Zavala-Araiza D, et al., 2017
[36] Jiayang Lyra Wang, et al., 2022
[37] Stokes S, et al., 2022

3.2 Example 2 – Framework for combination of numerous technologies

A recent peer-reviewed article[38] presents an 11-month methane measurement campaign at oil and gas production sites to improve conventional, bottom-up inventories by incorporating aerial-based site level measurements and continuous monitoring. Basin and operator-level, aerial-based, top-down measurements show lower methane emissions at end-of-project than during the baseline nine months earlier. This is potentially due to temporal variability, or emission reduction activities and monthly LDAR. The paper presents a case study investigating a 94% difference in bottom-up vs. top-down measurements at an unspecified production site. Top-down estimates were 1.8 times higher than an average emission rate estimate using continuous monitoring, suggesting temporal variability of measurements contributes to the estimate discrepancy. Further analysis showed the bottom-up inventory overestimated emissions for five months and underestimated them in the final two months. This was attributed to a gas processing unit swap, which matched with observed emission rates from continuous monitoring systems. The study also highlights the importance of record keeping of one-time events, maintenance, or upsets to help interpret continuous monitoring data when performing reconciliation with site level measurements.

The case serves as proof of concept to use continuous monitoring solutions to assess validity of periodic, top-down measurements and determine their relation to the temporal emission profile of a given site.

3.3 Example 3 – Simulations of technology combinations

A recent peer-reviewed article[39] shows the benefits of combining satellite, aerial, and continuous monitoring with OGI in a tiered approach, compared to OGI inspections alone.

The paper simulated combinations of methane detection technologies for facilities representative of the Permian Basin, where extensive datasets are available. Emission distributions in this region follow highly skewed emission rates with many high emitters and emissions spanning six to eight orders of magnitude. These datasets may not be representative of distributions and measurement capabilities in all regions.

Results found that combinations of technologies achieve larger reductions than single technologies. For example, a combination of satellites with daily surveys, aerial technologies with surveys at intervals of months, and OGI done once a year reached higher reductions than quarterly and monthly OGI inspections, and more than only aerial surveys at intervals of months plus OGI once a year. The application of continuous monitoring at priority sites with high potential to emit (sites with tanks and flares) reduced the time large leaks were emitting and achieved higher reductions than monthly OGI inspections alone.

Quick identification and repair of high emitters while maintaining periodic inspections of smaller leaks by combining OGI, continuous monitoring, aerial, and satellite inspections can achieve much higher reductions than quarterly or monthly OGI inspections alone.

[38] Daniels W, et al., 2023

[39] Cardoso-Saldaña, F. J, 2023

The paper focused on detection (LDAR), but these combinations could also be applied for quantification. Frequent surveying of super-emitters can help reduce the contribution of emissions from super-emitters to annual emissions, by either detecting and constraining event durations, or by monitoring and confirming the lack of emissions.

3.4 Example 4 - Aerial measurement combined with OGI and permanent sensors

One operator reported that it previously used only OGI for methane emissions detection. It then added aerial detection methods to identify larger leaks and prioritize follow-up. While the aerial method was useful for site/facility-level monitoring, the operator followed up almost all aerial detections using OGI to attribute emission sources to specific equipment or components. The operator noted that incorporating both aerial measurement and OGI saved time while also improving safety. Based on the prioritization established by the aerial surveys, the operator was able to consider the best place for continuous monitoring solutions. Although not able to detect every methane release, the addition of low-cost sensors proved useful for finding large leaks quickly.

3.5 Example 5 – Aerial measurements combined with permanent sensors

One operator considered the use of several methane emissions detection and quantification technologies, not only for compliance, but also to reduce emissions and costs. The operator hired an aircraft-based technology to perform measurements that would confirm compliance. Unfortunately, they found that measured emissions were many times greater than expected. OGI was used to follow up identified sources, though in many cases, the aircraft-based technology was able to sufficiently identify the source so that OGI follow-up was unnecessary. The addition of aircraft-based measurements helped reduce methane intensity by 75%.

The company also deployed several continuous monitoring technologies to cover sites or pieces of equipment with great potential for emissions, in particular, tank batteries and wellheads. Due to the increased frequency of monitoring and measurements, the operator began relying increasingly on measurement-based quantification using continuous monitoring technologies rather than periodic monitoring with aircraft-based measurements.

When performing reconciliation between the two measurement methods, successful reconciliation was found to be sensitive to wind conditions. The operator reported false negatives if continuous monitoring solutions were set up too close to emission sources, which could also affect successful reconciliation.

3.6 Example 6 – Site level quantification combined with OGI

One operator reported using a "layered" approach to technology deployment. It first deployed site level measurement technology, such as continuous monitors, drones, aircraft, or satellites. The operator selected the site level quantification approach based on the level of emissions expected and geographical considerations, including availability of the technology. However, the operator reported that none of the technologies it tested were found to be suitable for quantification. Insights from site level measurements were used to perform follow-ups with OGI cameras to identify the emission sources.

Depending on the quality of the site level measurements, the operator reported difficulties reconciling emissions between bottom-up inventories and site level quantification. Different results in repeated measurements made reconciliation challenging, particularly when technology performance did not match the providers' specifications. Site level measurements were useful, particularly when including imagery to assist with source attribution. However, they could also be misleading when the performance characteristics of the site level measurement were not properly documented and communicated, or if source attribution was inaccurate, as it would affect follow-up and prioritization of leak repair or mitigation. It seems that proper selection of site level measurement technology and consideration of all associated parameters is critical to successfully combining technologies.

4. Other recommendations and overarching elements

The following cross-cutting elements are covered in this section:

- Uncertainty.
- Data management and security.
- Internal practices and processes that are independent of the technology provider.
- Lack of independent standards for technologies.
- Interpretation of test results.

4.1 Understanding uncertainty

Uncertainty of methane measurements is a complex topic, and methods to calculate these uncertainties are not fully resolved and implementable with a widely agreed upon method. Therefore, many open research questions remain in this area. This section attempts to identify common sources of uncertainty, and documents one potential pathway for navigating uncertainty as part of this framework. However, other methods exist and will continue to be developed.

It is important to distinguish different types of uncertainties related to methane emissions detection and quantification, such as:

- Sensor uncertainty.
- Methodology uncertainty.
- Methodology uncertainty for a given measurement at a given time.
- Uncertainty related to aggregated emissions.

Sensor uncertainty refers to the accuracy of the measurement compared to the true concentration of methane in the air. Sensor uncertainty is often called precision error. Uncertainty related to the sensor can be much smaller than uncertainty related to the method for quantifying the methane emission rate.

Total uncertainty related to the methodology consists of uncertainties in the measurement by the sensor (sensor uncertainty) and how the results are used to quantify the emission rate. Methodologies may use assumptions to quantify the emission rate, which can also introduce uncertainty into the measurement. For example, using wind data from regional meteorological stations instead of from the site itself increases uncertainty,[40] since such readings may not reflect true wind conditions at the site.

Uncertainty of a measurement at a given time may be influenced by many factors. These can include the position of both the technology and the emission source, as well as the distance between them (greater distances increase uncertainty). Other factors that could increase this kind of uncertainty include methane emissions from background sources, as well as environmental factors such as wind conditions, precipitation, and cloudiness.

[40] Sherwin E, et al., 2021

Developing quantitative uncertainty estimates can be challenging for both source and site level measurements. One may get statistical variance measurements that could be used as a proxy for uncertainty. However, this depends on knowing all activities/sources of the group at the time of site-level measurement.

Some technology providers may document uncertainties or errors in quantified methane emissions on an aggregated basis rather than on a point-by-point measurement basis. In other cases, technology providers may provide uncertainty estimates from idealized tests (e.g., from controlled releases) rather than uncertainties that are applicable to the actual measurements at the facility of interest. Depending on the desired outcome of quantification and uncertainty, this may be misleading. If actual measurements have a larger uncertainty or error range than what is quoted by technology providers or from controlled release tests, this can make it difficult to reconcile the results from source level and site level measurements. Moreover, higher uncertainties on individual sources can impact the prioritization of emissions mitigation.

Care should be taken when evaluating technology uncertainties, including what the uncertainties represent. They may refer to individual or aggregated emissions, provide different confidence intervals (e.g., 1σ or 2σ), and may refer to relative or absolute uncertainty. Since different technologies may quantify emission rates using different methods, documented potential factors that introduce uncertainty should be considered.

The recognition of random variation in intra-estimate variability highlights the importance of incorporating robust uncertainty models into emissions quantification methodologies. Controlled release experiments provide a useful baseline for understanding these uncertainties, but care must be taken to acknowledge their limitations when applied to field conditions.

4.2 Data management and security

A challenge that may emerge as an increasing number of measurement and detection campaigns are performed is the management of the data, particularly with an increase in continuous monitoring.

The collection of data does not, by itself, lead to effective methane management. Operators need to ensure that the data collected are actionable and can inform the mitigation strategy or other objective. Some technology providers have started to offer data-analysis software that translates the data into relevant information. This can help operators better understand the methane landscape of their facilities and identify where action is required. It would otherwise be necessary for the operator to deploy internal procedures and systems to address the volume of data generated by the sensors, especially those involved in continuous monitoring.

Some data might be considered sensitive for oil and gas operators, whether directly related to methane emissions or other parameters in the context of methane management. Many interviewees highlighted that it is important to ensure data security and confidentiality, particularly if data is to be stored by the technology provider or on their cloud service.

4.3 Internal practices and processes independent of the provider

Internal practices and processes are needed for safe deployment, ensuring employees with the correct qualifications are available and trained. This is even more important for technologies that require access to the site.

Since technologies and detection/quantification needs are evolving, interviewees have recommended that operators develop internal practices and processes that are independent of a specific provider, as this allows for a smoother transition between brands or versions.

4.4 Lack of independent standards for comparing technologies

There are no enforced protocols or standards to test and report performance in a consistent and comparable format. This is not surprising, since the industry is still relatively new. Different technologies sense methane differently, quantify methane in different ways, attribute emissions to specific sources using different formats, and report methane emissions detection and quantification differently. Facilities like the Methane Emissions Technology Evaluation Centre (METEC) and the Total Anomaly Detection Initiative (TADI) testing complex have developed test protocols for all deployment methods excluding satellites, which are currently beyond testing capabilities. However, there are no requirements or standards for reporting. Much of the data is anonymized, presented in the best possible light, or only made public at the discretion of the participating technology provider. Technology testing may also be performed in a variety of environments (see Section 4.5). The lack of standards makes comparison challenging for companies, both in terms of selecting technologies and reporting emissions. It is recommended that the industry develop consistent practices that allow robust and comparable testing of different methane emissions detection and quantification technologies. This could include, for example, a unified definition of detection threshold and probability of detection using comparable metrics, such as probability of detecting emissions of 10 kg/h from 20 m at 3 m/s wind.

4.5 Interpretation of test results

4.5.1 Site layout

Technologies may perform well at a testing site; this does not guarantee similar performance in all locations and conditions. For example, in a realistic field scenario, with potentially multiple sources and plumes, background methane emissions can impair source attribution and increase uncertainty in quantified emission rates. Results may differ, for example, because the number of sensors used in semi-controlled environments exceeds the number that will be deployed in the field.

The variation of site layouts means that testing facilities will not be representative of all field conditions. Results from a test run on a well pad with spread out, discrete emission sources are likely to differ from an offshore platform with densely packed equipment, for example.

Placement of the sensor is important. If measurements are taken too close to the emission source, the plume may not be properly formed and may not be adequately detected, negatively impacting quantification algorithms. Deployment far from the source could also reduce the probability of detection.

While third-party testing sites may not match an operator's conditions, they do offer a more rigorous testing and validation process. Conducting controlled-release testing at third-party sites can demonstrate dedication to improving abilities and transparency. Results may still vary when deploying the same technology at a site with different characteristics from the testing site.

4.5.2 Probability of Detection (PoD)

In addition to minimum detection threshold, methane emissions detection and quantification technologies may include a PoD. This refers to detection sensitivity and is used to help understand the chances of detecting an emission, considering a number of factors. For example, a technology may have a stated PoD of 90% for sources emitting 10 kg/h, at a wind speed of 2 m/s, at 50 m from the source. This means that the technology is expected to detect 9 out of 10 sources in those specific conditions. A PoD provides more confidence that the technology will be able to detect emissions than the minimum detection threshold alone. A higher PoD may also be associated with a higher false-positive rate.[41] PoD can be determined through partially[42] or fully blinded[43] testing.

It is important to consider the extent to which conditions and other factors during testing represent the conditions at the operator's site. For example, testing may have taken place in open fields, large, simplified, or sparse sites, or using a large quantity of sensors, compared to the characteristics of the sites where the operator intends to deploy the technology. Large discrepancies can lead to significant differences in the probability of detection.

Future efforts should focus on refining uncertainty and probability of detection models to better capture the effects of aerodynamic influences, instrument-specific variability, and algorithmic processing, particularly for complex emission environments and infrastructure.

41 Bell C, et al.,. 2023
42 Qube Technologies,2022 https://highwoodemissions.com/wp-content/uploads/2022/09/2022-08-25_Qube-Probability-of-Detection-White-Paper.pdf.
43 Johnson M, et al.,2021

5. Conclusion

Methane emissions detection and quantification is a well-known challenge for oil and gas operators. An increasing number of technologies are available to tackle this essential aspect of greenhouse gas emissions inventory and mitigation. The aim of this Report is to help operators turn the current knowledge into actions at their facilities. The technology filtering tool and the technology data sheets provide a centralized and standardized database to help operators select and compare technologies. The decision trees offer guidance on deployment and data interpretation, depending on objective. There is currently no "one-size-fits-all" technology available, and a combination of solutions is required for methane emissions management. Some examples are presented in the Report. Selection and deployment cannot be fully summarized in a technology filtering tool or in decision trees. Other overarching elements should be considered by operators, some of which are detailed in the last sections of this Report.

This Report and its accompanying technology filtering tool, technology data sheets, and decision trees do not recommend or impose one technology or approach over another. They have been developed to provide a framework of detailed technology characteristics so that operators can make informed decisions when selecting and deploying the technology (or technology combinations) best suited to their circumstances, considering their objectives and their operating environment. It is hoped that this framework will help operators achieve their goals relating to upstream methane emissions management and reporting.

Glossary

Term	Definition
Basin	Wide geographical area with a collection of sites.
Bottom-up	Bottom-up estimates sum up individual emission sources within a facility to produce a single value. Bottom-up estimates can be synonymous with source level inventories.
Detection of methane emissions	Process of identification of methane emissions from potential sources, without the measurement of the mass quantity (flow rate, e.g., kg/h). The detection is typically performed above a threshold, and above ambient levels.
Detection threshold	The minimum [flow rate] of a gas, e.g., methane, which is reliably detectable by detection equipment. This is sometimes called a Minimum Detection Limit (MDL).
Equipment	A mechanical system where a single process or action takes place. Examples of equipment: compressor, tank, controller, pump, dehydrator, separator. A piece of equipment may include different components.
Equipment Component	A part or element of a larger whole. In the context of equipment [emissions], components are individual sealed surfaces on pressurized equipment such as flanges, valves, connections, pressure relief valves, open ended lines, etc. This is typically the most granular level of fugitive emissions reporting.
Equipment Group	A collection of equipment located in proximity, often within a delimited area. Examples of an equipment group: tank battery, group of compressors, dehydration units.
Measurement	The process of taking a reading of a methane emission. Measurement can be of any variable (volume, concentration, mass, frequency, and so on) that allows for detection or for an estimate of emission rate.
Measurement Informed Inventory	An inventory that is predominantly informed by data from methane measurements of the assets and sources in the inventory, where predominantly means methane emissions quantification informed by measurement can be based on 100% sample size or based on a statistically representative subset of samples. Note: This definition is different from the Veritas Protocol.
Quantification	Determining an emission rate, such as mass per time or volume per time. This can be done directly through measurement of the emissions, or indirectly through estimations, calculations, and modelling.

Term	Definition
Reconciliation	Reconciliation is the process of comparing source level inventories with independent site level measurements to produce emissions estimates (Oil and Gas Methane Partnership (OGMP) Uncertainty and Reconciliation guidance document). Other definitions of reconciliation exist, however, this is the one that is referred to throughout the document.
Screening	Evaluations with the main purpose of identifying sources of emissions. However, in some regulatory contexts, screening applies only to less rigorous or less sensitive detection approaches, such as AVO (Audio, Visual, and Olfactory). Screening typically refers to identifying emissions within a wide area, while detection typically refers to identifying emissions from specific sources.
Site	Collection of emission sources with some relation to one another within a delimited geographical area. Emissions from a site combine emissions from different equipment and components. Examples of sites: compressor station, offshore production platform. In the body of the report, site/facility will be referred to as "site" but can be interpreted as synonymous with "facility".
Site level measurement	Methane measurement applied to a site, without identifying specific sources at the equipment or component level. A site level measurement can be synonymous with a top-down estimate.
Source	A component within a process or equipment that releases methane to the atmosphere either intentionally or unintentionally, intermittently, or persistently.
Source level inventory	A record of all known sources of emissions and emission rates. An inventory provides a summary of emissions over a given period of time. A source level inventory can consist of measurement-based quantification, engineering calculations, or emission factors. Total emissions are calculated by summing data from each emission source. Source level inventory can be synonymous with bottom-up estimate.
Super emitter	Methane emission source that represents a disproportionate amount of the total methane emissions released from all sources[44].
Top-down	Top-down estimates measure methane at a facility level that may combine multiple emission sources, without being able to resolve them to specific sources. Top-down estimates can be synonymous with site level measurements.

[44] Ipieca-IOGP-GIE-Marcogaz Methane Emissions Glossary Methane Emissions Glossary

List of Acronyms

Acronym	Meaning
ATEX	Explosive Atmosphere
EED	Expected Emissions Distribution
EF	Emission Factors
EPA	Environmental Protection Agency
GTI	Gas Technology Institute
LDAR	Leak Detection and Repair
MDL	Minimum Detection Limit
MII	Measurement Informed Inventory
OGI	Optical Gas Imaging
OGMP	Oil and Gas Methane Partnership
PoD	Probability of Detection
SCADA	Supervisory Control and Data Acquisition

Appendix A: Methodology and data sources

The review of technologies performed as part of the recommended practices for methane emissions detection and quantification technologies relied on data sources with varying levels of independent validation. Data sources include (from most to least independent):

- peer-reviewed academic literature
- public datasets
- interviews with operators and service providers
- interviews with technology providers

Results were included in the technology data sheets and technology filtering tool.[45] In each case, the type of source is clearly identified.

For the development of the decision trees, data sources such as methodologies presented in international framework or protocols (such as OGMP 2.0 and GTI Veritas Protocols) were considered, together with the project team's extensive experience in methane emissions from the oil and gas sector, supplemented by input from operators and academic researchers. All decision trees were critically reviewed by the IOGP working group, whose comments were incorporated.

A.1 Literature review

A review of the literature was performed to collect information on the performance of detection and measurement technologies. Technology providers were asked to share case studies, company reports, and academic studies featuring their technology.

Academic papers covered independent comparisons of the performance of different technologies, often through semi or fully blind testing and controlled releases, in varied geographical locations. Technologies in these studies were typically segregated by type, such as handheld, drone, and aerial since the size and level of emissions identified by each type tend to differ. While results from studies often use different types of indicators, making direct comparisons difficult, the literature review informed an understanding of methane emissions detection and quantification practices, best-available knowledge, successful implementation, and related challenges, at the time of the Report.

Over 60 independent peer reviewed academic papers were reviewed. The complete list is available in Appendix C.

[45] https://www.iogp.org/workstreams/environment/environment/methane-emissions-detection-and-quantification/methane-detection-and-quantification-technology-filtering-tool/tool/

A.2 Interviews with technology providers

For all relevant technologies, providers were contacted for an interview to review publicly available data collected from their websites, industry testing, reports, and peer-reviewed literature, to confirm the technologies' capabilities. The interviews were semi-structured discussions following a template to ensure consistent collection of data from each provider. Interviews were conducted with over 30 technology providers, and multiple interviews for a single provider were carried out where required.

Some providers did not reply to requests for an interview, despite multiple attempts. Technologies whose providers were unable to be interviewed were not included in the analysis.

A.3 Interviews with service providers and operators

Interviews were conducted with service providers and operators, that is, technology users. These interviews were used to supplement information from technology providers to present a holistic picture of deployment in practice, and to identify advantages and limitations in diverse operating conditions. Interviews were conducted as open discussions, and the results incorporated into the technology data sheets and the main body of this Report.

Operators were also contacted for interviews and to share case studies and results from independent or internal benchmark testing. In total, 13 interviews with operators and service providers were conducted.

Appendix B: List of technologies assessed

Table B1 - List of CH4 technologies assessed

Technology name	Technology provider	Datasheet up to date as of:
GFM 2.0	AddGlobe	January 2023
Charm	Adlares	January 2023
PRISMA	ASI	January 2023
D-fenceline	Atmosfir	January 2023
Gas Mapping Lidar (GML)	Bridger Photonics	January 2023
Carbon Mapper	Carbon Mapper - Planet	January 2023
MetCam	CI Systems	December 2024
Autonomous 365	Clean Connect	January 2023
Worldview3	DigitalGlobe	January 2023
Sentinel-2	ESA	January 2023
TROPOMI	ESA	January 2023
XPLOROBOT Laser OGI	Exploration Robotics Technologies	December 2024
Fixed Wing Drone	Flylogix	December 2024
GHGSat Constellation	GHGSat	December 2024
Remote Methane Leak Detector (RMLD-CS)	Heath Consultants	December 2024
Detecto-Pak Infrared+		
(DP-IR+)	Heath Consultants	December 2024
DISCOVER Advanced Mobile Leak Detection (AMLD)	Heath Consultants	December 2024
HETEK Flow Sampler	HETEK Solutions Inc.	December 2024
Leaks Surveyor	Insight M	December 2024
Kuva Daylight	Kuva	January 2023
Longpath Laser System	Longpath Technologies	December 2024
SPOT Robotic Dog	MFE Instruments	January 2023
ORION	Mirico	January 2023
Landsat-8	NASA/USGS	January 2023
UAS Drone	Net Zero Aerial	December 2024

Technology name	Technology provider	Datasheet up to date as of:
MPS Methane Gas Sensor	NevadaNano	December 2024
EyeCgas 24/7	Opgal	January 2023
Hyperspectral monitoring solutions	Orbital Sidekick	January 2023
ALMA	Pergam-Suisse	December 2024
LMS (Laser Methane Scanner)	Pergam-Suisse	December 2024
SELMA Duo	Pergam-Suisse	December 2024
SELMA Roof-Dome	Pergam-Suisse	December 2024
Laser Falcon	Pergam-Suisse	December 2024
G4301 Gas Concentration Analyser	Picarro	December 2024
Canary X	Project Canary	December 2024
Mantis Flare Monitor	Providence Photonics	January 2023
QL320	Providence Photonics	January 2023
Axon	Qube Technologies	December 2024
SOOFIE	Scientific Aviation	January 2023
Scientific Aviation Manned Aircraft	Scientific Aviation	January 2023
DJI Matrice	Scientific Aviation	January 2023
Multi rotor drone	SeekOps	January 2023
Fixed wing drone	SeekOps	January 2023
Agni	Sensia	January 2023
Mileva 33	Sensia	January 2023
Mileva 33F	Sensia	December 2024
NuboSphere	Sensirion	December 2024
Hi-Flow 2	Sensors Inc	December 2024
Ventus OGI	Sierra Olympia	December 2024
LWIR OGI Camera	Sierra Olympia	December 2024
G300a	Teledyne FLIR	January 2023
GF77	Teledyne FLIR	January 2023
GF77a	Teledyne FLIR	January 2023
GFX 320 + QL 320	Teledyne FLIR	January 2023
PoMELO	UCalgary	December 2024

Appendix C: Selected peer-reviewed articles

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Alden C, et al. "Temporal Variability of Emissions Revealed by Continuous, Long-Term Monitoring of an Underground Natural Gas Storage Facility". *Environmental Science & Technology* 54:22. 2020. p. 14589-14597.

Alden C, et al. "Single-Blind Quantification of Natural Gas Leaks from 1 km Distance Using Frequency Combs". *Environmental Science & Technology* 53:5. 2019. p.2908-2917.

Allen D, et al. "Measurements of methane emissions at natural gas production sites in the United States". *Proceedings of the National Academy of Sciences of the United States of America* 110:44. 2013. p.17768–17773.

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International Association of Oil & Gas Producers

ipieca

OGCI Oil and Gas Climate Initiative

energy institute

This Report provides oil and gas operators with a framework and guidelines to help select and deploy methane emissions detection and quantification technologies that are tailored to their sites and objectives. It is accompanied by an online technology filtering tool, detailed technology data sheets covering over fifty technologies, and decision trees to guide deployment.

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