Supplementary information

Glossary

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

Lexicon

Table B1. General and metrological lexicon.

Accuracy	Closeness of agreement between a measured quantity value and a true quantity value of a measurand.[1]
Amount fraction	See **Mass fraction**, **Mole fraction**, or **Mixing ratio**. This property is related to concentration.
Bias	An estimate of a systematic error.[1]
Calibration	An operation that, under specific conditions, establishes a relationship between the quantity measured (with uncertainties) and a traceable measurement standard (with uncertainties).[1]
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., $\mu g\ m^{-3}$, $mol\ dm^{-3}$). 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.
Error	The difference between a measured value and a reference value.[1] There are two types of error: systematic (bias) and random error.
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.[1]
Measurement	The process of determining a physical quantity.[1]
Measurement uncertainty	A non-negative parameter which characterises the dispersion of measurement results attributed to a measurand.[1]
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),
Precision	The closeness of agreement among indications or measured values obtained by replicate measurements on the same or similar objects under specified conditions.[1]

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.
Repeatability	The measurement precision under a set of repeatability (conditions that are held fixed) conditions.[1]
Reproducibility	The measurement precision under reproducibility conditions[1], i.e. conditions that include different locations, operators, measuring systems, and replicate measurements on the same or similar objects
Resolution	The smallest change in a quantity being measured that causes a perceptible change in measured value.[1]
Sensitivity	The ratio of the change in the measured value to the corresponding change in the value of the quantity being measured.[1]
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.[1]
Uncertainty	See **Measurement uncertainty**
Validation	The assurance that a product, service, or system meets the required needs of the customer and other identified stakeholders.[1]
Verification	The evaluation of whether a product, service, or system complies with a regulation, requirement, specification, or imposed condition.[1]

Table B2. 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).
Cumulative Emissions	Total emissions for a period of time. Units (e.g. kg) and time period should be expressed.
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.[1]
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)[2] 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.
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 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.

Framework key word descriptions

Table B3. Definitions of types of aim.

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 B4. Examples and definitions of types of stakeholder.

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.
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 / implementer	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 B5. Definitions of types of actor.

Actor: An individual or organisation that plays a role in the monitoring

Actor	Definition
Operator, method provider, research group	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 B6. Definitions of types of driver.

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[3]).
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. Sub categories could be: • Emission factors: o Develop. o Improve. o Validate. • Understand the source: o Leakage paths. o Identify range of emissions. o Identify non-continuous emitters. o Measure gas composition. o Identify source type: Diffuse, elevated or point.
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 B7. Definitions of data reporting requirements, properties keywords.

Property	Definition
Spatial and temporal	
Geographic Location	Area or location to be monitored, for example, a set of GPS coordinates.

% Capture	Required percentage coverage of site (spatial) and (temporal).
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.
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	For definitions, refer to Tables B1 or B2: Categories are: Threshold (yes or no above a prescribed limit) Concentration Emission rate Cumulative emissions Emission flux 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 B8. Definitions of data reporting requirements, descriptions keywords.

Descriptions category	Definition
External factors	

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?
Reproducibility	A description of the reproducibility conditions and results (i.e. uncertainties under the tested conditions)

Table B9. Definitions of emissions source, properties keywords

Property	**Definition**
Physical characteristics	
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 (complex)	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 a combusted source.

Emission 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.
Spatial granularity	Refer to Table B2 for definitions, categories: component, functional element, site, regional, national and global.
Temporal granularity	Refer to Table B2 for definitions, categories: continuous and non-continuous.
Source type	Refer to Table B2 for definitions, categories: Diffuse, point, elevated.
Class	
Fugitive	Unintentional emissions, e.g. leaks.
Vented	Intentional emissions from processes, e.g. venting.
Incomplete combustion	Emissions resulting from incomplete combustion.

Table B10. Definitions of emissions source, descriptions keywords.

Descriptions category	Definition
Source	
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	Describes 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 Location Obstructions Accessibility	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.
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).

Table B11. Definitions of method, properties keywords.

Measurement requirements	Definition
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, emission flux, cumulative emissions, concentration, threshold or complex

Measurement performance	
Uncertainty	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, lowest (for example, sensitivity) to highest value (for example, highest emission rate likely to be observed).
Spatial / Temporal	
Spatial granularity	The scope of the method, for example, to measure each functional element and provide a site total or be able to measure specific components. Categories are: component, functional element, site, regional, national and global
Temporal granularity	The scope of the method, for example, to derive an annual report from continuous measurements to periodic. Categories are: snapshot, periodic and continuous.

Table B12. Definitions of method, descriptions keywords

Descriptions category	**Definition**
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).
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
Metrological factors and quality system	
Evidence of validation	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. Details of reproducibility and repeatability tests
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.
Auditing	How the method is audited.
Method transparency	Are the method properties to be accessible and open for viewing?
Reproducibility	A description of the reproducibility conditions and results (i.e. uncertainties under the tested conditions)

Table B13. Definitions of measurement instrument, properties keywords

Properties	**Definition**
Selectivity	Intended species that can be measured, quantified or detected. Species that could interfere with the measurements.
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). For example, a definition of the timescales for short term and long term draft and the measurand. A detailed breakdown of uncertainty into into its constituents: e.g. bias, random uncertainty etc
Dynamic range	
Signal to Noise ratio	
Linearity	
Drift – short term and long term	
Uncertainty	
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 B14. Definitions of measurement instrument, descriptions keywords

Descriptions category	**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 and limitations	A text field to describe any assumptions made in the defined properties, conditions or how the technique might be deployed and used.
	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.
Passive or sniffer	Sniffers are instruments where a sample of gas to be measured is directed towards a sensor by means of a generated air flow. Passive are instruments where the sensor is placed within the gas being measured without any generated air flow.
Physical	Ingress Protection (IP) rating, physical size and weight

Case study - Monitoring methane emissions from onshore LNG facilities

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[4]. This study was a collaboration between the Environmental Defence Fund, Oil and Gas Methane Partnership, and the Climate and Clean Air Coalition (CCAC). 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[4] 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[4] 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 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.

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 Tables B3 to B6 (above) and 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 large 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 Tables B7 and B8 (above) and Figure 3 in the main text (the data reporting requirements taxonomy).. 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 large 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 derived-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[5] for the refining of oil and gas provides information on performance, indicative costs, and drawbacks of highlighted methods; European Committee for Standardisation EN 17628[2].

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).

Defining the emission source(s)

There are 175 LNG terminals (sites) currently in operation globally[4]. Before the monitoring campaign the International Gas Union (IGU) (IGU World LNG Report[6], 2017) 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 Tables B9 and B10 and 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 B15 and B16 show examples for two sites: labelled emission source 1 and 2. In these tables 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.

Tables B17 and B18 show examples of two FEs: labelled emission source 3 and 4 located on site 1 and 2 respectively. The scope of this study was to investigate how EFs may differ between similar FE that may be located on the same site or different sites (across different nations). This framework provides a means to categorise FEs and highlight different characteristics and operational factors between similar FE that could affect EF.

Table B15. Emission Source 1 description using Figure 4 in the main text.

Emission Source 1		
Spatial Granularity	Site	
Properties	Physical characteristics – size	1000 × 1000 (m)
	Physical characteristics – multiple releases	20 (FEs): An example provided in Table B17
	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. Anonymised for the purposes of this paper.
	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 B16. Emission Source 2 description using Figure 4 in the main text.

Emission Source 2		
Spatial Granularity	Site	
Properties	Physical characteristics – size	1000 × 1000 (m)
	Physical characteristics – multiple releases	15 (FEs): An example provided in Table B18
	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. Anonymised for the purposes of this paper.
	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 B17. Emission Source 3 description using Figure 4 in the main text.

Emission Source 3		
Spatial Granularity	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	Site 1.
	Accessibility	Accessible by road.
	Interfering sources	Other FEs on site (methane).
	Topography	Flat.
	Obstructions	None.
	Lifecycle	Production.

Table B18. Emission Source 4 description using Figure 4 in the main text.

Emission Source 4		
Spatial Granularity	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 2.
	Accessibility	100 m × 100m access exclusion around flare.
	Interfering sources	N/A
	Topography	Flat.
	Obstructions	None.
	Lifecycle	Production.

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 B19 shows an example of defining a method specification based on the data reporting requirements and emissions source data.

Table B19. Method properties using Tables B11 and B12 (above) and 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[2]. Method transparency: the method scope, protocol and metrological factors to be described alongside the reported data in the form of a technical report.
Scope	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 derived 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[5].
Dependencies	Functional element activity data – in order to calculate EFs.
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.

Defining the method instrument, sampling strategy and emission quantification

The data reporting requirements specify an emission rate, therefore the method must consist of measurement instrument, sampling strategy and emission quantification elements. An example of a method element (i.e. instrument) is shown in Table B20.

Table B20. Instrument 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 7 in the main text), DIAL is categorised under: optical, absorption spectroscopy, active, open path.

With reference to the sampling strategy (Figure 8 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 B21.

DIAL combines the concentration data with wind measurements to produce emissions flux[4]. With reference to the emission quantification taxonomy (Figure 9 in the main text): Emissions quantification: measured flow, indirect, box method.

Tables B21 and B22 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 B19 and B20. Example of comparisons are given:

- In Table B21, metrological factors describe how the specification in Table B19 is met, in this case reference to a published article.
- In Table B22, the operating conditions are specified for the DIAL method which is compared against the criteria in Table B20.

Some properties were not specified in Tables 19 and 20, for example the limitations described in Table B22. 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 B21. 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[7]. Method meets standard EN 17628[2]. Wind sensors are calibrated on an annual basis. An uncertainty assessment of DIAL has been published[7], 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%.[8]
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 derived 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	A vertical range-resolved scan representing 2-D concentration data down wind of the

regarding the sampling strategy and measurement requirements	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 B22. 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).

Supplementary information references

1 International Vocabulary of Metrology – Basic and general concepts and associated terms (VIM), 3rd edition, https://www.bipm.org/doi/10.59161/JCGM200-2012, (accessed 22 August 2024).
2 EN 17628, https://standards.iteh.ai/catalog/standards/cen/1134347e-e278-42cd-9967-2a4f34ac0fe6/en-17628-2022, (accessed 22 August 2024).
3 OGMP 2.0 – The Oil & Gas Methane Partnership 2.0, https://ogmpartnership.com/, (accessed 22 August 2024).
4 F. Innocenti, R. Robinson, T. Gardiner, N. Howes and N. Yarrow, Comparative Assessment of Methane Emissions from Onshore LNG Facilities Measured Using Differential Absorption Lidar, *Environ. Sci. Technol.*, 2023, **57**, 3301–3310.
5 European Commission. Joint Research Centre. Institute for Prospective Technological Studies., *Best available techniques (BAT) reference document for the refining of mineral oil and gas industrial emissions: Industrial Emissions Directive 2010/75/EU (integrated pollution prevention and control).*, Publications Office, LU, 2015.
6 IGU World LNG Report 2017 – IGU, https://www.igu.org/resources/igu-world-lng-report-2017/, (accessed 22 August 2024).
7 Remote Sensing | Free Full-Text | Uncertainty Assessment of Differential Absorption Lidar Measurements of Industrial Emissions Concentrations, https://www.mdpi.com/2072-4292/14/17/4291, (accessed 22 August 2024).
8 R. Robinson, T. Gardiner, F. Innocenti, P. Woods and M. Coleman, Infrared differential absorption Lidar (DIAL) measurements of hydrocarbon emissions, *J. Environ. Monit.*, 2011, **13**, 2213–2220.