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A FRAMEWORK FOR CLASSIFYING METHANE MONITORING REQUIREMENTS, EMISSION SOURCES AND MONITORING METHODS

A CONNOR, J SHAW

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A Framework for classifying methane monitoring requirements, emission sources and monitoring methods.

A. Connor and J. Shaw

Environmental and Emissions Metrology Group
Atmospheric and Environmental Science Department

ABSTRACT
This report describes the need and concept of a framework that describes and classifies methane emissions monitoring requirements, emissions sources and monitoring methods using a set of taxonomies. It is envisaged that this framework will be developed into a standard to help facilitate more reliable transfer of information between stakeholders internationally.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

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Approved on behalf of NPLML by
Rod Robinson, (Science Area Leader).

CONTENTS

GLOSSARY/ABBREVIATIONS

CCAC	Climate and Clean Air Coalition
CCUS	Carbon Capture, Utilisation and Storage
CE-DOAS	Cavity-enhanced differential optical absorption spectroscopy
CEAS	Cavity-enhanced absorption spectroscopy
CRDS	Cavity ring-down spectroscopy
DIAL	Differential absorption LIDAR
DOAS	Differential optical absorption spectroscopy
FID	Flame ionisation detection
FTIR	Fourier-transform infrared
IMEO	International Methane Emissions Observatory
IPCC	Intergovernmental Panel on Climate Change
LAS	Laser absorption spectroscopy
LDAR	Leak detection and repair
LIDAR	Light detection and ranging
LNG	Liquid natural gas
LP-DOAS	Long-path differential optical absorption spectroscopy
MAX-DOAS	Multi-axial differential optical absorption spectroscopy
NDIR	Non-dispersive infrared
OA-ICOS	Off-axis integrated cavity output spectroscopy
OGMP	Oil and Gas Methane Partnerships
OP-LAS	Open-path laser absorption spectroscopy
TCD	Thermal conductivity detection
UNEP	United Nations Environment Programme

EXECUTIVE SUMMARY

Industries, governments, and regulators need emissions data which can be trusted to make informed decisions regarding methane abatement strategy and policies. There are many differing data reporting requirements metrics, as well as a diverse range of emission sources and methods for monitoring emissions. Different data structures and terminologies can be used to describe similar objects, activities or characteristics associated with methane monitoring. There is no accepted definition of a monitoring method. These issues can undermine confidence in data. This report describes a framework which aims to address these issues, based on a set of taxonomies and a common lexicon. It is envisaged that this framework will be developed into a standard to help facilitate more reliable transfer of information between stakeholders internationally. For example, to aid the development of test standards (between test laboratories, site operators and standards bodies) for methane monitoring systems to be used within an emerging industry.

1 INTRODUCTION

1.1 METHANE MONITORING LANDSCAPE

The atmospheric methane burden has gained much attention in recent years, most notably with the signing of the Global Methane Pledge in 2021 [1]. Efforts to reduce emissions of methane from anthropogenic emission sources, and thereby stall climate impacts, are potentially feasible and cost effective to implement [2]. However, implementing measures to mitigate methane emissions requires data that can be trusted and are truly representative of the emissions being monitored. Historically, the reporting of methane emissions has relied on the use of generalised emission factors. However, a lack of comprehensive measurement data and incomplete monitoring means that emission factors can vary widely leading to large discrepancies in national inventories [3]. This has led to a clear need to measure methane emissions for reporting emissions.

Mitigation of climate risk is not the only driver for monitoring methane emissions. There are also safety considerations and economic benefits to minimising leaks, as methane is both a valuable commodity and can form explosive air mixtures. Trust in emissions data, underpinned by metrological infrastructure and quality assurance practices, is essential to making informed decisions regarding methane reduction practices.

Methane emissions may need to be measured and reported over different spatial scales (from emissions on individual components to regionally aggregated emissions from multiple distinct sources) and temporal scales (from short-lived emission events to continuous emissions) to ensure that the measured data is representative of the emissions source. The reconciliation of datasets across these wide-ranging spatial and temporal scales can be especially challenging [4] and hence explicit understanding of the characteristics of different emission sources realistically requires the deployment of a wide range of complementary monitoring techniques. There are many differing requirements for reporting emissions and associated quality metrics, as well as a diverse range of emission sources (and associated environments) and methods for measuring emissions.

The following are different frameworks that have been developed to help navigate the methane monitoring landscape. It is evident from these frameworks that different terminology can be used to describe similar objects, activities and characteristics. It unsurprising that confusion concerning language, definitions and terminology is commonplace:

- GTI Energy has defined a set of protocols [5] that describe how to take measurements, process data and apply an assurance process, to all segments of the natural gas supply chain.
- The Energy Institute of Colorado State University have developed an Advancing Development of Emissions Detection [6] which focuses on technology testing.
- The Oil and Gas Methane Partnership (OGMP2.0) [7] has developed a case for a “gold standard” in methane reporting.
- There is also a glossary in the 2019 refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [8].

A specific example is the use of a term to describe a single or collection of physical objects in the gas industry that could emit methane. GTI Energy use the term ‘Asset’ [5], whereas the Energy Institute use the terms ‘Component’, ‘Equipment Unit’, ‘Equipment Group’ or ‘Facility’ – depending on whether one is referring to individual or groups of objects [6]. OGMP2.O uses ‘Asset’, ‘Operating unit’, ‘Site’, ‘Facility’, or ‘Source’ [7]. Terms used to describe objects in the IPCC glossary (which is not gas industry focused) include: ‘Pond’, ‘Manure’, or ‘Peatland’, or more generically, ‘Source’ [8].

There appears to be no accepted definition of what a method is or should consist of amongst stakeholders engaged in the monitoring of methane. For example, Unmanned Air Vehicles are commonly referred to as methods (they are platforms) as are individual instruments that measure concentration, this can lead to at best confusion, at worst the deployment of platforms or instruments that do not have the essential elements of a method, for example: a defined protocol, evidence of validation or quality assurance process. The Joint Committee for Guides, International Vocabulary Of Metrology (VIM) [15] defines a measurement method as “a generic description of a logical organization of operations used in a measurement”. To help ensure that decisions are based on data that can be trusted it is important to have an accepted definition and list of what constitutes a method.

1.2 THE NEED FOR A FRAMEWORK

This framework attempts to address this for emission monitoring by defining a method and what constitutes a method. It would therefore be of great value to have a common lexicon that is industry neutral and potentially cross reference the existing terms currently in use. In addition, there needs to be a common structure for how this information is represented. This report attempts to address the issues and create a common framework that describes how information should be structured. It would be logical to group terms that represent objects, activities, and characteristics into classifications that have similar properties and hence a taxonomy approach was adopted.

There have been previous attempts at developing taxonomies in the field of emissions monitoring, but these have generally focussed solely on monitoring methods and not considered the data requirements or emissions sources, including:

- A framework [9] [10] specifically for demonstrating equivalence between methane leak detection and repair (LDAR) programs in the context of methane emission mitigation, but not for methane monitoring more widely.
- A taxonomic structure of methane monitoring methods with a focus on spatial scalability [11].
- A review on the capability of satellites for monitoring methane emissions from the oil and gas sector [12].
- A review [13] and classification of methods for detecting natural gas pipeline leaks, some of which included the direct measurement of methane above-ground.
- Keywords [14] associated with methods for measuring methane emissions from oil and gas wells, many of which are captured across the taxonomies presented in this report.

This report presents the concept of a systematic framework that could be used to describe and categorise data requirements, emissions sources, and monitoring as a set of taxonomies that identify and categorise keywords, and a lexicon to define terminology. The principles of metrology are embedded into its design as are quality assurance and representation of the range of temporal and spatial scales. The framework is designed to be industry and technology neutral with an initial focus on methane, but could, in future, be adapted for other species.

We believe the framework will provide major benefits to the field of methane emissions monitoring by providing:

1. A harmonised system (with a lexicon) to help ensure a more reliable transfer of information and knowledge between method providers and stakeholders which would benefit the development of policy and regulations and the standardisation of methodologies. A harmonised system could also lead to more reliable reconciliation and integration of datasets since stakeholders will have consistent terminology and systems for describing information.
2. A means for industrial operators, regulators, and other stakeholders to select the most cost-effective monitoring solutions, or suite of complementary solutions, based on understanding the reporting requirements and source characteristics. It is recognised that existing monitoring requirements stipulated by regulators can be intentionally vague to allow for a flexible approach based on technologies that are available and within budget. There is a compromise to be made between performance and cost. The intention of this framework is that it would help a stakeholder navigate that compromise by providing a means to identify technological or methodological gaps that may need to be addressed in the future.
3. To help emerging industries or technology providers to navigate the complex methane monitoring landscape, for example stakeholders in the non-oil and gas industries who may want to apply similar practices to their needs.

The purpose of this report is to highlight the need for this framework and describe its concept along with a case study.

2 FRAMEWORK OVERVIEW

2.1 METHOD TO DEVELOP THE FRAMEWORK

The design of this taxonomy was carried out in two phases:

1. The collation of terms (keywords or phrases) that are used to describe and categorise methane reporting requirements, emissions sources, and monitoring methods and their associated technologies. The terms originate from four decades of work undertaken with a wide range of stakeholders: government departments, academia, standards committees, industry, collaborative research and development, instrument manufacturers, measurement service providers, site operators, technology innovators; and from a UK, European, and international perspective. It is recognised that multiple definitions exist that describe similar objects or properties; an attempt has been made to ensure that those chosen for this framework (or alternatives) are technology and industry neutral.

2. The design of the framework and taxonomy follows these concepts:
    - To sort terms to clearly distinguish between reporting requirements (what data is needed), emissions sources.
    - To sort keywords into ‘properties’ and ‘descriptors’. Properties are used to quantify and categorise and descriptors are used where some form of qualitative description is required to set context. For example, the physical height of an emission source can be quantified but may require some form of textual description to provide context, for example: ‘a vent located on top of a large building or flare stack’. Some keywords could be subjective, for example ‘ease of access for a monitoring location’; having the means to identify and categorise objective and subjective phrases is useful.
    - To describe a method and all its constituent parts.

- To categorise terms that have similar characteristics and to apply an object orientated approach to describing physical objects and their associated data.
- The principles of metrology must be embedded into this framework to ensure the creation of trustworthy data necessary for informed decision-making. Metrology is embedded into this framework by including relevant keywords such as uncertainty, traceability, and calibration into the taxonomies. All measurement quantities should be expressed using units defined by the International System of Units (SI) where possible, including those non-SI units that are considered acceptable for use within the SI [16]. However, we acknowledge that other systems of units may be in use but note that these provide a lower degree of traceability.

It should be noted that this work is not intended to review available methane monitoring methods, nor does it provide an intercomparison or even justification of all monitoring options. Detailed descriptions of methods can be found elsewhere although some particularly relevant literature is referenced for convenience.

2.2 KEY DEFINTIONS

The correct usage of terminology is important for developing standards globally. Therefore, a lexicon of key definitions in the field of emissions monitoring is included in the Appendix. The framework defines the following spatial categories used across many of the taxonomies:

- Component: defined as an entity that forms part of a process or system; on an approximate spatial scale of centimetres to metres (for example, a flange that joins two pipes). Component appears to be a widely accepted term for such a scale.
- Functional element: defined as a spatially separate entity that performs a specific purpose; on an approximate spatial scale of metres to hundreds-of-metres (for example, slug catcher at a refinery, a process tank, boiler unit, or storage unit). Synonyms widely used include “equipment” or “asset”. However, entities at this spatial scale may not necessarily be equipment (often mechanical in nature) or assets (often with implied ownership), they could be livestock, water treatment ponds, or areas of natural emissions. “Functional element” is therefore considered here to be a more appropriate term that could be applied universally across all emission source types.
- Site: defined as a spatially separate premises that performs an activity consisting of a number of functions or consists of one (or more) functional elements; on an approximate spatial scale of hundreds-of-metres to a kilometre (for example, a landfill site, tank farm, anaerobic digester plant). In some cases, there may be a cluster of sites that are in close proximity that would cover a scale greater than one kilometre (for example, a refinery). Synonyms widely used include “facility”, “plant” or “farm”. “Site” was chosen for industry neutrality.
- Regional: defined as a collection of industrial sites, or distinctive areas of transport, urban, or domestic activity; on an approximate spatial scale of one kilometre to hundreds-of-kilometres (for example, a city).
- National: defined as a collection of regions; on an approximate spatial scale of hundreds-of-kilometres and greater (for example, countries, or groups of countries). This scale is associated with national inventory reporting.
- Global: Referring to the total integrated system (emissions sources) on this planet.

2.3 FRAMEWORK STRUCTURE

The framework comprises three sets of taxonomies which are used to classify and define various properties and descriptors to provide a thorough but easily understood breakdown of each set (Figure 1). The taxonomies within each set are described in later sections. The three sets are:

1. Monitoring need: a set which classifies and describes the purpose of the emissions monitoring and what reported data is required.
2. Emission source: a set which classifies and describes the source to be monitored or being monitored (i.e., the different types of emission sources, their properties, and the environments in which they occur).
3. Monitoring method: a set which classifies and describes how the monitoring is to be undertaken.

The three sets of taxonomies could be used independently or in parallel. For example, developing a monitoring standard may require using just the monitoring need and emission source sets, whereas all three sets could be applied together to select an appropriate method to meet a particular need.

A case study demonstrating application of the framework to the measurement of methane emissions from liquefied natural gas (LNG) is presented in the Appendix. The case study provides an example of how to define the purpose and data reporting requirements using the monitoring needs set of taxonomies and examples of emissions sources are given using the emission source taxonomy to describe them. Part of the study involved selecting site to monitor, an example of how emissions source taxonomy could be used to achieve this was given. The monitoring methods set of taxonomies were used to define a specification for a method that could meet the data reporting requirements and used to describe the properties of a method (Differential Absorption Lidar) that was deployed to carry out the monitoring work.

The difference between the method specification and the properties of a method highlights the compromises that may have to made when choosing a method, such as budget, safety, logistical constraints. Such software could allow a user to follow the framework process, answering and responding to prompts, to deliver a final output of recommended monitoring methods, with relevant properties (for example, typical uncertainties, expense, time frame). Such software development is beyond the scope of this work, and it is anticipated that the framework will undergo further refinement before such a project is undertaken. It should be noted that the taxonomies within each set are not intended to be exhaustive but serve primarily as a basis for reflecting on the requisite considerations for monitoring of emissions.

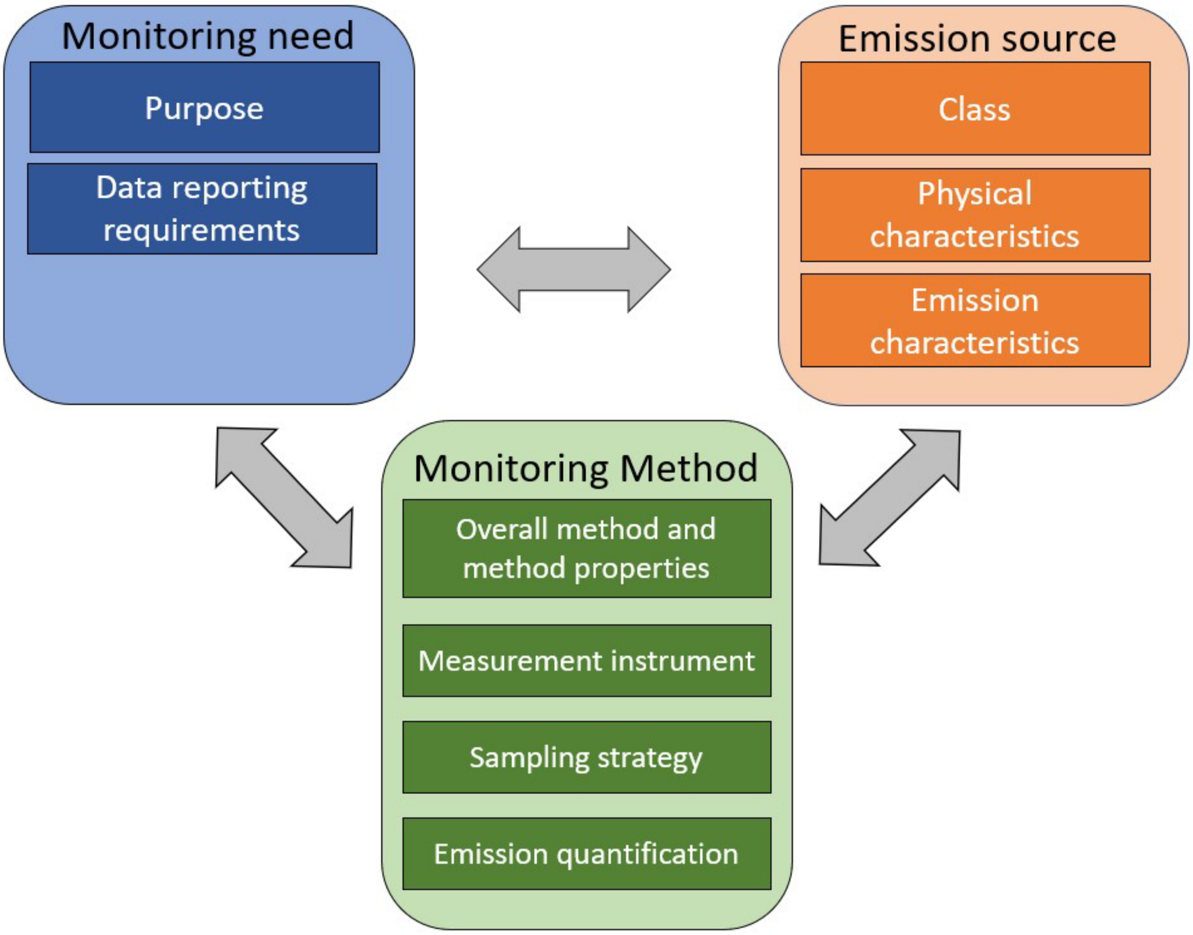

Figure 1. Overview of the methane emission monitoring framework showing three sets of taxonomies: the monitoring need, the emission source, and the monitoring method.

3 A SET OF TAXONOMIES THAT DESCRIBE THE MONITORING NEED

Two taxonomies are presented in this set; a taxonomy which defines and classifies the monitoring purpose and a taxonomy which defines and classifies the data reporting requirements. The monitoring purpose taxonomy (Figure 2) describes and classifies:

- Drivers: a factor that instigates emission monitoring,
- Aims: what is to be achieved by the emissions monitoring,
- Actors: those involved in the monitoring,
- Stakeholders: those who have an interest in the monitoring,
- Industry.

We distinguish two classes of monitoring:

- Emissions driven: The purpose is to measure a property of an emission source through either the methane concentration, emission rate, source location, or to detect a change. Examples are:
    - A Leak Detection and Repair (LDAR) programme,
    - Exploratory monitoring to gain knowledge about an under-studied emission source (for example, to understand how tropical wetland emissions respond to climate

change). Another example could be to understand the different types of emission sources from an emerging industry such as biogas.
- Obtaining the necessary evidence data for regulatory compliance of a landfill site(s).

For emissions driven monitoring, the data reporting requirements need to be defined and a method (or complimentary set of methods) chosen to undertake the monitoring of the emission source. The choice of method(s) should be based on the data requirements and the known characteristics of the emissions source (what is required). However, it is recognised that the choice of method may be limited by cost and availability (what is available). It is envisaged that the framework could be used to perform a gap analysis between the data requirements and the properties of the available method(s), i.e. to identify technological and methodological gaps. Another factor to consider is that very little may be known about the emissions source (for example sources in emerging industries) and therefore exploratory monitoring using a range of methods may be the best approach. The taxonomy should also point the user to existing frameworks or protocols relevant to specific industries, such as the GTI Energy Veritas protocols for monitoring emissions from oil and gas sites [5].

- Method driven: The purpose is to test a monitoring method. The driver could be method development, intercomparison or validation. For example, the purpose of method-driven monitoring may be to perform method development, with the aim of understanding a method's performance under particular conditions or for a particular application. A different example of method-driven monitoring could be the intercomparison of multiple methods applied to a controlled release experiment simulating a leak on a natural gas pipeline.

  The data requirements and monitoring method taxonomies could be used to select an appropriate emissions source for adequately testing the method(s) to produce the expected data reporting requirements. The taxonomy should also point the user to existing frameworks or protocols [6].

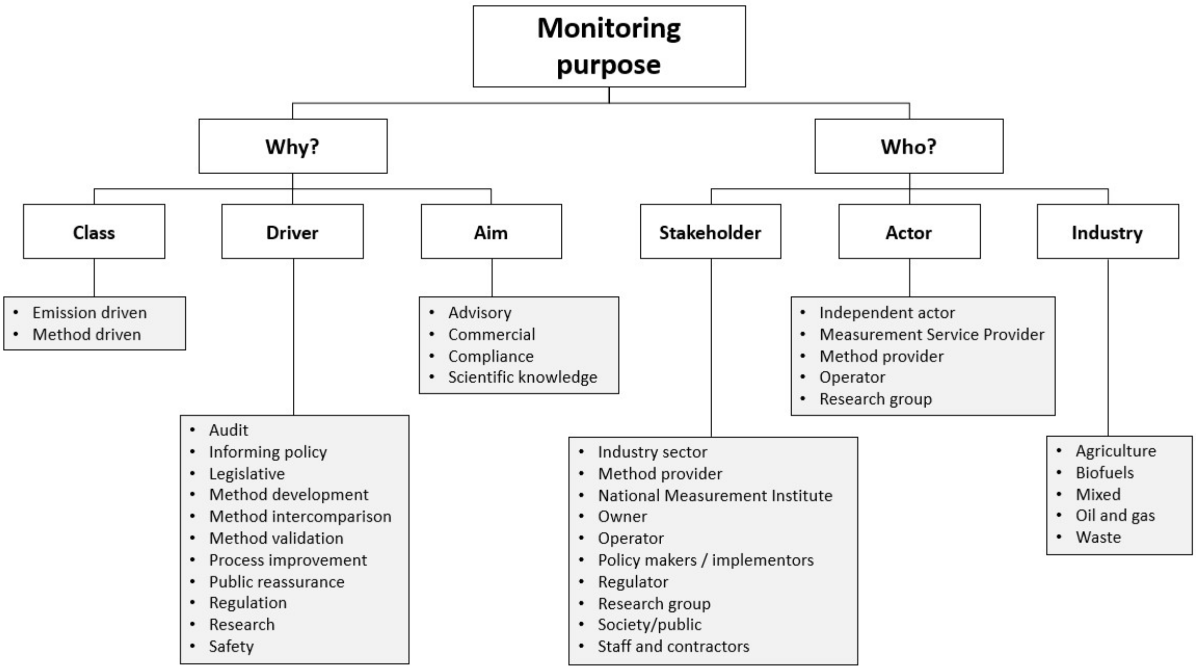

Figure 2. Taxonomy for describing and classifying the purpose of emission monitoring. Keywords are defined in the lexicon in the Appendix.

In many cases, the aims and drivers are intrinsically related, in that certain drivers imply certain aims. For example, drivers such as regulation, safety, or audit, usually have the aim of complying to a standard or procedure. This aim should, in turn, define the data reporting requirements, which may simply be reporting a site emission rate, or staying below a concentration-threshold. Other drivers, such as research, legislation (to provide advice or information for the development of specific policy legislation), informing policy, or public reassurance, often have the aim of producing advice or yielding scientific knowledge. Similarly, process improvement drivers will typically be for commercial aims. Method-driven drivers are likely to require complex data to provide the necessary information to adequately compare methods and their associated techniques. For example, the data reporting requirements for regulatory compliance will likely consist of succinct information about the emission rates and associated uncertainties, the emission sources monitored, and site conditions, whereas method development will require more detailed information, for example: detection limit, systematic bias, minimum quantifiable emissions, repeatability, linearity and response time (more than that detailed in Figure 3).

Who is affected by, and involved in, emission monitoring is also important when considering the monitoring purpose. This category is subdivided into stakeholders, actors, and industry. Stakeholders are defined as anybody with an active interest or concern in the monitoring conclusions. Actors are defined as those with an active role in undertaking the monitoring. Industry refers to the overarching industrial sector which is being monitored. Identifying the stakeholders and aims will help determine the complexity of data required; the data complexity is likely to be greater for purposes relating to scientific knowledge compared with purposes relating to compliance.

The actors may influence the appropriate method(s) which could be used, or the choice of method(s) may determine the required actor(s), for example, by identifying the required skill set to operate a measurement instrument. Understanding the industry is important since there may be data reporting or logistical requirements specific to certain industries, or different standards, protocols, and terminology that the taxonomy could highlight. Since these categories are related it is important that they are all considered holistically when determining the data reporting requirements.

Figure 3 illustrates the data reporting requirements taxonomy, which is divided into two separate classes comprising properties (keywords which can be quantified or categorised) and descriptions (keywords which cannot be easily quantified or categorised as they require some description to inform context; for example, the word budget could imply different meanings under different contexts). This distinction is made because the properties could be used in a database structure to select or categorise information to help choose a monitoring method. Here, the measurand is typically concerned with the “what”, whilst the data granularity defines the “where” (spatial) and the “when” (temporal) aspects of data. Data descriptions typically relate to the type of output required (for example, a dataset, a public report, a new standardised method), or to metadata which may be of relevance to the monitoring method itself.

Metrological factors are included in the data reporting requirements taxonomy because it is important that they are discussed when determining the reporting requirements and, if appropriate, included in the requirements. Understanding the metrology may be necessary when providing evidence of validation, or when deciding what auditing should be carried out, for example.

The data reporting requirements taxonomy defines the following temporal categories for data reporting:

- Snapshot: a single report representing a state at a given time, or two reports separated by a time period or before and after an event (for example, repair). The intention is that the number of reports are limited (most likely two or less).
- Periodic: a periodic report with a defined period (or frequency). The intention is that the number of reports are not necessarily limited (most likely more than two).
- To monitor continuously at a defined sampling rate.

The spatial and temporal properties will have quantitative properties associated such as geographic location, time of day, frequency of monitoring etc.

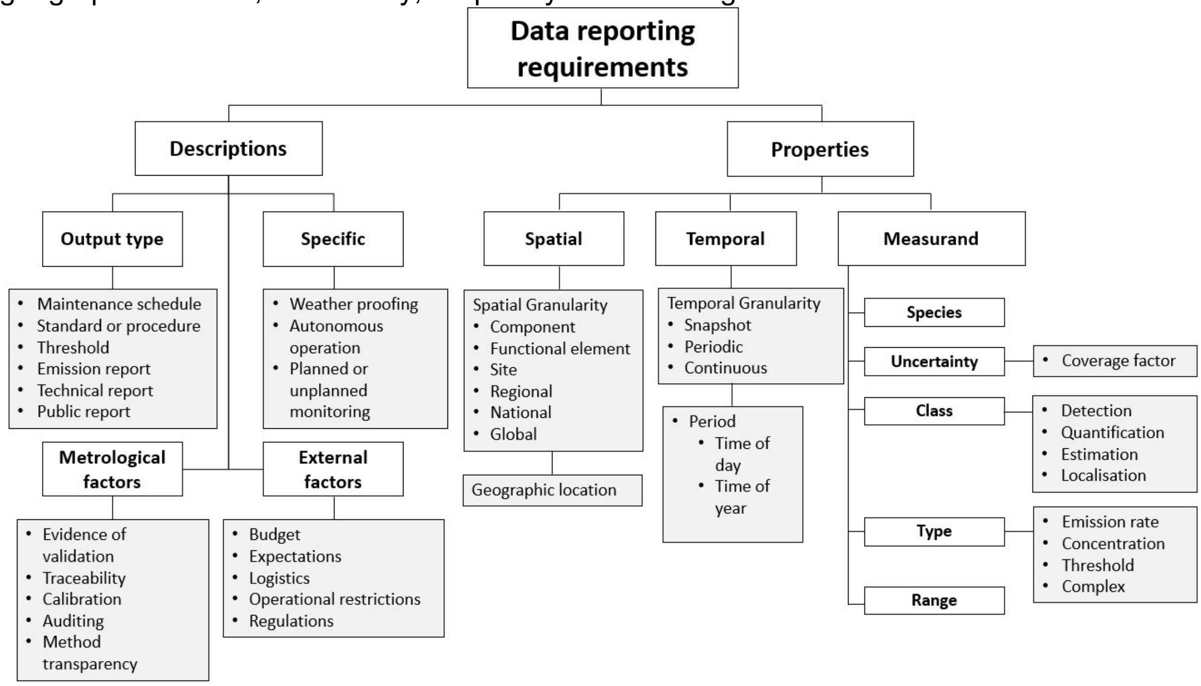

Figure 3. Taxonomy for describing and classifying the data reporting requirements. Many of the data reporting requirement properties could benefit from added description or context (for example, preferred units of measurement). Keywords are defined in the lexicon in the Appendix.

The purposes and data requirements for monitoring, as well as the stakeholders and actors relevant to a particular industry, may change over time. Hence, the taxonomies may need to be regularly reassessed to account for evolving circumstances.

4 A TAXONOMY TO DESCRIBE EMISSIONS SOURCES

The emission source taxonomy describes and classifies emission sources based on their characteristics such as spatial scale, emission characteristics, and physical properties (Figure 4). As with the data reporting requirements taxonomy, the keywords in the emission source taxonomy are distinguished as properties or descriptors. The emission source taxonomy presented here is principally concerned with describing and characterising anthropogenic or industrial emission sources. However, the taxonomy could be adapted to account for naturally-occurring methane emission sources too. The emission source taxonomy also allows for the identification and description of extraneous emission sources which may interfere with monitoring of the target emission source.

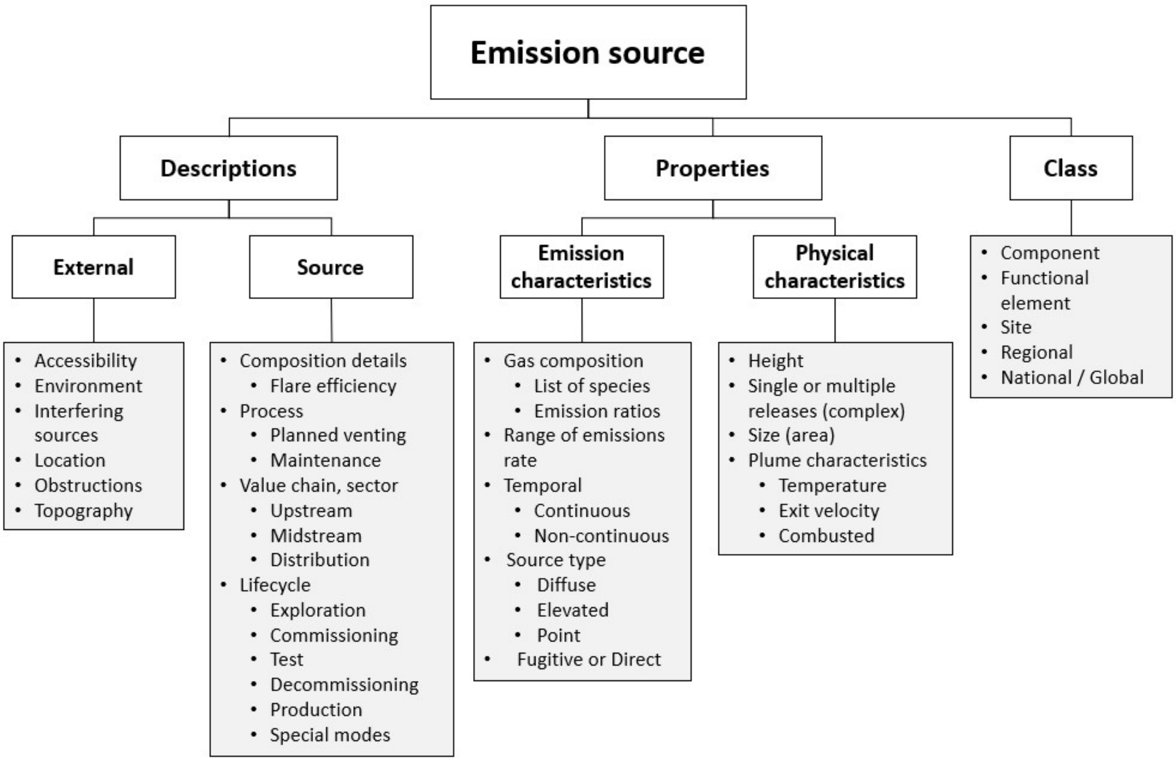

Figure 4. Taxonomy for describing and classifying emission source properties and characteristics. Many of the emission source properties could benefit from additional description or context (for example, preferred units of measurement). Keywords are defined in the lexicon in the Appendix.

Emission source properties are further subdivided into characteristics which can be classified as relating to the emission itself or relating to the physical nature of the source. Physical characteristics include details such as the height of the release point whilst emission characteristics include details such as gas composition and the temporal nature of the emissions (for example, continuous or non-continuous).

5 A TAXONOMY TO DESCRIBE MONITORING METHODS

A method is a procedure or a set of instructions for monitoring emissions, which may involve emission detection, localisation and/or quantification. Figure 5 illustrates a taxonomy that describes and categorises a method's properties. A method should describe the scope, protocol, and relevant metrological factors to provide evidence that the method can produce data which can be trusted (for example, evidence of method validation). The monitoring method determines the measurement requirements. The data reporting requirements (as previously described) describe what data is required, whereas the measurement requirements describe how the measured data is to be obtained, including performance criteria such as measurement uncertainty.

A method may be standardised, with prescribed procedures which describe the best available practice, method validation and verification, uncertainty estimation, and application under different circumstances. Alternatively, a method may be under active development, with procedures that are not yet defined due to a lack of knowledge regarding these aspects. It is expected that standardised methods will likely better meet the metrological requirements of monitoring, but it should be acknowledged that not all methods have undergone such rigorous analysis, particularly those that rely on emerging and state-of-the-art measurement and processing techniques.

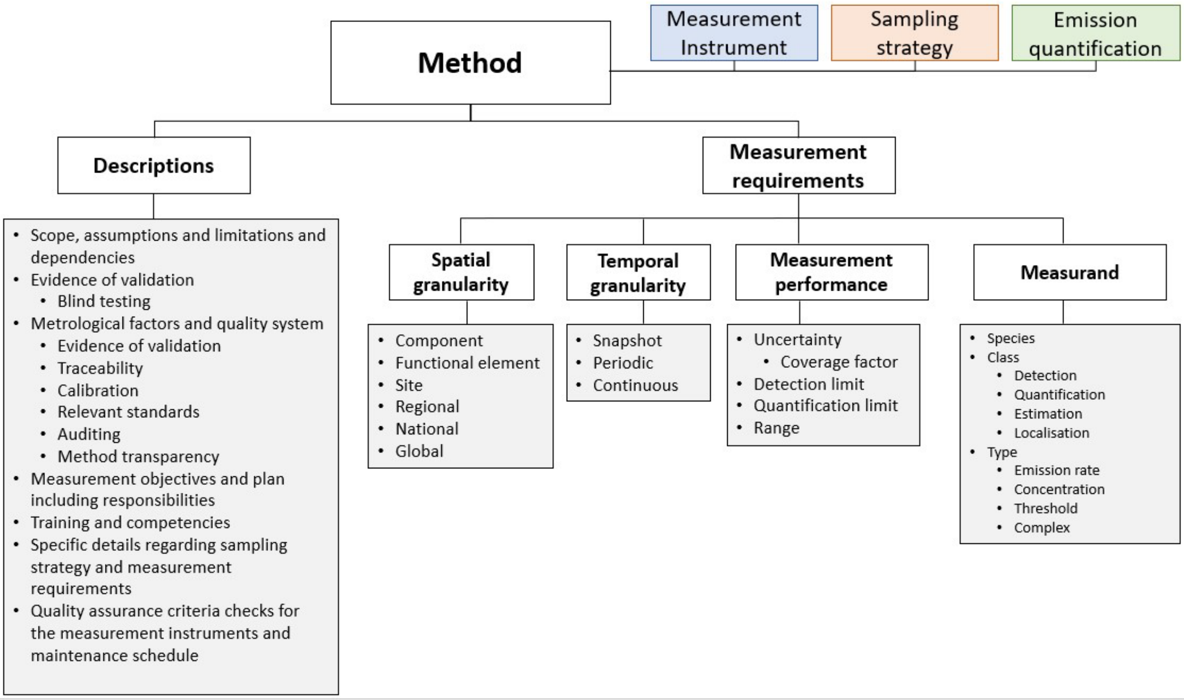

Figure 5. Taxonomy for describing and classifying a method and its properties. Keywords are defined in the lexicon in the Appendix.

In Figure 5, the specific details regarding sampling strategy and measurement requirements in the Description arm should be used to describe how the data are combined into a final report and how the performance, for example, measurement instrument spatial resolution determines the uncertainty and granularity of the reported data. The spatial and temporal granularity defines what the method can produce in terms of the reported data.

A method may contain the following method elements:

- Measurement instrument: a device used for making measurements. A measurement instrument contains a sensor or a detector. The choice of sensor or detector is based on the measurement requirements (which are in turn based on the data reporting requirements).
- Sampling strategy: this describes how the measurement data are collected and represented, as well as the platform used to collect the data.
- Emission quantification: this describes how the methane concentration measurements are converted into a methane emission rate (or emission flux).

A method must consist of at least a measurement instrument and a sampling strategy but does not necessarily require an emission rate calculation (for example, if only methane concentration needs to be measured for the purpose of emission detection or emission localisation only). Although there are many measurement instruments, sampling strategies, and emission quantification techniques available, the monitoring purpose may not be met by any single combination of these method elements alone.

Figure 6 illustrates a taxonomy which describes and categorises the properties associated with an element of a method, for example, a measurement instrument.

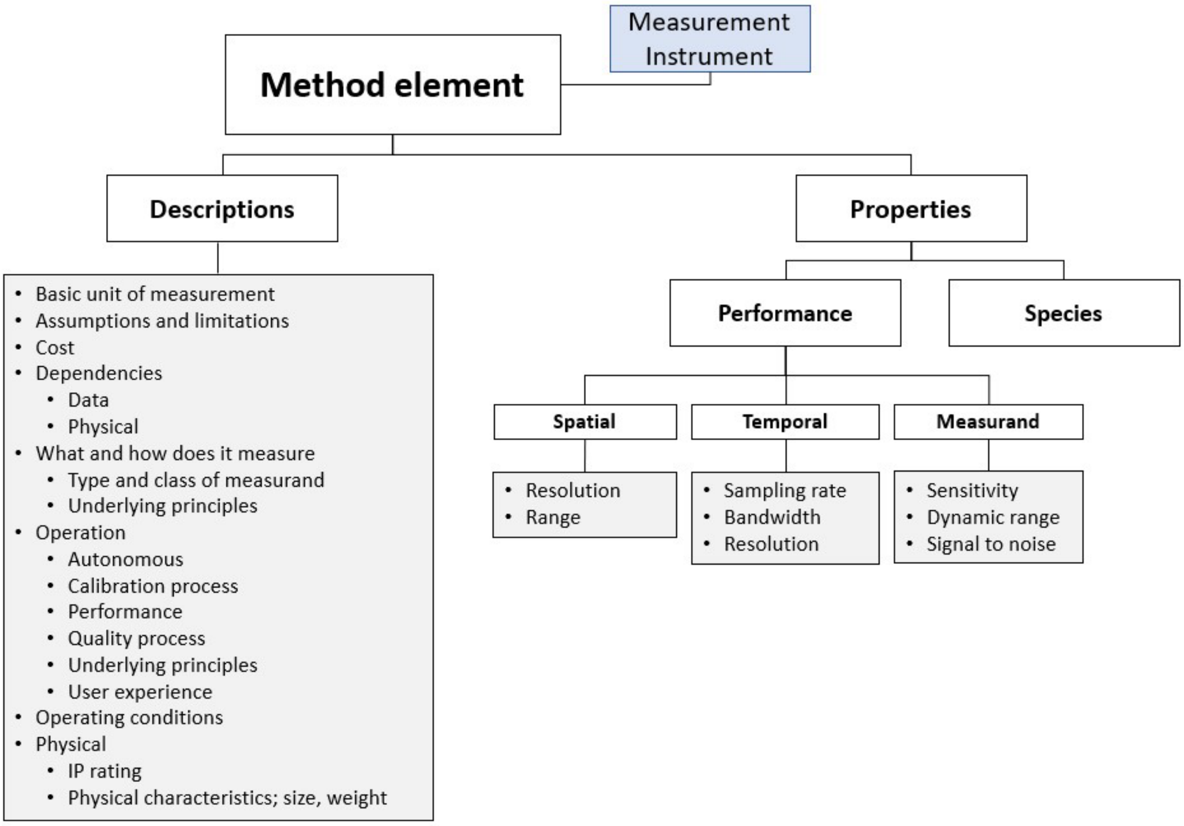

Figure 6. Taxonomy for describing and classifying a method element and its properties. Keywords are defined in the lexicon in the Appendix.

The following sub-sections present taxonomies for each of the three method elements. The taxonomies represent a possible structure which will be of benefit to users assessing the large, and often bewildering, array of techniques available for monitoring methane emissions. The taxonomies are not intended to be exhaustive, and some techniques may be absent. The design of the taxonomies allows for new measurement instruments, sampling strategies (and associated platforms), and emission quantification calculations to be integrated within them. Unfortunately, it is beyond the scope of this work to provide full and complete descriptions for each technique. Detailed descriptions of the underlying principles behind each technique can be found elsewhere.

We have tried to dispense here of the difficult and often problematic and ambiguous referral of methods as either bottom-up or top-down, which is largely dependent on the spatial and temporal scale in question and whether measurements are extrapolated to a greater spatial (or temporal) scale or disaggregated to a lower spatial (or temporal) scale [17,18]. For example, the definition of bottom-up could be equally applied to the measurement of component scale emissions (when assessing emissions from a single site) and to site scale emissions (when assessing emissions from a production region), and some methods could be applied equally to bottom-up or top-down measurements. It is important to reconcile independent emission measurements at multiple spatial and temporal scales to establish comparability across scales, but this is not always trivial [18].

5.1 MEASUREMENT INSTRUMENT

Figure 7 shows a taxonomy of methane measurement instruments for the measurement of atmospheric methane amount fraction (or methane concentration). Similar structures have also been presented by [19] and [20]. In the taxonomy presented here, measurement instruments are principally categorised as either optical or non-optical. For the measurement of methane, optical instruments typically exploit the vibrational frequencies of the carbon-hydrogen chemical bond and the absorption or emission of specific wavelengths of electromagnetic radiation in the infrared region [21]. Measurement instruments using absorption spectroscopy can be further differentiated based on their use of either an active light source (i.e., the measurement instrument has its own source of light, such as a laser), or a passive light source (i.e., the measurement instrument uses an external source of light, such as sunlight). Measurement instruments using absorption spectroscopy can be further distinguished based on the path the light source takes, and whether that path is within a closed system (closed-path), or open system (open-path).

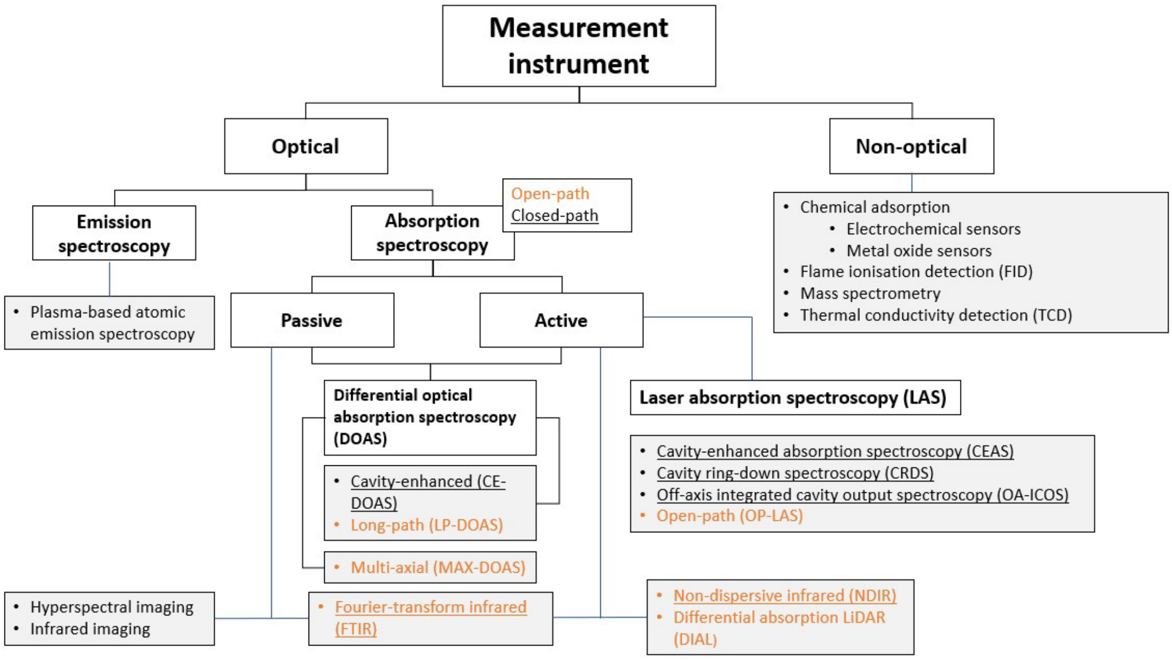

Figure 7. Taxonomy for describing and categorising measurement instruments with example techniques. The techniques listed are not exhaustive. Keywords are defined in the lexicon in the Appendix. Optical absorption spectroscopy instruments which typically make use of open-path light sources are highlighted in orange. Optical absorption spectroscopy instruments which typically make use of closed-path light sources are underlined.

5.2 SAMPLING STRATEGY

Figure 8 presents a taxonomy which defines and categories keywords and considerations for the strategy used for sampling methane. The sampling strategy will primarily differ depending on if the measurement instrument is a remote sensor or point-sensor as the former can measure at a distance and potentially cover large areas with one system, whereas a point-sensor has to be deployed in the measurement area and typically provides a much smaller coverage area. There are a number of considerations that aid with the development of a comprehensive sampling strategy; number of platforms used, the spatial and temporal density of sampling, and the number of repeat measurements. These are determined by the measurement requirements.

For a particular method the density of sampling may need to provide sufficient information to understand the emissions in terms of its temporal and spatial characteristics. For example, the temporal frequency of sampling should be sufficiently high enough to capture the shortest duration non-continuous emissions, or to capture the frequency of variability in continuous emissions. However, in some cases integrated or average data may be sufficient. The density of spatial sampling will have consequences for characterising the morphology of the emission plume and for distinguishing between multiple emission sources. In practice, achieving high levels of temporal and spatial granularity can be difficult to achieve.

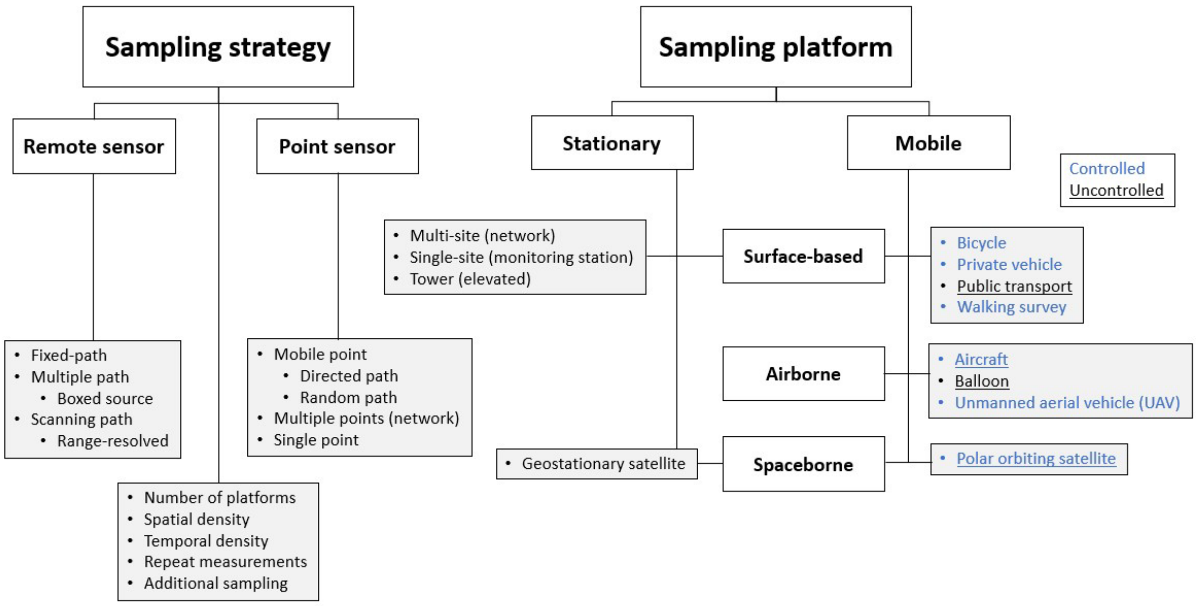

Figure 8. Taxonomy for describing and categorising sampling strategies and sampling platforms. Keywords are defined in the lexicon in the Appendix.

The choice of sampling platform (the platform upon which the measurement instrument is mounted) is part of the sampling strategy. Platforms can either be stationary (their geolocation is fixed) or mobile (their geolocation is variable). Some platforms may be capable of both mobile and stationary sampling, and both types of sampling may be used within the same method; for example, a car could be used to first find an emission plume (mobile sampling) and then sample within that plume by stopping within it (stationary sampling). Each class of sampling platform has different benefits and limitations. Mobile platforms can conveniently cover large spatial areas (particularly at the site spatial scale) without having to deploy multiple measurement instruments. However, mobile platforms can only capture a 'snapshot' in time at each location, whereas stationary platforms can be used to sample for lengthier time periods (or continuously) in a single location. On the other hand, multiple stationary platforms may need to be deployed to obtain the required spatial coverage, and there may be logistical or practical (for example, hazard zones) limitations that restrict their coverage, this could apply to mobile platforms too.

Sampling platforms can be further divided based on their sampling location within the atmosphere. Platforms can be operated on the ground (i.e., surface-based), above the ground but within the atmosphere (generally considered to be up to ~100 km in altitude; for example, [22,23]), or can be operated beyond the atmosphere (i.e., spaceborne; for example, [24,25]).

In the case of mobile platforms, their movement offers a further distinguishing feature. Movement can be either controlled (by a user) or uncontrolled. Controlled platforms can be directly manoeuvred to target sampling in a specific location whereas uncontrolled platforms cannot. Uncontrolled platforms may be subject to movement dictated by the local wind field, as is the case for a sampling balloon. In some cases, differentiating between controlled and uncontrolled may be problematic. This may occur when the data user does not have direct control of a platform which can be targeted at specific sources, as is the case for some satellites.

5.3 EMISSIONS QUANTIFICATION

The combination of methane concentration data (acquired by the measurement instrument) and the sampling strategy creates a data product such as a concentration-time series at a specific location or a two-dimensional map of concentrations. An emission rate may be derived from the data product using some form of emission model. Many of these models can equally be used to aid with identifying the source location or source origin of an emission. Figure 9 presents a taxonomy for classifying different emission models which can be used to estimate emission rates. Models can vary greatly in complexity, can be based upon differing assumptions regarding atmospheric physics, and may have different statistical approaches to dealing with the ambient atmospheric methane background.

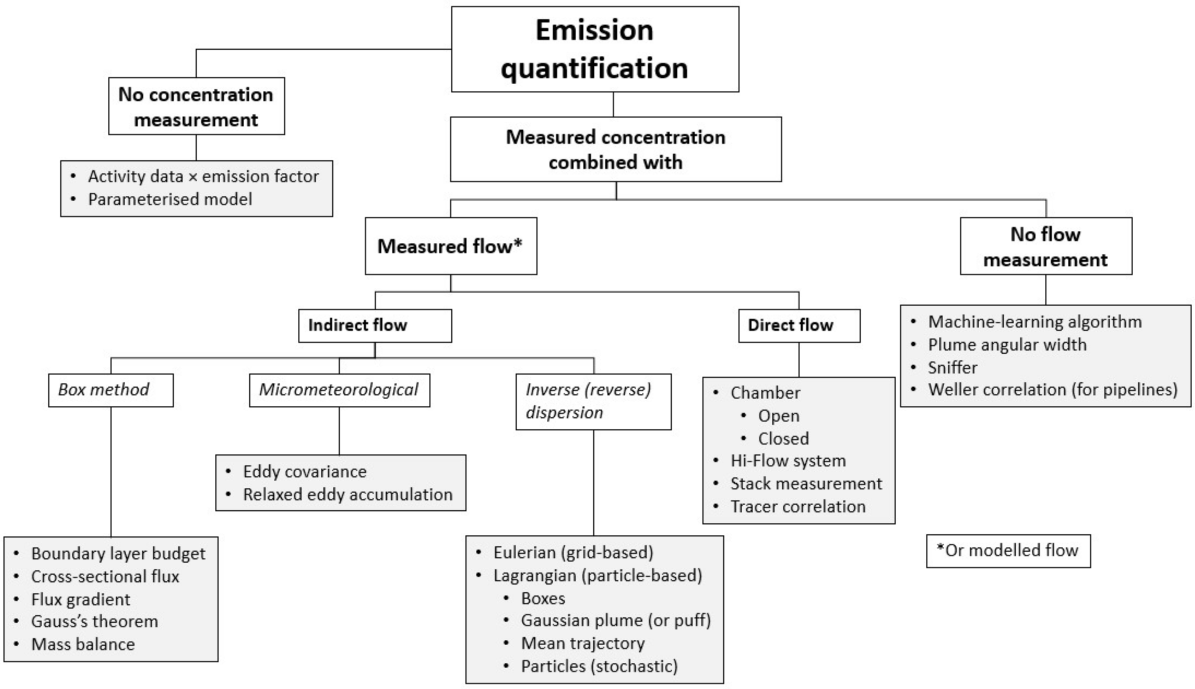

Figure 9. Taxonomy for describing and categorising models for calculating the emission rate. Keywords are defined in the lexicon in the Appendix.

The “no-methane-measurement” options are included here for completeness but do not require either of a measurement instrument or sampling strategy. For example, calculating an emission rate from an industrial site can be done using statistical activity data and previously calculated emission factors. Parameterised models use engineering-based calculations to estimate emissions [17]. Whilst this approach will estimate an emission rate, the result is reliant on the accuracy of previously calculated emission factors and activity data for the specific site or process. Methane-measurement-based options (all others) would be preferable in most cases for specific emission monitoring. It should be noted that emission factors and parameterised calculations can only be assessed for their accuracy (and updated) using a direct methane emissions monitoring method.

Emission rate calculation models can be classified in different ways. Some models make use of a correlation factor between the measured methane concentration and known emission rates derived under controlled conditions. This approach is commonly used in leak detection and repair (LDAR) programmes (or sniffer methods), in which the maximum concentration of methane measured within a certain distance of a leak is correlated to an emission rate using a lookup table. Models that rely on correlation factors are often simple to implement but rely on the accuracy of the derived correlation factors; correlation factors will be less applicable the further practical conditions differ from the controlled conditions. Machine-learning algorithms have applicability here for the rapid statistical processing of large amounts of data correlating emission observations and known emission rates (for example, [26,27]). However, many approaches using machine-learning models have yet to be validated and their metrological suitability remains generally unknown, particularly with respect to uncertainty derivation and transparency.

Other emission rate calculation models use a model of atmospheric flow, or transport and dispersion, to derive an emission rate from concentration data. Flow can be measured (or modelled) directly or indirectly. In direct flow approaches, the flow of air is contained and can be controlled using pressure differentials (for example, vacuum pumps). Indirect flow approaches use the wind field as a proxy for flow and assume that the atmospheric transport of methane is driven mainly by the wind and atmospheric turbulence. Box models are typically simpler and generally only account for larger scale dispersion driven primarily by the mean wind vector and boundary layer processing. More complex models, such as micrometeorological models and inverse dispersion models, may account for smaller scale and turbulent dispersion but at greater computational cost. Higher resolution meteorological data (measured or modelled) may be needed for the higher fidelity models.

6 SUMMARY

We present a harmonised framework for describing and classifying data reporting requirements, emissions sources, and monitoring methods, including a lexicon of terminology.

This report attempts to address the issues of terminology, the complexity of how data is represented, and the wide range of methods and their associated technologies by defining a set of taxonomies to represent this information. This framework makes a clear distinction between describing reporting requirements (what data is needed) and emissions sources and methods (how data is obtained). This distinction is necessary to highlight any methodological and technological gaps between data requirements and what data is obtained.

Terms (where relevant) have been separated into those that are qualitative (descriptions)and quantitative (properties) which provides the basis for categorising objective and subjective terms. The framework is industry neutral and aimed at stakeholders who may have different levels of experience from an operator in a mature industry (in terms of methane monitoring) to emerging industries and novel technology providers.

Methane reduction strategies must be based on data that can be trusted and are representative of the source being monitored. These criteria are fundamental to determining whether monitoring is adequate. Therefore, the principles of metrology and quality assurance are embedded into the framework along with a means to define the temporal and spatial scale of the reporting and monitoring.

The purpose of this report has been to highlight the need and concept behind this framework, not to define the framework in full. The next step is to develop this framework into a standard, initially a British Standards Institute Publicly Available Specification, and then eventually into an international standard, that could be used to facilitate more reliable transfer of information, for example between stakeholders developing standards or monitoring methods or reconciliation of datasets. Further work is required to develop the taxonomies further to provide a more comprehensive list of types of emissions sources, methods and associated technologies.

The terms defined in this report may require revision to ensure compatibility across industries. Further work is needed to cross reference the terms defined within the lexicon here with the wide-ranging terminology that is used throughout the methane monitoring landscape. A committee could be setup to make a final decision on terms and to manage the standardised framework. The ultimate aim is to develop this framework into an international standard.

It is envisaged that categorising and classifying reporting requirements, emission sources, and monitoring methods could, in future, be adopted and integrated into existing methane monitoring frameworks and standardise general practice to encourage consistency across industries, technologies, and monitored species. This framework also defines the essential ingredients of a method; currently there is no such universally accepted description in atmospheric monitoring.

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9 APPENDICES

9.1 LEXICON

Table A1. General and metrological lexicon.

Amount fraction	See **Mass fraction**, **Mole fraction**, or **Mixing ratio**. This property is related to concentration.
Calibration	An operation that, under specific conditions, establishes a relationship between the quantity measured (with uncertainties) and a traceable measurement standard (with uncertainties) [28].
Chemical constituent	The chemical measurand of interest (see also, **Target species**).
Concentration	The amount, or abundance, of a particular chemical constituent divided by the total volume of the mixture. Concentration may be expressed in units of mass or moles per unit volume (e.g., µg m^{-3}, mol dm^{-3}). Concentration is often used interchangeably with amount fraction.
Coverage factor (interval)	Interval containing the set of true quantity values of a measurand within a stated probability.
Detection limit	The lowest signal that can be reliably detected with a sufficient degree of confidence. Also referred to as the limit of detection. The analytical or technological detection limit may differ from the method detection limit.
Intercomparison	The act of comparing a method or technique with other methods or techniques, often to evaluate performance.
Mass fraction	The amount of a chemical constituent (in units of mass) divided by the total amount of all constituents (in units of mass). Mass fraction is a dimensionless quantity which is typically expressed in units of parts-per-million (ppm, 10^{-6}), parts-per-billion (ppb, 10^{-9}), or parts-per-trillion (ppt, 10^{-12}). Units of g/g are sometimes used to differentiate mass fraction from mole fraction (e.g., %g/g, mg/g, µg/g, ng/g).
Measurand	The physical quantity subject to measurement [28].
Measurement	The process of determining a physical quantity [28].
Measurement uncertainty	A non-negative parameter which characterises the dispersion of measurement results attributed to a measurand [28].
Mixing ratio	The amount of a chemical constituent (in units of mass or moles) relative to the amount of all other constituents, not including itself. Mixing ratio is a dimensionless quantity which is typically expressed in units of units of parts-per-million (ppm, 10^{-6}), parts-per-billion (ppb, 10^{-9}), or parts-per-trillion (ppt, 10^{-12}). If the amount of the chemical constituent is very small relative to all other constituents, the mixing ratio is almost identical to the mass or mole fraction.
Mole fraction	The amount of a chemical constituent (in moles) divided by the total amount of all constituents (in moles). Mole fraction is a dimensionless quantity which is typically expressed in units of parts-per-million (ppm, 10^{-6}), parts-per-billion (ppb, 10^{-9}), or parts-per-trillion (ppt, 10^{-12}). Units of mol/mol are sometimes used to differentiate mole fraction from mass fraction (e.g., %mol/mol, mmol/mol, µmol/mol, nmol/mol),

Quantification limit	Minimum quantifiable emissions, based on the uncertainty of the method
Reconciliation	The act of making measurements comparable and compatible with each other, for example, across a range of spatial or temporal scales.
Resolution	The smallest change in a quantity being measured that causes a perceptible change in measured value [28].
Sensitivity	The ratio of the change in the measured value to the corresponding change in the value of the quantity being measured [28].
Traceability	A property of a measurement result whereby the result can be related to a reference through a document unbroken chain of calibrations, each contributing to the measurement uncertainty [28].
Uncertainty	See **Measurement uncertainty**
Validation	The assurance that a product, service, or system meets the required needs of the customer and other identified stakeholders [28].
Verification	The evaluation of whether a product, service, or system complies with a regulation, requirement, specification, or imposed condition [28].

Table A2. Emissions-related lexicon.

Active spectroscopy	Optical spectroscopy which employs its own source of light, such as a laser.
Area (source type)	Area emissions are releases to the atmosphere from an extended area; for example, the surface of a wastewater pond.
Background (chemical background)	The amount of a chemical constituent in a remote location, or in the absence of local emission sources. The atmospheric background can be defined globally, regionally, or locally, and often changes with the season and the time-of-day. In practice, this quantity is difficult to measure with precision, and is therefore often represented statistically as a low-percentile value of the data.
Bottom-up	Bottom-up models account for emissions from the smallest possible emission sources at a spatial scale (i.e., component scale). Total emissions are calculated as a sum of all emissions from these individual sources, often making use of statistics and activity data to represent multiple similar components, functional elements, or functional processes. Bottom-up methods do not always involve observations of atmospheric methane and may make use of process-based models or emission inventories.
Closed path	Closed-path optical spectroscopy is used to measure the concentration of a chemical species within a physical closed system, such as a cell, which contains a sample of the atmosphere.
Component (spatial scale)	An entity that forms part of a process or system; on an approximate spatial scale of centimetres to metres (for example, a flange that joins two pipes).
Continuous emission	An emission that occurs continuously for a period greater than a prescribed threshold. The threshold (for example, 24 hours) should be defined in the taxonomy output. An example of a continuous emission is a landfill. The emission rate may vary.

Detector	A device or substance that indicates the presence of a phenomenon, body, or substance when a threshold value of an associated quantity is exceeded [28].
Diffuse (emission source type)	Emissions arising from a number of (generally small) sources within an extended area. The resultant emission can be considered an extended plume. In general, this term is used to contrast small unintended leaks and process emissions from identified ducted emissions in large vent stacks or chimneys. The draft standard EN 17628 (CEN/TC 264/WG38) [29] defines diffuse emission as ‘an emission to the atmosphere from an identified site or facility, not specifically directed to identified stack emission points’ with a note that ‘this term comprises the sum of various unaccounted channelled emissions, fugitive emissions and area emissions.’
Ducted (source type)	Emissions from a contained flow (for example, pipe) to the atmosphere.
Elevated (emission source type)	Elevated emissions are releases to the atmosphere from a source that is at height above ground, for example stack or flare. Ideally, the approximate height should be defined.
Emission (gaseous or particle)	The release or discharge of a chemical constituent from one system to another (typically to the atmosphere).
Emission flux	The emission rate through a surface, such as an emission area or a vertical plane (slice) through the atmosphere. Emission flux is typically measured in units of mass (or moles) per unit area per unit time (e.g., mg m^{-2} s^{-1}).
Emission model	A model which is used to calculate an emission rate from measured concentration data of the target species. Models vary substantially in their complexity and computational expense.
Emission monitoring	A method that can measure concentration or an emission rate (and associated uncertainties), or a detection system or emissions location system.
Emission rate	The rate of emission of a specific chemical species, typically to the atmosphere. The emission rate is typically measured in units of mass (or moles) per unit time (e.g., g s^{-1}, kg $hour^{-1}$).
Emission source	The specific source of emission of a chemical constituent to the atmosphere. The source will have a number of attributes associated with it which determine the type and pattern of emissions.
Emission quantification (method element)	Describes how the concentration measurement is converted into an emission rate.
Functional element (spatial scale)	A spatially separate entity that performs a specific purpose; on an approximate spatial scale of metres to hundreds-of-metres (for example, a process tank, boiler unit, or storage unit).
Fugitive emission	An unintended (or irregular) release (emission) of a chemical constituent to the atmosphere. Fugitive emissions are typically associated with anthropogenic activity and often considered to be leaks.

Global (spatial scale)	The total integrated system (emissions sources) on this planet.
Leak rate	Colloquially used as a replacement for emission rate, often with regards to an emission source which is not expected to be emitting under normal circumstances (i.e., a fugitive emission source), such as a natural gas pipeline.
LDAR	Leak detection and repair. A process in which a leaking component is identified and assigned a leak rate (often based on a correlation factor), prior to the leak being scheduled for repair (EN 15446) [30].
Measurement instrument (method element)	A device used for making measurements which consists of a sensor or a detector.
Method	A generic procedure or a set of instructions (either prescribed or guidance) employed for scientific measurement. In the case of emission monitoring, the method refers to a combination of a measurement technology, a sampling strategy, and an emission rate calculation or model. A method should describe the scope, protocol, and relevant metrological factors to provide evidence that the method can produce data which can be trusted (for example, evidence of method validation). A method will consist of a measurement instrument, sampling strategy and emissions quantification element (if reporting emissions rate) or suite of complementary method elements.
Method element	A *method* may contain one or more of the following *method elements*: measurement instrument, sampling strategy and/or emission quantification.
Monitoring	A generic term used to describe measurement, location and/or detection of emissions
National (spatial scale)	A collection of regions; on an approximate spatial scale of hundreds-of-kilometres and greater. This scale is associated with a national inventory reporting.
Non-continuous emission	An emission that occurs for less time than a defined threshold (see **Continuous emissions**), including sources that have a repeating cycle (periodic); for example, a pneumatic valve that emits once every hour for 5 seconds. Non-continuous emission sources may be short-lived, episodic, or periodic.
Open path	Open-path optical spectroscopy is used to measure the concentration of a chemical species across a path length across free space within the atmosphere.
Open path, open ended	An open path system with no physical retroreflector, the receiver is located at the same location as the transmitter, and the received energy is dependent on scattering and reflection within the atmosphere.
Passive spectroscopy	Optical spectroscopy which uses ambient light (such as sunlight) as a light source.
Periodic	A periodic report with a defined period (or frequency). The intention is that the number of reports are not necessarily limited (most likely more than two).

Point (source type)	Point source emissions are those arising from a specific localised release, such as a vent stack. In practical terms a point source is one giving rise to a narrow plume of emissions (from the perspective of the monitoring method).
Point-sensor (sampling strategy)	A point-sensor has to be deployed in the measurement area and typically provides a much smaller coverage area
Regional (spatial scale)	A collection of industrial sites, or distinctive areas of transport, urban, or domestic activity; on an approximate spatial scale of tens-of-kilometres to hundreds-of-kilometres (for example, a city, region, or country).
Remote-sensing (sampling strategy)	Remote-sensing (also referred to as standoff detection) involves the measurement of the properties of an object without making physical contact with that object. In the case of emissions measurement, the object is typically understood to be the emission plume. Therefore, a method which uses remote-sensing does not need to be physically located within the emissions plume (or even in the region where emissions may occur). The opposite of remote-sensing is referred to as a point measurement system (or in-situ sampling), and which needs to be physically located within the plume, or within the target region.
Sampling strategy (method element)	Describes how the measurement is collected and represented, and the platform used.
Sensor	An element that is directly affected by the phenomenon, body, or substance carrying the quantity to be measured
Site (spatial scale)	A spatially separate premises that performs an activity consisting of a number of functions or consists of one or more functional elements; on an approximate spatial scale of hundreds-of-metres to tens-of-kilometres (for example, a landfill site, tank farm, anaerobic digester plant).
Snapshot	A single report representing a state at a given time, or two reports separated by a time period or before and after an event (for example, repair). The intention is that the number of reports are limited (most likely two or less).
Target species	The chemical constituent of interest for emission measurement or monitoring.
Technique	A generic term used to describe a type of measurement instrument, sampling strategy, emissions quantification, or data process.
Top-down	Top-down models account for emissions using aggregated emissions from many individual sources. Emissions from smaller emission sources are not measured directly but may be estimated using models or assumptions. Top-down methods typically involve observations of atmospheric methane.

9.2 FRAMEWORK KEY WORD DESCRIPTIONS

Table A3. Definitions of types of aims.
Aim: what is to be achieved by the emissions monitoring

Aim	Definition
Advisory	To provide data for strategic or policy decision-making.
Scientific knowledge	To provide data for technological or scientific research activities.
Commercial	To provide data for economic gain such as reducing costs, waste, or maximising throughput.
Compliance	To check the reported data against a standard, regulation, or demand.

Table A4. Examples and definitions of types of stakeholders.
Stakeholder: An individual, group or organisation that is impacted by emissions, emissions monitoring (or lack of), have a vested interest or stake in the monitoring.

Stakeholder	Definition
National Measurement Institute	An organisation who realises, maintains, and develops their country's metrological infrastructure.
Regulator	An organisation who enforces emissions compliance with regulations.
Owner	Owner of a site or group of sites.
Operator	Operator of a site or group of sites.
Industry sector	A group of industries related in some way (for example, waste sector).
Method provider	An organisation that supplies a method (and its associated techniques) to carry out the monitoring.
Staff and contractors	People within an organisation that could be affected by the monitoring.
Society / public	People external to any acting organisation that could be affected by the monitoring.
Policy maker / implementers	An organisation which develops and enacts policy. Typically international, national, or local government.
Research group	An organisation that conducts research activities. Typically, a university, NMI, or collaboration of industries.

Table A5. Definitions of types of stakeholders.
Actor: An individual or organisation that plays a role in the monitoring

Actor	Definition
Operator, method provider, research group, NMI	Refer to the definitions under stakeholder.
Measurement service provider	An organisation charged with undertaking the monitoring campaign. They will either be provided with a method by an external organisation (method provider) or be the method provider.
Independent actor	An individual, group, or organisation that has impact, but in a non-direct, independent, or unintentional way (for example, wider society, the public).

Table A6. Definitions of types of drivers.
Driver: a factor that instigates the emission monitoring to happen

Driver	**Definition**
Regulation	The monitoring is to be undertaken due to a regulation. This could be mandatory or voluntary (for example, OGMP 2.0 [31]).
Safety	Monitoring undertaken due to an enforced safety procedure.
Audit	Monitoring undertaken to validate reported emissions against a standard.
Legislation Informing policy	Providing the necessary information for governments, regulators, and organisations to make informative decisions based on data, that would initiate and develop legislation, policies, regulations, and standards.
Public reassurance	Public are reassured by having the appropriate legislation, policies, regulations, and standards in place, and a means to enforce them through regulation. Potentially includes outreach and educational activities.
Process improvement	Conducting monitoring to detect, locate, and possibly quantify leaks, or improve efficiencies to reduce loss of a product (for example, methane).
Research	An investigation to establish facts and provide data to help decision making.
Method development	To develop (enhance, improve, increase scope) a method and its associated techniques.
Method intercomparison	To compare a method (uncertainties), defining the scope and conditions.
Method validation	To compare the method performance (uncertainty) against a standard.

Table A7. Definitions of data reporting requirements, properties keywords.

Property	**Description**
Spatial and temporal	
Geographic Location	Area or location to be monitored, for example, a set of GPS coordinates.
Period	Period to be measured, for example, time of day and year.
Temporal granularity	Snapshot: a single report representing a state at a given time. Periodic: a periodic report with a defined period (or frequency). Continuous: a continuous report with a defined sampling rate.
Spatial granularity	Component: defined as an entity that forms part of a process or system; on an approximate spatial scale of centimetres to metres (for example, a flange that joins two pipes). Functional element: defined as a spatially separate entity that performs a specific purpose; on an approximate spatial scale of metres to hundreds-of-metres (for example, a process tank, boiler unit, or storage unit). Site: defined as a spatially separate premises that performs an activity consisting of a number of functions or consists of one or more functional elements; on an approximate spatial scale of hundreds-of-metres to tens-of-kilometres (for example, a landfill site, tank farm, anaerobic digester plant).

	Regional: defined as a collection of industrial sites, or distinctive areas of transport, urban, or domestic activity; on an approximate spatial scale of tens-of-kilometres to hundreds-of-kilometres (for example., a city, region, or country). National and global: defined as a collection of regions; on an approximate spatial scale of hundreds-of-kilometres and greater.
Data capture percentage (target)	How much (%) of an area (for example, site) to cover or time period to cover (for example, once per month).
Measurand	
Species	The gas species to be measured (for example, methane).
Uncertainty	Target expanded uncertainty to be reported. Expressed as a percentage of the mean emissions rate, for example: Low: < 30% Medium: 30 to 70% High: > 70% Or user specified. The coverage factor (Refer to the Lexicon)
Class	Detection, quantification, estimation and/or localisation.
Type	Threshold (yes or no above a prescribed limit) Concentration Emission rate Complex: consisting of a number of output types of varying complexity; for example, emission rate correlated with activity data, or 2D concentration plots.
Range	Range of measurement, a descriptor should be used to define exactly what this means, for example, minimum quantifiable emissions rate to maximum value that can be measured.

Table A8. Definitions of data reporting requirements, descriptions keywords.

External factors	**Description**
Budget	The approximate budget to perform the monitoring. This must include sufficient context, for example, what the budget must include towards logistics, maintenance etc.
Logistics	Transport: related to the movement and deployment of the monitoring system. Safety: specific site safety requirements; for example, explosive atmospheres, safety courses, access hours etc.
Expectations	Any other requirements not covered.
Operational restrictions	Specific risks or restrictions (for example, explosive atmospheres ATEX).
Regulations	Region or country specific restrictions.
Specific	
Weather proofing	For example, required ingress protection rating.

Autonomous	Whether manual effort must be minimised to acquire data (for example, for continuous monitoring, difficulty in physical access etc.).
Planned to unplanned monitoring	Is the required monitoring part of a planned routine or unplanned (for example, part of an effort to find and fix a repair).
Output type	
Maintenance schedule	An output that initiates, develops, or maintains the maintenance schedule for specific components, functional elements, or for a site.
Standard or procedure	An output that initiates, develops, or maintains standards or procedures.
Threshold	A binary output (for example, above or below a prescribed threshold).
Emission report	Emissions rate with a defined unit (for example, kg/h) and uncertainty.
Technical report	A range of output types (for example, emissions rate, concentration plots, time series data) that form part of a technical report.
Public report	A range of output types that would publicly available (for example, a peer reviewed journal).
Metrological factors	
Evidence of validation	Evidence of how the method was (or will be) validated including scope, conditions, protocol and results.
Traceability	How the output was (will be) related to a relevant standard, (either a reference or primary reference for a given unit).
Calibration	How the method was (will be) calibrated including methods and scope.
Auditing	How the method was (will be) audited.
Method transparency	Are the method properties (defined in Figure 5) accessible and open for viewing?

Table A9. Definitions of emissions source, properties keywords

Physical characteristics	**Description**
Height	Physical height (approximate): this could be used to evaluate access requirements or whether remote-sampling would be more appropriate for monitoring, for practical or health and safety reasons. This should have some reference to a defined reference (descriptions field). Mostly applicable to a functional element, could be maximum height of an object on a site.
Single or multiple releases	For example, to differentiate between single or multiple sources that contribute to a diffuse plume. This keyword requires a descriptions field to set context.
Size (area)	Approximate physical size of the region, site, or functional element being monitored.
Physical plume characteristics	Temperature, exit velocity and whether combusted.
Emission plume characteristics	
Range of emission rate	Range of emission rate(s) (if known) for the target emission source(s).

Gas composition	List of known species, and their composition (if known), in the emitted gas.
Temporal characteristics	Continuous or non-continuous. If “non-continuous”, include temporal details about the source if known (i.e., short lived, episodic, or periodic). This information could be obtained from the site operator.
Source type	Diffuse, point, elevated.
Fugitive or direct	Unintentional emissions or intentional such as a vent or stack

Table A10. Definitions of emissions source, descriptions keywords.

Source	**Description**
Lifecycle	A description of the current lifecycle of the site, functional element, or component: exploration, commissioning, test, decommissioning, post decommissioning, production, special modes.
Composition details	Flare efficiency
Process	Describe relevant operational activities such as planned venting or maintenance
Value chain or sector	Relevant sector such as upstream, production, distribution – relevant to the industry
External	
Topography	A description of the topography, accessibility, location, and physical obstructions that could affect emissions monitoring. For example: ground structure (paved or unpaved) or fences could affect accessibility, topology such as hills or embankments could affect line-of-sight, wind flow, or wind measurements. Site structures (e.g., overhead gantries) could also affect line-of-sight measurements.
Location	
Obstructions	
Accessibility	
Environment	Local climate that could affect measurement or nearby activities that could affect measurements (for example, steam venting that could be an interfering source for techniques that are sensitive to water vapour).
Interfering sources	Nearby extraneous and interfering sources that could affect measurements (for example, a neighbouring functional element or site).
Emission characteristics	To be used to provide additional context to the properties and keywords.

Table A11. Definitions of method, properties keywords.

Measurement requirements	**Description**
Measurand	
Species	Species to be covered by the method
Class	Detection, Quantification, Estimation and/or Localisation to be covered by the method
Type	Type of output to be covered by the method, i.e. emission rate, concentration, threshold or complex (described in the descriptions below)
Range	Range of measurements to be covered by the method, lowest (for example, sensitivity) to highest value (for example, highest emission rate likely to be observed).

Measurement performance	
Uncertainty (Emission rate)	Value as a percentage of the mean. Specify whether standard or expanded (and coverage factor).
Detection limit	Refer to the Lexicon
Quantification limit	Refer to the Lexicon
Range	Range of emissions or concentration that can be measured
Spatial / Temporal	
Spatial granularity	The scope of the method, for example, to measure each FE and provide a site total or be able to measure specific components.
Temporal granularity	The scope of the method, for example, to derive an annual report from continuous measurements -> periodic.

Table A12. Definitions of method, descriptions keywords

Keywords	**Description**
Scope, assumptions, limitations and dependencies	A description of the scope of the method. Assumptions: for example how uncertainty was derived and conditions. Limitations: for example: temperature or environmental limitations. Dependencies: Data (e.g., wind) or physical (e.g., retroreflector).
Metrological factors Evidence of validation and quality system	Evidence of how the method was (or to be) validated including scope, conditions, method, and results. Including evidence of blind testing against a controlled release source.
Traceability	How the output is related to a relevant standard.
Calibration	How the method is calibrated including methods and scope.
Relevant standards	Applicable standards in the traceability.
	How the method is audited.
Method transparency	Are the method properties to be accessible and open for viewing?
Measurement objectives and plan including responsibilities	A description of the protocol or reference to a procedure. A description of sampling protocol and emissions rate calculations specific to the method, for example how the measurements from different techniques are pieced together to form the final reported data. List responsibilities of all the actors including instrument operators, quality assurance, liaison with the site etc
Specific details regarding sampling strategy and measurement requirements	Description of how the measured data from each technique is combined into a final report and how the performance of each technique (for example resolution) determines the uncertainty and granularity of the reported data. The spatial and temporal granularity defines what the method can produced in terms of the reported data.
Training and competencies	Including operating of equipment (related to the source or method and its associated measurement instruments)
Quality assurance criteria checks and maintenance schedule	Specific for the measurement instruments as recommended by the manufacturer

Table A13. Definitions of method elements, properties keywords

Keywords	**Description**
Species	Species that can be measured, quantified or detected.
Measurand	
Sensitivity	These will require some textual description to describe how the tests were performed and the conditions the tests were undertaken (e.g. laboratory)
Dynamic range	
Signal to Noise ratio	
Temporal	
Resolution	Temporal resolution of the technique in terms of measurement and output.
Sampling rate	Of the technique
Bandwidth	
Spatial	
Resolution	Spatial resolution of the technique in terms of measurement and output.
Range	Applicable to remote-sensing, range of measurement.

Table A14. Definitions of method elements, descriptions keywords

Keywords	**Description**
Basic unit of measurement	A description of what the basic unit of measurement is, for example, DIAL it is a called a scan which is a measurement if emissions rate and units are kg/h.
Assumptions	A text field to describe any assumptions made in the defined properties, conditions or how the technique might be deployed and used.
Limitations	For example: temperature or environmental limitations.
Cost	Product cost, cost to hire, deployment costs.
Dependencies	Data (for example, wind) or physical (for example, retroreflector).
What and how does it measure?	Description for setting context and explain dependencies, for example, needs wind etc. Describe the type of measurand if complex (for example, 2D concentration plot). Underlying principles.
Operation	Autonomy, user experience, quality process, calibration process, performance, underlying principles.
Operating conditions	Restrictions in use.
Physical	IP rating, physical size and weight

9.3 CASE STUDY - MONITORING METHANE EMISSIONS FROM ONSHORE LNG FACILITIES

9.3.1 Background

An emissions monitoring campaign was conducted by the National Physical Laboratory which supported a study to better quantify the oil and gas contribution to global emissions of methane [32]. This study was a collaboration between the Environmental Defence Fund, Oil and Gas Methane Partnership, and the Climate and Clean Air Coalition (CCAC) [33]. The monitoring campaign was specifically aimed at quantifying methane emissions from the main processes and activities involved in the liquid natural gas (LNG) chain, including: the liquefaction of gas (at export terminals), ship loading/unloading, and storage and regasification (at import terminals). LNG was chosen as it is a discrete section of the oil and gas sector with clearly defined activities, and there has been significant growth in LNG activities in recent years with little knowledge of emissions.

The aims (referred to as goals in Innocenti et al. 2023) [32] were to provide information on emissions from LNG from selected sites globally to help define industry emission factors (EF) and identify key technological and operational factors that affect emissions. This was achieved by quantifying methane emissions from key functional elements (FE) to allow EFs to be determined for each FE using activity data.

The study provided the opportunity to:

- compare EFs from similar FEs across different sites (referred to as plants in Innocenti et al. 2023) [32] during both liquefaction and regasification,
- demonstrate what could be achieved with a larger sample size, improving inventory accuracy and potential methane reduction,
- identify emissions from non-continuous sources and super-emitters – to allow more accurate inventory reporting and targeted maintenance and repair.

An important goal before the campaign was to define the data reporting requirements, select appropriate LNG sites to monitor and define the essential elements of a monitoring method, including evidence of validation. The framework was only developed after this monitoring campaign; therefore, the framework has been applied retrospectively using the relevant information from the campaign. This case study demonstrates how the framework could be used to define the reporting requirements and select a monitoring site. The monitoring methods set of taxonomies are used to define a specification for a method that could meet the data reporting requirements and used to describe the properties of a method (Differential Absorption Lidar) that was deployed to carry out the monitoring work. The difference between the method specification and the properties of a method highlights the compromises that may have to made when choosing a method, such as budget, safety, logistical constraints.

9.3.2 Defining the data reporting requirements

The goal of the monitoring needs taxonomies is to define the data reporting requirements. A prerequisite to defining the data reporting requirements is to define the purpose of, and drivers for, the monitoring, as well as the relevant stakeholders and actors. Readers are referred to Figure 2 in the main text for the taxonomy that describes and classifies the purposes for emission monitoring.

The purpose of the monitoring was to establish facts about emissions sources (class: emissions driven, driver: research) to develop EFs, to identify and understand non-continuous sources and super emitters. The data will be used for technological and scientific research activities, will provide evidence for improving emissions inventories (aim: scientific knowledge), and provide information for more targeted maintenance and repair (secondary aim: commercial).

Relevant stakeholders include: Industry sector (oil and gas, LNG), a national measurement institute: UK's National Physical Laboratory (NPL) who were tasked with undertaking the measurement campaign), and the owner(s) and operator(s) of each site. The reported data needed to be publicly available to allow dissemination of information to future potential stakeholders: regulators, research groups, policy makers, method providers – therefore there should be the ability to convey relevant information whilst ensuring that the needs of the operator(s) and owner(s) remain anonymous.

Relevant actors include: NMI (NPL, who were conducting the measurements), the site operator(s) (who provided site activity and process data).

The reporting requirements and emissions source characteristics should be used to choose a method or complimentary suite of methods. However, it is recognised that in practice a compromise will ultimately have to be made between the performance of the chosen method (which will affect the quality of reported data) and the budget. Therefore, metrics such as granularity, uncertainty, and range of emissions (based on lowest quantifiable emissions rate) will most likely be targets set when initially defining the reporting requirements, but these targets may have to be revised at a later time.

Readers are referred to Figure 3 in the section (the data reporting requirements taxonomy) in the main report. Based on the aims (scientific knowledge), ideally as much information is required about the emission sources as possible. The required spatial and temporal granularities could initially be defined as:

Spatial granularity:

- Functional element (FE): to investigate the development of EFs (at the FE scale), understand common characteristics of similar FEs, and identify non-continuous and super emitters – ultimately to yield more accurate inventory reporting.
- Site: regassification type and liquification type, to compare EFs across these different sites and obtain site total emissions.
- Regional/National/Global: out of scope for this campaign.

Temporal granularity:

- A periodic high frequency report will provide the highest granularity of data but may be impractical and not cost effective.
- Snapshot: once only at each site but may not provide representative data.

A capture percentage of 100% would include all components, FEs, and sites, and at all times (continuous). However, the feasibility of undertaking such a study is dependent on cost and whether additional sites provide additional value, as well as the logistics, accessibility, and willingness of sites to participate (voluntary programme). Therefore, a survey of sites was conducted to assess the capture percentage that would yield the greatest scientific knowledge within the limitations of the budget.

Based on the aim, the uncertainty target would be set at <30% with a coverage factor of k = 2.0 (approximately 95%) for a reported measurement.

Metrological factors: Evidence of validation of the monitoring method (blind testing against a controlled release of methane), traceability, calibration, auditing (of the monitoring method) and method transparency are important factors to highlight during the definition of the data reporting requirements. These are requirements that should ideally be placed on the selection of a method, but this will be a cost versus performance judgement.

Based on the background information provided, the following properties are more straightforward to define:

Measurand:	Methane.
Class:	Quantification.
Type:	Emission rate.
Output type:	Emission/technical report and EFs.
Specific:	Needs to be able to monitor at any time of the year (and day or night) and the ability to operate outdoors. Possible autonomous operation (although this will be a cost versus performance judgment) and be able to monitor unplanned or planned events. Applicable standards: Industrial Emissions Directive 2010/75/EU Best Available Techniques (BAT) reference document [33] for the refining of oil and gas provides information on performance, indicative costs, and drawbacks of highlighted methods; European Committee for Standardisation EN 17628 [29].
External factors:	Needs to be able to measure on sites with explosive atmospheres and difficult to reach structures (e.g., tanks, pipework). Needs the logistics ability to operate in different countries (shipping, transport, potential movement on site).

9.3.3 Defining the emission source(s)

There are 175 LNG terminals (sites) currently in operation globally [32]. Before the monitoring campaign the International Gas Union (IGU) (IGU World LNG Report, 2017 [34]) was used to identify data to collect and potential facilities at which to carry out monitoring campaigns. The suitability of each site was based on various criteria such as: the costs and logistics of transporting the chosen method (which uses a mobile DIAL facility) to each site, access and dimensions of each site, measurement feasibility based on the reporting requirements, how representative the site was of the industry as a whole, and whether the site added scientific value to the study (for example, geographic coverage and range of processes at each site). Due to budget constraints the campaign was limited to five sites. The emission source taxonomy (refer to Figure 4 in the main text) could be used to list prospective sites and potentially list each FE on each site. The criteria would be defined in the properties and descriptive keywords for each emission source, using the taxonomy to help identify the five most appropriate sites to monitor. An advantage of using the taxonomy to help select sites is that prospective sites can be compared using a common basis.

Tables A15 and A16 show examples for two sites. Each site is described as a single emission source, although in practice each site will consist of multiple sources which could be described by listing all the FEs on site. In turn, each FE could be broken down into its respective components. The taxonomy provides the means to describe emission sources at different spatial scales (classes).

Tables A17 and A18 show examples for two FEs. These FEs may be located on the two site examples given in Tables A15 and A16. FEs of the same type (for example, LNG tanks) may be located at both sites 1 and 2, and they may share common features, particularly physical characteristics. However, the FEs could be listed to highlight and distinguish different characteristics, for example access restrictions.

Table A15. Emission Source 1 description using Figure 4 in the main text.

Emission Source 1		
Class	Site	
Properties	Physical characteristics – size	1000 × 1000 (m)
	Physical characteristics – multiple releases	20 (FEs): List of FEs.
	Physical characteristics – height	30 (m): Tallest stack, height relative to ground.
Descriptions	General	Liquification terminal in region A. The site receives natural gas, processes the raw material, and converts to LNG by liquefaction. The LNG is then loaded onto a ship.
	Location	Country x, state/region y.
	Accessibility	Accessible by road, remote location, located by coast, internal site is restricted access.
	Environment	Sub-tropical, cyclone season May to September – potential to disrupt monitoring.
	Interfering sources	No known sources external to site.
	Topography	Site is flat ground, approximately at sea level.
	Obstructions	None.
	Lifecycle	Midstream and distribution

Table A16. Emission Source 2 description using Figure 4 in the main text.

Emission Source 2		
Class	Site	
Properties	Physical characteristics – size	1000 × 1000 (m)
	Physical characteristics – multiple releases	15 (FEs): List of FEs.
	Physical characteristics – height	30 (m): Tallest stack, height relative to ground.
Descriptions	General	Regasification terminal in region B. The LNG is unloaded from a ship, converted to natural gas, then processed ready for regional distribution.
	Location	Country a, state/region b.
	Accessibility	Accessible by road, located by coast, internal site is restricted access.
	Environment	Temperate.
	Interfering sources	Natural methane source (peat bog) nearby.
	Topography	Site is on sloping ground; approximately at sea level at one end rising to 10 m (above sea level) at the other end.
	Obstructions	None.

	Lifecycle	Midstream and distribution Production.

Table A17. Emission Source 3 description using Figure 4 in the main text.

Emission Source 3		
Class	Functional element	
Properties	Physical characteristics – size	10 × 10 (m)
	Physical characteristics – height	5 (m): Tallest height relative to ground
	Emission characteristics – composition	Methane
	Emission characteristics – source type	Diffuse, point (vent), and possibly elevated
	Emission characteristics – temporal	Continuous and non-continuous (vent).
Descriptions	General	LNG Tank.
	Location	Emission Site 1.
	Accessibility	Accessible by road.
	Interfering sources	Other FEs on site (methane).
	Topography	Flat.
	Obstructions	None.
	Lifecycle	Production.

Table A18. Emission Source 4 description using Figure 4 in the main text.

Emission Source 3		
Class	Functional element	
Properties	Physical characteristics – size	1 × 1 (m).
	Physical characteristics – height	30 (m): Tallest height relative to ground
	Emission characteristics – composition	Mixed: methane, NO_x, CO_2.
	Emission characteristics – source type	Elevated.
	Emission characteristics – temporal	Non-continuous.
Descriptions	General	High pressure flare.
	Location	Site 1.
	Accessibility	100 m × 100m access exclusion around flare.
	Interfering sources	N/A
	Topography	Flat.
	Obstructions	None.
	Lifecycle	Production.

9.3.4 Defining a monitoring method

The monitoring method should ideally be based on the data reporting requirements and the characteristics of the emission source(s) and ensuring a chosen method meets all the essential elements. Table A19 shows an example of defining a method specification based on the data reporting requirements and emissions source data.

Table A19. Method properties using Figure 5 in the main text.

Scope	To measure methane emission rate (and calculate an EF) for each selected FE and estimate a total methane emission rate for each selected site.
Metrological factors	Evidence of validation (including evidence of blind testing against a controlled source), traceability, calibration and auditing. Method to meet standard EN 17628 [29]. Method transparency: the method scope, protocol and metrological factors to be described alongside the reported data in the form of a technical report.
Description of the protocol	The method will measure an emission rate for each selected FE (up to 20 per site) with an uncertainty. The measurements obtained for each FE will be combined with activity data (provided by the site operator) to calculate an EF for each FE. The emission rate measurements and EFs will be presented in the form of a technical report. The estimated total site emission rate will be calculated by summing the emission rates for each FE (taking into consideration upwind sources) and an uncertainty calculated for the site total.
Limitations	There may be limitations on the deployment location of measurement instruments due to the logistical and safety challenges associated with areas that contain explosive atmospheres and elevated sources (up to 30m).
Status	An established method that has evidence of validation and an associated uncertainty. A method listed as a Best Available Technique.
Dependencies	Functional element activity data.
Spatial granularity	To cover FE and site scale.
Temporal granularity	Snapshot (single report for each FE) and periodic (multiple reports for each FE) to be considered.
Uncertainty target	Based on the aim, the uncertainty target would be set at <30% with a coverage factor of k = 2.0 (approximately 95%) for a reported measurement.
Species	Selectively measure methane within the presence of gases such as CO_2 and NO_x.
Class	Quantification.
Type	Emissions rate.
Other	The emission rate and EFs will be listed in a technical report, along with calculations.

9.3.5 Defining the method elements

The data reporting requirements specify an emission rate, therefore the method must consist of measurement instrument, sampling strategy and emission quantification elements. The element descriptions (shown in Table A20) and their properties could be used to define specific requirements.

Table A20. Method element properties using Figure 6 in the main text.

Operating conditions	To be able to operate any time of year (or day/night), outdoors, autonomous - depending on costs, measure explosive areas, operate in multiple countries, there needs to be road access, wide range of environments from temperate to sub-tropical, operate on gently sloping ground - paved roads.

Performance (spatial) resolution	To measure diffuse, point (vent) and elevated sources (up to 30 m). Target performance 3 m to 20 m spatial resolution to be able to approximately locate and distinguish emissions from FEs.
Performance (spatial) range	Maximum size of FE is 100 m length. The diffuse emissions from such FEs may cover a larger area. Depends on the sampling strategy; for example remote-sensing, optical range up to 300 m or network of point-sensors to provide coverage.
Temporal resolution	Continuous and non-continuous sources.
Other	The method will need to be deployed at 5 sites.

Based on the method specification, specific requirements and required method elements a list of candidate methods (and associated method elements) could then be listed along with their associated properties. The candidate methods could then be short listed based on performance versus budget constraints, practicality, logistics and safety factors. The choice of method and its associated elements should be based on holistic consideration of the different types of measurement instrument, sampling strategy, emissions quantification and their properties and descriptions. For example, to report one snapshot for each FE rather than measure periodically on a continuous basis to reduce costs; however, in this case an assumption would be that each snapshot would be a representative sample of the emission rate.

One of the main considerations is whether to use a remote-sensing or point-sensing sampling strategy. Point-sensing may not be possible due to the requirement of measuring areas containing explosive atmospheres, flares and elevated sources. A remote-sensing sampling strategy would require an optical, open path system. To be able to operate day or night the measurement instrument should not necessarily rely on sunlight, therefore an active measurement instrument may be more appropriate than a passive measurement instrument. For the LNG emissions monitoring, the UK National Physical Laboratory (NPL) mobile differential absorption Lidar (DIAL) method was chosen.

With reference to the measurement instrument taxonomy (Figure 9 in the main text), DIAL is categorised under: optical, absorption spectroscopy, active, open path.
With reference to the sampling strategy (Figure 10 in the main text), the NPL mobile DIAL method would be categorised under: remote-sensor, scanning path, resolved range. The sampling platform would be categorised under: mobile, surface based, vehicle.
However, further information detailing how measurements are combined to produce an emissions report (for each FE as well as the site total) need to be described in the method taxonomy (Figure 5 in the main text) under 'Specific details regarding the sampling strategy and measurement requirements'. An example is given in Table A21.

DIAL combines the concentration data with wind measurements to produce emissions flux (Innocenti et al. 2023). With reference to the emission quantification taxonomy (Figure 11 in the main text): Emissions quantification: measured flow, indirect, box method.
Tables A21 and A22 describe the properties of NPL's mobile DIAL method, the former table describing the generic method properties and latter more specific (method element) properties. These should be compared to the data reporting requirements and specifications shown in Table A19 and A20. Example of comparisons are given:

- In Table A21, metrological factors describes how the specification in Table A19 is met, in this case reference to a published article.
- In Table A22, the operating conditions are specified for the DIAL method which is compared against the criteria in Table A20.

Some properties were not specified in Tables A19 and A20, for example the limitations described in Table A22. In practice it may not be possible to specify all the properties in the associated taxonomies as some may not be relevant (depending on the method) and some would be for consideration in terms of overall cost and logistics.

Table A21. Example Method properties of the NPL mobile DIAL method.

Scope	To measure methane emission rate (and calculate an EF) for each selected FE and estimate a total methane emission rate for each selected site.
Metrological factors	Validation, traceability, calibration, quality assurance and uncertainty of the method is described in (Innocenti et al. 2022)[35]. Method meets standard EN 17628 [29]. Wind sensors are calibrated on an annual basis. A uncertainty assessment of DIAL has been published [35], and the validation of the DIAL was previously carried out via a series of controlled field experiments including tests against controlled methane releases from a test stack, all showing agreements on the order of ±20% [36].
Description of the protocol	The method will measure an emission rate for each selected FE (up to 20 per site) with an uncertainty. The measurements obtained for each FE will be combined with activity data (provided by the site operator) to calculate an EF for each FE. The emission rate measurements and EFs will be presented in the form of a technical report. The estimated total site emission rate will be calculated by summing the emission rates for each FE (taking into consideration upwind sources) and an uncertainty calculated for the site total.
Assumptions	The estimated site total emission rate is the sum of all the emissions rates for each FE, taking into account upwind sources. Method captures the whole plume. The snapshot measurements (at the time of campaign) are representative of the mean average emission rate from each FE. Any wind measurements representative of wind field over the whole site.
Limitations	There may be limitations on the deployment location of measurement instruments due to the logistical and safety challenges associated with areas that contain explosive atmospheres and elevated sources (up to 30m). The NPL DIAL requires road access.
Status	An established method that has evidence of validation and an associated uncertainty. The method is listed as a Best Available Technique.
Dependencies	Functional element activity data.
Specific details regarding the sampling strategy and measurement requirements	A vertical range-resolved scan representing 2-D concentration data down wind of the target area (i.e., FE being measured) is acquired at each location. This data is combined with a wind profile (generated from measured wind data) to produce an emission rate. For the NPL mobile DIAL method, the average of four scans are reported for each location (and an uncertainty calculated using their standard deviation and a specified coverage factor). FEs that extend over distances greater than the range of the measurement instrument will require combining emission rates from multiple scans. Additional scans upwind of each FE will need to be combined with the data.

Spatial granularity	Whole site (depending on size and conditions), FE and site scale.
Temporal granularity	Snapshot (single report for each FE)
Detection limit	1 kg/h
Species	Can selectively measure methane within the presence of gases such as CO_2 and NO_x.
Class	Quantification.
Type	Emissions rate.
Other	The emission rate and EFs will be listed in a technical report, along with calculations.

Table A22. Example method element properties of the NPL mobile DIAL method.

Limitations	Requires road access for a 20-tonne vehicle.
Dependencies	Activity data to produce EFs.
What and how does it measure	Uses laser absorption spectroscopy tuned to two wavelengths; one tuned to the absorption peak of methane, and an adjacent wavelength chosen to minimise absorption by the target gas (methane). Produces range-resolved concentration from scattered light of the target area, where the DIAL is directed downwind of this area. This data is combined with wind data to produce an emission rate. Multiple measurements are made to create an average emission rate and uncertainty.
Operation	Requires two specialists to operate. The measurement instrument is portable and can move around the site (to several locations per day). Automatic and continuous calibration using a glass cell filled with a standard reference gas. Reports undergo quality assurance processes at NPL. 30+ years' experience and operation at a wide range of sites.
Operating conditions	Can operate any time of year (or day/night), outdoors, not autonomous, it uses a remote-sensor so can safely measure explosive areas and elevated sources, has operated in multiple countries, requires road access, can operate in a wide range of environments from UK (temperate) to Australia (sub-tropical), can operate on gently sloping ground, includes a pitch and roll sensor to offset gradients.
Physical	20 tonne mobile vehicle.
Performance (spatial) resolution	3.75 m to 20 m (depending on data averaging to reduce noise).
Performance (spatial) range	100 m to 300 m depending on atmospheric conditions. Can move on site to cover multiple areas.
Temporal resolution	Each scan (basic unit of measurement) takes approximately 10 minutes. Continuous and non-continuous sources.
Species	Methane.
Sensitivity	1 kg/h.
Dynamic range	200+ kg/h.
Other	The method is mobile so can be deployed at all 5 sites in turn and can measure elevated sources (at >30 m).

9.4 APPENDIX REFERENCES

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